University Centre in Svalbard

AG-349-849: Geological Constraints on CO2 Storage

Field report

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~~6/1/2016~~6/29/2016

Contents

1 – Introduction

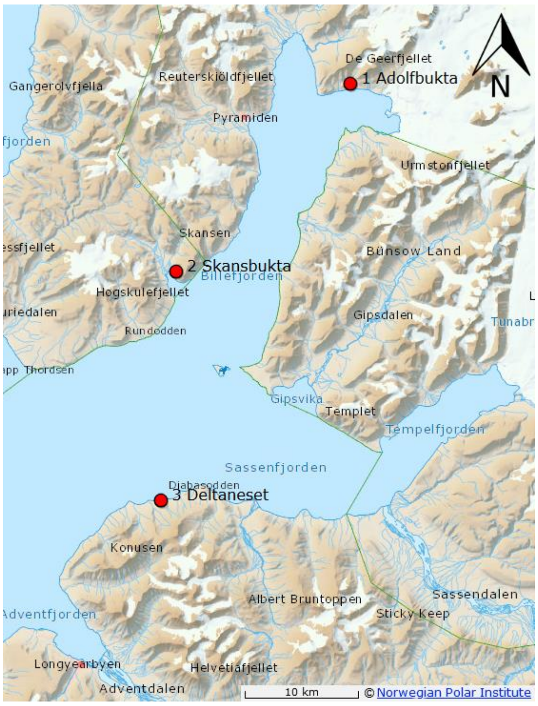

Fig. 1 – Overview of localities, map from toposvalbard.npolar.no. See table 1 for the precise GPS coordinates

The fieldwork was carried out as part of the "Geological Constraints on CO_2 Storage" course at UNIS on Svalbard. The aim of this fieldwork is to understand the geological system required for CO_2 storage purposes, consisting of reservoir and seal rocks. Therefore, different sediment sequences are investigated, described and interpreted with respect to petrophysical properties (porosity, permeability), structural and sedimentological features, as well as their influence on connectivity.

In order to successfully store CO_2 it first needs to be injected as a supercritical fluid, where the temperature and pressure must both exceed 34°C and 74 bar respectively. This is mainly to increase it's density and thus decrease the volume and buoyancy in the reservoir. During injection the increase in reservoir pressure must not exceed the fracture pressure to ensure the seal is not perforated, as this would lead to CO_2 leakage. Therefore the preferred system involves a highly anisotropic permeability system where horizontal permeability far exceeds the vertical. Furthermore having a larger vertical heterogeneity is beneficial to store a large volume of CO_2 in the subsurface in several discrete aquifers and not raising reservoir pressures too high.

Three locations were visited (Fig. 1, Table 1), each representing a different sedimentary system and thus exhibited various properties with respect to fluid flow.

Table 1 – GPS coordinates of the visited localities

№	Location	Date	UTM 33X	
1	Adolfbukta	22 June 2016	538760	8734763
2	Skansbukta	23 June 2016	523202	8718119
3	Deltaneset	24 June 2016	521885	8697756

2 – Adolfbukta – 22nd June 2016

The area of interest is located on the Eastern fault block of the Billefjorden Trough (Fig. 2), a west-dipping half-graben basin of Carboniferous age. The major faults are N-S trending; the investigated block forms the footwall of the Løvehovden normal fault. While the sediments on the other side of Billefjorden at the abandoned mining town Pyramiden are of Devonian age, the investigated succession is part of the Ebbadalen Formation of Carboniferous age. The depositional environment was controlled by tectonics causing a syn-rift basin filling dipping roughly in SW direction (Braathen et al., 2011).

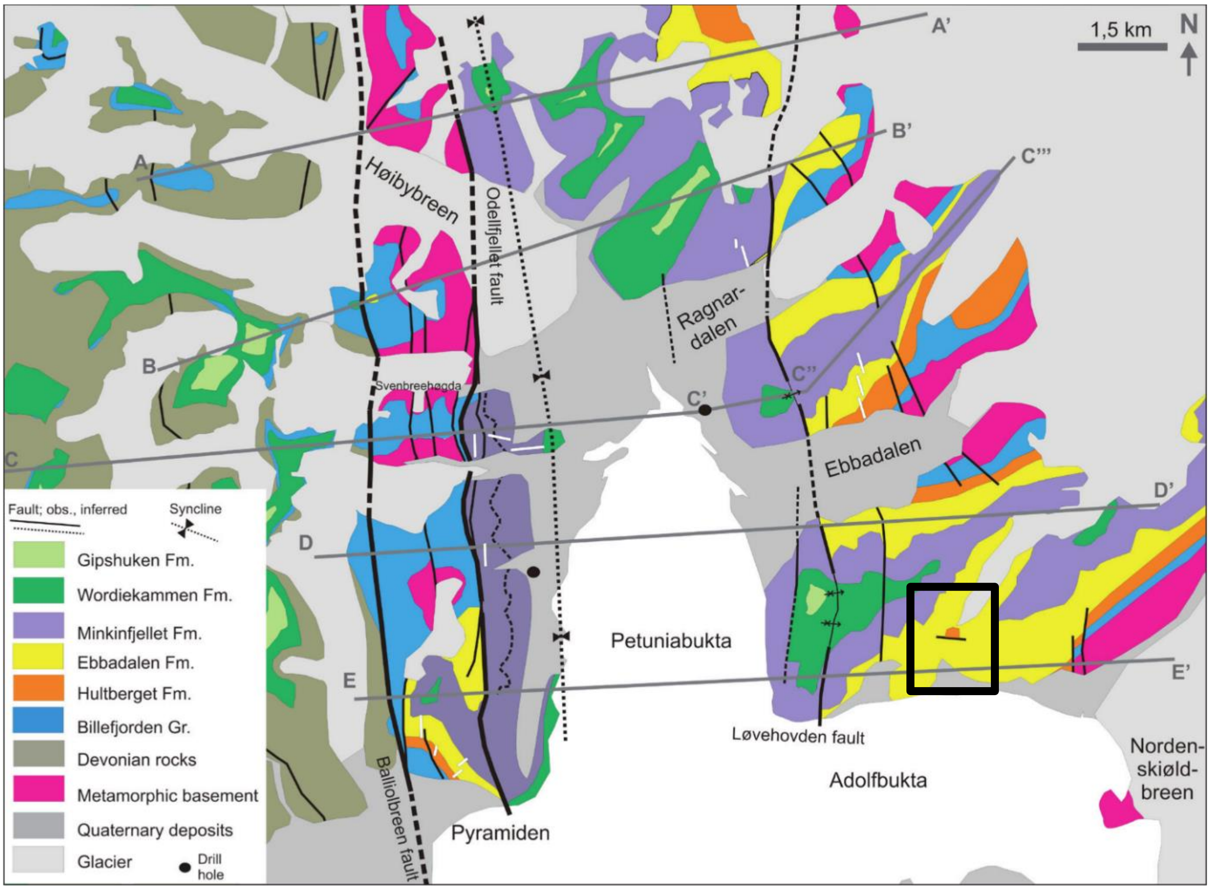

Fig. 2 – Map of the Billefjorden Trough, its formations and the local fault network. The fieldwork area is marked by the black rectangle. Modified from Braathen *et al.* (2011).

