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Department of Geosciences

The Bigganjárgga Tillite re-visited: a stratigraphic and sedimentological study

Egil Edvardsen

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University of Tromsø – The Arctic University of Norway

Abstract

The Neoproterozoic “tillite”-bearing sequences of the Smalfjord Formation in Varanger, northern Norway have retrieved considerable attention in geological literature since first described and discovered over a century ago. Much of the attention relates to the so-called Reusch’s Moraine also known as the Bigganjárgga Tillite, which rests directly on top of a striated sandstone surface pointing to glacial scouring and a glacial origin (i.e. a tillite). Correlations of similar deposits from the same era elsewhere in the world have resulted in theories of a world-spanning glaciation, the “snowball Earth”-theory, where great amounts of the Earth was covered by snow and ice. However, the theory is criticized by many, and better understanding of diamictite deposits in general have caused several re-evaluations (globally) of these presumed tillites, which apparently can be easily confused with various coarse-grained gravity flow deposits (i.e. debrites and slump deposits).

In this thesis, the classical type locality for the Varanger Ice Age at Bigganjárgga in Varangerbotn, eastern Finnmark, has been scrutinized with one question in mind, is the Bigganjárgga Tillite really a tillite or may it represent something else? In order to answer this question, a detailed facies analysis is combined with a digital outcrop model and thin section analysis. From the facies analysis, four facies associations are recognized: FA 1 – thin-bedded sandstone (representing fluvial deposits), FA 2 – thick-bedded diamictite (representing tillite or debrite deposits), FA 3 – thin-bedded sandstone (representing turbidites) and FA 4 – thin-bedded diamictite (representing fine-grained debrite or slump deposit). The appearance of rip-up mud clasts and several associated negative imprints within FA 1 suggest that the unit most likely was consolidated before erosion of the Bigganjárgga Unconformity (a part of the regional Varangerfjorden Unconformity) and deposition of the Bigganjárgga Diamictite (FA 2) took place. A confirmation to this was given by stylolite observations in the field and imbricated grains (with irregular grain-grain contacts), and quartz cementation in the petrographic analysis consistent with pressure solution occurring at a considerable burial depth (c. 2 km in sedimentary basins with normal geothermal gradient). Thus, it seems likely that the debated striations associated to the Bigganjárgga Unconformity developed in consolidated material, implying glacial abrasion.

The Bigganjárgga Unconformity at the outcrop is seen in relation to the extensive regional Varangerfjorden Unconformity where clear evidences for glacial erosion have been reported in

previous studies. Therefore, it is assumed that the investigated unconformity was made by glacial erosion that occurred at regional scale. The Bigganjárgga Diamictite (FA 2) itself is seen in relation to the surrounding units below and above. Due to the appearance of FA 3 (turbidite sandstones) and FA 4 above (fine-grained gravity flow deposits) the diamictite, a regional relative sea level rise is assumed eventually drowning and flooding the diamictite body. The preserved evidence surrounding the Bigganjárgga Diamictite that caused the glacial origin assumptions are the cemented sandstone and the regional unconformity below with striations correlative to nearby glacial direction features, the burial by fine-grained turbidites and fine-grained gravity flow deposits with randomly clasts up to cobble size units above the diamictite associated with subsidence and ice rafted debris.

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Egil Edvardsen **Mai 2019**

Abbreviations

TKFZ – Trollfjorden-Komagelv Fault Zone

SRFZ – Sredni-Rybahi Fault Zone

VFZ – Varangerfjorden Fault Zone

VFU – Varangerfjorden Unconformity

CTF – Central Timan Fault

WTF – West Timan Fault

KP – Kanin Peninsula

TVR – Tanafjord-Varangerfjord Region

BRS – Barents Sea Region

BGD – Bigganjárgga Diamictite

BGU – Bigganjárgga Unconformity

Ma – “Mega annum” or “Million years”

FA – Facies Associations

Contents

1 Introduction

In Varanger in Finnmark, Northern Norway, a Late Precambrian diamictite unit rests directly upon preserved striations carved into a cross stratified sandstone (Reusch, 1891; Bjørlykke, 1967). The units are separated by an unconformity, which represents a hiatus with a potential lack of as much as 150 Ma of strata (Siedlecka, 1990, referred in Rice & Hofmann, 2000, p. 357). This is one of a few places in the world where a diamictite is deposited directly upon a striated pavement. Mostly, it is referred to as the Bigganjárgga Tillite, lithostratigrapically belonging to the Vendian Smalfjord Formation. Several interpretations exist in the literature regarding the depositional history of the diamictite itself (e.g. Edwards, 1984). The first and most famous one was presented by Reusch (1891), and encourage a glacial origin for the striations and the diamictite. There have been done several works in Finnmark on this unit and correlative deposits and many have agreed on the glacial origin (e.g. Holtedahl, 1918; Føyn, 1937; Reading & Walker, 1966; Bjørlykke, 1967; Banks et al., 1971; Siedlecka & Siedlecki, 1971; Edwards, 1975; 1997; Føyn & Siedlecki, 1980; Nystuen, 1985; Rice & Hofmann, 2000). The "snowball Earth" hypothesis proposed by Harland (1964b) was one of the most important reasons to why many supported the glacial interpretation for the type locality of the Varangian Ice Age.

The second interpretation arose due to the skepticism to the glacial theory (Dal, 1900). Thus, several authors have suggested that the diamictite was a deposit made by a subaqueous gravity flow and the striations to be made by material sliding down a slope scouring into the underlying sediment surface (Crowell, 1964; Jensen & Wulff-Pedersen, 1996; Arnaud & Eyles, 2002). In addition, Edwards (1975) developed a third interpretation combining the two others suggesting that the diamictite was deposited as a flow till. Due to the disagreement, not only in regards of the opposing interpretations, but also in regards to documented observations, a re-evaluation of all the published literature and available data seems necessary.

Objective

Thus, in regards of the disagreement, the objective of this master thesis is to provide an extensive review of published literature about the Smalfjord Formation in general and those related to the Bigganjarga Tillite in particular. An outcrop investigation focusing on the sedimentology and stratigraphy is presented to provide stratigraphic context. Throughout the years, there have not been many studies focusing on the petrography of the sedimentary rocks at Bigganjárgga most likely due to the protection by law of the outcrop. A permission to collect four samples was given specifically for this project by the local county council (Nesseby Kommune/ Fylkesmannen i Finnmark; Appendix 1).

In addition, a constructed photographic 3D-modell of the outcrop (Appendix 3) and petrographic analyses of the collected samples add new insight to the origin of the Bigganjárgga Tillite. Combined with the published literature, this will contribute a modern and objective interpretation regarding the depositional history of the so-called Bigganjárgga Tillite, referred to as the Bigganjárgga Diamictite for the remaining part of the thesis until a conclusion of its origin is reached.

Figure 1 The famous sketch by Reusch (1891) and a present-day photograph showing the main features with the striated surface and the diamictite itself.

2 Geological setting

2.1 Tectonic framework

The crystalline Precambrian bedrock, autochthonous and allochthonous sedimentary rocks, and detrital sediments characterize the Varanger Peninsula. Variations in conditions have occurred during the formation, under different tectonic regimes and climate changes. From the four known glaciations from the Cryogenian and Early Ediacarian periods in the world, two are documented in Finnmark, which together are referred to the Varangian Ice Age (Levine et al., 2006; Chumakov, 2008; Nystuen, 2013b).

2.1.1 Rodinia and Baltica

The Precambrian supercontinent, Rodinia, was during the Late Precambrian 850-750 Ma ago, broken into several pieces (Fig. 2.1), one of them being Baltica. The exact position of Baltica and its orientation during the Neoproterozoic era have been studied by many, some proposing the controversy idea that the continent was tectonically inverted (Hartz & Torsvik, 2002; Torsvik, 2003), whereas other ones were rejecting it (Cawood & Pisarevsky, 2006).

In the northeastern and northwestern corner of Baltica, respectively along the Timanian and Baltoscandian margins (Fig. 2.1b), the continent were suffering severe deformation during the Timanian and Caledonian orogenies.

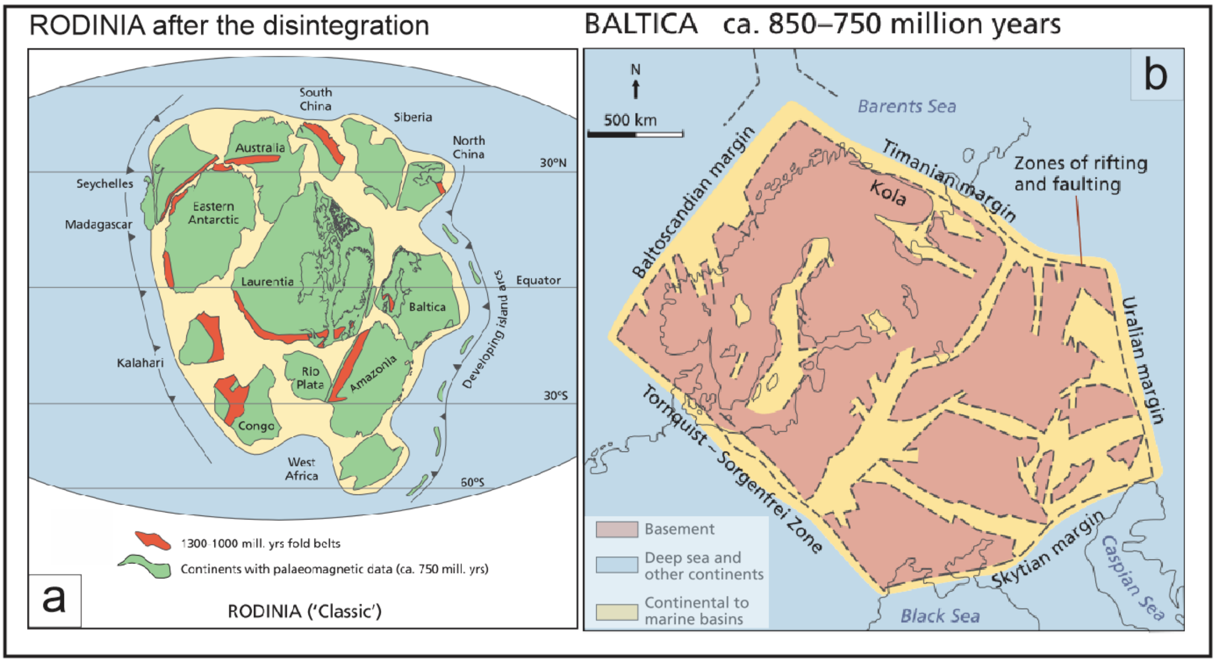

Figure 2.1 (a) The classical opinion of the way Rodinia may have looked like after the break up, with Laurentia and Baltica aside each other oriented according to north/south and the Equator. (b) The Baltic Shield is presented with its margins, tectonical zones and surrounding oceans. Both from Nystuen (2008a).

2.1.2 The Timanian Orogeny, 600-560 Ma ago

The Timanian Orogeny occurred 600-560 Ma ago on the eastern side of the Baltic Shield along the Timanian Margin (Fig. 2.1b). The heaviest oceanic plate was subducted under the less dence Baltic Continent, resulting in the formation of volcanic island arcs, folding and crusting against the Baltic Continent. Traces of what happened are best seen in the Timan Region in today's Russia, given the name, but also on the northeastern side of the Trollfjord-Komagelv Fault Zone (TKFZ) in Norway, the orogeny is visible (Siedlecka & Siedlecki, 1967; Siedlecka, 1975; Roberts & Siedlecka, 2002; Fossen et al., 2013; Nystuen, 2013b). Siedlecka et al. (2004) even proposes that the Seiland province in western Finnmark might provide traces of a Late Riphean to Vendian Balto-Timanian triple junction from the borders between the Timanian Margin, the Baltoscandian Margin and a third unknown riftarm or province.

2.1.3 The Caledonian Orogeny, 500-405 Ma ago, and the Wilson-cycle

Some hundred million years later, another orogeny took place – the Caledonian Orogeny. To explain the Caledonian Orogeny one have to know about the Wilson cycle. The Wilson-cycle, first stated by John Tuzo Wilson (1963) is a well-known and accepted interpretation concerning the plate tectonical processes on the Earth (Nordgulen & Andresen, 2013; Polat, 2014). There exists several models of the cycle (e.g. Trujillo & Thurman, 2008; Nystuen, 2013a) and it can be used on any opening- and closing time course between two continents. As the tectonic forces on the Earth never stops, there are no definite beginning on the cycle. Nevertheless, as a beginning, look at Rodinia, a supercontinent existing in the Precambrian. The supercontinent was, according to (Cawood & Pisarevsky, 2006; Nystuen, 2008a; 2013a; 2013b), broken into smaller continents, such as Laurentia and Baltica, during the rifting phase. The course in the cycle is presented in Fig. 2.2. After the rifting, the spreading went on in the spreading phase with an active rift axis producing new oceanic floor in the Iapetus Ocean. At some stage, the extensional forces declined and the compressional forces established its presence by introducing subduction zones and islandic arcs as in the island arc phase. As the time went by, the compressional forces prevailed the extensional forces by adding several subduction zones as the ocean was closing. The islandic arc mountain ranges gained further greatness in the foreland in the closing phase before the collisional phase "ended" the cycle. The resulted in the total growth of the Caledonian mountain range on a newly made continent (Nordgulen & Andresen, 2013). Fig. 2.1a shows the classical or traditional opinion of how Rodinia looked like before the splitting and contains the pre-continents to what later became Laurentia and Baltica, in addition to several other pre-continents (Nystuen, 2008a; 2013b).

The rocks west on the Baltic shield in today's western Finnmark were close to the Baltoscandian Margin and the gradually growing mountain range during the Caledonian Orogeny and are accordingly allochthonous nappes. Further east towards the Varanger Peninsula, the rocks are para-autochthonous or autochthonous (Fig. 2.3). Due to their distance from the center of the collision of the continents, well preserved crystalline bedrock and terrigenous rocks of Precambrian age are present there (Nystuen, 2013b; 2013a).

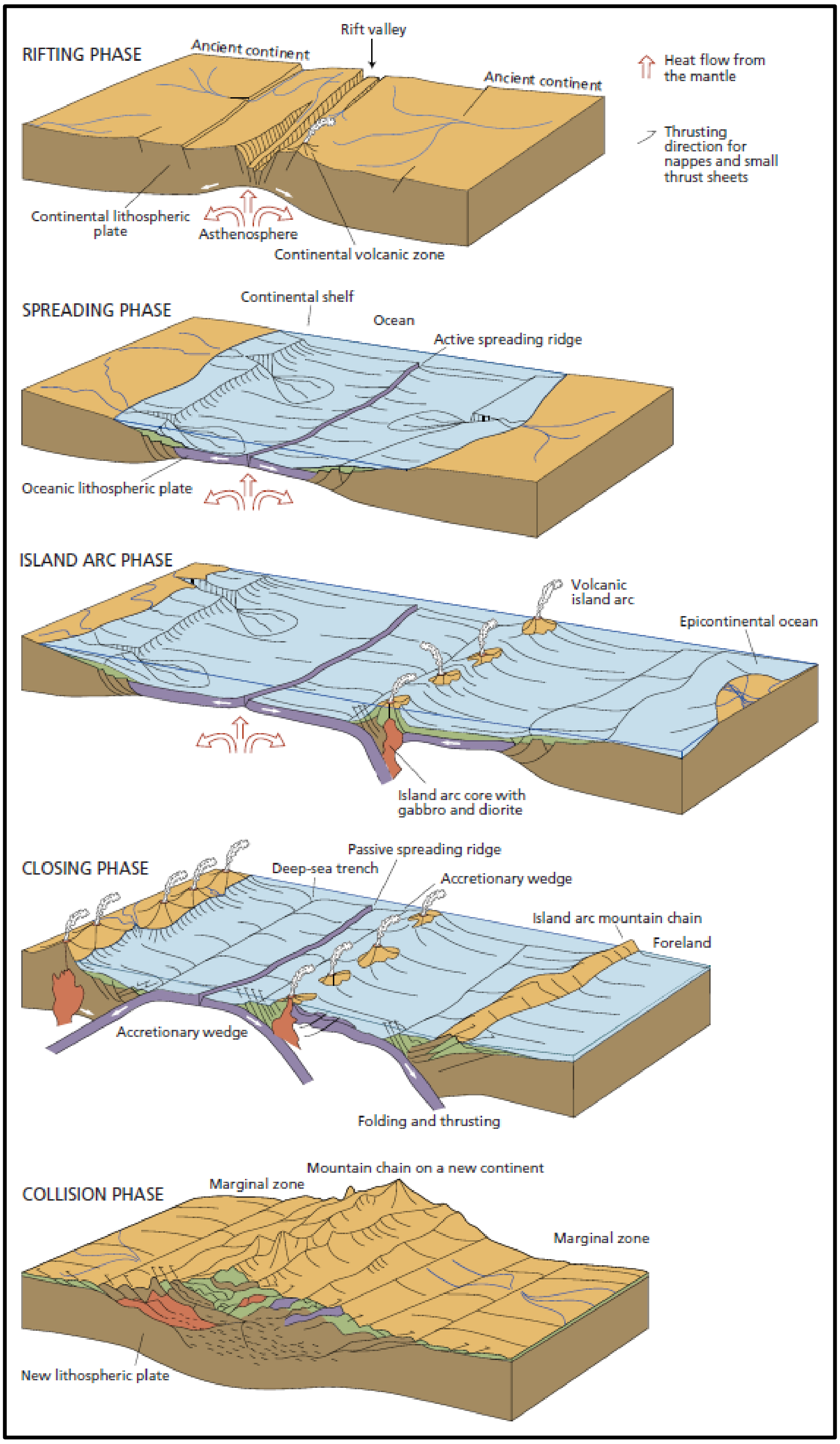

Figure 2.2 The complete Wilson Cycle in five steps in a model from Nystuen (2008b). From the top starting with the rifting phase followed by spreading phase, island arc phase, closing phase and collision phase.

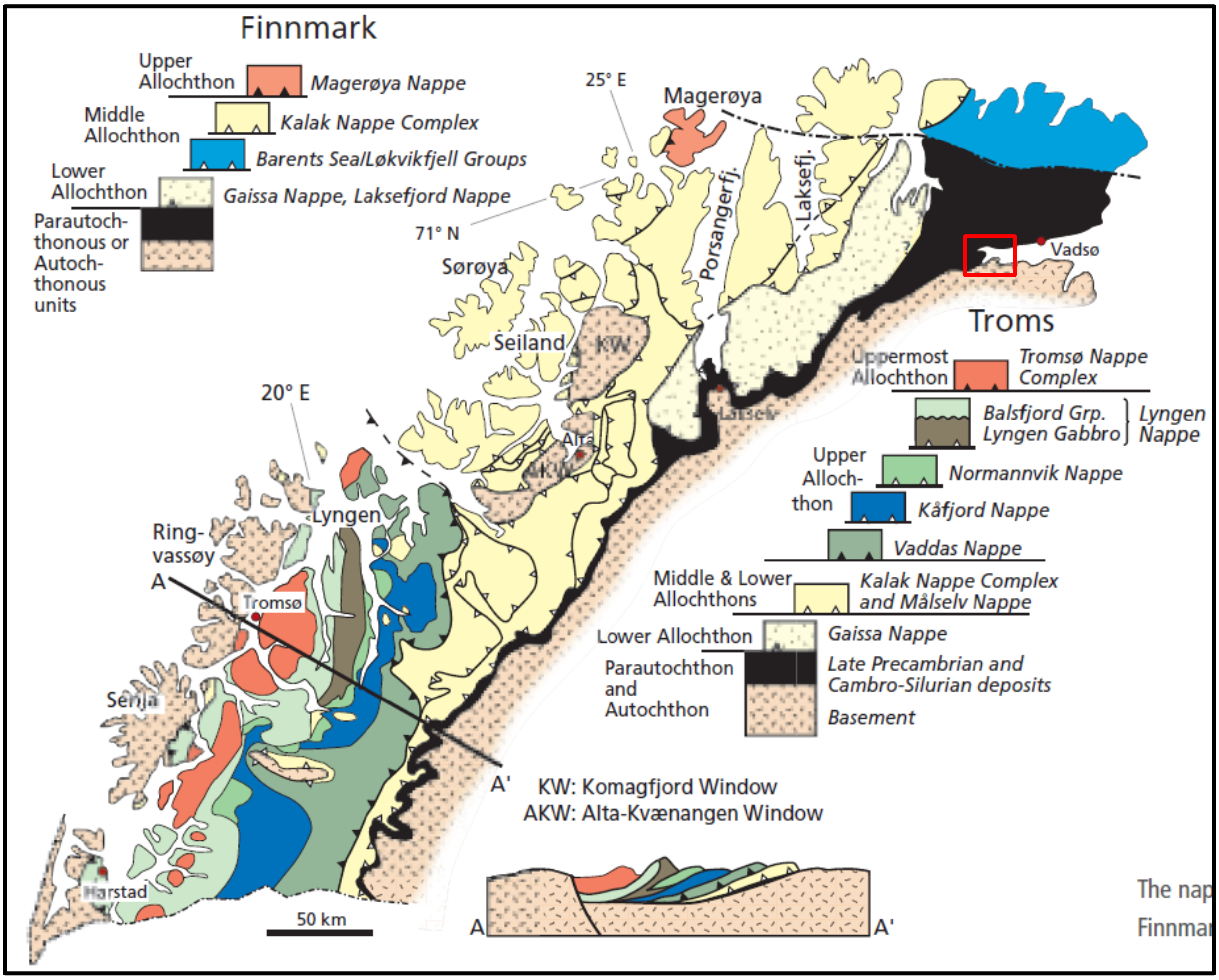

Figure 2.3 Division of the Caledonian nappe series of Troms and Finnmark counties, northern Norway, from lower to uppermost in Troms and from lower to upper in Finnmark. In addition, the autochthonous and para-autochthonous deposits in black and the bedrock in beige with brown dashes are seen in both counties. Red box marks study area. Modified from Fossen et al. (2008).

2.1.4 The Trollfjord Komagelv Fault Zone

The autochthonous rocks in the Tanafjord-Varangerfjord Region make up a considerable part of the Varanger Peninsula, but there are also parts from the Middle Allochthon in the Caledonian nappe series present, namely the Barents Sea Group (Fig. 2.3). A regional lineament divides the Varanger Peninsula into two geological regions from northwest to southeast; the autochthonous Tanafjord-Varangerfjord Region and the allochthonous Barents Sea Region (Siedlecka & Roberts, 1992). The regional lineament is known as the Trollfjord-Komagelv Fault Zone (TKFZ) (Siedlecka & Siedlecki, 1967), a fault zone which still was active during the Caledonian Orogeny. According to Nystuen (2013b), the TKFZ was a zone of weakness already present once Rodinia broke up and a fault zone in Precambrian times. In addition, the eastward continuation of the TKFZ was an important structure in the Timanian Margin, where it is referred to as the Sredni-Rybachi Fault Zone (Section 2.1.2). Townsend et al. (1987) even mention the possibility of a reactivation in Late Paleozoic, Mesozoic or even Cenozoic times. Siedlecka & Roberts (1992) presented the TKFZ as the "most prominent structural feature of the peninsula", and according to Fossen et al. (2013), this fault is in a class of its own ranging for hundreds of kilometers. Despite the sedimentary successions are from more or less the same time period, they do not correlate other than that because they accumulated in very different tectonic settings (Siedlecka & Roberts, 1992).

Numerous of authors have tried to give an explanation related to the rocks around the TKFZ, among others (Siedlecka, 1975; Johnson et al., 1978; Pesonen et al., 1989). The most prominent interpretation was gained by Kjøde et al. (1978) from palaeomagnetic data from mafic dykes and proposes a "[…] minimum of 500 km of dextral strike-slip translation along the TKFZ […]". Thus, a proposition by Nystuen et al. (2008) decreased the length of the lateral translation along the TKFZ. The transition of the fault zone into Russia as the Sredni-Rybachi Fault Zone (SRFZ) was further elaborated by Røe (2003) . The TKFZ and the SRFZ were together, "[…] thought to correspond to the CTF [Central Timian Fault] […]" (Røe, 2003, p. 259), a fault in the Kanin-Timan Region in Russia. This serve as a support for the tectonic importance of the TKFZ and found why it is worthy gaining more information on the theme. Meanwhile the localization of the TKFZ in big parts are on land, at least those parts investigated, another fault zone was argued for under Varangerfjorden; the Varangerfjorden Fault Zone.

2.1.5 The Varangerfjorden Fault Zone

Holtedahl (1918) and later Røe (2003) proposed a fault zone under the present day seafloor of the Varangerfjorden (Fig. 2.4b, Fig. 2.4c) and called it the Varangerfjorden Fault Zone (VFZ). The argumentation of Røe (2003) relied on the correlation between the the Veinesbotn Formation on the southern side of the fjord, and the Riphean succession including the Vadsø and the Tanafjorden groups on the northern side of the fjord. According to her, a younger age is found in the Veinesbotn Formation than previously assumed which then implies "[…] the presence of a major fault zone hidden beneath Varangerfjorden […]" (Røe, 2003, p. 259). Note however, that the VFZ have not yet been documented in the subsurface, and that the presence of this structural element was rejected by Roberts et al. (2011) based on reflection seismic data gathered in the outer Varangerfjorden area.

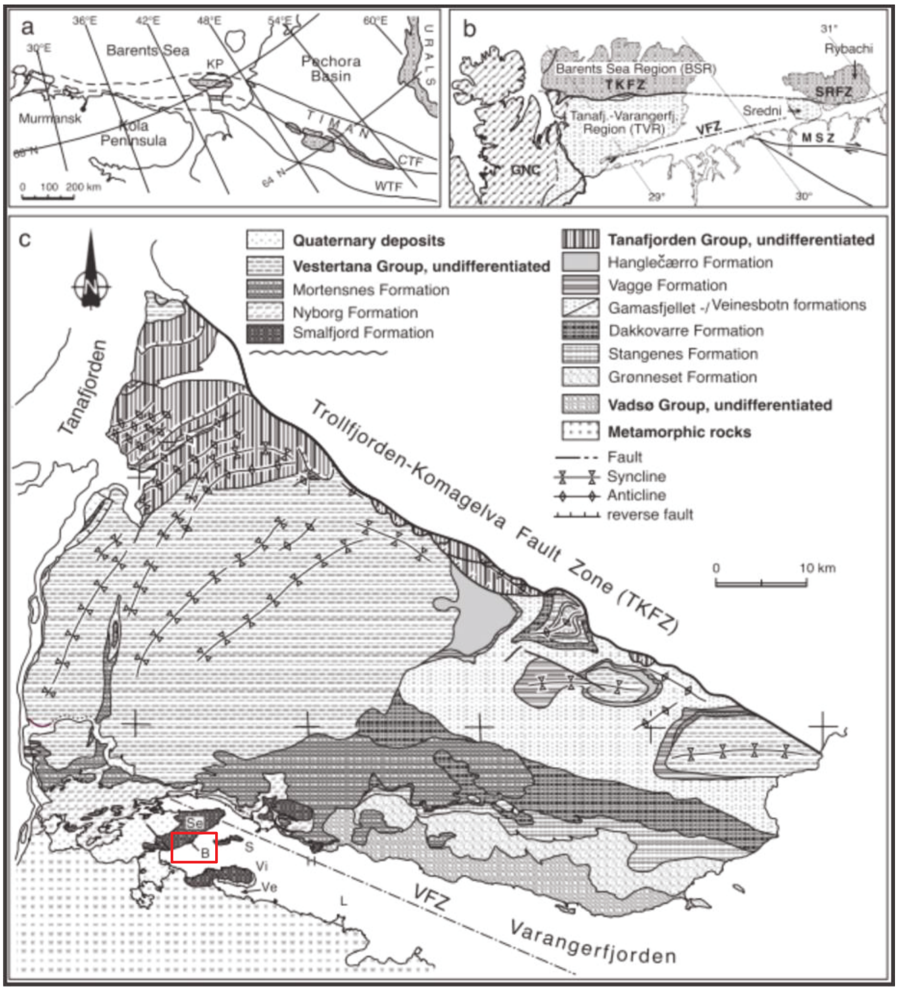

Figure 2.4 (a) Map showing the regional setting in northern Europe and Russia in the Timan-Varanger Belt related to regional fault zones, e.g. Central Timan Fault (CTF), West Timan Fault (WTF) and Kanin Peninsula (KP). (b) Shows the relationship between the Trollfjord-Komagelv Fault Zone (TKFZ), the Sredni-Rybachi Fault Zone (SRFZ) and the Varangerfjorden Fault Zone (VFZ) in the border areas of Norway and Russia. (c) A geological map of the Tanafjord-Varangerfjord Region (TVR). Red box marks the study area outside Karlebotn. Locations marked with letters, B-Bigganjárgga Diamictite, H-Handelsneset, L-Lattanjar'ga, S-Sjåholmen, Se-Selesnjar'ga, Ve-Veinesfjorden and Vi-Vieranjar'ga. Modified from Røe (2003).

2.1.6 Glacial impacts

2.1.6.1 Climate variations

In the Proterozoic eon, the variations in climate were shifting rapidly as tropical climate was recurrently and abruptly terminated and replaced by immense cold. Severe variations in the amounts of greenhouse gases (i.e. CO_2 and CH_4) in the atmosphere (Hoffman et al., 1998b; Bodiselitsch et al., 2005) and crowning carbonates (cap carbonates) may have been the critical factor for these rapid changes and traces of them (Chumakov, 2008). No less than four glacial periods are known from the Cryogenian period and the Early Ediacaran period which occurred between 850 to 600 Ma ago in the world. In Finnmark, two glacial periods have traditionally been suggested, one documented by the Smalfjord Formation and yet another by the Mortensnes Formation (see Fig. 2.6). Together they have been given the name the Varangian Ice Age and corresponds respectively to the Marinoan Glaciation (Nystuen, 2013b) and the Gaskiers Glaciation (Levine et al., 2006) elsewhere.

2.2 Lithostratigraphic framework of the Varanger Peninsula

The visibility of the crystalline Precambrian basement in Eastern Finnmark increases southwards as it outcropping more towards south. Deposited unconformably on the bedrock are sedimentary successions of Late Precambrian and Cambrian-Ordovician age, ranging in thicknesses around 4000 to 5000 meters (e.g. Edwards, 1984; Siedlecka & Roberts, 1992). On the southwestern side of the TKFZ, in the Tanafjord-Varangerfjord Region, the sedimentary divisions consist of the Vadsø, the Tanafjorden and the Vestertana groups (Banks et al., 1974; Siedlecka & Roberts, 1992), all thinning southwards against the basement and the Varangerfjorden. Northeast of the TKFZ in the Barents Sea Region, the sedimentary divisions consists of the Barents Sea Group, the Berlevåg Formation (Føyn, 1937; Reading, 1965) and the Løkvikfjellet Group (Siedlecka & Siedlecki, 1967).

2.2.1 Tanafjord-Varangerfjord Region

The Tanafjord-Varangerfjord Region (TVR) located south of the TKFZ comprises as mentioned three groups, approximately 4000 meters in total thickness (Siedlecki & Levell, 1978). First, the lowermost Riphean Vadsø Group (Siedlecka & Roberts, 1992), formerly named the ‘Older Sandstone Series’ (Banks et al., 1974), then the Late Riphean Tanafjorden Group (Føyn, 1937) later revised and shortened by Siedlecka & Siedlecki (1971), and last the Vendian to Lower Cambrian Vestertana Group (Siedlecka & Siedlecki, 1972), formerly the “Tillite-bearing series” (Reading, 1965). The expansion of the TVR stretches towards west heading out of the Varanger Peninsula and the Vestertana Group and comprises the Digermulen Group with the gradual appearance on the Digermulen Peninsula west of Tanafjorden (Føyn, 1937).

2.2.1.1 The Vadsø Group – syn rift

The Riphean Vadsø Group as a nomenclature (Siedlecka & Siedlecki, 1971; Banks et al., 1974; Siedlecka & Roberts, 1992) is the lowermost sedimentary successions in the Varangerfjord area and sits directly above the crystalline bedrock. The thicknesses are approximately between 290 meters to 660 meters (Siedlecka & Siedlecki, 1971) along the northern shore of Varangerfjorden on these gently deformed northward dipping beds. The group comprise seven formations (Banks et al., 1974; Røe, 2003) with the Veidnesbotn Formation making the seventh and lowest one, or six according to a recent paper by (Røe, 2003) were the Klubbnasen Formation is the lowest one and the Veidnesbotn Formation is presented as belonging to the Tanafjorden Group. In addition, the following formations are still as proposed by Banks et al. (1974) and are the Fugleberget, the Andersby, the Paddeby, the Goldneselva and the Ekkerøya formations (Fig. 2.5). Interpretations of the sedimentary facies and depositional characteristics within show depositional environments variating between being fluvial and deltaic prevailing syn-rift conditions in the extensional Timan Varanger Belt (Røe, 2003).

2.2.1.2 The Tanafjorden Group – post-rift

The Late Riphean Tanafjorden Group (Røe, 2003), formerly the “Older Sandstone Series” (Siedlecka & Siedlecki, 1971) and later the “Tana Subgroup” (Føyn, 1937) are resting on the unconformity on top of the Ekkerøya Formation, a regional unconformity according to (Bjørlykke et al., 1967) in the Vadsø Group. This marks the beginning of the lowest Grønneset

Formation in the Tanafjorden Group. Afterwards follows the Stangnes, the Dakkovarre and the Gamasfjellet formations proposed by Rice & Townsend (1996), the Veidnesbotn, the Vagge, the Hanglečearro and the Grasdalen formations (Røe, 2003). The successions exibit relatively consistent thicknesses along the Varanger Peninsula (Fig. 2.5), all together somewhere between 1468 to 1665 meters (Siedlecka & Siedlecki, 1971). The formations were mainly accumulated in shallow marine environments (Siedlecka & Siedlecki, 1971; Siedlecka & Roberts, 1992; Røe, 2003) prevailing post-rift extensional conditions and any unconformities within are absence. Nevertheless, the uppermost Grasdalen Formation, which marks the boundary of the uppermost Tanafjord Group to the Smalfjord Formation in the Lower Vestertana Group are somehow difficult to differentiate from each other due to the erosional unconformity between them (Johnson et al., 1978).

