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# Sub-seismic scale characterization of turbidite sandstone architecture and facies in base-of-slope onlaps: A case study in the Battfjellet Formation, Svalbard

MSc. Thesis

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## Abstract

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The boundaries of deep-marine fan deposits have been targets of study over the past few years due to their potential of stratigraphic traps in the oil and gas exploration. The onlap of these deposits on the base-of-slope is one of these boundaries. Although base-of-slope onlaps are considered one of the most common stratigraphic traps mechanism, the internal architecture of these configurations is still unraveled due to the shortage of outcrops and the low-quality of seismic image unable to reveal key internal sedimentary features. This study aims to define the architecture based on facies associations using recollected data which includes sedimentary field logs, photo-panels and field notes from the well-preserved outcrop of the Cliniform 14 part of the Batfjellet formation.

This analysis shows a classification of 11 lithofacies comprising 5 facies associations. The facies association analysis suggests that these up-dip pinch-out traps belong to a scour field in the channel-lobe transition zone environment (CLTZ), a zone where erosion, by-pass and infilling are continuously taking place. A division of proximal, middle and distal for this CLTZ is proposed to differentiate the transition of the facies. Base-of-slope architecture comprises several incision surfaces, given by different episodes of scouring. The facies that are infilling the scours in the proximal CLTZ, close to the source, are mainly comprised by thin bedded amalgamated sandstones with grain sizes from very fine to coarse interbedding with thin horizons of siltstones and mudstones. The facies infilling the scours in the medial CLTZ, where major density of scouring is observed, encompasses facies associations from thin to thick amalgamated sandstones, thin bedded sandstones, grain sizes from very fine to coarse and interbedding thin horizons of siltstones and mudstones and several episodes of slumping at the top of the infill. Finally, the facies next to the distal CLTZ at the proximal lobe are dominated by thick bedded amalgamated sandstones and the occurrence of the scours in this area is slighter in comparison with the middle zone.

The understanding of the internal characteristics of the base-of-slope onlaps is helpful to approach the geological risks, mainly in trap closure and sealing, encountered during the exploration of this potential reservoirs.

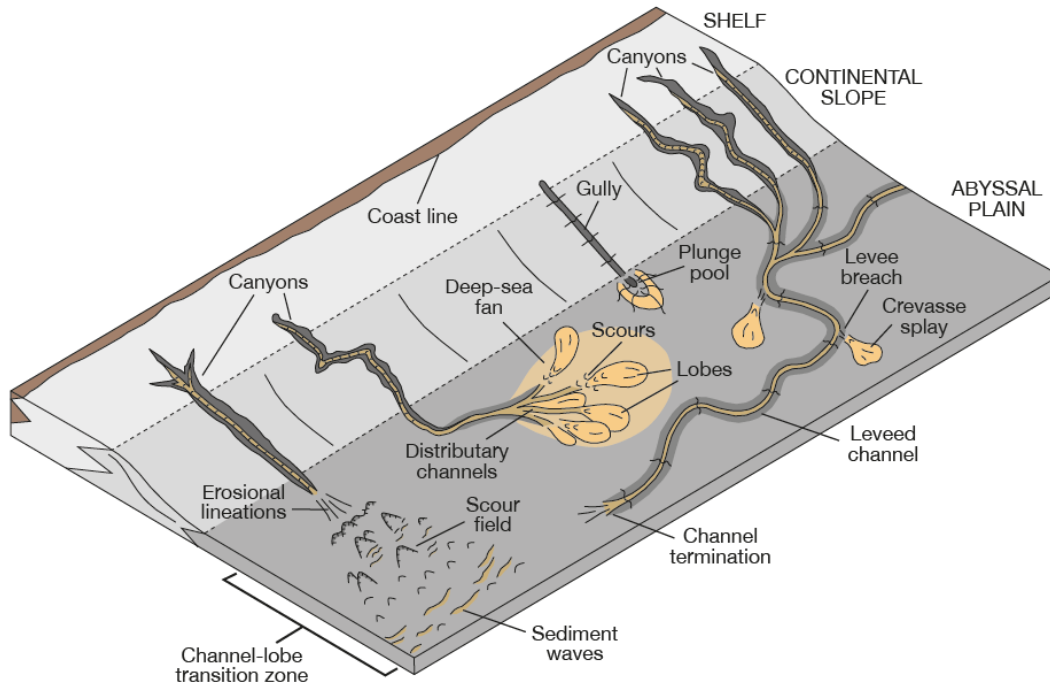
## 1. Introduction

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Deep-water marine deposits shape more than 65% of the sedimentary record of the Earth surface (Pickering & Hiscott, 2015). Due to the remoteness of the deep sea, the processes, systems and architectures are still a challenge to be explored and understood.

Turbidity currents are one of the main mechanisms of transport for deep-water marine sediments (Kuenen & Migliorini, 1950; Lowe, 1982; Talling et al., 2012). These gravity-driven sediment flows are funneled down from the shelf and slope through canyons or gullies onto the basin floor (Canals et al., 2006; Daly, 1936). After confinement, the sediments are transport and deposited by turbidity currents through levee channels (Klaucke et al., 1998). However, previous studies at the base-of-slope (Macdonald et al., 2011; Pohl et al., 2020; Wynn et al., 2002) show that at the end of the confinement the sediments pass through a stage of erosion, sediment bypass and infilling, in the area known as the Channel-Lobe Transition Zone “CLTZ” (Macdonald et al., 2011; Emiliano Mutti & Normark, 1987; Pohl et al., 2020; Wynn et al., 2002) (Figure 1). The CLTZ is defined by the area of transition between the well-defined channels and the well-define lobes (Emiliano Mutti & Normark, 1987). After leaving the CLTZ these sediments are deposited on the basin floor as lobes, forming the submarine fans. Deep-marine fans are considered to be the biggest repositories of sediments in the world’s ocean (Emilliano Mutti et al., 1999; Pr lat et al., 2009; Shanmugam, 2019; William R. Normark, 1970) and are well known to be potential sites of reservoirs for hydrocarbons (Bastia, 2012; Weimer et al., 2004). Furthermore, their importance extends to mineral and rare-earth elements reservoirs, physical oceanography (Cochonat et al., 2007) and geohazards for oil/gas pipelines (Zaker, 2008) and communication cables (Heezen & Ewing, 1952; Hsu et al., 2009).





**Figure 1. Different types of sedimentary systems of deep-marine environments created by sediment gravity flow deposition across the CLTZ (Took from Florian Pohl, 2019).**

Whereas stratigraphic traps of hydrocarbons in submarine fans are commonly prospected in the lobes of the deep-water systems (Brooks et al., 2018; Huang, 2018; Saller et al., 2008), the boundaries of the deep-marine fans have become important for oil and gas exploration as mechanisms of stratigraphic traps. Specially in fields where structural traps are not present or in mature fields where the typical and with low geological risk stratigraphic traps have been already tested. Therefore, future exploration points towards the identification of current less explored stratigraphic traps, such as pinch-outs (Figure 2). Although they are considered one of the most common mechanisms of stratigraphic traps in the petroleum industry (Amy, 2019) the geological risk present in these type of traps is one of the factors that limited the exploration of these possible reservoirs. However, the reservoir potential of these stratigraphic geometries is encouraging (Amy, 2019). Thus, the importance of the understanding of key aspects of these types of traps, which may provide relevant insights to de-risk forthcoming exploration opportunities among the oil and gas industry.

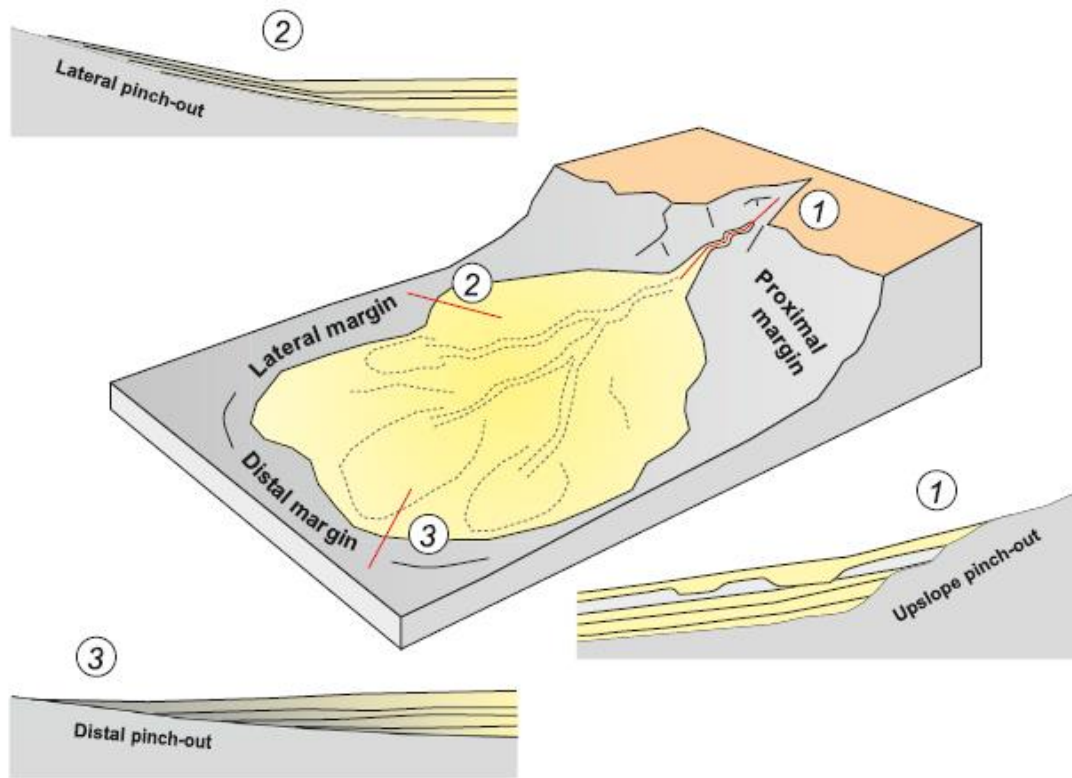


Figure 2. Illustration of the types of pinch-out traps encountered in deep water settings, showing the up-slope onlap as part of the proximal margin pinch-outs. Taken from Amy et al., 2000.

Pinch-out traps are classified by Amy et al as proximal, lateral and distal (Figure 2). Base-of-slope onlaps, also known as up-slope pinch-outs (Figure 4), form part of the proximal margin of this classification. These base-of-slope onlaps are associated to deep-marine fan deposits and are located in the CLTZ. Up-slope pinch-outs are formed by erosion and bypass on the slope (Amy, 2019) when a decrease of the ocean floor gradient, known as slope break, leads to sediment deposition on the basin floor (Pohl et al., 2020).

Although these traps are commonly found in the subsurface, there are still plenty unknown features about these sedimentary configurations, due to the low resolution of the seismic data (Figure 3) and the shortage of analog outcrops showing these stratigraphic architectures.

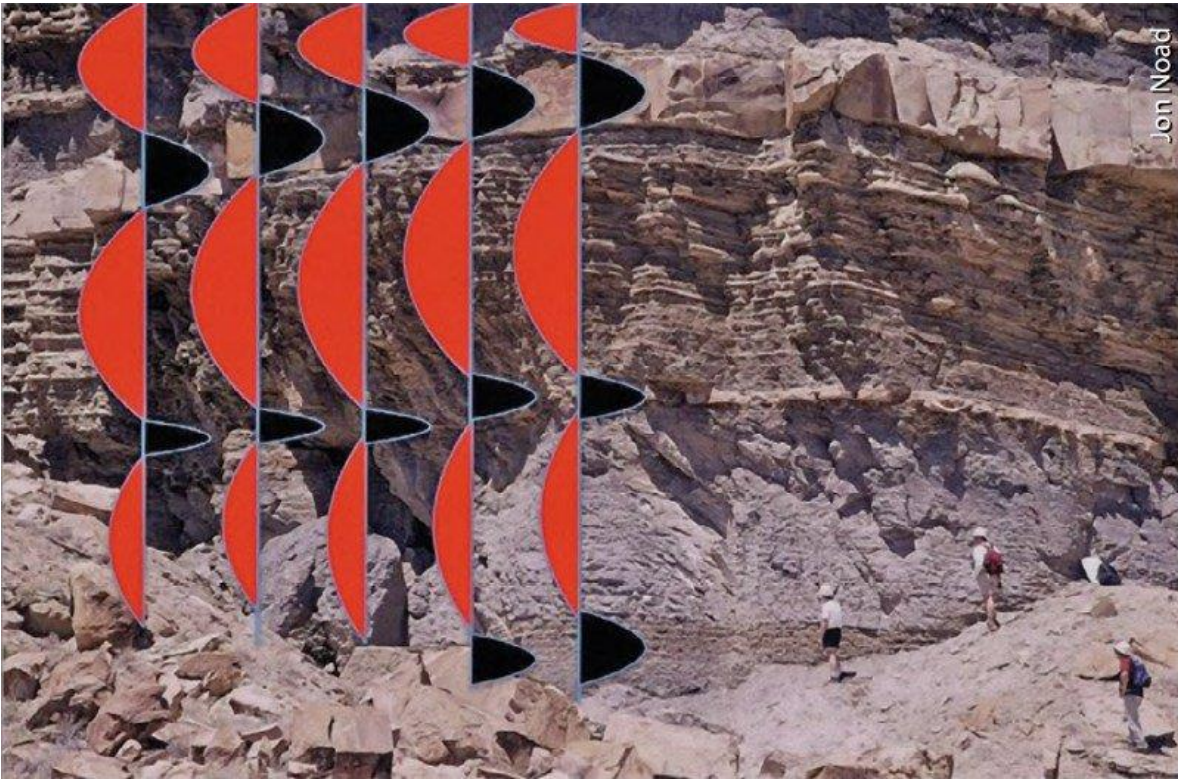


Figure 3. Comparison of resolution between an outcrop image and seismic wiggles. Note that one wiggle covers several events of thin beds. Original image without scale. Taken from Jon Noad, 2017.

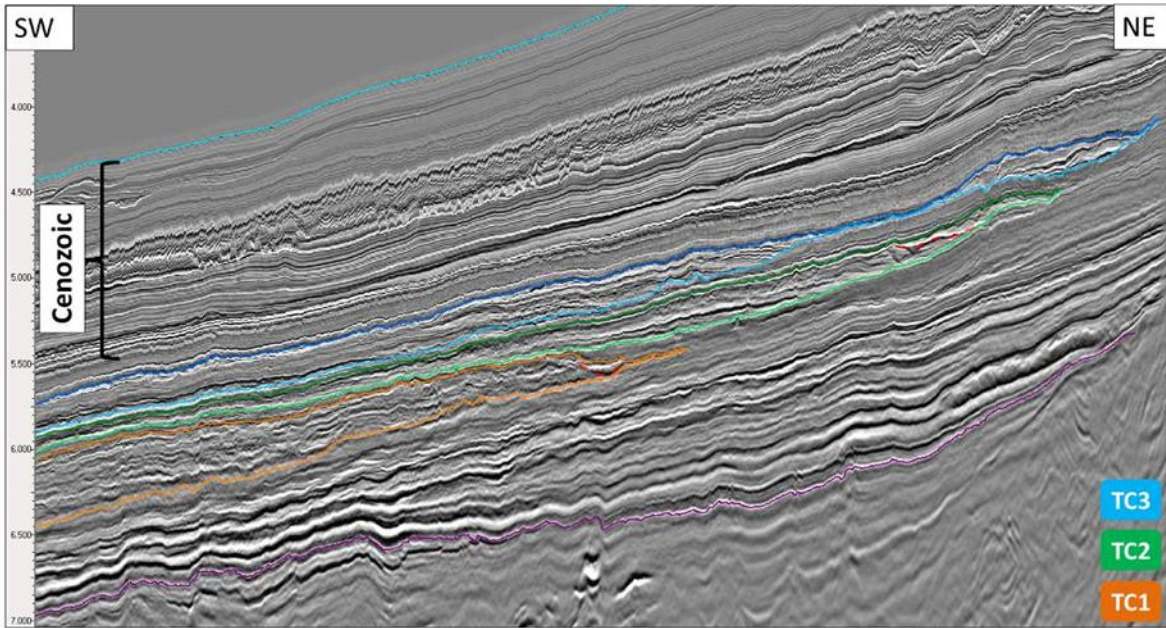


Figure 4. Seismic interpretation of base-of-slope onlaps in deep-water turbidites on the offshore of Ghana. In color orange, green and blue are drawn the base-of-slope pinch-outs and in red dotted lines some scours. Original image without scale. Taken from Martin et al., 2015.



Previous studies about base-of-slopes onlaps mainly offer large-scale descriptions of their architecture, geometries and facies, whereas many of the key features of their internal configuration are poorly or not visible in seismic scale (Amy, 2019; Brooks et al., 2018; Hansen et al., 2019; Jobe et al., 2016; Johannessen & Steel, 2005; McCaffrey & Kneller, 2001; Pohl et al., 2020; Prather et al., 2012). For example, changes in sedimentary facies, such as thin bedded layers, cross-lamination, grain sizes, etc., are not visible in seismic sets but possible to observe in outcrops.

Therefore, the aim of this study is to define the architecture and facies of these stratigraphic traps by studying an outcrop complex. Outcrop analogues help to close that gap between the seismic resolution and the well borehole data (wireline logs, core data, etc) and can provide insights at sub-seismic resolution, such as geometric properties of the reservoir and seal rock architecture (Sullivan et al., 2000). The outcrop analog used in this study are the turbidite deposits of the Clinoforn 14 of the Battfjellet formation located in the Tertiary Central Basin of Svalbard, Norway. The outcrop complex exhibit continuous sequences of the entire shelf-margin and basin floor (Clark & Steel, 2006), making this a unique study area. Clinoforn 14 is known as having well exposed and preserved outcrops which allows a proper visualization and interpretation of the sedimentary structures along the sequences.

The methodology of this study comprises facies analysis based on the interpretation and correlation of 22 digital sedimentary logs which are distributed over ~2.6 km. In addition of the interpretation of several photo-panels taken from the fieldwork done in the Tertiary Central Basin of Svalbard, Norway.

The results obtained from the base-of-slope onlap analog description will contribute to have a better understanding of these kind of depositional architectures that act as deep-marine oil and gas traps. These further insights will be relevant to tackle common challenges involved during the hydrocarbon exploration, such as the geological risks present in the closure and seal capacity of this kind of traps (Amy, 2019).

## 2. Literature review

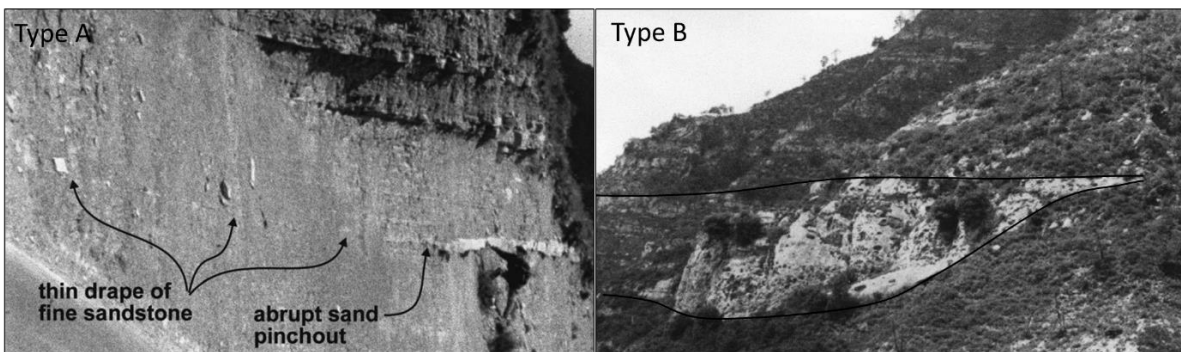
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### 2.1. Previous research on base-of-slope onlaps

Previous studies about base-of-slope onlap types were performed by McCaffrey & Kneller (2001), Amy (2019), and F. Pohl et al., (2020) giving insights about the base-of-slopes

onlaps according to the geometry, trap style and slope-break system, respectively. Table 1 shows a summary of the description given by these authors about these up-dip pinch-outs.

A classification based on bed geometry is given by McCaffrey & Kneller (2001). McCaffrey & Kneller (2001) defined different geometries by describing the bed grading, bed thickness and flow type, either steady, quasisteady or surge-type (Kneller, 1995) of oblique or lateral frontal slope outcrops. Known as type 2 pinch-out trap in the classification of Amy (2019). Type A geometries present ungraded or weakly normally graded character, are compound by individual turbidite beds without erosion between them and thinning towards the confining surface with an abrupt pinch-out, produced by a steady or quasisteady flow in the turbidity currents (McCaffrey & Kneller, 2001). Type B geometries present normal grading, deposits are comprised by turbidites thickening towards the confining slope with erosion within the beds, produced by surge-type flows of typically high velocity. Alternations of both types of geometries can be possible in one stratigraphic unit (McCaffrey & Kneller, 2001).



**Figure 5. Outcrops showing type A and type B geometries pinching out towards the lateral or oblique frontal slope. Modified from McCaffrey & Kneller, 2001.**

The trap style classification for up-dip pinch-outs by Amy (2019) is divided mainly by two styles: stratigraphic and structural. This classification was described with the seismic interpretation of published studies on oil and gas fields that were inferred as pinch-out traps. Amy (2019) refers to the term pinch-out as the lateral stratigraphic termination of a reservoir against seal rocks as a result of deposition, erosion or facies variations.

Amy (2019) focused on proximal margins where the upslope pinch-outs occur and the hydrocarbon accumulation trapping is critical. The study summarizes that the stratigraphic traps are divided into depositional and erosional pinch-out with no fault association (Figure 6) (Amy, 2019). Whereas the structural styles are divided in pinch-out on to faults scarp, pinch-out into growthn fault, normal fault trap, inverted fault trap, dip closure and erosional

pinch-out and pinch-out over fault controlled slope, this last one being a combination of both stratigraphic and structural style (Figure 6) (Amy, 2019).

