BACHELOR’S ASSIGNMENT

The SP2 snow penetrometer: Accuracy and usability in terms of its intended use, avalanche forecasting

Nøyaktighet og bruk av snøpenetrometeret SP2

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Preface

We would link to thank Atle Gerhardsen for lending us the SP2, giving us access to the profile data and Avanet/MountainHub, and for giving us the opportunity to test the Scope.

A big thanks goes to our supervisors Simon de Villiers and Kalle Kronholm. They threw us into the world of snow science and lent us a helping hand when we got lost in the dark. This work would not have been possible without your helpful insights.

For taking the time to answer our questions, special thanks are due to Avatech.

The work on this thesis has been a ride filled with learning, joy, frustration, and long hours spent in the library.

The thesis is divided into six sections: Introduction, literature review, methods, results, discussion and conclusion. The results and discussion sections have been deliberately separated to allow discussion across results to maintain a focus on the broader picture.

Sogndal, 01-06-2017

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Abstract

The snow cover stratigraphy is an important factor in the present operational avalanche forecasting. Manual methods for recording snow profiles and snow hardness is widely used. These traditional methods lack objectivity and are observer dependent. The rammsonde proved to increase objectivity of hardness measurements, but the low vertical resolution leads to avalanche-prone features, such as thin weak layers, being overlooked. The SMP has shown that it can accurately, objectively and reliably provide detailed information on the snow stratigraphy and has greatly contributed to the study of snow.

The recently developed SP2 tries to pack the same features into an affordable and compact design. This would allow rapid collection of quantitative and objective measurements of snowpack features associated with snow stability, and could potentially be an accommodation for observers working in avalanche forecasting. In this study, we have investigated the SP2s accuracy and repeatability by performing field and lab tests, and by comparing its ability to quantify snow stratigraphy against traditional methods such as manual snow profiles.

The SP2 showed that it could record the main stratigraphic features of the snow covers and that it had consistent hardness measurements. The results are restricted to the tested snow conditions, but indications were given that the hardness measurements are too coarse to resolve measurements in soft snow. The penetrometer is limited by poor accuracy in the depth measurements, where possible contributing factor may include unprecise surface determination and push-rate variability. With increased accuracy and force sensitivity the SP2 or similar penetrometers have the potential of becoming valuable tools for avalanche observers.

Sammendrag

Kjennskap til snøens lagdeling er en forutsetning for riktig snøskredvarsling. Snøprofiler som viser variasjoner i hardhet blir brukt for å beskrive lagdelingen, og disse er som oftest laget på bakgrunn av målinger av håndhardhet. Dette er en manuell målemetode som ikke gir et absolutt mål på hardhet. Ulike varianter av snøpenetrometere har gjort mer objektive målinger mulig, men disse har foreløpig vært i begrenset bruk i Norge. SnowMicroPen, som er utviklet for bruk i snøforskning, har gjort det mulig å måle snødekkets egenskaper på et svært detaljert nivå.

SP2 ble utviklet for å pakke høyoppløste målinger av hardhetsvariasjoner i snødekket inn i et bærbart format. Raskere og mer presis innsamling av hardhetsprofiler vil være til stor hjelp for observatører som må kartlegge potensielle skredproblemer over store områder. Vi har gjennom felt- og labforsøk testet hvor nøyaktige og reproduserbare målinger gjort med SP2 er, vi har sammenlignet disse med manuelle snøprofiler og vi sett på hvordan bruk av SP2 kan inngå i en systematisk snødekkeundersøkelse.

Forsøkene har vist at SP2 kan gjengi hovedelementene i ulike snøstratigrafier, men at unøyaktige dybdemålinger kan være problematisk. Unøyaktighetene ser ut til å være relatert til både usikker overflategjenkjenning og variasjoner i penetrasjonshastighet. Presise og reproduserbare hardhetsmålinger er observert i tørr og tilstrekkelig hard snø, mens våt og myk snø gir mer usikre målinger. Resultatenes gyldighet er begrenset til snøforhold lignende de vi testet i, som blant annet ikke inkluderer typisk nysnø- og fokksnøforhold. SP2 har potensiale til å bli et viktig verktøy for skredobservatører, men mer nøyaktige dybdemålinger og økt følsomhet i myk snø er nødvendig for påliteligheten.

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1 Introduction

In the last 44 years, 238 people have lost their lives to snow avalanches in Norway. The primary concern of the Norwegian Avalanche Warning service is reducing the number of fatalities, and one of their means for achieving this goal is publishing daily avalanche forecasts throughout the winter. As awareness among recreationists increases, forecasted avalanche problems are more frequently being taken into consideration, and the death toll for the winter season 16/17 was the lowest observed in the past ten years.

Digital penetrometers with high resolution have been developed to be an aid in avalanche forecasting (Abe, Decker et al., 1999; Schneebeli & Johnson, 1998). They have the advantage of rapidly collecting information on stratigraphic features that allow avalanche formation, such as depth to a weak layer and the properties of the overlying slab. Penetrometers can therefore be a valuable tool for avalanche observers, resulting in better avalanche forecasts and fewer accidents.

The snow penetrometer chosen for this study is the SP2, a rapid push, high resolution penetrometer intended to be used by avalanche professionals (Christian, Whittemore et al., 2014). The probe is developed by the American company Avatech. The work on this thesis has been directed by some underlying questions. First, we had to learn how the SP2 works. Then we questioned if the SP2 can detect and differentiate between snow layers, with a focus on avalanche-prone structures. As a part of this, we also wanted to evaluate if the measurements are precise and repeatable. Ultimately, our results could be used to assess the usability of the SP2, in terms of its intended use; avalanche forecasting.

2 Literature review

2.1 Snow

Alpine snow is a very complex medium. Snow is the weakest of the surficial materials found on Earth (McClung & Schaerer, 2006). Bonds between ice particles define the strength of the snowpack. In most snow found in avalanches ice particles make up a mere 20%, with the rest being air (McClung & Schaerer, 2006). The snow cover experiences a whole variety of conditions over a short time frame compared to its lifespan (Colbeck, 1991).The snow cover can consist of over 15 snow layers (Sturm, Holmgren et al., 1995). Some layers are formed on the snow surface, while others form within the snow cover due to metamorphism.

Snow on the ground, existing close to its melting point, is a rapidly changing medium consisting of a mixture of water in three different phases; ice, water and water vapor. Small changes in the physical conditions in and around the snow lead to changes in the physical properties of the snow. Snow strength is closely related to the formation of bonds between snow crystals (also called sintering). The formation of these bonds is strongly affected by the conditions near the crystal and grain surfaces (McClung & Schaerer, 2006).

The snow cover is prone to changes and variation due to external and internal drivers. During deposition, the snow is affected by the precipitation, wind and sublimation. After deposition, the main drivers are wind, temperature and radiation (Schweizer, Kronholm et al., 2008). Metamorphism is the primary internal driver. These external and internal drivers are controlled by local meteorological conditions (Kronholm, Schneebeli et al., 2004). The last driver is disturbance from other external factors like avalanches or skiers. All these processes affect each deposited layer of snow.

2.1.1 Spatial Variability

The variation in the snow pack, caused by various external and internal processes, is known as the spatial variability of the snow cover. The variability can be observed at regional and mountain range scale, slope scale and sub-slope scale (Schweizer et al., 2008). The variation is dependent on the external and/or internal processes acting at the considered scale. Weak layers tend to be more continuous across a slope in terms of penetration resistance than slab layers (Schweizer et al., 2008). However, in terms of microstructural strength, weak layers tend to have higher variation than slab layers (Bellaire & Schweizer, 2011). The release of a dry-snow slab avalanche is significantly affected by the scale of variation (Schweizer et al., 2008). The variation in the stability, the length-scale of this variation and the mean stability are suggested as controlling factors of slope stability (Kronholm & Schweizer, 2003).

The spatial variability found in snow covers means that evaluation of slope stability should never be based on one single snowpack observation (Schweizer et al., 2008). The uncertainty may be reduced by performing more than one test on the same slope (Birkeland & Chabot, 2006). All the different methods of measuring spatial variability are associated with measuring errors (Schweizer et al., 2008) that contribute to an apparent spatial variability. These errors must be filtered out to get a measure of the actual spatial variability.

2.1.2 Hardness

Snow hardness can be defined as "a measure of the strength of snow in compression" (McClung & Schaerer, 2006, p. 75). It is measured as units of force per unit area, Pa. At microstructural scale, mechanical processes associated with the ice particle interactions must be overcome by the work done by the applied force. These are processes like ice contact sintering, sliding and rotation at ice particle contacts, and deformation of ice particles and ice particle contacts in tension, compression, shear, torsion and bending (Johnson & Hopkins, 2005). Snow hardness is related to the compressive strength of the snow and can therefore be used to evaluate the stability of the snow pack.

Snow hardness is measured by pushing an object into the snow and assessing the force required to get the object to penetrate the snow. The hand hardness test (American Avalanche Association, 2016; Fierz, Armstrong et al., 2009) is the most common measurement method of snow hardness. The scale has 6 different levels based on the largest object that can be inserted at a given force. Slight variations in the hardness can be indicated with + and -. The recommended max force is 10 to 15 N (Fierz et al., 2009). Hand hardness is plotted on a ordinal scale (Pielmeier & Schneebeli, 2002). Hand hardness measurements are often converted to fit on a logarithmic scale to be able to compare them with micro penetrometer and ram hardness (Pielmeier & Schneebeli, 2002). Höller and Fromm (2010) showed that the hand hardness steps correspond well with force on a logarithmic scale. The resolution varies with the height of test device and ranges from 0.3 cm for knife to 7cm for fist (Pielmeier & Schneebeli, 2003).

Table 2.1. Hand Hardness Index (American Avalanche Association, 2016)

Symbol	Hand Test	Term
F	Fist in glove	Very Low
4F	Four fingers in glove	Low
1F	One finger in glove	Medium
P	Blunt end of pencil	High
K	Knife blade	Very High
I	Too hard to insert knife	Ice
N/O	Not observed	

The hand hardness test is the method of choice for avalanche observers due to its simplicity. It requires very simple tools, is quick and an intuitive way of measuring snow hardness. It also gives direct interaction between the observer and the snow. However, it is heavily user biased and lacks vertical resolution. The estimation of force applied to the snow is user dependent, and the difference in hand and glove size has an impact on how the snow hardness is measured (Floyer, 2008). Observers still tend to identify the critical thin weak layers that are relevant for the assessment of the snow stability using hand hardness tests. Hand hardness profiles are an important part of the manual snow profile and have proved to be a good indicator of potential instabilities (Schweizer & Jamieson, 2007; Van Herwijnen & Jamieson, 2007). Over the years various methods have been developed to gather more objective measures of snow hardness, including force-resistance penetrometers.

2.2 Avalanches

"The two general types of snow avalanches are called loose-snow avalanches and slab avalanches" (McClung & Schaerer, 2006, p. 73). Loose-snow avalanches start and fan out from one point at or near the snow surface. Granules of snow of low cohesion are entrained by collisions. The slide spreads out as it moves down the slope into a shape resembling a tear-drop. Loose-snow avalanches are released if snow is set in motion and the slope is steep enough. The other type of snow avalanche, the slab avalanche, is regarded as a more dangerous type. The slab avalanche releases when a thin weak layer overlain by relatively cohesive slab fails. Propagating fractures causes an entire block of snow to be cut out and slide down the slope.

Failure of a weak layer occurs when the applied stress overcomes the resisting forces in the layer. The most important resisting force is the shear strength, which in general can be looked at as the sum of cohesion and friction (McClung & Schaerer, 2006).

As mentioned above slab avalanches are only possible if certain criteria are met in the snowpack - a cohesive slab overlying a weak layer or interface (Kronholm & Schweizer, 2003). Avalanche practitioners therefore try to identify whether or not this specific type of stratigraphy is found in the snowpack when assessing the likelihood for slab avalanches. This can be predicted from analysis of past and present weather data. The most accurate method is to go out in the field and record to test the existing snowpack directly.

Research has greatly increased and is still increasing our understanding of the various physical processes in the snowpack. With increased knowledge, the need for more quantitative measurements of layer properties has arisen (Floyer, 2008). A valuable tool for providing this information might be high-resolution penetrometers.

2.3 Hazard evaluation / forecasting

Assessing the snowpack stratigraphy has for a long time played a major role in operational avalanche forecasting. The concept of systematically describing and recording snow structure was introduced as early as in the 1930's. Today, "snowpack factors are considered to be *class II* data" (McClung & Schaerer, 2006, p. 149). This includes the determination of the different layers in the snowpack and their properties such as hardness, size and shapes of crystals, temperature, penetrability and other properties. Instability factors are found in class I and include recent avalanches, (in)stability tests, fracture propagation and whumphs. Class III consists of meteorological factors such as the amount of new precipitation, solar radiation, air temperature, wind speed and wind direction. Forecasted weather is also found in class III.

The classes are based on the relevance for assessing snow instability. Class I gives direct evidence of instability and should be weighted greatest. Seeing an avalanche occurring gives you more direct information on the snow instability than recognizing potential weak layers in the snowpack. Meteorological data, class III, are mainly used to determine the future changes in snowpack stability.

A snow profile is the standard method of representing snowpack stratigraphy. Typically, time and date of the profile is recorded together with some parameters about the current weather. Each identified snow layer with its associated hardness is graphically recorded. Properties such as grain type and size, moisture content, and possibly density of the snow is recorded for each layer after The international classification for seasonal snow on the ground (Fierz et al., 2009). A temperature gradient is often included and shown graphically. Stability test results are often noted at the respective layer interface.

The observers working for the Norwegian Avalanche Warning Service (NAWS) use a method called the Systematic snow cover diagnosis to assess the snowpack (Müller, Landrø et al., 2015). The method was developed by G. Kronthaler (Kronthaler, Mitterer et al., 2013) as a part of the education at Lawinenwarndienst Bayern (the avalanche warning service in Bayern) in 1999. Systematic snow cover diagnosis is based around the concept of "finding the most prominent weak layer, testing the weak layer - slab combination with a fast test and interpret the result by considering the processes that lead to the situation observed" (Kronthaler et al., 2013, p. 199).

Systematic snow cover diagnosis is separated in three different parts: The small test block, analysis of the weak layer and evaluation of the weak layer. The small test block is a tool for finding and visualizing weaknesses in the snow cover. It is different from a CT and ECT because stability is not measured (Kronthaler, Mitterer et al., 2009). A snow column of 40x40cm is isolated down to a depth of about one meter. The column is then tapped on the side with increased intensity with a shovel until it is brought to a failure. In this manner, weak layers are identified (Kronthaler et al., 2013). A simplified snow profile can also be used to visualize the snow pack. Simplified means that only the weak layer and the neighboring layers are described in detail, while the rest of the snow cover is only roughly described.

The analysis of the weak layers focuses on the grain shape and the bonding with under- and overlying layers. The crucial part is to identify the process behind the formation of the weak layer and to see if the grain shape is identified with faceting, rounding or wet snow metamorphism. The evaluation of the weak layer is done by looking for four unfavorable properties of the weak layer and one unfavorable property of the overlying slab. The properties looked for in the weak layer are: Easy failure, if the layer is thin, if the grains are big, and if the is layer located within 1 meter from the snow surface. The unfavorable property of the slab is that it is cohesive but soft (Kronthaler et al., 2013).