The logged outcrop is located on the western edge of the No Name valley. A melt water stream flowing in N-S direction causes sharp V-shaped edges and pebble filling in the valley. Immediately south of the outcrop location the stream enters the coastal area and forms a small delta into Adolfbukta. The logging was started at 1:00am, some drizzle occurred, it was cloudy with bright light. The outcrop appeared in a dark colour and was damp. Fig. 3 displays seven distinctive sequences that could be identified consisting of thicker beds alternating with finer layers. Some of these beds are pinching out laterally.

The sequences start with a flaky silt bank of a 20 to 40 cm thickness and gradually change into a sandy bank of very fine to medium grain sizes, the amount of silty material is decreasing in the sand banks. The boundaries at each sequence's base is sharp. Therefore, the sequences can be described as coarsening upwards (the lower most 40 cm of the sequence is shown in Fig. 4 left). The internal structure of the sand bars shows unidirectional ripples, the paleocurrent orientations are indicated in the log (Fig. 4 right**Error! Reference source not found.**). The general orientation of the bedding could be measured with 230/06 (dipping direction), fracture planes could be identified at 122/88.

Further up in the Ebbadalen Formation, gypsum and anhydrite concretions are found, probably washed in from the evapori~~a~~te layers of the Minkinfjellet Formation (Braathen et al., 2011).

Fig. 3 - Overview of the outcrop on the western side of No Name Valley in Adolfbukta. Seven coarsening-up sequences can be identified. The red line corresponds to the sedimentary section measured.

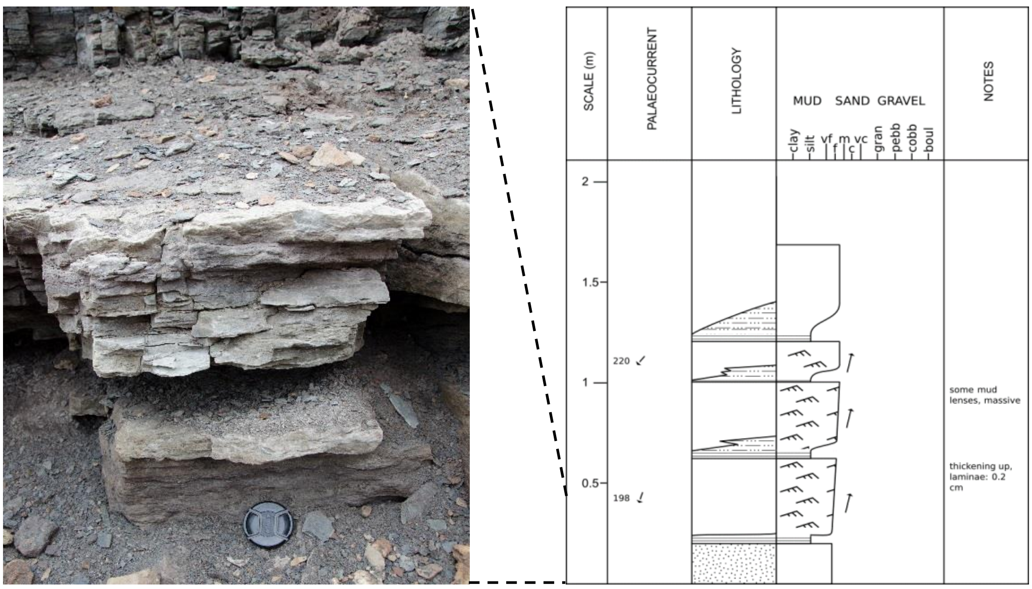

Fig. 4 – Left: Close-up of the lowermost two coarsening-up sequences. Right: Sedimentary log of the studied location

The sand bodies have a good potential for CO_2 storage, although the influence of cementation is questionable. The occurrence of internal seal would block the flow in a vertical dimension, and would force the injected fluids to follow the bedding, away from the injection source. However, the sand bodies are not laterally continuous, which could drastically limit the reservoir potential of this unit. The paleo current direction is pointing towards the fault and is an indicator for the syn-rift sedimentation in this area. The evaporitic successions overlying the studied formation can serve as seal in a storage system.

North of the investigated area a W-E striking normal fault can be observed, somewhat antithetic to the major Billefjorden Fault system. It caused throwing down of the sediments of Ebbadalen formation and exposure of red mudstones of the Hultberget Formation underlying the Ebbadalen formation (See Fig. 2 for location). The Fault gauge is marked by the presence of yellow gypsum, which would act as a barrier to fluid flow. No damage zone seems to occur within the close vicinity of the fault. The whole system would then be regarded as a localised barrier.

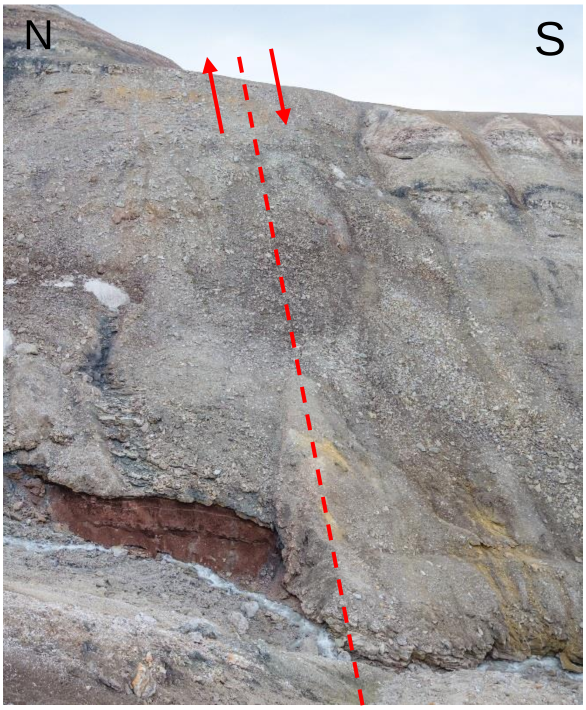

Fig. 5 - W-E striking normal fault causing exposure of red mudstones of the Hultberget Formation on the bottom left corner of the footwall.