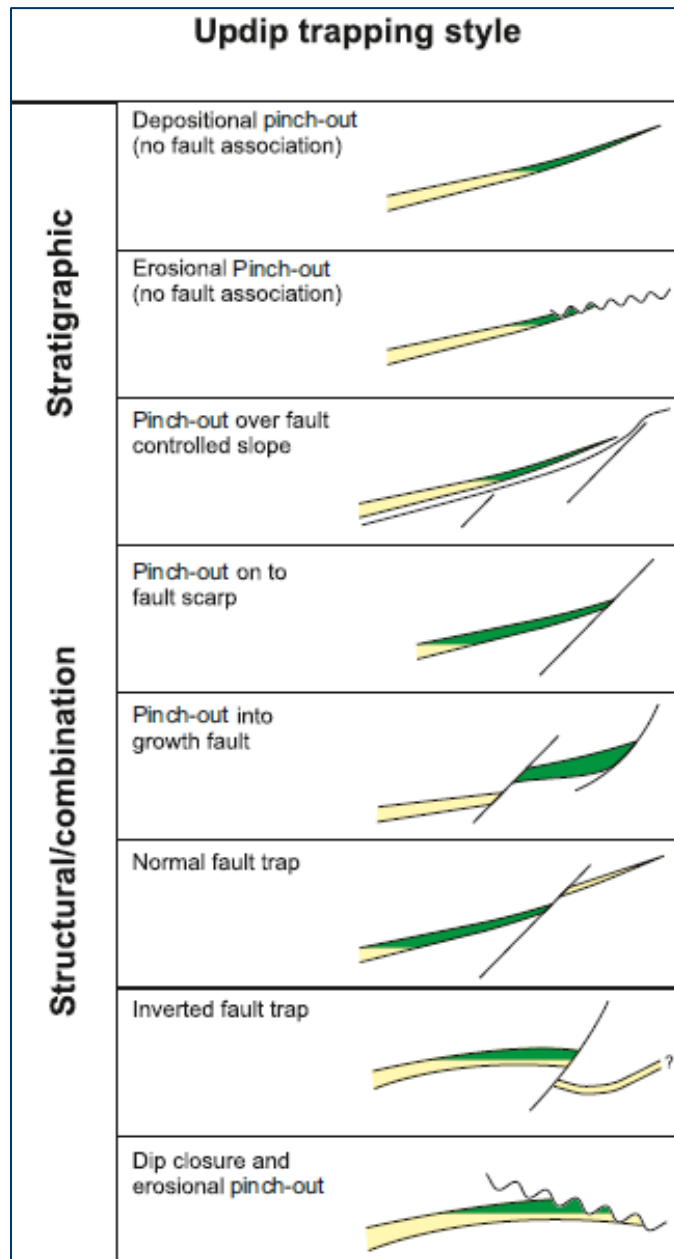
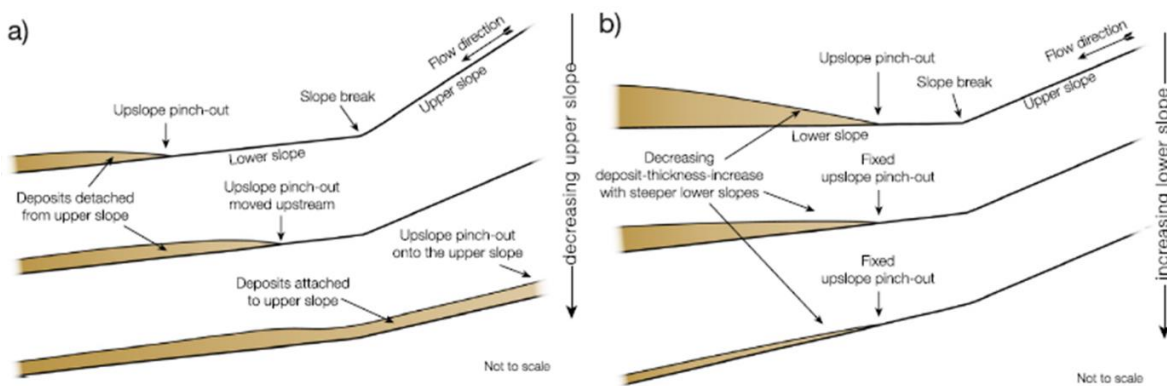


Figure 6. Amy (2019) upslope pinch-out trap's classification. Taken from by Amy (2019).

The Slope-break classification scheme by F. Pohl et al. (2020) is divided into a slope-attached and slope detached sedimentation pattern. The authors studied in flume-tank experiments the impact of the slope-break geometry (upper and lower slope gradient) on the position of the upslope pinch-out and its thickness distribution (Figure 7) (Pohl et al., 2020).

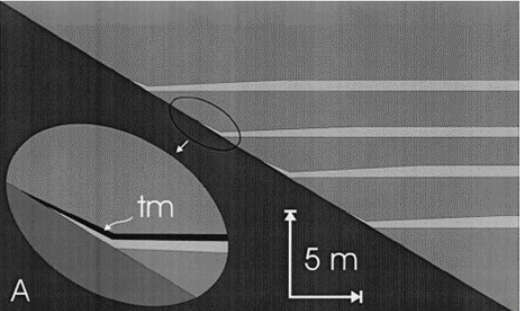
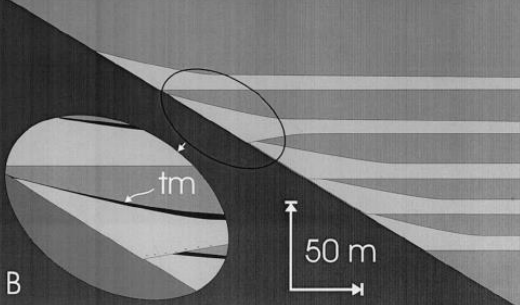
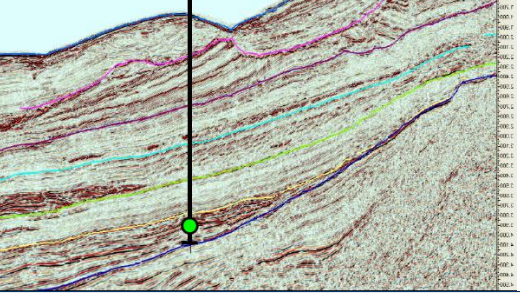
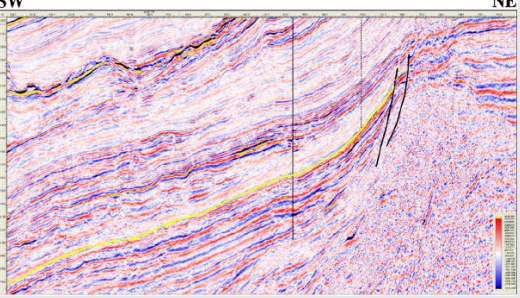
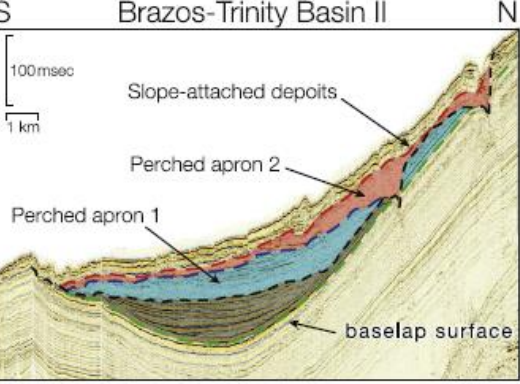
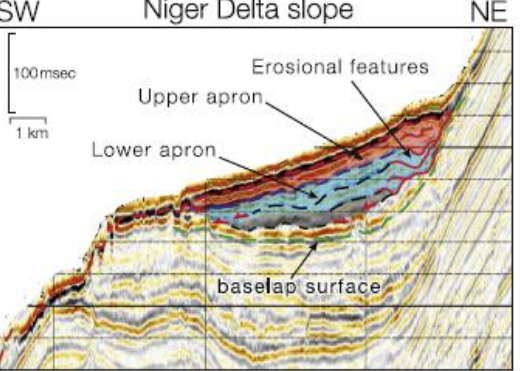


F. Pohl et al. (2020) concluded that the thickness of the upslope pinch-out is controlled by the lower slope angle, an increment in the lower slope angle results in a thinner layer of deposit sediments. The upslope pinch-out location is controlled by the upper slope steepness, where an increase results in a basinward shift of the pinch-out (Figure 7). This last result defines the classification from F. Pohl et al. (2020) where the slope-attached sedimentation pattern is the product of a subtle angle in the upper slope impacts in the connection between the sandstones of the upper and lower slope. Whereas a steep angle in the upper slope results in a slope-detached sedimentation pattern where the sands are not connected (Figure 7) (Pohl et al., 2020). Figure 4 shows a seismic example of how a slope-detached pattern evolves with the decrement of the steepness in the upper slope resulting in a gradual shift of the pinch-out position moving towards the upper slope. This slope-detached sedimentation patterns are more likely to form a hydrocarbon trap without thief sands risk (Pohl et al., 2020). (Amy, 2019) refers to this kind of patterns as depositional pinch-out traps with no fault associated (Figure 6) and he also points out the geological risk of the trap as consequence of the connection of the sandstones with the feeder system and the higher systems at the shelf.



**Figure 7. Schematic illustration showing the evolution from a (a) slope-detached sedimentation to a slope-attached sedimentation due to the decrement of steepness in the upper slope. And the (b) evolution of the thickness variations due to the increment of the lower slope angle. Note that when the lower slope angle is changed and the upper slope angle is fixed, the upslope pinch-out location remains fixed as well. Taken from F. Pohl et al. (2020).**

Table 1. Base-of-slope onlap models from previous studies based on large scale datasets. After McCaffrey and Kneller, 2001, Amy, 2019 and Pohl et al., 2020.

	Models	Description	Examples
<p style="writing-mode: vertical-rl; transform: rotate(180deg);">GEOMETRY</p> <p style="writing-mode: vertical-rl; transform: rotate(180deg);">According to McCaffrey and Kneller, 2001</p>	<p><b>Type A geometry</b></p>	<p>Turbidites thin onto the confining surface; abrupt pinch-out; individual beds; no erosion into earlier deposits (McCaffrey &amp; Kneller, 2001)</p>	
	<p><b>Type B geometry</b></p>	<p>Turbidite sandstones commonly thicken toward the confining slope; beds may incise into earlier deposits (McCaffrey &amp; Kneller, 2001)</p>	
<p style="writing-mode: vertical-rl; transform: rotate(180deg);">TRAP STYLE</p> <p style="writing-mode: vertical-rl; transform: rotate(180deg);">According to Amy, 2019</p>	<p><b>Pure stratigraphic</b></p>	<p>No fault association; erosional pinch out; pinch out over a fault-controlled slope (Amy, 2019)</p>	
	<p><b>Combined stratigraphic-structural</b></p>	<p>Pinch out on to fault scarp; pinch out into growth fault; normal fault trap; Dip closure and erosional (Amy, 2019)</p>	
<p style="writing-mode: vertical-rl; transform: rotate(180deg);">SLOPE BREAK SYSTEM</p> <p style="writing-mode: vertical-rl; transform: rotate(180deg);">According to Pohl, et al., 2020</p>	<p><b>Slope-attached sedimentation</b></p>	<p>In presence of a break of slope due to a subtle steepness of the upper slope (Pohl, et al., 2020)</p>	 <p>(Prather et al., 2012)</p>
	<p><b>Slope-detached sedimentation</b></p>	<p>In presence of a break of a slope due to a greater steepness of the upper slope (Pohl, et al., 2020)</p>	 <p>(Prather et al., 2012)</p>

Whilst Amy (2019) and Pohl et al. (2020) base their classification on large-scale observations from seismic interpretation and flume tank experiments and do not go in deep within the facies classification and base-of-slope internal architecture. McCaffrey & Kneller (2001) do make use of sub-seismic scale analysis for their classification with the study of different outcrops by describing grain sizes, facies changes and flow direction through cross lamina measurements but in outcrops of oblique or lateral frontal pinch-outs. Similarly, to McCaffrey & Kneller (2001), this study will go through the sub-seismic analysis but applied to the up-slope pinch-outs studied by Amy (2019) and Pohl et al. (2020). With the use of an outcrop from the Cliniform 14 of the Battfjellet formation that shows well preserved and continuous sequences from the slope to the basin floor. By giving a detailed facies classification and associations of this outcrop, a better understanding of how the reservoir rock and the seal rock behave along a base-of-slope onlap and the possible risks that can be faced during hydrocarbon exploration will be obtained.

### 3. Geological setting and stratigraphy

The Tertiary Central Basin is located in the main island Spitsbergen of the Svalbard Archipelago in the Arctic ocean (Figure 8). With a width of about 60 km and a length of 200 km (Ronald J. Steel et al., 1985) this basin has been interpreted as a foreland basin by (Ronald J. Steel et al., 1985) and as a piggy-back basin by (Blythe & Kleinspehn, 1998).

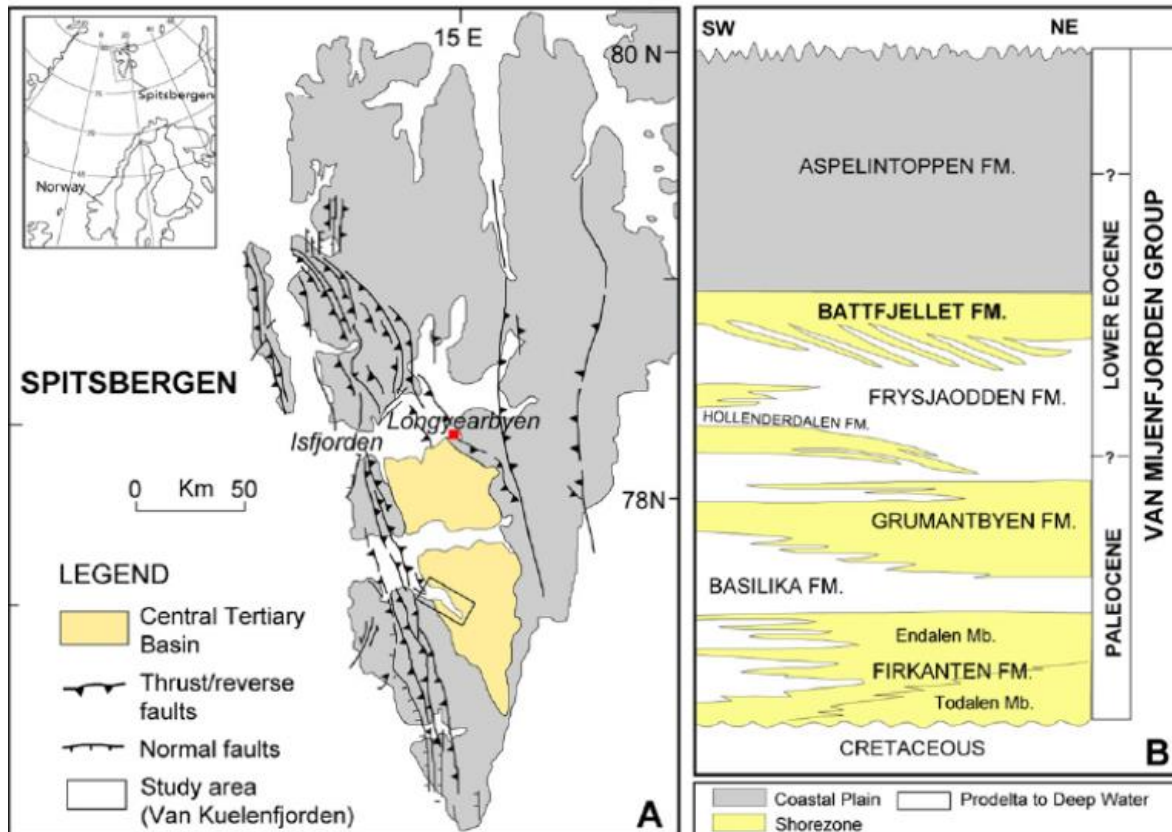
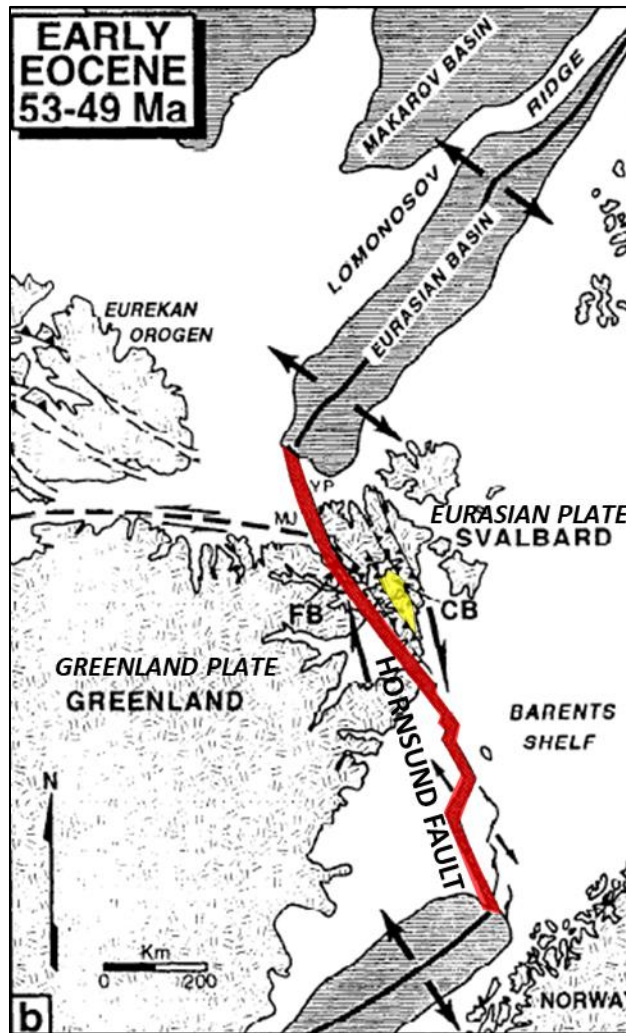


Figure 8. Spitsbergen archipelago location. (A) Area of study showed in a black rectangle (modified from Blythe & Kleinspehn, 1998) and stratigraphy of the Van Mijenfjorden Group, where the Battfjellet formation belongs to Lower Eocene age (modified Steel et al. (1985). Taken from Uroza & Steel (2008).

During Late Cretaceous to Early Cenozoic the opening of the Norwegian - Greenland Sea started. By the northward progression of the opening, during the Paleogene, Svalbard (part of Eurasia) and Greenland were separated along the Hornsund intracontinental dextral transform (Aamelfot, 2019; Blythe & Kleinspehn, 1998; Steel et al., 1985). This transform boundary experienced a phase of dextral transpression resulting in the Spitsbergen Orogen (Aamelfot, 2019; Blythe & Kleinspehn, 1998; Johannessen et al., 2011; Ronald J. Steel et al., 1985; Uroza & Steel, 2008) (Figure 9). Sequentially, the loading of thrust sheets along this Orogen formed the Central Basin (Ronald J. Steel et al., 1985; Uroza & Steel, 2008), which was filled with marine and continental sediments (Johannessen et al., 2011). The basin fill shows an asymmetric basin shape with varying thicknesses from 1.5 km in the North-East to 2.5 km in the South-West (Aamelfot, 2019).





**Figure 9. Early Eocene tectonic reconstruction showing the transform boundary (red) that originated the Spitsbergen Orogen and the Central Tertiary Basin of Svalbard. CB = Central Basin (yellow); FB = Forlandsundet Basin; YP = Yermak Plateau; MJ = Morris Jessup Plateau. Modified from Blythe & Kleinspehn, 1998.**

The main deposit direction of these sediments during the early Paleocene was from east to west, due to western tectonic subsidence and eastern uplift of the crust (Johannessen et al., 2011). Later, during the formation of the Orogen the transport changed dominantly from west to east, transversally from the growing of the fold-and-thrust belt (Helland-Hansen, 1990; Johannessen et al., 2011). The age of the Central Basin clastic deposits ranges from Paleocene to Lower Eocene and possibly Oligocene (Grundvåg et al., 2014) which are part of the Van Mijenfjorden Group (Harland et al., 1976). Steel et al., 1985 divided the Van Mijenfjorden Group into seven formations (Figure 8B): Firkanten formation, Basilika formation, Grumantbyen formation, Hollendardalen formation, Frysjaodden formation, Battfjellet formation and Aspelintoppen formation.

The focus of this study will be the Clinoforn 14, which is part of the Eocene Battfjellet formation. The Battfjellet formation belongs to the depositional system of the Tertiary Central Basin of Svalbard. This formation is exposed in the mountainsides of Van Keulenfjorden at the west coast of Spitsbergen (Figure 8).

This formation is interpreted as stacked sequences prograding eastwards including shelf-margin delta and barrier coastline to basin-floor deposits with thickness from 60 to 200 m (Figure 11) (Steel J. & Olsen, 2002; R. J. Steel, 1977). Its transition from the Frysjaodden formation shows a gradual coarsening upwards from offshore shales to proximal siltstones and sandstones layers (Aamelfot, 2019).

Battfjellet formation shows variations of facies types and successions all along the Central Basin (Müller & Spielhagen, 1990). Towards the Nordenskiöld Land, the lowest unit of this formation consists of shales interbedded with parallel or ripple-laminated silt and sandstones beds (R. J. Steel, 1977). Whereas the upper unit mainly presents interbedded sandstones and mudstones, fining upwards, intercalated with parallel- and ripple- or trough-shaped lamination (Helland-Hansen, 1990).

In Van Keulenfjorden area, the lower unit is a succession of medium-grained sandstones intercalated with planar laminated siltstones and fine sandstones. Whereas the upper unit consists of siltstones and shales alternated with coarsening-upward sandstones (Müller & Spielhagen, 1990).

Towards Torrel Land, the lower unit is mainly interlayered shales, siltstones and fine-grained sandstones, coarsening upwards to cross-bedded sandstones. Crossbedding shows north-west transport direction (Müller & Spielhagen, 1990). Sandstones beds seem to pinch-out to the northeast. The upper unit indicates shoreface environments, distributary channels and tidal deposits. Paleocurrents display directions of northeast, north and northwest (Müller & Spielhagen, 1990).