To be able to evaluate the avalanche danger over a large area, information from one point observation must be extrapolated to the larger geographical area. So-called “process thinking” is a method where theoretical knowledge about the transformation processes in the snowpack is used to evaluate the snow stability, based on snow and weather observations. Since the external and internal processes tend to be the same over a larger area, it is possible to make assumptions about the stability if the impact of elevation, aspect and terrain are considered (Müller et al., 2015). Using this method, it might be sufficient with one test to correctly estimate the avalanche danger in unstable conditions. Two or more tests are needed if the conditions are stable (Kronthaler et al., 2013). The systematic snow cover diagnosis approach is a way of eliminating the need for many observations, which often is too time-consuming when done manually.

2.4 Penetrometers

Penetrometers work by inserting a tip of certain size and shape using a load cell into the snow and measuring the force applied to it. The aim is to provide information on load and penetration distance giving an index for the hardness of the material (Lee & Huang, 2015). The hardness index can then be used to model material properties, such as cohesion and friction angle. These properties are, as mentioned above, the main constituents of the shear strength of snow. Penetration force is often graphed on a logarithmic scale to enhance the resolution in softer types of snow (Pielmeier & Schneebeli, 2003). Using the surface area of the penetrometer tip, the force (N) can be converted to hardness values (Pa) but this should be done with caution.

Seemingly converting force values to hardness values could allow comparisons to be made between different penetrometers. One problem with doing this is that snow hardness measurements are dependent on the shape and size of the penetrating object deforming the snow (Mellor, 1964). For compacted snow not to accumulate in front of the tip, the deforming snow in front of the penetrating object must be removed. A sharp, narrow tip allows the compacted snow to quickly be ejected from penetrometers path. A blunter, wider tip would increase the amount of compacted snow ahead of the tip. Converting values to units of strength (Pa) and comparing these between different penetrometers should therefore only be done with a thought in mind that the strength values are linked to the hardness values given by a specific tip (Floyer, 2008).

The geometry of the cone has an effect on the hardness measurements. For a given half-angle, the penetration force increases when the diameter of the tip increases. Hardness on the other hand is inversely proportional to diameter^2. Hardness therefore increases when diameter decreases (Lee & Huang, 2015). Model results also showed that for a given diameter hardness increases with smaller half-angles (Lee & Huang, 2015). The penetration measurements are higher when the tip is embedding into the snow than when the tip is fully submerged in the snow. This will cause a tip with a smaller half-angle (and larger height) to measure a longer section of higher penetration force when submerging into a layer, than a tip with a larger half-angle (Lee & Huang, 2015). This is shown in **Figure 2.1**. Testing of the SMP tip showed that the current microstructural parameters are not capable of explaining the interaction between the ice matrix and the tip (Bellaire, Pielmeier et al., 2009). Sensitivity studies conducted by Lee and Huang (2015) found that 86% of the penetration force is accounted for by cohesion in the snow.

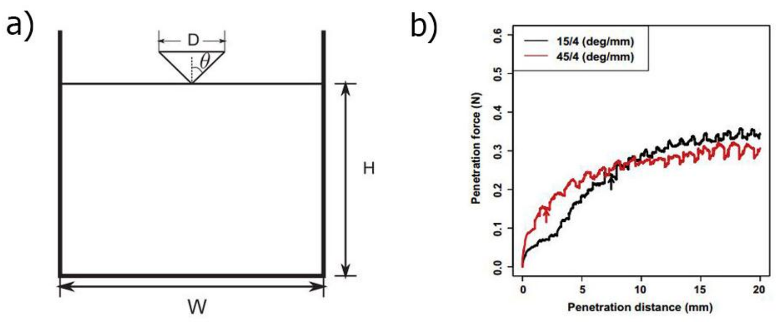

Figure 2.1.

a) Schematic figure of a penetrometer tip and the penetration process. D: diameter of the cone, θ: half-angle of the cone, W: width of snow domain, H: height of snow domain. Picture borrowed from Lee and Huang (2015).

b) Load-displacement curve for two different cones (4mm diameter, half-angle 15 (black) half-angle 45 (red)). The arrows indicate the height of the respective cone on the horizontal axis. The tip with smaller half-angle measures a longer section of higher penetration force. Picture borrowed from (Lee & Huang, 2015).

The first snow penetrometer was adapted from a cone penetration test used in soil mechanics by R. Haefeli. The penetrometer was called the swiss rammsonde and was introduced in the late 1930´s (Bader, Neher et al., 1939). Since then many attempts have been made to improve the usability and sensitivity of penetrometers (Floyer, 2008). None of the currently available penetrometers are used systematically in the field. For avalanche forecasting purposes the rammsonde remains the reference instrument (Fierz et al., 2009). At the turn of the century the snow micro penetrometer (SMP) was released (Schneebeli & Johnson, 1998). The SMP is a highly sensitive digital penetrometer where the penetration is driven by a motor. The company Avatech recently developed commercialized versions of digital penetrometers, called the SP1 and the SP2.

How to read snow properties from penetrometer signals has been an important field of research since the introduction of the high resolution penetrometer. In an avalanche perspective, the ultimate scenario is to develop a method for certain, objective assessment of snow stability. This has proven to be challenging, partly because of the complex interaction between the weak layer and the slab (Bellaire et al., 2009) and spatial variability on the slope scale that can either promote or hinder failure (Schweizer & Reuter, 2015). A measure of point stability combining the micro-structural strength and the depth of the weak layer derived from SMP data was introduced by Schweizer and Reuter (2015), addressing some of the interactions between the weak layer and the slab. Attempts to estimate slope stability from variations in point stability, however, are so far unsuccessful (Schweizer & Reuter, 2015). While most studies have used micro-structural parameters derived from SMP-signals, Floyer and Jamieson (2009) predicted fracture character using force gradients at the boundaries of weak layers identified in signals from the lower-resolution SABRE penetrometer. They suggested that higher resolution may not be necessary to identify weak snow layers.

2.4.1 Rammsonde

The rammsonde is the standard instrument for measuring hardness due to its simplicity and robustness. The ram measurements are still used by avalanche forecasters and in snowpack models (Durand, Giraud et al., 1999).

The rammsonde is a 1m long tube with a conic tip at the end. The tip has an apex angle of 60° and a maximum diameter of 40mm. Extensions can be attached to the tube to probe deeper snow packs. A hammer of weight P is used dropped on top of the probe to drive the rammsonde into the snowpack. For a certain number (n) of drops from a given drop height (h), the penetration depth increase (e) is manually recorded. The penetration resisting force (R) is calculated as $R = nhP/e + P + Q$, with Q being the total weight of the tubes (Hagenmuller and Pilloix, 2016). The depth resolution of the rammsonde depends on the snow hardness due to the fact that it is force-driven. Resolution is worse for soft snow than for hard snow, where the resolution is at best 1 cm (Pielmeier & Schneebeli, 2003). The hardness resolution depends on the chosen drop height and is limited by the weight of the tubes and the hammer.

2.4.2 Snow MicroPenetrometer (SMP)

The snow micro penetrometer measures high-resolution profiles at a fast rate. The resolution allows microstructural parameters to be interpreted from the fluctuation in the penetration force (Proksch, Löwe et al., 2015; Satyawali, Schneebeli et al., 2009). It is mainly used for research purposes due to its high cost and fragility.

The SMP drives a measuring tip vertically down in the snow with a motor at a constant speed of 20 mm s^{-1}. At this speed it records 250 force measurements per mm. The conic tip has an apex angle of 60° and a maximum diameter of 5 mm. The depth accuracy is around 1cm, due to movement of the motor when hitting hard layers. The force sensor has a resolution of 0.01 N and measures in the range 0-40 N (Hagenmuller & Pilloix, 2016). It can measure to a depth of 1.6m.

2.4.3 SP2

The Snow Probe 2 (SP2) is a lightweight snow penetrometer intended to fill the gap between the low resolution rammsonde and the costly SMP. It is constructed to be used by snow professionals and therefore favor usability and ease of transport. The SP2 is supposed to have better vertical positioning than Avatech's first penetrometer, the SP1 (Hagenmuller, Pilloix et al., 2016).

The SP2 consists of a probe with a small, conic measuring tip, measuring 6 mm in diameter and a 60° apex angle (**Figure 2.2**). The measurement length of the probe is 147 cm. The probe is manually driven down into the snow with hand power. The recommended probing speed is between 1-2 s, giving a penetration speed in the order of 1 ms^{-1}. The sampling frequency of 5000Hz gives about 3 to 7 measurements per mm which is then resampled to 1 measurement per mm. The force sensor has a measuring range from 0-28N or 0-1000 kPa (Avatech, 2016). The accuracy of the sensor is empirically determined and Avatech states that it is around ±30 kPa (±0.7N). The absolute depth accuracy is stated to be ±5cm in the range 0-50cm, ±10cm in the range 50-100cm and ±2cm in the range 100-147cm (Avatech, 2016).

The probe measures depth using a combination of the signals from an infrared sensor, an optical sensor and the force tip sensor. The infrared sensor computes the distance to the surface using reflection intensity and angle. Two optical sensors located at the bottom section of the probe helps determining ground truth in combination with the force sensor, and their outputs are used to scale the measured depth (Hagenmuller & Pilloix, 2016). An accelerometer is placed in the probe to help detect movement and to help with error messages and user feedback.

Lutz and Marshall (2014) found through studying the SP1 that the depth accuracy was displeasing. The SP1 was later recalled and the SP2 was released in January 2016, with promises of improved accuracy. Different studies have compared the SP2 to the SMP and rammsonde. The SP2 was found to have an inaccuracy of up to 20cm in depth measurements compared to the SMP (Pielmeier & van Herwijnen, 2016). The SP2 was successful in identifying the main stratigraphic features but the force sensor struggled to identify the vertical hardness variations in softer layers (Hagenmuller et al., 2016). The rapid data collection of the SP2 was found to simplify the task of observers but cannot be used singlehandedly for stability assessment (Berbenni, Chiambretti et al., 2016). Combining signals from closely placed tests using a numerical model is suggested as a way of getting correct observations (Hagenmuller et al., 2016). A matching algorithm showed success in combining several profiles from the SP1 (Hagenmuller & Pilloix, 2016).

Figure 2.2. The SP2 in its collapsed form. The conic measuring tip can be seen at the bottom of the shaft. Photo by Åsmund S. Karlsnes

3 Methods

This section is a description of the standard operating procedures of the SP2, the recording of manual snow profiles, setup of the field and lab tests and the methods used to process and analyze the data.

3.1 SP2

The SP2 requires only one operator who starts the test, pushes the penetrometer into the snow and validates the profile on the LCD screen of the device. The procedure was as follows.

1. The SP2 was assembled and turned on.
2. The SP2 was aligned vertically and held steadily 1-5cm above the undisturbed snow surface. The infrared depth sensor was faced away from the sun.
3. The test was initiated by pressing the TEST button, which triggers the probe to start recording. At this point the penetrometer calculates the air pressure. After 0.5s the probe beeps to tell you that the probe can be pushed into the snow.
4. The penetrometer was pushed vertically into the snow while trying to maintain a constant speed at around 0.7-1.3 m s^{-1}. The data collection stops after 3.0s, giving a 2.5s window for collecting data.
5. The penetrometer automatically stops the data recording at the sound of two consequent beeps. At this point the LCD screen reads *processing data*.
6. The probe was left in the snow and the depth was recorded manually from the scale on the side of the probe, to the nearest 0.5cm.
7. The profile was validated on the built in LCD screen before removing the probe.

If the probing was halted or stopped during the test, e.g. due to thick crusts or ice layers, the profile was discarded and the test redone at the same location. Profiles were also discarded and redone if error messages were generated. This could happen if the accelerometer didn’t record movement at the start of the test, if no snow surface was detected or other irregularities.

Software version V-2.1.07 was used during this study.

3.2 Manual Snow Profiles

At each site investigated snowpack, weather and site parameters were recorded. The snow profiles were done after the guidelines given by the American Avalanche Association (American Avalanche Association, 2016).

Figure 3.1. Emil Solbakken records the snow temperature after excavating the side wall at the study site at Strøngeskaret. Photo: Åsmund Karlsnes.

During the fieldwork a transect in the snowpack was dug out. The transect was dug deeper than the measurement length of the probe (>150cm) and longer than the transect of profiles taken (>220cm). The transect was dug perpendicular to the slope aspect and the vertical back wall was evened out using a snow shovel (**Figure 3.5**). The sidewall on the shaded part of the transect was evened out parallel to the slope aspect. This side wall was used when recording the manual snow profile and was dug out last (**Figure 3.1**). All the measurements were recorded by hand and then digitally recorded using the built in snow profile editor developed by Avatech. The following parameters were recorded at each site:

3.2.1 Site and Weather

The parameters recorded about the test sites were: Location (using the built-in GPS of the SP2 and manually checked on maps), elevation, slope aspect and slope angle (using a compass and inclinometer respectively).

The recorded weather parameters were: Sky condition, wind speed and direction, air temperature and precipitation. See American Avalanche Association (2016) for detailed information on these parameters.

3.2.2 Snowpack

3.2.2.1 Temperature

Temperature was measured shortly after excavating the pit wall to minimize the exposure time the snow had to air temperature. Temperature was measured every 5cm on the shaded pit wall and recorded to the nearest 0.1°C. These measurements were taken using a Comark DT400 thermometer with an accuracy of +/-0.5°C. The snow profile editor supported only steps of 0.5°C. The thermometer was horizontally pushed tip first into the snow. The snow surface temperature was measured by laying the thermometer in the shade on the snow surface.

3.2.2.2 Layers

The layer identification was done on the shaded side wall of the transect and then traced to the main transect wall. The layer identification was done by inserting and moving around an object in the snowpack to detect changes in snow hardness (**Figure 3.2**). The depth to each layer interface was determined using a fixed ruler located in the corner of the snow pit. Depth and layer thickness were recorded to the nearest cm.

Figure 3.2. Emil Solbakken during layer identification at the Hemsedal 2 study site. Layer identification was done on the side wall of the transect. The ruler was used to measure depth.

3.2.2.3 Hand Hardness

The hand hardness scale used has been discussed previously in **section 2.1.2**. and is summarized in

Table 2.1. Due to previously discussed problems with user bias the hand hardness test was performed by the same operator for all tests.

3.2.2.4 Grain form and grain size

Grain form and size of the snow crystals in each identified layer, including the snow surface, were recorded manually in the snow pit. Snow was gently scraped onto a crystal card and the grain forms were studied using a hand lens. The crystal grain forms were classified according to the International classification for seasonal snow on the ground (Fierz et al., 2009). Subclasses were included if possible to identify. The main crystal forms identified throughout the fieldwork conducted in this paper are shown in **Table 3.1**. Crystal grain size was recorded with two values: The mean grain size and the maximum grain size. The size was determined using a hand lens and the mm grids on the crystal snow card.

Table 3.1. The main crystal forms identified throughout the fieldwork. Classified after ICSI Classification for seasonal snow on the ground (American Avalanche Association, 2016).

Abbreviation	Grain type
DF	Decomposing and fragmented precipitation particles
DH	Depth hoar
FC	Faceted crystals
FCxr	Rounding faceted particles
IFil	Horizontal ice layer
MF	Melt forms
MFcl	Clustered rounded grains
MFcr	Melt-freeze crust
MFsl	Slush
RG	Rounded grains
RGxf	Faceted rounded particles

3.2.2.5 Liquid water content

The water content in each identified layer was recorded in 1 of 5 different classes (Fierz et al., 2009) using hand tests. The snow was classified as dry if making a snowball was hard, moist if snowballs were easily made, wet if water was visible using the lens, very wet if water could be squeezed out of the snow and soaked if the snow was flooded with water.

3.3 Field Measurements

The field testing of the SP2 was done at three different undisturbed locations over three days in late March 2017. At two of the locations two tests were conducted within 500m of each other. The sites were located in Sogn og Fjordane and Buskerud county, and are described in **Table 3.2** and mapped out in **Figure 3.3**.