2.2.1.2.1 The Varangerfjorden Unconformity?

The erosional boundary separating the Vadsø and Tanafjorden groups from the Vestertana Group represents an unconformity of regional extent, referred to as the Varangerfjorden Unconformity (VFU) (Siedlecka & Siedlecki, 1971). The low angle unconformity also occur beneath the lower diamictite in the Smalfjord Formation at Bigganjárgga (the stratigraphic focus and study area of this thesis) was proposed to be part of a glacial palaeovalley following the morphological outline of the present day Varangerfjorden already by Bjørlykke (1967). Several others have also established such a regional connection (e.g. Holtedahl, 1918; Rosendahl, 1931; 1945; Føyn, 1937; Edwards, 1984; Laajoki, 2001; 2002).

2.2.1.1 The Vestertana Group – a period of variations

Resting above the Tanafjorden Group is the Vendian to Lower Cambrian Vestertana Group (Reading, 1965), a 1317-1665 meter thick group comprising five different formations. The first one, containing the well-known Bigganjárgga Diamictite is the Smalfjord Formation. Because this unit is the main focus of this study, further elaboration will be provided in Section 2.2.2. The overlying succession comprises the Nyborg, the Mortensnes, the Stappogiedde formations (with three members, respectively the Lillevatn, Innerelva and Manndrapselva), and at top the Breivik Formation (Reading, 1965). As insinuated by the former names for the Smalfjord and Mortensnes formations – “Lower Tillite” and “Upper Tillite” respectively (Fig. 2.6), they were early on interpreted to be of glacial origin, and accordingly the turbidites in the Nyborg

Formation were interpreted to be of interglacial origin (Føyn, 1937). Despite the general consensus of a glacial interpretation, an opposing mass flow interpretation has also been suggested for the Bigganjárgga Diamictite (e.g. Crowell, 1964; Jensen & Wulff-Pedersen, 1996; Arnaud & Eyles, 2002).

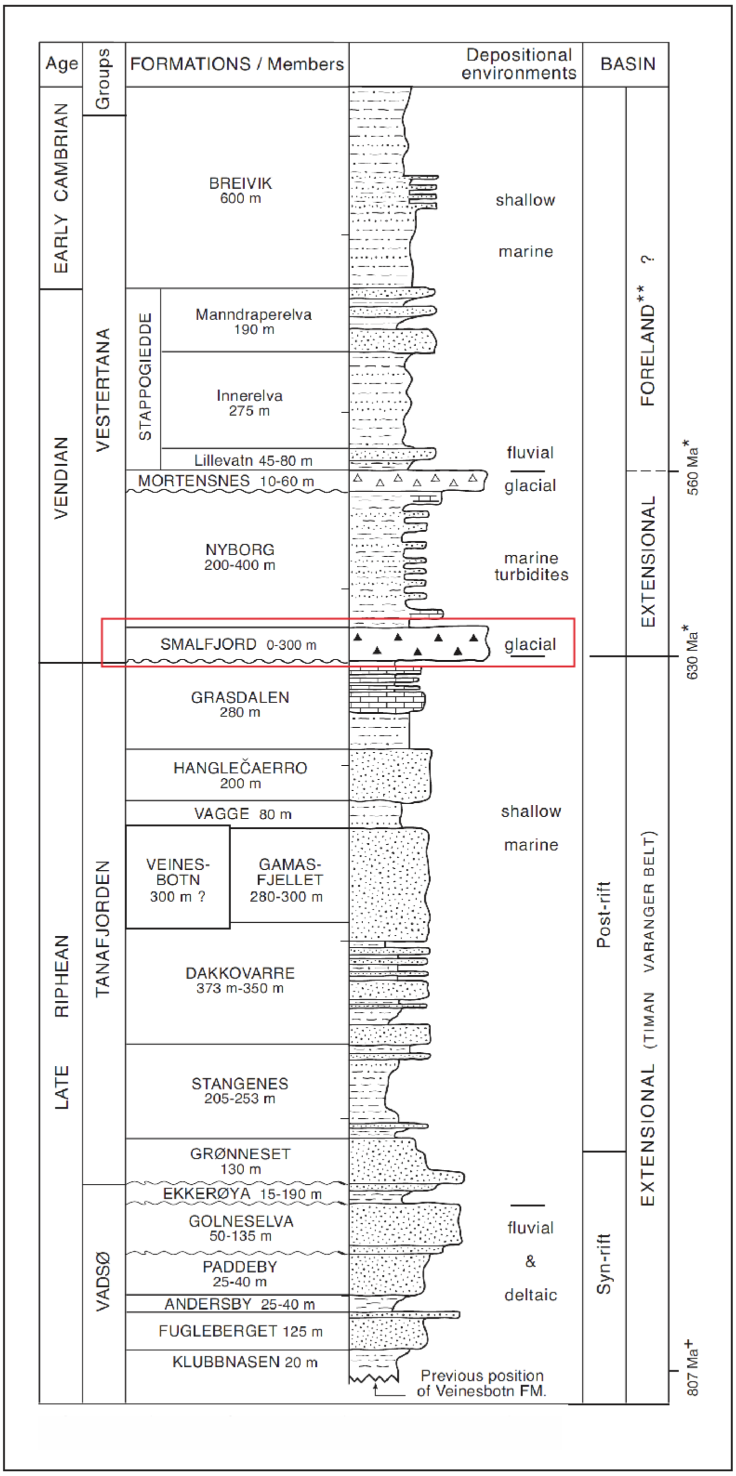

Figure 2.5 Lithostratigraphic presentation of the Vadsø, Tanafjorden and Vestertana groups in the Tanafjord-Varangerfjord Region. The red box shows the emplacement of the Smalfjord Formation. Modified from Røe (2003).

The younger formations above relate to nearshore and shelf environments. The tectonic setting for the basin evolution in the Vestertana Group is interpreted as transitional from extensional through Vendian to a foreland basin setting in Vendian to Early Cambrian (Røe, 2003), (Fig. 2.5).

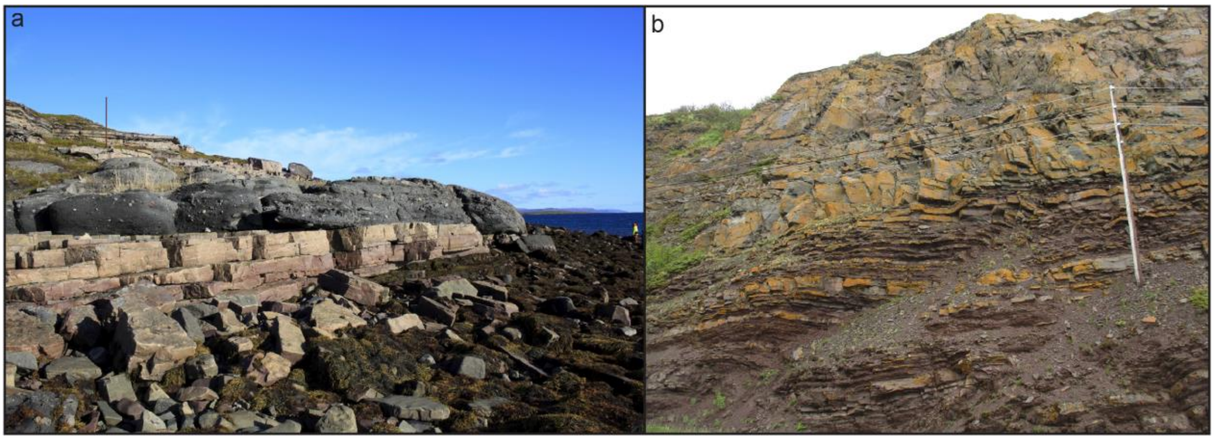

Figure 2.6 The two formations in the Vestertana Group that have given name to the Varangian Ice Age. (a) The classical outcrop in Karlebotn showing the so-called Bigganjárgga Tillite in the Smalfjord Formation. (b) According to Siedlecka et al. (1998), an inconformity separates the lower Nyborg and the upper Mortensnes formations from each other north of the road at Bergeby, east of Nesseby. This lower part of the Mortensnes Formation includes the Mortensnes Tillite (massive unit above electrical pole). Photo: Sten-Andreas Grundvåg.

2.2.2 The Smalfjord Formation – The host of the Bigganjárgga Diamictite

The lowest formation of the above-mentioned Vestertana Group, the Smalfjord Formation (Bjørlykke, 1967; Edwards, 1975) is deposited on top of the Grasdalen Formation of the Tanafjorden Group and the Vadsø Group with a 1-2 degree regional unconformity (e.g. Føyn, 1937; Reading & Walker, 1966; Bjørlykke, 1967). This is the formation onto where the Bigganjárgga Diamictite rests (Fig. 2.10a & b). The formation is exposed on Laksefjordvidda, the Tanafjorden area and partially at the innermost part of Varangerfjorden (Føyn, 1937; Reading & Walker, 1966; Bjørlykke, 1967; Banks et al., 1971; Føyn & Siedlecki, 1980; Rice et al., 2011).

2.2.2.1 Laksefjordvidda and Krokvatn Palaeovalley

The presence of three layers of diamictites intervening two layers of sandstones were recognized in the Smalfjord Formation by Føyn & Siedlecki (1980) in the area around Krokvatnet on Laksefjordvidda. Respectively, the names are Lower, Middle and Upper Krokvatn Diamictites and Lower and Upper Krokvatn Sandstones. They are deposited in a north-south trending palaeovalley eroded into the underlying Tanafjorden Group on Laksefjordvidda (Føyn & Siedlecki, 1980; Rice et al., 2011).

2.2.2.2 Tanafjorden area

Correlations have been made between the Upper Krokvatn Diamictite from the Laksefjordvidda area and the Smalfjord Formation in this area (Føyn & Siedlecki, 1980; Edwards, 1984). Repetitions of erosional surfaces, diamictites and laminated mudstones, sometimes with intervening sandstones were found best exposed at Gæssenjar'ga and Louvtat (Reading & Walker, 1966; Føyn & Siedlecki, 1980; Edwards, 1984; Hansen, 1992; Arnaud & Eyles, 2002; Rice et al., 2011).

2.2.2.3 Varangerfjorden and Varangerfjorden Palaeovalley

It has been proposed that the Smalfjord Formation in the Varangerfjorden area correlates to the lower to middle part of the Krokvatn succession (Føyn & Siedlecki, 1980). In total there are two diamictite facies and four sandstone and conglomerate facies described and identified from the outcrops investigated, at Vieranjar'ga, Nesseby, Handelsneset, Sjåholmen and Bigganjárgga (Bjørlykke, 1967; Edwards, 1975; Føyn & Siedlecki, 1980; Edwards, 1984; Laajoki, 2001; Arnaud & Eyles, 2002; Laajoki, 2002; Baarli et al., 2006; Arnaud, 2008). In addition, descriptions of palaeoislands or monadnocks made of Neoarchean to Paleoproterozoic gneisses protruding the Neoproterozoic sedimentary Tanafjorden and Vestertana groups are provided for the area around Karlebotn (Bjørlykke, 1967; Laajoki, 2004; Baarli et al., 2006; Levine et al., 2006). Their shape were according to Levine et al. (2006) a result of glacial, marine and continental erosion processes and in general aligned with one of the main fault directions in the region (N20°W). Laajoki (2004) showed traces of glacial erosion from Pleistocene and the Marinoan glaciation in the Larajæg'gi outcrop, and Levine et al. (2006) announced that the Smalfjord Formation directly onlaps the monadnocks.

2.2.1 Barents Sea Region

The Barents Sea Region (BSR) north of the TKFZ comprises three lithostratigraphic units on the Varanger Peninsula. A last group, the uppermost Digermulen Group is only seen on the Digermulen Peninsula (Banks et al., 1971). Therefore, the first group on the Varanger Peninsula is the Late Riphean (Vidal & Siedlecka, 1983) to early Vendian Barents Sea Group (Siedlecka & Siedlecki, 1967). Following is the most likely Vendian Løkvikfjellet Group (Siedlecka & Siedlecki, 1967; Siedlecka & Roberts, 1992; Siedlecka et al., 2004), which is transgressively and angular unconformable deposited on the previously mentioned Barents Sea Group (Siedlecki & Levell, 1978). Lastly is the Berlevåg Formation (Siedlecki & Levell, 1978), which is trust upon the two other groups and may be considered as part of the Kalak Nappe complex found on the Norkynn Peninsula (Siedlecka & Siedlecki, 1967).

2.3 Theories for the origin for the Bigganjárgga Diamictite

To avoid confusion among the handful of various interpretations of its origin and to facilitate discussion later on, a presentation of the previous published models will follow below.

2.3.1 Tillite origin

After the discovery of the "Reusch's Moraine" in 1891 (Fig. 1 & Fig. 2.7), a geological remnant from a bygone era, this have undoubtedly been the interpretation endorsed by most geologists (Reading & Walker, 1966; Bjørlykke, 1967; see Fig. 2.8; Edwards, 1975; Nystuen, 1985; Rice & Hofmann, 2000). A few names have been suggested for the Bigganjárgga Diamictite throughout the years. However, all of these have always been related to the interpretation that says a cross-stratified sand first was deposited and lithified, before protracted erosion by a glacier eroded the sandstone for several hundreds of meters with the resulting regional unconformity (at the outcrop referred to as the Bigganjárgga Unconformity). Once the glacier started to retreat, the striations were carved into the sandstone and the conglomerate was deposited on top as a till (i.e. glacial debris deposited directly from ice). Despite Reusch's conviction and his slightly patronizing postulations such as «At man har ægte isbrefurer for sig og ikke nogen slags stribning på speil, vil vel enhver, der kjender disse fænomener, kunne overbevise sig om paa stedet» (Reusch, 1891, p. 83), not all have agreed upon this interpretation.

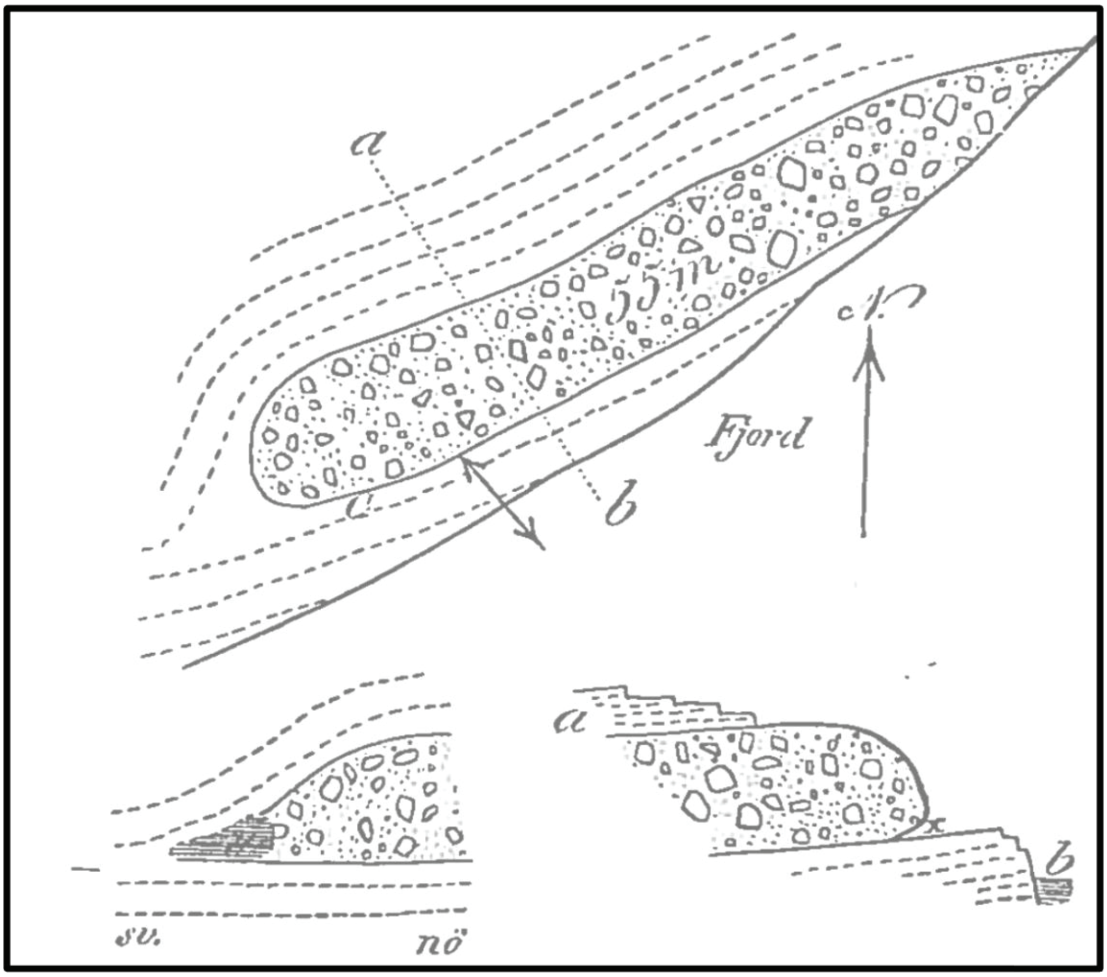

Figure 2.7 A sketched map from the Bigganjárgga outcrop and a cross section through the BGD from the first time described. Modified from Reusch (1891).

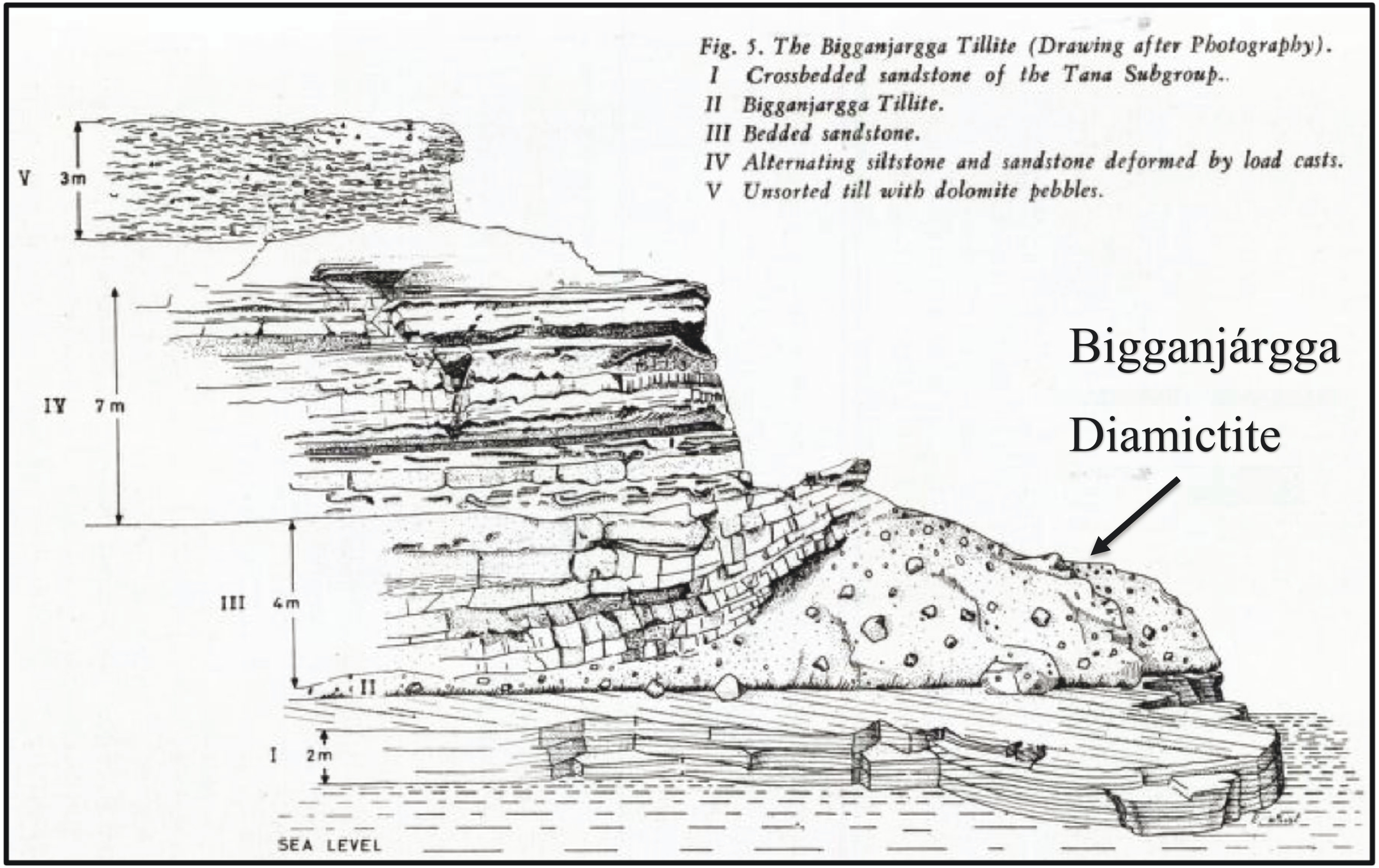

Fig. 5. The Bigganjargga Tillite (Drawing after Photography).
I Crossbedded sandstone of the Tana Subgroup..
II Bigganjargga Tillite.
III Bedded sandstone.
IV Alternating siltstone and sandstone deformed by load casts.
V Unsorted till with dolomite pebbles.

Figure 2.8 A drawing made by Bjørlykke (1967) from a photograph marking the appearance of the stratification at the Bigganjárgga outcrop. The names of the units from the paper (I – V) are also seen in the figure. Modified from Bjørlykke (1967).

2.3.2 Debrite origin

Critical reinvestigations of the Bigganjárgga Diamictite caused Crowell (1964) to suggest that its origin might as well be related to a gravity driven mass flow rather than a glacier. By his opinion, as “masses of till-like material […] can form as the result of so many diverse processes” (Crowell, 1964, pp. 97-98), further evidence had to be presented if the “Tillite origin” should maintain as the correct interpretation. He also mentioned that after his “very profitable few hours spent along the north shore of the Varangerfjord […] several important questions needed to be answered before glacial origin could be accepted without reservation” (Crowell, 1964, p. 95). After a brief account, these doubts comprise the way that the diamictite lens was surrounded by the quartzitic sandstone. The sandstone below the diamictite was for instance according to him by no means of another age than the diamictite itself. Thus, the striations in that sandstone were thought to probably have been made when the sand still was soft, and their way of formation could as likely have been made by rocks sliding as by gouging ones.

This criticism and the notion that “distinguishing between different types of diamictites is difficult and sometimes impossible” (Jensen & Wulff-Pedersen, 1996, p. 138), were among the reasons leading to Jensen & Wulff-Pedersen’s postulations proposing that the Bigganjárgga Diamictite being a lithified debris flow deposit – a debrite. Additionally, they pinpoint that the majority of the early workers did not address this problem and that they only “discussed the diamictites in a stricktly glacial context” (Jensen & Wulff-Pedersen, 1996, p. 138). Another argument was related to the lack of contemporaneous deformation in the sequence which would reject a slump or slide theory according to Reading & Walker (1966). However, they also mention that the diamictite coincide with a period where glacial activity supposedly was widespread and that this would support and be of importance for a glacial interpretation. Notwithstanding, this was not decisive in their conclusion.

A similar interpretation was reached by Arnaud & Eyles (2002), however suggesting that the debrite originated from moraine material deposited under rift basin settings on a subaqueous debris apron. They suggest the possibility that glacial ice could have contributed with material either directly or through fluvioglacial systems, but except that, they did not see any evidence of direct glacial deposition. Respectively, referring to the schematic depositional model for the Smalfjord Formation and the stratigraphic cross-section in Fig. 2.9 from Arnaud & Eyles (2002; their Fig. 9 & Fig. 2).

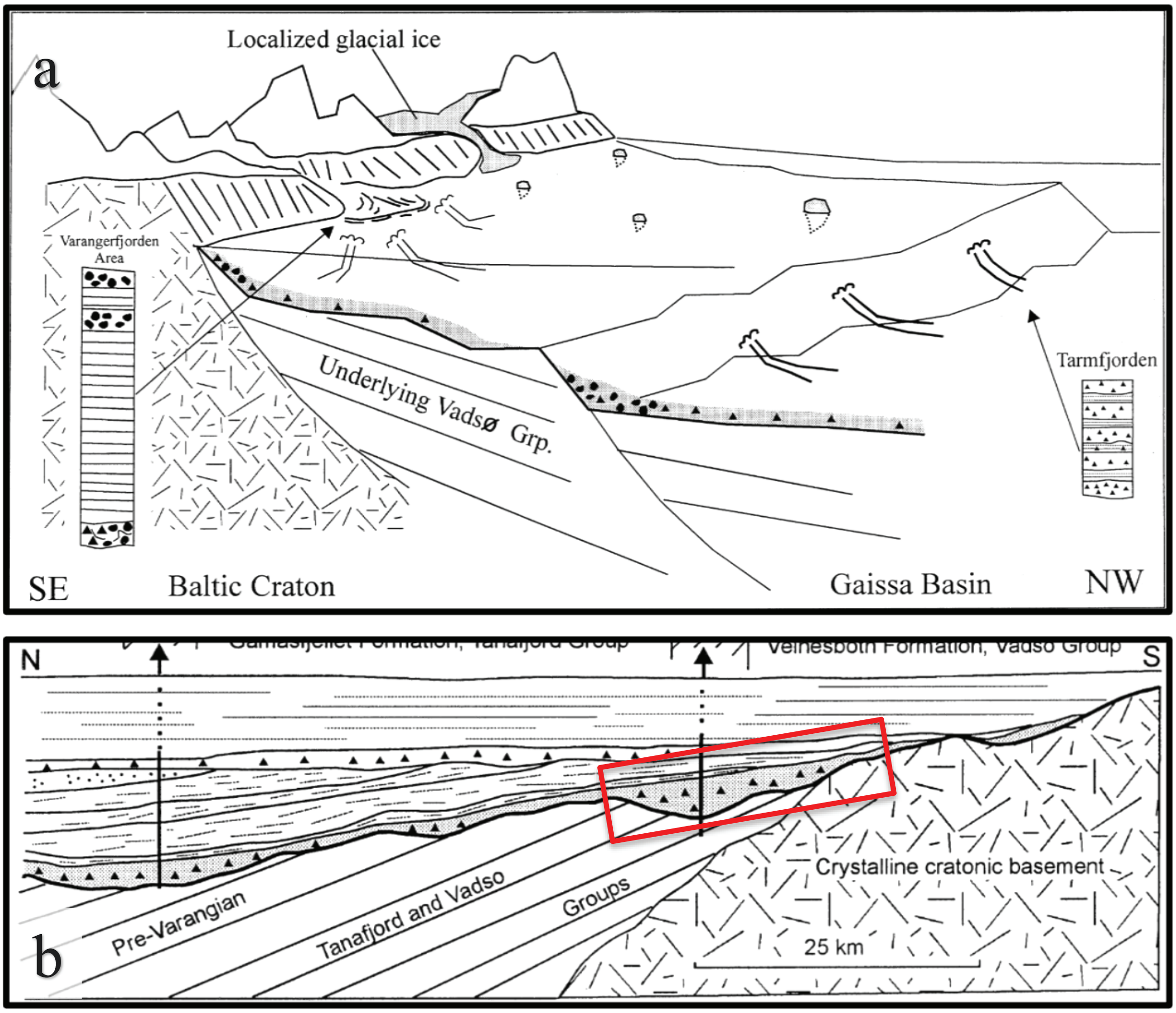

Figure 2.9 (a) Schematic depositional model showing the interpreted environment once the BGD was deposited. The model is used for and describe the occurrence of the Smalfjord Formation in Varangerfjorden and Tarmfjorden areas. (b) The grey shaded area inside the red box shows the presumed geometry and stratigraphic position of the Smalfjord Formation in the Varangerfjorden area. Both figures are modiefied from Arnaud & Eyles (2002).

2.3.3 Flow till origin

A third theory emerged as an alternatively combination of the two others after Edwards endeavor in 1975. The erosional and depositional agent was still thought to be a glacier, but he presumed that the deposit, that he called "[…] [the] debris-rich stagnant glacial ice […]"(Edwards, 1975, p. 91), was only temporarily deposited once the glacier had retreated. Subsequently, melting of the ice in the ice-cored moraine took place, leaving the unstable material to flow downslope as a flow till. The sequence making the melt out tills was thereupon repeated, with the result being the central portion of the melt-out till surrounded by flow tills on both flanks (Fig. 2.11).

The melting glacial water would have caused sorting whereas the variations in this melt water due to volume changes associated with melting ice would have caused disruptions. During the later transgression, erosion was greater on one of the flanks, leaving traces of the flow tills only at the opposite flank. He further explains the lack of striations westwards of the diamicitite because of erosion down to that surface exposing it and erasing the glacial striations. This strong erosion was apparently absent during the deposition of the diamictite itself. The sandstone above containing a few pebbles and a block of tillite (diamictite) was according to him deposited during a following rapid submergence of the diamictite explaining the erosion and winnowing which occurred to the exposed parts of the diamictite. The till nomenclature is here used in the same way as Edwards (1975) describes it in his paper.

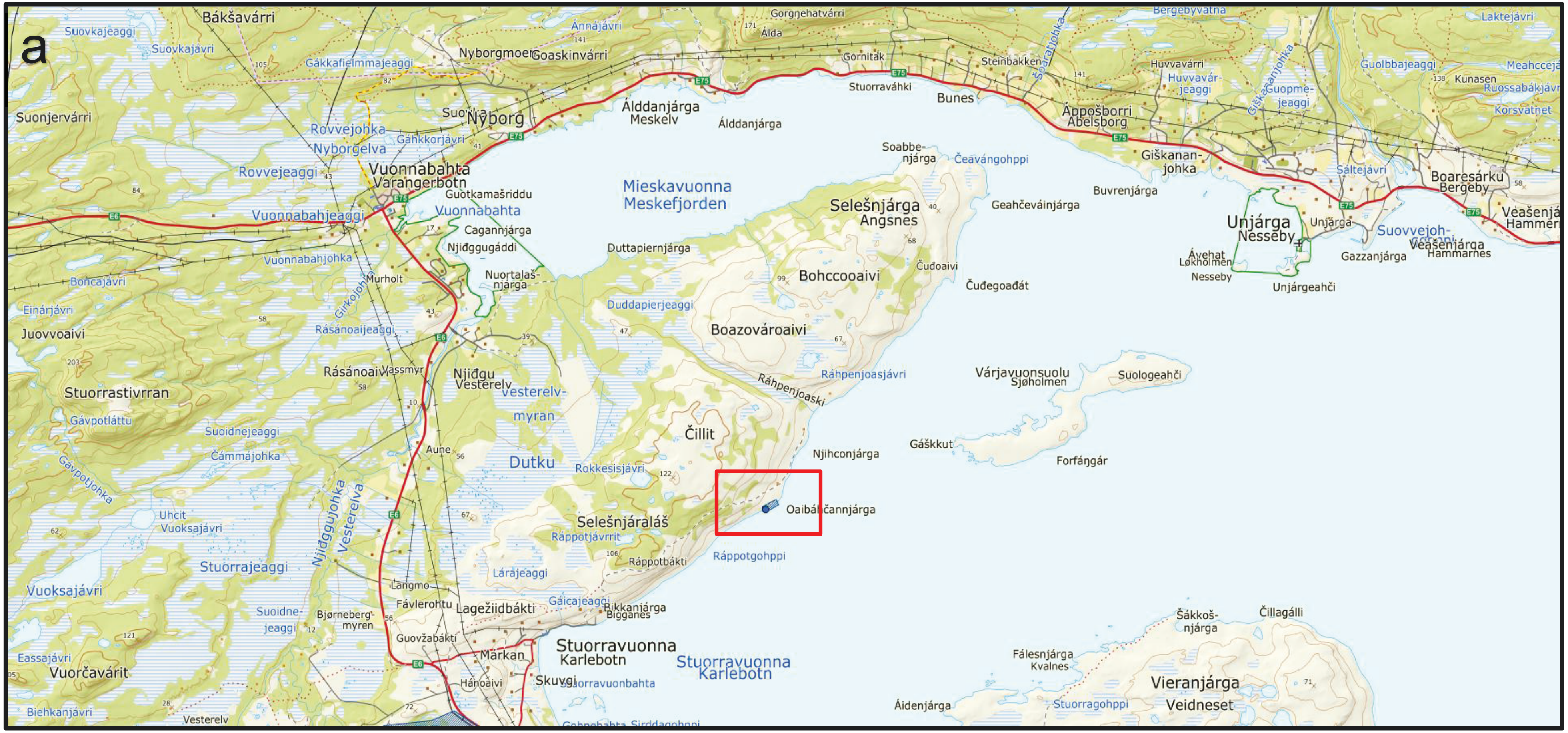

Figure 2.10 (a) Map of the study area at Selesjárgalás in Varangerbotn, the red box marks the location of the Bigganjárgga Diamictite. From Norges geologiske undersøkelse & Norge i bilder (2019): https://geo.ngu.no/kart/geologiskarv/ .

Figure 2.10 (b) Close-up of the borders for the nature monument are marked by a red box. From Norges geologiske undersøkelse & Norge i bilder (2019):
https://geo.ngu.no/kart/geologiskarv/ .

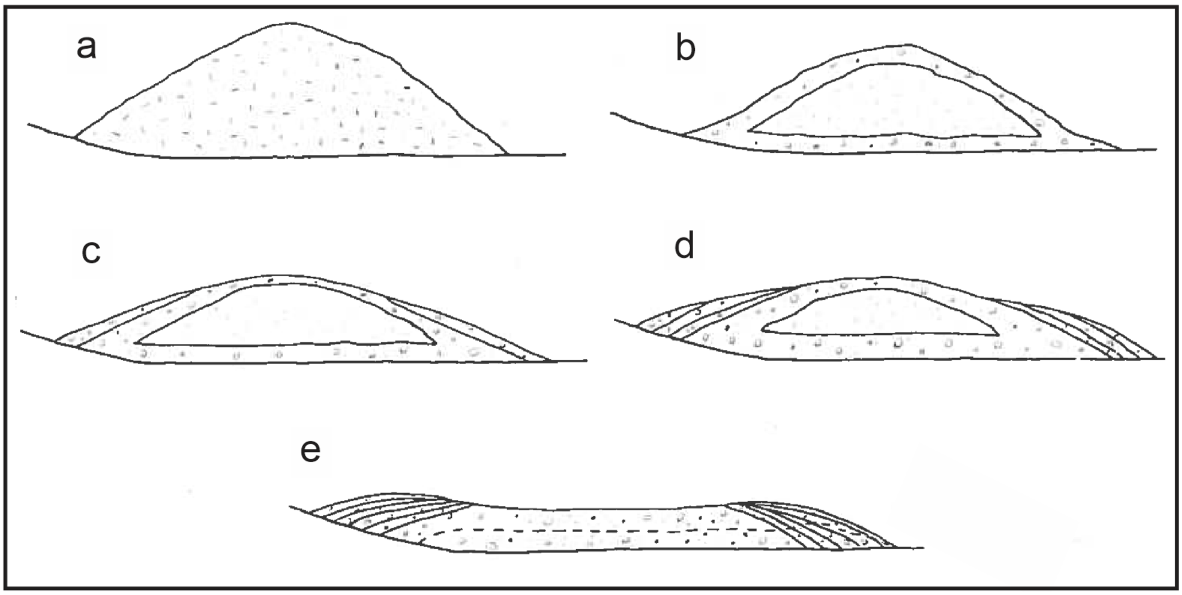

Figure 2.11 Stages in the formation of the Bigganjárgga Diamictite according to Edwards (1975). (a) The original ridge of debris-rich stagnant ice. (b) Melting of the exterior part of the ice core causing formation of melt-out till on each side. (c) The unstable melt-out till on top of the ice core will gradually flow downslope as a flow till. (d) The melting process were repeated and several layers of flow till accumulated on top of each other. (e) After complete meltdown of the interior ice core, a central portion of the melt-out till were surrounded by the flow tills on the flanks. The area below the dashed line marks the final remnant, which were left for posterity after erosion and winnowing during the following transgression. Modified from Edwards (1975).