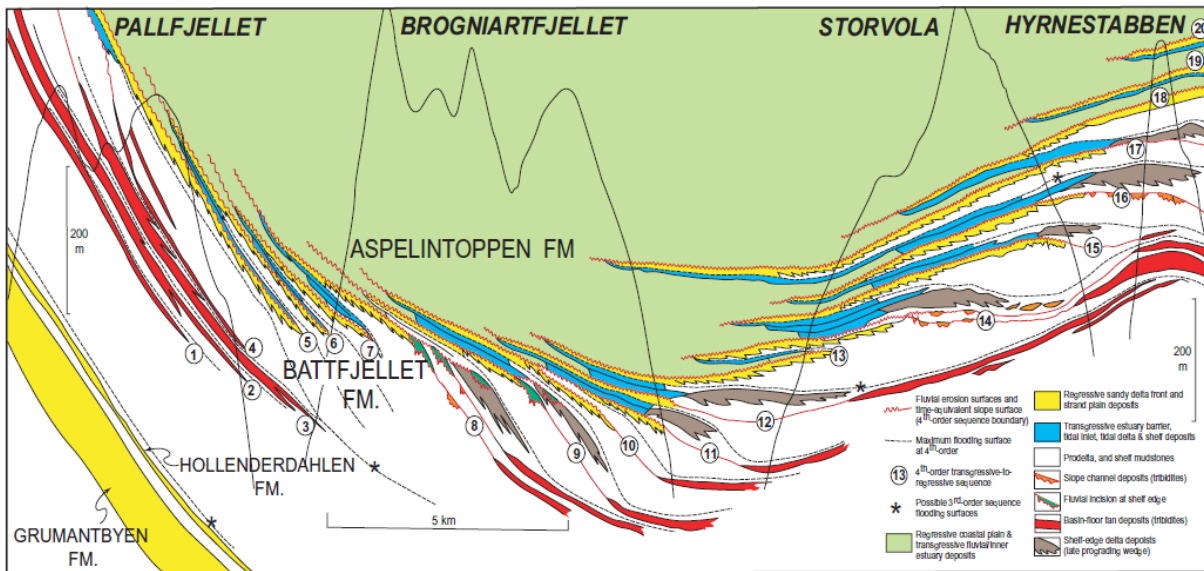
Considered part of the third depositional cycle of regression (Aamelfot, 2019). In the northern and southeastern areas of the Central Basin the final regression is shown by a gradual transition from offshore to lower shoreface in the lower part of the Battfjellet formation (Müller & Spielhagen, 1990). And it is followed in the upper part by coarsening upward sandstone beds (Müller & Spielhagen, 1990). The clinoforns of this formation show



a continuously increasing stratigraphic level reaching further eastward (Helland-Hansen, 1990; Kellogg, 1975), which is an evidence of an accelerated coastline progradation.

The sequences of the Batfjellet formation from shelf-margin delta to basin-floor are divided in 20 clinofolds of 4<sup>th</sup>-order, deposited on an total time interval of approximately of 6 Ma (Steel J. & Olsen, 2002; R. J. Steel, 1977) (Figure 10).

### VAN KEULENFJORDEN TRANSECT: LOWER EOCENE FACIES



**Figure 10.** Interpretation of a transect in the northern block of Van Keulenfjorden showing the 20 clinofolds developed within a total time interval of approximately 6 Ma (Steel J. & Olsen, 2002). The late prograding wedge, channel–levee complex, upper-slope channel and basin-floor-fan sections were measured from Clinofold 14 in Storvola and Hyrnestabben (Clark & Steel, 2006). Taken from (Steel J. & Olsen, 2002).

The aim of this study will be on the base-of-slope deposits of the Clinofold 14 (CF14), exposed in the Storvola and Hyrnestabben outcrops. Clinofold 14 has been described as a stacking of amalgamated progradational units with flat shoreline trajectory interpreted as a result of a steady to falling stage of the relative sea level (Figure 11) (Uroza & Steel, 2008). Evidence of fluvial incision in the shelf-edge canyons was interpreted by Clark & Steel (2006) as the result of a lowstand where the sea level fell below the shelf edge of this clinofold. Fluvial erosions and collapse sediments, where part of the sand is distributed onto the slope and the basin floor (Ron J. Steel et al., 2000; Uroza & Steel, 2008).

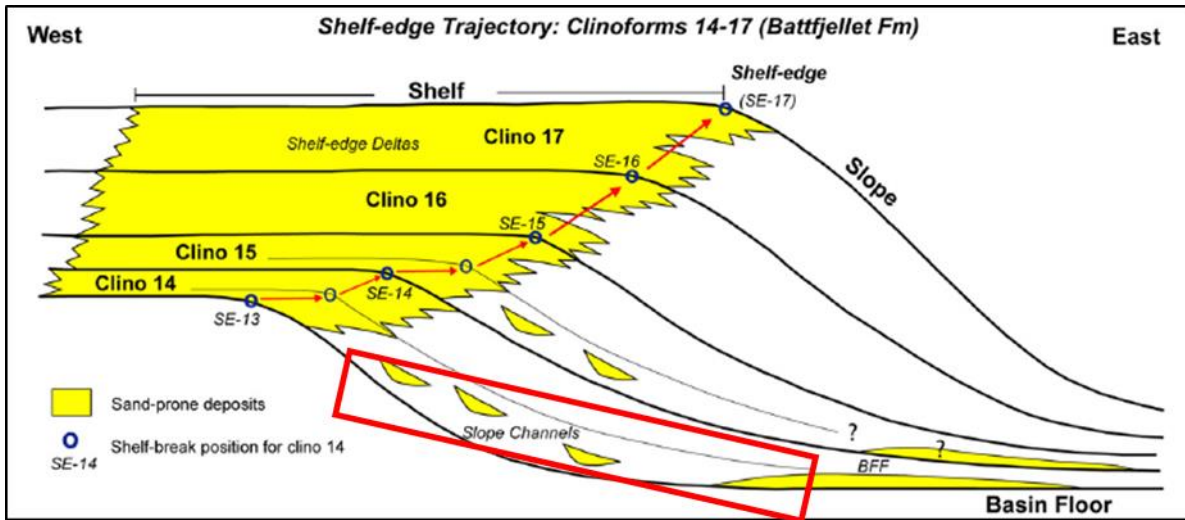


Figure 11. Sketch of the Clinoform 14 to 17, where the CF14 shows a flat trajectory of the shelf-break, slope channels and basin floor fans. The red square shows the segment of this study. Modified from Uroza & Steel (2008).

Clark & Steel (2006) classified four sub-environments on the turbidites of this clinoform (Figure 12): (1) canyon or gully fill, (2) late prograding wedge, (3) channel-levee complex, and (4) basin-floor fan. These turbidites are deposited at three periods of the lowstand: (A) early, (B) middle and (C) late.

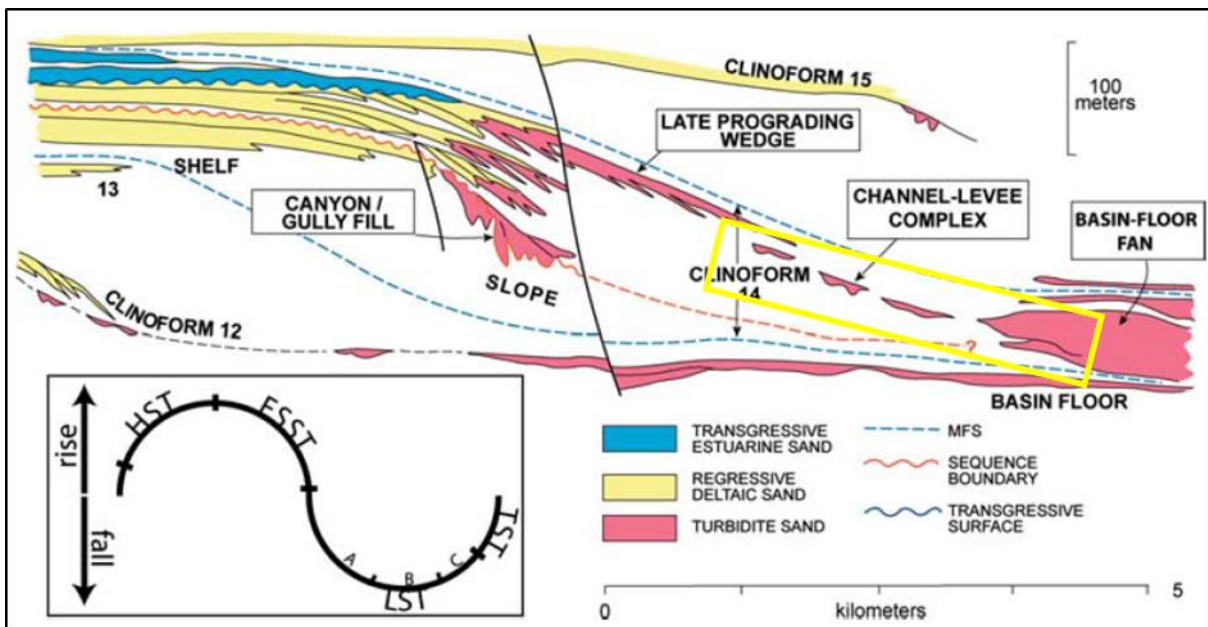


Figure 12. Interpretation of the sequence stratigraphy of Clinoform 14. The yellow square shows the segment of this study. Modified from (Clark & Steel, 2006).

## 4. Methodology and data set

### 4.1. Digitalization of field logs

From a total of 24 field logs taken in Storvola and Hyrnestabben mountains for the Clinoform 14, 22 were digitized with Adobe Illustrator CC 2017 software on a scale of 1:20 (Figure 13). The data was collected on a fieldtrip at Svalbard, Norway by the scientists Yvonne Spychala, Sten-Andreas Grundvåg, Florian Pohl and Joris Eggenhuisen from the 3<sup>rd</sup> to the 11<sup>th</sup> of August 2017. The symbology used for the digitized logs is indicated on Figure 14.

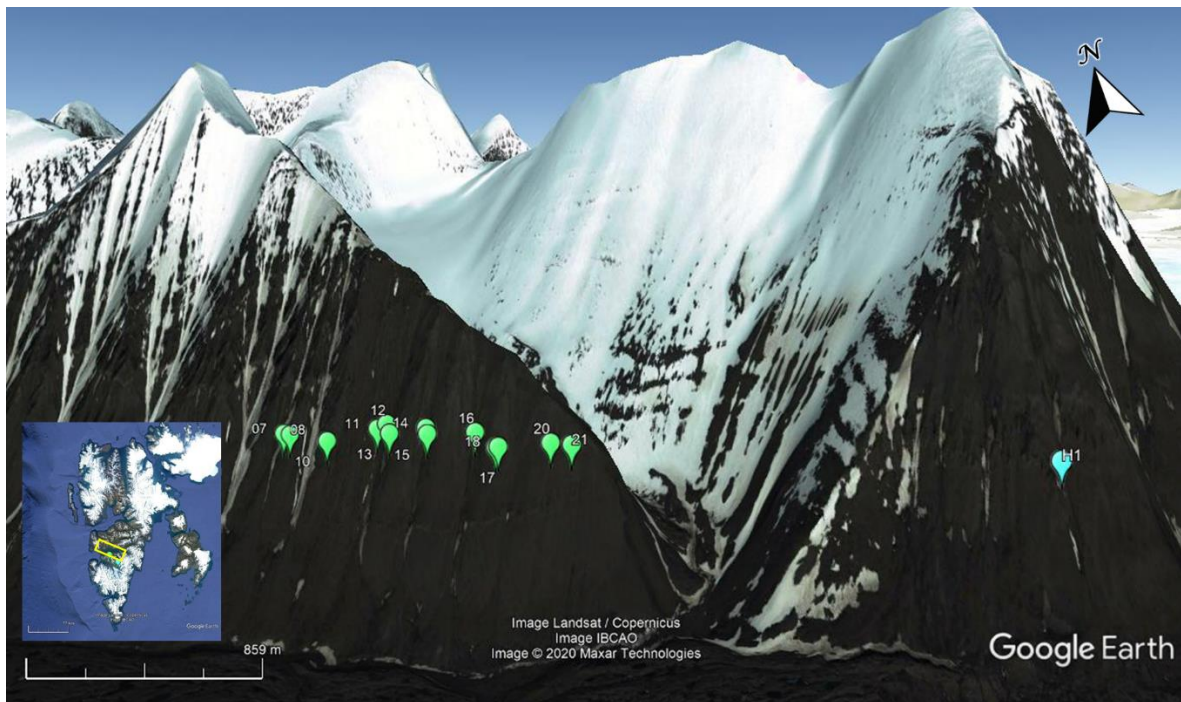


Figure 13. Location of some of the field logs taken for the Clinoform 14. The green tags represent the Storvola outcrops and the blue tag Hyrnestabben. (Image with vertical exaggeration).

SYMBOLOLOGY					
	Siltstone		Coal clast		Slope shale above
	Sandstone		Mud chips		Slope shale below
	Shale		Sand lenses		Ripples
	Red siltstone		Shale chunks		Flutes
	Parallel lamination				Incision surface
					Cross lamination
					Deformation or slumps
					Beginning or ending of the log

**Figure 14. Lithology and symbols used for the digitalization of the field logs for CF14.**

#### 4.2. Lithofacies and facies association

The lithofacies were classified and interpreted based on the information of the digitized field logs photopannels observations and field notes. The sediments of the Clinoforn 14 mainly comprises sandstones, siltstones, mudstones, coal clasts and mud chips. 11 lithofacies were defined based on combinations of the following properties: lithology, grain size, amalgamated vs. interbeds, bed thickness, bed shape, sedimentary structures, type of clasts, type of lamination and boundary type (Table 2).

Facies associations were based upon the stacking patterns of these 11 lithofacies, which showed a genetic relation and repetition along the vertical successions of the logs. This resulted in 5 facies associations which reveal a specific proximal-distal facies tract.

#### 4.3. Log correlation and photo-panel construction

A log section was constructed from West to East, starting with the logs in the Storvola outcrops, finishing with the logs of the Hyrnestabben outcrop (Figure 15). Logs are named with the prefix CF14 and numbered from 01 to 21 for the Storvola outcrops and H1 for the log in Hyrnestabben. Not all the logs are placed in numerical order, the section starts at the West with the log 04, continuing in numerical order until the log 13. Then the logs 01 and 02 are between the 13 and 14, which then continues from the log 14 to the 21. Finally, the log 03 is between the log 21 and H1, the section ends with the log H1 at the East of the study area. The position of the log section is oblique to the South-East sediment transport direction (Clark & Steel, 2006; Petter & Steel, 2006; Plink-Björklund et al., 2001; Ronald J. Steel et al., 1985).

The correlation was done by following the incision surfaces logged in the field, verifying the correlation, where possible, with the photo-panel observations. When there was lack of image between the outcrops, the assumption that the incision surfaces have a possible connection along the log section was done. Support by the observations of the lateral merging of isolated scours through time results in large areas of amalgamated scours reaching dimensions of for example 3 km width and 6 km length in the CLTZ (Macdonald et al., 2011; Wynn et al., 2002). When there was not photo-panel data, the correlation criteria for the incisions was considering the stacking patterns and facies associations below and on top of the incision surfaces. Note: Log number 03 was taken in the edge of the Storvola mountain and it seems to have a large projection in reference to the whole section, showing different facies in comparison with the log 21 and H1 which are the ones flanking it. To avoid an inaccurate correlation of lithofacies this log was not taken into account for the final correlation.

The photo-panels were constructed with Adobe Illustrator CC 2017 software considering the ones that had the best image to follow the incision surface correlation. This resulted in a section with 6 logs overlying 3 photo-panels where the incision surfaces and bed terminations are shown clearly and can be followed for interpretation. The digitized logs overlying the photo-panels are not in the same scale between them but scaled to the outcrop depending the perspective of the taken image.

After the tie between the data of the digitized field logs and the photo-panels, 9 different incision surfaces were identified along the outcrop correlation. Where 3 appear to have larger lateral continuity.

The log section was flattened in the stratigraphically youngest of these 3 incision surfaces. A flatten section, also known as stratigraphic section, is done by using a datum or reference level to make it totally plane. Assuming that this reference surface was horizontal when deposited, therefore no original depositional slope at the level is shown. The horizon selected to flatten is one that shows a large coverage across the section. The other surfaces, above and below, are modified by hanging them in reference to the flattened surfaces, allowing to observe bed thickness variations, lithofacies variations, continuity of the interpreted packages, truncations, paleotopographic relief, etc.



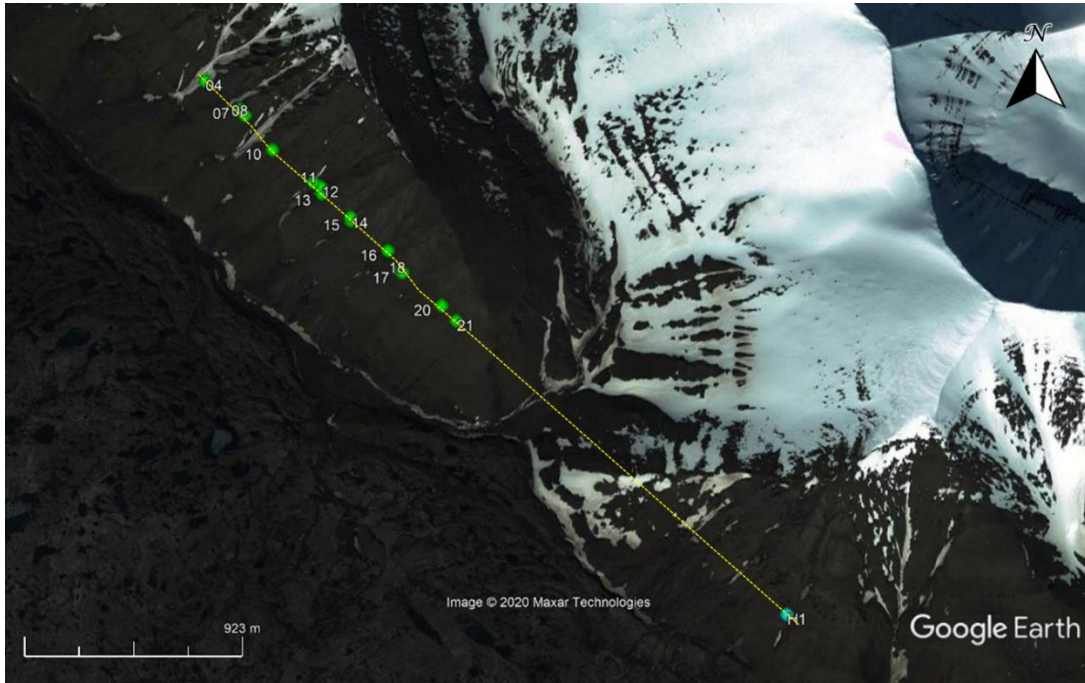


Figure 15. Trajectory of the log correlation section represented in a yellow dashed line.

## 5. Results

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### 5.1. Lithofacies

From the detailed analysis of the field data 11 lithofacies were defined along the CF14 (Table 2). The interpretation of the processes that influenced the deposition of these facies considers the description of known facies' models such as the Bouma sequence (Figure 16) for turbidity deposits, as well as the models of high- and low-density turbidity flows (Cartigny et al., 2014; Lowe, 1982; Postma et al., 1988) (Figure 17).

Characteristics such as lithology, grain size, amalgamation, interbedding, thickness, lamination, soft sediment deformation, presence of clasts and boundary type were considered for the descriptions below.



Grain Size	Bouma (1962) Divisions		Interpretation
	Symbol	Description	
Mud	$T_{ep}$	Pelite	Pelagic sedimentation
	$T_{ef}$	Massive or graded Turbidite	fine grained, low density turbidity current deposition
Sand Silt	$T_d$	Upper parallel laminae	? ? ?
	$T_c$	Ripples, wavy or convoluted laminae	Lower part of Lower Flow Regime
	$T_b$	Plane parallel laminae	Upper Flow Regime Plane Bed
Sand (to granule at base)	$T_a$	Massive graded	(?) Upper Flow Regime Rapid deposition and Quick bed (?)

Figure 16. Bouma sequence description used for the lithofacies interpretation (Bouma, 1962).

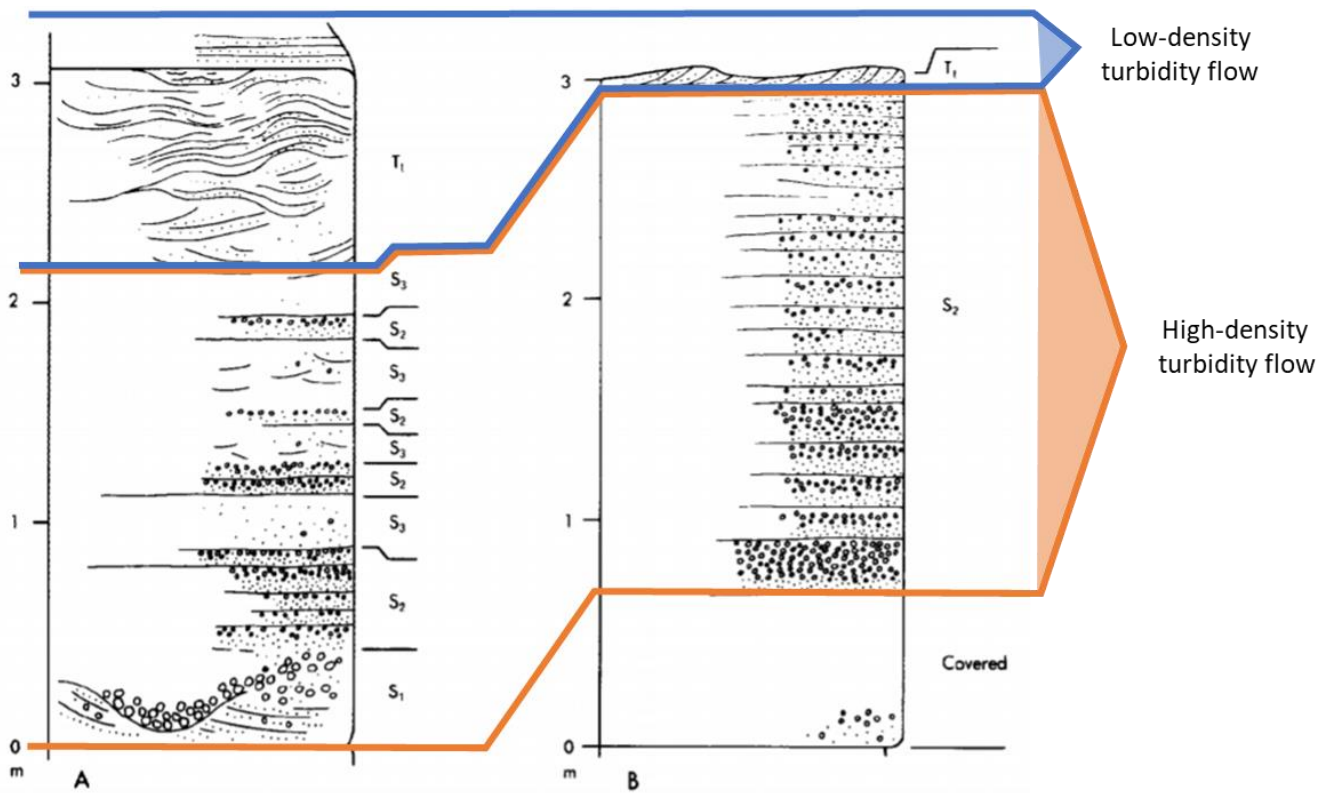












Figure 17. Bed units that comprise the divisions of high- and low-density depositional stages of turbidity currents (Modified from Lowe, 1982)

Table 2. Lithofacies classification for the Clinoform 14 of the Batfjellet formation at Svalbard, Norway.