Table 3.2. Field sites.

Date	Location	Elevation	Slope angle	Aspect	Transect name
27-March-2017	Strøngeskaret, Hemsedal	1128	21	E	Hemsedal 1
27-March-2017	Strøngeskaret, Hemsedal	1196	20	E	Hemsedal 2
28-March-2017	Øvre Salen, Filefjell	1531	22	E	Filefjell 1
28-March-2017	Øvre Salen, Filefjell	1436	22	N	Filefjell 2
31-March-2017	Svartholten, Sogndal	1131	17	E	Svartholten

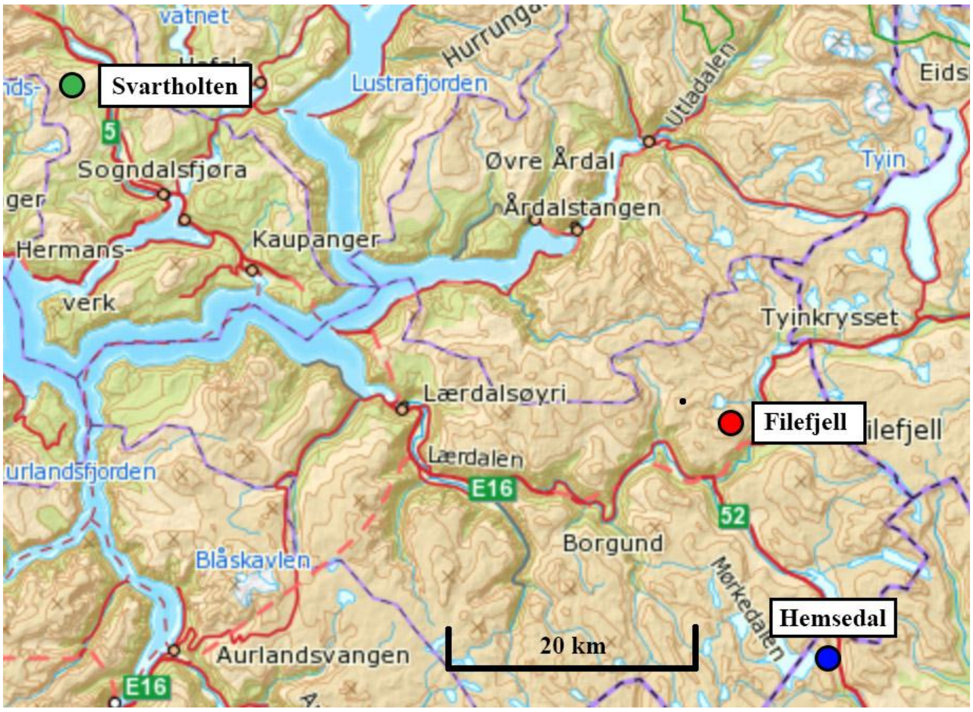

Figure 3.3. Map of field locations.

At these three sites a total of 110 valid penetrometer pushes were completed. Every location was first probed with an avalanche probe to make sure that the terrain below was even and that the height of the snowpack was the same. The data collection was done as earlier described in **section 3.1** and **0**. The same operator performed all the pushes with the SP2, while the second operator took notes and filmed the process via a static camera. Penetrometer pushes were done before digging out the transect in all but one of the locations (lower Strøngeskaret). The penetrometer tests were done along a line perpendicular to the aspect of the slope and spaced out with an interval of 10cm between each test. The tests were done along an avalanche probe with markers every 10cm (**Figure 3.4**). At each site a minimum of 22 tests were done. All the snow profiles were recorded by the same operator.

Features that could uniquely be identified in the penetrometer signals were measured at some locations to test the accuracy of the depth measurements. These features were typically pronounced crusts in the snowpack. They were measured manually with a ruler along the probe holes that were exposed after excavating the transect wall (**Figure 3.5)**. The depth to the top of these layers were measured to the nearest 0.5 cm. These depth measurements are prone to errors due to slope effect, misalignment of the ruler and parallax measurement errors, giving an estimated accuracy of ±1.5cm.

Figure 3.4. The SP2 in use by Emil Solbakken during fieldwork at Øvre Salen. A static camera records the testing. Photo: Åsmund Karlsnes.

Figure 3.5. The back transect wall at the Hemsedal 2 site at Strøngeskaret. The vertical lines in the snow are the probing holes made during SP2 probing. Photo: Åsmund Karlsnes.

3.4 Lab measurements

Two different lab tests were designed and conducted to validate different aspects of the penetrometer signal produced by the SP2. The goal of the lab tests was to be able to investigate different properties of the penetrometer in a controlled environment and with reduced sources of error.

3.4.1 Penetrometer signal in air

The first lab test was designed to inspect the penetrometer signal output when only travelling through air. The penetrometer was pushed down into an open cardboard box. A gimmick snow surface consisting of normal printer paper lay on top of the box. Probing was done according to the procedure in **section 3.1**. At the bottom of the cardboard box was a layer of hard styrofoam to stop the probing motion, and protect the tip from getting damaged. All the tests were filmed with a static camera.

3.4.3 Depth Accuracy

The second lab test was designed to test the depth accuracy of the penetrometer and investigate possible penetration rate effects. A wooden construction, seen in **Figure 3.6**, was used to place resistance markers at fixed heights. Normal printer paper was used as resistance markers. These were tightly taped to the wooden rack and replaced after each test. At the bottom of the wooden rack was a layer of industrial styrofoam to stop the motion and protect the tip. Aluminum foil was used as the surface reflector. The starting height above the surface was fixed for each test. All the tests were recorded with a static camera. The camera was placed in a position where it would be easy to identify when the probe tip hit each layer. This was done to be able to study penetration rate effects. Probing was done according to the procedure in **section 3.1**.

Figure 3.6. The construction used to test the depth accuracy of the SP2 in the lab. The printer papers work as resistance layers. The tinfoil is used as a reflector for the IR-sensor. Photo: Emil Solbakken.

3.5 Data processing and analysis

3.5.1 Goals of analysis

Processing and analysis of the collected data was done with the aim of describing the SP2's performance in terms of:

1. The accuracy of depth measurements
2. The accuracy of hardness measurements
3. Usability

By accuracy we mean how close measurements are to actual values. An important part of this is the precision, which describes the variation of the measurements. For example, the depth to a layer as measured by the SP2 in multiple profiles can be evaluated by the variation in measured depths giving the precision and the difference between the average depth and the actual depth gives the accuracy.

For depth measurements, the key elements were considered to be the determination of the surface, total depth, layer depth and layer thickness. In other words, to find out if the SP2 knows its vertical position at the start, at the end and during a test. The purpose of measuring depth is to place hardness measurements at correct depths.

Hardness measurements were evaluated on the basis of their repeatability and precision. To verify the accuracy we would need to know the true hardness or have comparable measurements from a more accurate penetrometer, like the SMP. In addition to describing the hardness variation of profiles, layers and transects, SP2 hardness was compared to hand hardness measurements.

Knowing the accuracy of measurements, we evaluated the usability of the SP2 as a tool in avalanche observation and forecasting. Since the Systematic Snow Cover Diagnosis (SSD) is used as framework for danger evaluation by the Norwegian Avalanche Warning Service, we based our approach on this method. The evaluation is found as a part of our discussion.

3.5.2 Snow cover data

A graphical presentation of the snow cover profiles was made using the online Avanet snow profile editor. To compare snow cover profiles to SP2 profiles, data tables of snow properties per mm depth were made for all transects. Data included hand hardness, primary and secondary grain type, grain size and water content. Hand hardness recordings were transformed to hand hardness index with half-steps for convenience in analysis, according to **Table 3.3**. Snow cover profiles are available in **Appendix B**.

Table 3.3. Hand hardness index classes used in this thesis.

Hand hardness	F	F+ 4F-	4F	4F+ 1F-	1F	1F+ P-	P	P+ K-	K	K+	Ice
Hand hardness index	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6

3.5.3 Penetrometer data

The output from the SP2 is profiles of penetration resistance measurements in kPa, processed and averaged for each mm depth. Another word for penetration resistance is the more general term “hardness”, which is also used throughout the thesis. In the field, profiles are shown on the built-in screen a few seconds after a test is finished, as shown in **Figure 3.7**. When profiles are uploaded to Avanet, the Avatech web portal, they are graphed as in **Figure 3.7** and can be shared with other Avanet users. Uploaded data can also be made available for download in csv-format.

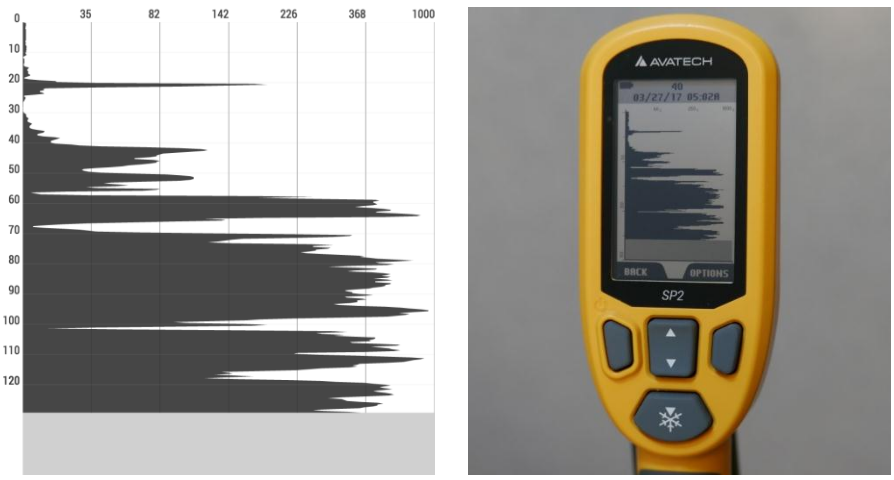

Figure 3.7. SP2 hardness profile as shown on Avanet (left) and on the built-in screen (right).

Downloaded profiles were split into separate datasets for each transect and lab session. They were then numbered, sorted and plotted according to their transect position. Note that we have referred to specific SP2 profiles in two ways. A profile ID *p[profile number]* addresses a profile from a specific day. The transect position *[1-20]* refers to a profile in a specific transect.

In order to minimize operator error, two criteria were used to validate transect profiles. The first two profiles in a transect were always rejected. If more than one profile was taken for a given position, the profile that best resembled the profiles in neighbouring positions was selected. When valid profiles were selected for 20 succeeding positions, a new dataset and a cross-section plot of hardness along the transect, based on the selected profiles, formed the basis for further analysis.

3.5.4 Video analysis

Video recordings of all the SP2 tests were analyzed to verify penetration rate and other operational aspects. In a frame-by-frame review of each test, the time from when the probe tip entered the snow to the downward motion stopped was calculated to give the penetration time. If a temporary stop was observed in a test, the test was noted as choppy. Verification was also made to ensure that the tip was in free air just above the surface when the test started. The procedure was the same for lab tests.

3.5.5 Layer identification and tracking

While methods for automatic identification of snow layers based on parameters derived from penetration resistance signals have been developed (Havens, Marshall et al., 2013; Satyawali et al., 2009), they are based on micro-structural properties measured by the highly sensitive SMP. In its current state, the SP2 is not built to measure resistance on the micro-scale, and identification of layer boundaries is a fully manual task.

We considered the tracking of layers to have three main purposes. First, the assessment of depth accuracy required identification of consistent stratigraphic features at different depths. Second, defined layers of fairly homogenous snow, identifiable in both SP2 profiles and the snow cover profile, were desired to evaluate hardness measurements. Last, to consider the usability of the SP2 in avalanche danger evaluation, the detection of potential weak layer and slab combinations was essential. Using these criteria, we selected data suited for each purpose.

To track layers along a transect in detail, we used a two-step approach as described by Kronholm et al. (2004). First, the main structures shown in the SP2 profiles were compared to the manual snow cover profile. Based on the stratigraphic sequence and the relative hardness to adjacent layers, approximate locations of layer boundaries were identified in the SP2 profiles. Exact locations of boundaries were then determined by examining each boundary on a cm-scale. Transition zones, the often gradual increase or decrease in resistance on a mm- to cm-scale around layer boundaries, were not treated separately. The transition zones are related to both snow properties, the sensor tip length (Bellaire et al., 2009) and, in averaged profiles, the processing algorithm. The boundaries were set approximately to the points of highest change in hardness gradient (change of hardness per depth), but always in favour of low values to keep the hardness in weaker layers low. Placement of layer boundaries is illustrated in **Figure 3.8**.

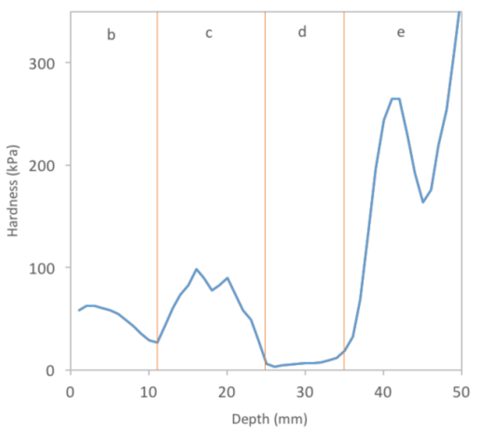

Figure 3.8. Approximate locations of layer boundaries set for a section of p40 from Hemsedal 2.

Simplified tracking was done on additional transects by following the same procedure, but for selected layers, layer boundaries or resistance peaks of interest. SP2 profiles show resistance variations on a cm-scale and less, which is far more detailed than what is obtained from a manual snow cover profile. This difference in resolution became very apparent when examining the cross-section transect plots and the associated snow cover profiles. A full delineation of identifiable layers along all transects would be preferable, but we considered trying to see clearly through numerous non-consistent crust layers and ice lenses would be time-consuming and of little value.

3.5.6 Identification of air measurements

In profiles from penetrometers like the SMP and the SABRE, the first hardness measurements are always measured in air. Identification of the snow-air interface is computed afterwards using the resistance-distance signal, as described by (Satyawali et al., 2009). The SP2, on the other hand, is set up to automatically locate the surface, which is then defined as the reference depth (depth zero). Measurements considered to be above the surface are not included in the processed profile. Precisely how the SP2 calculates the surface level is unclear, but the depth sensor, the eyes on the probe end and the accelerometer are involved (Avatech, personal communication, March 30, 2017).

In a lab setup we measured profiles in free air to see what the typical signal looks like. These signals were compared to the signals obtained in the field, in profiles where the surface signal was obvious. We could then use the observed typical hardness range and variation to manually estimate surface depths in profiles with softer surface snow.

3.5.7 Measures of accuracy

3.5.7.1 Layer depth

The depth from the defined surface of a profile to a layer is in the SP2 user manual referred to as the absolute depth. Absolute depth accuracy can be described by the variation in depth measured by the SP2 to a certain layer, and the difference between measured depth and actual depth.

3.5.7.2 Layer thickness

In terms of accuracy, the thickness of a layer can be generally defined as the difference in depth between any two data points in a profile, also called the relative depth (Avatech, 2016). The accuracy of the relative depth depends on the absolute depth accuracy of those two points.

3.5.7.3 Repeatability

The repeatability of hardness measurements is here regarded as a measure of whether identical hardness profiles would be produced from identical snow covers. This is only hypothetical due to the variable nature of the snow stratigraphy, where the degree of variation will depend on the scale. Spatial variability of micro-structural strength, which is related to the hardness, are found to be less for weak layers than slabs (Bellaire & Schweizer, 2011; Kronholm et al., 2004). A direct comparison of hardness between profiles is not productive, as the depth measurements are not accurate.