3 Method

3.1 Fieldwork

During the summer and autumn of 2018, the Bigganjárgga Diamictite outside Karlebotn was visited two times. The first visit was on a field excursion in the course Geo-3113 – Exogene geology carried out from the UiT The Arctic University of Norway, and the second visit took place later in the autumn for supplementary work for this thesis. Since the investigations of the locality have been going on thoroughly for years, the time spent there were mainly used to look up on what was already described in published litterature. In addition, complementary sedimentary logging throughout the outcrop, numerous of photography's and four samples for petrographic studies were collected.

3.1.1 Sedimentary logging and facies analysis

In the Smalfjord Formation at Bigganjárgga, four partly interfingering units were of interest to this study, two sandstone units and two diamictite units. All of the four sections were conventionally logged during the fieldwork with an aim to describe and characterize the different lithologies, bed thicknesses and the grain size distribution as well as sedimentary structures. In particular, the two sandstone units were of interest as they earlier were described as being similar and exhibiting no sedimentological differences (Dal, 1900; Jensen & Wulff-Pedersen, 1996).

3.1.2 Strike measurements of striations and rib- and furrow structures

The upper surface of the lower sandstone unit, earlier mentioned to represent the Varangerfjorden Unconformity, contains both primary and secondary structures, namely rib and furrows on the top surface (representing trough cross-bedding in the vertical section) and secondary striations carved into the same surface. Their geographical orientations were measured as strike orientations using a Silva Compass during the fieldwork.

3.1.3 Photogrammetry

The best way to study an outcrop are to physically be in the field and investigate it by conventional methods (i.e., sedimentary logging and so on). Nevertheless, the options evolve as new technologies develop. A nearly as good or even better studying method for quantification and interpretation of larger outcrop sections is to use a set of photographs of the object taken in the field from numerous directions and angles and later combine them into a 3-dimensional (3D) visualization model (e.g. Pavlis et al., 2010; Pavlis & Mason, 2017). This method, referred to as photogrammetry (e.g. Lillesand et al., 2015) makes us able to zoom and spin the created model in ways not possible in the field. In addition, a digital mode enable rapid quantification of surfaces, lineaments, fractures, and various structures. For photo collection purpose, a Canon EOS 500 digital single lens reflex camera with an 18 – 55 mm objective were used. (The adjustment of the objective was carefully adapted to 18 mm to the photographs for a result of highest possible quality on the forthcoming model. This was to diminish the work combining points in different photographs). The set of photography's were captured systematically at several points on a transect of the outcrop during ebb tide which made it possible to traverse the entire outcrop along on the seaside. Between each point, there were about five meters. In each point a set of photographs were captured rotating around to catch all visible parts of the deposit. Additional photographs for the thesis were captured with a Canon EOS 60D digital single lens reflex camera with a 18 – 135 mm objective, a Canon IXUS 500 HS compact camera and a Panasonic Lumix DMC-GX1 mirrorless digital camera with a 14 mm objective.

3.1.4 Sampling of rocks for petrographic studies

A special permission granted by the local county counsil for this thesis gave the opportunity to collect four samples from the Bigganjárgga outcrop for further research. One sample was gathered from each of the two sandstones above and below the Bigganjárgga Diamictite, one from the Bigganjárgga Diamictite itself, and one from the upper diamictite, totalling four samples. In regards to the protection, the samples were carefully picked and handled with care. When choosing the exact spot to pick the sample, the aim was to not break loose any solid rock fragments from the outcrop, but rather take semi-loose rocks that still were in situ thus minimizing the visual impact of the sampling. For the sampling purpose, a hammer and a chisel were used. The size of the rock samples were restricted to be in a size range of 0.5 – 1 dm^3 (see Appendix 1).

3.2 Processing of collected material

3.2.1 Redrawing of sedimentary logs

After the fieldwork, the four sedimentary logs were redrawn in detail by hand from the sketches. Subsequently, the sketches were imported into the software CorelDraw X8 (version 18.1.0.661) for digitalization and further artistic processing.

3.2.2 Modelling of palaeodirectional data

The measured palaeodirectional data were plotted in rose diagrams in the software Rozeta 2.0 (Pazera, 2003). A rose diagram display is commonly used to present mean directions and standard deviation on palaeocurrent indicators (Nichols, 2009). Such frequency distribution of two-dimensional orientation data were then plotted in a circular histogram. This can be done in different ways, but rose diagrams based on a linear frequency scale have for a long time been normal to use in the sedimentological literature. This is however, an incorrect presentation of the data which "[…] leads to gross distortions of the shape of the rose" (Nemec, 1988, p. 149). By using a non-linear frequency-scale, the results will be presented in a more correct way (Nemec, 1988). However, because of the relatively low amount of gathered measurements in this work, this would not be accounted for in this thesis.

3.2.3 3D-modelling – virtual outcrop from photogrammetry

A multi-view 3D reconstruction of the Bigganjárgga Diamictite was generated after the fieldwork from 240 high-resolution digital photographs. The software used to make the model was Agisoft Photoscan Professional Edition (version 1.4.4.), an advanced program for creating professional 3D content from still photographs. The generation of the 3D-visualization had several steps, and the pre-processing and processing steps followed the described recommendation by Agisoft (2018) . The steps from outcrop to virtual outcrop can e.g. be summarized as in Fig 3.1.

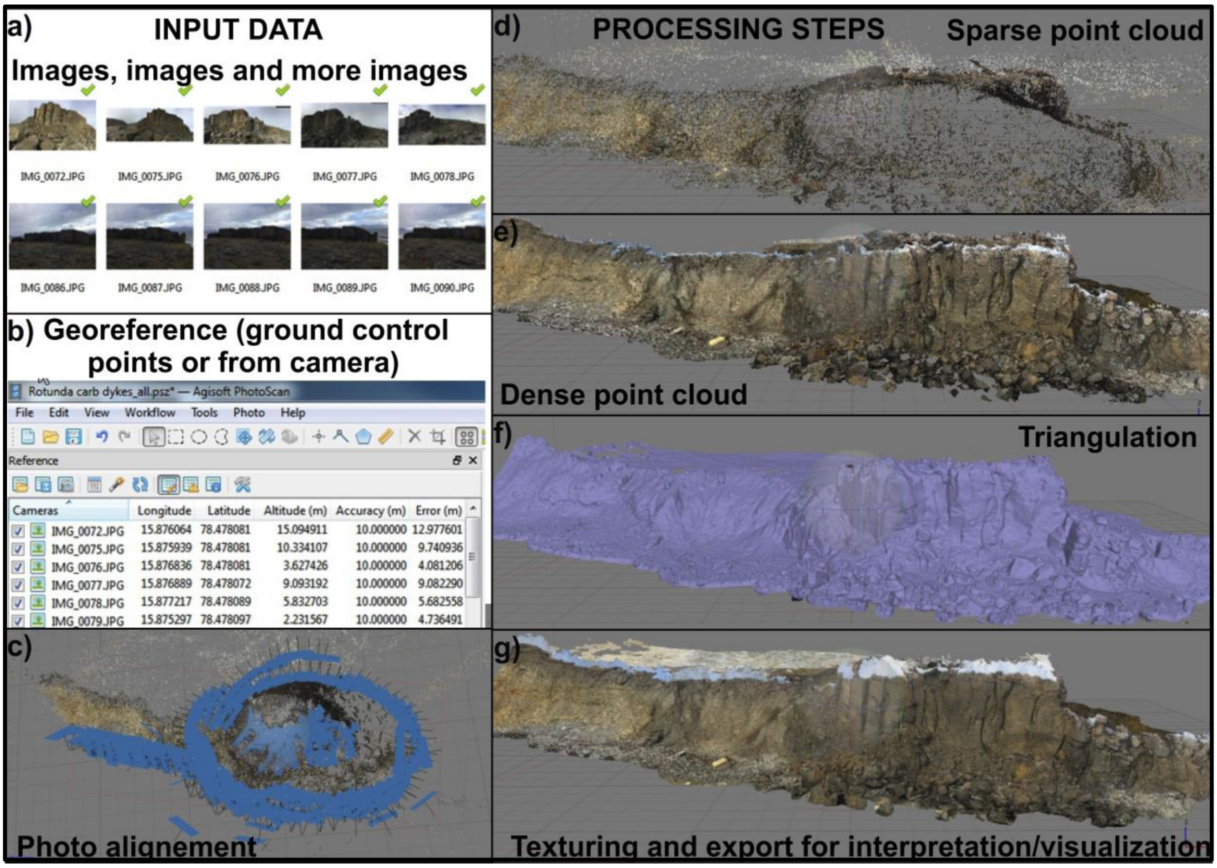

Figure 3.1 The composed path from outcrop to virtual outcrop. This figure does not show the actual model made of the BGD, but is an example of the processing steps in general when making such a model. (a) A collection of the imported photographs in the input data window. (b) The georeferencing window contains the geographical emplacement to the captured pictures. (c) The photo alignment window gives a view of were each photograph are captured relative to the outcrop location. Each blue rectangle means one photograph and in this case, the captured photographs are collected by circulating around the object. (d) Generated sparse point cloud. (e) Generated dense point cloud. (f) Generated mesh. (g) The final generated texture or 3D virtual outcrop model. Modified from Senger et al. (2016).

3.3 Laboratory work and Microscopy

After the fieldwork, supplementary work on the samples were conducted in Emilbua and in the geology lab at the Department of Geoscience at UiT – The Arctic University of Norway.

3.3.1 Preparation/production of thin sections

The author did the sawing of the samples into cubes. The size of the cubes were approximately 1 * 2 * 3 cm. Thereupon, the cubes were delivered to the staff at the geology lab were the final polishing of the cubes and gluing of the thin sections were conducted.

3.3.2 Microscopy and analysis of thin sections

The thin sections were analyzed using a Leica DMLP microscope. The focus was to analyze the mineralogical and textural maturity of the samples, such as mineral distribution, grain size, grain roundness and orientations and capture it in photographs. The photographs of the thin sections were captured with a Leica DCF 450 camera connected to the software LAS (version 4.12).

4 Results

4.1 Sedimentary analysis

The sedimentary logs made from the outcrop at Bigganjárgga document significant changes in lithologies, sedimentary facies and thus the interpreted depositional environments. Nine recurrent facies are recognized in the logged sections, ordered and summarized in Table 1. The facies have been grouped into four facies associations, FA 1 to FA 4, each representing distinctly different depositional environments. The vertical changes and the general character of the facies associations combined in sedimentary logs will be described later on in this chapter.

Table 1 Facies descriptions. Indicated are the facies relations to facies associations, thin sections, sedimentary structures and geometries, and depositional environment.

Facies associations (FA)	**Facies (F)**	**Thin sections (TS)**	**Grain size and lithology**	**Sedimentary structures and geometries**	**Interpretation**
FA 1 – Thick-bedded sandstone	F1	TS 2	Medium to coarse-grained sandstone.	Bed thickness: 10 – 30 cm. Cross-bedded sandstone, tabular sets. Lower contact overgrown by seaweed. Sharp contact to the overlying facies.	Deposition from migrating 2D-dunes.
	F2		Fine to medium-grained sandstone.	Bed thickness: 5 – 10 cm. Plane parallel bedded/ laminated sandstone. Sharp contacts to the lowerlying and to the overlying facies.	Deposition from suspension in slow-flowing/still water.
	F3		Medium grained sandstone.	Bed thickness: 5 – 20 cm. Massive sandstone. Sharp contact to the lowerlying and to the overlying facies.	Rapid deposition because of high amount of sediments available compared to flow discharge.

	F4		Very fine to medium-grained sandstone.	Bed thickness: 2 – 5 cm. Ripple cross-laminated sandstone. Sharp contact to the lowerlying facies and gradual transition into the overlying facies.	Deposition from migrating ripples under uni-directional flow, commonly superimposed on larger dunes.
	F5		Medium-grained sandstone.	Bed thickness: 10 – 15 cm. Trough cross-bedded sandstone. Gradual transition into the lowerlying facies and sharp contact present as the BGU to the overlying facies. Negative imprints associated with rip-up mudstone clast are also seen in this facies.	Deposition from migrating 3D-dunes developing under higher velocities than F1.
FA 2 – Thick-bedded diamictite	F6	TS 3, TS 3.1	Diamictite. Coarse-grained matrix. Clast sizes ranges from 1 to 60 cm.	Bed thickness: 180 – 250 cm. Coarse-grained matrix-dominated/supported diamictite. Erosional angular unconformity below and angular unconformity on top.	Deposition by either subaqueous debris flow, flow till or basal melt out till.
FA 3 – Thin-bedded sandstone	F7	TS 1	Fine grained sandstone.	Bed thickness: 10 – 20 cm. Massive sandstone. Angular unconformity to the	Deposition by surge-type low density turbidity current.

				lowerlying facies and gradual transition into the overlying facies.	
	F8.1		Very fine to medium-grained sandstone.	Bed thickness: 5 – 20 cm. Soft sediment deformed sandstone. Gradual transitions below and above – medium-grained sandstone load casted into the very fine-grained sandstone.	Deposition by turbidity currents followed by soft sediment deformation caused by shear from over-riding flow, or rapid deposition and de-watering.
FA 4 – Thin-bedded diamictite	F8.2	TS 4	Siltstone matrix. Clasts ranges from very coarse sand to pebbles and rare cobbles.	Bed thickness: 10 – 120 cm. Soft sediment deformed siltstone/ diamictite. Lowerlying contact not available (overgrown). Sharp contact to the overlying facies. When contacts are present inside the unit, both the lowerlying and the overlying contacts are sharp.	Deposition from fine-grained, mud-rich debris flow.
	F9		Coarse-grained sandstone matrix. Pebble clasts.	Bed thickness: 5 – 10 cm. Coarse-grained diamictite. Sharp contacts to the lowerlying and the overlying facies.	Deposition from slump deposits.

4.1.1 FA 1 – Thick-bedded sandstone

4.1.1.1 Outcrop descriptions

This is the basal association of the four studied units and it consists of ~1 meter of gently dipping sandstone beds, which disappear below FA 2 respectively from west to east in the outcrop. The colour varies from red to brown and yellow. The grain size varies from fine-grained to medium-grained sandstone. Observed structures in the unit are planar cross-bedding, plane parallel bedding and lamination, ripple cross lamination, trough cross-bedding in addition to massive structureless sandstone (F1 – F5 in Table 1 & Fig. 4.3). Below the plane parallel bedding (Fig. 4.4a), imprints (Fig. 4.4b & c) made after deposition of sub-consolidated or cohesive mud clasts (rip-up mud clasts) and later infilling around them resulted in well preserved negative imprints with mudstone content (Fig. 4.4d). The mudstone clasts are divided into several packed layers. There was also observed a rough surface with uneven down curved structures < 1 cm in size similar to stylolites (Fig. 4.3g).

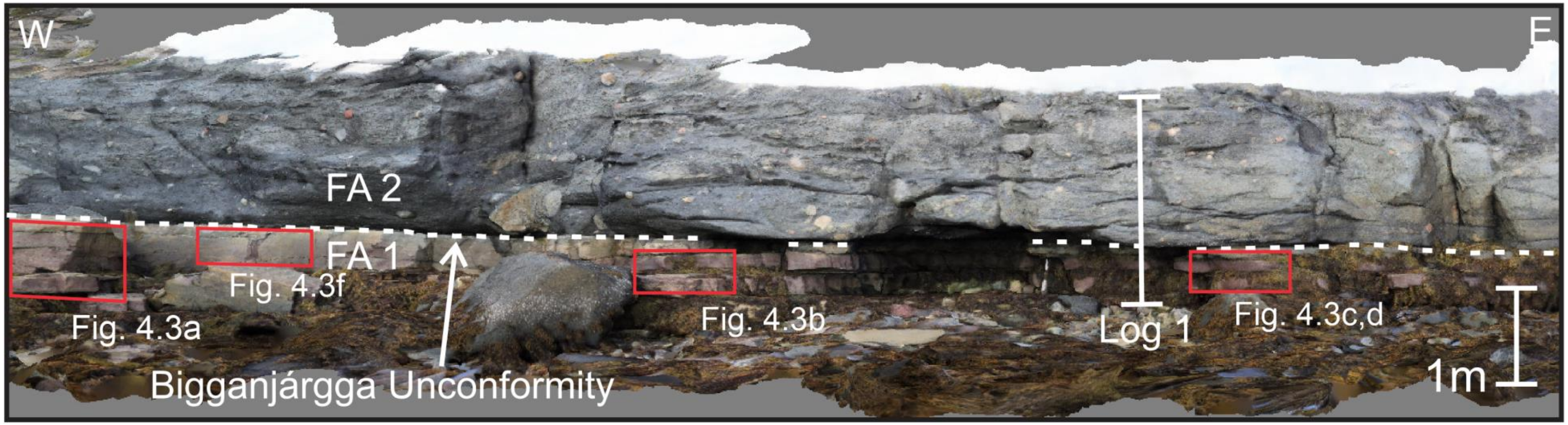

Figure 4.1 An overview that shows the logged units in log 1 (Fig. 4.2) as a white vertical line, the Bigganjárgga Unconformity as a white near horizontal dashed line, and red boxes showing were the facies (Fig. 4.3) in log 1 are visible.

Log 1

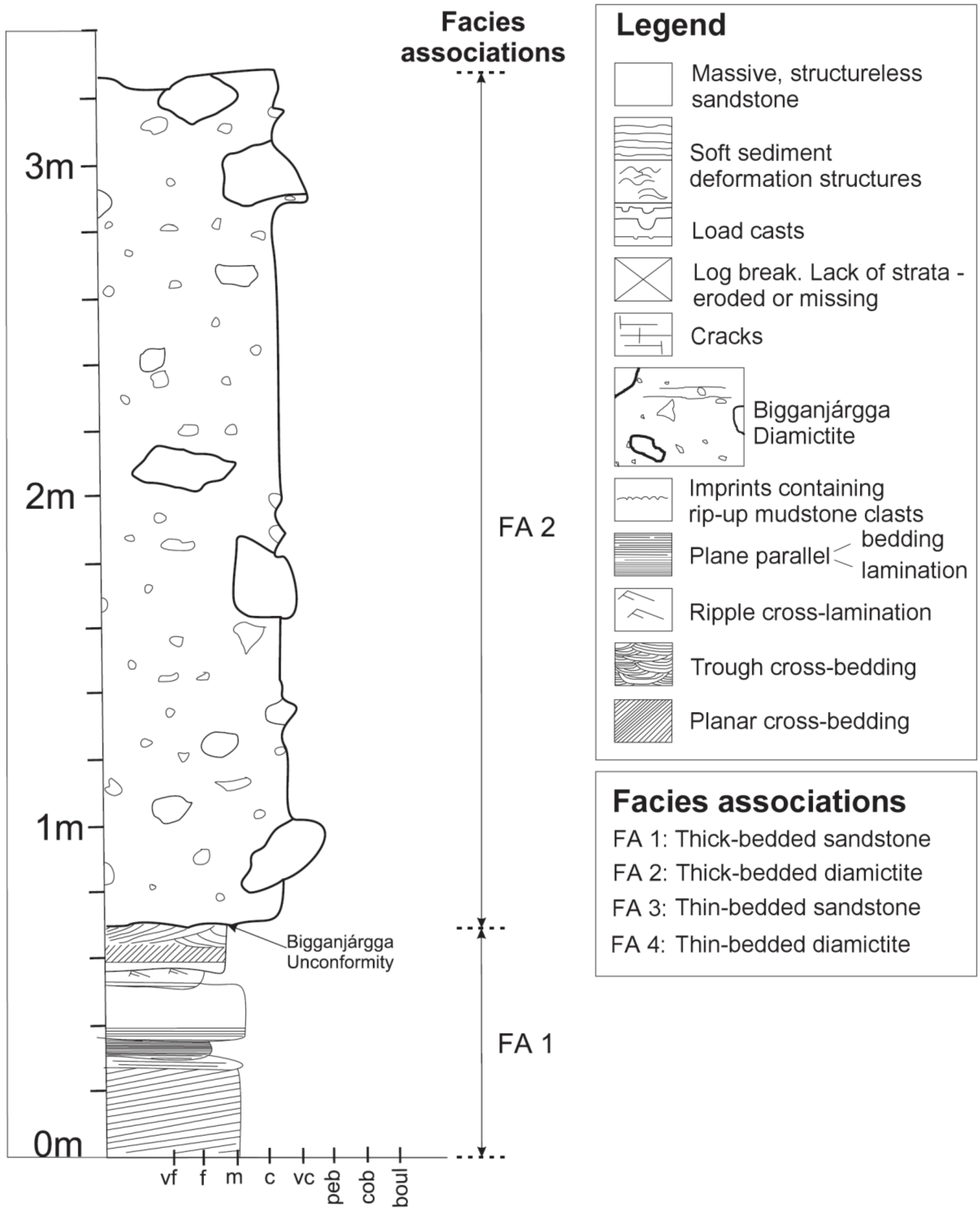

Figure 4.2 The thick-bedded sandstone unit (FA 1) below the Bigganjárgga Unconformity and the thick-bedded diamictite unit (FA 2) representing the Bigganjárgga Diamictite itself. The interpreted facies associations are also indicated in the figure together with the location of the Bigganjárgga Unconformity (regional unconformity to the Varangerfjorden unconformity). A legend describes the observed structures, and the legend accounts for all the logs presented in this chapter.

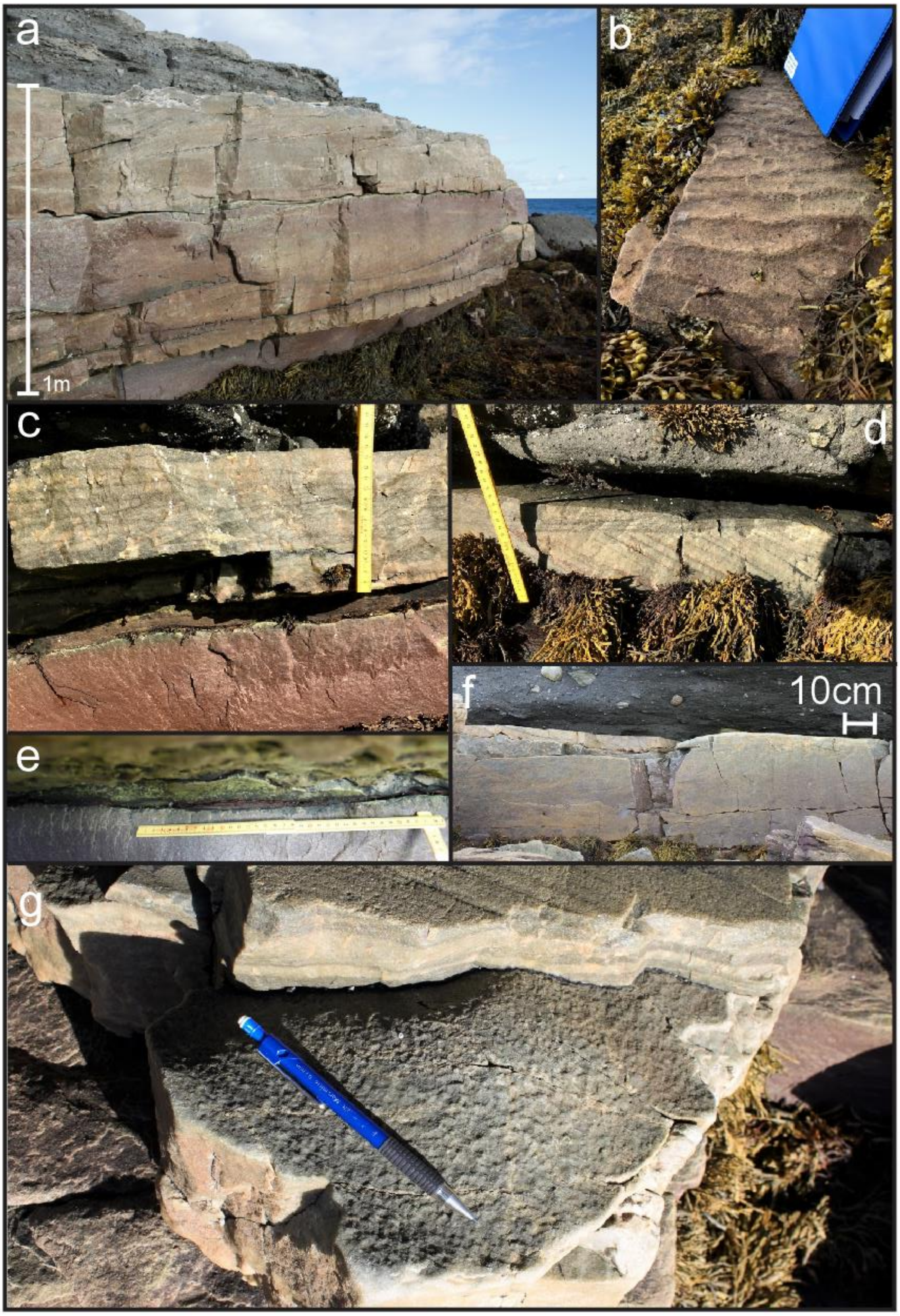

Figure 4.3 FA 1 in a closer view. (a) The entire unit present at ebb tide, from the lower parts covered with seaweed, through gentle dipping trough cross-bedding, and to the Bigganjárgga Unconformity connecting the next FA 2 at the top. (b) A bedding plane of ripples exposed from within the unit (A4 paper-folder for scale). (c) Planar cross-bedding cut by trough cross-bedding on top of a red sandstone bed. (d) Clearly visible planar cross-bedding eroded by trough cross-bedding on the bedding top surface right below the Bigganjárgga Unconformity and the Bigganjárgga Diamictite. (e) Ripple cross lamination. (f) A few meters west of (d) still close to the bedding top surface, massive sandstone with slightly visible trough cross-bedding in the upper part is present. (g) Uneven surface inside the unit (below pen) with stylolites. The BGU is seen c. 5 cm above the structures.

Figure 4.4 Imprints at Bigganjárgga. (a) The negative imprints (yellow arrow) in FA 1 as seen from below in (b). A woman for scale. (c) West of the Bigganjárgga Diamictite, imprints are seen at the surface of the sandstone. (d) Imprints found in a boulder by the shore in very proximity of the main outcrop. Inside a few of the imprints marked by a red box there was found preserved content similar to rip up clasts or mud clasts (e.g. Li et al., 2017). Thorough inspections concluded with a silt – clay content. The red arrow in (a) shows the relative location. Further imprints directly on the Bigganjárgga Unconformity are visible in Fig. 4.22. (e) A closer view of the content in the marked imprint in (d). The thin layering may be associated to schistosity that appears in shaly mudstones. Photo of d & e: Sten-Andreas Grundvåg.

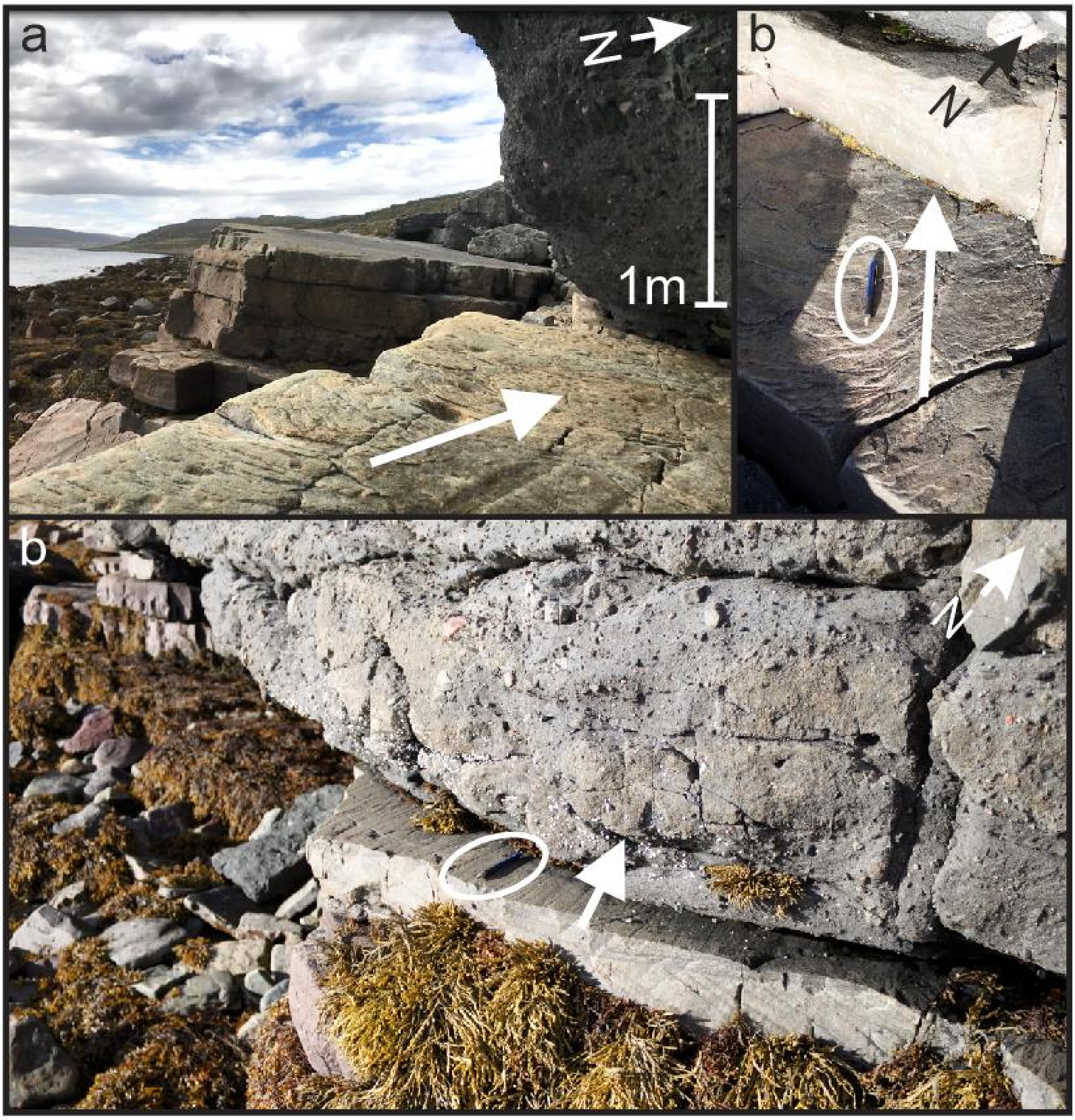

Figure 4.5 The observed primary rib and furrow structures are visible at several bed surfaces of the thick-bedded sandstone unit (FA 1). (a & b) are from the top of the unit at the Bigganjárgga Unconformity, whereas (c) is from lower within the unit. The paleo-migration direction towards north-northwest is marked with red arrows. Pen in white circle for scale, c. 15 cm.

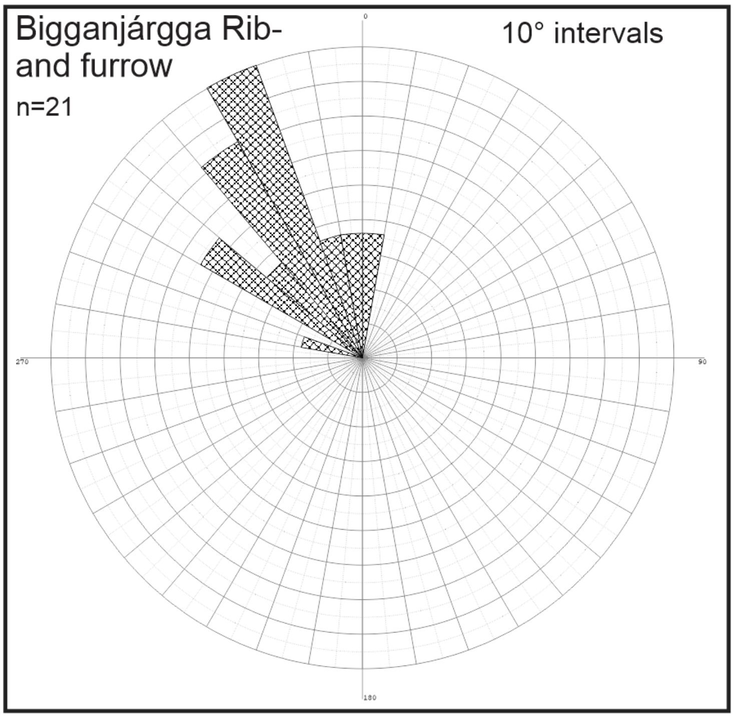

Figure 4.6 The measurements of the rib and furrows as presented in a rose diagram. 21 measured directions on the structures were collected. Three-dimentional observations in the field gave the opportunity to tell the migration direction of the dunes which mainly are towards north-northeast.