3 – Skansbukta – 23rd June 2016

The sedimentary succession at Skansbukta spans the lower to upper Permian, and is part of the Gibshunken Fm., overlain by the spiculitic-rich Kapp Starostin Fm. Both formations could be a possible target reservoir for CO_2 storage and thus a sedimentary section will be measured to assess its feasibility. The Permian sequence of the Kapp Starostin formation is at roughly 2km depth under Longyearbyen and thus outcrop analogues may show greater fractures and other diagenetic features that may not be present at depth. This unit has not yet been drilled into at the Longyearbyen CO2 lab. The units are postulated to thicken southwards thanks to correlations between Dicksonland and Akseloya (Ehrenberg et *al*. 2001). Thus the sequence observed at outcrop level may be adequate for comparison beneath Longyearbyen.

The same gypsum-anhydrite beds observed at Adolfbukta are also outcropping here. Therefore the dissolution and precipitation of these calcium sulphates along once permeable discontinuities threatens to limit fluid flow, unless dissolved again by fresh water.

The following page is a copy of the log measured at Skansbukta (Fig. 6), 19.5 meters in length within the paleotropical deposits of the Gibshunken Fm. (Fig. 7). The two pages following displays pictures (Fig. 8, Photo 1 - 9) taken along the log, characterising the different sedimentary facies, with photo numbers corresponding to the log in green colour.

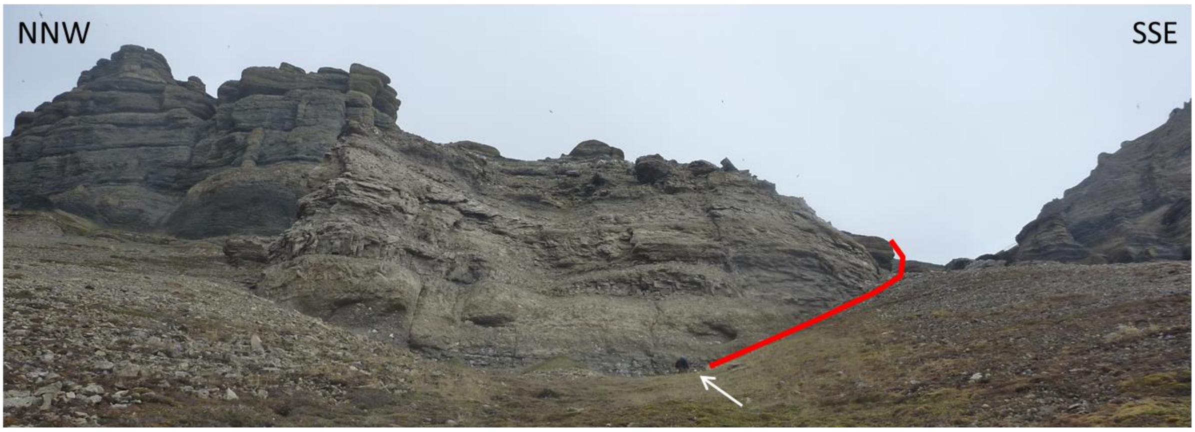

Fig. 6 – The red line corresponds to the measured section, while the white arrow points at the geologist for scale.

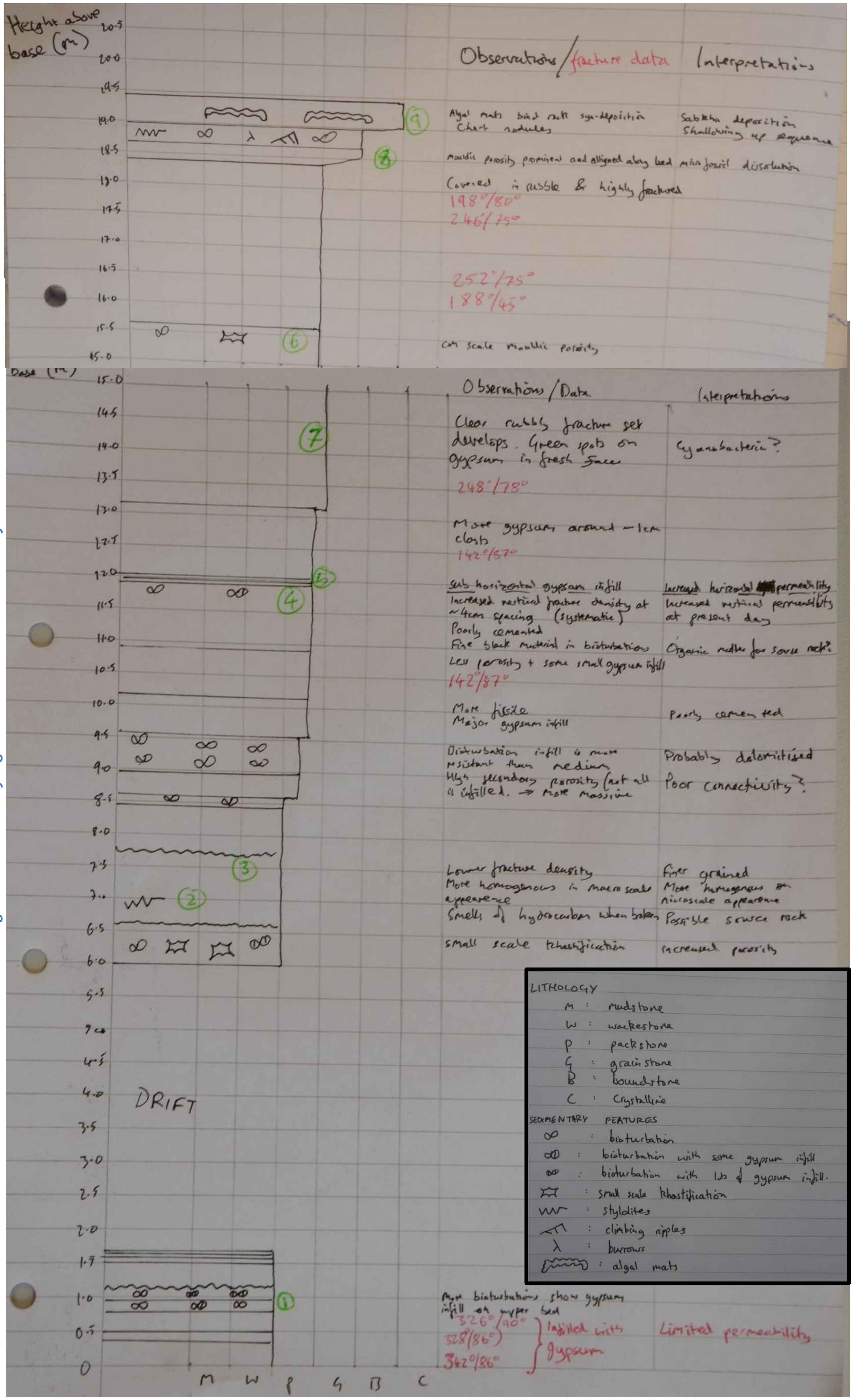

Fig. 7 – Sedimentary log of the measured sedimentary section

Photo 1: Bioturbated wackestone-packstone with varying mud content. Gypsum infills some bioturbations suggesting fluid has previously flowed and may continue to do so.