3.5.7.4 Statistical measures

Accuracy and precision are described using basic descriptive statistics. For a single sample, the mean and the standard deviation (SD) represents the expected value and the expected spread of values, respectively. If the sample data is normally distributed, the 95 % confidence interval is given. To test for normality the Shapiro-Wilk test was used. The coefficient of variation (CV) is also used to describe dispersion of hardness samples to compare variation in samples with different means.

For a group of samples, for instance hardness measurements of the same layer across a number of profiles, the mean of the sample means describes the expected layer mean and the standard error of the mean (SEM) describes the dispersion.

3.5.8 Evaluation of usability in terms of the Systematic snow cover diagnosis (SSD)

As described in section **2.3**, the Systematic snow cover diagnosis is a methodical approach to assess stability by evaluating the properties of the most prominent weak layer. The output is an estimate of both the strength and the prevalence of the weak layer, using snow processes as a key element. By focusing on the layers that influence stability the most, less time is used in each pit, which allows more pits in a larger area. The SP2 is developed to help avalanche professionals find and map avalanche problems even more efficiently, potentially reducing the need for digging while allowing mapping of the spatial variability with a significantly higher resolution.

To investigate how the SP2 can be used in the framework of the SSD, we first looked at each step of the analysis to identify how the use of a penetrometer in general could make an improvement. We then evaluated the SP2's ability to perform each of the specified tasks, addressing strengths and weaknesses using examples from our field data.

4 Results

4.1 Field data

4.1.1 Transect data

For all five transects, a minimum of 22 profiles and a detailed snow cover profile was collected. All SP2 transect profiles and snow cover profiles are presented in **Appendix C** and **Appendix B**. A total of 139 profiles were collected to produce 110 valid profiles. Hard crusts causing either a shallow test or a very variable penetration rate were the main issue leading to expected non-valid tests.

4.1.2 Snow conditions

Locations were chosen in hope of finding dry snow covers where potential weak layers were present. Early winter was on all field sites dominated by less amounts of snow than normal, partly due to events of warm temperatures and rain. The dry and cold weather that followed caused refreezing, and faceted layers formed high up in the snow cover. More precipitation as snow in late February and March buried these layers, and locally also layers of surface hoar, causing widespread instabilities in the Hemsedal and Filefjell area. By the time of our field trips, warming of the snow cover and partly refreezing had significantly increased stability.

The snow covers investigated was on overall characterized by a thick layer of frozen, old meltforms overlaid by moist to wet rounded and faceted snow. Multiple melt-freeze crusts, thin ice layers and ice lenses were present in the upper layers. Rounded or partly melted faceted crystals were found around the most prominent crust layers. The field day in Hemsedal was warm, causing wetting and the presence of free water in the uppermost layers. On Filefjell, the higher pit revealed a completely dry snow cover less affected by melt-freeze processes. The previously critical weak layers in the area were either not found or, as was the case for most of the faceted layers, found to be in a state of rounding or melting.

4.2 Lab data

From the first lab setup, where penetrometer signals in air were measured, 10 profiles were collected. In the second lab setup, where depth accuracy was addressed, 20 profiles were collected.

4.3 Accuracy of depth measurements

4.3.1 Surface determination

Of 66 profiles in which the surface layer is hard an easily observable, 55 have the surface defined above the actual surface. This is seen in Figure 4.1, where measurements above the observed surface are in air and are distinguishable from the snow measurements below.

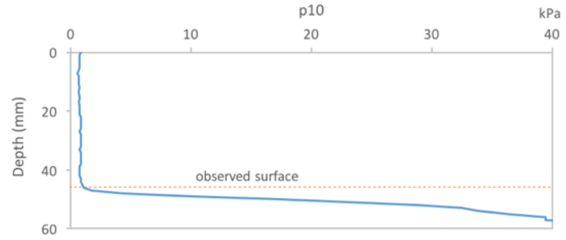

Figure 4.1. Example of manually identified surface depth in a profile from where the surface layer was hard.

The remaining 11 profiles show high hardness from the beginning, indicating that the surface is defined below the actual surface and that the first snow measurements are missing in the profiles. Observed surface depths are plotted in **Figure 4.2**, with the unknown negative surface depths plotted with depth equal to zero. Including the zeros, the mean surface depth is 37 mm and the standard deviation 35 mm. If the negative values were known, the mean would probably have been closer to zero and the standard deviation slightly higher.

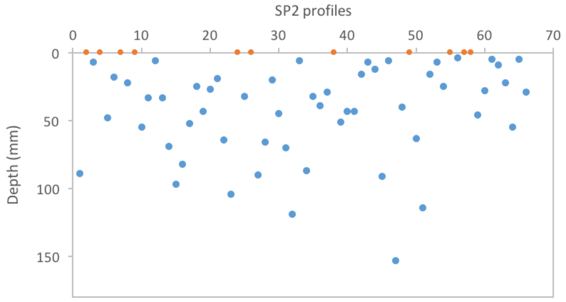

Figure 4.2. Scatterplot of observed surface depths. Orange dots represents profiles where the measured surface is above the defined surface.

In lab measurements, using aluminium foil as the surface reflector and a sheet of paper as the surface resistance, the force measurements corresponding to the top layer of paper is only observable in 5 of 20 profiles and the maximum observed surface depth is 9 mm. The small number of observations indicates that the mean surface depth is negative.

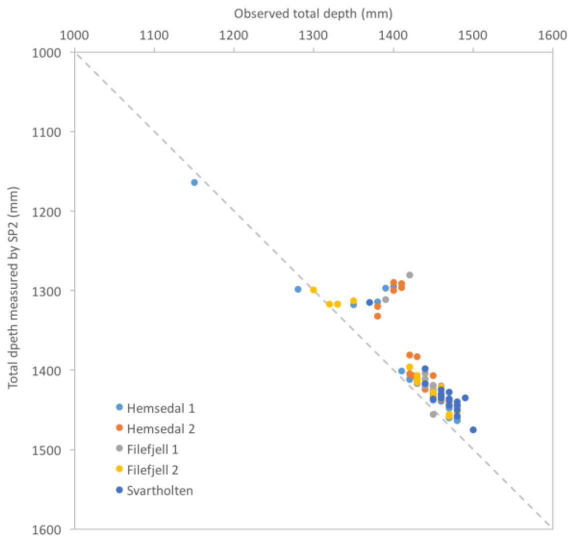

Figure 4.3. Total depth measured by the SP2 plotted against manually measured total depth. The dotted line marks the one-to-one ratio.

4.3.2 Total depth

Figure 4.3 shows how the total depth measured by the SP2 matches the manually measured total depth. The mean difference between SP2 total depth and observed total depth is -32 mm with a standard deviation of 27 mm. While the depths larger than 1400 mm are nicely clustered, something is going on in the range from approximately 1350 to 1400 mm. There are no SP2 total depths measured in this range, despite observed depths covering the same range.

4.3.3 Depth to layers

Figure 4.4 shows the depth measured by the SP2 to tracked layers in the Hemsedal 1 transect. The stratigraphy was in general observed to be more or less parallell to the surface. Negative surface depths are plotted as zero. Layers **b** - **d** are thin crust layers, plotted by the depth of their respective resistance peaks.

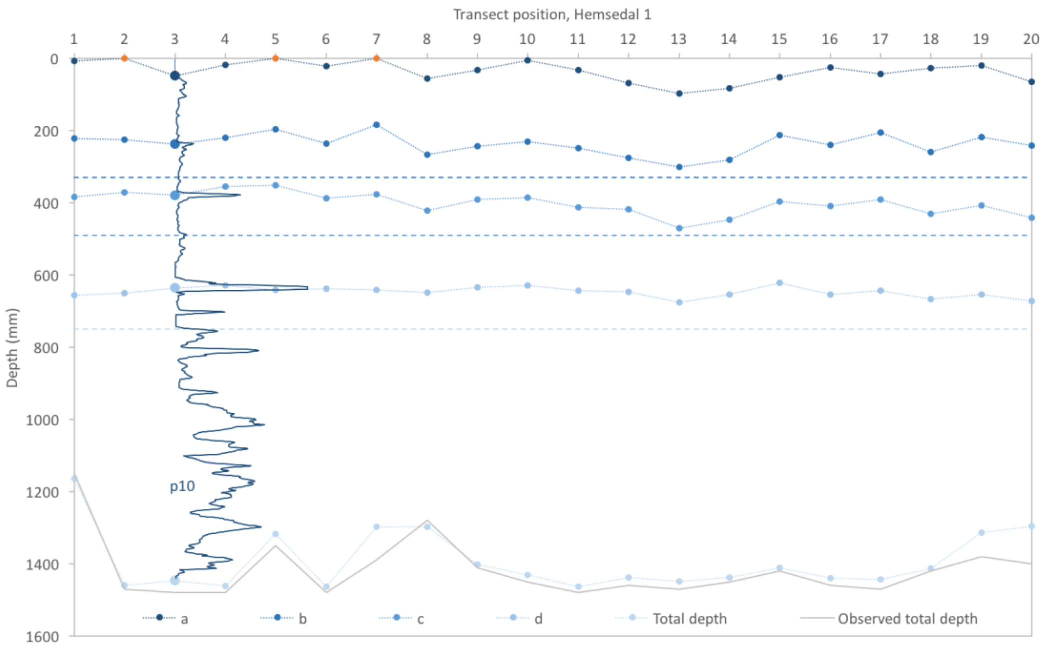

Figure 4.4. Depth to surface (layer a) and three thin crust layers (b-d) along the Hemsedal 1 transect, identified in SP2 profiles. Depth to the peak hardness of each layer is used, tracked signal features are shown in profile p10. The dotted lines represent depth to the crust layers as recorded in the snow cover profile.

In Filefjell 1, depth to the upper boundary of a consistent ice layer was manually measured at each transect position. The same boundary was identified and tracked in the SP2 profiles. As seen in **Figure 4.5**, the measured depth was less than the actual depth in all profiles. Actual depth was measured to be between 39 and 41 cm, with a mean of 39.5 cm, while the mean depth measured by the SP2 was 31 cm, with a standard deviation of 3 cm.

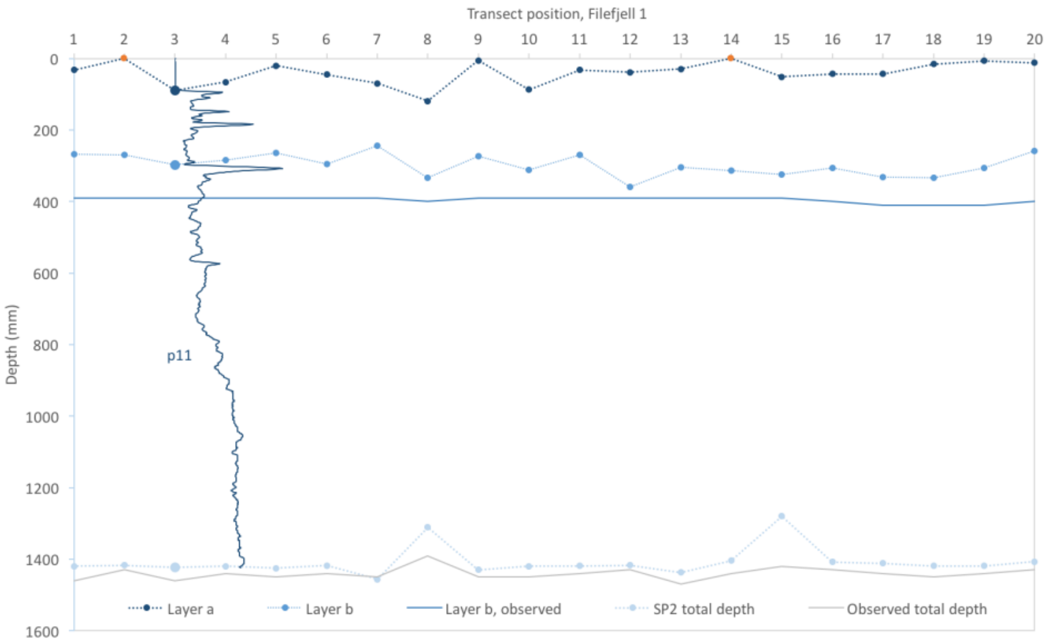

Figure 4.5. Depth to surface (a) and the upper boundary of a crust layer (b) along the Filefjell 1 transect, identified in SP2 profiles. The solid line shows the actual depth to layer b, manually measured at each position. Tracked signal features are shown in profile p11.

In the Hemsedal 2 transect data 10 different snow layers that could be traced across the SP2 profiles were identified, whereas nine of them could be matched with the manual snow cover profile. **Figure 4.6** shows how the identified layers are distributed in each profile and are compared to the manual snow cover profile. Depth measurements to the upper boundary of each layer are given in **Table 4.1**. Overall, the mean layer depths along the transect are close to the layer depths in the snow cover profile, with a maximum mean difference of 6 cm (layer **g**) and a mean of under 2 cm. The depth measured to layers **c-e** are slightly on the short side, while layer **g-k** are measured below. However, that the mean is precise does not reflect the variation in depth along the profile, which is shown by the standard deviations of the mean layer depths ranging from 4 to 6 cm.

The amount of air measurements is generally high and seems to vary a lot, and should only be considered as possible air measurements due to difficulties in distinguishing between air and soft, wet surface snow.

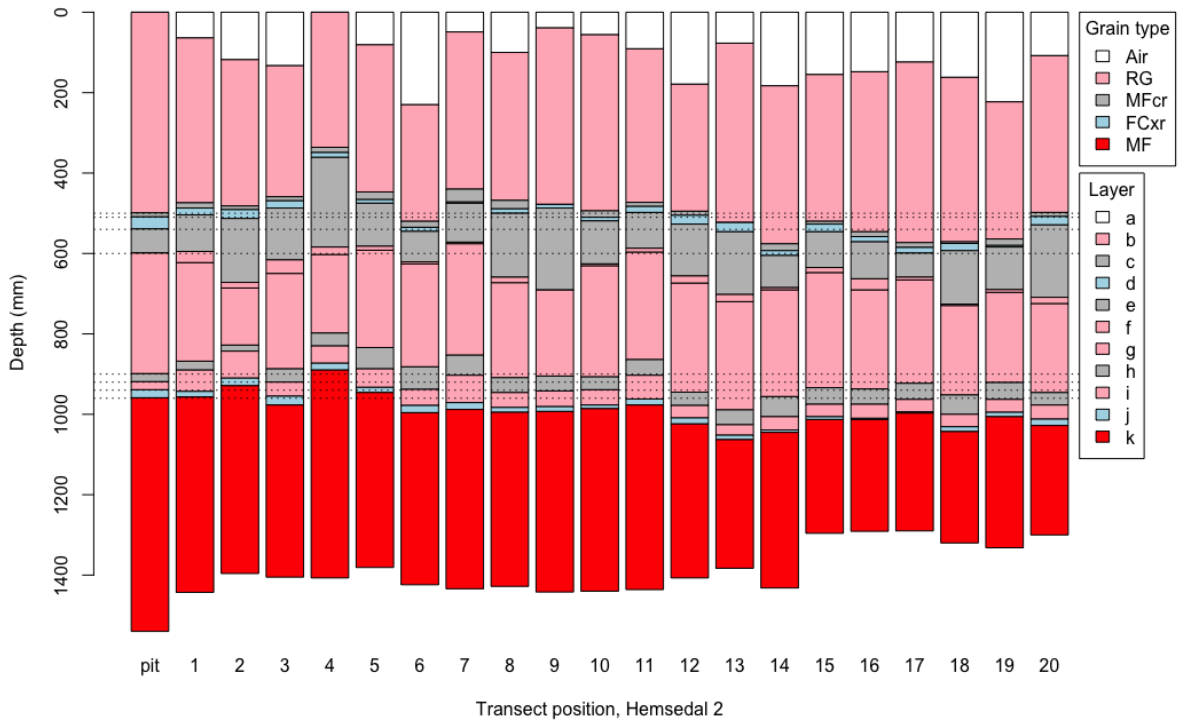

Figure 4.6. Stacked barplot showing the depth to and thickness of layer b-k identified in SP2 profiles from the Hemsedal 2 transect. The bar labeled "pit" shows the stratigraphy manually recorded in the snow cover profile, with layer boundaries extended as dotted lines. Layer a represents possible air measurements, since the surface could not be identified with certainty.