4.1.1.2 Petrographic descriptions

Thick-bedded sandstone – Thin section 2

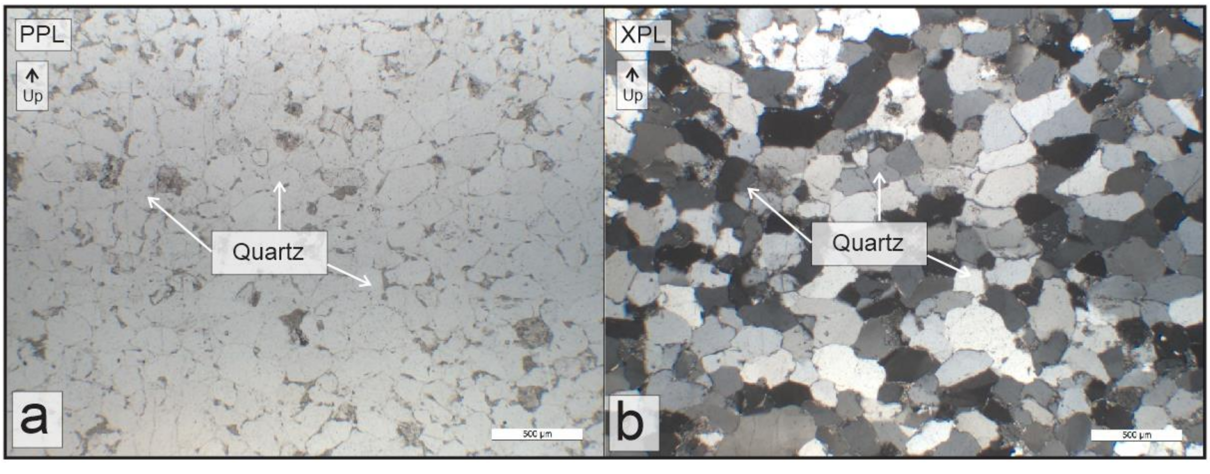

Figure 4.7 The thin section from the thick-bedded sandstone (FA 1) as seen in plane polarized light (PPL) in (a) and in cross polarized light (XPL) in (b). The contacts between the grains are irregular. Sorting are quite well regarding the mineral composition. The upward direction are indicated together with the mineral quartz (zoned black, grey and white grains) and a scale in 500 microns.

The majority of the framework grains consists of quartz, which are cemented or packed close to each other leaving the amount of matrix absent. In relation to this, there were observed stylolites in the field. In addition, there are minor amounts of feldspar carbonate. In PPL quartz are almost transparent, feldspar are clear to cloudy and carbonate are colourless. In XPL birefringence colour are weak for quartz and feldspar and very strong for the carbonate once rotating in the microscope stage. The grain size varies from less than 100 to 400 microns with the majority ranging from 200 to 300 microns. Due to cementation of the grains, the grain shape is hard to establish perfectly (Adams et al., 1984), but their shape mirrors somewhat low sphericity and varies from subangular to very rounded, with the majority being poorly rounded (following terminology outlined by Powers, 1953; Pettijohn et al. 1987) . The grains are moderately well sorted to well sorted (following terminology outlined by Folk & Ward, 1957; Spencer, 1963; Sahu, 1964; Friedman, 1979; Blott & Pye, 2001). Because directional orientations of the thin section are similar to the original orientation in the depositional record, the grains show a slightly angular dip, or imbrication, in the horizontal direction.

4.1.1.3 Interpretations

Environmental interpretation

Small grain size variations decrease the plausible transportation agents to those environments with even flow velocities. Palaeoenviromental interpretations can be submitted for sub-marine, fluvial, glacio-fluvial and aeolian environments. The existing primary sedimentary structures are supportive for a flowing transportation agent (i.e. the trough cross-bedding and planar cross-bedding made by migrating dunes), whereas the ripples do not embrace nor exclude an unidirectional flow (Bridge, 1978; Press & Siever, 1986; Allen, 1994; Collinson et al., 2006). The observed imprints containing mud-rich clasts (Fig. 4.4) were possibly made from eroded mud-rich clasts which were transported to and incorporated in the sand, but do not sign as a concluding evidence for the depositional environment them self as they can be related to several environments (i.e. fluvial-deltaic, tide-dominated, wave dominated and deep water envoironments) (e.g. Li et al., 2017). Thus, a criterion for these features is transportation by fluid flows which will exclude an aeolian environment for those sections of the unit. Without excluding any of the possible environments, Johnson (1975) supported a shallow marine environment for the entire Tanafjorden Group, which comprise this unit. The eroded mud clasts omitted an aeolian environment, and the primary structures associated to near laminar flows can rule out the most abundant distribution agent of clastic sediments in the deep ocean, the turbulent turbidity current. This means that flowing water in either a fluvial environment or in a shallow marine environment seems to have been the transportation agent once the sandstone were deposited.

Petrographic interpretation

Regarding the nature of the framework grains, grain size, sphericity, sorting and orientation the textural maturity of the thick-bedded sandstone is considered to be submature to mature (e.g. Folk, 1951; Nichols, 2009), whereas the mineralogical maturity is considered to be mature (Pettijohn, 1954; Okada, 1971). The provenance is difficult to sufficiently determine because the sample consists mostly of quartz (Mange & Maurer, 1992). However, several provenances related to the orientation of the grains are still plausible; the first is related to long transportation distance before final deposition were the traces of imbrication thereby shows stream activity during the deposition (e.g. Pettijohn, 1957; Nichols, 2009). This would be suggestive for a fluvial environment or shallow marine environment due to the degree of maturity, both texturally and mineralogically (e.g. Suttner et al., 1981; Ferree et al., 1988). The second one relates to the grain-grain contacts and the compact sedimentation of the sandstone that can be associated with pressure solution at a considerable burial depth (e.g. Baron & Parnell, 2007; Gratier et al., 2013) (i.e. stylolites which were observed macroscopically in the field both in FA 1 and in FA 3, respectively Fig. 4.3 g & Fig. 4.14i). Quartz cementation occur theoretically at about 2 km depth in sedimentary basins with normal geothermal gradients. Enough overburden is therefore required for this to happen. Potentially, bearing in mind the suggestion of a shallow marine environment by Johnson (1975), this can occur in during infilling of a shallow marine basin close to a fluvial dominated delta (Bjørlykke, 2010).

4.1.2 FA 2 – Thick-bedded diamictite

4.1.2.1 Outcrop descriptions

This is the second lowest of the four studied units in the outcrop and comprises a lens shaped matrix supported diamictite with cemented coarse sand grains. All together, the lens measures 70 m in length and 3 m in high. Variations in the colour of the matrix are seen from grey to light brown. The light brown parts seem to occur in small lenses within the grey diamictite (Fig. 4.10). Their length directions were roughly the same as the length direction of the entire diamictite itself and the size spanned from ~ 0.5 to 2.0 meters. With the blue eye, no evident characteristics were seen compared to the rest of the diamictite (besides the colour). Thin section descriptions of the contact between such a lens and the surrounding grey diamictite follow in Section 4.2.2.2. Randomly occurring clasts in various sizes and shapes are found within the matrix. The clasts ranges from medium pebbles to small boulders (1 cm – 30 cm), but medium boulders up to 60 cm occur too rarely. Medium to very coarse pebbles (1 – 3 cm) are the most prominent clast size (Fig. 4.11). Their shape varies from well rounded to very angular and shows both high and low sphericity. The clast lithologies vary among granites and sandstones both locally derived (see F6 in Table 1 & Fig. 4.11). The relation between matrix and clasts does vary internally. At some places did the clasts of pebble size dominate (Fig. 4.10d), whereas on other places was the matrix/clast content more even distributed with big variations in clast sizes (pebbles to boulders) (Fig. 4.11 g). There was looked for faceted or striated clast with poor results. One clast of cobble size had a line feature that might be a striation or faceting, but appeared very weak (Fig. 4.11c). Weak developed layering in the diamictite occur occasionally parallel to the length direction (Fig. 4.10a). Another set of layering of the diamictite was thicker and occurred with layers dipping to east (Fig. 4.11e & Fig. 4.19b). The same Fig. 4.19a & b shows that FA 2 fills a channelized feature below marked by the dipping appearance of BGU towards east. Internally in the unit on the eastern side, a small section contained imbricating clasts (Fig.4.26h). Totally 10 clasts were measured and the median dip orientation was 70 degrees east. Additionally on the same side of the unit, there were seen compressed, round shaped lobes (Fig. 4.26a & b). The internal structure was thin-bedded sheets stacked on top of each other and looked much the same as the thin layering in Fig. 4.10a. There were also observed winnowing features, with holes (Fig. 4.10c) and emanating ridges (Fig. 4.26c & e) pointing out of the diamictite. The unit is divided in one facies, F6 respectively, referring to Table 1.

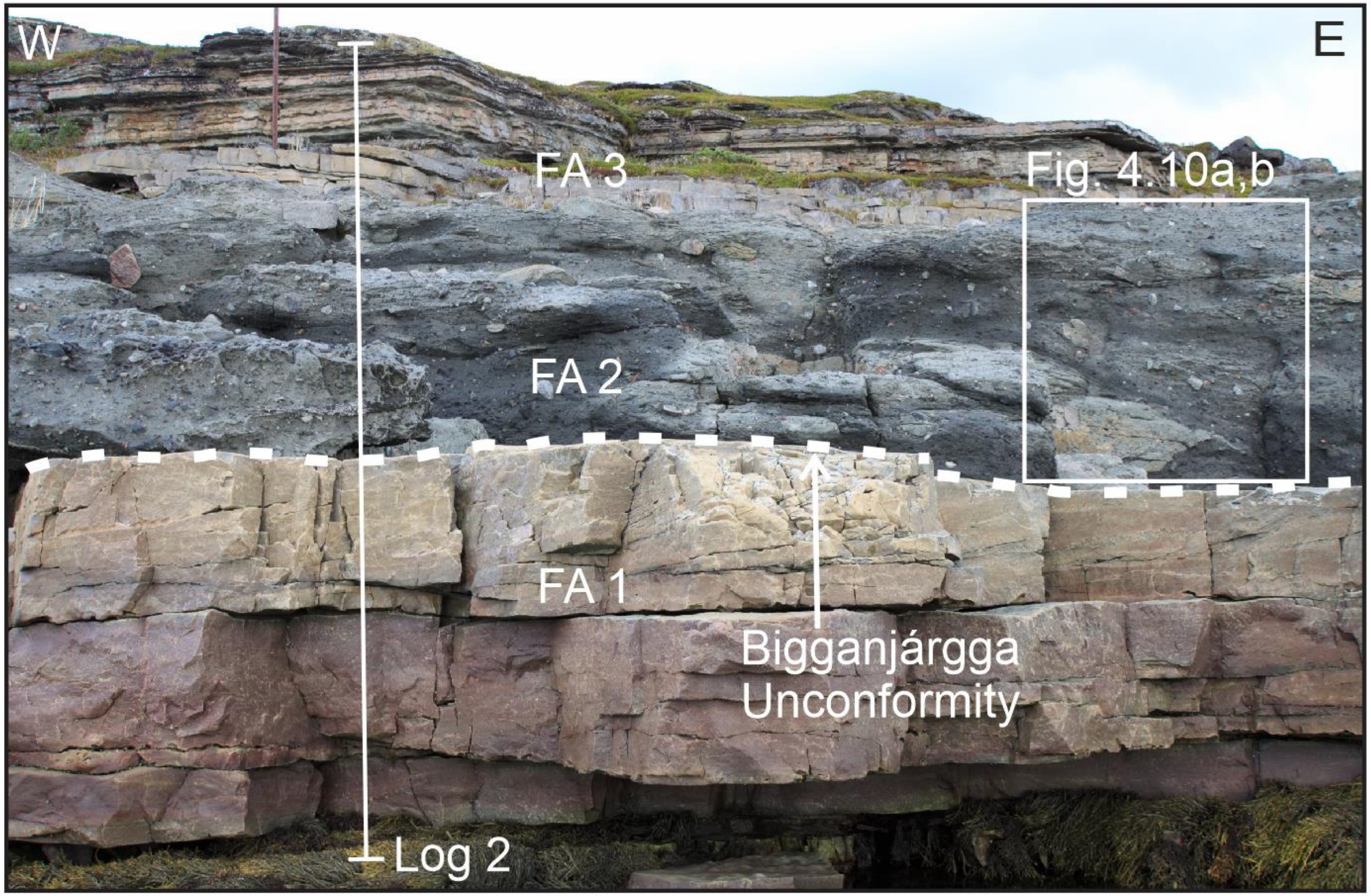

Figure 4.8 An overview showing the logged units (FA 1 – FA 3) in log 2 in Fig. 4.9. The BGU is marked by white dashed line. The white box shows the location of Fig. 4.10a & b.

Log 2

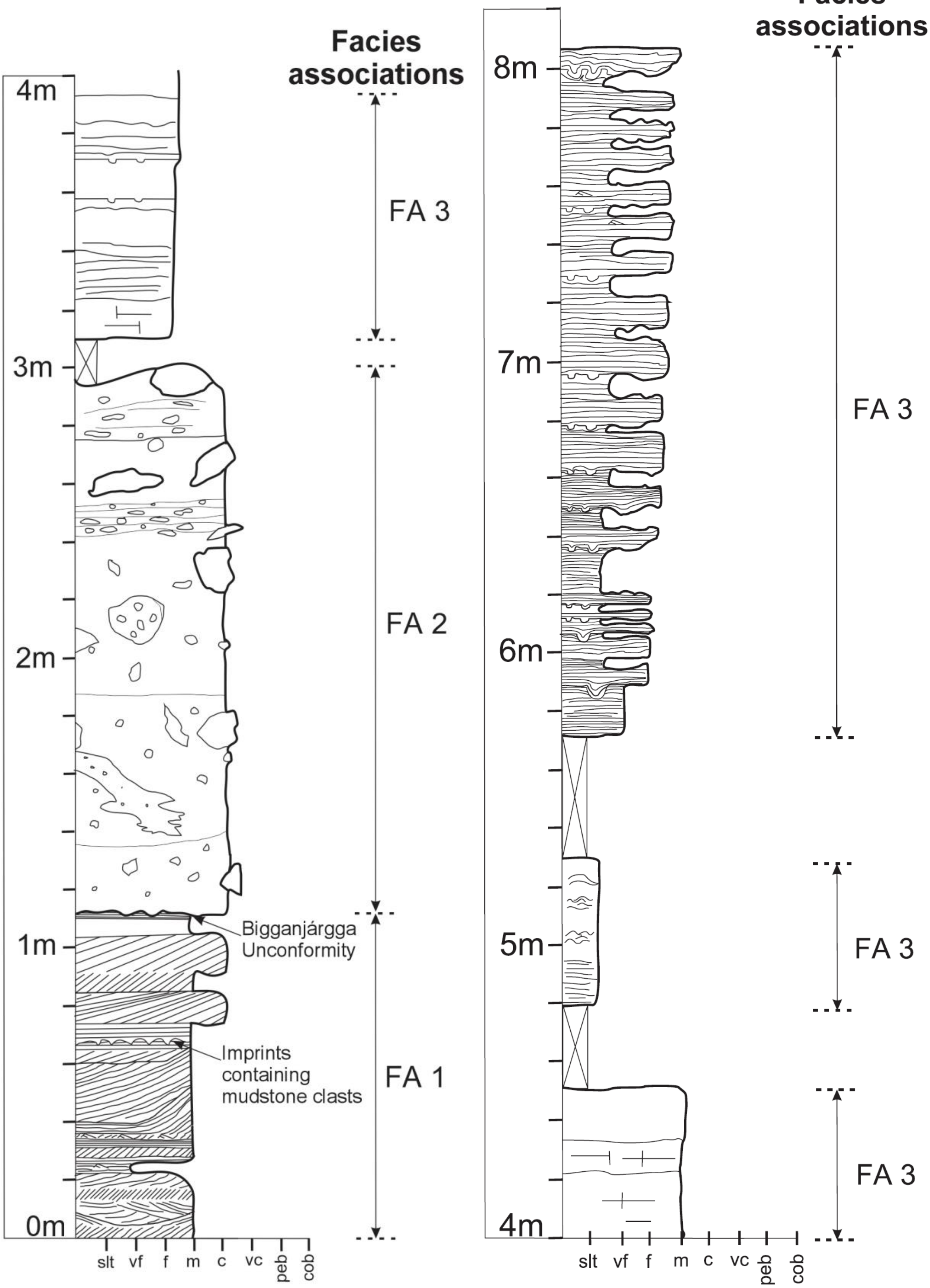

Figure 4.9 Log 2 comprises three facies associations together in one log. From the lower FA 1, into FA 2 and FA 3 the BGU and the imprints where mud clasts were found are marked by arrows. Legend is shown in Fig. 4.2.

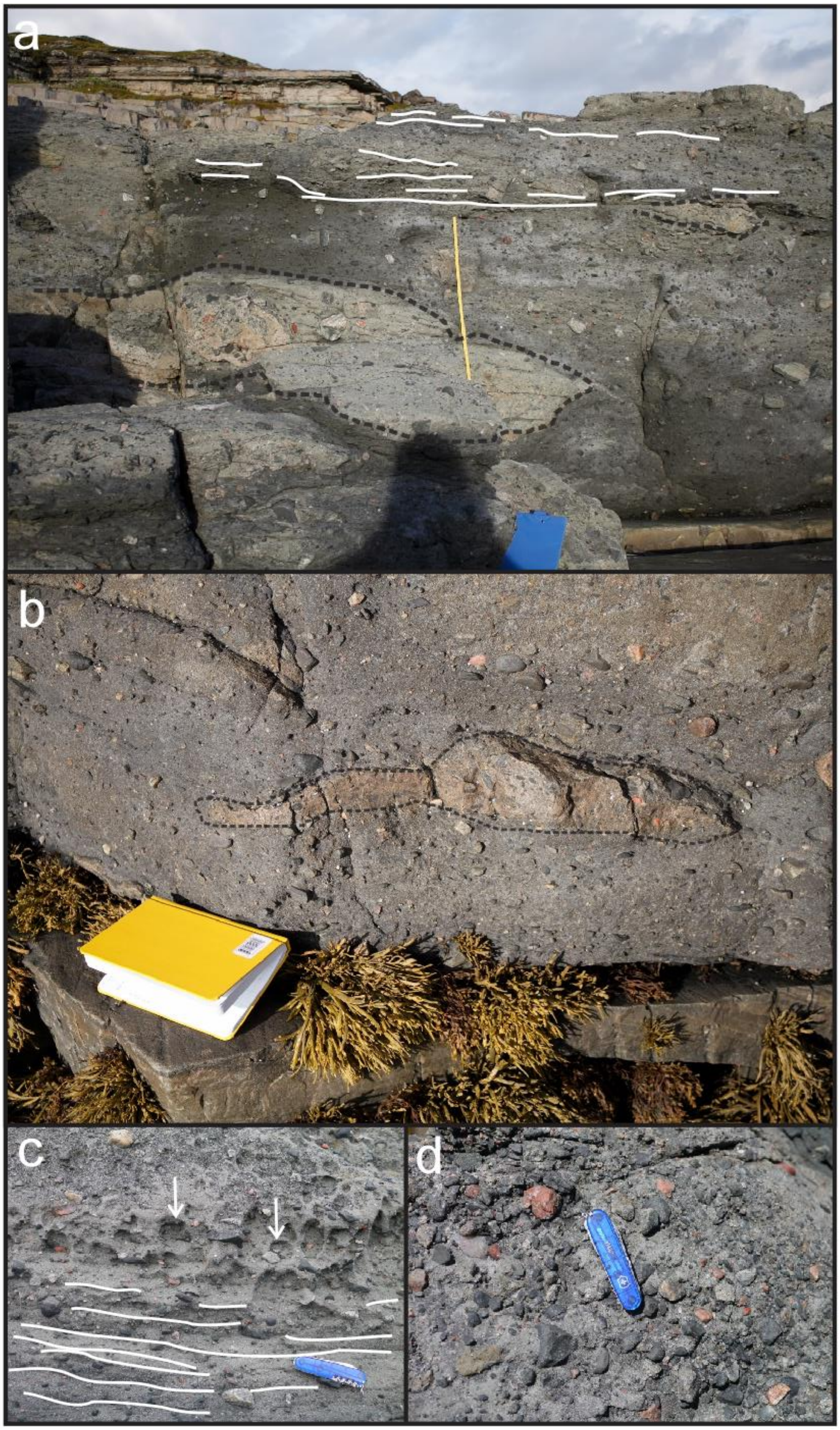

Figure 4.10 Close up of FA 2. (a & b) Observed light/brown lenses from within the diamictite are marked by black dashed lines. Weak layering were also seen in the upper part of the photograph (white layering). (c) Weakly bedded diamictite (white lines) and "holes" with lacking material (white arrows) (see also Fig. 4.26). Pocketknife for scale, c. 10 cm. (d) An area where the diamictite was composed of a greater amount of clasts than matrix.

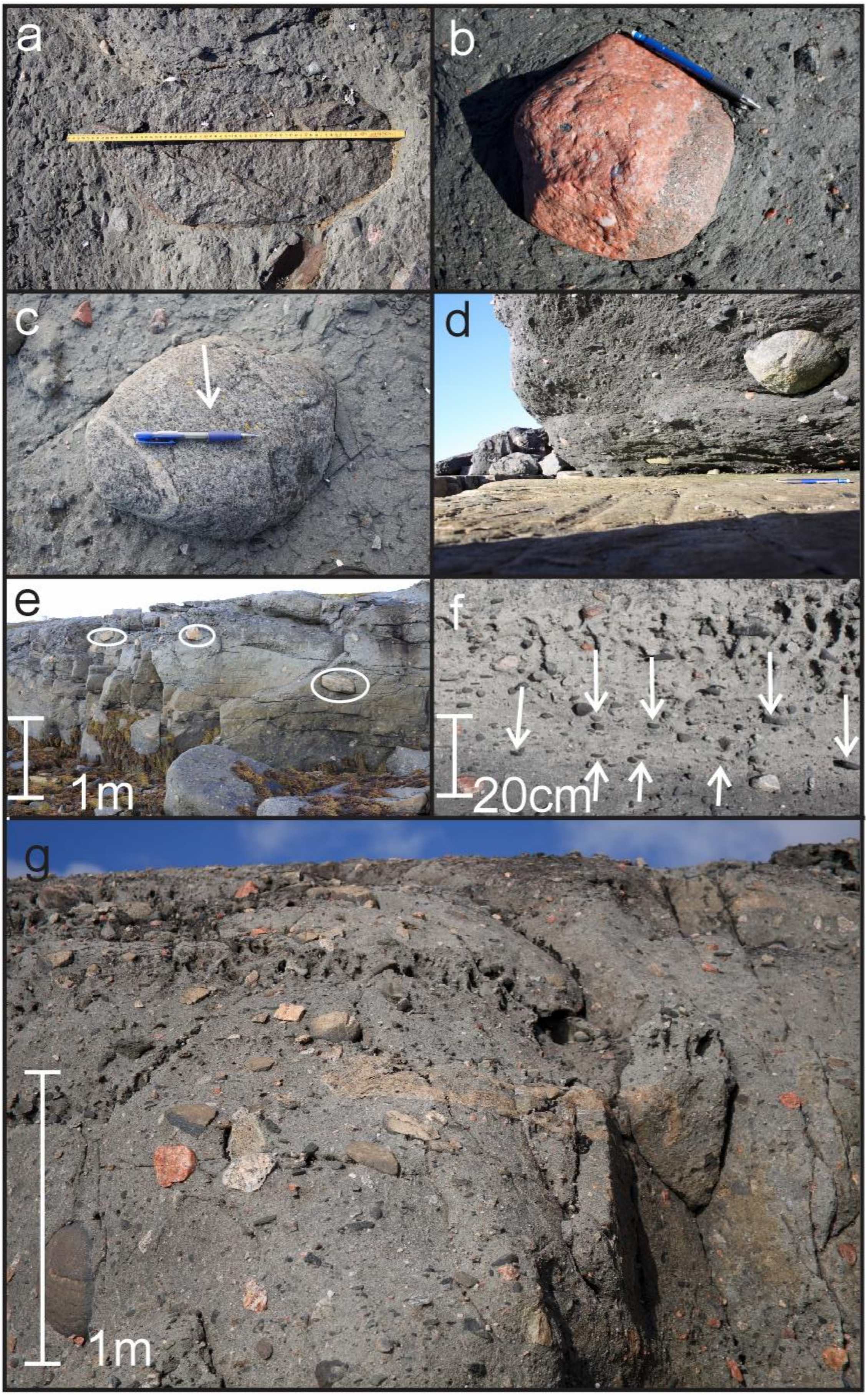
a
b
c
d
e
1m
f
20cm
g
1m

Figure 4.11 A selection of the shapes and lithologies of the clasts in FA 2. (a) The biggest boulder observed in the unit ~ 60 cm diagonally on the longest axis. (b – d) Intermediate sized clasts of different lithologies (pen c. 15 cm for scale). The clast in (c) has an arrow pointing on a line feature which goes along the pen that might be a striation or faceting. (e) An overview showing the distance between three unintended well rounded clasts (white circles). Note the dipping layers. (f) Small clasts 1 – 3 cm in grain size. Bedding is visible from left to right with slightly imbricated clasts. The direction of the transport were roughly measured by the dip of the clasts (n=10) were to 70 degrees. Measures follow in Appendix 3. (g) Very angular to very rounded shaped clasts close to each other in a limited part of the diamictite.

4.1.2.2 Petrographic descriptions

Thick-bedded diamictite – Thin section 3 & 3.1

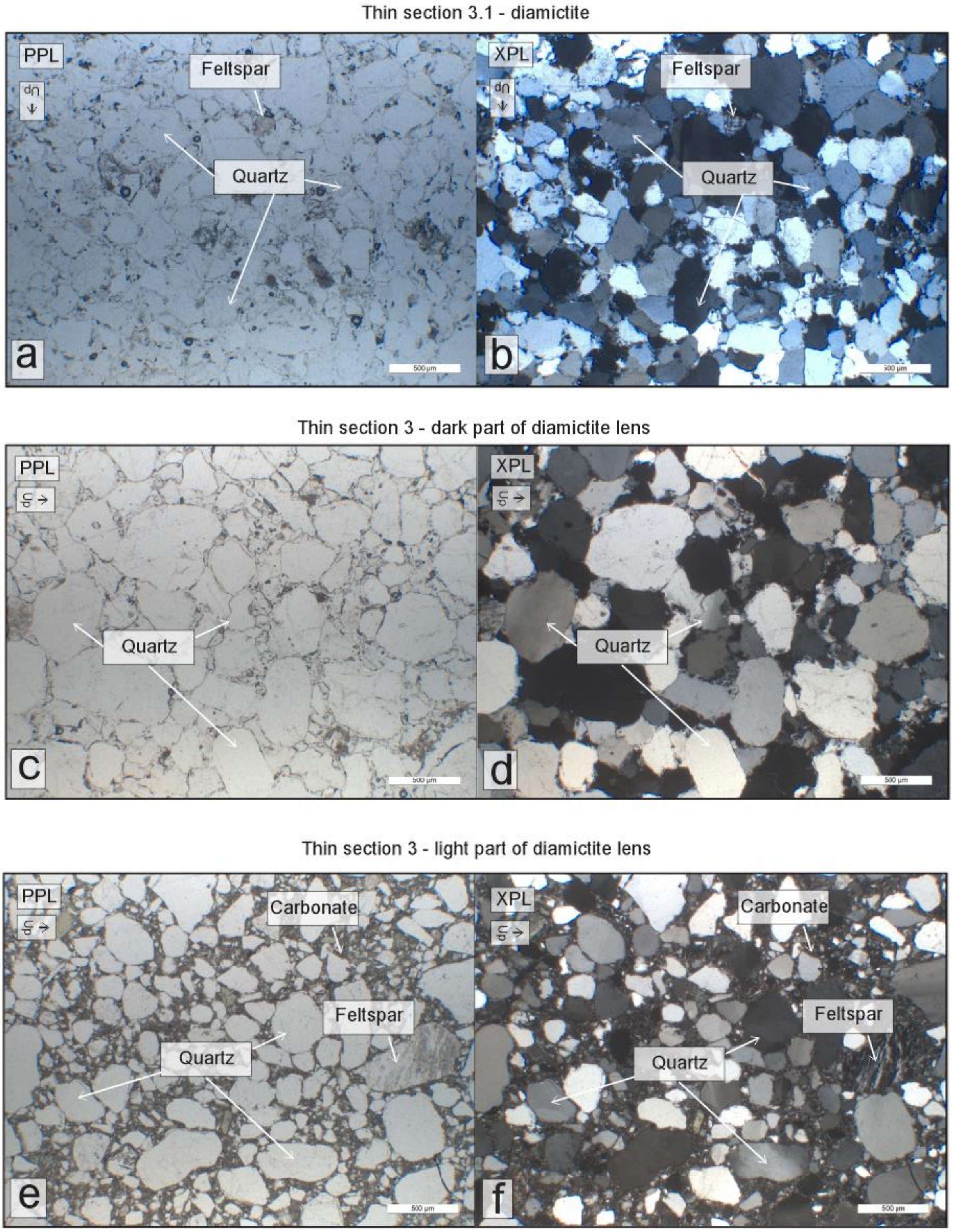

Figure 4.12 Thin sections from the thick-bedded diamictite (FA 2). (a & b) The thin section of the thick-bedded diamictite (FA 2) as seen in plane polarized light (PPL) and in cross polarized light (XPL). The contacts between the grains are still irregular between some of the grains. The sorting is worse than in the thin section of FA 1 regarding the mineral composition.The upward direction is indicated together with the minerals quartz (zoned black, grey and white grains) and feldspar (twinning) and a scale in 500 microns. (c & d) The thin section of the contact between the light lens and the dark (grey) diamictite in the thick-bedded diamictite as seen in plane polarized light (PPL) and in cross polarized light (XPL). The upward direction is indicated together with the mineral quartz (zoned black, grey and white grains) and in a scale in 500 microns. (e & f) The thin section of a lens in the thick-bedded diamictite as seen in plande polarized light (PPL) and in cross polarized light (XPL). A similar lens can be seen in Fig. 4.10. The sorting in this light part of the lens is worse than in the two previous thin sections in this figure. The upward direction is indicated together with the minerals quartz (zoned black, grey and white grains), feldspar (twinning) and carbonate (high birefringence colour) and a scale in 500 microns.

Thin section 3.1 – diamictite

The majority of the framework grains (Fig. 4.12a, b) consists of quartz, but minor parts of feldspar are also present. In PPL quartz are transparent and feldspar are clear to cloudy, and in XPL their birefringence colour is weak once rotating the microscope stage. The grain size varies from 100 to 500 microns with the majority ranging from 200 to 300 microns. Their shape mirror high sphericity and varies from very angular to subangular with the majority being angular (following terminology outlined by Powers, 1953; Pettijohn et al. 1987) . The sorting of the grains exhibit a moderately sorted to moderately well sorted structure (following terminology outlined by Folk & Ward, 1957; Spencer, 1963; Sahu, 1964; Friedman, 1979; Blott & Pye, 2001). There seems to be no preferred orientation of the grains in the thin section.

Thin section 3.1 – dark part of diamictite lens

Although this thin section (Fig. 4.12c, d) in hand specimen should be very similar to thin section 3.1, there are some differences. The majority of the framework grains are quartz. In PPL quartz are transparent and in XPL birefringence colour are weak once rotating the microscope stage. The grain size varies from 100 to 600 microns with the majority ranging from 300 to 400 microns. Their shape mirrors a combination of high to low sphericity and varies from poorly rounded to very rounded with the majority being rounded (following terminology outlined by Powers, 1953; Pettijohn et al. 1987) . The sorting of the grains exhibit a moderately sorted to poorly sorted structure (following terminology outlined by Folk & Ward, 1957; Spencer, 1963; Sahu, 1964; Friedman, 1979; Blott & Pye, 2001). There seems to be no preferred orientation of the grains in the thin section.

Thin section 3.1 – light part of diamictite lens

The majority of the framework grains (Fig. 4.12e, f) are quartz and feldspar and cement composed of carbonate. In PPL quartz is almost transparent, feldspar is clear to cloudy and carbonate is colourless. In XPL birefringence colour are weak for quartz and feldspar and very strong for the carbonate once rotating in the microscope stage. The grain size is chaotic and varies from 100 to 600 microns. Their shape mirrors a combination of high to low sphericity and varies from very rounded to angular with the majority being rounded (following terminology outlined by Powers, 1953; Pettijohn et al. 1987) . The sorting of the grains exhibits a very poorly sorted to poorly sorted structure (following terminology outlined by Folk & Ward, 1957; Spencer, 1963; Sahu, 1964; Friedman, 1979; Blott & Pye, 2001). There seems to be no preferred orientation of the grains in the thin section.

4.1.2.1 Interpretations

Environmental interpretation

The nature of a diamictite containing such a wide variety of grain sizes as seen in FA 2 strongly reduces the plausible depositional environments. To move a pebble 60 cm wide, a substantial energy source is acquired. Flowing water which is the most significant transport media of them all (e.g. Pye, 1994; Allen, 1997), can hence be excluded due to its low viscosity and transport potential. The maintaining mechanisms are then gravity, gravity-driven flow mechanisms and ice. Out of the gravity driven depositional processes, the immediate variations in rounding of the clasts in the deposit and the relatively high amount of matix would neglect a solely rock fall/debris fall or snow flow origin. Remaining is the debris flow which not could be ruled out at this point. A high-viscosity debris flow would explain the vide varieties of grain sizes, their various shapes, matrix/clast relationship and bedding present in the unit (Prior et al., 1984; Sohn, 2000). However, a mass transported and deposited by a comparable glacier or ice sheet can display the same characteristics (Harland et al., 1966) and could hence not be neglected from the evidence present at this point.

Petrographic interpretation

Regarding the nature of the framework grains, grain size, sphericity, sorting and orientation the textural maturity is considered to be as following: submature to mature in thin section “3.1 diamictite” (Fig. 4.12a, b), and submature for the remaining thin section “3.1 dark part of diamictite lens” (Fig. 4.12c & d) and thin section “3.1 light part of diamictite lens” (Fig. 4.12e, f). The mineralogical maturity is considered to be mature for thin section “3.1 diamictite” and thin section "3.1 dark part of diamictite lens", and immature for the last thin section "3.1 light part of diamicitite lens" (Folk, 1951; Pettijohn, 1954; Okada, 1971; Ferree et al., 1988).

The provenances for the two first thin sections (Fig 4.12a, b & c, d) are difficult to sufficiently determine because the sample mostly consist of quartz (sett inn Mange & Maurer, 1992). However, regarding the textural and mineralogical maturity seen in the thin sections, the sample would probably be related to a relatively long transport distance before final deposition. By comparing these thin sections to the last one (Fig. 4.12e,f), the last one would probably be related to a shorter transport distance were poorer sorting have time to occur (Folk, 1951; Suttner et al., 1981; Ferree et al., 1988; Cardona et al., 1997).