Lithofacies CF14		Description	Interpretation	Outcrop view
F1	Siltstones and mudstones	Laminated siltstones and sandy mudstones with flat boundaries and thickness from <2 cm to 1 m.	Interpreted as hemipelagic sediments deposited by suspension in a tranquil environment in the absence of sand sediment supply.	
F2	Thin bedded sandstones and mudstones/siltstones	Very fine to medium grain individual sandstones interbedding with siltstones and mudstones, both types of beds present thicknesses from <0.5 cm to <5 cm. Commonly with sharp base and undulating top, rarely with wavy base. Typically presents plane parallel lamination and occasionally ripple lamination.	The packages of mudstones and siltstones are interpreted as hemipelagic sediments or the Te-division of Bouma sequence (Bouma, 1962). The sandstones are interpreted as deposits of the dilute turbidity current (Cartigny et al., 2014; Lowe, 1982; Postma et al., 1988).	
F3	Amalgamated thin bedded sandstones	Very fine to medium grain sandstone beds from 2 cm to 15 cm thickness, mainly sharp tops, rarely wavy. Commonly undulating and erosive bases. Occasionally wedge-shaped beds and coarse grains at the base. Typically presents plane parallel lamination.	These facies are interpreted as deposits of continuous turbidity flow events, probably high-density currents (Cartigny et al., 2014; Lowe, 1982; Postma et al., 1988) where the new flow event eroded the previous deposited bed.	
F4	Amalgamated thick bedded sandstones	Very fine to medium grain sandstone beds occasionally with coal clasts commonly at the top of the bed and sporadic mud chips or coarse grains at the base, rarely on the top. Thickness from 20 cm to 50 cm. Bed tops are often flat and occasionally undulating. Bed bases are mainly wavy and erosive. Beds are structureless or with plane parallel lamination.	These facies are interpreted as deposits of continuous turbidity flow events, probably high-density currents (Cartigny et al., 2014; Lowe, 1982; Postma et al., 1988). With coal clasts carried from the source probably the coal rich deltas, and sporadic rip-up mud clasts which result from the erosion and rework of the previous bed (e.g. mudstone and siltstone) when the new event flow occurred.	
F5	Lenticular sandstones	Very fine to fine grain sandstone from 2 cm to 15 cm thickness, with wavy tops and bases. Commonly surrounded by siltstones. Occasionally with cross-lamination.	Low density turbidites, deposits from the transition of by-pass to deposition. The wavy structure suggests that there was transport coupled with deposition of sediments.	
F6	Sandstones with ripple and parallel lamination	Very fine to medium grain sandstone beds with cross-lamination. Commonly overlaying parallel lamination sandstone beds.	The ripple lamination sandstones and climbing ripples are interpreted as Tb-division of Bouma sequence and the parallel lamination as Tc-division (Bouma, 1962). These facies are interpreted as deposits of turbidity currents at larger sediment fallout rate, part of the low-density flow of a turbidity current (Cartigny et al., 2014; Emiliano Mutti & Normark, 1991; Emiliano Mutti et al., 1999).	
F7	Sandstones with sole marks and bioturbation	Very fine to medium grain sandstone beds from <0.5 cm to 50 cm thickness with tool marks of ~116° direction and roundish shaped bioturbation traces on the bed bases.	Interpreted as beds deposited by turbidity flows, the bioturbations suggests that there was a period of tranquility where the organisms had enough time to live in the sands and the sole marks are evidence that the flow carried organic matter that created left tool marks on the base of the bedding.	
F8	Sandstones with coal clasts	Very fine to medium grain sandstone beds from <0.5 cm to 15 cm thickness. Granule to cobbles (Wentworth, 1922) mainly subangular and occasionally sub-rounded (Benn & Andrews, 2007). Commonly found at the top of the beds, sporadically at the base. Bases and tops are generally eroded.	Interpreted as continuous deposits of turbidity flows, probably high-density currents (Cartigny et al., 2014; Lowe, 1982; Postma et al., 1988). The coal clasts come presumably from the coal rich deltas and are present mainly on the tops because of their density is lower than the sandstones.	
F9	Sandstones with mud chips	Very fine to medium grain sandstone beds from <0.5 cm to 15 cm thickness. Cobbles to boulder (Wentworth, 1922) mainly sub-rounded and occasionally rounded (Benn & Andrews, 2007). Typically, in the base of the beds and occasionally in the top. Bases and tops are generally eroded.	These facies are interpreted as deposits of continuous turbidity flow events, probably high-density currents (Cartigny et al., 2014; Lowe, 1982; Postma et al., 1988). Every new event flow eroded and transported part of the previous basal layer (e.g. mudstone and siltstones layer), resulting in the deposit of rip-up mud clasts at the bases.	
F10	Slumps	Very fine to medium grain sandstones and siltstones, contorted, mixed with mud and coal clasts.	These structures are interpreted as the displacement of an unconsolidated bed as a removal of the slope.	
F11	Sandstones with load casting	Very fine to medium grain sandstones beds with load casting at the base, showing a sinuous and bulgy shape engrave in the underlying mudstones.	These loading structures are formed during soft-sediment deformation, when a rapidly deposited dense layer of sand is overlying a less dense layer of mud or silt. Which results in a gravitationally unstable arrangement where the mud liquifies and the denser sand descends into it creating the bulges of the load casts.	



## 5.2. Facies associations

In total 6 facies associations were defined with the 11 lithofacies. In contrast with the model proposed by Clark & Steel, 2006 for this slope deposits as channel levee complexes, here the depositional environment interpreted from the facies associations and the photo-panel correlation is a scour field in the channel-lobe transition zone in which episodes of erosion, by pass and deposition is encountered (Macdonald et al., 2011; Pohl, 2019; Wynn et al., 2002). Here the term erosion will be referred to the erosion surfaces between amalgamated beds. Meanwhile the term scouring will referred to the greater erosions, known as scours or incision surfaces, done by the flow relaxation of the sediments after the loss of confinement in the channel-lobe transition zone and that remain open for long periods of time (>0.2 m.y.) with phases of isolation, amalgamation and infilling (Macdonald et al., 2011; Pohl, 2019).

### □ FA1 - Amalgamated thin bedded sandstones (Figure 18):

Characterized by massive thin bedded sandstones (F3) with amalgamated surfaces. Rarely interbedding with horizons of siltstones and mudstones (F1). The bases are erosive or sharp and the top of the beds show sporadic coal clasts (F8). Packages thickness vary from 0.5 to 5 meters. The presence of lenticular sandstones (F5) and tool marks at the base of the bedding (F7) suggests these deposits are part of a zone with erosion, by-pass and deposition. This is supported by the presence of bioturbation at the base of the bedding and the parallel lamination with ripples (F6), generally this both lithofacies are present together suggesting episodes of by-pass and deposition with large sediment fallout rate where the organisms had enough time to settle in the sandstones. Moments of erosion are seeing when mud chips (F9) are encountered commonly at the base of the beds which indicates that turbidity currents eroded the previous bed floor and carried out rip up clasts in the flow that was deposited in the facies. These facies associations are representative of the proximal facies of the CLTZ, but are found all along the base-of-slope profile.

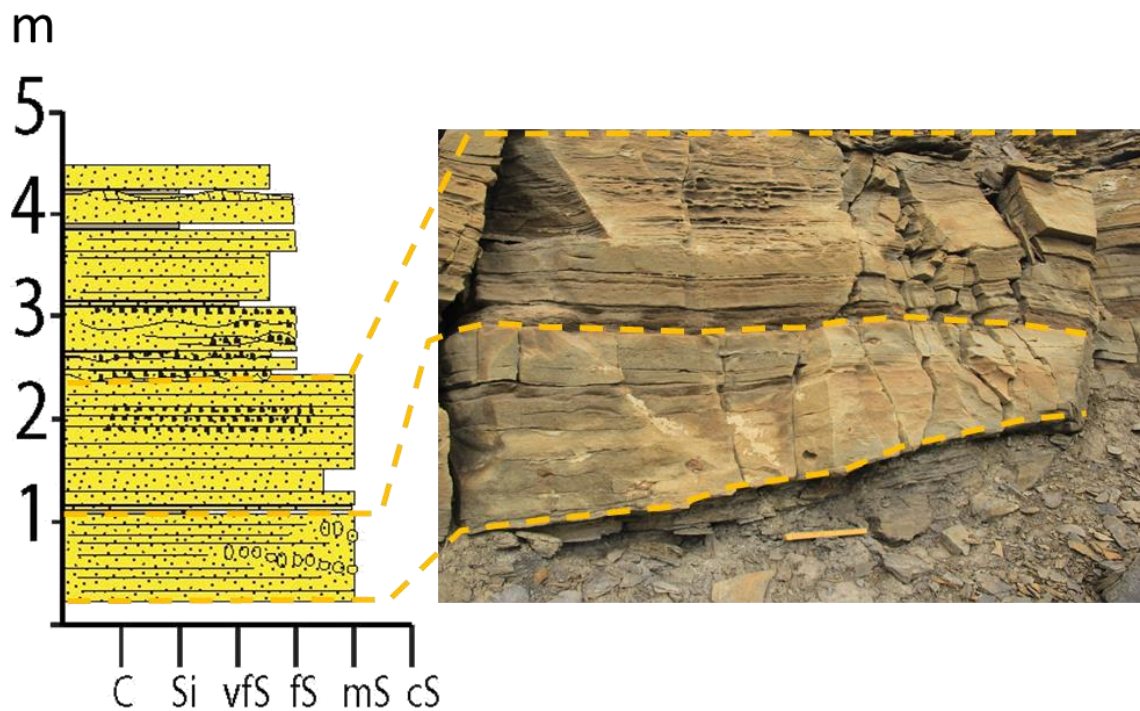


Figure 18. Example of amalgamated thin bedded sandstones in digitized field log and outcrop image of the log of the log 10.

□ FA2 - Amalgamated thick bedded sandstones (Figure 19):

Characterized by massive thick bedded sandstones with amalgamated surfaces (F4). With erosive bases and sharp tops. Sporadically interbedded with siltstones and mudstones (F1). Packages thicknesses vary from 1 to 15 meters. Interpreted as the continuous deposit of sediments from turbidity flow events of probably high-density (Cartigny et al., 2014; Lowe, 1982; Postma et al., 1988). The structures of soft sediment deformation such as load casting (F11), supports the interpretation of a rapid and continuing deposition of the flows. Just as the facies association 1, the thick bedded sandstones are comprised by sandstones with ripple and parallel lamination (F6). At difference of the FA1, these facies associations present greater thickness and less presence of rip-up clasts and sandstones with sole marks, but not bioturbation is observed (F7). As well this facies association are in the area where there is less presence of incision surfaces. Suggesting that these facies were in a part of the system where erosion with continuous deposition was greater than by-pass and scouring. Therefore, these facies are interpreted as distal facies, as part of the proximal lobe.

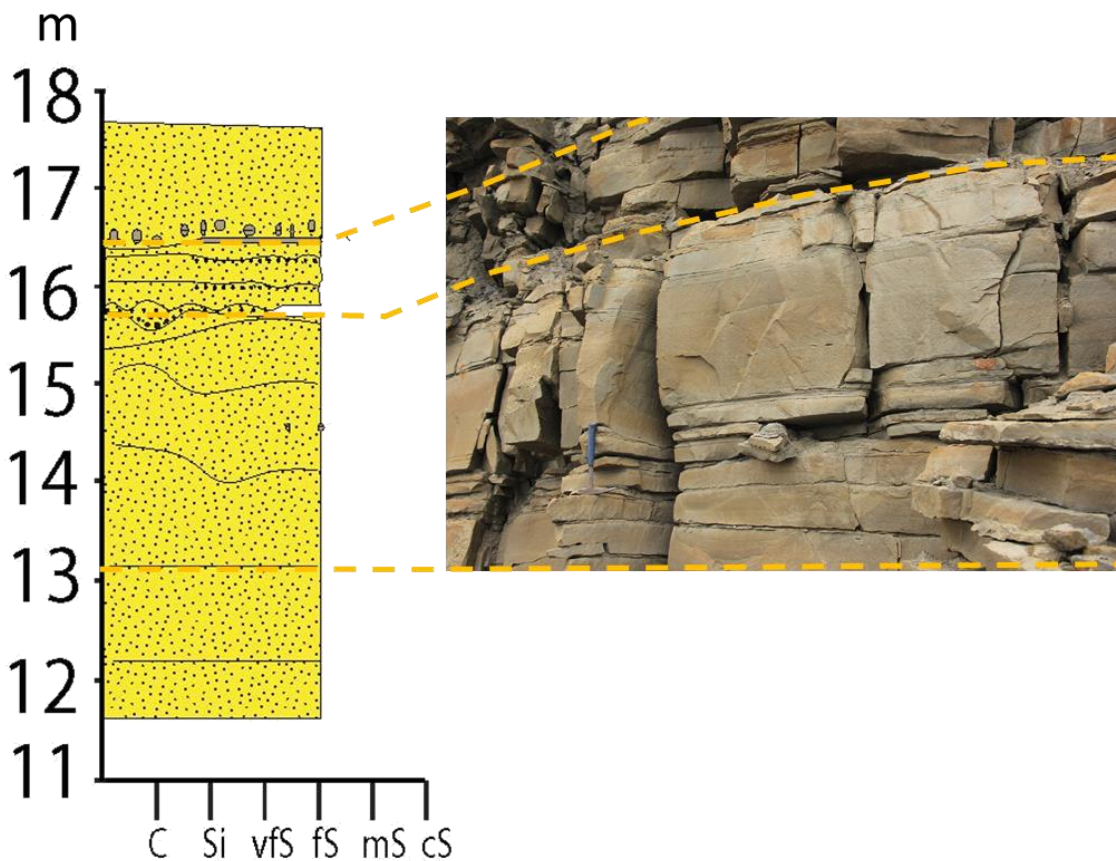


Figure 19. Example of amalgamated thick bedded sandstones in digitized field log and outcrop image of the log H1.

□ FA3 - Thin bedded sandstones (Figure 20):

Characterized by thin bedded sandstones from <1 cm to <5 cm thick interbedding with siltstones and mudstones (F2). With sharp bases and undulating tops. Packages thicknesses vary from 0.5 to 1 meter. Interpreted as sediments deposited by the dilute stage of the turbidity flow. Just as the FA1 and FA2 ,the sandstones of this facies association present lenticular beds (F5), ripple and parallel lamination (F6), sole marks and bioturbation at the base of the beds (F7), coal clasts at the top and mud chips (F8 and F9) and the base and load casting (F11). Suggesting that these facies were also part of the by-pass and deposition zone. The presence of thicker beds of siltstones and mudstones in comparison with the FA1 and FA2 suggests that these deposits had longer periods of tranquil deposition and shorter periods of sand contribution. These facies associations are representative of the medial and distal facies, part of the CLTZ and the proximal lobe, respectively.

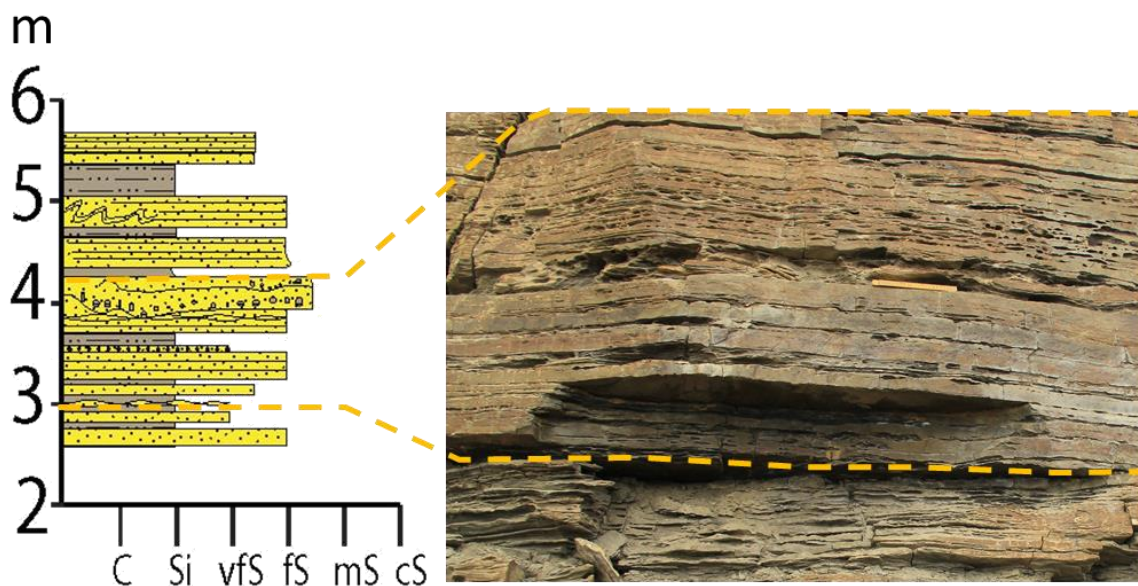


Figure 20. Example of thin bedded sandstones unit in digitized field log and outcrop image of the log 11.

□ FA4 - Heterolithic beds (Figure 21):

Characterized by beds of sandstones from <0.5 cm to < 5 cm thick (F2) interbedded with siltstones and mudstones (F1). Sometimes sand beds present wavy tops or wavy bases. Thicknesses of the packages vary from 0.2 to 4 m. Sandstones and siltstones/mudstones deposits appear to be almost equivalent in amount. Other lithofacies that characterized this facies association are the lenticular sandstones (F5) and ripple and parallel lamination (F6). These facies association are the ones where most of the bioturbation is seen (F7). The presence of bioturbation suggests that these facies where deposit in a tranquil environment, where erosion was less or none. These facies association are encountered close to the FA3, suggesting less input of sand sediments. These facies associations are generally present in the medial facies of the CLTZ.



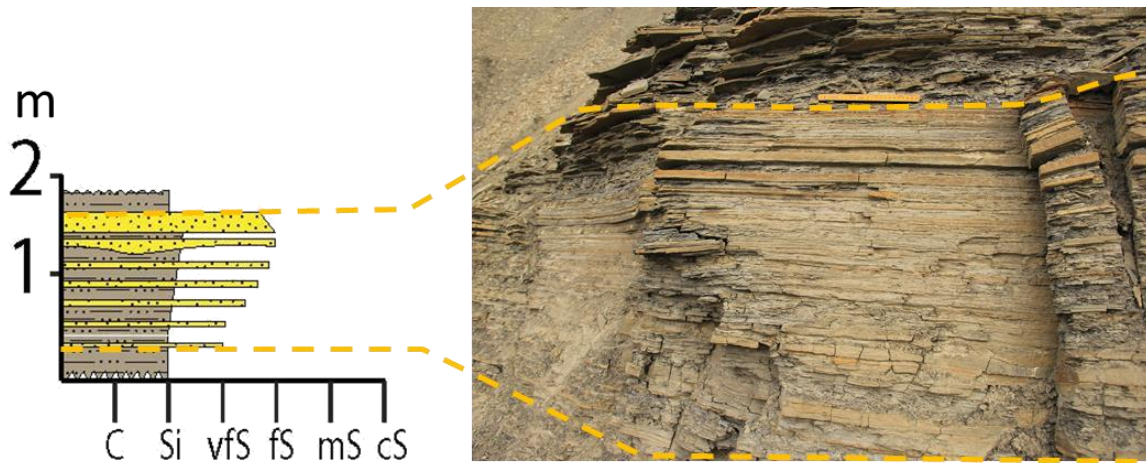


Figure 21. Example of heterolithic beds in digitized field log and outcrop image of the log 04.

□ FA5 - Siltstones and mudstones (Figure 22):

Characterized by fine grain siltstones and mudstones with flat boundaries (F1). Thicknesses of the beds vary from <2m to 1 m. The facies association are interpreted as the hemipelagic sediments deposit by suspension in a tranquil environment. These facies are characteristic of the overlying and underlying sediments of the incision surfaces and are closely related to the FA4 which suggests that there was a lack of sand sediment supply or the possible transition of the abandonment of the system.

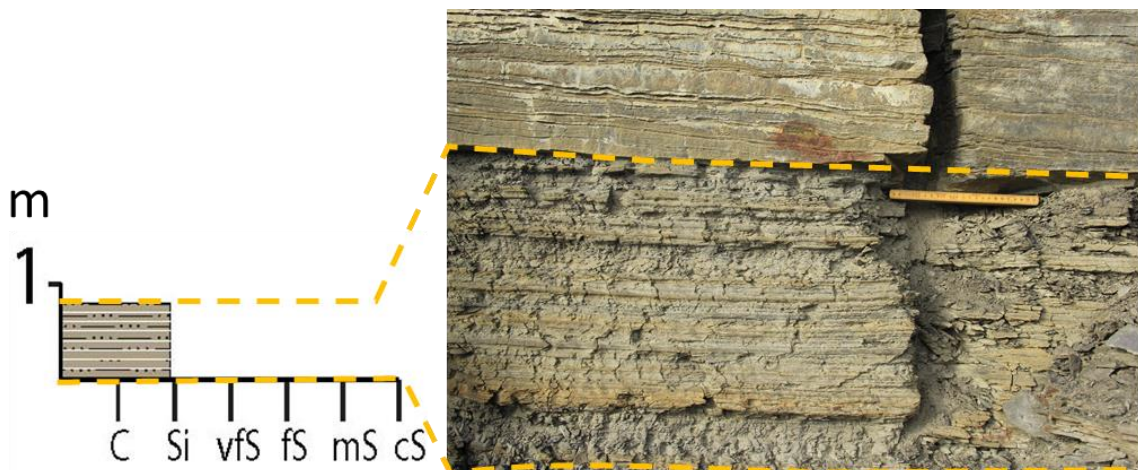


Figure 22. Example of siltstones and mudstones unit in digitized field log and outcrop image of the log 16.

□ FA6 – Slumps (Figure 23):

These facies associations are bounded by incision surfaces and are characterized by contorted shape beds (F10) of sandstones and siltstones/mudstones with erosive bases and wavy tops. They present thicknesses from 0.5 m to 2 m. These facies are interpreted as

episodes of instability in the slope. Most of these facies' associations are more present in the medial facies, and rarely visible in the medial and proximal facies of the CLTZ.