Photo 2: Stylolite. This may act as an effective barrier to vertical fluid flow. They are found only in more cohesive units.

Photo 4: Showing a decreased fracture density in a more cohesive unit where stylolites are common, possibly a function of reduced grain size. These stylolites will inevitably reduce permeability, particularly vertically. Storativity will be little affected. Hammering of the rock reveals a strong hydrocarbon smell.

Photo 5: Increased fracture density at the top of bed. Fractures generally sub vertical and systematically spaced at 4 cm with some connecting horizontal fractures. They are open and relatively smooth greatly enhancing permeability and thus injectivity.

Photo 6: Horizontal gypsum infill along some weakened laminations. Possibly only occurs close to the surface during unloading and opening of horizontal discontinuities. These infills would make an effective barrier to flow.

Fig. 8 – Pictures of the different sedimentary facies and other relevant geological features documented at Skansbukta

Photo 7: Slight green tinge, probably due to the presence of cyanobacteria.

Photo 6: Centimetre scale mouldic porosity develops due to dissolution of fossil shell fragments. Whilst some (secondary) pores are isolated they may still be connected by initial porosity. Some secondary pores are connected meaning a non-ubiquitous increase in permeability is to be expected. Storativity is largely increased.

Photo 8: Micro and macrofossil dissolution is aligned parallel to bedding planes. Likely the dissolution of spicules and other sponges caused this secondary porosity. Due to the horizontal alignment here connectivity appears good and an increase in horizontal permeability and thus critically injectivity can be expected, with a furthermore increase in storativity.

Photo 9: 40 cm of algal mats bind the rock syn-deposition. Horizontal continuity is moderate. Clearly sub-horizontal fractures open along laminations at the surface: fluid flow is likely encouraged at depth thus increasing horizontal permeability. Vertical fractures still exist allowing pathways for CO_2 migration. Some lenses of muds exist in places where ponds may have formed and dried out, these are isolated so are little threat to the injectivity.

Fig. 6 (follows) – Pictures of the different sedimentary facies and other relevant geological features documented at Skansbukta

The sequence at Skansbukta shows a dual porosity system which may lead to a largely heterogeneous permeability within the Gibshunken Fm. (as well as in the Kapp Starostia Fm.). Dissolution of shell fragments, and/or SiO_2 sponge spicules may create a connected secondary porosity that may enhance matrix flow in an otherwise tightly cemented rock. Horizontal fractures are clearly visible at the surface yet these are unlikely to remain open at 2 km depth. Sub-vertical fractures are however more likely to remain open and thus allow for fluid flow. This system can hence be modelled using a dual-porosity dual-permeability approach.

The depositional environment observed in the measured section corresponds to shallow marine, tropical water carbonate deposits, overlain by sabkha plains deposits. An analogous environment of deposition may be considered to be the Bahamas and thus a similar sequence under Longyearbyen is to be expected. The overlying gypsum beds pose the greatest threat to this reservoirs permeability, the precipitation in secondary pore space and fractures is abundant and likely reduces permeability in an otherwise well cemented limestone.

Matrix permeability has been assessed using plug tests which will neglect the added permeability of fractured surfaces. Fig 9 shows how the light coloured spiculite of Disckson Land (near outcrop locality studied in this paper) can have a permeability of up to roughly 70 mD. It is also important to note that the permeability of this unit 800km to the south in Akseloya will still possess the majority of its permeability and porosity (see 4's and 6's) observed at outcrop level. Therefore at Longyearbyen where this unit is at depths of 2km we can expect the rock to still function as a slightly permeable reservoir with a moderate to good porosity.

Presence of a strong hydrocarbon smell when hammering the rock reveals that this rock has likely had oil migrating through it. This lends credence to its ability allowing fluids to effectively flow through it. Furthermore at 2km depth the overlain calcium sulphates would act as an effective seal.

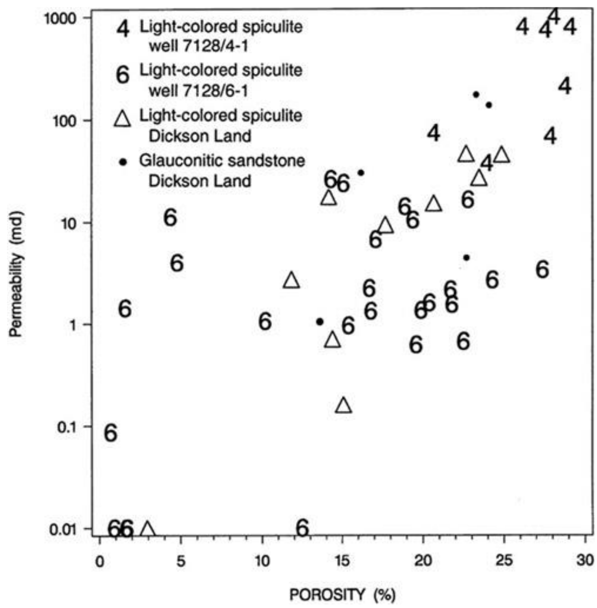

Fig. 9 - Plot showing permeability and porosities of core plugs (2.54cm) from outcrop samples (Dickson Land, ~50km north of Longyearbyen) and whole core (Finnmark Platform, ~800km SE of Longyearbyen) (from Ehrenberg *et al.* 2001).

4 – Deltaneset – 24th June 2016

Located on the southern shore of Sassenfjorden, at the eastern edge of the Central Tertiary Basin (CTB), the area East of Deltaneset displays the main Upper Triassic, upward-coarsening reservoir sequences targeted within the CO2-Lab project in Longyearbyen, as well as the overlaying Jurassic mudstone of the Agardhfjellet Fm., which represent the main sealing unit in the area (Fig. 10). However, the most efficient seal might actually be the internal *décollement*. It is important to state that this potential reservoir is strongly underpressured in the subsurface of Adventdalen (50 bar to low). The rock layers gently tilting towards the CTB, it is possible to measure a section through the reservoir sequences along the beach. It is important to note that several doleritic dykes and sills of the Diabasodden Suite have been injected during the Cretaceous (Nejbert *et al.* 2011), mainly within the soft rocks of the system, ~~(still?)~~ channelising fluid flow at their base, as testified by the occurrence of pockmarks at the rim of the intrusions (Senger *et al.* 2013).