4.3.4 Thickness of layers

Considering layer **a** - **d** in Hemsedal 1 (**Figure 4.4** and **Table 4.1),** where the absolute depths vary but mostly in the same direction, the relative depths vary less than the absolute depths. In Filefjell 1 (**Figure 4.5** and **Table 4.1**), the variation in depth to layer **a** and **b** does not coincide to the same extent, and the relative depth varies more than the absolute depths. In Hemsedal 2, the crust layer **e** is on average measured to be twice as thick as observed in the field and also shows large variation. The other layers have more consistent thicknesses, and as in Hemsedal 1 the absolute depths vary in similar patterns.

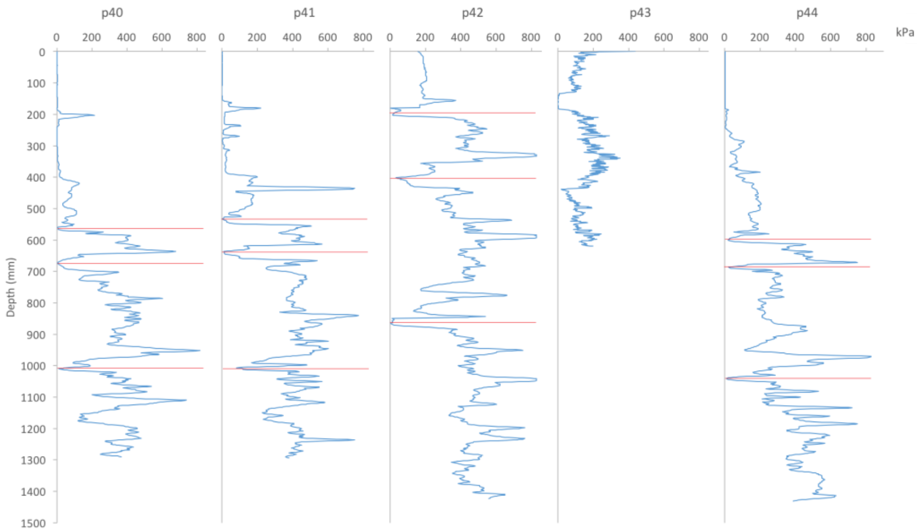

Figure 4.7. Successive profiles from Hemsedal 2 showing signs of depth scaling. The red lines mark three consistent stratigraphic features.

Figure 4.7 shows five successive profiles from Hemsedal 2, observed to have a total depth of 1410-1480 mm. **p42** and **p43** stand out and were regarded as unvalid when briefly examined during testing. The execution of the two tests are from video recordings confirmed not to differ in any major way from the adjacent tests. Though extreme cases, they can be used to illustrate some issues connected to depth measurements. The signal in **p42** appear stretched out; every section of the profile is prolonged compared to the "normal" profiles, and the upper section stretches above the defined surface. **p43** seems compacted, though it is difficult to identify the same sections.

The thinnest layer recorded in Hemsedal 2 is layer **c**, manually recorded as a 10 mm melt-freeze crust. Mean thickness in SP2 profiles is 14 mm with a standard deviation of 6 mm. The thinnest soft layer is layer **j**, a 20 mm faceted layer, measured by the SP2 to a mean thickness of 13 mm and a standard deviation of 5 mm.

Measured depths to the paper layers in lab 2 are shown in **Figure 4.8**. The surface layer is only present in five profiles. The accuracy of the depths measured to layer **b** and **c** is far off, while layer **d** and **e** are precisely determined. By analysing video recordings, the time between each hit of a layer boundary was determined for all profiles. Comparing this to the actual thickness of the layers, the penetration rate was found to vary. In **Figure 4.9** the average penetration rate through layer **b** and **c** is compared to the measured layer thicknesses. The result indicates that varying penetration rate may explain some of the variation in measured layer thickness.

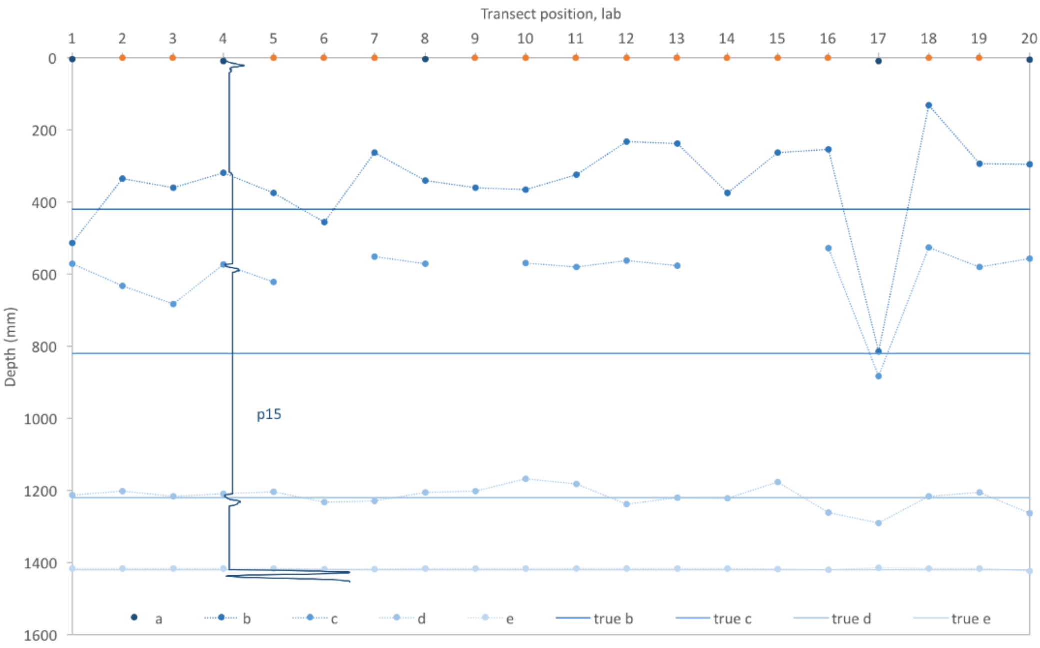

Figure 4.8. Depth measured by the SP2 compared to actual depth in a lab setup. The signal from layer c was missing in four of the profiles. p15 shows the tracked SP2 signal features..

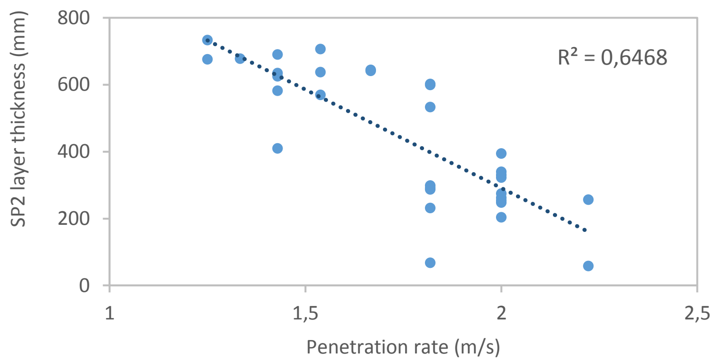

Figure 4.9. Measured thickness of layer b and c plotted against the average penetration rate through the layer in each test. The regression line indicates that measured layer thicknesses are affected by changes in penetration rate.

Table 4.1. Summary of depth measurements. N is the number of layer observations, with the total number of profiles in parenthesis. Layer depth is the manually measured depth to the upper boundary of the layer. 95 % confidence interval is given for normal distributions (p > 0.05, Shapiro-Wilk).

				SP2 layer depth						SP2 layer thickness				
Transect	Layer	N	Layer depth (mm)	Max	Min	Mean	SD	95 % conf. int.	Layer thickness (mm)	Max	Min	Mean	SD	95 % conf. int.
All transects	Surface	55 (66)	0			37	35							
Hemsedal 1	a	17 (20)	0	97	0	35	28	± 55	330	233	161	202*	19	± 37
	b	20 (20)	330	300	183	237*	29	± 57	160	199	135	164*	19	± 37
	c	20 (20)	490	470	351	401*	31	± 60	260	290	206	246*	23	± 44
	d	20 (20)	750	676	621	647*	14	± 28						
Hemsedal 2	b	20 (20)	0	230	0	116**	61**	± 120**	500	449	290	381**	45**	± 88**
	c	18 (20)	500	576	336	496	60	± 118	10	32	4	14	6	± 12
	d	20 (20)	510	593	349	509	56	± 110	30	23	3	14	6	± 12
	e	20 (20)	540	605	361	523	56	± 110	60	223	60	123	44	± 86
	f	19 (20)		726	572	644	47	± 92		34	4	14	9	
	g	20 (20)	600	730	576	660	46	± 90	300	286	142	242	34	
	h	20 (20)	900	989	798	902	49	± 96	20	56	15	38	10	± 20
	i	20 (20)	920	1026	830	940	52	± 102	20	68	26	41	12	
	j	20 (20)	940	1052	873	981	44	± 86	20	22	3	13	5	± 10
	k	20 (20)	960	1063	890	993	41	± 80		517	272			
Filefjell 1	a	18 (20)	0	119	0	40	33	± 64	395***	328	189	269	39	± 77
	b	20 (20)	395***	367	259	310	30	± 58						
Lab 2	a	5 (20)	0	9	0	1			420	806	132			
	b	20 (20)	420	815	132	345	138		400	394	58	257	89	
	c	16 (20)	820	882	526	598	85		400	733	409	622	77	± 152
	d	20 (20)	1220	1291	1168	1218	30		400	249	124	200	29	± 57
	e	20 (20)	1420	1424	1415	1417	2							

*) SP2 depths are to the peak hardness, layer depth to the upper layer boundary. Expected difference 10-40 mm.
**) Based on a surface identification involved with some uncertainty.
***) Average depth. Manually measured layer depth varied from 390-410 mm.

4.4 Accuracy of hardness measurements

4.4.1 Sensor accuracy and hardness resolution

The accuracy of hardness measurements is in the SP2 user manual specified to be ± 30 kPa. This is empirically determined, and the force sensor has from the manufacturer an accuracy equivalent to +/- 15 kPa (Avatech, personal communication, March 30, 2017). It is not stated if this applies regardless of the magnitude of the hardness measured. Because the hardness output is an average of the input from the force sensor, the true variation in measurements is not observable. If the average is based on the number of observations per mm depth, this gives approximately 3-6 observations per mm with the stated force recording frequency of 5000 Hz, penetration time 1-2 s, maximum penetration depth and assuming constant penetration rate. The relatively low number of observations might indicate that hardness measurements are sensitive to variations in penetration rate.

Extracting unique values of hardness from a dataset, we observed that the averaged hardness seems to be rounded according to a fixed range of values. This may explain some of the uncertainty added by processing. **Figure 4.10** shows the resolution of the hardness measurements, found as the difference between unique observed values in data from Svartholten.

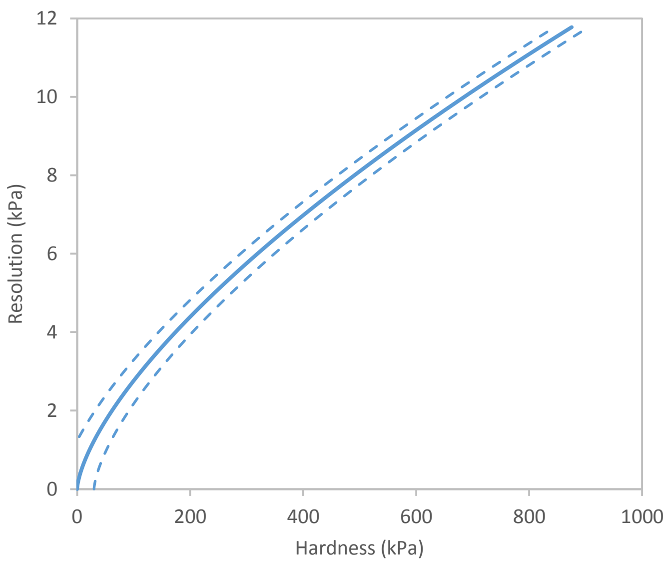

Figure 4.10. The resolution of hardness measurements depends on the absolute hardness. Obtained from observed unique values in the Svartholten dataset. The dotted lines show the absolute hardness ± 30 kPa, which is the stated accuracy.

4.4.2 Air measurements

Hardness measurements in air from 10 lab profiles are shown in **Figure 4.11**. The signals oscillate in a seemingly random manner within the range 0.5-2.5 kPa. The mean hardness is 1.45 kPa and the standard deviation 0.33 kPa, measured over a distance of 300 mm. Some disturbance is present down to 40 mm depth, where 5 profiles show various distances of zero hardness. Signals from field tests resemble the lab signals, as seen in Figure 4.12 with measurements from Filefjell 1. Each signal is cut at the depth where the surface was located. The mean (2.0 kPa) and the dispersion (SD=0.93 kPa) are higher than measured in the lab, but are affected by the large variations down to ~ 40 mm depth and signals of limited depth. There is also some uncertainty related to the manual identification of the snow surface.

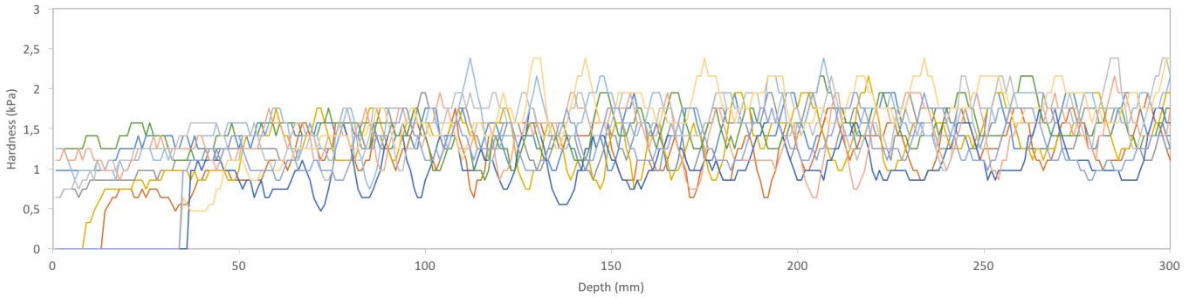

Figure 4.11. SP2 profiles of hardness measured in lab tests without any resistive layers.