4.1.3 FA 3 – Thin-bedded sandstone

4.1.3.1 Outcrop descriptions

This unit occurs on top of the thick-bedded diamictite (FA 2; the Bigganjárgga Diamictite) and comprises a ~5 m thin-bedded sandstone unit thinning laterally and onlapping (Christie-Blick, 1991; Bjørlykke, 2010 - general prinsiples of onlapping sequence stratigraphy) towards the top surface of the underlying diamictite (FA 2) below on both sides (east and west) (Fig. 4.24 & 4.28). Grain size ranges from fine grained to very fine grained sandstone (Table 1, facies F7 and F8.1). The colour of the unit are grey to brown and the unit begins as massive sandstone (Table 1, F7 & Fig. 4.14h, i) that gradually changes to fine grained horizontally bedded and laminated sandstone (Table 1, F8.1 & Fig. 4.14a – g). In fractures along bedding in the massive sandstone there were observed rough surface with uneven down curved structures < 1 cm in size similar to stylolites. More intense soft sediment deformation occur towards the upper part where the sandstones alternate with siltstones (Fig. 4.14a – e). Observed structures are plane parallel lamination and bedding and load casts at the base of the beds.

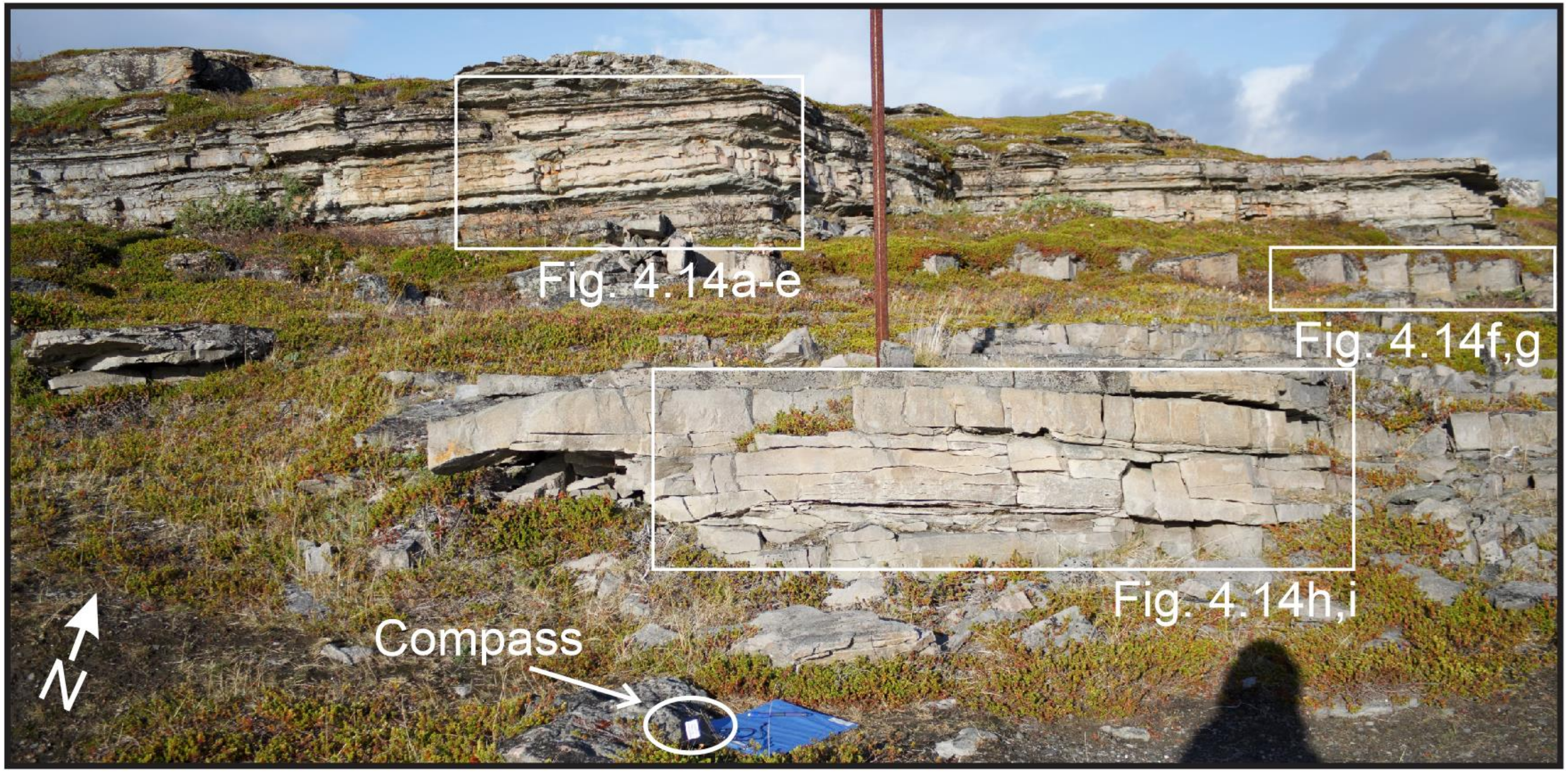

Figure 4.13 An overview that shows FA 3 and its location, the logged area in log 2 (white vertical line) (see Fig. 4.9) and were the close up photographies in Fig. 4.14 are collected (red boxes). Because there is vegetation cover locally covering the bedding, certain parts of the outcrop is not exposed and consequently not logged. Compass for scale, c. 8 cm.

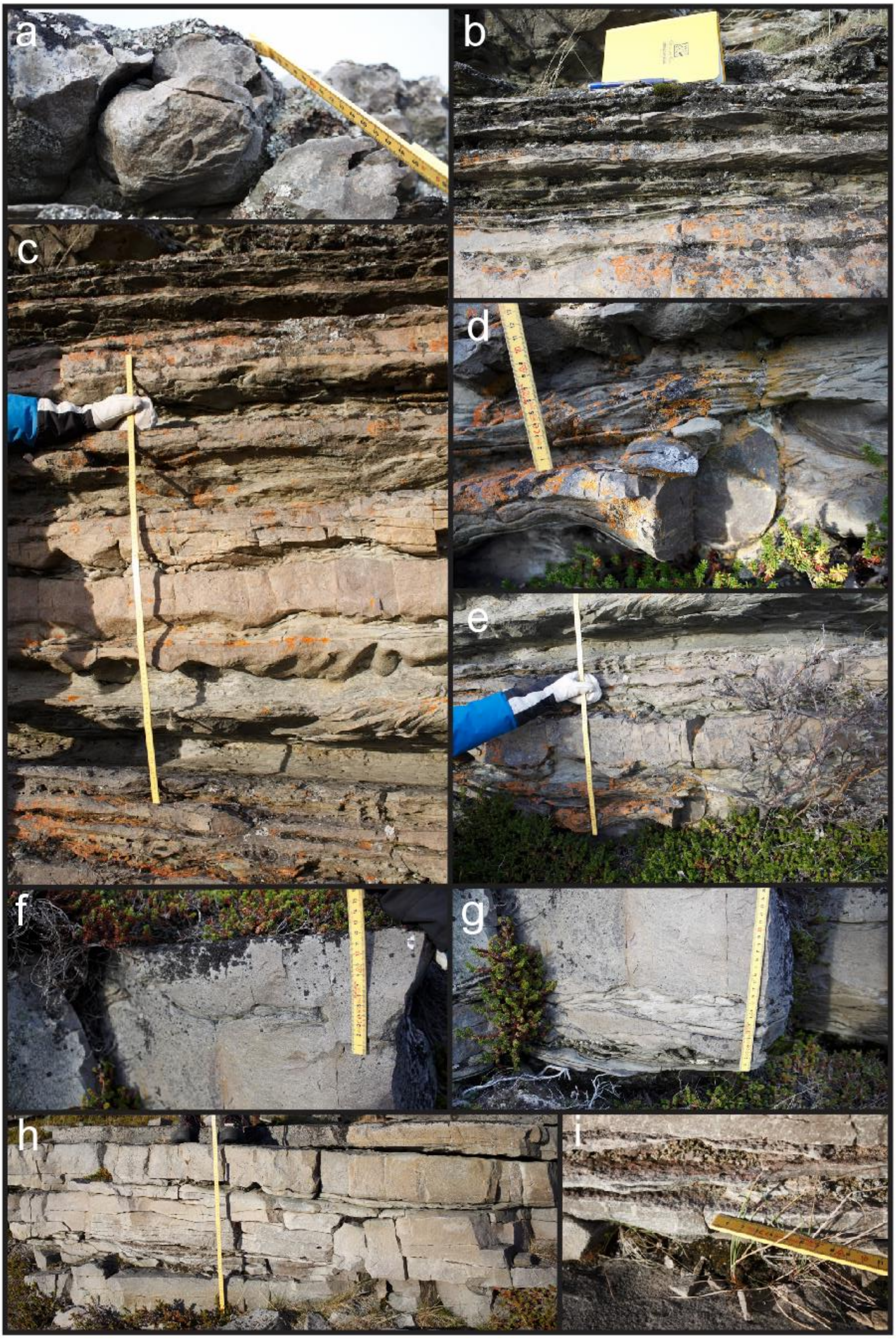

Figure 4.14 The detailed photographs of the unit and from the red boxes in Fig. 4.13. (a) The biggest load cast from the top of the logged unit. (b) Interfingering layers of medium grained sandstone and very fine grained sandstone. Book for scale (19 cm). (c) Massive fine grained sandstone layers interfingering and load casted into very fine grained sandstone layers. (d) A load cast in cross section. (e) In the lower part of the red box in Fig. 4.13, the changes between the different sandstone layers increases compared to higher up in the unit. (f & g) In the middle of this unit a transition between soft sediment deformed sandstone from the upper part and massive sandstone from the lower part of the unit were seen. (h) Massive sandstone with numerous of fractures. Along some of these fractures presumably following the layering there were made observations of stylolites (i). For the log of this unit, see Fig. 4.9.

4.1.3.2 Petrographic descriptions

Thin-bedded sandstone – Thin section 1

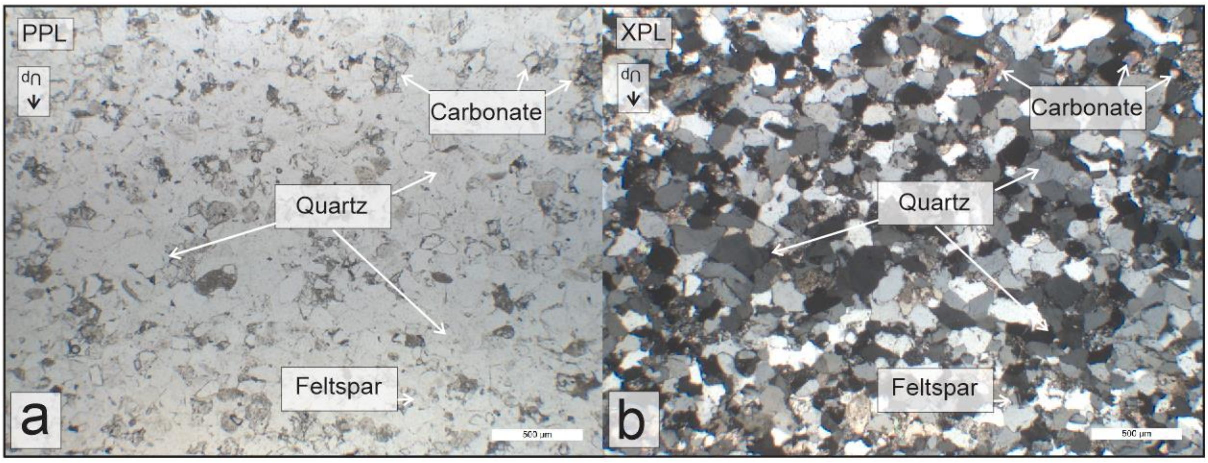

Figure 4.15 The thin section from the thin-bedded sandstone (FA 3) as seen in plane polarized light (PPL) and in cross polarized light (XPL). The upward direction is indicated together with the minerals quartz (zoned black, grey and white grains), feldspar (twinning) and carbonate (high birefringence colour) and a scale bar in 500 microns.

The majority of the framework grains consists of quartz, but also feldspar and carbonate are present. In PPL quartz is almost transparent, feldspar is clear to cloudy and carbonate is colourless. In XPL birefringence colour of quartz and feldspar are weak and very strong for carbonate once rotating the microscope stage. Grain size varies from 25 to 300 microns with the majority ranging from 100 to 200 microns. Cementation between the grains is present to a certain point (following terminology outlined by Adams et al., 1984), but there is also a matrix present separating the grains. Thus, both high and low sphericity are presentable for the grain shape variating from very angular to subangular. Though, the majority of the grains shows high sphericity and are angular. The sorting of the grains exhibit a moderately sorted to poorly sorted structure (following terminology outlined by Powers, 1953; Pettijohn et al. 1987) . There seems to be no preferred orientation of the grains in the thin section.

4.1.3.3 Interpretations

Environmental interpretation

The massive sandstones and siltstones in this unit showed few structures, but had many deformed layers with load casts that can be related to gravity flow deposits in submarine environments. Additionally, when regarding the changes in grain size from medium sandstone in the lower part of the unit to fine and very fine grained interfingering sandstones in the upper part, an increasing transportation distance from the available sediment source (i.e. due to a relative sea level rise/transgression) are reasonable. However, in contrast to the decreasing grain sizes within the unit that i.e. may be associated with a gradually reduction in flow, the observed soft sediment deformation structures can be assigned to different diagnostic features. They are i.e. rapid sedimentation rates, reverse density gradation and shear forces from bypassing water flows or a combination. Recognizing these features will again limit the potential distance from the sediment source (Mills, 1983) decreasing the alternatives. With the interpretation of the Nyborg Formation above that represents post-glacial transgression (Rice et al., 2011) in mind, a reasonable environment for the deposition of the unit may be a shallow marine environment. In such an environment the sedimentation rates and the water amount are relatively high, which can cause instability in the sediments making possibilities for gravity driven processes to occur (e.g. Lowe, 1982; Mills, 1983; Hjellbakk, 1993; Drinkwater et al., 1996).

Petrographic interpretation

Regarding the nature of the framework grains, grain size sphericity, sorting and orientation the textural maturity of the thin-bedded sandstone is considered to be submature to immature (e.g. Folk, 1951), whereas the mineralogical maturity is considered to be immature (Pettijohn, 1954; Okada, 1971). This means the provenance would most likely be related to a moderately transportation distance from the source before final deposition (Folk, 1951; Suttner et al., 1981; Ferree et al., 1988; Cardona et al., 1997).

4.1.4 FA 4 – Thin-bedded diamictite

4.1.4.1 Outcrop descriptions

This is the highest of the four studied units. The FA is a tabular 1 – 2 m thick unit that reaches all across the outcrop in the length direction (followed for at least 100 m) without thinning out and consist of a fine grained matrix with clasts. The colour of the unit are brown to yellow, the matrix is made of siltstone to very fine sandstone and the clasts within ranges from fine pebbles to large cobbles (4 mm – 12 cm). A lens of coarse sandstone with pebbles occurs once (see log 3 in Fig.4.17 and Fig. 4.16). Observed structures include plane parallel bedding and lamination and soft sediment deformed layering (Fig. 4.16).

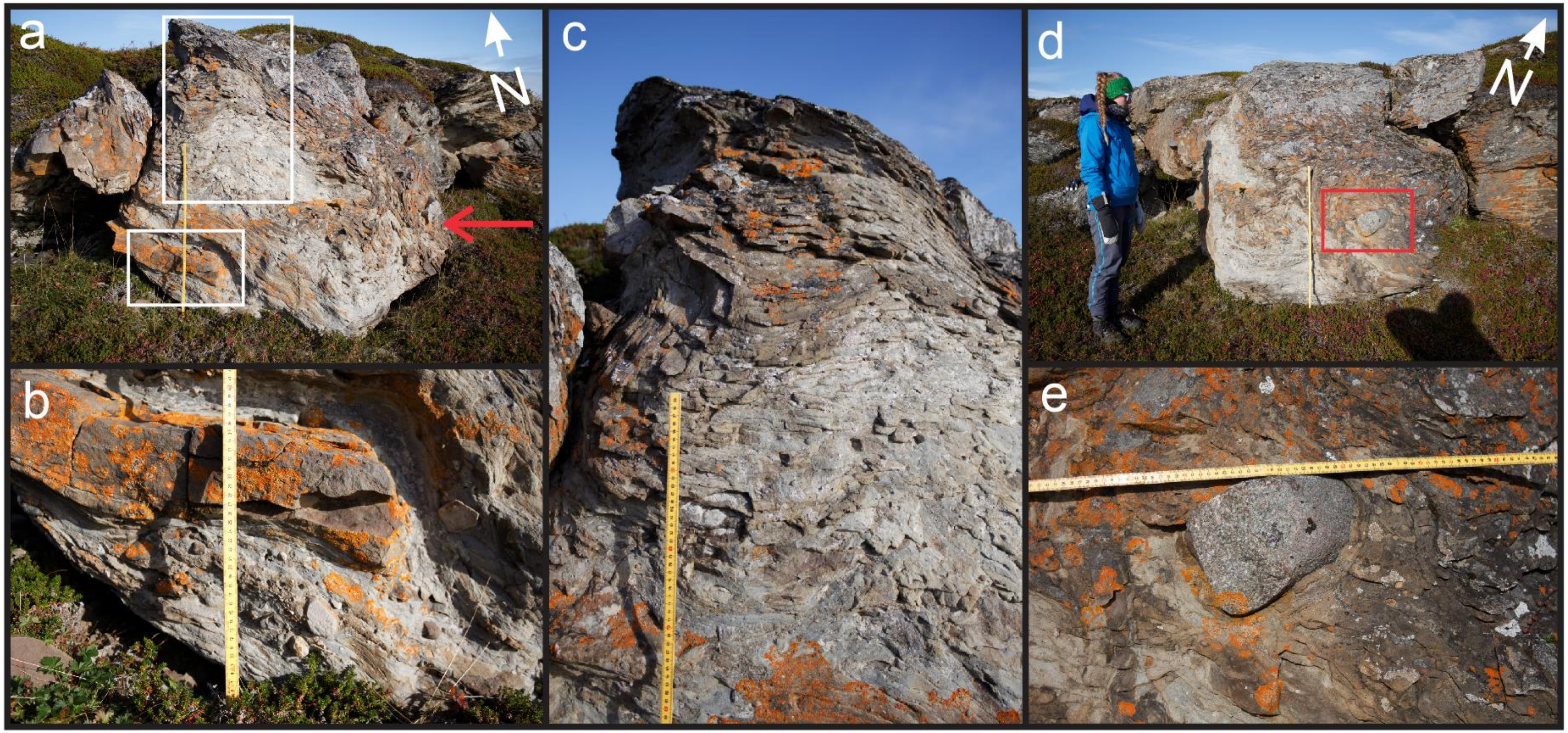

Figure 4.16 An overview and a closer view of FA 4. (a) The log is collected on a large boulder which is broken off the nearby terrace enscarpment (i.e. practically in situ). White boxes show the location of (b & c). Red arrow shows the directional view of (d). (b) A coaser lens within the thin bedded siltstone layers on the lower part of the boulder. (c) Thin-bedded siltstone layers in the upper part of the boulder. (d) The same boulder as seen from another side (see red arrow in (a). Red box show the view in (e). (e) A large granitic cobble-sized clast approximately 20 cm in diameter is draped within the thin-bedded layers in the diamictite.

Log 3

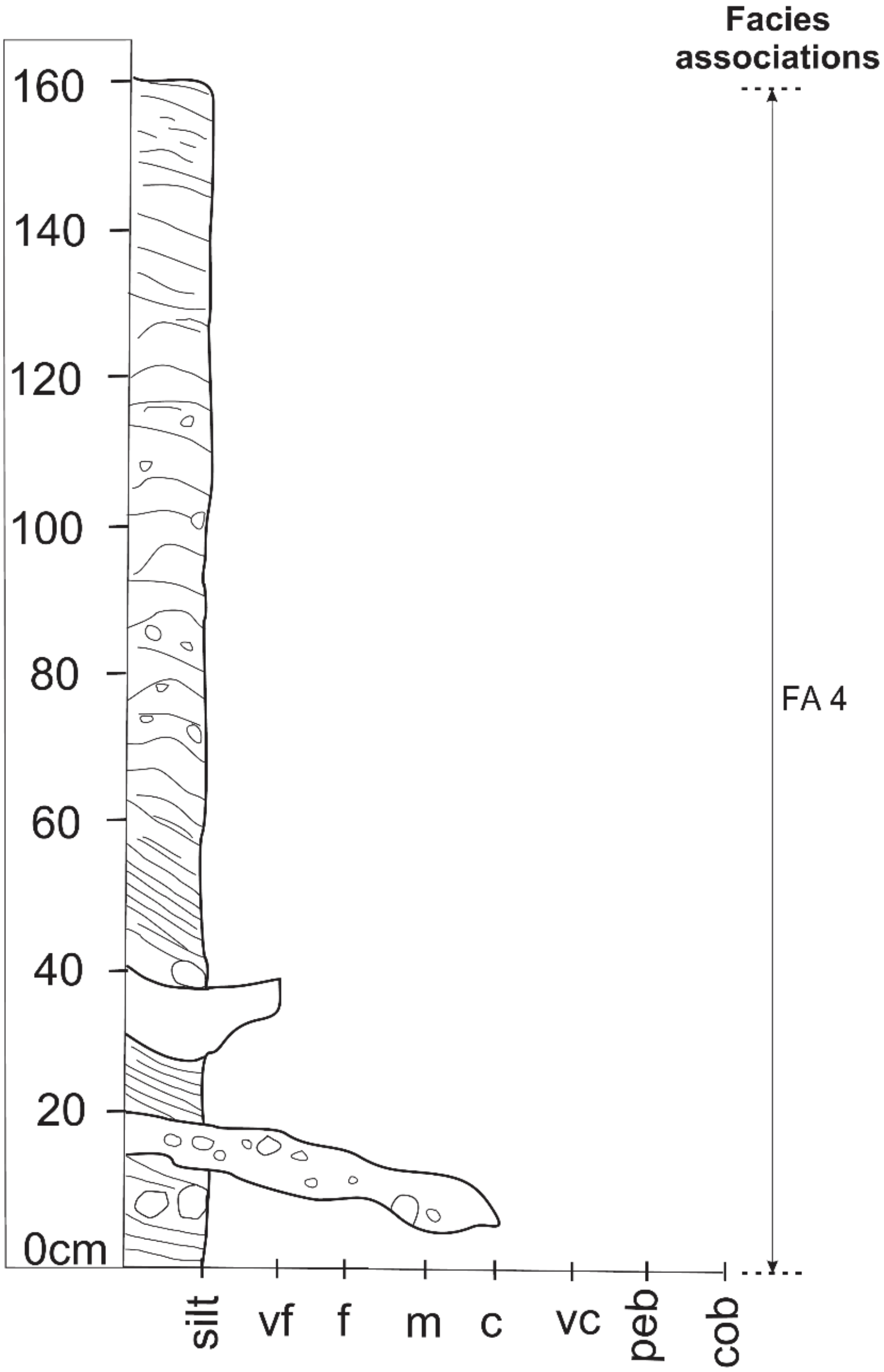

Figure 4.17 Log 3 comprises the last facies association and contain soft sediment derformated layers of siltstone and a lens of coarser material and a upcoarsening sequence. Occacionally there are pebbles within the siltstone layers and one cobble were draped by siltstone layers (see Fig. 4.16e).

4.1.4.2 Petrographic descriptions

Thin-bedded diamictite – Thin section 4

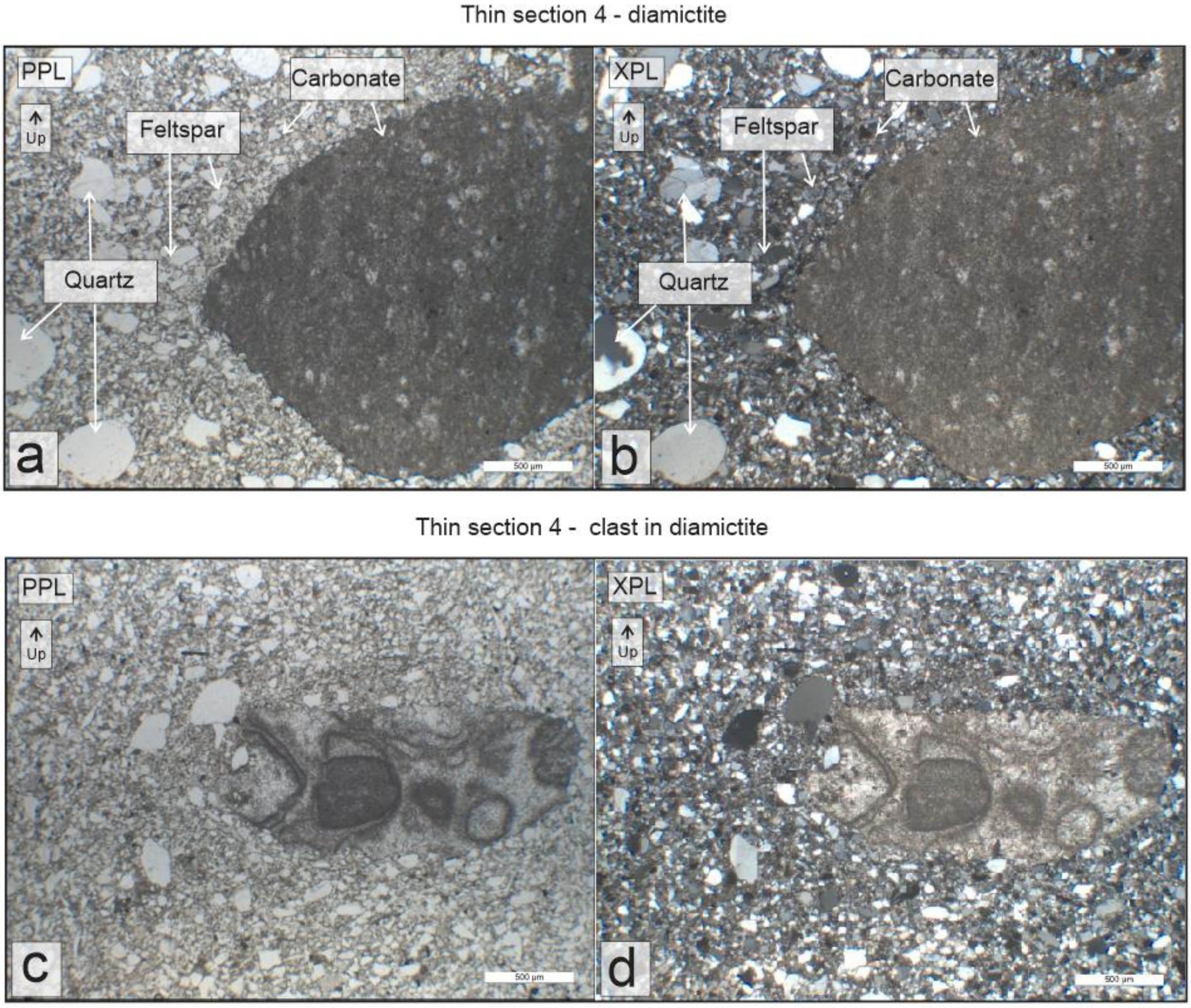

Figure 4.18 Thin section of the thin-bedded diamictite (FA 4) with fine grained matrix and clasts as seen in plane polarized light (PPL) in (a & c) and in cross polarized light (XPL) in (b & d). The upward direction is indicated together with the minerals quartz (zoned black, grey and white grains), feldspar (twinning) and carbonate (high birefringence colour or brown) and a scale in 500 microns. (c & d) A carbonate clast with oncolite growth inside and an erosive border which probably are transported to Bigganjárgga from an area containing consolidated carbonates.

The framework grains are composing a fine grained matrix that consists of quartz, feldspar and carbonate. In PPL quartz is almost transparent, feldspar is clear to cloudy and carbonate is colourless. In XPL birefringence colour of quartz and feldspar are weak and very strong for carbonate once rotating the microscope stage. Grain size varies from less than 50 to 500 microns with the majority ranging from 50 to 100 microns. Their shape mirror high sphericity and varies from very rounded to very angular with the majority being subangular (following terminology outlined by Powers, 1953; Pettijohn et al. 1987) . The sorting of the grains exhibit a very poorly sorted to poorly sorted structure (following terminology outlined by Folk & Ward, 1957;

Spencer, 1963; Sahu, 1964; Friedman, 1979; Blott & Pye, 2001). Compared to the coarse grained matrix in FA 2 this one is silt grained. There seems to be no preferred orientation of the grains in the thin section. In another part of the thin section a carbonate clast with an erosive border and oncolites inside is located.

4.1.4.3 Interpretations

Environmental interpretation

The grain size in the unit is in general small consisting of silt, but diminishing amounts of coarser grained sandstone and pebbles (and rare cobbles) are also found mixed within the siltstone. Fine grained deposits can be found in several environments (i.e. flood plains and deep ocean (e.g. Hjellbakk, 1993)), but the coarser clasts limits the plausible environmental explanations. Processes known for transporting small grain sizes like silt are flows of different kinds (both as bedload and suspended load, and gravity flows) and are dependent on the Bernoulli effect and critical velocity of the flow (De Blasio et al., 2004; Collinson, 2006; Nichols, 2009). In a low density/viscous fluid flow, suspension as a process alone cannot for this unit be responsible for the entire deposition as the sufficient turbulent motion suspending the finest material not is able to suspend the coarser grains in the same way. However, water rich high-density flows may suspend load of greater sizes (i.e. turbidity flows and debris flows (Collinson, 2006)). Taking in consideration the observed draped cobble (Fig. 4.16d & e) it seems unlikely that it was derived from the same location as the finer material due to its anomalous size and low presence in the unit. It may be derived during transportation and embedded in the flow. Another plausible solution may be derivation from floating ice as ice dropped debris (e.g. Nystuen, 1985; Thomas & Connell, 1985). The soft sediment deformed siltstone layers may be associated with a water rich substance for instance in an ocean, but it can occur both subaerial and subaqueous and does not determine the environment alone (Mills, 1983). When considering all the mentioned factors the unit is interpreted to most likely be a consolidated cohesive mudflow or slump (e.g. Lowe, 1982; Collinson, 2006) derived in a marine environment due to the domination of the fine grain size with pebbles and rare occurrence of cobbles and pervasive soft sediment deformation (Lowe, 1982; Nystuen, 1985; Thomas & Connell, 1985).

Petrographic interpretation

Regarding the nature of the framework grains, grain size sphericity, sorting and orientation the textural maturity of the thin-bedded diamictite is considered to be submature (e.g. Folk, 1951) whereas the mineralogical maturity is considered to be immature (Pettijohn, 1954; Okada, 1971). In the case of this unit this means that the provenance would most likely be related to a combination of transportation distances, thus the majority of the grains are acquired from long transportation due to the small grain size (Folk, 1951). The carbonate clast with oncolites in Fig. 4.18c & d is suggestive with either a source area consisting of a carbonate lithology (among other), or that the flow passed a carbonate environment where it was picked up (i.e. does the Grasdalen Formation consist of carbonates (Rice et al., 2011)).

4.2 Stratigraphic lateral relationship of the facies associations

The transition between the different FA's are almost as important as the FA's themselves. The Bigganjárgga Unconformity, which occur between FA 1 and FA 2 is the most studied contact at the outcrop (e.g. Føyn, 1937; Bjørlykke, 1967; Edwards, 1984; Laajoki, 2001; 2002) and is also documented in the present study to be an unconformity (Section 4.2.1). However, since an aim in this study was to differentiate the two sandstones from each other, the contact between FA 2 and FA 3 is almost as interesting. The contact between FA 3 and FA 4 was not studied during the fieldwork for this thesis, partially because of the lacking visibility in the terrain. Below, descriptive photographs and sketches are presented to give a better understanding of the contacts and the relationship between the FA's.

4.2.1 The Bigganjárgga Unconformity – lateral and vertical geometries and relationships between FA 1 and FA 2

The surface that upon the Bigganjárgga Diamictite rests, respectively between FA 1 and FA 2 (i.e. the Bigganjárgga Diamictite), is related to the more widespread regional unconformity referred to as the Varangerfjorden Unconformity (VFU) which separates the Vadsø and Tanafjorden groups from the Vestertana Group (e.g. Bjørlykke, 1967; Laajoki, 2001). The unconformity at the outcrop site is for the remaining part referred to as the Bigganjárgga Unconformity (BGU), although it is a segment of the VFU.

4.2.1.1 Outcrop description

The BGU occurs as a slightly dipping 1 – 2 degrees (indirectly measured by Føyn, 1937) sandstone surface with northward strike located within the top part of FA 1 (Fig. 4.19 and 4.20) at Bigganjárgga. The unconformity is best exposed as a pavement on the west side of the outcrop (Fig. 4.20). Even though dipping, the pavement occurs planar there. Both towards east and west, the pavement of the unconformity disappears into and between the thick-bedded sandstone (FA 1) and the thin-bedded sandstone (FA 3). Additionally, towards west the unconformity cuts down into the structures in the thick-bedded sandstone (FA 1) below (Fig. 4.19) making a channelized feature. The down cutting is so prominent that it disappears down into the ocean. The pavement contains striations and imprints that can be described as follows.

Striations

Two sets of clearly visible striations are seen carved into the unconformity pavement (Fig.4.20). The first striation set is orientated E-W (white dashed lines in Fig.4.20b) and is the least prominent one, it is shorter and narrower than its counterpart. On a small sandstone pavement (Fig.4.21a) before it disappears into and between FA 1 and FA 2, there are several striations of the same orientation (E-W, Fig. 4.21b, c & d) that have similarities to slickenside. The striations in Fig. 4.21b & d appears planar on the surface, whereas the one in Fig. 4.21c is deeper carved. All these striations have in common that they have several furrows preserved close to each other, either on the planar surface or on all sides in the carved striation. The other striation set is oriented NW-SW (yellow dashed lines in Fig.4.21), cuts deeper into the pavement and may leave ridges on the sides. Both sets of striations have cases of straight lines and cases were they curve sideways in the length direction. A constructed rose diagram shows the orientations of the striation sets and the measures used to this is appended in Appendix 2.