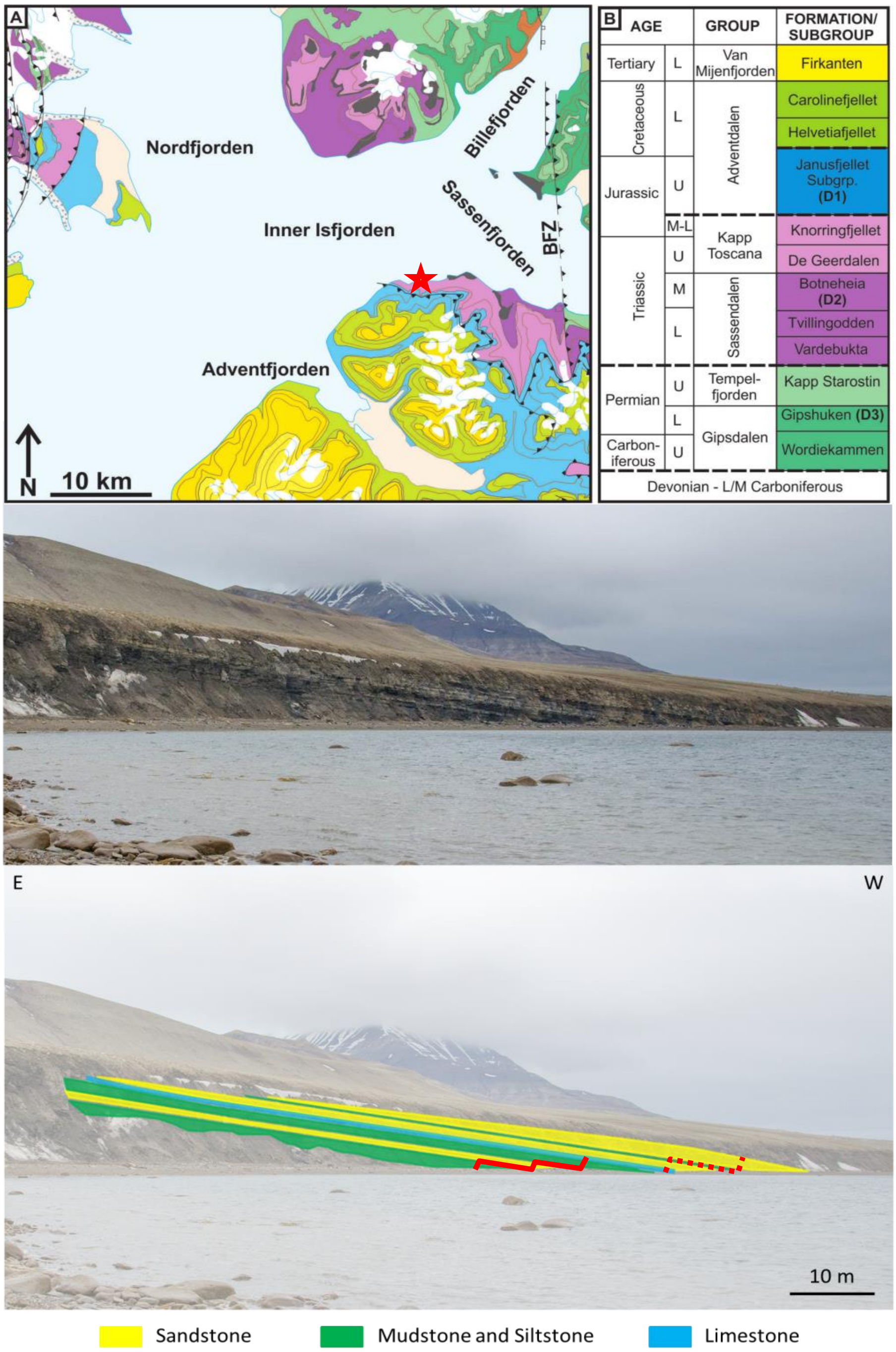

Fig. 10 – Upper part: Geological map of Isfjorden, the visited locality is marked by the red star (from Srikumar *et al.* 2014)

Lower part: Picture of the measured section (red line) within the Upper Triassic De Geerdalen Fm. The dashed line represents the section measured by other groups. GPS coordinates of the picture: 33x 0522143 - 869721

The 4 m measured section is located on ~~the~~ “B~~b~~each 2”~~, at the coordinates: 33x 0521885 – 8697756~~ (Fig. 11). It displays at its base an upward-coarsening sequence from (i) dark grey, finely laminated undulating and bioturbated siltstone, with cm to dm-scale lenses of rippled very fine, and very fine to fine grained sandstone, into (ii) a wavy-bedded very fine to fine grained sandstone. Burrows measure up to 1 cm in diameter, and are marked by the presence of an oxidised horizon at their rim. At 1.50 m, a strong erosive surface characterises the base of the overlying 0.80 m thick fine grained sand beds. The interval between 2.30 and 3.30 m is somewhat similar to the lowermost measured unit, displaying the same kind of coarsening up sequence, with rippled lenses of very fine to fine grained sandstone lenses within a matrix of finer material at the base, and a fine to medium grained sandstone at the top. This matrix of finer material is, however, slightly coarser-grained in this metre-thick interval than in the lowermost part of the section. At 3.30 m, the rock testifies of a dramatic change in Paleo-environmental conditions, with the deposition of 0.70 m thick, laterally extensive wacke-pack limestone.