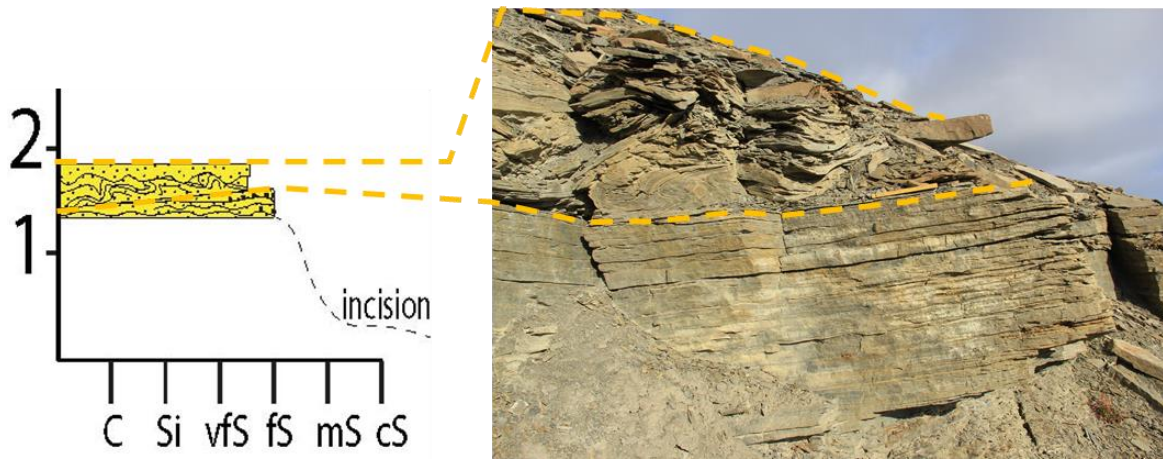


Figure 23. Example of slump unit in digitized field log and outcrop image of the log 17.

### 5.3. Sedimentary logs and correlation panel

The correlation of the 21 logs and the correlation panels result in the interpretation of 9 different incision surfaces. Named as IS1 to IS10 (Figure 24 and Figure 25). Three of these incisions were considered major incisions because of the extension they show along the log section and based on the compiled data from the field books. The section was flattened in the IS9, which is the incision that presents the greater length. This made possible to observe the morphology of the base-of-slope onlap (Figure 25). The log correlation shows how the thickness between the basal incisions IS1 and IS2 and the top incision IS9 vary from West to East, becoming greater towards the East in the Hyrnestabben log (Figure 25 and Figure 29). The pinching out of the sequences is clearly observed towards the West in the log 04 from Storvola. The facies association variations in the system are also clearly seen along the correlation and will be discuss in detail in the next chapter.

In overall the grain size trend that the logs present is finning upwards. Considering the facies between the main incisions IS1 and IS9, the next results of the grain size trends are observed for each area from proximal to distal facies (Figure 28). The proximal facies show an overall grain size blocky trend of the sandstone beds (FA1). The overall trend of the grain size along the log section is finning upwards for the medial facies. And the overall grain size trend in the distal facies shows a blocky trend in the sandstone packages.

The photo-panel correlation result in the observation of the layer behavior onlapping, draping or downlapping the incision surfaces. And gave a better view of how the incision was cutting the layers in the logs (Figure 26).

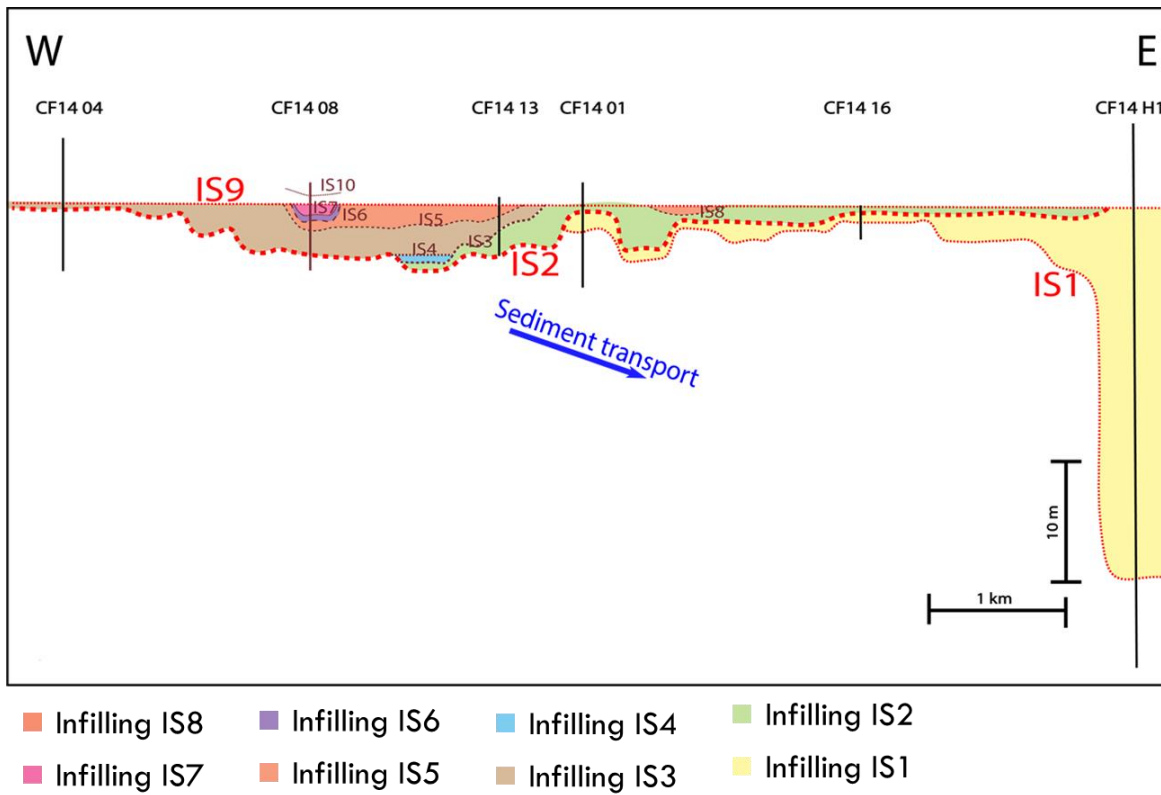


Figure 24. Illustration of the 10 incision surfaces and the infilling of IS1 to IS8 correlated along the section.



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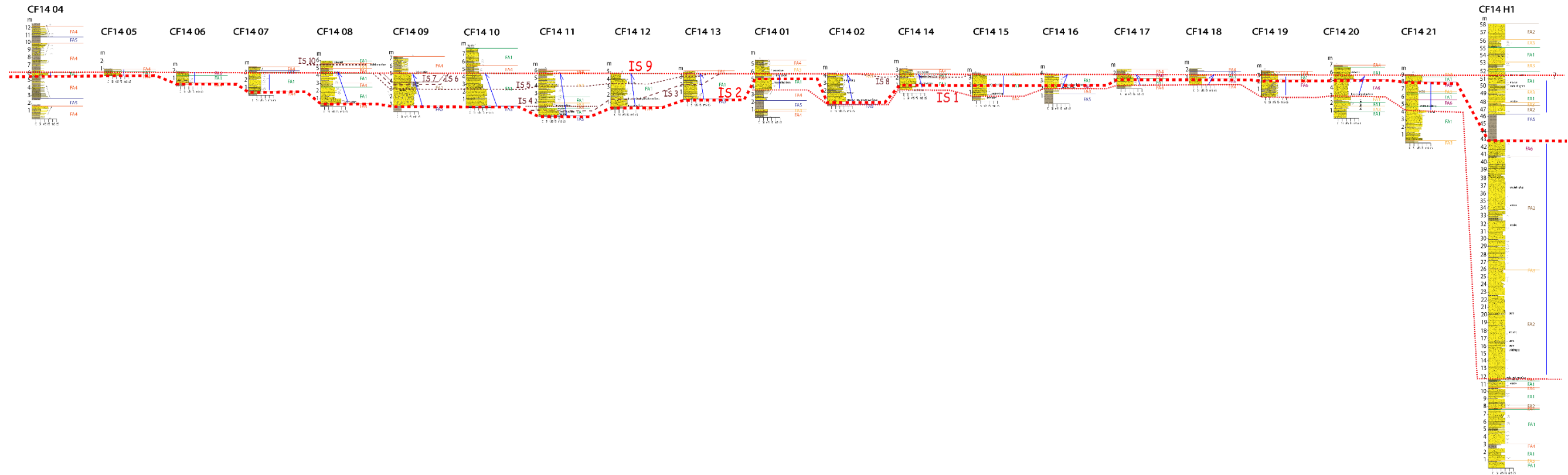


Figure 25. Sedimentary log correlation of the main incision surfaces, showing the changes of facies associations along the section and the thickness of the layers.

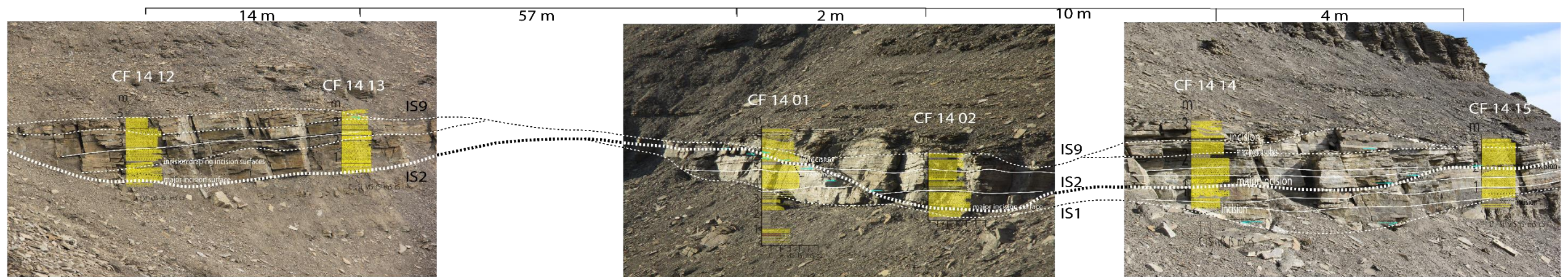


Figure 26. Photo-panel interpretation of the incision surfaces and the beds terminations observed in the outcrop. Note that the distances are no scaled and the logs are modified according to the photo-panel perspective.

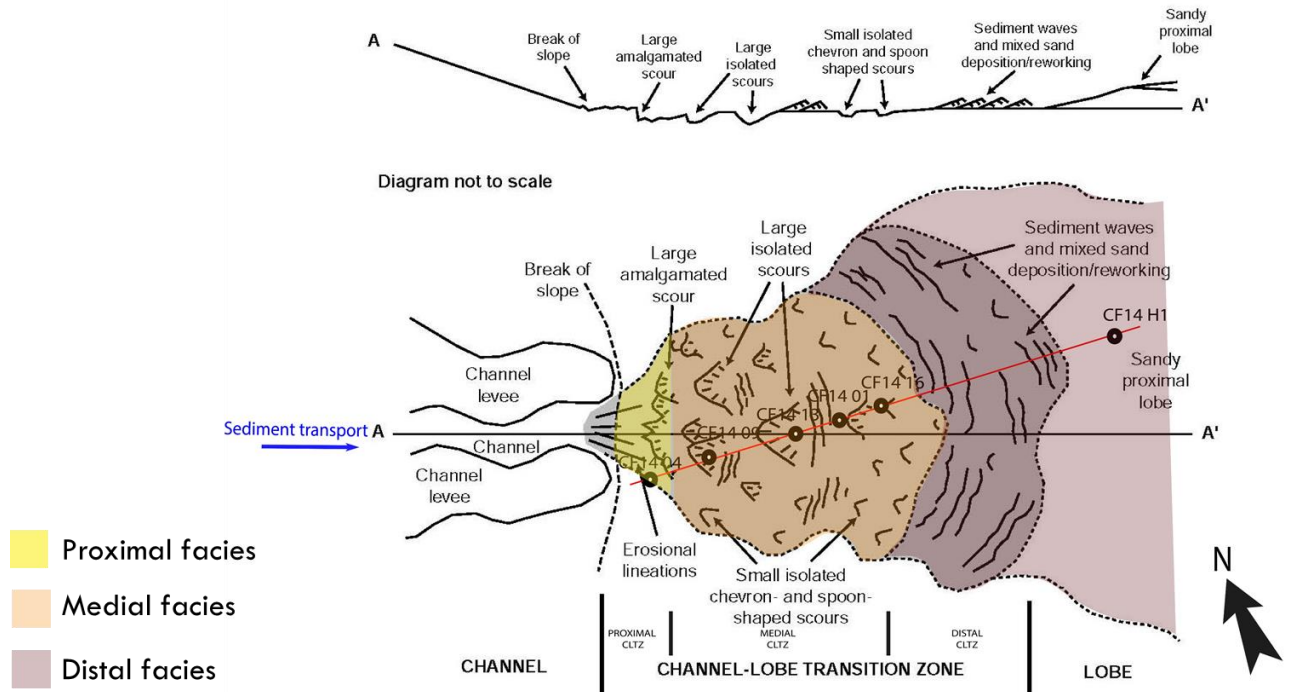
## 6. Discussion

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### 6.1. Sedimentary architecture

According to the logs and the photo-panel interpretation the base-of-slope onlap consists in several incision surfaces or scours which vary in length (Figure 28). These scours are filled with deposits of sandstones from fine to coarse grain, with abundance of rip-up mudstone clasts at the bottom, erosive or sharp bases, result of several events of turbidity currents. In the oblique log section, the thickness of this infill deposits varies from 0.5 m to 30 m from West to East respectively (Figure 28). The thicknesses of these packages are possibly the result of continuum erosion in the channel-lobe transition zone. Closer to the source in the proximal and medial zones the deposited layers experiment greater erosion and scouring in comparison with the distal facies. This is in accordance with the flow relaxation mechanism which explains the formation of scour fields in the CLTZ right after the loss of confinement or a break of slope (Pohl, 2019). The grain size tendency in the sandstones of the proximal facies is blocky pattern, the trend in the medial facies is mainly finning upwards and the distal trend is blocky pattern. The overall trend of the grain size in the logs is finning upwards which suggests a waning input of sand sediments and a possible abandonment of the system. The Figure 29 shows a representation of the logs position from proximal to distal with an aerial view of the Storvola slope.

The facies architecture described below was defined according to the observations made between the 3 major incision surfaces IS1, IS2 and IS9. The proximal, medial and distal architecture is based on the model from Wynn et al. (2002) of the channel-lobe transition zone (Figure 27).



**Figure 27. Model of scour field in the CLTZ selected for the interpretation of the facies association of this study. Modified from Wynn et al. (2002)**

- *The proximal facies*, interpreted as the proximal CLTZ are encountered in the logs from 04 to 07, is characterized by the facies associations of thin bedded amalgamated sandstones (FA1). Nearest to the sediment source at the West, in the logs 04 and 05, the tops and bases of the sandstone beds are wavy and the siltstones/mudstones facies are very rare. Basinwards, approaching to the middle CLTZ, in the logs 06 and 07, the packages of sands become thicker and the bases and tops tend to be sharp. An event of slumping (FA6) is observed in the log 06 where the thickness of the package starts to become greater from 0.5 m to 2 m. The thicknesses of this proximal zone increase gradually from 0.5 m to 3 m (Figure 25). A blocky grain size tendency is observed (Figure 28).
- *The medial facies*, interpreted as the medial CLTZ are encountered in the logs from 08 to 21, is characterized by the facies associations of slumps (FA6), thin bedded amalgamated sandstones (FA1), heterolithic beds (FA4) and thin bedded sandstones (FA3) with presence of coal clasts at the tops and mud clasts at the bases, sharp and erosive tops and bases, lenticular bedding, sandstones lenses embedded in mudstones/siltstones, bioturbation, ripples and sole marks. The presence of siltstones/mudstones beds is more frequent in comparison with the proximal facies. The medial CLTZ is the one that presents the major density of

incision surfaces, this are observed from the log 09 to the log 14. Isolated facies of thick bedded amalgamated sandstones are observed in the log 09 with abundance of floating clasts is observed, this thick sand overlap with the area where several minor incision surfaces (IS5, IS6 and IS7) are seen. Thicknesses are very variable along these middle facies. Closer to the West thicknesses start from 4 m (log 08) increasing gradually to 6 m (log 11) and decreasing to 2 m (log 01) towards the East. After this decrement the thickness increases slightly to 4 m (log 02) and decreases gradually to 1 m (log 18) finishing with a gradual increment of 5 m (log 21) thickness in the border with the distal facies. In the last decrement to increment of thickness from the log 16 to 21 several slump facies (FA6) are observed, bordered by two of the major incision surfaces (IS1 and IS2). The general trend of the grain size is finning upwards (Figure 28).

- *The distal facies* interpreted as the proximal lobe, near to the distal CLTZ, are present in the log H1 and are characterized by the facies associations of thick bedded amalgamated sandstones (FA2), thin bedded sandstones (FA3), thin bedded amalgamated sandstones (FA1). With presence of ripples, sole marks and coal clasts at the top of the beds. The presence of mud clasts at the bases of the beds is very sporadic. Erosive bases and undulating tops are less frequent too. An event of slumping (FA6) is observed down the major incision surface IS2, just as the slump events observed in the medial CLTZ. A thick isolated event of siltstones and mudstones (FA5) is observed right after the slump event on top of the IS2. The distal zone is the one that presents the greater thicknesses of the three sub-environments, given mainly by the presence of the thick bedded amalgamated sandstones (FA2). An abrupt increment of thickness from 5 m (log 21, medial CLTZ) to 39 m (log H1) is observed. Blocky trend of grain sizes is observed (Figure 28).



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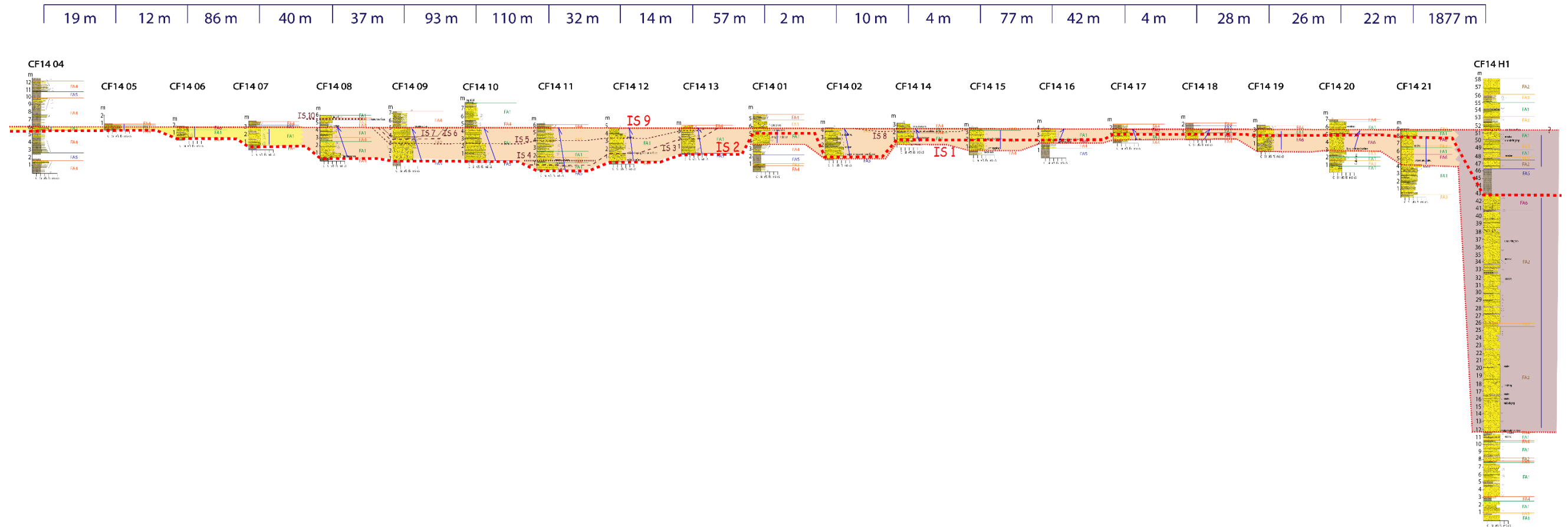


Figure 28. Stratigraphic correlation showing the proximal (yellow), medial (orange) and distal (purple) facies with the facies associations.

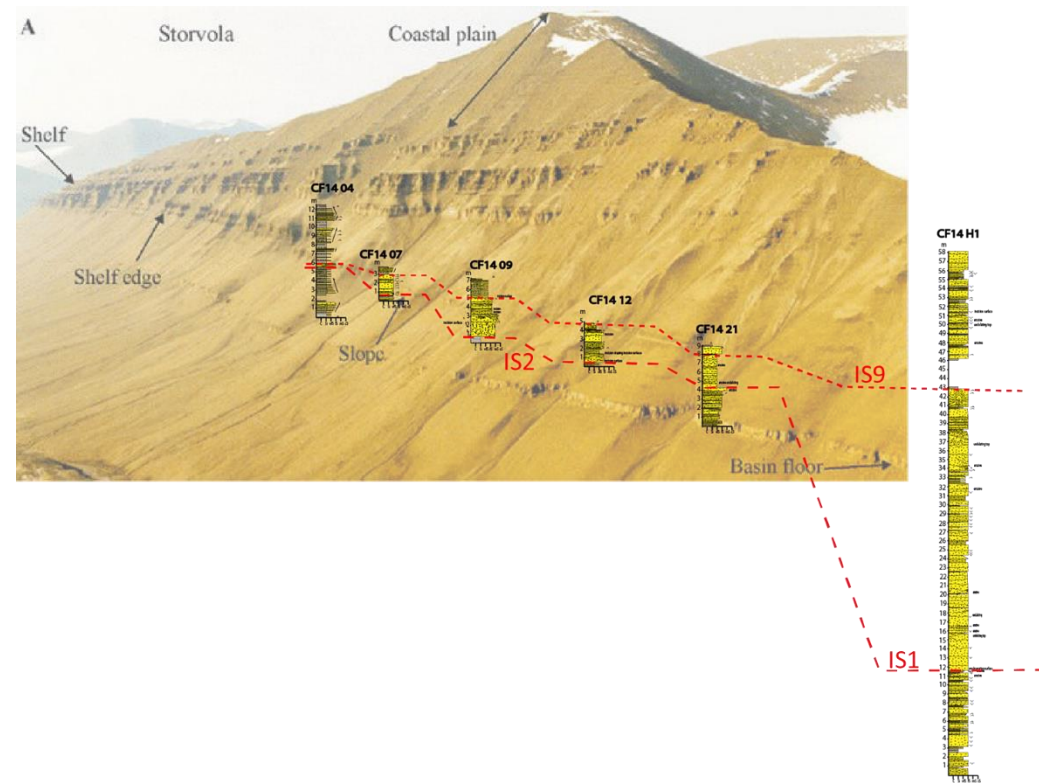


Figure 29. Representation of the base of slope of the Clinoform 14 with the aerial image of Storvola with the logs overlapping. Note that for reasons of visualization the IS1 and IS2 are drawn as one incision and that the position of the logs are not in the correct coordinates. Modified from (Plink-Björklund, 2005).