Imprints

On top of the unconformity pavement, there are several imprints (Fig.4.22). It has to be noted that this is not the same imprints as seen internally in FA 1. These are sited on the unconformity pavement. There is no standard appearance of these imprints, some are 1 to 2 cm deep, others are only a few mm deep. Their shapes are irregular (i.e. round and elongated) and some of the shortest elongated ones may be confused to the shortest striations (the E-W striation set) if not carefully scrutinized (Fig. 4.22d). One imprint is infilled with a clast (Fig. 4.22 f), but does not fill the entire imprint up to the unconformity pavement.

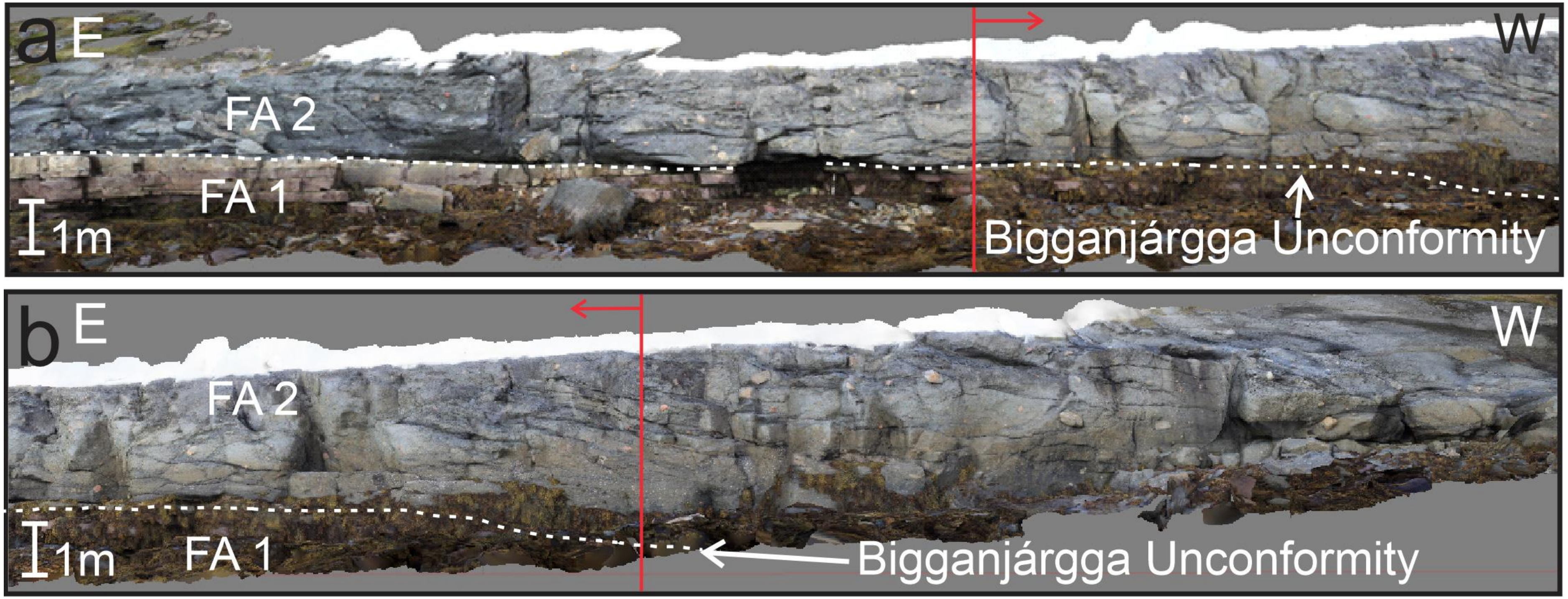

Figure 4.19 A captured overview from the 3D-model that shows how the BGU (white dashed line) between FA 1 and FA 2 (a & b) cuts into FA 1 and dips/disappear (b) towards west. There is a continuation of the photograps from the upper right corner to the lower left corner (red arrows shows direction and red vertical lines shows approximately where the overlap begins in the two photograps). Additionally view of this eroded contact (cleaned for the occacion) can be found in Fig. 5 in Laajoki (2001).

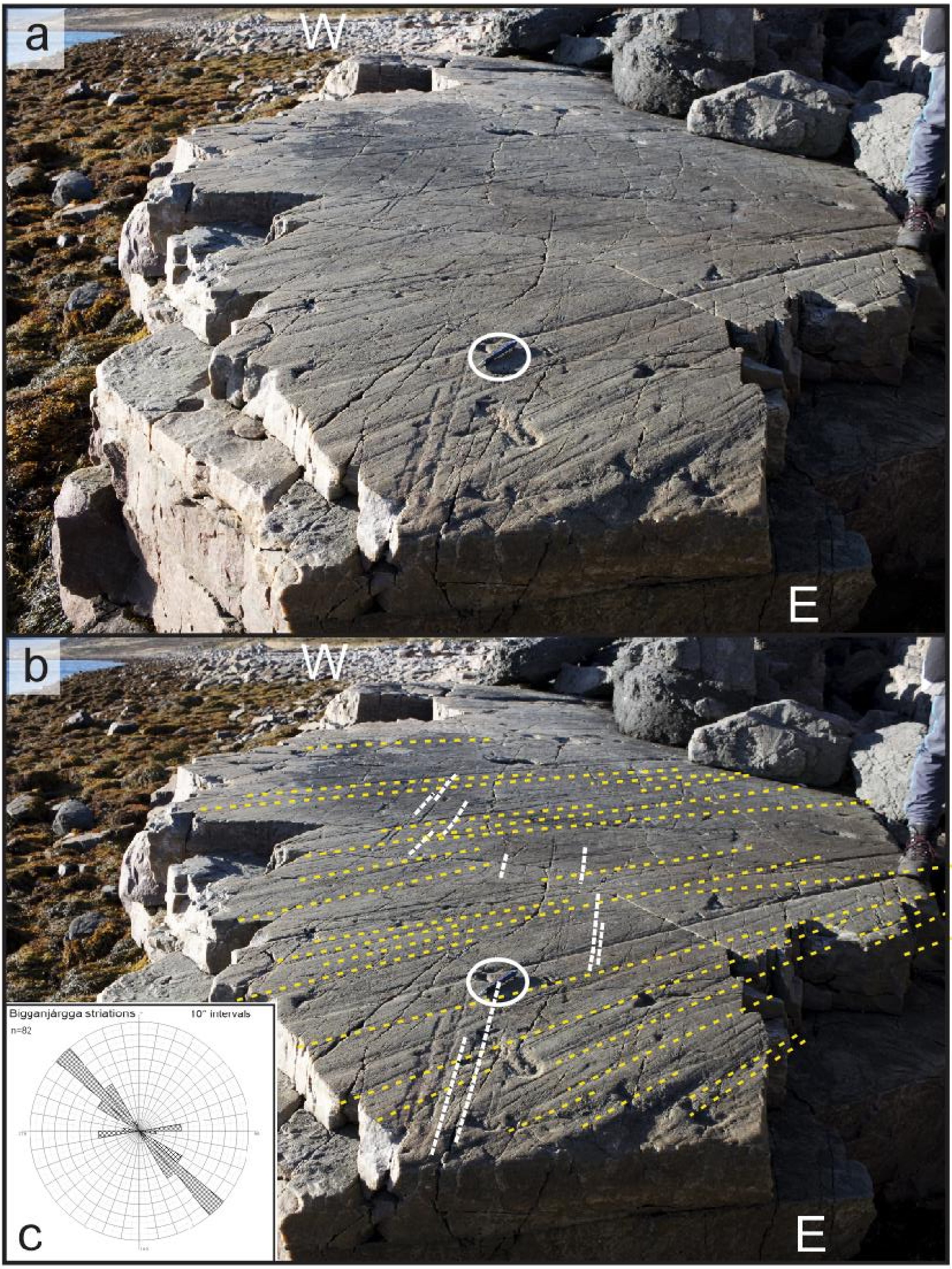

Figure 4.20 (a) The striated surface of the BGU with the marked striations (b). The yellow dashed lines (near horizontal in the figure) mark the main striation orientation (NW-SE), whereas the white dashed lines (near vertical in the figure) mark the second striation orientation (E-W). Pen for scale in white circle (c.15 cm) (c) A generated rose diagram for the 82 measured striations where the orientations of the two striation sets can be seen. North is up and the intervals are 10 degrees.

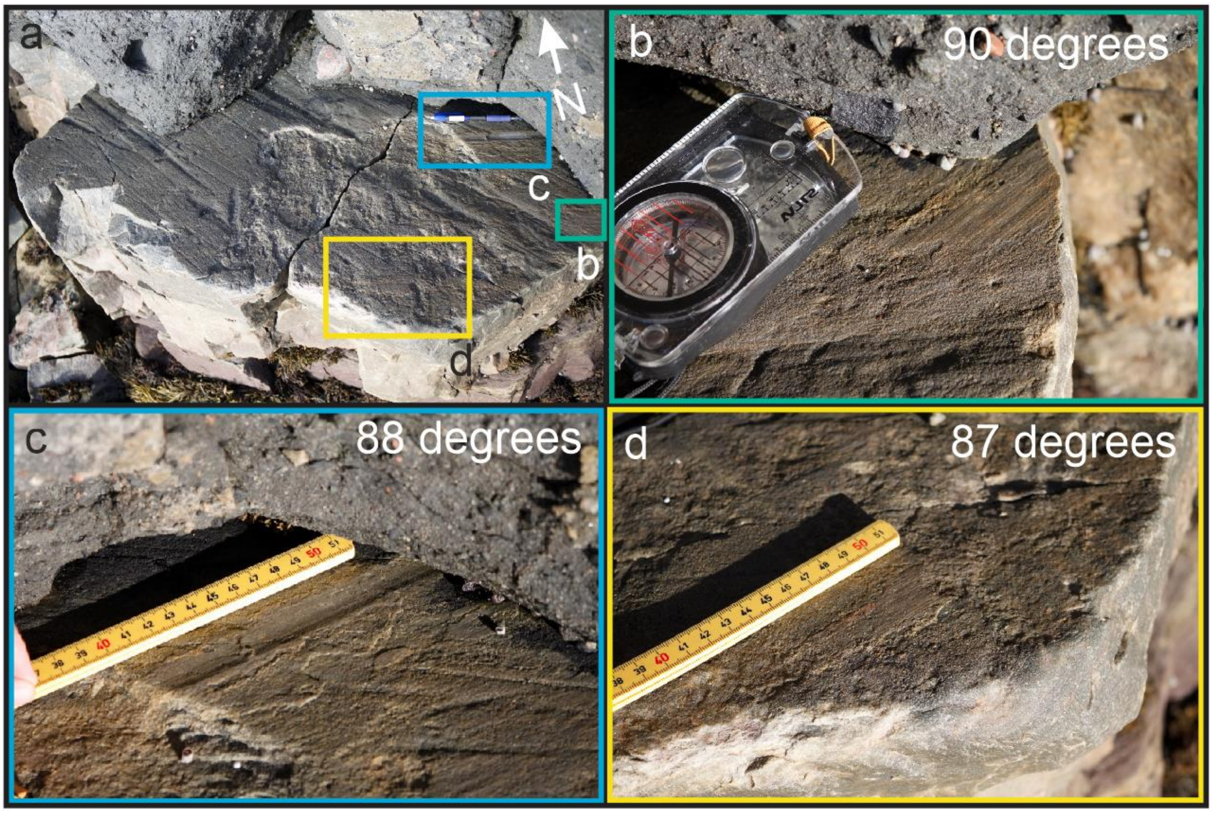

Figure 4.21 The second noticable striation orientation also seen on the BGU. (a) An extending overview of the collected striations (green – b, blue – c, yellow – d). All these striations had several furrows close to each other in the same direction. Similarities to slickenside were proposed by Laajoki (2002).

Figure 4.22 A selection of the different imprints from the Biggajárgga Unconformity. (a) An overview of the striated surface at its best exposure. (b) The surface as seen from above, photograph captured from the top of the Bigganjárgga Diamictite. (c –e) Close up of different imprints. (f) Like seen in Jensen & Wulff-Pedersen's article (1996), this was the only rock found that was pushed into the sanstone and still were preserved in place. Photos (a), (c), (d) & (e): Sten-Andreas Grundvåg.

4.2.1.2 Interpretation

The contact/BGU was observed cutting down into the layers of the thick-bedded sandstone (FA 1) (Fig. 4.19). Laajoki (2002) did describe this as a channelized part of the Varangerfjorden Unconformity. The relationship between the contact at Bigganjárgga and the confirmed regional unconformity (Rosendahl, 1931; 1945; Edwards, 1984) in Finnmark strengthen the establishment for an unconformity and give a shove in the direction of a glacial abrasional origin for this contact (as rejected by the “non-glacial school”). Because a substantial big glacier passing the area undoubtedly could erode consolidated rocks in “valley-size” without problems concerning stratigraphy and bedrock (Flint, 1971), this seems credible without any conclusions made. Besides, glacial abrasion of this contact surface was established as a considerable erosive agent by Laajoki (1999; 2002). Traces of the erosion of a great amount of the stratigraphy in FA 1 at Bigganjárgga in relationship to the regional unconformity as proposed by Siedlecka (1990); referred in Rice & Hofmann (2000), are supported by thin section observations from the lowest unit (FA 1) in this thesis. The cementation and the orientation of the quartz grains in this unit, relates to the overpressure between grains (i.e. deep burial by overburden sediments) and would hence support the presence of a hiatus. Although supporting a hiatus, the thin sections does not tell anything about the way the sediments/rock were transported from the location. Nonetheless, the observed features of erosion between rock bodies and/or a hiatus does support the criteria making it a unconformity (e.g. Salvador, 1994).

4.2.2 Lateral and vertical geometries and relationships between FA 2 and FA 3

Compared to the BGU, the contrary contact above the Bigganjárgga Diamictite and between FA 2 and FA 3, has received less attention in the literature.

4.2.2.1 Outcrop description of the contact

Well-exposed contact zones between FA 2 and FA 3 are seen on both flanks of the Bigganjárgga Diamictite, respectively referred to as the western (Fig. 4.23, 4.24 & 4.25) and the eastern (Fig. 4,27, 4.28 & 4.29) contacts. In addition, exposures of the surface of the diamictite itself are seen between the flanks, referred to as the middle contact (Fig. 4.26).

Western contact between FA 2 and FA 3

The thinning lens shaped flank of the Bigganjárgga Diamictite (FA 2) that is stretching westward is onlapped (following terminology outlined by Christie-Blick, 1991; Bjørlykke, 2010) by the thin-bedded sandstone (FA 3) above (Fig. 4.24). The contact border is uneven with clasts embedded/included within the lowermost and first onlapping sandstone layers (Fig. 4.25b). Note that these clasts are not to be compared to the internal rip-up mud clasts in FA 1. The contact itself is seen for approximately 10 meters.

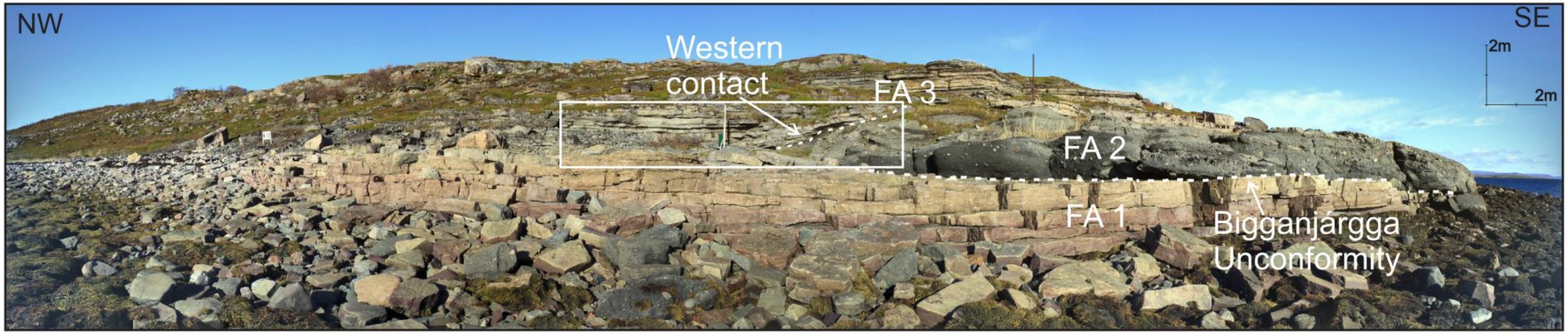

Figure 4.23 An overview of the western side of the outcrop displaying the three lowest facies associations (FA 1 – FA 3). The contact between FA 2 and FA 3 (referred to as the western contact) is marked in a white box (see Fig. 4.24 & 4.25). In addition, the contact itself and the BGU are marked by white dashed lines. Since the photograph in the figure is composed of several photograps to a single panorama, the view is somehow twisted a bit. Therefore, the BGU will for instance might be a little more twisted than in reality. Referring to the appended 3D-model in Appendix 3 for a correct view of the outcrop without illusion distortions.

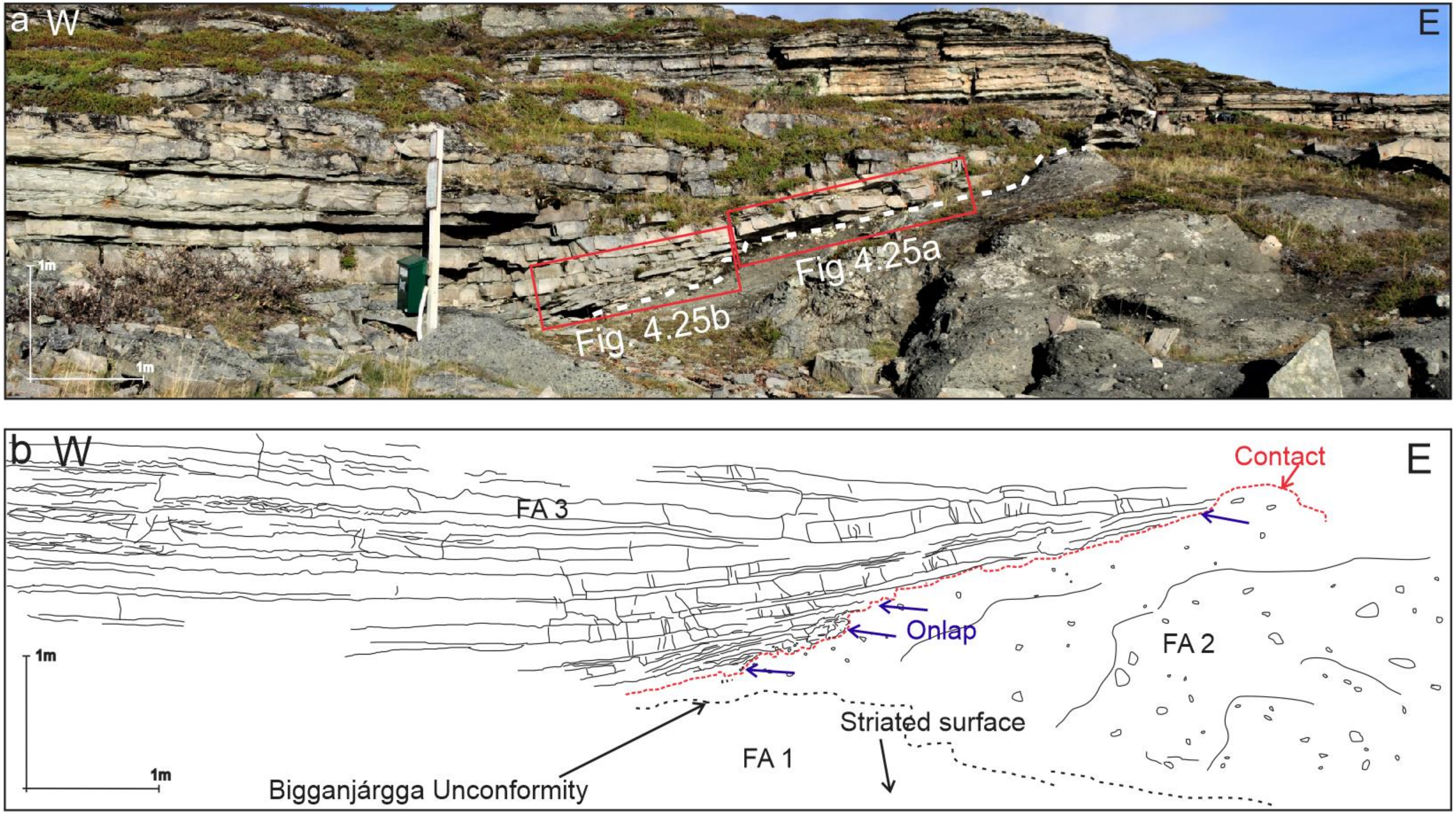

Figure 4.24 The western contact between FA 2 and FA 3. (a) Photograph of the contact where the white dashed line shows the contact zone and the red boxes shows where the figures in Fig.4.25 are captured. (b) A sketch made out of the photograph in (a) showing the three facies associations present (FA 1 – FA 3), the contact between FA 2 and FA 3, the Bigganjárgga contact and the striated surface, and the onlapping sequence of the sandstone layers in FA 3 onto the thick-bedded diamicite (FA 2) are marked by blue arrows.

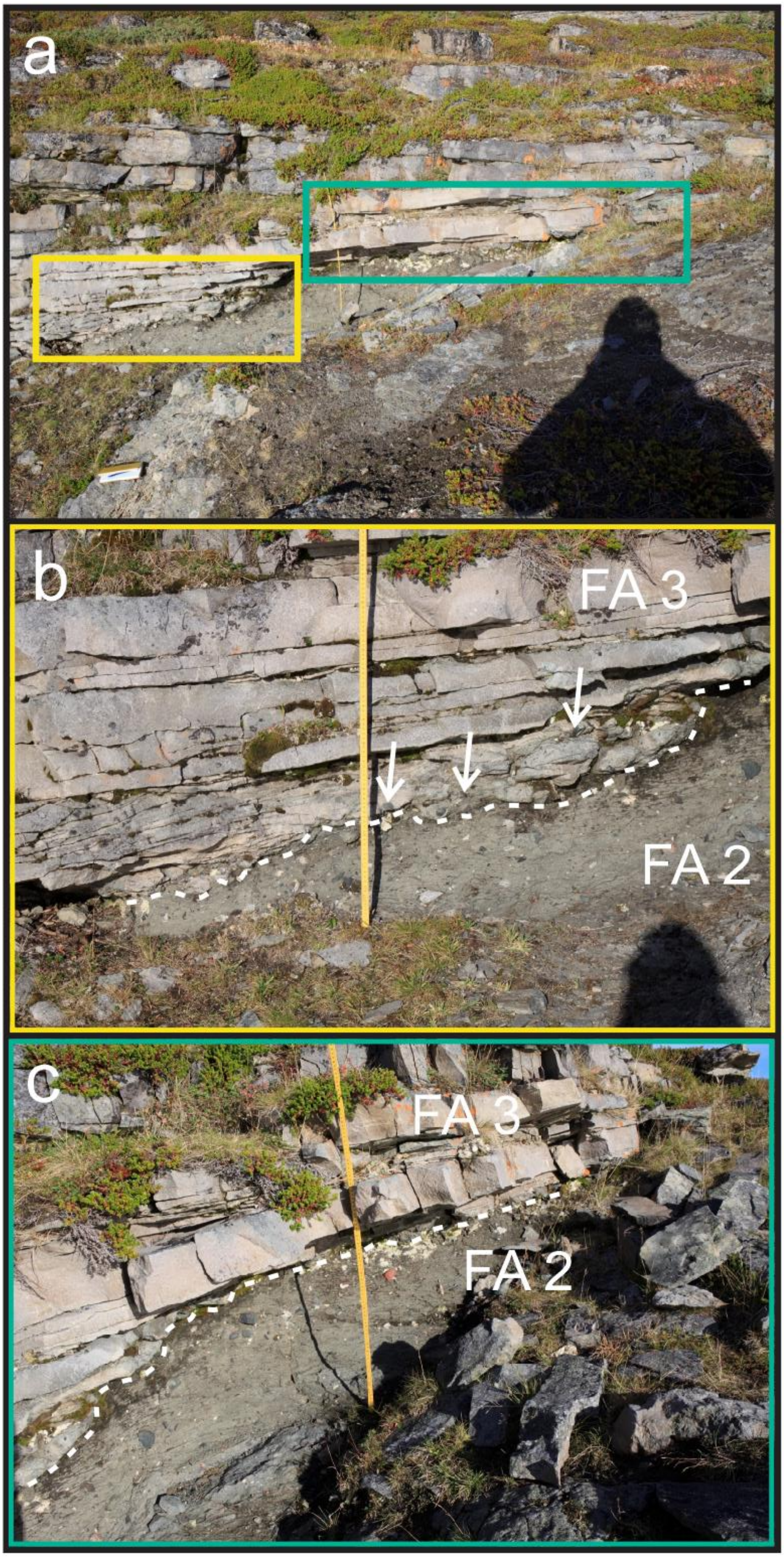
a
b
FA 3
FA 2
c
FA 3
FA 2

Figure 4.25 The onlapping sequence of the western contact. (a) Approximate location of the views of the contact in (b – yellow) & (c – green). (b) In the lower part of the thin-bedded sandstone unit inside the onlapping sandstone layers (FA 3) furthest to west, there are clasts (red arrows) that most likely are derived from the thick-bedded diamictite (FA 2) below. In relation to this observation, the contact (white dashed line) was uneven in this area. (c) In the upper part of the thin-bedded sandstone unit the contact (white dashed line) between the two facies associations is sharper and the thicknesses of the onlapping layers are more even.

Middle contact between FA 2 and FA 3

On top of the thick-bedded diamictite (FA 2), the surface is exposed. The best exposures are seen in the eastern side of the outcrop were stacked/layered lobes can be seen (Fig. 4.26). There are also consolidated rock fragments of the unit which seem to be more resistant than its surroundings. This has resulted in ridges emanating in the surface of the unit (see Fig. 4.26 c, e & g). The contact between FA 2 and FA 3 is hard to see at this point of view because the gradual transition and the weathering erosion.

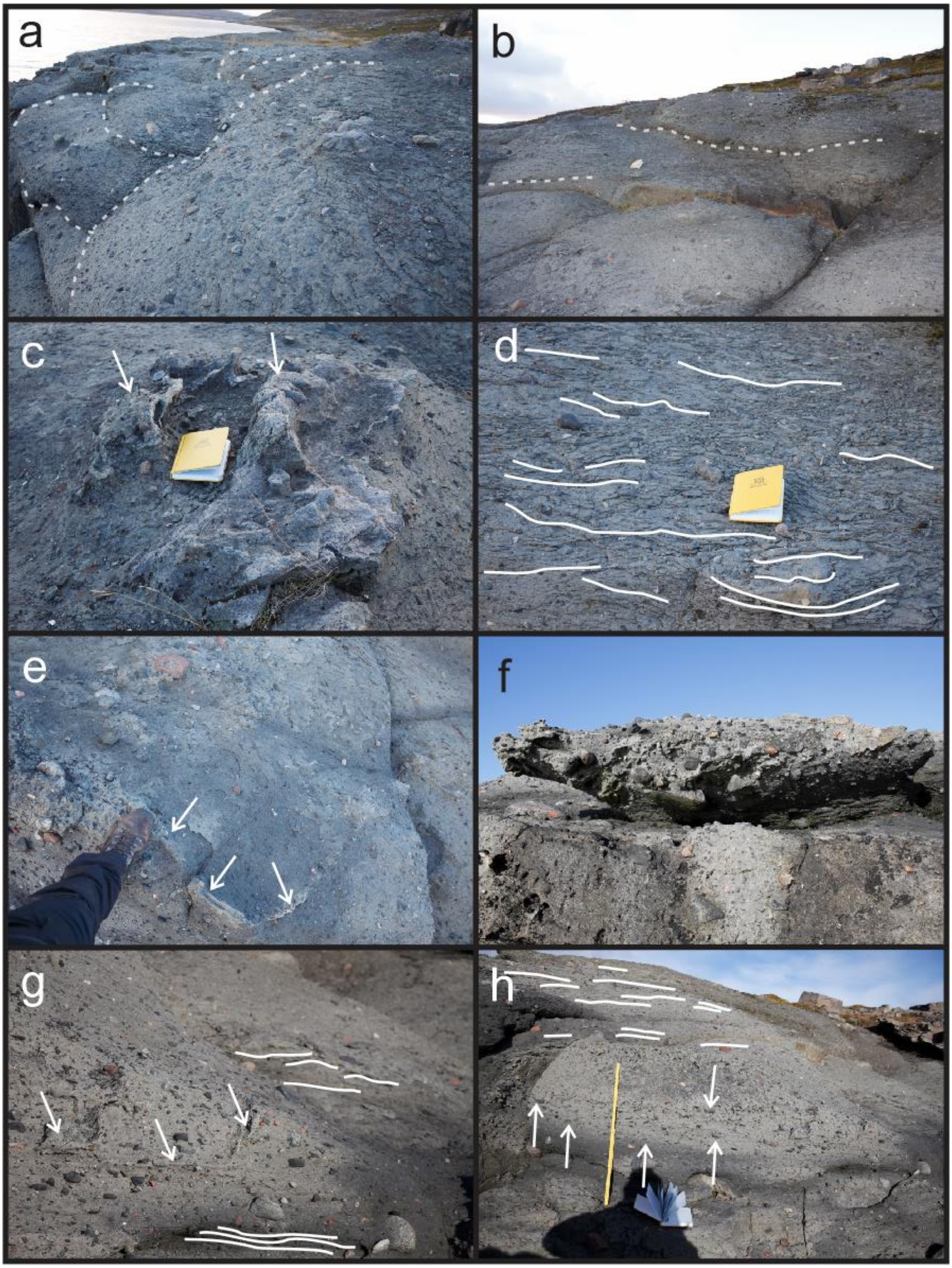
a
b
c
d
e
f
g
h

Figure 4.26 The middle surface of the thick-bedded diamictite. (a) The surface as seen from east towards west. White dashed lines are suggests lobe-like features. (b) The surface as seen from southeast to northwest. Also here the lobe-like features are suggested by white dashed lines. (c) One of the best exposed consolidated rock fragments. White arrows mark emanating ridges on top of the unit that was more resistant to erosion. Book (19 cm) for scale. (d) The white lines marks thin-bedded layers on top of the unit. Layering like this was found in several of the lobes indicated in (a & b). (e) White arrows mark another emanating ridge (see (c)). Foot for scale. (f) An exposed part of the unit that ranged above the rest of the unit. Similarities to the emanating ridges in (c) and (e) can be seen, but this of greater extent (about 3 meter long). (g) Both thin-bedded layering and emanating ridges are seen here. (h) Imbrication of some of the clasts within the lower part of the photograph (white arrows) would suggest a horizontal flow direction (see Appendix 2 for measures of clast orientation). In the upper part thin-bedded layers were seen.

Eastern contact between FA 2 and FA 3:

The thinning lens shaped flank of the Bigganjárgga Diamictite (FA 2) that are stretching eastward are also onlapped by the thin-bedded sandstone (FA 3) above (4.28). Inside the sandstone layers, two lenses of a diamictite material much alike in composition to FA 2 (Fig. 4.28 & 4.29b &c) and singular inbedded/embedded clasts (Fig. 4.29d & e) are seen. The nature of the contact is irregular and can be traced laterally for 20 to 30 meters.

Figure 4.27 An overview of the eastern side of the outcrop displaying the three facies associations visble (FA 1 – FA 3). The location of the contact between FA 2 and FA 3 (referred to as the eastern contact) is marked by a white box (see Fig. 4.28 & 4.29). In addition, the contact and the BGU are marked by white dashed lines. The length between the daches separates the contacts from each other. Since the photograph is composed of several photographs to a sigle panorama, the view are somehow twisted a bit. Therefore, the outcrop will might be a little more twisted than in reality. Referring to the appended 3D-model in Appendix 3 for a correct view of the outcrop without illusion distortions.

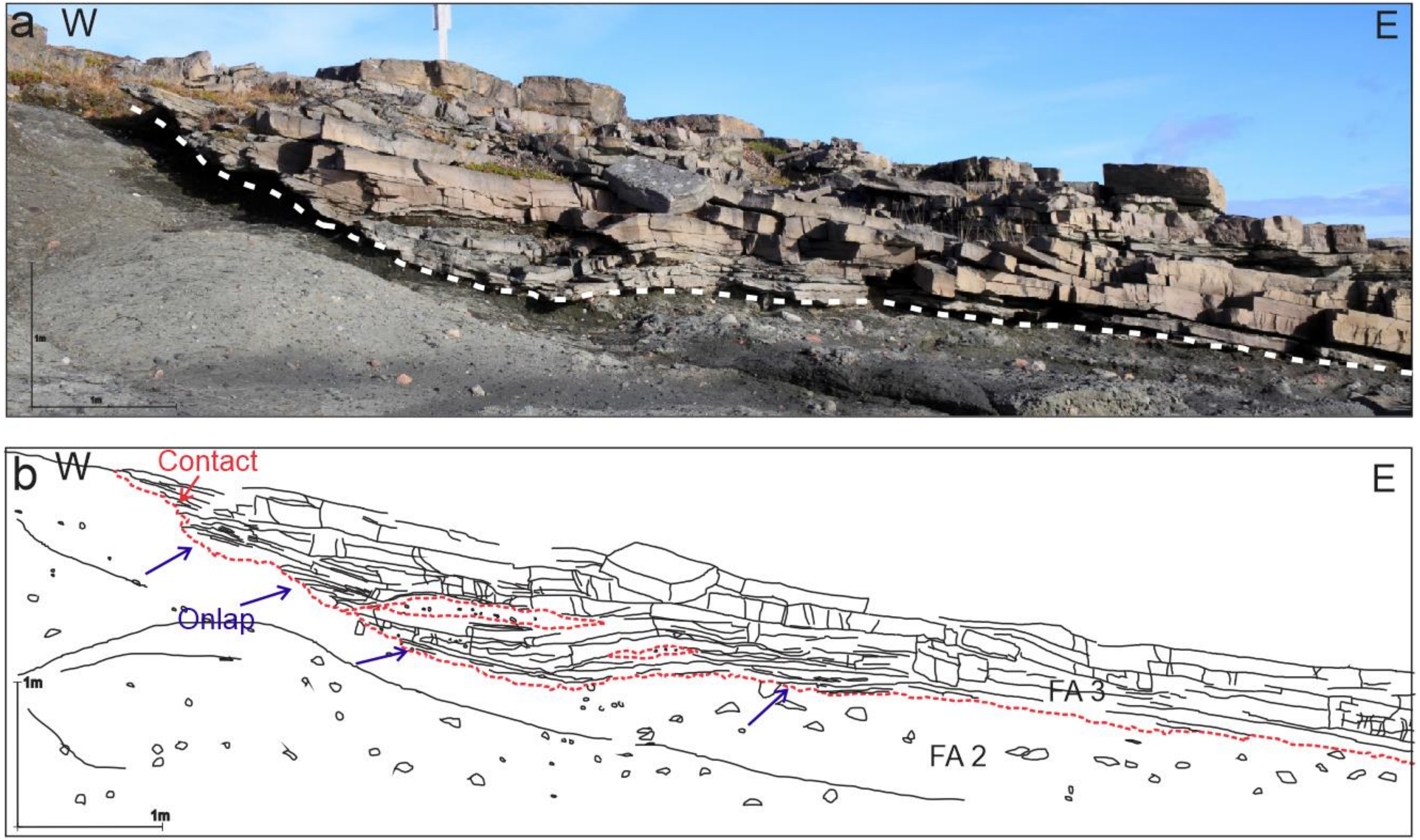

Figure 4.28 The eastern contact between FA 2 and FA 3. (a) Photograph of the contact where the white line shows the contact zone. (b) A sketch made out of the photograph in (a) showing the two facies associations present (FA 2 & FA 3), the contact between them and the onlapping sequence of the sandstone layers in FA 3 onto the thick-bedded diamictite (FA 2) are marked in blue.