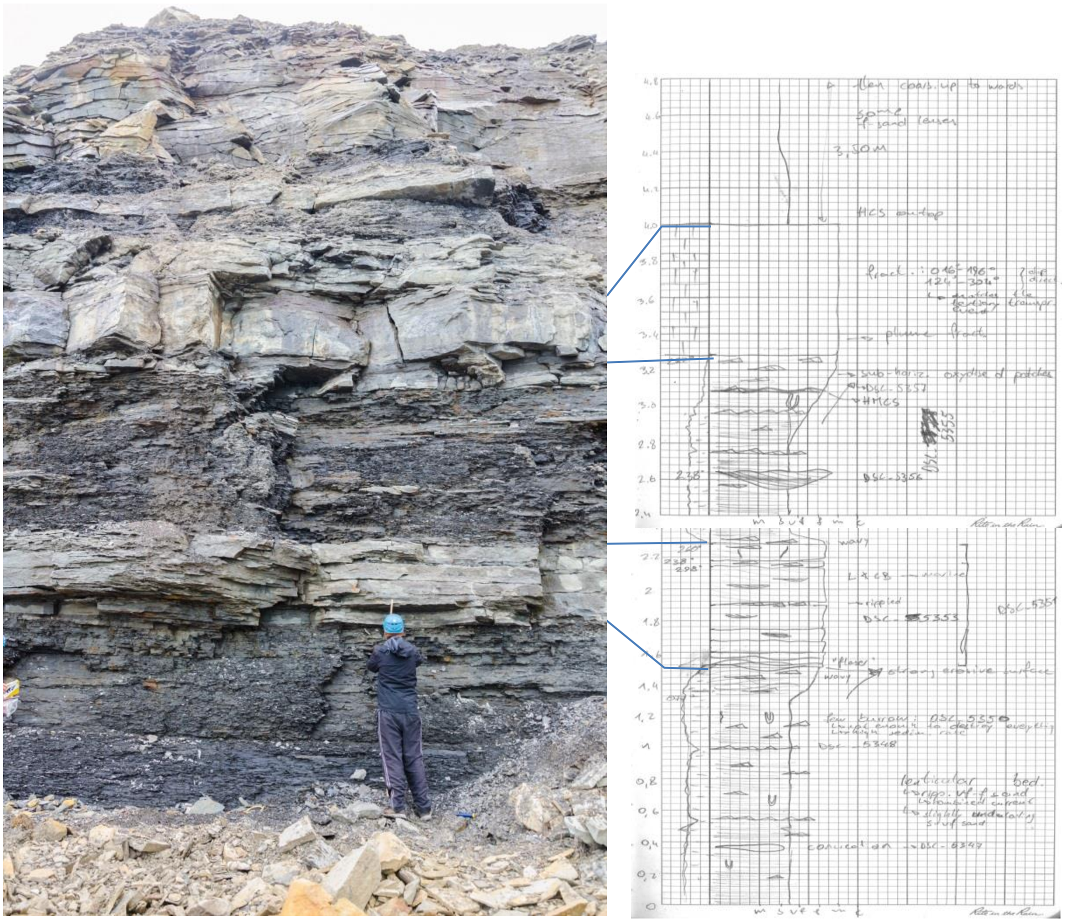

Fig. 11 – Picture of the measured sedimentary section, and its corresponding sedimentary log, the top of the measured section is at 4.0 m.

The measured sandstone beds are generally well cemented but not necessarily fractured, and their matrix permeability value is low, due the occurrence of quartz overgrowth “associated with fibrous illite and chamosite” (Mørk 2013). On the contrary, the measured limestone bed, despite being also characterised by a low matrix permeability, comprises two sets of fractures, both perpendicular to the bedding plane, respectively striking 016°-196° and 124°-304°, coinciding with the stress regime induced by the Tertiary Transpression (Leever *et al.* 2011). These fractures are the main conduits for fluids, if not cemented. The lowermost siltstone intervals probably act as a barrier to vertical fluid flow, forcing the fluids to travel within the sand bed. The second silt- to very fine grained lenticular interval might have had a higher potential for fluid flow compared to the lowermost part of the section, due to a slight increased grain size, hence a better permeability. The diagenetic history that these rock has undergone surely killed that fluid carrying potential with the formation of micro Quartz crystal within the matrix.

Overlying the measured sedimentary section, the topmost part of the parasequence is represented by a 6 m thick, metre-scale trough cross-bedded sandstone, corresponding to a distributary channel system. This unit was subsequently flooded by a rising sea-level, depositing a second coarsening-up parasequence, and its train of mudstones and sandstones. This sandstone interval corresponds to the main potential reservoir unit of the measured location. It is however well cemented, and its matrix permeability value hence remains low. Nevertheless, this sandstone is heavily fractured and this fractures are (probably) the only permeable features allowing fluids to flow through the rock. 23 fracture planes have been measured (but not corrected) and plotted in a stereonet (Fig. 12), showing the existence of at least three fracture sets, eventually four, respectively striking (i) NW-SE, (ii) SW-NE, (iii) SSW-NNE. More measurements are required to obtain a representative and valid statistic. The orientation of these fractures fits relatively well with the fractures measured in the underlying limestone bed, and hence, were nucleated as a consequence of the Tertiary Transpression (Leever *et al.* 2011).

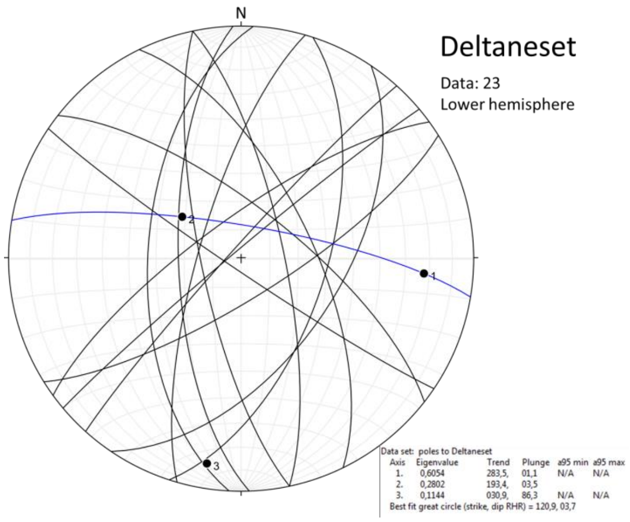

Fig. 12 – Stereographic projection of the fractures measured in the uppermost, trough cross bedded sandstone,

Some normal faults have also been observed in the overlying Knorringfjellet Fm. at Konusdalen, with a throw of approximately 3 m (Fig. 13). These features are of great importance for fluid flow studies, and their characterisation is of pivotal importance for flow modelling, as they will decide if two juxtaposed sandstone bodies will communicating or not, depending on the presence of clay minerals, smeared within the fault gauge, acting as an impermeable membrane for fluid flow. Mulrooney & Braathen (2015) interpreted these extensional features either (i) as a consequence of the fold complex collapse during the final phase of the Tertiary Fold and Thrust Belt, or (ii) as a result of the ocean opening between Greenland and Norway.