## 6.2. Facies model

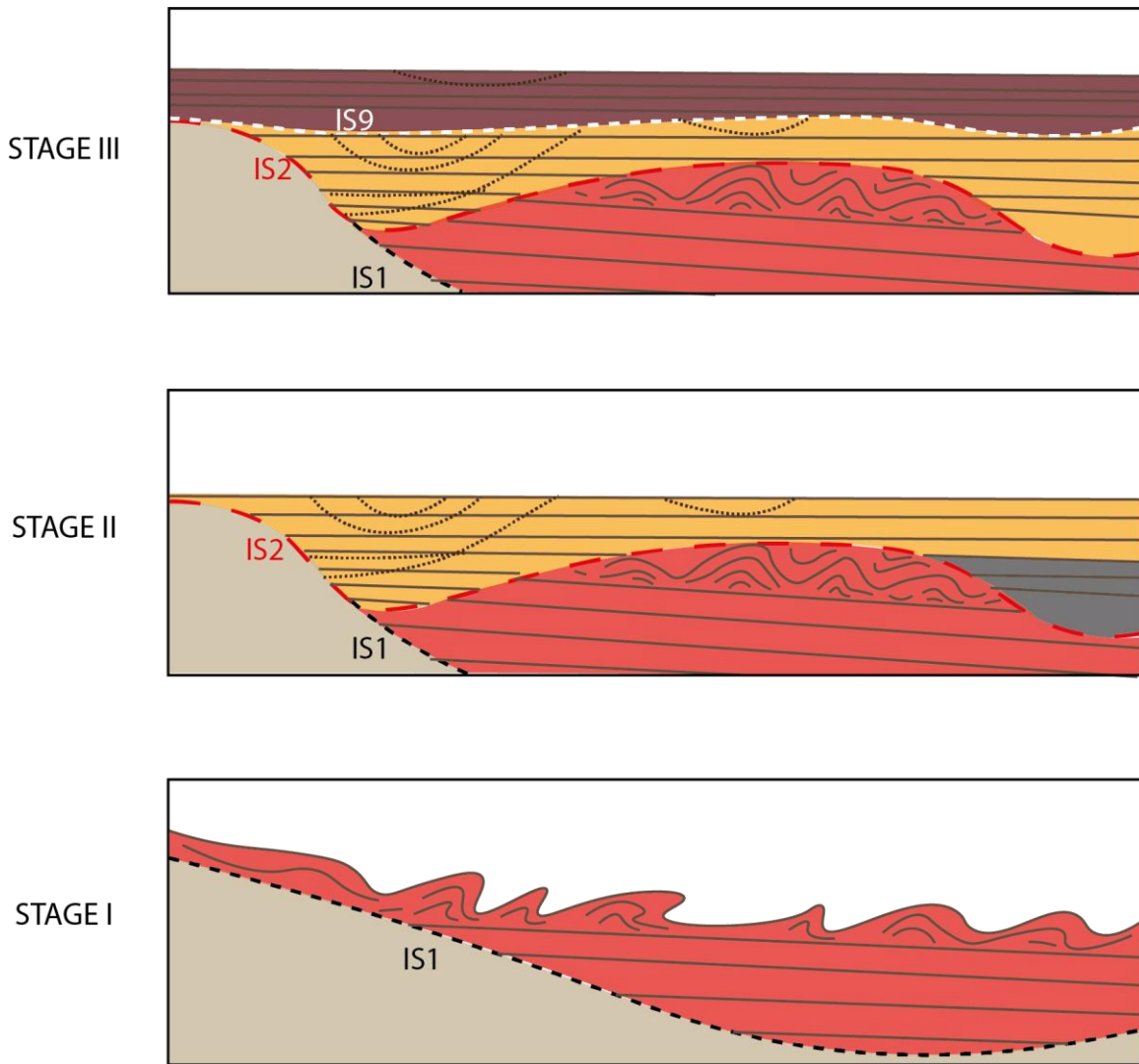
The model interpretation will be from the major oldest incision (IS1) observed to the major youngest incision (IS9), where the main action of the turbidity system is observed and the morphology of the base-of-slope pinch-out is recognized.

A possible model for the base-of-slope onlap in the channel-lobe transition zone resulting from the interpretation of the logs and photo-panels is compound by 3 main stages of scouring and deposition marked by the three major and regional incision surfaces: IS1, IS2 and IS9 (Figure 30).

- *The first stage* of scouring IS1 was correlated in the logs 01 to H1, part of the medial and distal area of the system. This incision surface is cutting through basal facies of mainly heterolithic units (FA4) with siltstone and mudstone facies (FA5). Except for the logs nearest to the East where the basal facies are more sandstone rich (FA1, FA3 and FA4). On top of this incision surface two events happen, the first one is the deposition of sediments in the medial and distal areas and the second one is the cut through of the IS2 resulting in the truncation of the IS1 in the proximal and medial areas. It is unknown if the IS1 existed in the proximal areas and then was cut by the IS2 or merged with the IS2 after another episode of scouring. In the event of deposition after IS1, the facies associations filling this scour are thin bedded amalgamated sandstones (FA1) and slumps in the middle area (FA6) changing to thick bedded amalgamated sandstones (FA2), thin bedded sandstones (F3) and slumps (FA6) in the distal area. The greatest thickness observed in the log H1 was deposited after this incision surface 1 and a main characteristic of the top of the deposition event of this phase is the slumping underlying the IS2. A possible interpretation of this episode of slumping is that the relief created after the scouring of the CLTZ provoked an instability on the slope and the deposition of this facies (Figure 30).
- *The second stage* of scouring IS2 was correlated along the logs 04 to 21 part of the proximal and middle facies. This incision surface 2 is cutting through the IS1 and in overlying the slump deposits. The filling facies of this incision surface 2 are thin bedded amalgamated sandstones (FA1) in the proximal logs and a intercalation of FA1, thin bedded sandstones (F3) and heterolithic beds (FA4) in the middle and distal areas. An isolated slump (F6) is seen in the log 17 in the medial CLTZ as well

as an isolated event of siltstones and mudstones (F5) in the log H1 in the proximal lobe. The thickness of the deposits become greater in the beginning of the middle CLTZ from the log 08 to 13, then the thickness reduces considerably from the log 14 to the 21, finally, the thickness increases towards the distal log H1. An interpretation of this period of time is that when the scouring of the IS2 occurred it created a deeper relief in the western middle zone of the profile, which resulted in the deposition of thin bedded and thin bedded amalgamated sandstones in this catchment area (Macdonald et al., 2011). During the infilling of the proximal-medial part of the IS2, smaller scouring phases took place in the deeper side of the IS2. These smaller incisions (IS3 to IS8) were filled with the same facies association as the major incision surface 2. These two events explain why the distal CLTZ was greatly filled by mudstones and siltstones during this period of time. After the deeper side of the IS2 got filled with sediments, the sandstones were able to reach the distal parts of the system to fill the incision surface 2 (Figure 30).

- *The third stage* of the system comprehends the scouring of the IS9, which was correlated all along the profile throughout all the logs. The infilling of this event is comprised by heterolithic units (FA4) with siltstones and mudstones (F5) in the proximal areas. Thin bedded amalgamated sandstones (FA1) with FA4 in the middle CLTZ and FA1 with thin bedded sandstones (FA3) and thick bedded amalgamated sandstones (FA2) in the distal CLTZ. A smaller scour occurred during this phase in the beginning of the middle area. The grain size of these deposits of this last phase are becoming finer with higher intercalation of siltstones and mudstones. Possible interpretations of this latest phase is a waning of the sediment input or the possible transition to the abandonment of the turbidity system in the area (Figure 30).



**Figure 30. Schematization of the evolution of the three main scouring or incision surfaces stages of the facies model.**

### 6.3. Reservoir trap analog

It is known that base-of-slope pinch-outs are stratigraphic traps with reservoir potential (Amy, 2019). Although there have been commercial discoveries in up-dip pinch-outs, the lack of high-resolution image impacts on the efforts of de-risking the possible geological risks encountered in base-of-slope onlaps (Amy, 2019). Mainly the seal capacity and the trap efficiency are the factors of risk of these kind of stratigraphic structures (Amy et al., 2000; Pohl et al., 2020). Therefore, a detailed analysis of the facies that comprise these potential reservoirs is important to approach the challenges for the prospection of these traps.



The base-of-slope onlap analyzed in this study can be positioned in the classification of traps given by (Amy, 2019) (Figure 6) as an erosional pinch-out trap with no associated fault. Whereas the pinch-out classification from Mccaffrey & Kneller (2001) is for oblique frontal slopes, there is a correlation with the geometry type B where erosion between thick bedded sandstones is what characterize these geometries. The difference is that these type B geometries thicken towards the confining slope, whereas the architecture of the clinoform 14 is thinning towards the confinement. To place the base-of-slope onlap of CF14 in the classification given by Pohl et al. (2020) is necessary to consider the analysis of facies from the shelf edge to the base-of-slope to observe the connection of events and facies variations. Thus, this information is not included in this study, the geometry of the proximal facies of the base-of-slope suggests that this pattern is similar to the slope-detached sedimentation, due to the thinning of the bedded sandstones unit towards the confining slope. To confirm this observation further studies in the CF14 can be run.

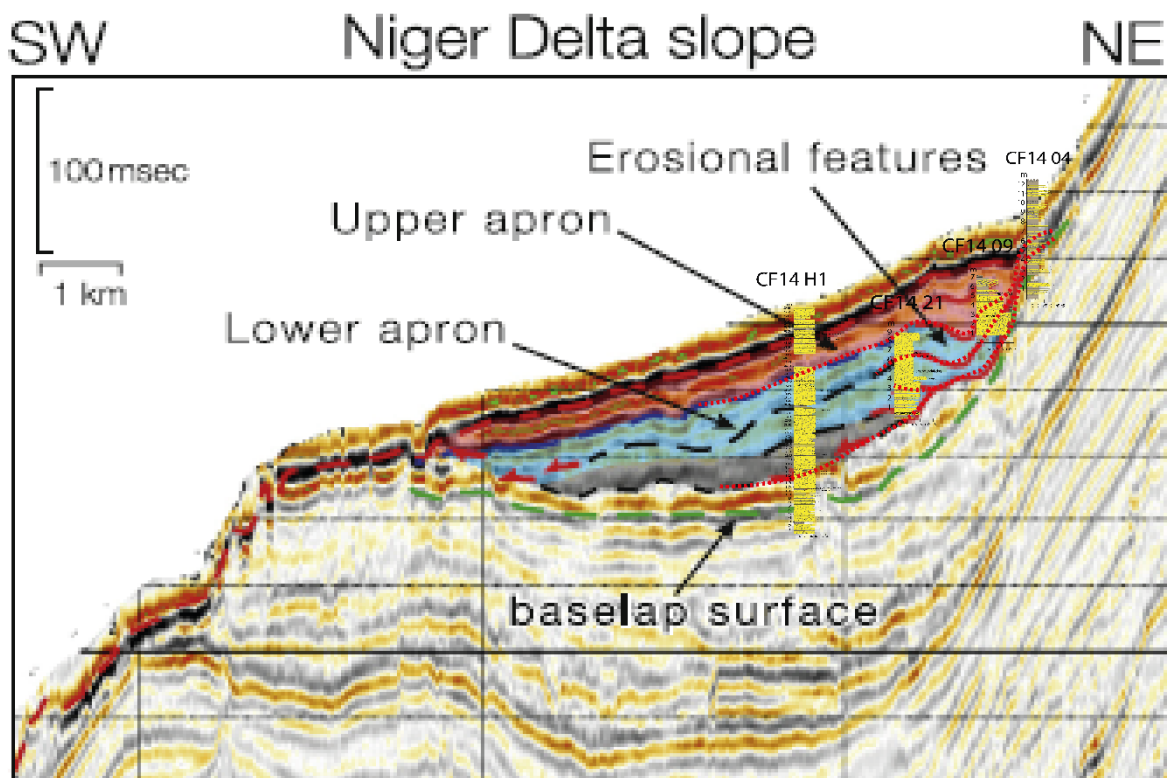
The architecture revealed from this study shows that up-slope pinch-outs are rich in bedded sandstones, mainly amalgamated and sporadically interbedded with siltstones and mudstones. Meaning that the reservoir rock is clearly existent in the system. The areas with thicker amalgamation of sandstone beds are part of the proximal lobe (Figure 25 and Figure 31) and can act as good oil and gas repositories.

The main concerns about this base-of-slope onlap traps is the lateral and vertical sealings and the trap closure. As mentioned by Amy (2019) the base-of-slope systems are propense to present erosion, this is confirmed with the presence of incision surfaces all along the log profile in CF14. These incision surfaces can behave as paths of secondary migration for the hydrocarbons, therefore compromising the efficiency of the lateral sealing. Lateral sealings can occur when there is a juxtaposition between seal rocks (mudstones and siltstones) and sandstones in the incision surfaces. Such deposits are possible based on the observation of the second stage of deposition (Figure 30) in the facies model for CF14, where a thick layer of siltstones with mudstones was identified in the log H1. Macdonald et al. (2011) also observed that some scours are filled by thick muds.

In distal areas of the system the presence of thin bedded siltstones and mudstones interbedding with thick bedded sandstones confirm the presence of top seals. The risk of trap closure occurs in the lateral connectivity of the sandstones towards the proximal higher areas of the system.

Amy (2019), Mccaffrey & Kneller (2001), Pohl et al. (2020) agree in the presence of thief sandstones at the proximal facies of the system, resulting in the risk of oil or gas leakage. This is confirmed by the presence of heterolithic beds in the proximal facies. Whereas the mudstone and siltstone facies of this heterolithic beds can behave as efficient top seals, the presence of thin bedded sandstones are a risk for the lateral displacement of hydrocarbons, compromising the closure of the stratigraphic trap.

For a better understanding of the trap closure risks given by the thief sands likely present in the higher systems connected with the base-of-slope, it is recommended for future work to perform an analysis of the behavior of the facies variations between the shelf and the base-of-slope.



**Figure 31. Illustration of a base-of-slope-detached sedimentation in a seismic section showing how the architecture of the interpreted logs would fit in a seismic model. In red dotted lines is the correlation of the incision surfaces interpreted in the field logs and their correlation with the interpretation of the seismic image from proximal to distal facies. (Logs do not present the same vertical scale for image purposes) Modified from (Prather et al., 2012).**

## 7. Conclusions

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Sub-seismic analysis of the Cliniform 14 using outcrops images and field sedimentary logs gave new insights about the architecture of the base-of-slope onlap.

The base-of-slope onlap architecture at Svalbard consists in several incision surfaces or scours with different lengths. This suggests that the sedimentary environment in a scour field in the Channel-Lobe Transition Zone, an area known by its constant erosion, by-pass and deposition (Macdonald et al., 2011; Pohl, 2019). The proximal area of the CLTZ is characterized by the facies associations of thin-bedded amalgamated sandstones (FA1) with grain sizes from very fine to coarse, with erosive bases and tops. The medial area of the CLTZ is characterized by the facies associations of thin bedded amalgamated sandstones (FA1), thin bedded sandstones (FA3), heterolithic beds (FA4) and sporadic thick-bedded amalgamated thick bedded sandstones (FA5) and slumps (FA6). Next the distal CLTZ are the distal facies of the proximal lobe which are characterized by the facies associations of thick bedded amalgamated sandstones and these facies present the greatest thickness of the system.

The facies model proposed consists in 3 main stages of scouring and deposition, marked by the presence of 3 major incision surfaces (IS1, IS2 and IS9).

- ❑ Stage I – Compound by the major incision surface IS1 and infill by the thick-bedded amalgamated sandstones (FA2) identified in the distal log H1. A phase of slumping (FA6) is observed at the end of this stage
- ❑ Stage II – Occurs with the scouring of the second major incision surface IS2 and it is filled by mainly thin bedded amalgamated sandstones (FA1) and thin bedded sandstones facies (FA3). This stage is defined by several periods of minor scouring.
- ❑ Stage III – Compound by the third major incision surface IS9 which is filled by mostly heterolithic beds (FA4), thin bedded sandstones (FA3) and siltstones with mudstones (FA5). In this stage a possible waning of the input is interpreted.

The characterization of the architecture of a base-of-slope onlap confirms the expected risks for sealing and trap closure, such as the presence of thin bedded sandstones in the higher areas of the up-dip pinch-outs and the presence of incision surfaces, both features can act as pathways of hydrocarbon secondary migration. Whereas top seal is present all along the system, the lateral seal and the closure of the trap are the main factors of risk of this kind of stratigraphic traps. Lateral sealing can occur when thick fillings of siltstones with mudstones

take place in the system, resulting in the juxtaposition of seal rocks with sandstone facies. The presence of reservoir rock is in the whole profile of the base-of-slope but further analysis about the connectivity of the thief sands with higher systems (shelf margin) can be done to comprehend better the behavior of this facies and de-risk this kind of stratigraphic traps.

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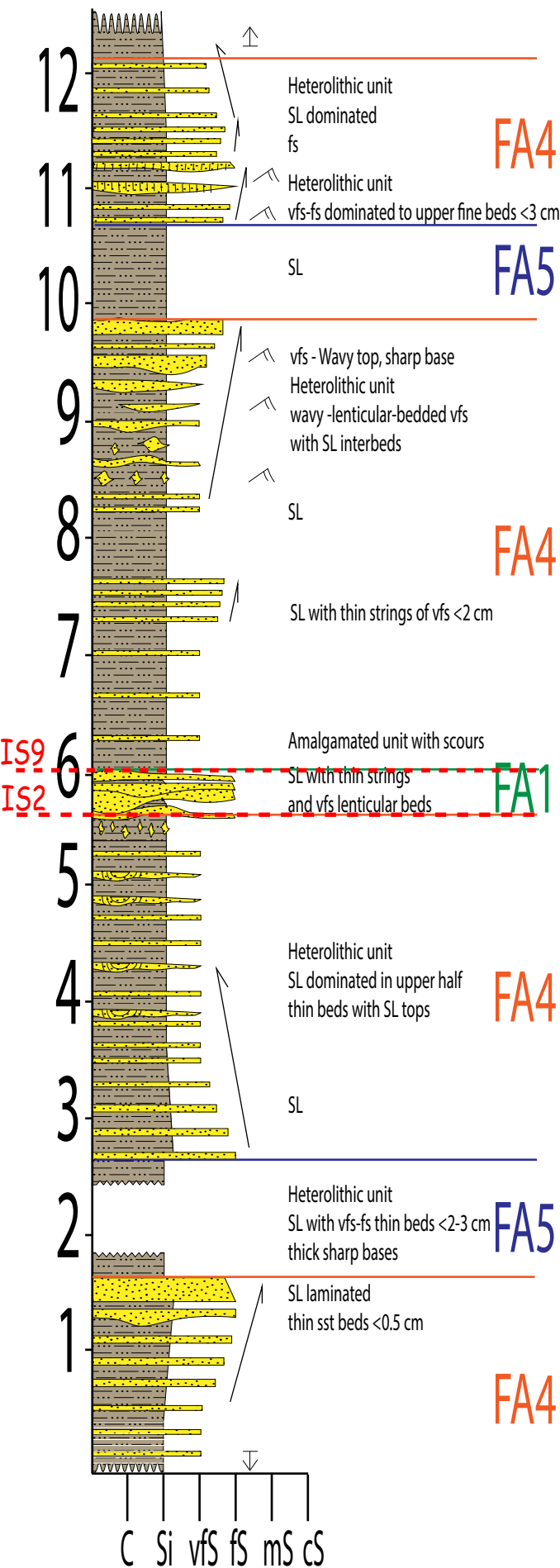
## 10. Appendix

### 10.1. Digitized logs and photo-panels

SYMBOLOLOGY					
	Siltstone		Coal dust		Slope shale above
	Sandstone		Mud chips		Slope shale below
	Shale		Sand lenses		Ripples
	Red siltstone		Shale chunks		Flutes
	Parallel lamination				Incision surface
					Cross lamination
					Deformation or slumps
					Beginning or ending of the log