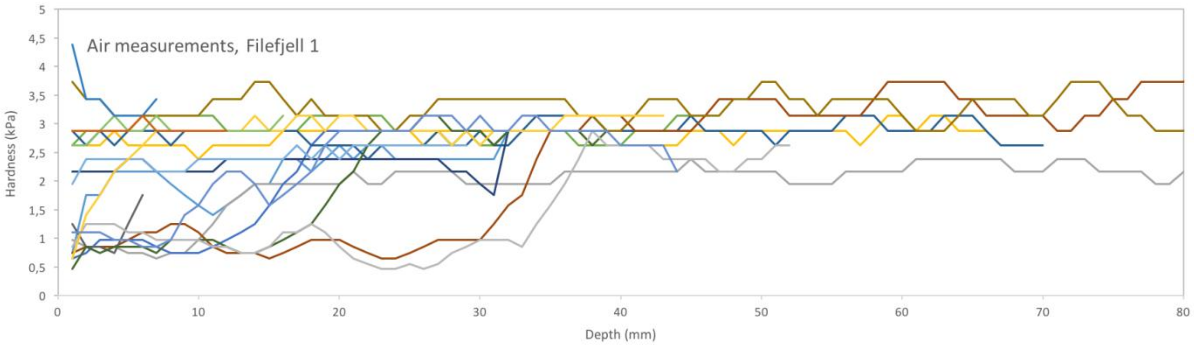

Figure 4.12. SP2 profiles of hardness measured in air at Filefjell 1. The profiles are cut at the determined air-snow interface.

Air measurements and some of the surface signals in profiles from Hemsedal 2 are shown in **Figure 4.13**. The coloured profiles show signals that first look more or less like typical air signals, then hardness decreases to below-air values before eventually increasing to what can be considered to be certain snow measurements.

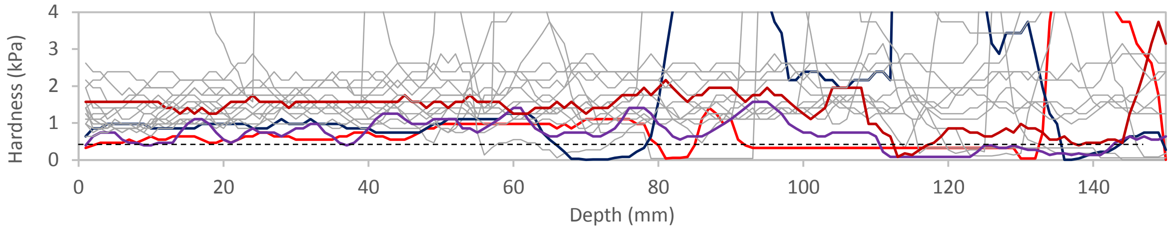

Figure 4.13. Signals from the upper 150 mm of the Hemsedal 2 transect profiles. Typical air measurements are observed to be between 0.5 and 3 kPa. The coloured profiles show examples of typical air-signals followed by a decrease in hardness. The dotted line represents the lower limit of the measurements believed to be in air.

4.4.3 Soft snow

Hardness in layer **b** in Hemsedal 2 was manually observed to have consistent hand hardness 3-4 (index). SP2 profiles show very variable hardness, and long sections of low hardness are observed to be below air hardness values, as shown in **Figure 4.14**.

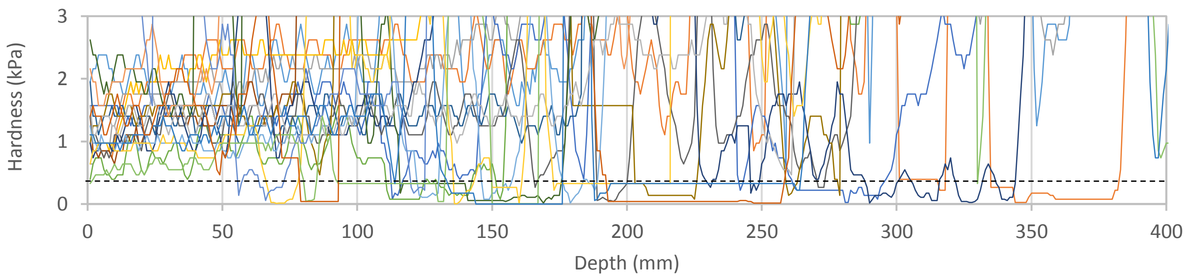

Figure 4.14. Signals from the upper 400 mm at Hemsedal 2. The dotted line shows the observed lower limit of air measurements. Lower values are repeatedly measured inside the upper snow layers.

At Svartholten, a 12 cm layer of unbounded new snow was found over a hard and thick melt-freeze crust. **Figure 4.15** shows the first 10 cm of the transect profiles. The signal corresponding to the hit of the hard layer is easily identifiable. In many of the profiles, a small peak followed by consistent measurements noticeably higher than air measurements is observable before (above) the crust signal. These measurements are probably from the soft surface layer and have values in the range 0-15 kPa.

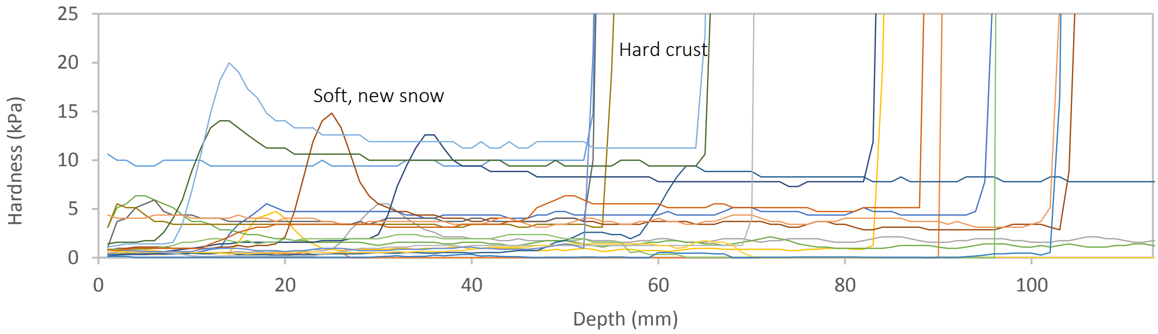

Figure 4.15. SP2 profiles of hardness measured in soft snow of hand hardness 1F above a melt freeze crust at Svartholten. Small peaks in hardness is observed right after the probable surface signal.

4.4.4 Repeatability

Visually examining the transect profiles, the signal shapes and magnitudes seem in general to correlate well on the profile scale. In sections of profiles where variable meltforms, crusts and ice lenses are expected, fewer similarities are observed. The difference in signal character between homogenous, dry winter snow and an old pack of meltforms can be seen by comparing the lower parts of the profiles in **Figure 4.16** and **Figure 4.17**. While the profiles from Filefjell 1 show similar signal shapes and hardness values, the profiles from Hemsedal 1 have similar shapes but a significant and consistent difference in the measured hardness. In both figures the profiles are from adjacent transect positions.

While the numbers are not very meaningful themselves, comparing the cumulative hardness measured for the Hemsedal 1 (**Figure 4.16**) and Filefjell 1 (**Figure 4.17**) transects show some interesting differences probably related to both the snow cover characteristics and the SP2 measurements. From the wet and vertically variable snow cover in Hemsedal 1 there are large and seemingly random variations in measured hardness between profiles. Less variation is seen in Filefjell 1. Here the snow cover was dry and more homogenous, and the cumulative plot shows small differences and a slight progressive increase in hardness along the transect. In Hemsedal 1, there is also an example of what looks like up-scaled hardness. The large difference in hardness between **p23** and **p24**, and their positions 10 cm apart, indicate that the differences can not only be related to snow variability.

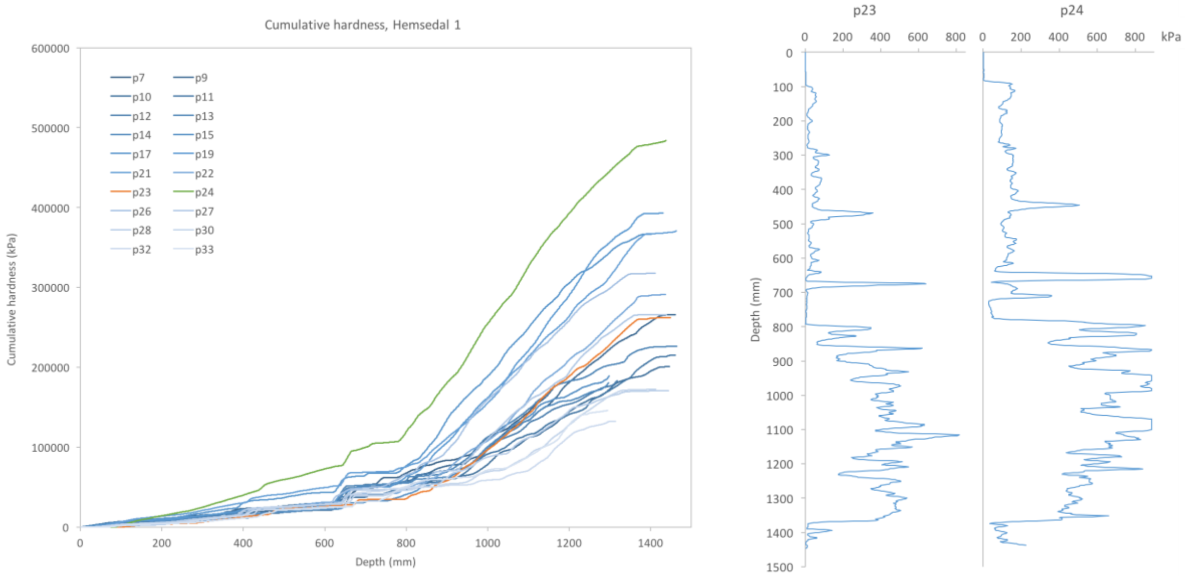

Figure 4.16. Hardness differences between profiles in wet, variable snow in Hemsedal 1 are observable in profile plots (right) and a plot of cumulative hardness (left). Profiles p23 and p24 are from adjacent positions.

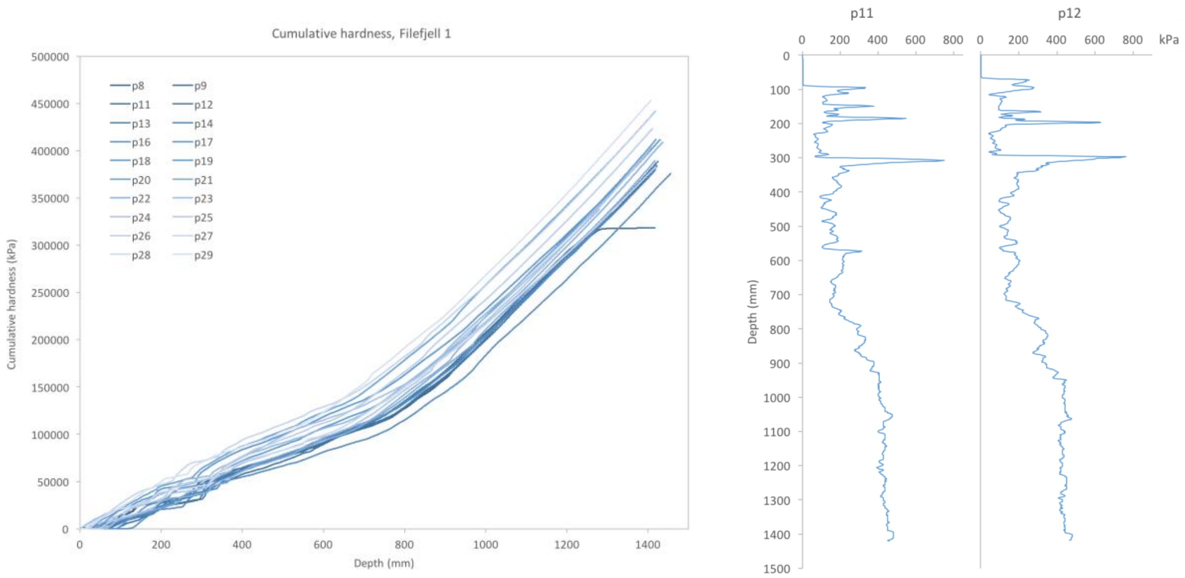

Figure 4.17. Cumulative hardness (left) and profile plots (right) showing hardness differences between profiles in dry, homogenous snow at Filefjell 1. Profiles p11 and p12 are from adjacent positions.

A distance of constant hardness is observed in some profiles where a hard crust layer was penetrated. **Figure 4.18** shows two examples from Svartholten. Constant hardness is present in profiles observed to be “choppy” as well as in profiles regarded as fine with respect to penetration rate. As for the profiles from Svartholten in **Figure 4.18**, the measured hardness is

863 kPa and 829 kPa respectively, and close to the upper hardness limit, but constant hardness is also observed for lower values.

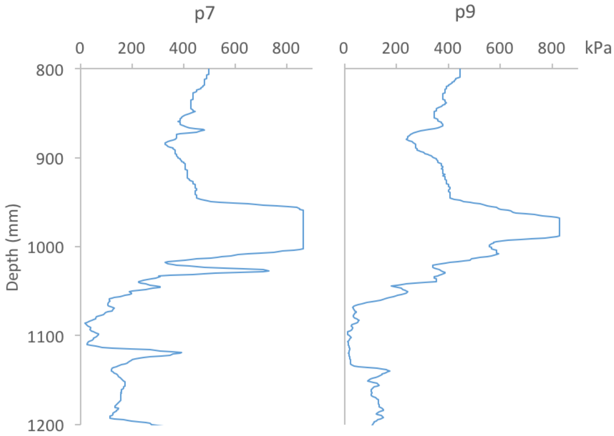

Figure 4.18. Sections of SP2 profiles where constant hardness is measured when penetrating the same hard layer at Svartholten.

4.4.5 Layer variability

To see how the measured hardness of a layer varies on a transect scale, we analyzed the identified and tracked layers in the Hemsedal 2 transect. Hardness distributions for each layer in each profile are available in **0**. Mean hardness, standard deviation and coefficient of variation (CV) were calculated for each sample. **Figure 4.20** and **Figure 4.21** show the distributions of means and CV. The means show the variation in mean layer hardness from profile to profile, and the CV represents the hardness variation inside each layer relative to the mean. Total layer means and dispersions for the full transect are summarized in **Table 4.2**.

The largest absolute variation in layer means is found for the melt-freeze crusts (layer **c**, **e** and **h**). Thin and soft layers have the least (layer **d**, **f**, **j**), but also for layer **b** the means are relatively consistent. Layer **k**, which consists of old meltforms and appears very messy in hardness profiles, also shows a low absolute dispersion of means. The lowest dispersion of means relative to the total layer mean is in fact found for layer **k**, having a relative standard error of the mean of 1.7 %. Large relative variation is found among the softer layers **b**, **d** and **j**, where layer **j** has the largest with a relative SEM of 27 %.

While layer **b** has relatively consistent means, it has the highest dispersion in each sample with most CV's between 100 to 150 %. Layer **g** and **k** show consistent and low CV's, meaning that the measured hardness is fairly close to and equally distributed around the mean in each sample. For layer **j**, which had the largest relative dispersion of hardness means, the variation in CV among the samples is also high. Sample distributions of layer **j** are shown in **Figure 4.19**. Layer hardness is consistently measured below 30 kPa and within a range of 20 kPa in all but one sample.