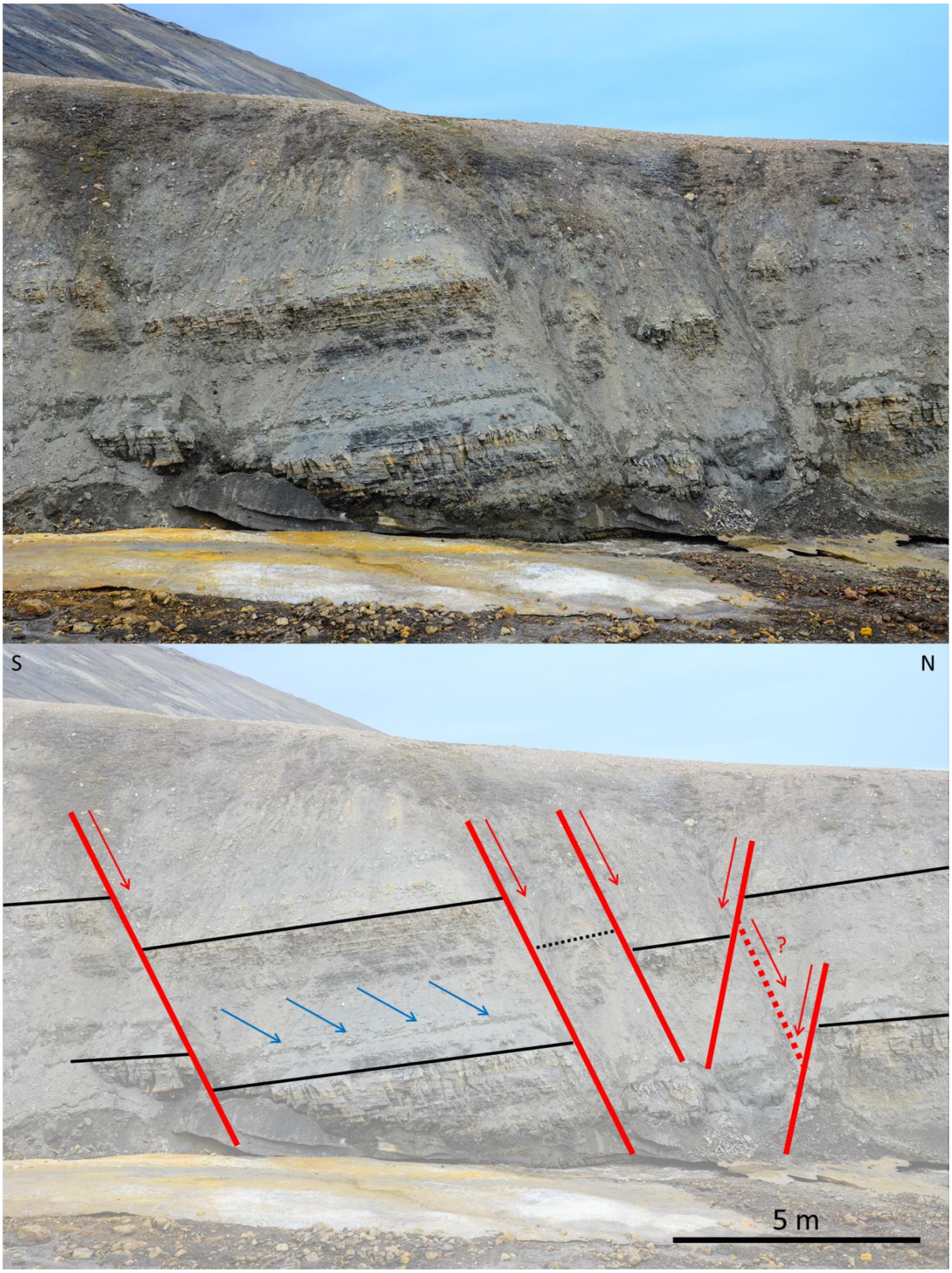

Fig. 13 – Tectonic sketch of the normal fault observed at Konusdalen. The blue arrows point at a moist rock layer, showing some concentrated fluid flow near a sub-seismic scale sedimentary tight layer.

5 – Core Logging – 26th June 2016

A 5 m long core has also been measured as part of this exercise (Fig. 14). The core itself belongs to the BH-1A borehole, drilled as part of the CO_2-Lab project. It corresponds to the depth interval comprised between 765.00 and 770.00 m. Between 770.00 and 766.45 m, the core consists of a coarsening upward sequence of siliciclastic rocks, of varying bioturbation content, before being overlain by dark mudstone, as part of a second parasequence. Note that some fractures display evidence of slick and slide (Fig. 15). Most of the rock units are tight, and fluid flow would probably be concentrated within thoroughly fractured intervals (marked in orange in the log (Fig. 16), or potentially through the damage zone of these fractures, as their permeability values are several orders of magnitude higher than the matrix porosity, and only a small portion of the flow would circulate through the matrix. Nevertheless, one can still model this system using a dual-porosity dual-permeability approach.

Fig. 14 – Picture of the measured core, 770.00 mark in the upper left corner

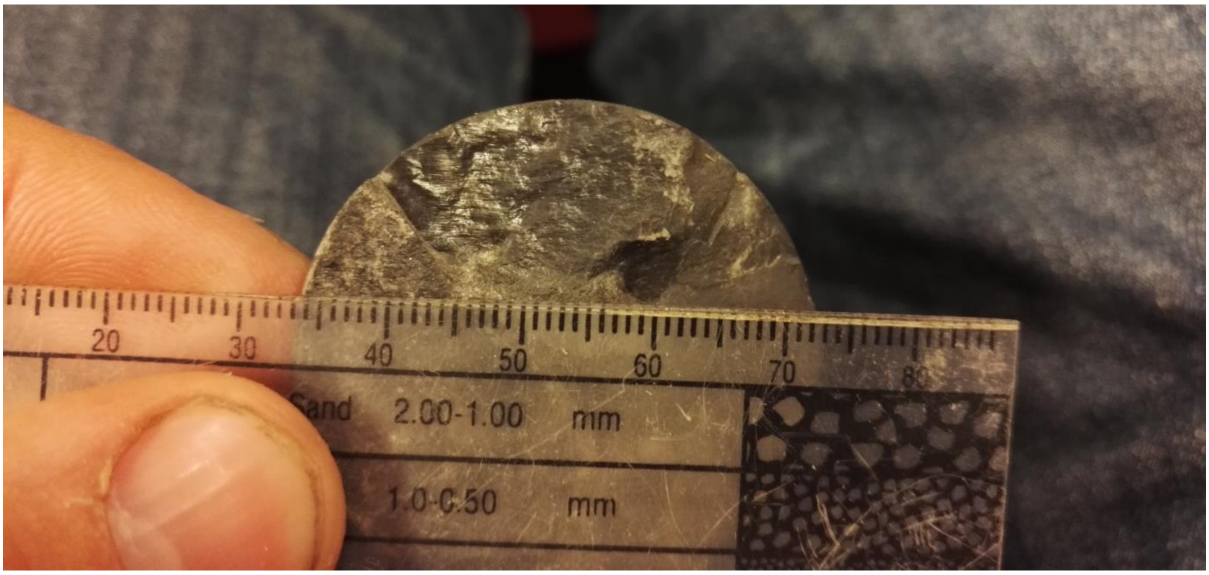

Fig. 15 – Picture of a fracture plane displaying evidence of slick and slide movement, sub-parallel to the ruler, 767.50 m deep.