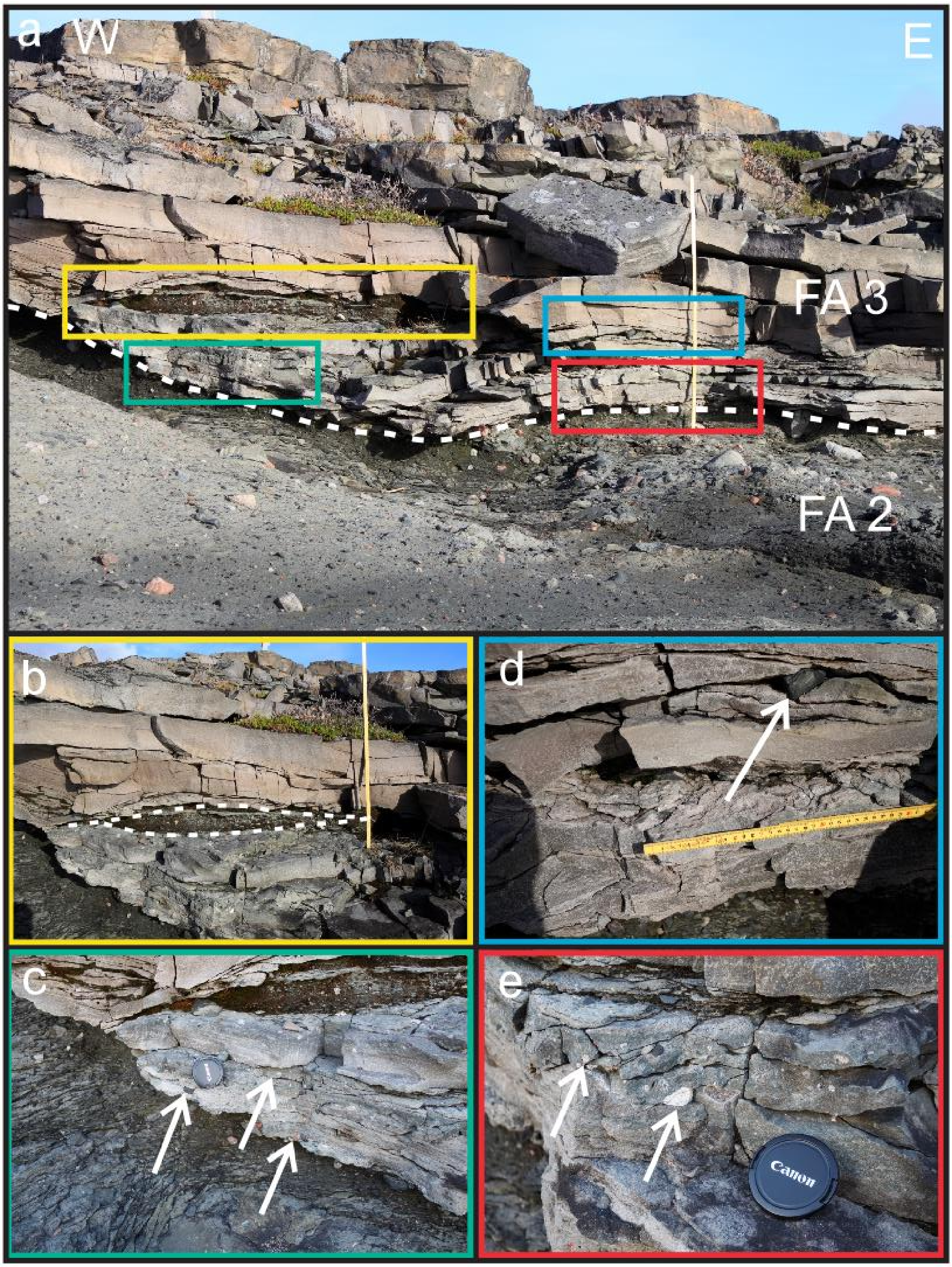
a
W
E
FA 3
FA 2
b
d
c
e
Canon

Figure 4.29 The western upper contact. (a) Included within the thin-bedded sandstone unit above the upper western contact are masses that look very similar to the thick-bedded diamictite unit from below the contact. Eastern contact are marked by a white dashed line. (b – yellow) One of the lenses containing diamictite mass (white dashed line). (c – green) Below the lens in (b) there are clasts embedded within the sandstone. (d – blue) A clast measuring ~ 4 cm are tilted within the sandstone beds. (e – red) Clasts incorporated within the sandstone unit.

4.2.2.2 Interpretation

The first perspective when describing this contact is the remarkable differences between the two facies associations (diamictite versus sandstone). Whereas the diamictite consist of a wide variation of grain sizes, the lithology of the sandstone is much more homogeneous. This is correlative with severe changes in depositional environment from one facies association to the other (Nichols, 2009; Leeder, 2011). When studying the contact itself, onlapping sequences of sandstone layers were observed on both sides of the outcrop (Fig. 4.25, 4.28). A break like this in facies in the stratigraphic record is according to Christie-Blick (1991) an expression of stratigraphic discontinuities also termed unconformities. Some of the medium grained sandstone layers did also contain clasts (pebbles) of a noticeable greater size (Fig. 4.25 & 4.29). These may be derived from the unit below (FA 2). The interbedded diamictite lenses seen in the sandstone can according to Arnaud & Eyles (2002) say something about the conditions during the onlapping sequence. Another supportive evidence encouraging that FA 2 was non-consolidated during deposition of the onlapping FA 3 will be the winnowing features (emanating ridges of exposed consolidated rock fragments observed on the middle part of FA 2, Fig. 4.26). If interpreting their formation as result of turbulent winnowing effect (Edwards, 1984; Menzies & Shilts, 2002) occurring on top of the lens in FA 2 (i.e. during transport of sand in a flow to deposition of the sandstone layers on the flanks), the clasts could as likely have been entrapped and mixed within the sandstone layers when deposited. However, when determining the character of the contact between FA 2 and FA 3, the onlapping sandstone layers as a break in the stratigraphic record in addition to the facies changes are enough evidence for establishing the contact an unconformity (Christie-Blick, 1991; Bjørlykke, 2010).

5 Discussion

5.1 Reconstruction of depositional history from sedimentary facies analysis

Sedimentary facies analyses have proven to be a useful tool for the descriptions and interpretations of depositional features in a stratigraphic sequence, as well as being crucial for palaeogeographic reconstructions (Miall, 1987). Facies analysis can be used to organize outcrop observations and eventually shed new light on the palaeoenvironmental evolution and aid in deducing changing ancient conditions in the stratigraphic record (e.g. Miall, 1987). Below, the four different facies associations recognized in this study will be discussed in more detail, focusing particularly on the stratigraphic boundaries that separate them.

5.1.1 FA 1 – Thick-bedded sandstone – fluvial origin?

Depositional environment and regional correlation

The thick-bedded sandstones of FA 1 belong stratigraphically to the Veinesbotn Formation (Røe, 2003). The lithostratigraphic position of the unit is debated and it has traditionally been placed at the base of the Vadsø Group (Banks et al., 1974; Hobday, 1974) as well as within the Gamasfjellet Formation in the Tanafjorden Group (Røe, 2003). However, the interpretation within has not changed accordingly since the first time interpreted. The facies within the unit and their respective interpretations (F1, F2, F3, F4, F5; Table 1) point to an environment dominated by unidirectional currents and bedload/traction transport of sand-grade sediment, possibly reflecting a fluvial dominated environment (e.g. Miall, 1987; Bridge, 2009). This is in line with the interpretations made by Hobday (1974) which suggested that the sandstone beds (Facies A in Hobday (1974)) consisted of braided stream deposits.

Negative imprints within FA 1 – eroded rip-up mudstone clasts

The negative imprints that were found at a certain horizon within the unit and locally were found to contain remains of lithified mudstone clasts are interpreted to be weathered rip-up mudstone clasts (Fig. 4.4d & e) (e.g. Li et al., 2017). The formation of such intraformational clasts relates to changing depositional conditions and local erosion events. Since there has only been found one extrabasinal lithic clast pushed into the top surface of FA 1 just below the BGU and the base of FA 2 (see Fig. 4.22f; Jensen & Wulff-Pedersen, 1996), could the other negative imprints described at this surface at the BGU instead be associated with weathered intraformational mudstone clasts? In case of accepting that the majority of the imprints are made of weathered mudstone clasts rather than physical imprints made from extrabasinal clasts, the suggestion that the lithic clasts at the base of FA 2 made the imprints has to be re-evaluated. Combined with the high degree of cementation and compaction of the grains within FA 1 as observed in thin section (Fig. 4.7), it seems more logical that most of the imprints relate to weathered mudstone clasts. This would for instance support Edwards (1997) interpretation, which suggested that the sandstone was consolidated prior to the development of the BGU and deposition of FA 2. Edwards also mentions that the occurrence of sandstone clasts within the Bigganjárgga Diamictite (FA 2 of the present study) are consistent with a degree of consolidation of the source where these sandstone clasts originate. Erosion and reworking of an unconsolidated sand unit would in comparison not have been seen as sandstone clasts in the diamictite of FA 2, but rather as the finer sand grains incorporated into the matrix. Because the sandstone clasts previously have been assigned to belonging to the sandstone unit below (FA 1) (Bjørlykke, 1967), a consolidated substrate seems to be a reasonable explanation.

The existence of mudstone clasts in the imprint as seen in Fig. 4.4d was suggested previously by Rice & Hofmann (2000), referring to them as mudflakes. However, the lack of evidence for the preservation of such mudstone clasts was stressed out by Laajoki (2002). However, the present study demonstrates the presence of such mudstone clasts, thus filling a void in the overall discussion of the origin of the majority of the imprints (apart from the single imprint where a lithic clast still is preserved as shown by Jensen & Wulff-Pedersen, 1996).

5.1.2 The contact between FA 1 and FA 2 – The Bigganjárgga Unconformity

The abrupt and dramatic boundary between FA 1 and FA 2 is one of the stratigraphic contacts that have received most attention in the Varanger area (e.g. Holtedahl, 1918; Føyn, 1937; Bjørlykke, 1967; Jensen & Wulff-Pedersen, 1996; 1997; Edwards, 1997; Laajoki, 2001; 2002). Thus, radical new observations that may contribute to the discussion are difficult to discover. Nevertheless, many details are worth further discussion. An example is the large amounts of the stratigraphy above the thick-bedded sandstone (FA 1) that have been suggested removed by Rice & Hofmann (2000), which also indicate a hiatus comprising of c. 150 Ma. They estimated the removal of c. 2.5 km of the strata. The petrographic analysis of the unit from the thin section in this thesis affirm this. Thus, if using the stratigraphic division suggested by Røe (2003), a substantial amount of the hiatus is removed and the thin section will no longer be affirmative. Although, the unconformity studied at Bigganjárgga belongs to the regional Varangerfjorden Unconformity, it is referred to as the Bigganjárgga Unconformity (BGU) in this study. The regional character of the unconformity is outlined in several previous publications (Rosendahl, 1931; 1945; Bjørlykke, 1967; Edwards, 1984; Laajoki, 2001). However, according to Jensen & Wulff-Pedersen (1996), the BGU is of local character and only occur within the Vestertana Group. Such an interpretation is dramatic and misleading and thus gave these authors the opportunity to debate numerous mis-conceptions in their paper, as cited by Edwards (1997). The publication by Jensen & Wulff-Pedersen (1996) stand out as one of the few contributors that have confronted the overall and generally accepted glacial interpretation, but have in the following almost 25 years not been welcomed or approved by the community.

However, some of the features at the BGU can support a debrite origin, or at least not completely reject it. The channelized feature of the BGU cutting layers of FA 1 (Fig. 4.19) together with the striations seen on the exposed sandstone pavement can for instance have been made by the erosive forces occurring below a turbulent gravity flow (i.e. fore-running turbidity current in front of a debris flow (e.g. Hampton, 1972; Talling et al., 2012; Saha et al., 2017). If so, this must have been a pre-event from before deposition of the Bigganjárgga 'Debrite' since a debris flow not is able to erode in the same way. In regards of the result from this thesis suggesting a consolidated sandstone in FA 1 before erosion of the BGU took place and deposition of FA 2 occurred, the local erosive forces must have been going on for a long time and been applied by multiple turbulent gravity flows to manage to erode kilometres of consolidated strata. Afterwards, deposition of FA 2 must have occurred. Thus, by comparing the regional correlation between the VFU and the BGU i.e. by apparent similarities between glacial orientational indicators at several localities included at Bigganjárgga as suggested by Laajoki (2001), gives an impression of a regional erosive force more prominent than a local one. A glacial origin for the BGU is therefore supported in this thesis. Regardless the formation, the presence of evidence for an unconformity between FA 1 and FA 2 at Bigganjárgga is clear (following terminology outlined by Salvador, 1994).

Striations and the lithic rock imprint

The two sets of striations seen on the top surface of FA 1 at the BGU (Fig. 4.20) give an impression of the directional movement for the medium that made them. These are however only orientation indicators, as directions cannot be determined with the existing features at the outcrop. Previous observations from nearby areas (such as a channel structure at Sjåholmen, numerous of cross-beddings in the Kvalnes Conglomerate, flute cast structures at Hammernes (Bjørlykke, 1967) and preserved features at the Larajæg'gi outcrop (Laajoki, 2004)) indicate that the direction was from SE towards NW and/or from E towards W at the time when the striations on the BGU were made. This is in line with the observations made in this study (see rose diagrams in Fig. 4.6 & Fig. 4.20.c). If one accept this transport direction, it provides an explanation for the high amount of Precambrian basement clasts in the Bigganjárgga Diamictite as demonstrated by Bjørlykke (1967) (i.e. derivation from a southerly Precambrian basement source). It is also noteworthy that the orientation of the present day Varangerfjorden fits to this transport direction as mentioned by (Bjørlykke, 1967; Edwards, 2004), thus it is only on an orientation line (NW/SE or W/E) and not a directional line (towards NW or W). If using these evidences, the origin of the striations can be accepted to be related to glacial abrasion.

However, striations can still be related to a debrite origin. In regards to the negative imprints earlier discussed to be made mostly by weathered mudstone clasts incorporated in the sandstone unit, the degree of compaction and cementation of FA 1, the erosional character of the BGU (being a segment of the regional VFU), the orientation of the striations in combination with the basement clast content in FA 2 (derived from basement source in the south), the explanation by Jensen & Wulff-Pedersen (1996) which suggests that the clasts at the base of the diamictite were responsible for the imprints in a loosely consolidated sand loses its credibility. Their main evidence for rejecting the striations to be of glacial origin was supported by the single lithic clast that is apparently pushed into the sandstone unit below the BGU (FA 1) being preserved at the termination of one of the striations. Therefore, they concluded that the sandstone below the BGU (FA 1 in this thesis) was unconsolidated or sub-consolidated during the deposition of the Bigganjárgga Diamictite (FA 2 in this study). However, such an interpretation is not supported from the thin section analysis of the unit in this thesis, which indicate a very mature, highly cemented and compacted sandstone below the BGU and less mature compacted sediments above. Jensen & Wulff-Pedersen (1996) do also admit the importance and the following results of a consolidated thick-bedded sandstone unit (FA 1) at the time when the Bigganjárgga Diamictite was deposited. Thus, they uses the consecutive result with a non-consolidated to semi-consolidated unit (FA 1) in detail to argue that the BGD-clasts made the striations. As a matter of fact, lithic clasts preserved at the termination of the striations were searched for by the present author, but none were observed (apart from the one single lithic clast also described by Jensen & Wulff-Pedersen (1996) i.e. in Fig. 4.22d).

However, the lithic clast observed on the BGU (Fig. 4.22f) can theoretically originate from the BGD (FA 2) and be the agent responsible for the occurrence of the striations as suggested by Jensen & Wulff-Pedersen (1996). In such a case, an unconsolidated to sub-consolidated sediment would be preferred because it would demand a lower physical pressure from the clast in the diamicton to be submerged. If the substrate was unconsolidated to sub-consolidated, the striations can be attributed to the scouring effects (i.e. tool marks or scour marks) made by a turbulent fore-running turbidity current ahead of the more laminar and less erosive debris flow following it (e.g. Sanders, 1960; Hampton, 1972; Talling et al., 2012; Saha et al., 2017). If opposite, and the substrate (FA 1) was consolidated when the diamicton (FA 2) was deposited above (like the results from this thesis suggest), it seems more likely that the clasts in the BGD (FA 2) would have been ejected into the unconsolidated diamicton rather than into the consolidated substrate below as suggested for the single lithic clasts observed on the BGU.

Thus, the striations could still be made in a consolidated substrate if applied by the turbulent fore-running gravity flow because of its eroding force. However, due to the confirmation of a consolidated substrate in this study, their assignment of the imprint and the striations to be made by the clasts in FA 2 do not seem credible.

Rice & Hoffman (2000) did a thorough description of the striated surface and emphasized another important evidence for a consolidated sandstone unit below the BGU (FA 1 in this study). They mention that the planarity of the BGU most likely would be related to erosion of a consolidated substrate. Their defence was reasoned to that if the opposite was to be the case (erosion of an unconsolidated substrate/soft sediment deformation), the bottom scouring effects applied by glacial or non-glacial kind not would leave a planar surface like the BGU. This does however not fit to all of the observations and descriptions of the BGU in this thesis, nor those applied by Laajoki (2001; 2002) (i.e. eastern channelized part of BGU cutting down into the unit below (FA 1) (Fig. 4.19). Their use of the planarity of the BGU to support a consolidated substrate during the following erosion is therefore not accepted in this thesis.

Bestman et al. (2006) did a critically study on one striation on the surface of the BGU and detected a preserved cataclasite in connection to the ridges of the striations (Fig. 3 in Bestman et al. (2006)). Their petrographic analysis were consistent with a glacial origin, or it did more especially count as "[…] evidence of episodic fast moving glaciers […]" (Bestmann et al., 2006) which thus insinuate a glacial origin for the striations.

On top of a sandstone bed seen just below the BGU (at the base of FA 2) before it disappears towards east, striations with remarkable resemblance to slickenside (e.g. Doblas, 1998) were observed (Fig. 4.21). The striations had more or less the same orientation as the second set of striations in Fig. 4.20 (those superimposed on the main orientation). Striations like these can easily be confused with tectonically formed slickenside according to Shrock (1948) and Crowell (1957). Tectonic deformation related to these observations was however rejected by Laajoki (2002) based on the lack of other supporting evidence in the Bigganjárgga Diamictite. Instead, he suggested this as a quartz coating "[…] deposited by diagenetic low temperature metamorphic fluids […]" (Laajoki, 2002). This suggests that the BGU was a well-defined boundary surface where such fluids could have flowed and not a result of tectonic movement of the diamictite body along the BGU. In accordance to the observed striations along the contact and the insight given from the literature, a glacial origin for the BGU is accepted.

5.1.3 FA 2 – Thick-bedded diamictite

Until this point in this thesis, FA 2 has objectively been referred to as a diamictite (sensu Flint et al., 1960a; 1960b) due to its lithological appearance in the field supported by thin section observations (Fig. 4.10, Fig. 4.11, & Fig. 4.12). This term has traditionally been used for poorly sorted sediments where its origin is uncertain and hard to establish. For the case of FA 2 in this study, the clasts and matrix as observed in the outcrop do not show any distinct features that point the interpretation in a certain direction. The diamictite is lens shaped and thick bedded, and consists of a coarse-grained matrix bearing lithic clasts ranging in size from 1 cm to 60 cm. Previous workers have generally favoured two main, but opposing interpretations for its origin, being either a tillite or a debrite.

Sedimentary characteristics of FA 2

The sedimentological logs of the Bigganjárgga Diamictite (FA 2; Fig. 4.9) show that it is a poorly sorted, non-calcareous, (terrigeneous) deposits consisting of various sand-grade grains and larger pebbles and cobble-sized particles in a sand-rich but muddy matrix, thus qualifying to be classified as a diamictite (sensu Flint et al., 1960a; 1960b). These observations are supported by thin section analysis and are therefore unquestionable (thin section; Fig. 4.12, field observations; Fig. 4.10, Fig. 4.11, and log; Fig. 4.9). Additionally, light coloured lenses (Fig. 4.10a, b), weak layering (Fig. 4.10a, c & Fig. 4.26d, h) and lobe-features (fig. 4.26 a, b) were seen. The light-coloured lenses were not remarkably different from the rest of the unit when investigated in the outcrop, but thin section analysis gave another insight (i.e. lower textural and mineralogical maturity, finer grained matrix). The lenses wedging out from east to west parallel to the length direction of the outcrop. The existence of layering itself would suggest deposition from a steady laminar flow typical of a debris flows. The imbrication of the clasts within such layers as seen in Fig. 4.26h will point towards a unidirectional stream (i.e. in moraine material, debris flow deposits, beach gravel and fluvial deposits (e.g. Ore, 1964; Bourgeois & Leithold, 1984; Bennett et al., 1996) at least there (~70 degrees). The lobate features observed on the eastern side of the unit (Fig. 4.26a) may be associated both with gravity flow tills (Menzies & Shilts, 2002), and alluvial fan deposition (e.g. Heritier et al., 1979; Wescott & Ethridge, 1980). Superimposed lobate features within such a diamictite deposit may also reflect episodic and pulsating flow and deposition. This means that the unit does not have to be made all at once, but that it might have been made over several recurrent periods of sediment flow. Diamictite lobes like this are known from many different depositional environments, for instance representing mass flow deposition in deltaic systems (e.g. Wescott & Ethridge, 1980), debris flow deposition (in subaerial fans and submarine slopes) (Miall, 1985) and within glacial deposits such as basal tills and melt-out tills (Edwards, 1975). Thus, a recognition of a certain depositional agent from the logs and outcrop observations cannot prove a glacial nor a debris flow origin. The lobate features are best visible at the eastern side of the outcrop, but layering throughout the whole unit may be seen in relation to this as sectioning the unit (eastwards dipping layers; Fig. 4.19b). Edwards (1975) explained this as the result of flow-till running off a melting package of ice and debris from a glacier (see Section 2.3.3). This seem to be a rather good explanation for the lobe formation, but this theory have often been neglected in more recent literature.

The matrix of FA 2 was best studied by a petrographic thin section analysis. The two thin sections used for this purpose were made out of the same hand sized sample to show the difference between the general matrix and the light coloured lenses which occur in places. The occurrence of feldspar and carbonate together with quartz in the light coloured lenses suggest a lower degree of maturity and possibly lower burial depth than for the stratigraphically lower FA 1 which was quartz-dominated, highly compacted and tightly quartz cemented (Baron & Parnell, 2007). The general dark grey part (Fig. 4.12 c & d) of the matrix (Fig. 4.12a & b) contained less of these minerals. A possible explanation for these differences may have been that the parts composing the lenses were picked up on the way during the flowing event that deposited FA 2 and mixed within. This could explain the maturity differences between the matrix in the light coloured lenses and the general dark grey diamictite matrix, since they not have the entirely same depositional history. Another solution may be attributed to different diagenetic effects (i.e. porosity). If the matrix of the lenses had another porosity than the rest of the dark grey matrix surrounding them, then the degree and type of cementation occurring would be different (e.g. Burley & Worden, 2003).

Lastly, the supposedly striated boulders elaborated in the early study by Bjørlykke (1967) must also be considered. Striated boulders have by many geologists been a requirement before accepting an ancient deposit as glacial (Blackwelder, 1929). However, as accentuated by Blackwelder in 1929, "[…] boulders indistinguishable from those of glacial origin have been found in situation where there seems to be scarcely any possibility if such action having occurred [in mudflows]". Thus, chatter marks and striations which often can be subscribed glacial can also be made at storm dominated beaches where no glacial activity occurs (Waters, 1960). The lack of such striations in the boulders within FA 2 is pointed out by other writers such as Arnaud & Eyles (2002), which favours a debrite origin, and hence the lack of striations is used as to neglect the glacial theory. Supposedly and contiguously, the origin of striations or the lack of so on a given boulder would work both ways without neglecting either the debrite or tillite interpretation. Vague evidence of such striations on boulders were found during the fieldwork for this thesis (Fig. 4.11c). This was also reported by Jensen & Wulff-Pedersen (1996).

When considering both the appearance and mineralogical composition of the diamictite unit and of the internal clasts, there are apparently no kind of order. The larger clasts are dispersed randomly throughout the whole diamictite. In regards of the nature of an ideal terrestrial debris flow, the largest clasts would typically flow on the top of the flowing mass due to density and buoyancy differences, thus resulting in inverse grading (e.g. Hampton, 1979). However, the lack of inverse grading in FA 2 does not exclude a debris flow origin, as debrites sedimentologically may exhibit a large degree of variability. If considering the lithic clast correlations that are made to the monadnocks in Karlebotn (Bjørlykke, 1967; Levine et al., 2006), thus a southerly source are discussed earlier, it would give the ability to measure the length from the source, which the clasts originate from, to the sink where the clasts was deposited in a diamictite body. The short length could hence be used to explain the poorly sorted structure of the diamictite. Another question arises when discussing the matrix of the diamictite. The provenance of the matrix could be the result of many diverse terrestrial processes crushing and reworking the sediments several times (e.g. Weltje & von Eynatten, 2004) (i.e. fluvial material, glacial material, re-gathered glacial debris made into a gravity flow and gravity flows in general). However, the clasts within do not necessarily have the same history, firstly, because of their anomalous bigger size compared to the matrix, and secondly, because of the correlation proposal connects them to a local area in Karlebotn. This makes the determining of the provenance for the fine-grained matrix in the BGD a rather complex process.

5.1.3.1 Comparison to other "tillite"-bearing successions

Precambrian diamictite deposits have since their first discovery been interpreted as tillites, and thus they have been and still are a theme of great interest and several debates (e.g. Crowell, 1957; 1964; Edwards & Føyn, 1981; Hambrey et al., 1981; Eyles et al., 1985; Eyles, 1993; Jensen & Wulff-Pedersen, 1996; 1997; Edwards, 1997; 2004; Hoffman et al., 1998a; Arnaud & Eyles, 2002; 2004; Bodiselitsch et al., 2005; Etienne et al., 2009; Arnaud et al., 2011). Eyles (1993) mention the statements made by Schermerhorn in the mid 1970's (e.g. Schermerhorn, 1974; 1977) that "[…] most ancient tillites are in fact, mass flow deposits related to active tectonism […]" (Eyles, 1993) to be a stinging identifier for the need of critical re-visitations of the former tillites in the Earth history. Some Neoproterozoic tillites have been re-interpreted as gravity flow events (e.g. Uhlein et al., 1999), whereas others have been more complex to evaluate (including the BGD; (Bjørlykke, 1967; Edwards, 1975; 1997; 2004; Nystuen, 1985; Jensen & Wulff-Pedersen, 1996; Rice & Hofmann, 2000; Laajoki, 2001; 2002; Arnaud & Eyles, 2002; 2004)). Additionally, Eyles (1993) states that "Late Proterozoic glacially-influenced strata occur on all seven continents and [mostly occur in] two tectonostratigraphic types [which are] compressional plate margins [and] extensional plate margins […]". The Late Proterozoic strata in the second tectonostratigraphic category do correspond to extensional rifting occurring during the Marinoan glaciation (Eyles, 1993). Could a comparison of such deposits existing in an extensional rift basin where gravity flows deposition often occur and the BGD in the Smalfjord Formation (commonly referred to as a part of the Varanger Ice Age) (Gorokhov et al., 2001), potentially in an ancient rift basin, suggest that the BGD also could be a gravity flow deposit? Probably not, as the features that can be used in the interpretation are few and not very distinguishing. However, comparisons have been made to other "similar-tillites" around the world and these may either serve to strengthen or disprove a glacial origin for the BGD and hence the snowball Earth hypothesis.

Moelv, Southern Norway

In southern Norway, the Late Precambrian Moelv tillite rests directly upon an erosional contact (Nystuen, 1976). Clear associations are seen to the BGD in northern Norway (i.e. partly flow till interpretation like Edwards (1975), and a following sea-level rise after deposition). Thus, it is dated to correlate to the tillite in the Mortensnes Formation and not to the Smalfjord Formation in Finnmark(Bingen et al., 2005).

United States of America

The Squantum Tillite in the Boston Basin consist of a massive diamictite overlayered by turbidites comparable to the BGD. When first interpreted, it was thought to be of glacial origin, but have later been re-interpreted to be a deep marine mass-flow deposit (Carto & Eyles, 2012). Even though suggested to be a bit younger (c. 580 Ma) than the Bigganjárgga Diamictite, it has like the BGD earlier been used as support for the snowball Earth theory by a few authors.

Brazil

A rather interesting Neoproterozoic diamictite deposit is located in Brazil and is described by Uhlein et al. (1999). It is suggested that the material was first deposited on a craton and later reworked by gravity flows. This interpretation is very similar to the interpretation made by Arnaud & Eyles (2002) on the BGD (see Section 2.3.2). If this is an appropriate analogue, maybe the effect of tectonic faulting causing mass movement into a basin (i.e. in the palaeovalley at Varangerfjorden (Bjørlykke, 1967)) in Finnmark has not been thoroughly enough considered? Røe (2003) propose the presence of the Varangerfjorden Fault Zone (VFZ), which may have acted as the driver for the tectonic events.

Namibia and Congo craton

Striking similarities are reported from tillite units in the Neoproterozoic Gariep Complex and its stratigraphic equivalents in Namibia (Germs, 1995; Gorokhov et al., 2001), and in the Congo craton (Kennedy et al., 1998). The two tillites in the Gariep Complex and in Namibia are separated by a terrigenious dolomite succession comparable to the successions present in both Tanafjorden and Varangerfjorden. The youngest tillite is dated to be of Early Vendian age (600-650 Ma) comparable to the stratigraphy in the Smalfjord Formation, whereas the oldest one is estimated to Late Riphean age (725-700 Ma) (Germs, 1995). Together with one tillite preserved in central Namibia, the presence of an unconformity close by the tillites is seen similar to the unconformity at Bigganjárgga. Two tillites in the Congo craton are also covered by cap carbonates and do respectively represent the Sturtian and Varanger Ice Age/Marinoan glaciation (Kennedy et al., 1998).

Scotland

Correlations to the Marinoan glaciation (<630 Ma) have also been made to the Port Askaig Tillite in the Dalradian Supergroup of Scotland by Brasier & Shields (2000), but these have later been rejected and instead correlated to correspond to the Sturtian glaciation (>700 Ma) based on carbon isotopic values. Nonetheless, this event is evidence for glacial activity that occurred at a latitude lower than previously assumed possible and is hence noteworthy.

Greenland and Svalbard

Comparisons of the stratigraphy corresponding to the Varanger Ice Age in Finnmark have also been made to diamictites on Greenland and Svalbard (Fairchild & Hambrey, 1995). The diamictites on Greenland are all capped by dolomites and represent glacial terrigenious and glacio-marine deposits (Nystuen et al., 2008). These have been compared to the deep-marine glacial debris flow deposits on Svalbard (Fairchild & Hambrey, 1995). Both are comparable to the Neoproterozoic stratigraphy in Finnmark. Regardless that not all of the stratigraphy was counted for everywhere, sedimentary architectures predominating of shallow marine sediments and chemostratigraphic ages suggest well-fitting correlations to environments of the same kind between the three places. It has to be mentioned that once Rodinia was present, these three areas were much closer to each other, which can explain the observed similarities.

Australia

A paper about Late Precambrian varvites in South Australia based on palaeomagnetism or natural remanent magnetisation deposited during the Marinoan glaciation was proposed by Embleton & Williams (1986). The seasonality of the varvites were connected to the annual deposition of gravity flows from a distal periglacial lake and were gathered at a palaeolatitude of 5 degrees. Even though deposited from a distal periglacial lake which could be located at a higher latitude, 5 degrees of latitude are close to the present Equator that today are associated with warmer climate. Therefore it would support a colder climate or widespread global glaciation as suggested by Hoffman et al. (1998) where lakes repeatedly froze and melted (i.e. like in Arctic regions today).

The Sturt Tillite in Australia

The Sturt Tillite is one of two diamictite units in Australia related to a Neoproterozoic snowball Earth theory (Sumartojo & Gostin, 1976). The occurrence of striated and faceted clasts was taken into consideration when interpreting them as glacial deposits. The deposit has been dated to be c. 716.5 Ma and has been the origin for the Sturtian glaciation (Le Heron et al., 2011).

5.1.3.2 The Bigganjárgga Diamictite as a climatic indicator

Regardless of the conclusion of this thesis, the BGD will continue to serve as a climatic indicator for the palaeoclimate in the Neoproterozoic era in some way or another (i.e. tillite origin; cold climate and snowball Earth, debrite origin; more various climate predictions). If interpreted as a tillite, a relatively cold climate with glaciers or ice sheets existed without melting can be predicted as plausible (Harland et al., 1966). If not interpreted as a tillite, but instead as a debrite, the plausible palaeoclimate combinations are variating more and it does not work that well as a climatic indicator since gravity flows can occur in several environments (i.e. in subaerial and subaqueous environments (e.g. Schermerhorn, 1974; Nichols, 2009)). Subaqueous gravity flows can for instance occur in the ocean inconsiderate if a continent is covered by ice or not (Rampino, 1994). Thus, the high presence of water in such a submarine debris flow can be used to tell that the area was covered by water at the time of deposition.