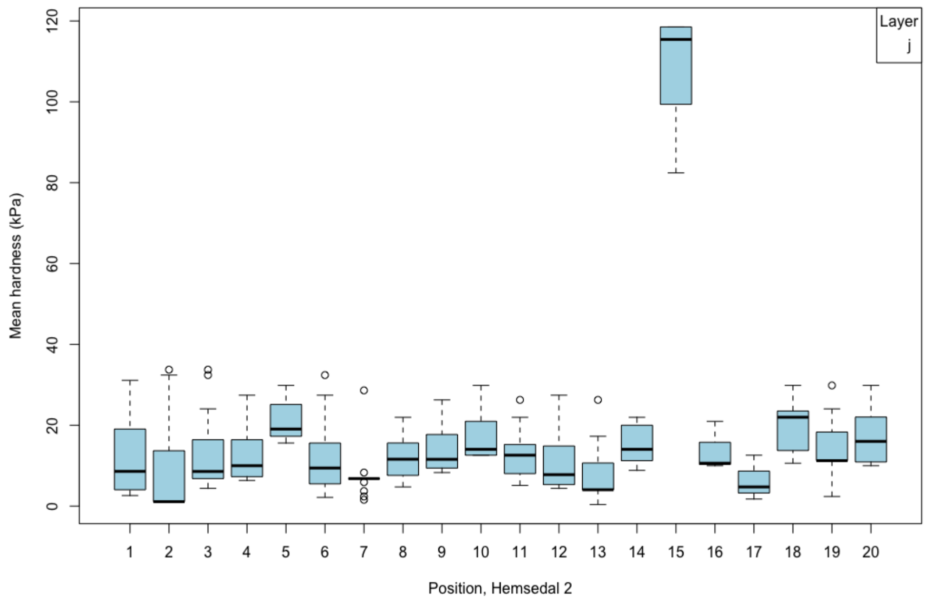

*Figure 4.19. Boxplots of hardness measurements of layer j at each transect position. Lines represent the median and boxes span the interquartile range (IQR). Whiskers extend to the maximum and minimum values, but maximum 1.5*IQR away from the median. Values further away are defined outliers, shown as small circles.*

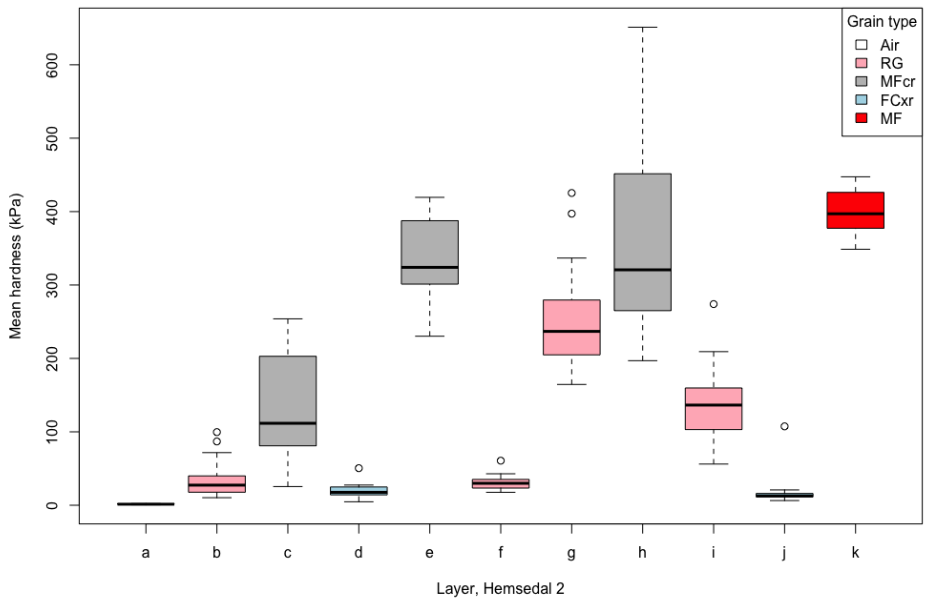

*Figure 4.20. Boxplots showing distributions of mean hardness for each layer in the Hemsedal 1 transect. Mean, SEM and number of observations are given in Table 4.2. Lines represent the median and boxes span the interquartile range (IQR). Whiskers extend to the maximum and minimum values, but maximum 1.5*IQR away from the median. Values further away are defined outliers, shown as small circles.*

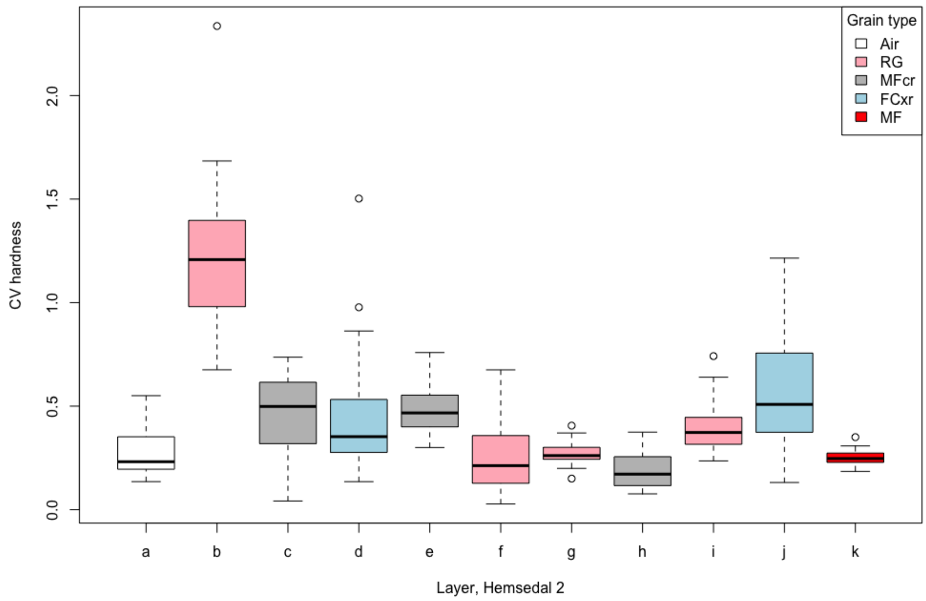

*Figure 4.21. Boxplot showing distributions of coefficient of variation (CV) for each layer in the Hemsedal 1 transect. The number of observations for each layer is given in Table 4.2. Lines represent the median and boxes span the interquartile range (IQR). Whiskers extend to the maximum and minimum values, but maximum 1.5*IQR away from the median. Values further away are defined outliers, shown as small circles.*

Table 4.2. Summary of hardness measurements at Hemsedal 2. (n is the number of layer samples, mean hardness is the mean of the sample means, SEM is the standard error of the mean hardness, relative SEM is the standard error divided by the mean hardness, mean CV is the mean of the sample CV's)

Transect	Layer	n	Mean hardness (kPa)	SEM (kPa)	Relative SEM	Mean CV	Primary grain type	Hand hardness index	Water content
Hemsedal 2	a	19	1,5	0,1	0,067	0,28	Air	-	-
	b	20	35,1	5,6	0,160	1,24	RG*	3.5*	W*
	c	18	132,0	17,0	0,129	0,46	MFcr	5	W
	d	20	19,3	2,2	0,114	0,46	FC	2.5	V
	e	20	334,5	11,6	0,035	0,49	MFcr	5	V
	f	19	30,8	2,3	0,075	0,28	RG	4	W
	g	20	252,9	15,8	0,062	0,27	RG	4	M
	h	20	363,0	27,7	0,076	0,19	MFcr	5	M
	i	20	138,5	11,2	0,081	0,40	RG	3	M
	j	20	17,8	4,8	0,270	0,57	FC	2	M
	k	20	398,4	6,8	0,017	0,25	MF	5	M

*) Generalised values, layer b represents several manually recorded layers that could not be discriminated in SP2 profiles.

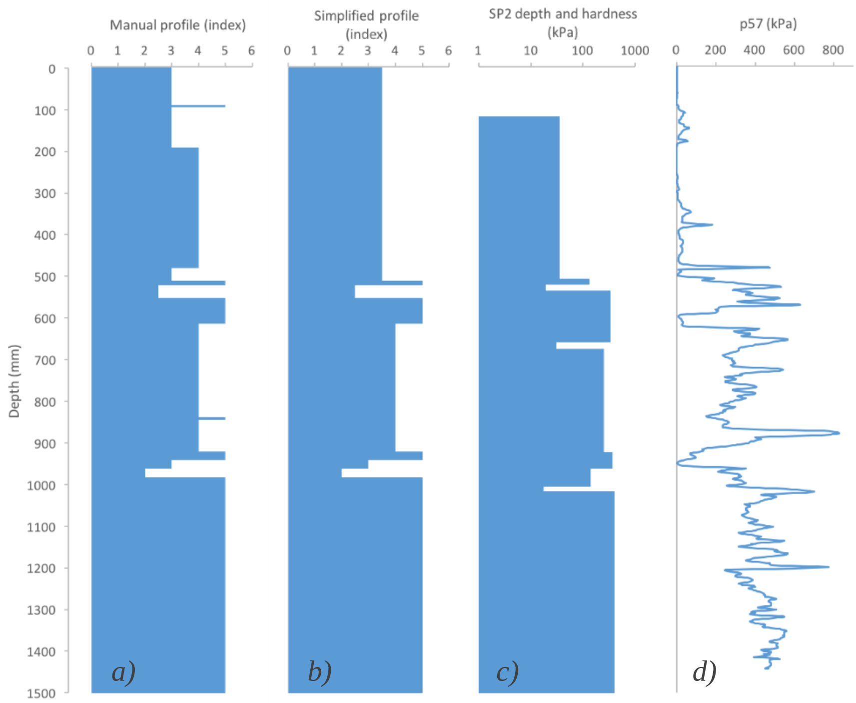

Figure 4.22. Comparison of hardness profiles obtained for the Hemsedal 2 transect. a) The manual hand hardness profile. b) Simplified manual hand hardness profile only containing layers identified in SP2 profiles. c) Mean layer depths and hardness as measured by the SP2 along the transect. d) SP2 profile from position 1, next to where the manual snow cover profile was recorded.

4.4.6 Correlation to hand hardness

Hand hardness profiles and SP2 profiles in each transect are plotted side by side and can be found in **Appendix C**.

A simple correlation of hardness measured by the SP2 and manually measured hand hardness is performed using the Hemsedal 2 transect data. **Figure 4.23** shows hardness measurements plotted by the corresponding hand hardness index for all the identified layers. The means show a positive trend, which indicate that increasing SP2 hardness is related to increasing hand hardness. Note that this is only a presentation of the data; the relationship is not statistically determined.

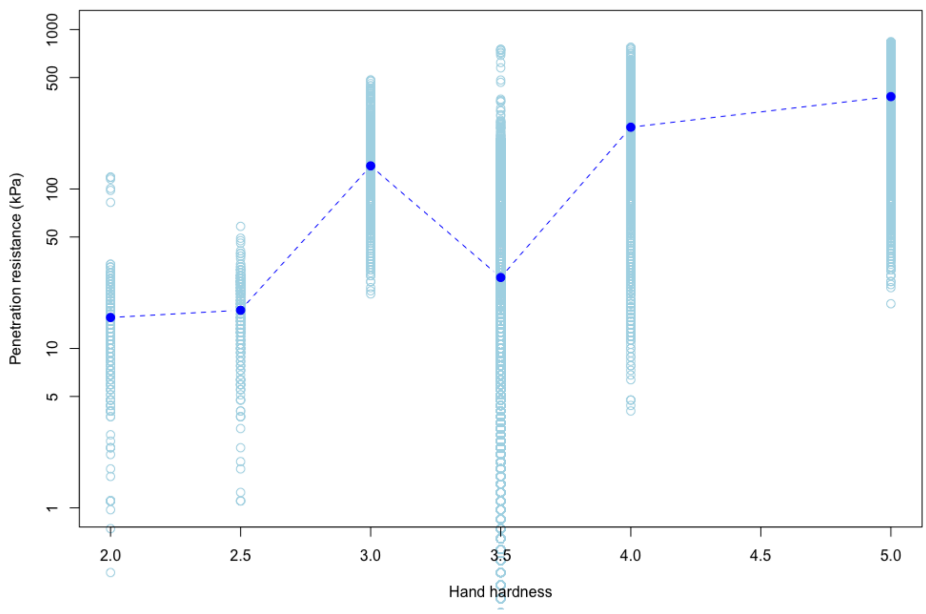

Figure 4.23. Hardness measurements plotted by the corresponding hand hardness index for layers in the Hemsedal 2 transect. Light blue circles show single observations and solid blue dots represent the mean. Penetration resistance is plotted on a logarithmic scale to match the semi-logarithmic nature of the hand hardness scale (see Literature review).

5 Discussion

5.1 Research questions - choice of approach

To be able to assess the usability of the SP2, in terms of avalanche forecasting, some underlying questions needed to be answered. Knowing how the SP2 works was essential to understand how an output signal is reached through an interaction between the operator, hardware and software.

To fit it in the frameworks of avalanche practitioners the penetrometer would need to be able to detect and differentiate between snow layers. Slabs and weak layers are the essential prerequisites for avalanche release and the penetrometer would be useless for avalanche practitioners if it struggled with identifying these. Another important factor is the reliability of the penetrometer. It needs to produce consistent results so that the observer can confidently evaluate the stability of the snow without second-guessing the output. The full understanding of the probe was partly limited due to unknown technical specifications and restricted knowledge about the processing algorithm.

5.2 Choice of methods - strengths and weaknesses

This section is focused on discussing the strengths and weaknesses of the chosen methods. The main discussion points here are why the methods were chosen, limitations with the chosen methods, and what could have been done differently.

5.2.1 Field locations and Snow conditions

The locations for field testing were chosen to be able to test the penetrometer in snow covers that were interesting in regards to snow stability. Our pursuit of interesting slab and weak layer combinations lead us to locations where the snowpack recently was considered unstable. Weather changes during the days before field testing lead to stabilization of the snow packs. Stability tests that were performed didn't give any significant results and evaluating if the SP2 could recognize weak layers or interfaces found by stability tests was therefore excluded from the analysis.

The snow covers, being heavily affected by various melt-freeze processes, was not ideal. It differed from a typical avalanche-prone winter snow pack, where typically a soft, shallow slab lies over a weak layer (Schweizer & Jamieson, 2001). Ideally, testing various winter snow packs, with both persistent and non-persistent weak layers, would allow further evaluation of the penetrometer under unstable snow conditions. The many hard layers of melt-freeze crusts and ice lenses also made it hard to maintain constant penetration rate.

Locations were also chosen in regards to safety. This limited us to terrain with a slope under 30°. Even though these locations weren't prone to avalanches, the same layering was expected to be found here as in the surrounding avalanche terrain.

5.2.2 Transect setup

The transect setup (**Figure 5.1**) was chosen to limit large-scale variability and limit the errors due to operator variability. Doing 20 tests at each site would ensure that we had enough data to justify our results. By having a transect length of 2 m the spatial variability was expected to be almost negligible and differences could easier be attributed to measuring errors. The manual snow profiles could therefore be presumed valid for the entire transect. A problem with this assumption is that discontinuous and very variable layers might not be present in all SP2 profiles and matching layers and features in the profiles could be problematic. We might have missed variation in features and layers when visually inspecting the transect that may have been important to get a precise determination of the depth accuracy. Noting the depths to marker layers that could be uniquely identified in the signal for each probing could have been a way to better ensure precise comparison between observed and measured depth. Confidently identifying these markers in the SP2 signal could prove to be tricky. The effect of push-rate variability could be further explored by using a motor to drive the penetrometer down into the snow at set speeds, but this is beyond the scope of this work.

The decision to use the same operator for testing with the SP2 through all the tests was made to reduce errors in the probing procedure. This means that nothing can be said about operator variability, which might be important if the results from penetrometer testing are to be compared between users. Previous research has suggested that user bias was not evident in the measurements (Pielmeier & van Herwijnen, 2016).

To be able to better validate the hardness measurements of the probe a force gauge could be mounted on top of the probe. This would give a measure of the force exerted by the operator, which could then be compared with the force measurements of the penetrometer. In this way the force sensor could be checked to work adequately. The force exerted on the probe would probably be higher than the measurements of the force sensor due to friction of the penetrometer shaft, friction in the piston and the shape of the shaft that may cause the penetrometer to be supported in other places than the tip. These forces could be hard to calculate. Another way to verify the force sensor would be to compare measurements to a reference penetrometer, such as the SMP.