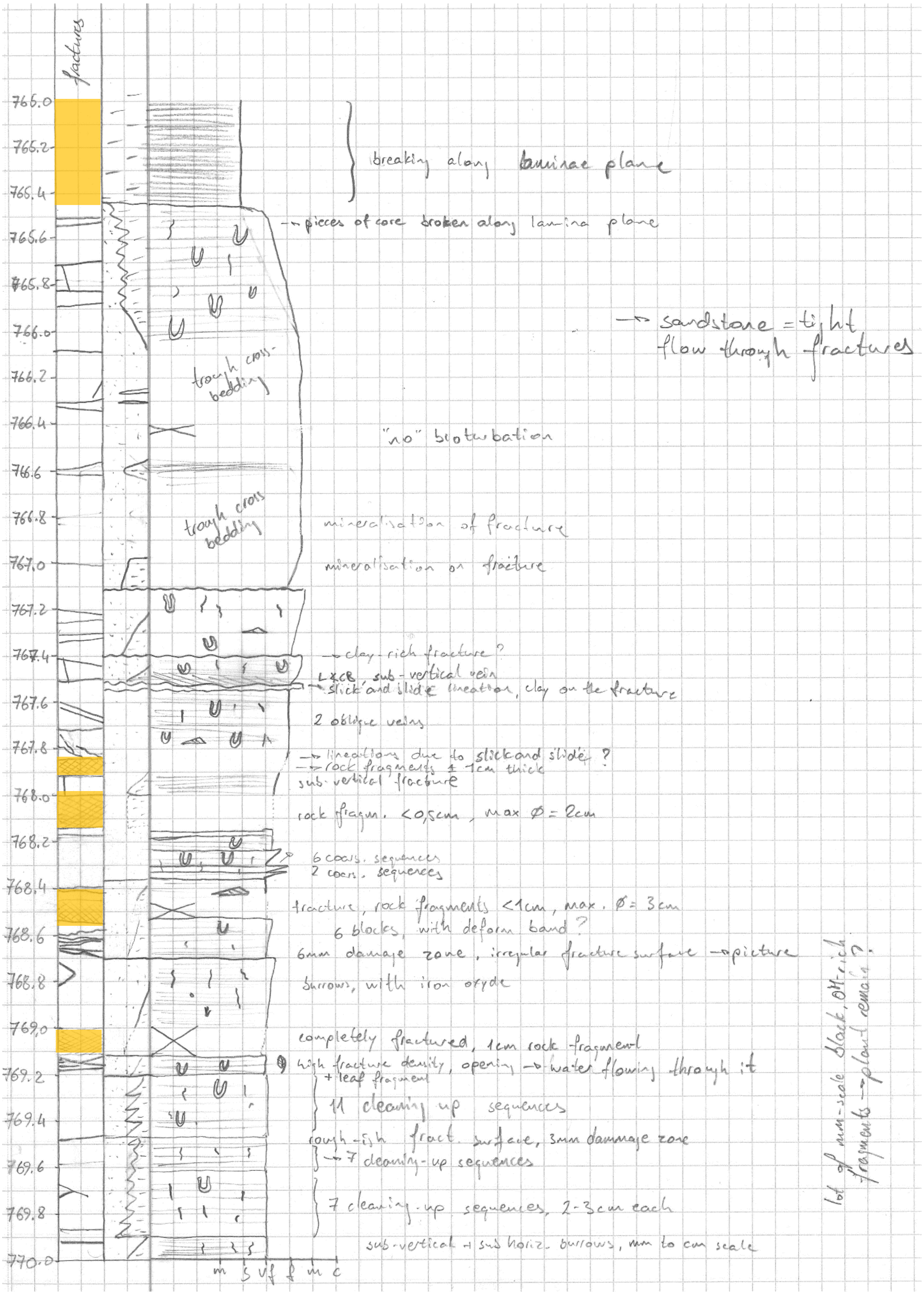

Fig. 16 – Sedimentary and structural log of the BH-1A core, between 765.00 and 770.00 m deep. Orange rectangles mark thoroughly fractured intervals.

6 – Summary

Out of the three studied rock units, the most effective reservoir for fluid flow seems to be the Permian limetstone beds, documented at Skansbukta, as suggested by the strong oil smell expelled of the rock when hammered, proving that fluids can migrate through the pores of such a rock formation. Secondly, the presence of cm-scaled bioturbations, filled with evaporitic material which would be dissolved once penetrated by fresh water, would drastically increase the porosity and the permeability of the matrix. Fractures however, might potentially be filled by calcite crystal, and hence act as a baffle to fluid flow. Nevertheless, this system could use a dual-porosity dual-permeability approach if modelled.

The coarsening-up rock units observed at Adolfbukta remain however interesting in the perspective of reservoir study, as their heterolithic sedimentary architecture would prevent the fluids to flow vertically too easily, forcing them to flow parallel to the bedding, away from the fluid source. The challenge in such a rock succession is to uncover the lateral continuity of these pinching out sedimentary beds, as well as the eventual connectivity between them. The presence of a sealing fault in the direct vicinity of the reservoir units would also act as baffle for fluid flow, potentially allowing the pressure to build up above the fracture pressure.

Finally, the reservoir units targeted for the CO_2-Lab project in Adventdalen are, surprisingly, the rock properties least inclined for any efficient fluid flow. The sandstones are tight, with the occurrence of Quartz overgrowth and pore filling clay minerals. Fur~~e~~thermore the reservoir itself, in the subsurface of Adventdalen, is characterised by ca. 50 bar of underpressure, explained by (1) the presence of 20 m of dry permafrost below the surface and (2) by a depletion of water, corresponding to 20 and 30 bar of underpressure respectively. This low pressure reservoir conditions, coupled with a low temperature gradient, complicates the maintenance of the injected CO_2 as supercritical fluid within this rock unit. The targeted sand beds also display 2 to 3 sets of fractures, a direct consequence of the Tertiary Transpression. These fractures will undoubtedly channelise any injected fluid flow, as their permeability values are several orders of magnitude higher than the matrix permeability, leaving little chance for the matrix to efficiently participate in the effort of carrying some of these flows any further. However, a dual-porosity dual-permeability modelling method might still be envisaged for any further reservoir study.

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