Neoproterozoic sedimentary sequences are found in the stratigraphic record other places in the world (i.e. see Section 5.1.3.2). Many of them are time-wise correlative to each other and linked to various glacial palaeoenvironments. If the BGD was interpreted as a tillite, the snowball Earth theory (Harland, 1964; Hoffman et al., 1998a) that some would label rather controversial (e.g. Eyles, 1990; Carto & Eyles, 2012) compared to what is known about the present climate would strengthen its credibility. The locality at Bigganjárgga has traditionally served as the type locality for the Varanger Ice Age, and if re-interpreted as not being related to a glaciation, firstly, the type locality has to be changed, and secondly, the Varanger Ice Age as a glaciation in the region will maybe lose its credibility. Evidences for the time equivalent Marinoan glaciation elsewhere will of course continue to exist, but it will be a severe loss for the supporters of the Neoproterozoic snowball Earth theory. The BGD as a climatic indicator is therefore quite important locally, regionally and globally. Besides, if the Varanger Ice Age was to be depreciated, both of the associated glacial deposits within have to be disproven. The other one, being the Mortensnes Formation have not been criticised corresponding in the literature. Thus, recently, it has again been correlated to the Gaskiers glaciation (~580 Ma) according to fossils (Jensen et al., 2018).

5.1.3.3 Tillite or debrite – Regional stratigraphic implications

When considering the regional implications that can be affected by the interpretation of the BGD, it can end in two ensuing ways; one where the Neoproterozoic glacial history of the Earth can be told (global snowball Earth), and a second one where the history of the Neoproterozoic in an enclosed area in Finnmark can be told (limited to the depositional environments before, during and after a debris flow event). The first one, the tillite-theory will as mentioned above (Section 5.1.3.2) submit as evidence to the snowball Earth theory (Harland, 1964; Hoffman et al., 1998a). Tremendous amounts of work is completed in connection to these tillites through time and if a tillite origin is rejected, even more working hours awarded an already critical community has to be added to the re-evaluation. If maintained as being a tillite it can also be used in the demanding jigsaw-puzzle arranging the sub-continents of Rodinia during the Proterozoic eon.

The second way of interpretation, the debrite-theory will for sure cause most debate and will eventually neglect the importance of the BGD as a deposit. This will remove the Neoproterozoic rocks in Finnmark and Norway from a world spanning perspective and if settled to be a debrite, and other re-evaluations of tillites in the world follow, several Proterozoic glacial periods will have to be revised. In addition, considering tectonics as an affective factor on gravity flows may have played a bigger role in the Neoproterozoic than previously predicted. However, an eventual debrite interpretation can also just cause even more discussions from those of the "glacial school" trying to defend the tillite interpretation.

5.1.4 FA 3 – Thin-bedded sandstone – onlapping turbidites?

The facies within the unit and their respective interpretations (F7 & F8.1; Table 1) points to an environment where turbidity currents occurs, possibly reflecting a shallow marine to marine environment (e.g. Lowe, 1982; Mills, 1983; Bouma & Ravenne, 2004). Previous interpretations of the unit and the Nyborg Formation above comprising siltstone and turbidites have pointed to a sea-level rise after deposition of FA 2 (e.g. Edwards, 1972; 1984; Rice et al., 2011).

An important part of the present sedimentological investigations was to prove that the two observed sandstones (FA 1 and FA 3) at the outcrop were different units in time and space and not representing a continuing series. A few meters off the western termination of the BGD, the two hiatuses which are present at the central parts of the outcrop (Section 5.1.2 & Section 5.1.5) can be hard to separate and appear as a single surface within an apparent continuous sandstone series. Dal (1900) and Jensen & Wulff-Pedersen (1996) stated that there are no differences that can be seen between the sandstones of FA 1 and FA 3. As separations of the sandstone units, including an acknowledge of hiatuses can be a central part if trying to explain a progressive deeper basin (e.g. Eyles et al., 1985; Eyles, 1993), a division is anticipated. For this purpose, several evidences were recognized. The most obvious ones were the grain size changes (Fig. 4.9) and the soft sediment deformation structures (Fig. 4.14) observed within FA 3. The grain size began as the same (medium) in FA 3 as the dominating grain size in FA 1, but in FA 3, it was more massive and lacked structures like those observed in FA 1. The medium grained massive sandstone part in FA 3 lasted for approximately half a metre or so and then the grain size dropped and the soft sediment deformation structures began to be present. Thereupon, rapid interbedding variations between fine to medium sandstone and very fine sandstone began and the load cast structures between them were a fact. Some of the deposited layers were in a way preserved horizontal, which also were seen in layers in FA 1, but other than that, the sandstones were distant.

The thin section analysis did also support that they are different. Thus, some variations within the FA 3 unit from the base to the top, clearly evidences were present. The presence of feldspar and carbonate in FA 3 suggested a lower maturity than observed in FA 1. Textural and mineralogical maturity can be used to separate units from each other and correlate them to other depositional environment conditions (Folk, 1951; Burley & Worden, 2003; Bjørlykke, 2010).

Orientation of the grains was not seen in FA 3. This is different from FA 1 where the orientation was widespread. Nevertheless, there was observed stylolites in this unit too (Fig. 4.14i) that can cause orientation of grains like those observed in FA 1 (Fig. 4.7). Stylolites can occur under several conditions (e.g. Baron & Parnell, 2007). In the case of those observed in FA 3, seen in combination to the observed soft sediment deformation structures (load casts) within, they may be evidence for an environment with high sedimentation rate (Baron & Parnell, 2007; Bjørlykke, 2010). It could also be the result of a deposition of layers with different density and water content. However, this will be based on macroscopically observed features and not microscopically observations like in FA 1.

Most authors have anticipated the differences between the sandstones (e.g. Bjørlykke, 1967; Edwards, 1975; 1984; 1997; Nystuen, 1985), and combined with the presented evidence revealed in this thesis, their separation is a fact.

5.1.5 The unconformity between FA 2 and FA 3

The contact between FA 2 and FA 3 is regarded as an unconformity (see Section 4.2.2.2) on the same basis as the BGU between FA 1 and FA 2. One severe argument once regarding a contact as an unconformity is the present hiatus in the stratigraphy. The absence of the contact (i.e. towards west) where FA 2 is no longer preserved is also important and another factor when considering the contact as an unconformity. What caused a depositional break is in many cases very difficult to establish. Spence et al. (2016) pinpoints the importance of scrutinizing non-depositional surfaces – like those at Bigganjárgga – once established. They mention that if evidence of sea level changes over time and the time of deposition is established (i.e. throughout or at the end of a glaciation), the contacts can be associated to periods of cooling.

The evidences that were found in accordance to this specific contact (onlapping (Fig. 4.24, Fig. 4.25, Fig. 4.28 & Fig. 4.29), winnowed surfaces (Fig. 4.26), interbedded diamictite lenses and clasts (Fig. 4.25 & Fig. 4.29)) can all be interpreted as consecutive results of a rapid deposition in a deepening basin (e.g. Christie-Blick, 1991; Menzies & Shilts, 2002; Nichols, 2009; Leeder, 2011). Onlap on the flanks of the diamictite (FA 2) could be the result of an inundating of the diamictite (FA 2). After the inundation, FA 2 was an elevated ridge on the seafloor. Once the turbidites interpreted to compose FA 3 then reached the flooded FA 2, they first flowed over, thus onlapping the lower parts of the flanks of the diamictite before they covered the rest of FA 2. The winnowed surfaces may be the result of the winnowing effect occurring above the diamictite once the turbiditic flow passed over. At this time the onlapping was still occurring. Some of the winnowed material was deposited soon after the erosion of the surface of the diamictite, which could be seen as the interbedded clasts and diamictite lens. If the sea level starts to rise slowly or abrupt, an observed onlapping sequence like the one observed right above the unconformity between FA 2 and FA 3 can be the result (Christie-Blick, 1991). Admittedly, being on top of the Precambrian bedrock, onlapping is also seen in Karlebotn not far away by layers in the Smalfjord Formation onto the monadnocks present there (Levine et al., 2006). Neproterozoic glacial abrasion of the monadnocks is also confirmed by Laajoki (2004) under the onlapping sequence. These observations confirm the existence of an environment with onlapping attributes in the area much alike those at Bigganjárgga. The comparison of the two areas located close by each other can be used to defend a Neoproterozoic inundation of the area and the BGD as an elevating moraine on the seafloor (like the monadnocks), which then was onlapped and later totally covered. However, since the Nyborg Formation above is suggested to be composed of turbidites (e.g. Reading, 1965) thus ascribe a submarine environment, the diamictite could also have been a submarine debris flow deposit which was onlapped by turbidites on the seafloor.

Degree of consolidation of FA 2 when FA 3 was deposited

There are several evidences that FA 2 (BGD) were not completely consolidated at the time when FA 3 onlapped and eventually draped the diamictite body. The first is the emanating ridges (Fig. 4.26) interpreted as the result of winnowing processes (Edwards, 1984; Nystuen, 1985; Laajoki, 2001) which could have been made when a flow (i.e. turbidity current) passed by causing a pulling effect and hence eroded the fines of the diamictite body (Menzies & Shilts, 2002). This can be regarded as a possible explanation for the formation of the remaining ridges.

However, at the outcrop there seemed to be both fine material, like mentioned by Menzies & Shilts (2002), and coarser material remaining in the ridges. Could this i.e. be due to a compactional force applied by a sliding lobe in its bottom border? Even though the speed of a floating lobe is decreasing and it is close to its final destination there might still be an erosional force between the lobe and the substrate below. This force may compact small parts of the basal parts of the lobes, with the result being the emanating ridges marking the borders of the lobes that were harder to erode for the turbidity currents. Some type of reworking of the deposited diamictite can also be the case. Potentially, a moraine and a debrite could both have been reworked during a sea level rise.

The interbedded lenses of seemingly BGD-like material (Fig. 4.29b) are also important once considering that the onlap of the unconformity occurred rapid on top of an unconsolidated BGD (FA 2). If the lens content is interpreted as abraded from the BGD, firstly the unconsolidated state of the BGD is acknowledged. Secondly, if considering that FA 3 follows the principle of superposition, the basal onlapping sandstone layers of FA 3 were deposited first and will be oldest. Thereupon, deposition of the diamictite lens follows and will be younger before those sandstone layers above of FA 3 further onlapped FA 2, the sandstone layers already deposited in FA 3 and the diamictite lens.

The clasts that were seen inside the lowest sandstone layers on both flanks of the BGD (Fig. 4.25 & Fig. 4.29) are also consistent with FA 2 being unconsolidated during deposition of FA 3. The severe differences in the sorting of the grain sizes from FA 2 to FA 3 indicate that the clasts interbedded in FA 3 most probably are derived from another source with the unconsolidated diamictite of FA 2 being the obvious source candidate.

Is there a sedimentological difference between FA 1 and FA 3?

The most severe petrographic differences between the two sandstones are the maturity differences and the degree of cementation present between the grains. The thin section analysis from FA 1 shows a mature sandstone where cementation between the quartz grains has occured, whereas the analysis from FA 3 shows an immature sandstone without oriented grains. Sedimentological differences are also present with a structures pointing to a fluvial environment in FA 1 and structures pointing to a shallow marine to marine environment in FA 3.

The confirmation that the contact between FA 2 and FA 3 is an unconformity is important as it can be used to confirm the differences between FA 1 and FA 3. In places where the diamictite body of FA 2 is not present, FA 3 lies directly upon the BGU and the thick-bedded sandstone in FA 1. Although the sandstone of FA 1 and FA 3 may appear similar to the untrained eye, there are several differences. However, it is noteworthy that Dal (1900) and Jensen & Wulff-Pedersen (1996) remarked the sandstone units as completely similar with no differences at all, although they are clearly separated by a depositional break. This break in the deposition between the deposition of FA 1 and FA 3 is in general no other than the BGU break. Thus, it is concluded that FA 1 and FA 3 exhibit different sedimentological and petrographic differences reflecting deposition by various processes and in significantly different depositional environments. It is also clear that the lower sandstone unit (FA 1) has experienced higher burial depth (i.e. higher degree of compaction and cementation) than FA 3, thus confirming a significant hiatus between the two units.

5.1.6 FA 4 – Thin-bedded diamictite – gravity flow deposit?

The diamictite of FA 4 has to be considered differently than the diamictite in FA 2 even though they both are diamictites. There is for instance evidences showing that they exert significantly different petrographic and sedimentological character (i.e. matrix grain size, clast size and lithology, and preserved structures) from another (logs; Fig. 4.9 (FA 2) & Fig. 4.17 (FA 4) and observations; Fig. 4.10, Fig. 4.11, Fig. 4.12 (FA 2) & Fig. 4.16, Fig. 4.18 (FA 4)). The combination of a dominating siltstone matrix and the presence of some few larger clasts (up to cobble size) in FA 4 makes for instance a solely hemi-pelagic or pelagic deposition (which are responsible for a considerable part of deposition of the finest particles in the deep ocean (e.g. Nichols, 2009)) unlikely, unless the larger clasts represent ice rafted debris. This is because transportation in suspension are limiting and carry only the smallest grain sizes (e.g. Press & Siever, 1986). Ice rafted clasts might however be present in the deep ocean sediments or in glaci-marine environments (Shumway, 1953) (i.e. deposition as dropstones from ice rafted debris), but will then not appear randomly mixed within the matrix (Bennett, Doyle, et al., 1996) like observed at the investigated outcrop (Fig. 4.16d & e). Thus, stria, faceting or draping which usually are the the most reliable features when assessing origin on ice-berg rafted dropstones (Thomas & Connell, 1985; Gilbert, 1990) were not observed in the present study. The majority of the observed clasts were were small and of pebble size and features as draping and onlapping were thus hard to recognize.

By only considering the matrix and the pebbles together and exclude the observed cobble (Fig. 4.16d & e), which by percentage can be considered an accessory part of the deposit, the potential and necessary energy needed to get the pebbles there is radically reduced (e.g. Press & Siever, 1986). In that case, the cobble has to be considered as transported by another source than the diamictite itself (i.e. as mentioned as a dropstone), if not eventually being a debris flow deposit. Dropstones are transported by floating ice and therefore consistent with submarine deposition and neglect subaerial deposition (Gilbert, 1990). The remaining plausible environments for the emplacement of gravity flow deposits are then fluvial, shallow marine to marine and shelf (e.g. Schermerhorn, 1974; 1975; Rampino, 1994; Leeder, 2011). Besides, all the environments can be affected or unaffected by glaciations or glaciers.

Thus challenging to prove, there is evidence of movement of the diamictite in the thin section. In the thin section in Fig. 4.18c & d, a transported extrabasinal carbonate clast with eroded borders was observed. Unlikely many of the other small and cemented carbonate clasts observed in the matrix, the preserved border on the extrabasinal carbonate clast gives the impression that the clast has been eroded before accumulated into this unit. Thus the provenance and the fact that all of the clasts are transported (gravity flow interpretation of FA 4 and turbidites below (FA 3) and above Nyborg Formation), this border gives an impression connecting the clast for instance to the nearby dolomitic Grasdalen Formation (Arnaud & Eyles, 2002; Rice et al., 2011).

The length (> 100 meters) and the thickness (1 to 2 meters) of the unit give an impression of an event of substantial size that must have had a big forcing effect and influence on whatever it passed. The thin layers in the diamictite that are slightly deformed and that were interpreted as soft sediment deformation structures, do further imply a high water content in the gravity flow once moving (Mills, 1983). Increased water content that has low viscosity will therefore reduce the total viscosity (e.g. Hampton, 1972; Lowe, 1982; De Blasio et al., 2004) and the buoyancy of the flowing FA 4 when mixed (Hampton, 1979), which reduces the potential to carry big grain sizes. This could explain the low content of cobbles in the unit and discredit but not neglect subaerial deposition compared to submarine due to less water content available on land than in in the ocean and the fact that subaerial gravity flows travel shorter (Hungr et al., 2014).

The overall fine grain size, presence of outsized clasts, soft sediment deformation and the presence of turbidites above and below (FA 3), a subaqueous sediment gravity flow deposit is suggested (e.g. slump deposit or fine-grained debrite; Shumway, 1953; Schermerhorn, 1974; 1975; Hampton, 1979; Mills, 1983; Thomas & Connell, 1985; Press & Siever, 1986; Gilbert, 1990; Rampino, 1994; Bennett, Doyle, et al., 1996; Blikra & Nemec, 1998; De Blasio et al., 2004; Nichols, 2009; Leeder, 2011; Hungr et al., 2014).

5.2 Further work

Despite previous investigations of the Bigganjárgga Tillite, further inspections are still possible. The fieldwork for this thesis was limited to a few days applying cheap and simple conventional field methods (in line with the methods applied in previous studies). However, more sophisticated and expensive methods have the potential to generate more and important data which may contribute to the discussion of the origin of the Bigganjárgga Tillite. Additionally, the formal protections made for the outcrop locality have caused caution among the geologists studying it, and have possibly hampered further development and creative thinking and interpretation of the debated deposit. If the present author was given the time and financial support, the following list summarize some ideas for further work:

- *Lateral observations of the contact between FA 1 and FA 2.* The contact has been thoroughly studied at the outcrop at Bigganjárgga, but lateral observations may also be important. Numerous of studies have concerned the Varangerfjorden Unconformity. However, those places where FA 3 are directly deposited on FA 1 (i.e. westwards of the outcrop) would still be of interest.
- *Excavation and study of the contact between FA 3 and FA 4.* This was not done in this thesis due to an estimated extensive amount of work needed to reveal it under the vegetation covering (and to avoid conflict with the laws of protection). The contacts surrounding the Bigganjárgga Diamicite (FA 2) have been proven to be very important. A thorough study of the mentioned contact may be just as useful.
- *Construction of new high-resolution 3D outcrop model.* The constructed digital 3D outcrop model from this thesis (Appendix 3) have been useful in the way of making the outcrop possible to view from the office after the fieldwork and for lateral tracing of surfaces, external geometries and internal layering. However, the resolution of the model can be further improved by using a higher-resolution camera or ground-based laser scanning (i.e. LIDAR – light detection and ranging). Additionally, the use of a drone to capture the photographs is recommended. This will give the possibility to create a 3D outcrop model covering all of the major stratigraphic units in one model, which will improve the characterisation of the entire outcrop.

- *GPR data and "behind-the-outcrop"-drill cores.* Because of the restrictive protection of the outcrop itself, the methods of gathering data in depths are sparse. For this purpose, the use of ground penetrating radar (GPR) can be used both inside the restricted area and in nearby areas to reveal the extent and subsurface of the diamictite body. To reinforce and supplement the GPR data, drill cores from outside the protected area can be collected (i.e. "behind-the-outcrop drilling").
- *Reflection seismic data of the inner part of Varangerfjorden.* The structural elements below the seafloor of the inner part of the Varangerfjorden should also be inspected thoroughly. Suggestions of the presence of a fault zone below the seafloor (the Varangerfjorden Fault Zone) was proposed by Røe (2003), but later rejected by Rice et al. (2011) based on seismic data from the outer part of the fjord. However, no subsurface data exist from the inner part of the fjord. Thus, it may be speculated that reflection seismic data (in particular high resolution seismic) from the inner fjord could reveal the existence of potential faults, unconformities and larger diamictite bodies in the subsurface.

6 Conclusion

The depositional history concerning the Bigganjárgga Diamictite and its adjacent deposits are complex. From interpreted in 1891 by Reusch in a time when " […] little was understood of sediment gravity flows and other non-glacial processes that also produce poorly-sorted sediments […]" (Eyles, 1993), and "[…] the argument of Agassiz (1840) that existing glaciers had been much more extensive in the recent past […]" (referred in Eyles, 1993) were fresh in mind for most geologists, a glacial interpretation fitted well for the BGD. Reviews of earlier interpretations in the literature complemented by new data collected for this thesis have resulted in the following interpretation:

Based on reviews of earlier interpretations in the literature complemented by a detailed sedimentological facies analysis and stratigraphic investigations of the Bigganjárgga outcrop section in combination with thin section analysis and digital outcrop models, the following conclusions are drawn:

1. FA 1 (thick-bedded sandstone) was deposited in a fluvial environment, possibly braided system. Heavy overburden caused compaction (i.e. grain orientations, pressure solution with development of stylolites) of the sand to sandstone and cemented the grains.
2. A regional unconformity in Finnmark also present at Bigganjárgga suggests a long lasting event with great amount of erosion at regional scale (hiatus lasting for 150 million years, 2.5 km of strata removed) – various stratigraphic evidences at Bigganjárgga and other nearby outcrops suggest this erosion to be glacial (striation orientations at Bigganjárgga, channel structure at Sjåholmen, cross-beddings in the Kvalnes Conglomerate, flute cast structures at Hammernes). The compaction, orientation and cementation of the grains in FA 1 presume thick overburden and therefore, FA 1 at Bigganjárgga was most likely consolidated and deeply buried prior to commencement of the glacial erosion and before deposition of the thick-bedded diamictite of FA 2.

3. Thick facies analysis and combined environmental interpretations of the FA's suggests that FA 2 most likely was deposited as a moraine (based on its external geometry, position on top of a regional low-angle unconformity with carved striations, and internal composition and fabric). Thus, since the time span between the formation of the Bigganjárgga Unconformity (BGU) and the deposition of the overlying thick-bedded diamictite are uncertain, FA 2 does not need to be deposited right after the erosion (could be much younger than the hiatus itself). The evidences for a later subsidence and sea level rise leaves the possibility that FA 2 was deposited during the melting retreat of a glacial cap. Thus, it is concluded that the diamictite is of glacial origin and correctly referred to as a tillite.
4. Turbidite sandstones of FA 3 (thin-bedded sandstone) onlap and drape FA 2 (with coarser clasts inside those layers close to the diamictite body) and occur directly onto the unconformity and FA 1 in places where is not present. The turbidites were most likely deposited in a glacio-marine to shallow marine environment on top of a non-consolidated or semi-consolidated FA 2 (as evident by the erosive products in the onlapping beds).
5. Soft sediment deformation structures and an upward reduced grain size support a continuing relative sea-level rise (transgression).
6. Even smaller grain sizes in the succeeding diamictite unit of FA 4 suggest further deepening and deposition of FA 4 from a mud-rich subaqueous debris flow in a glacially affected shallow marine to marine environment.
7. This study shows that the sedimentological features preserved at the Bigganjárgga outcrop can be correlated to those preserved at other regional tillite outcrops in the world from the same era (Varanger Ice Age and the Marinoan Glaciation). Deducing this, the Bigganjárgga locality will still work as a type-locality for a Precambrian glaciation and for those in the community supporting a snowball Earth theory.

7 References

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Appendix 1 – Fieldwork application

Permission from Fylkesmannen in Finnmark is attached below.

FYLKESMANNEN I FINNMARK
Miljøvernavdelingen

FINNMÁRKKU FYLKKAMÁNNI
Birasgáhttenossodat

Norges Arktiske Universitet
Att.: Sten-Andreas Grundvåg
Sten-andreas.grundvag@uit.no

Deres ref	Deres dato	Vår ref	Vår dato
	30.08.2018	Sak 2018/3525	27.09.2018
		Ark 432.0	

Saksbehandler/direkte telefon: Tor Asbjørn Aslaksen Simonsen – 78 95 03 14

Fylkesmannen i Finnmark gir UiT/Norges Arktiske Universitet dispensasjon til å samle inn seks steinprøver fra Bigganjarga naturminne. Se nærmere detaljer og vilkår i vedtaket nedenfor.

Bakgrunn

Det vises til søknad fra UiT/Norges Arktiske Universitet datert 21. august 2018 vedrørende innsamling av steinprøver fra Bigganjarga naturminne.

Steinprøvene skal samles inn i forbindelse med to mastergradsprosjekter i geologi ved UiT/Norges Arktiske Universitet. Til sammen skal det samles inn seks steinprøver med størrelse rundt 0,5 – 1 dm^3. Prøvene vil fortrinnsvis bli samlet inn fra løsblokker i nærheten av det faste fjellet. Kun 1 -2 av prøvene vil være av selve tillitten. Flesteparten av prøvene vil bli samlet fra lagene som opptrer under, ved siden av og over selve tillitten. Til innsamling av prøver vil det benyttes hammer og meisel.

Bakgrunnen for innsamling av prøvene er tredelt:
1. Gjennom forskning er det ønskelig å kaste nytt lys på historien bak lokaliteten.
2. Institutt for geovitenskap ønsker økt tilstedeværelse i Finnmark (spesielt Varangerbotn og Varangerhalvøya).
3. Utdanne en ny generasjon med geologer med arktisk erfaring og med tilknytning til Nord-Norge.

Ansvarlig for prosjektet er Sten-Andreas Grundvåg ved UiT/Norges Arktiske Universitet. I følge Grundvåg må prøvene samles inn fra Bigganjarga naturminne fordi den aktuelle tillitten (fossil og forstenet moreneavsetning) kun er eksponert i fredningsområdet.

Verneformål og verneforskrifter
Det offisielle navnet på lokaliteten som huser en forekomst av «eokambrisk» morenekonglomerat er Bigganjarga naturminne.

I henhold til nr. 3 i forskrift om fredning av forekomst av «eokambrisk» morenekonglomerat av 6. januar 1967 nr. 2, er forekomsten av «eokambrisk» morenekonglomerat med underliggende isskurt kvartsittunderlag fredet mot skade av enhver art og det er forbudt å fjerne deler av konglomeratet eller underlaget.

Formålet med fredningen er å bevare en unik forekomst av «eokambrisk» morenekonglomerat med underliggende isskurt kvartsittunderlag

Vurdering
Søknaden behandles iht. forskrift om fredning av forekomst av «eokambrisk» morenekonglomerat av 6. januar 1967 nr. 2 og naturmangfoldloven av 19. juni 2009 nr. 100.

I følge verneforskriften nr. 2 er omsøkte tiltak forbudt. Siden det ikke finnes spesifiserte dispensasjonshjemler for de omsøkte tiltakene, må søknaden behandles etter nml. § 48, jf. nml. § 77. Av denne bestemmelsen går det fram at dispensasjon bare kan gis dersom tiltaket ikke strider mot vernevedtakets formål og ikke kan påvirke verneverdiene nevneverdig, eller dersom sikkerhetshensyn eller hensynet til vesentlige samfunnsinteresser gjør det nødvendig.

Av forarbeidene til naturmangfoldloven framgår at nml. § 48 ikke kan anvendes for å utvide rammen trukket opp i vernevedtaket. Nml. § 48 skal være en sikkerhetsventil for tiltak som ikke kunne forutses eller spesielle/særskilte tilfeller som ikke ble vurdert på vernetidspunktet. Bestemmelsen åpner for at det kan gis dispensasjon dersom det ikke strider mot vernevedtakets formål og ikke kan påvirke verneverdiene nevneverdig. Vilkårene er kumulative, det vil si at begge vilkårene må være oppfylt for at Fylkesmannen kan dispensere for omsøkte tiltak. Det at vilkårene er oppfylt, gir ikke krav på dispensasjon. I avveiningen av om dispensasjon skal gis, må det foretas en skjønnsmessig vurdering.

Det fremgår av nml. § 8 at «kunnskapsgrunnlaget» skal være oppfylt før myndighetene fatter vedtak i saken. Bikkanjárgatillitten er en forstenet morene (morene-konglomerat) fra en istid i begynnelsen av jordens oldtid (eokambrium) for ca. 600 millioner år siden. Skuringsstripene på kvartsittunderlaget er dannet under samme istid (kalt "Varangeristiden"). Eokambriske morene-konglomerater er også kjent fra andre strøk av jorden. Bikkanjárgatillitten er imidlertid den eneste kjente med en kombinasjon av moreneavsetning og isskurt underlag, og er derfor som geologisk naturminne enestående i verden.

Fylkesmannen mener det foreligger et godt kunnskapsgrunnlag, blant annet gjennom verneplanprosessen med tilhørende registreringer og fagrapporter, generell kunnskap om sårbarhet for forstyrrelser i området, befaringer til området, Naturbase og Artsobservasjoner, jf. nml. § 8 om «kunnskapsgrunnlaget». «Føre-var-prinsippet» i nml. § 9 tillegges derfor liten vekt.

Fylkesmannen kjenner ikke til at det er gitt dispensasjon til uttak av steinprøver fra den aktuelle lokaliteten i seinere tid, og Fylkesmannen anser således lokaliteten til å være forholdsvis urørt. Det aktuelle omfanget av steinprøver som skal tas ut er svært begrenset og vil etter Fylkesmannens vurdering ikke føre til forringelse av lokaliteten som helhet, jf. nml. § 10 om «økosystemtilnærming og samlet belastning».

For å unngå at lokaliteten reduseres i verdi, bør uttak av steinprøver foregå forsiktig og med riktig utstyr, jf. nml. § 12 om «miljøforsvarlige teknikker og driftsmetoder». Dette innebærer at prøver av tillitt og lagene under selve tillitten fortrinnsvis bør tas fra løsblokker rundt selve lokaliteten, og at det benyttes utstyr som hammer og meisel. Det kan nevens at tillitten og lagene under i hovedsak ligger i flomålet, og at den største trusselen for lokaliteten oppstår gjennom bølgepåvirkning/sjøgang, erosjon og forvitring.

Fylkesmannen kan ikke se at det begrensete uttaket vil stride mot verneformålet eller kunne påvirke verneverdiene nevneverdig, og har kommet fram til at en vil gi dispensasjon til det omsøkte tiltaket. Videre mener Fylkesmannen at forskning og forhåpentligvis økt innsikt om lokaliteten vil være positivt for den videre forvaltningen av området.

Vedtak
Fylkesmannen i Finnmark gir UiT/Norges Arktiske Universitet dispensasjon til å samle inn steinprøver fra Bigganjarga naturminne.

Dispensasjonen er gitt med hjemmel i § 48 i lov om forvaltning av naturens mangfold (naturmangfoldloven) av 19. juni 2009 nr. 100.

<u>Dispensasjonen er gitt på følgende vilkår</u>:
1. Det kan samles inn inntil 6 steinprøver med størrelse ca. 0,5 – 1 dm^3, hvorav 1 prøve kan samles av selve tillitten
2. Til innsamling av steinprøver skal det brukes enkelt utstyr som for eksempel hammer og meisel.
3. Steinprøvene kan samles inn av mastergradsstudentene Egil Edvardsen og Julia Skorgenes, og må foregå i tidsrommet 27. september – 7. oktober 2018.
4. Ferdsel innenfor verneområdet må foregå på en slik måte at lokaliteten ikke skades/forringes.
5. Mastergradsoppgaver/forskningsresultater knyttet til denne dispensasjonen sendes Fylkesmannen i Finnmark så snart de foreligger.

Klageadgang
Vedtaket kan påklages til Miljødirektoratet av en part eller annen med rettslig klageinteresse med en frist på 3 uker fra vedtaket er mottatt, jf. forvaltningsloven §§ 28 og 29. En eventuell klage skal stiles til Miljødirektoratet, men sendes til Fylkesmannen i Finnmark.

Med hilsen

Bente Christiansen
fylkesmiljøvernsjef

Tor Asbjørn Aslaksen Simonsen
overingeniør

Dette dokumentet er godkjent elektronisk og derfor uten underskrift.

Kopi:

Statens naturoppsyn ved Arne Petter Sarre	arne.petter.sarre@miljodir.no
Nesseby kommune	postmottak@nesseby.kommune.no

Vedlegg:
1. Forskrift om fredning av en forekomst av «eokambrisk» morenekonglomerat av 6. januar 1967 nr. 2.
2. Kart som viser avgrensning av lokaliteten.
3. Bilder av Biggjanjarga naturminne.

Appendix 2 – Palaeodirectional indicators

All of the orientation measurements used to make the rose diamgrams is attached below in separate tables.

First, striations in the thick-bedded sandstone (FA 1)/ BGU. The prominent striation direction from 1 to 130 and the less prominent striation from 131 to 164:

Measure number	Orientation in degrees	Measure number	Orientation in degrees
1	129	42	318
2	309	43	132
3	132	44	312
4	312	45	132
5	140	46	312
6	320	47	137
7	144	48	317
8	324	49	128
9	137	50	308
10	317	51	138
11	134	52	308
12	314	53	143
13	134	54	323
14	314	55	136
15	142	56	316
16	322	57	134
17	129	58	314
18	309	59	144
19	130	60	324
20	310	61	144
21	130	62	324
22	310	63	134
23	130	64	314
24	310	65	134
25	139	66	314
26	309	67	136
27	134	68	316
28	314	69	131
29	130	70	311
30	310	71	134
31	136	72	314
32	316	73	128

33	131	74	308
34	311	75	132
35	139	76	312
36	319	77	141
37	138	78	321
38	318	79	139
39	138	80	319
40	318	81	148
41	138	82	328

Measure number	Orientation in degrees	Measure number	Orientation in degrees
83	141	124	331
84	321	125	136
85	139	126	316
86	319	127	149
87	139	128	329
88	319	129	151
89	136	130	331
90	316	131	90
91	134	132	270
92	314	133	90
93	138	134	270
94	318	135	91
95	145	136	271
96	325	137	90
97	144	138	270
98	324	139	89
99	125	140	269
100	325	141	82
101	140	142	262
102	320	143	90
103	128	144	270
104	308	145	88
105	141	146	268
106	321	147	91
107	124	148	271
108	304	149	86
109	126	150	266
110	306	151	91
111	152	152	271
112	332	153	90

113	142	154	270
114	322	155	90
115	146	156	270
116	326	157	90
117	132	158	270
118	312	159	89
119	148	160	269
120	328	161	92
121	144	162	272
122	324	163	92
123	151	164	272

Rib and furrow orientations from the thick-bedded sandstone:

Measure number	Orientation in degrees
1	146
2	133
3	172
4	152
5	122
6	106
7	150
8	126
9	128
10	158
11	147
12	176
13	158
14	160
15	138
16	146
17	162
18	183
19	188
20	162
21	158

Orientation of imbricated clasts in thick-bedded diamictite lobe from the eastern side of the diamictite:

Measure number	Orientation in degrees
1	62
2	78
3	63
4	62
5	54
6	68
7	68
8	82
9	81
10	79

Appendix 3 – Fold out of digital outcrop model

For the digital version, see attached version of the fold out model. For the printed version, see fold out of digital outcrop model below.

Appendix 3 – Fold out of digital outcrop model