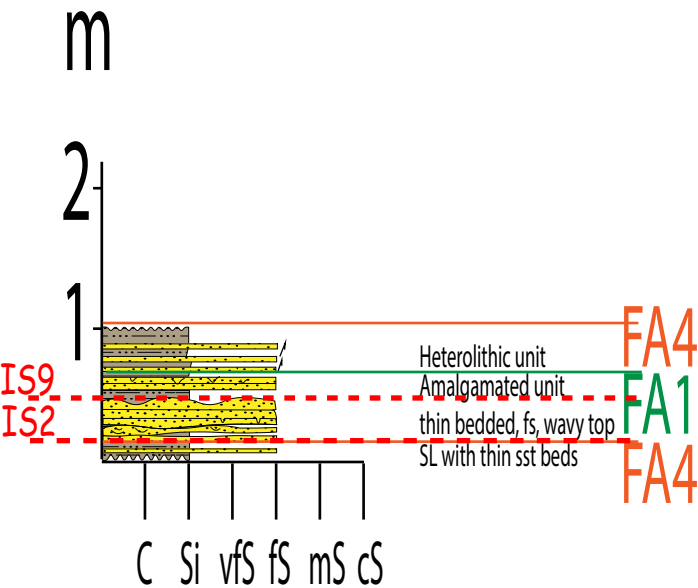
# CF14 04

m

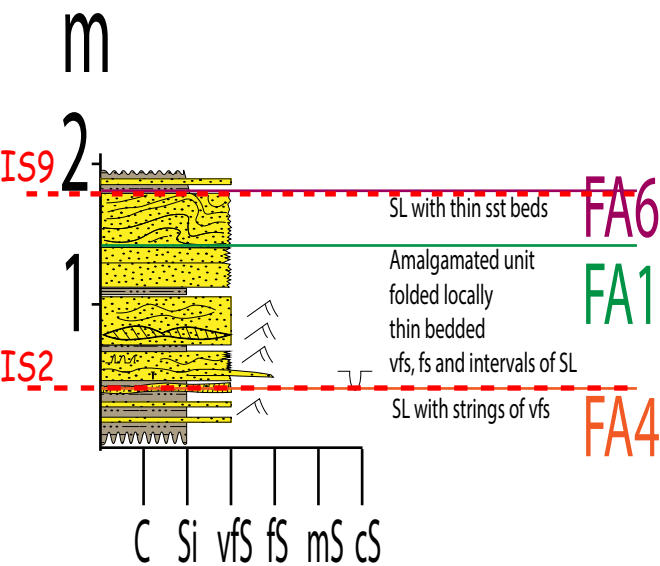




# CF14 05

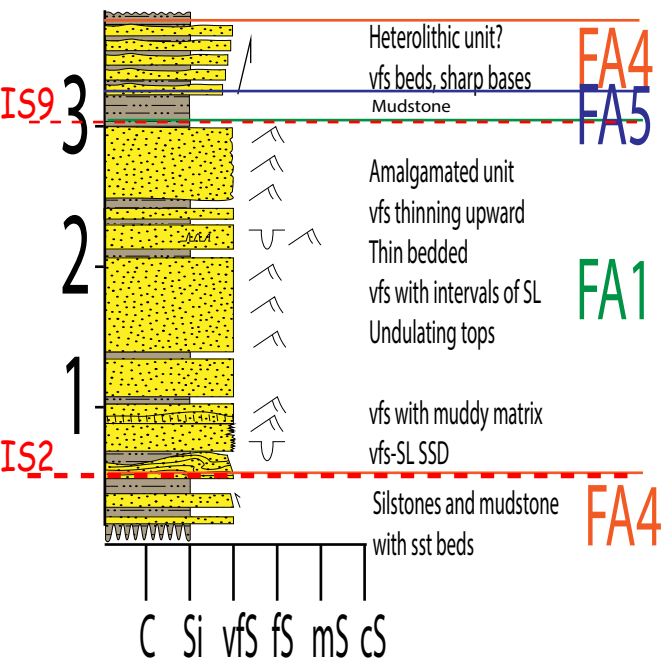


# CF14 06

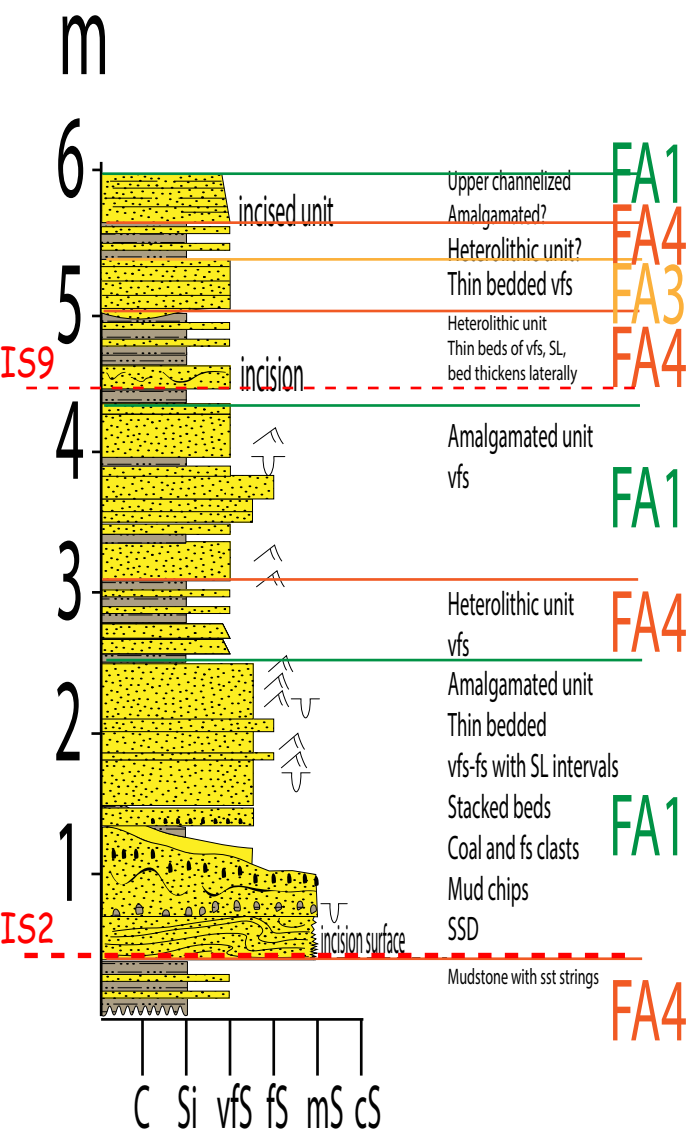


# CF14 07

m

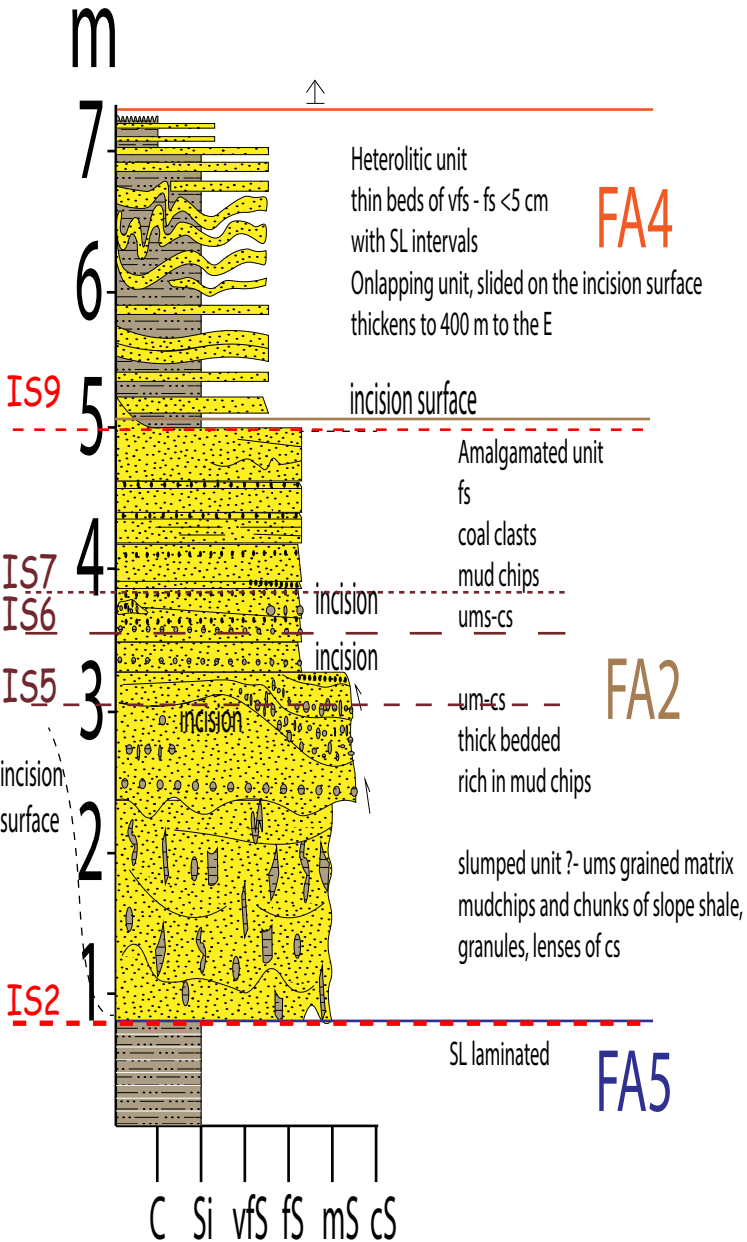


# CF14 08

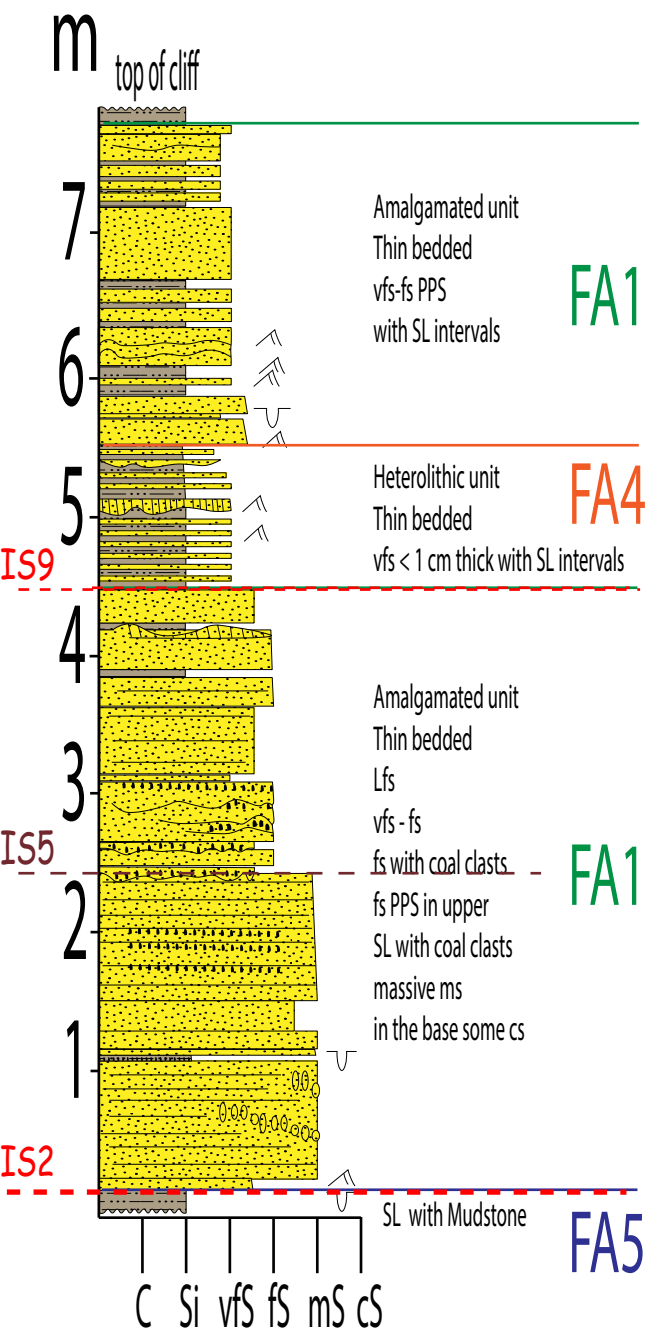




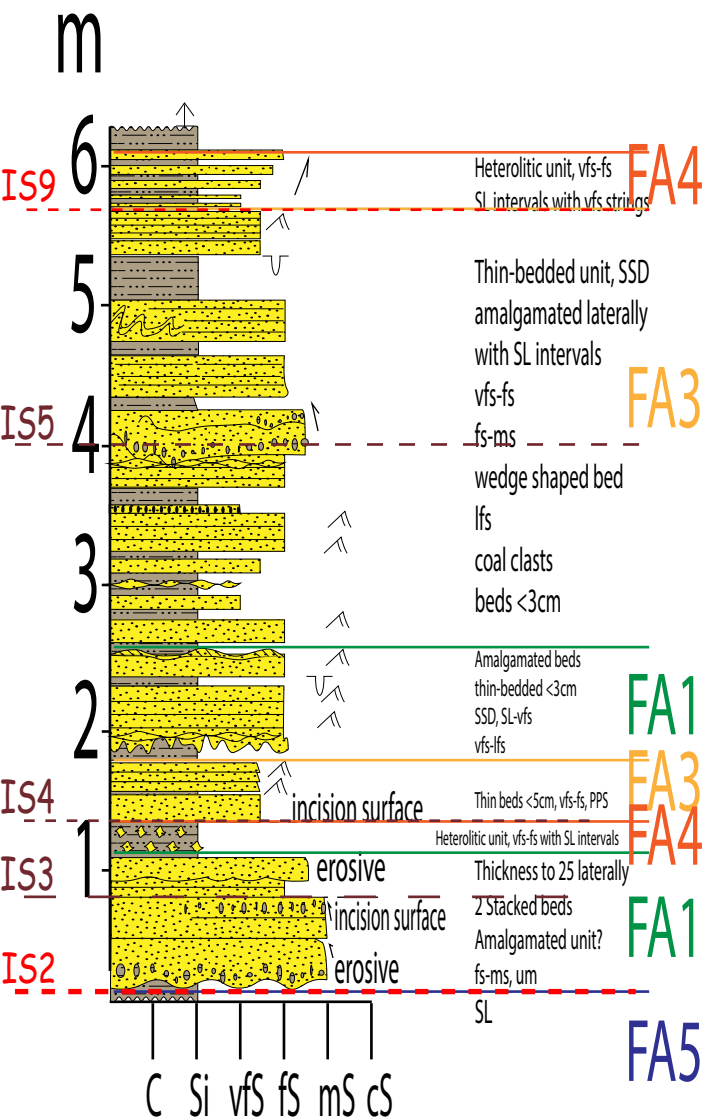
# CF14 09



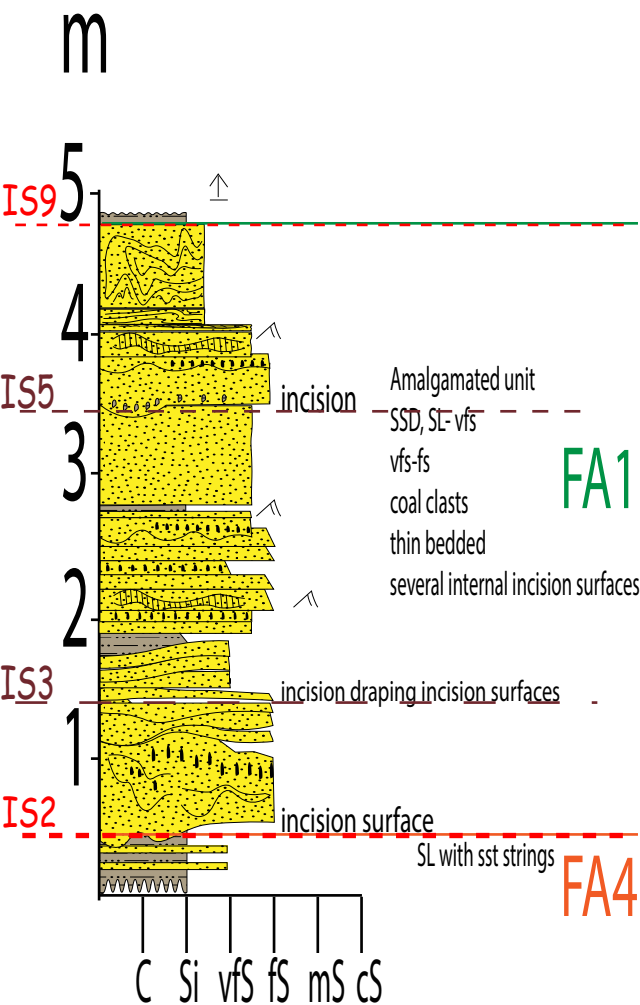
# CF14 10



# CF14 11

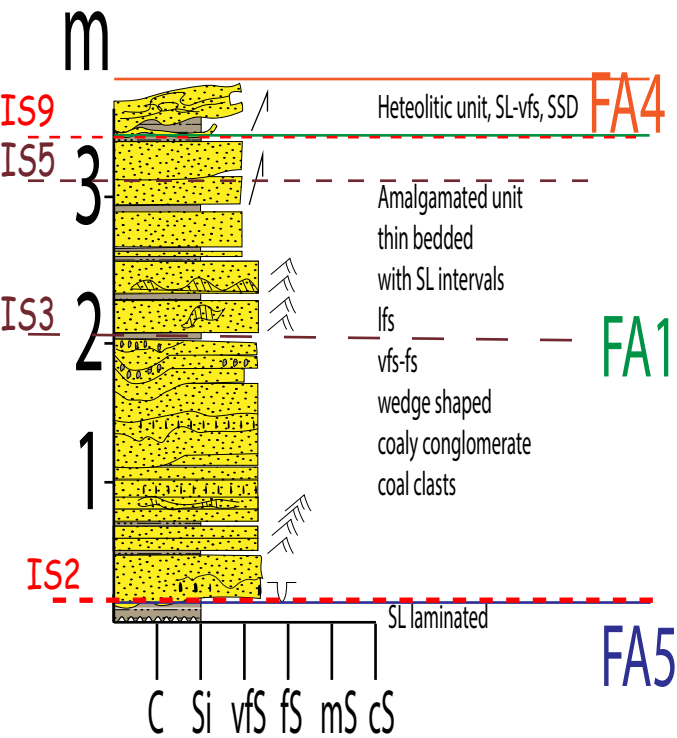


# CF14 12



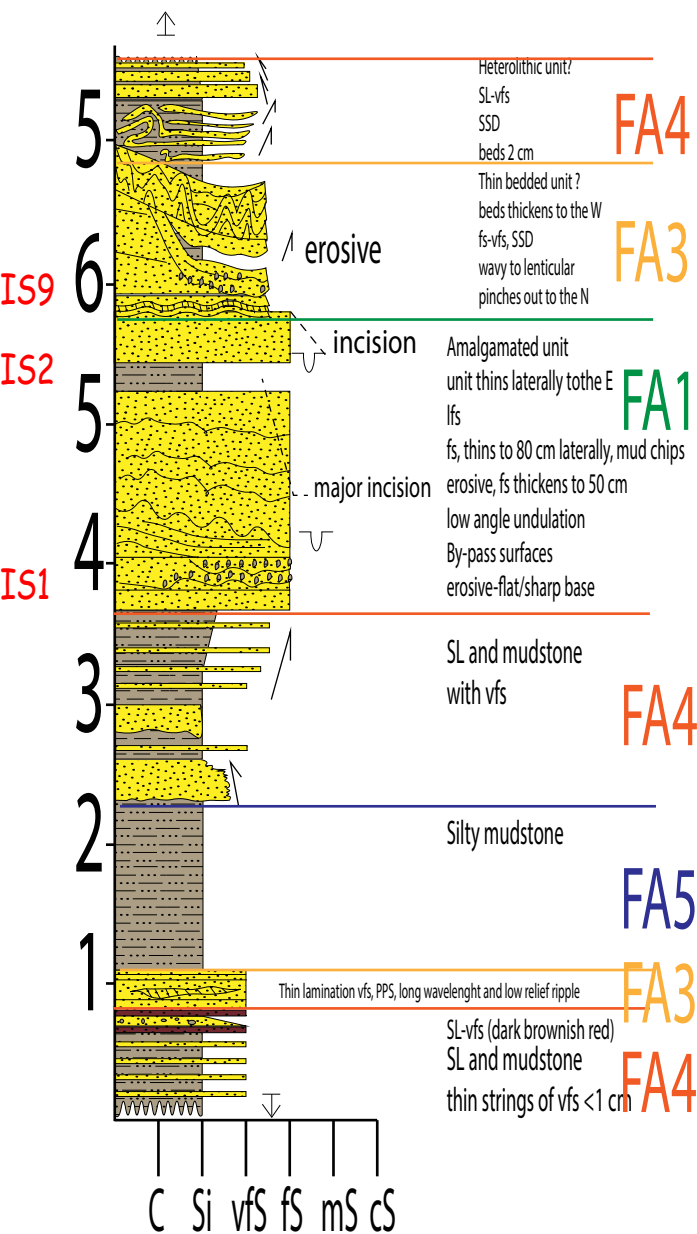


# CF14 13

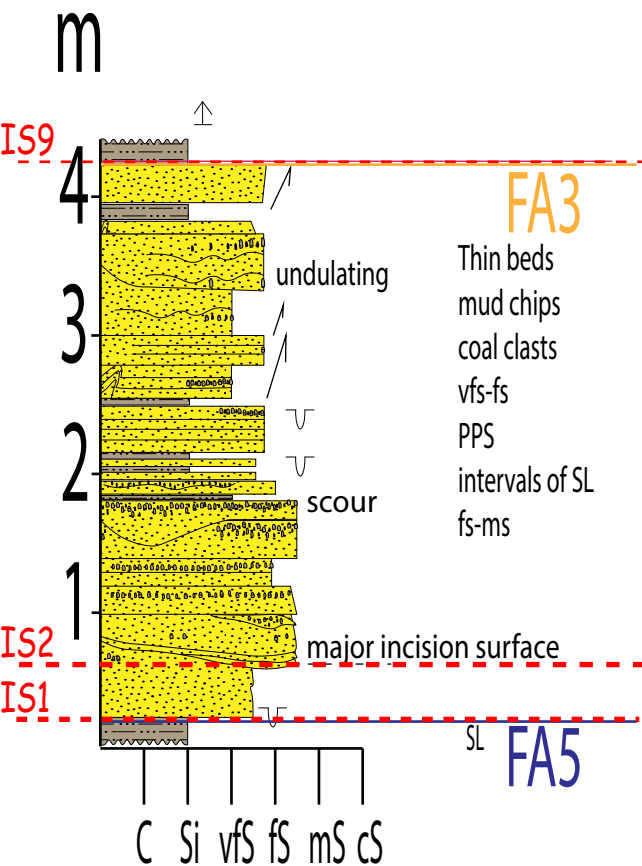


# CF14 01

m

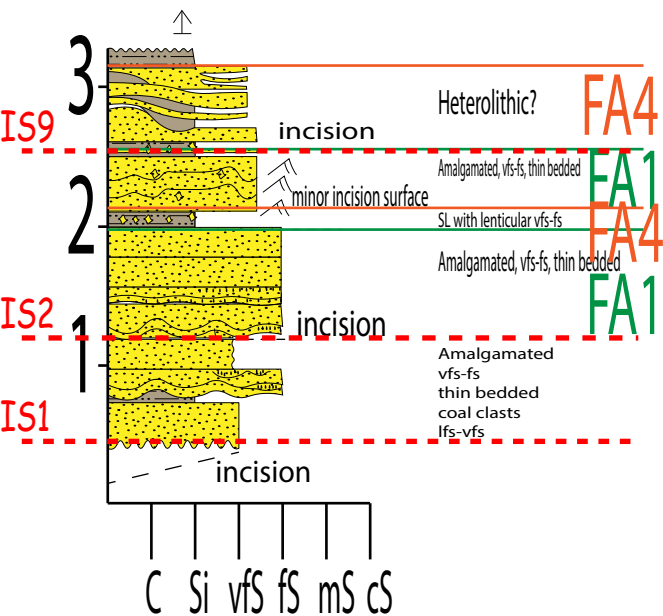


# CF14 02

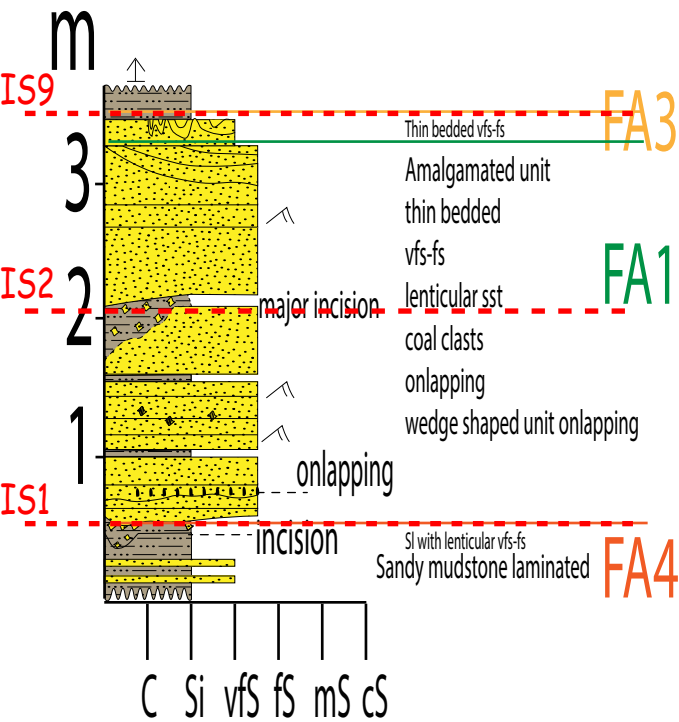


# CF14 14

m

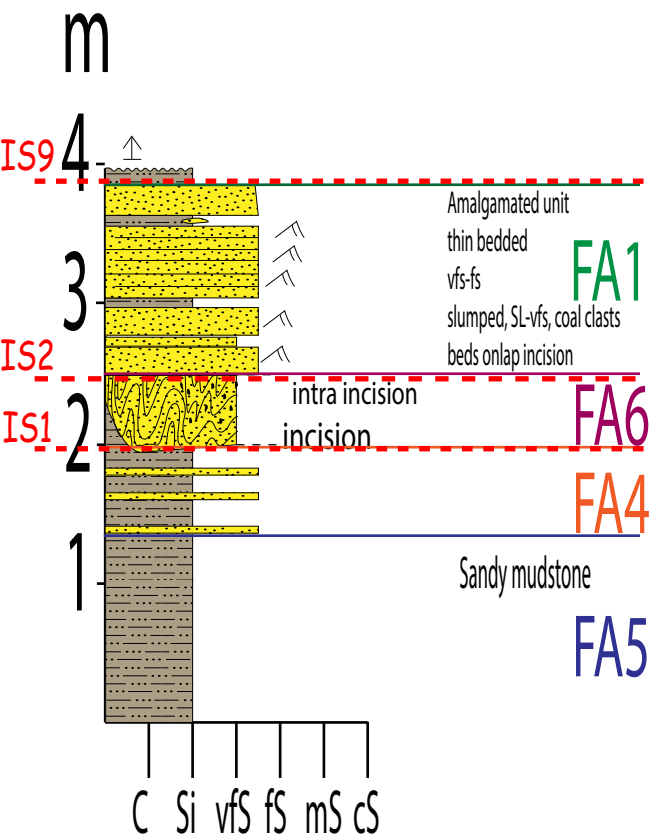


# CF14 15

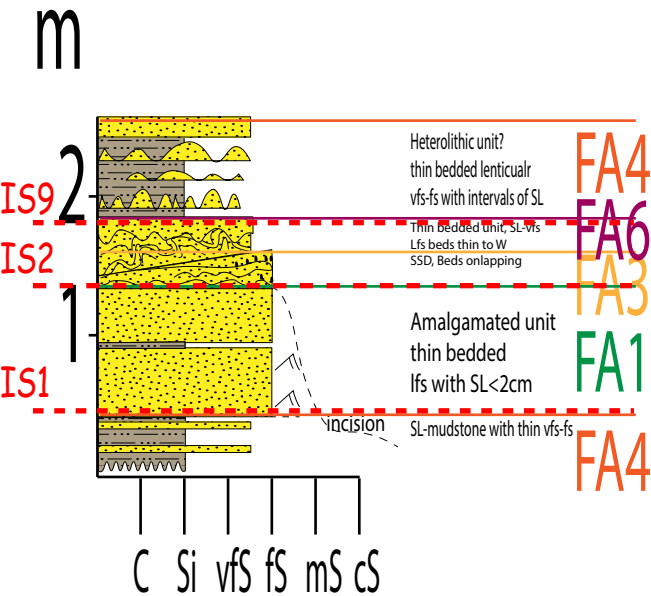




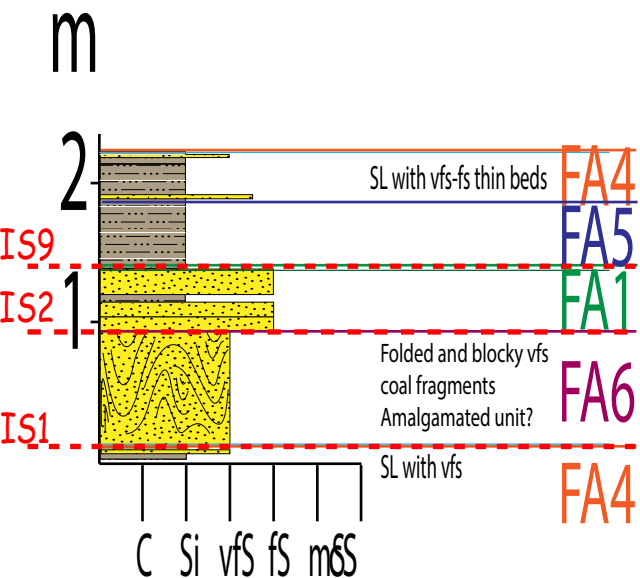
# CF14 16



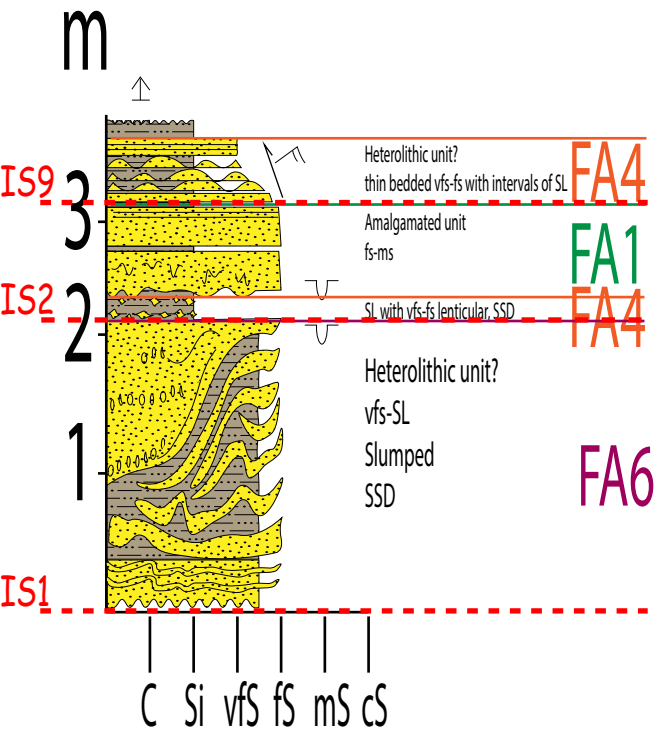
# CF14 17



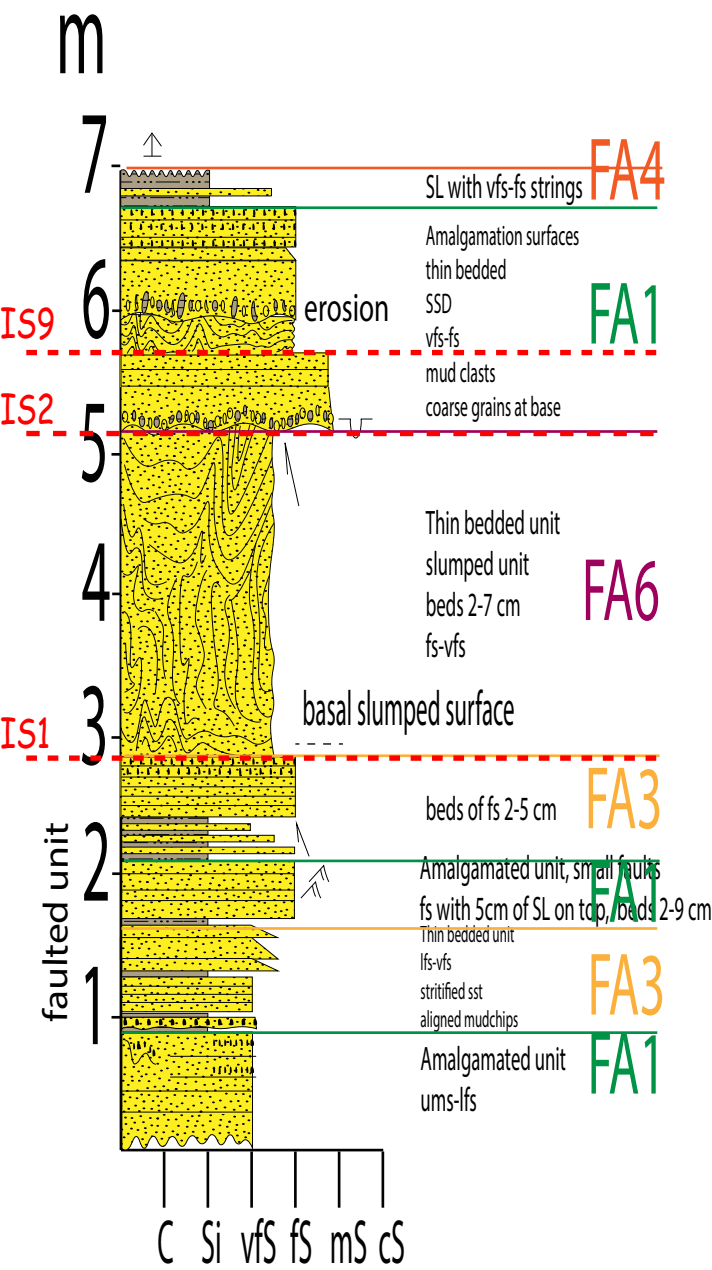
# CF14 18



# CF14 19

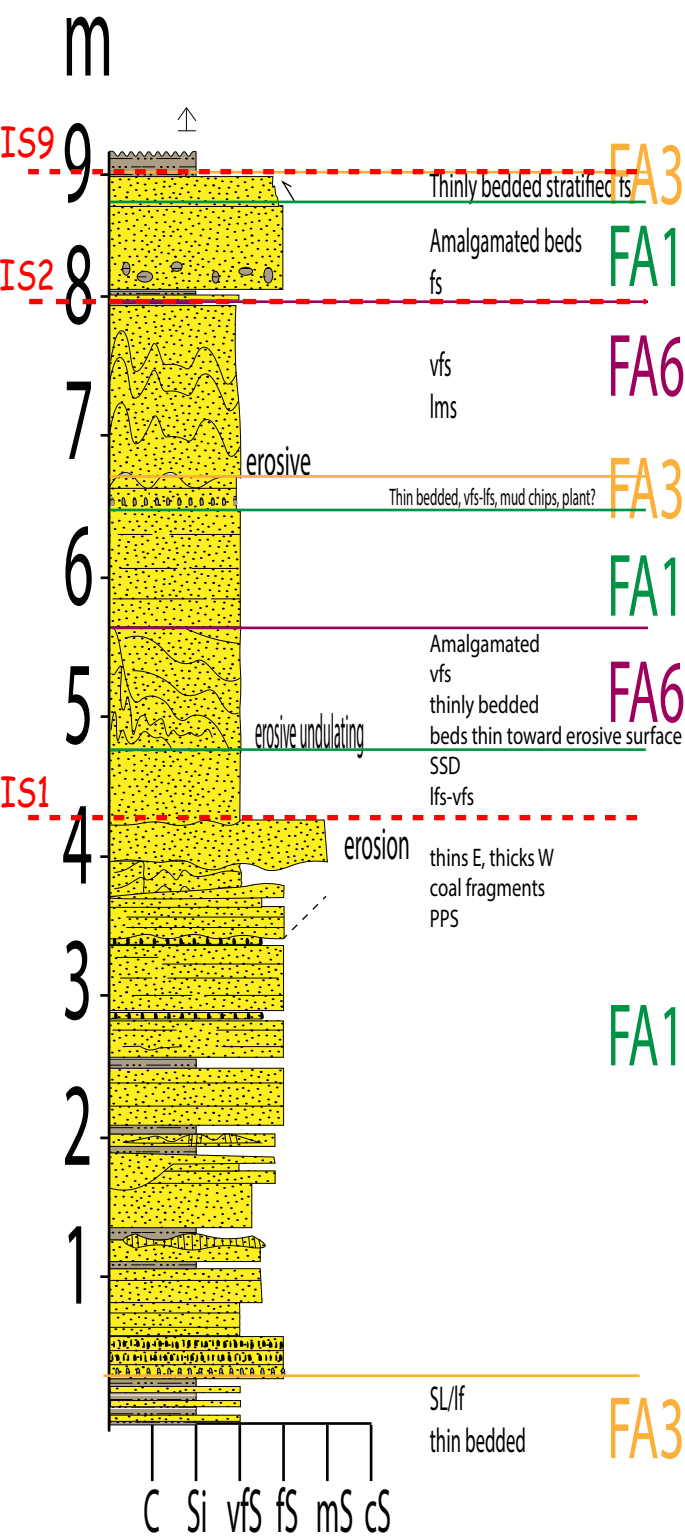


# CF14 20

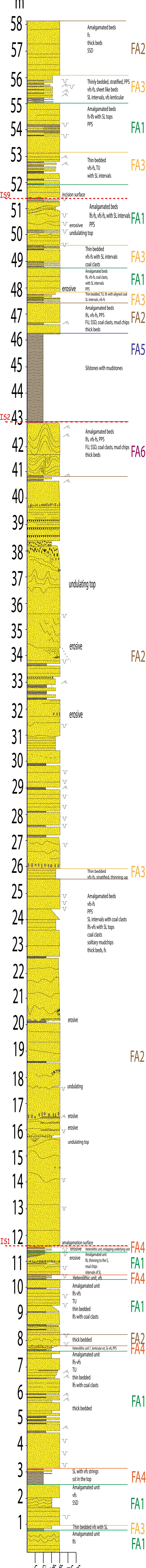




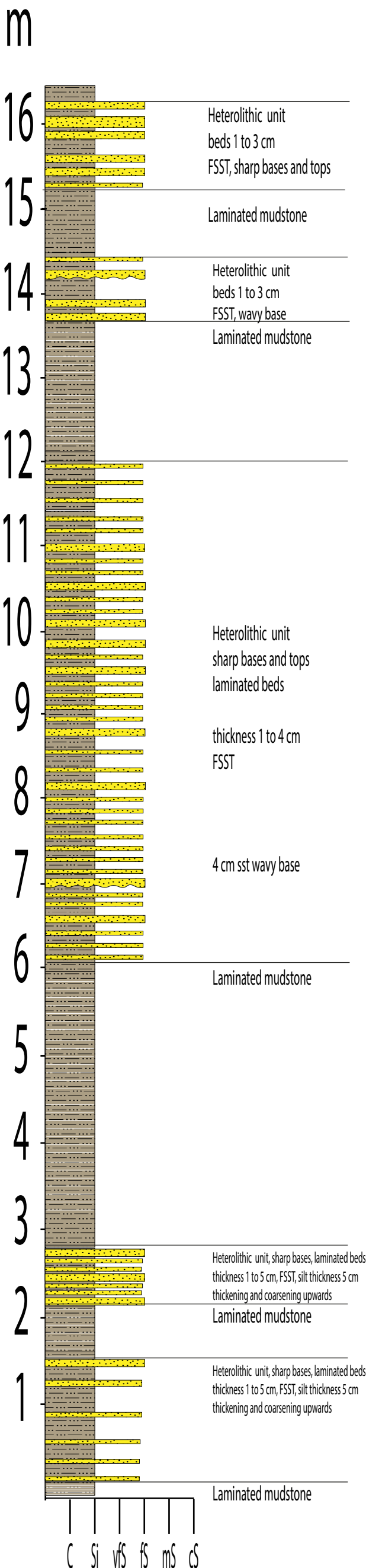
# CF14 21



# CF14 H1



# CF14 03





14 m

CF 14 12

CF 14 13

m

m

5

3

4

2

3

1

2

1

IS9

IS2

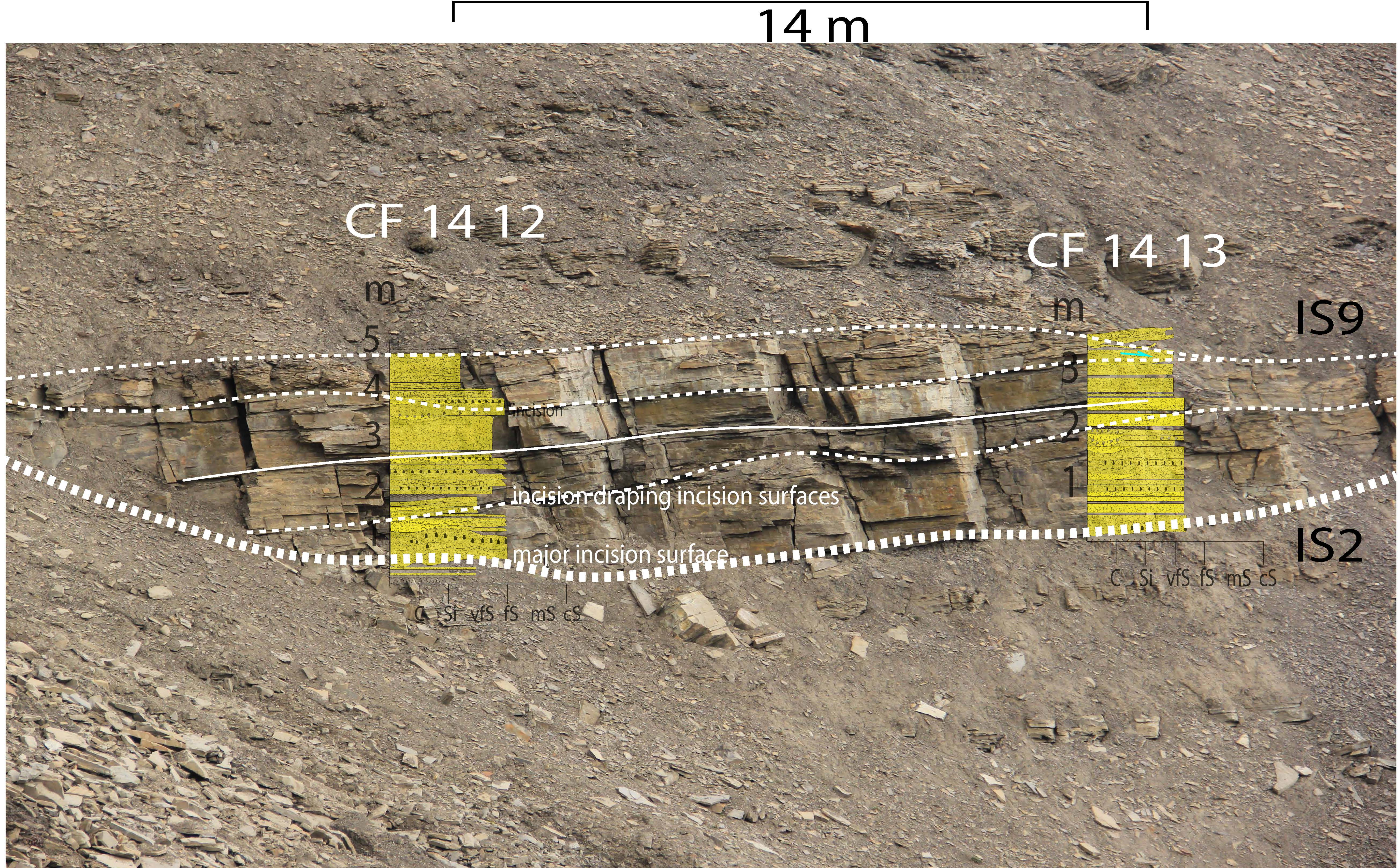
incision

incision-draping incision surfaces

major incision surface

C SI vFS FS mS cS

C SI vFS FS mS cS

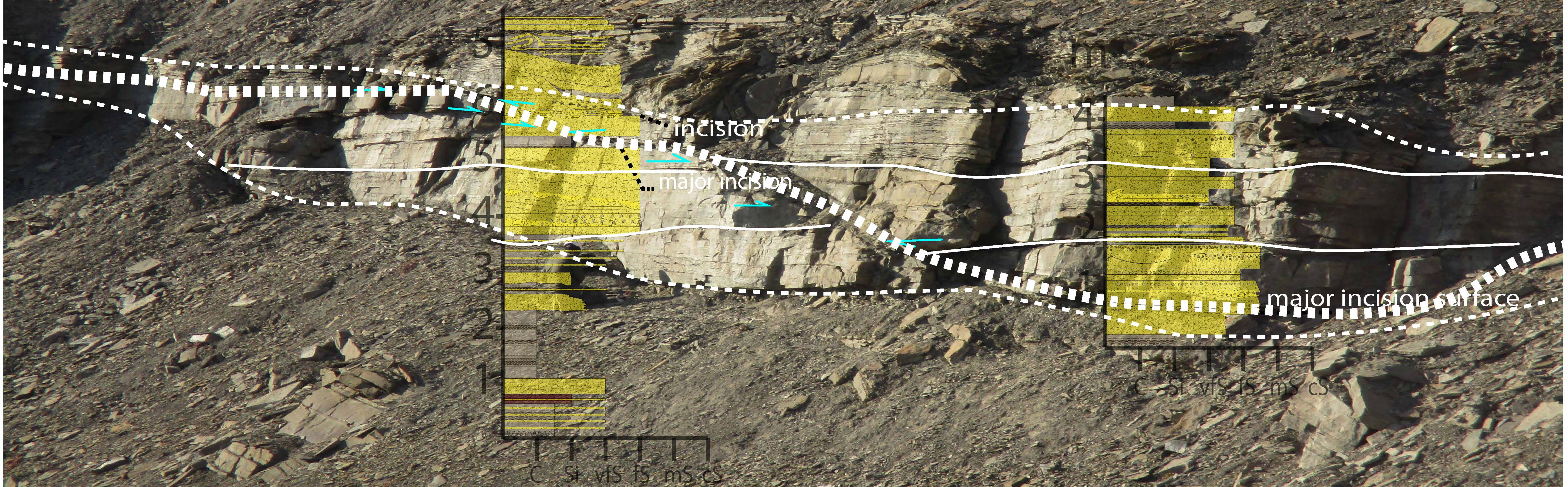




2 m

CF 14 01

CF 14 02





4 m

CF 14 14

m

3

incision

2

minor incision surface

1

major incision

incision

C Si vfs fs mS cS

CF 14 15

m

3

major incision

2

1

incision

C Si vfs fs mS cS