Figure 5.1. A typical transect setup under excavation. The penetrometer tests were done along the avalanche probe. The picture is taken at the Filefjell 2 test site. Photo by Åsmund S. Karlsnes.

5.2.3 Lab setup

Lab tests were performed to get a better understanding of how the penetrometer worked. They were designed to test possible sources of error seen in the results from the field work. The lab tests set out to test specific variables while reducing other sources of error. One limitation of the lab tests is that the results are only valid for the lab and have to be interpreted and then extrapolated to the results from the field measurements. They still proved to be valuable in the understanding of the penetrometer. The number of conducted lab tests were limited due to time constraints.

5.3 Depth measurements

Examination of layers in the 50-100cm range across the different test sites shows that the average depth is -8.9cm off, with a minimum offset of -2.0 cm and maximum offset of 14.7cm. Our results from one specific ice layer (**Figure 4.5**) show that the absolute depth measurements are -8.5cm off on average. This is more than the stated ± 5 cm in the depth range 0-50 cm. The results show that the depth measurements suffer from high variation and lack of consistency. The focus for this section will be to compare the observed accuracy with the stated accuracy given by Avatech and discuss possible sources of error.

5.3.1 Consistency and scaling of the signal

The profiles shown in **figure 4.7** are examples showing that neighboring tests lack depth consistency. Some sections of the profiles seem to be expanded, while others seem to be compressed. Being successive profiles and having a maximum distance from each other of 30cm this kind of variability in the layer depths is not expected. The profile **p43** is an extreme case, which was discarded and redone in the field. The profile in **p43** also prompted rechecking of previous profiles. We then found the peculiar shape of **p42** likely to be a problem as well, and it was also disregarded and redone. Without the weird signal in **p43** we would probably have kept **p42**. The profiles we kept seem to line up quite nicely, and some of the variability seen in the profiles might be linked to spatial variability.

The "transformed" signal that is seen in **figure 4.6** can be seen in all of our test sites. This variation in the depth and thickness of layers is too great to be caused by spatial variability. Apparently there is a scaling effect of how hardness is distributed with depth, which can have a large impact on both relative and absolute depths. This scaling affect leads to an apparent spatial variability (Sturm & Benson, 2004). This means that the observed variability is not due to spatial variability in the snow pack, but instead is linked to variation in the depth signal. Floyer (2008) saw the same kind of expanding and compressing of the signal when using the SABRE penetrometer. He concluded that it was due to variation in the depth signal. It should be mentioned that the SABRE penetrometer only uses an accelerometer to measure depth and comparing the signals between these two penetromers should therefore be done with caution.

The scaling of full profiles might indicate that the measured depth at the start and at the end of a test are the base of the depth calculations. A precise determination of the surface would therefore be important. This can also mean that penetration rate, or more specifically the time spent in each layer, is crucial for the calculated layer thickness.

5.3.2 Surface Determination

The penetrometer tries to define a surface, but the automatic identification of the snow surface involves some uncertainty, which can lead to varying lengths of air measurements, including none at all, at the start of each profile. Manual surface determination was easily done in 66 of the 110 profiles by examining the profile signals. The surface depth could easily be identified as long as it was in the profile and the surface hardness was high (**Figure 4.1**). When testing the SP1, Lutz and Marshall (2014) also had problems with data missing in the upper part of the snowpack, and the offset in the upper part of the profile was found to be ~10cm in some profiles. Some of the profiles were missing the first 15-30 cm of measurements.

The penetrometers difficulty of determining the snow surface could be explained by the IR-sensors accuracy at the start of the test, where it is 1.5 meters above the snow surface. Solar transmission in the upper layers of the snow cover might lead to a delay in surface identification causing the surface to be defined under the actual surface as seen in **Figure 4.2**. Results from the second lab test showed that the SP2 also troubled with determining the surface in a controlled environment. Only 5 of the 20 measurements contained the actual surface in the signal, which could indicate that the surface often was defined beneath the actual surface and the rest of the signal was cut out.

It seems that the scaling of the profile signal is heavily dependent on the determination of the surface. This can be seen in, **Figure 4.4**, **Figure 4.5, Figure 4.6** and **Figure 4.8**. Errors in the determination of the surface seem to affect the signal throughout the meausuring length. This effect can especially be seen in **Figure 4.4**, where patterns in the depth measurement of the actual surface layer can be seen having an effect on the markers layers below. The effect seems to decrease with depth, and the variations are almost normalized at crust layer **d**. The same figures show that the depths to the marker layers are measured to be less than the observed depths in the upper parts of the snowpack.

The transect shown in **Figure 4.6** also seems affected by variable determination of the snow surface. It might also seem that passing through the crust layer **e** affects the signal below. This might be due to push rate variability. Note that this transect had soft, wet snow at the snow surface and that some of the manually determined surfaces in the profiles might be wrongly placed. Some of the depth variation could be explained by variable layer depth and snow properties, but that cannot explain the variation in surface depth.

5.3.3 Push-rate variability and the impact on layer thickness

The second lab test was designed to test effects of push rate variability, within the probing recommendations given by Avatech. The recommended probing time is 1-2 seconds. Given a max measurement length of 1.5m, this would mean that the probing rate should be in the range 0.75-1.5 m/s. Maintaining constant probing speed is also recommended. The total time of the probing in the lab was measured to be ~1 second and therefore in the lower end of the recommended time range. We found that a certain speed was needed to not generate error messages. It seems that the accelerometer needs to detect a certain starting speed to register a valid test. This makes sense when measuring a snow pack because you need a certain momentum to probe down into the snowpack.

Video analysis of the lab tests proved that some of the variation in layer thickness may be caused by the variation seen in penetration rate (**Figure 4.9**). Some of the sections were measured having an average probing rate of 2.5 m/s, way above the recommended rate. An implication of this is that with the sampling frequency of the penetrometer you would only get 2 force observations per mm. This may explain why some of the resistance markers were left out of the signal. Probing rate may have been much higher than the average when passing through layers. The thin printer paper may have been passed through so quickly that the force sensor didn't register it, or it was filtered out by the processing algorithm due to the few measurement points.

Penetration rate is especially variable in the field where significant changes in hardness leads to significant changes in penetration rate. The graph in **Figure 4.9** indicates that measured layer thickness is highly dependent on penetration rate. A higher rate leads to a decrease in the measured layer thickness. When probing through snow covers one can expect that the penetration rate is much higher when passing out through a crust layer into a soft layer, than when passing through the crust itself. This would mean that the crust layer would be measured thicker than the actual thickness, and the soft layer would be measured thinner than the actual thickness. This effect can be seen in the profiles taken in Hemsedal 2, where a melt-freeze crust (**e)** is on average measured to be twice as thick as the manual recorded thickness, 12cm compared to the 6cm measured. The softer underlying layer (**g**) is measured to be 6 cm thinner than observed (**Table 4.1**). This is twice as much as the stated relative accuracy in this measuring range suggests.

Relatively higher penetration rates in upper parts of the snowpack than in the lower parts might be an explanation of why layers in the upper parts are measured too shallow. Hard layers might lead to the operator adding momentum at the start of the testing to ensure penetration through this layer. Fast penetration rates would consistently measure layers to be thinner than they actually are, and the top of the snow pack would look more compact in the measurements than it really is. This may answer why a layer can be measured shallower even though the surface is determined to be underneath the actual surface.

5.3.4 Total depth

Since the IR-sensor is closer to the snow surface at the end of the test we would expect the depth measurements to be more accurate further down in the snowpack. Our results confirm this and the SP2 seems to be quite accurate in the measurement of the total depth. The same was found by Hagenmuller et al. (2016) for the SP2 and the SP1 (Hagenmuller & Pilloix, 2016) The total depth tends to be slightly underestimated as seen in **Figure 4.3**. The same figure illustrates a discrepancy in the measurements between 1350 to 1400mm. What causes the penetrometer to not measure in this range is uncertain. There are profiles that contain observed depth in this range, but they have been measured by the penetrometer to be around ~1300mm. These deviant measurements originate from all the different test sites so the problem is probably unrelated to snow pack factors. There might be a connection to sunlight causing interference with IR-sensor, since there is a slight correlation between the deviant measurements and the amount of sunlight during testing, but this is not confirmed. It is probably linked to the processing algorithm or faults in the IR-sensor. Complementary measurements need to be made with different snow packs and weather conditions to be able to estimate how much the depth accuracy is affected by the reflectance of the snow surface.

5.3.5 Future research

The variation seen in the depth accuracy seems to be related to two main problems; one: Unprecise determination of surface; two: High variability in penetration rates during tests. Hard layers may have caused such a high push rate variability that the sampling rate of the unit might have been too low to accurately know where it is. Uncertainty is also added by not knowing how the processing depth algorithm works. The “eyes” are supposed to help determining the exact location of the snow surface since the IR-sensor can be very noisy (Avatech, personal communication, March 30, 2017) but how they work is unknown.

Further experiments should be done in various snow and weather conditions to see how much the accuracy is affected by reflectance of the snow surface. One could also try to test different reflectors in the lab, to determine which gives the most precise measurements. An alternative could be to use a reflector, e.g. aluminum foil, when conducting field tests to compare results. In field measurements, the depth of the snow surface had a downward offset of up to 15cm (**Figure 4.2**) which is much higher than the maximum offset of ~1cm observed when using aluminum foil as the reflector. This could mean that having a better reflector might improve the probe’s ability of defining the surface.

Tests should also be conducted to see how much variation in penetration speed affects the depth accuracy and layer thickness. A high speed camera would allow a more precise analysis. The probe should also be tested with a motor driving it down at constant speed. One solution to get more precise depth accuracy would be to apply a matching algorithm to several profiles, to get one that is representative for the snow pack. Hagenmuller and Pilloix (2016) were able to cut the standard deviation and maximum deviation of errors in half when their matching algorithm was used on SP1 profiles. Studies should also be done on how much layer thickness affects the overall mechanical snow stability, and thereby getting and understanding of what level of depth accuracy is needed in a framework of real-time stability analysis.

5.4 Hardness measurements

An evaluation of the hardness measurements would ideally also include an assessment of the absolute hardness, with the objective of calibrating the SP2 hardness to existing penetrometer data. This is usually done by comparing side-by-side profiles from different penetrometers. We did not have access to other penetrometers for this study, which means that hand hardness was our only comparable hardness measure. The focus of this section will therefore be on repeatability, hardness variability and the relation to hand hardness profiles, rather than on the absolute hardness values. Two studies (Hagenmuller & Pilloix, 2016; Lutz & Marshall, 2014) have confirmed that the absolute hardness measured by the SP1, and later the SP2 (Pielmeier & van Herwijnen, 2016), was close to SMP measurements, which is the most used reference for hardness measurements.

5.4.1 Sensitivity and measurements in air and soft snow

The automatic identification of the snow surface involves, as described, some uncertainty. Distinguishing air measurements from measurements in soft surface snow is found to be difficult even when analyzing profiles on a mm-scale. In general, the observed air signals have a mean in the range 0.5-4 kPa and oscillates in a somewhat irregular pattern (**Figure 4.11**, **Figure 4.12**), with amplitudes usually below 0.5 kPa. These characteristics are practically useless looking at the displayed profile in the field. To prevent loosing or misinterpreting data from the near-surface snow, the automatic detection of the surface level must be improved.

A solution could be to implement an automatic detection of air measurements in the SP2 signal processing. We tried a method similar to the one described by (Satyawali et al., 2009) to detect air measurements in the processed profiles, but met some challenges. First of all, there may be no certain air measurements in a profile that can be used to characterize the signal. If there are air measurements, they are averaged and no variation on the micro-scale can be used to distinguish the air signal from the snow signal. Also, the SP2 calibrates the force sensor to air pressure at the start of each test, which implies that the air signal may vary from profile to profile. Variations between profiles are added by the processing as well, when hardness per time is transformed to hardness per depth, making the signal pattern dependent on the highly variable depth measurements. The conclusion is that an automatic detection of air probably has to be based on the unprocessed data.

Another aspect is the sensitivity of the force sensor. How much resistance is needed to produce signals distinguishable from the air signal? Or put another way, how soft can the snow be and still be detected? One of the factors causing uncertain surface identification in profiles from the Hemsedal 2 transect was actually a decrease in hardness to "below-air" values, found at depths between the typical air signal and certain snow measurements (**Figure 4.13**). Low values were also observed inside the upper snow layers, and not necessarily in the same profiles (**Figure 4.14**). Under certain conditions, resistance in snow can thus be measured to be less than the pressure in free air. The uppermost layers were manually observed to be at least 1F hard and to contain large amounts of free water. Hardness measurements in unbounded, but moist, new snow at Svartholten were observed to be both noticeably higher and lower than the air measurements (**Figure 4.15**).

These highly variable and probably inaccurate measurements observed in the lower hardness range might be related to both snow properties and sensor issues. An accuracy of ± 30 kPa is very likely to affect these measurements. Even though the processing algorithm might set the signal to the same reference level inside a single profile, that level might be different in the next profile. The air calibration of the force sensor is likely to play a role here, but as this is highly unknown territory it won't be discussed any further.

5.4.2 Repeatability issues

A general source of variable hardness measurements from penetrometers is compaction and deformation mechanisms around the probe tip (Floyer & Jamieson, 2010; van Herwijnen, 2013). These mechanisms behave differently in dry and wet, and hard and loose snow. For soft, moist snow, the compaction zone was found to be large due to capillary cohesion and low strength of the surrounding snow by Floyer and Jamieson (2010). The compaction zones were also observed to grow and collapse in cycles. Although these results are only valid for the specific tip used in the experiments, the rounded SABRE tip with a diameter of 12 mm, the concepts might be relevant to penetration of snow in general. Compaction of cohesive snow in front of the probe tip might explain the detection of very soft, moist snow at Svartholten (**Figure 4.15**). It might also have contributed to the very variable measurements from layer **b** in Hemsedal 2 (Feil! Fant ikke referansekilden.).

The least repeatable hardness measurements, regardless of magnitude, are found for profiles taken in wet snow. In addition to effects related to the interaction between the snow and the probe tip, issues with restricted motion of the tip relative to the force sensor was experienced using the SMP in wet snow covers (Kronholm, 2004). A thin film of water may form around the piston connecting the tip and the sensor, and if the water freezes it will limit the in- and outward movement. As a result, the piston might get stuck in a compressed position. Small fluctuations might still be recorded, but the friction limits the ease and the range of motion and can cause dampened signals and an offset in hardness as observed in profiles from Hemsedal 1 (**Figure 4.16**). A dampening effect is not observed, but that might be due to the signal processing. In dry snow, found at Filefjell 1, no similar variability was observed (**Figure 4.17**).

Constant hardness is present in a number of profiles at the depth where a hard crust layer was penetrated. The signals reach a hardness peak similar to normal, neighboring profiles, but stay constant for a distance afterwards that is often much longer than the measured thickness of the crust. Here a stop in downward motion of the full probe could be part of the explanation, since “choppy” tests with noticeable penetration rate variations are observed. If the distribution of hardness with depth depends on rate variations, measurements recorded while the probe is stationary would be distributed over a prolonged distance. A stop is likely at a peak in penetration resistance, which is observed in the examples from Svartholten (**Figure 4.18**). However, as increased force is needed to push through the hard layer, we would not expect constant hardness to be measured before the break-through. Constant hardness is observed to be in the range 840-870 kPa, and no higher values are seen in any profile. Constant peak values might then be the result of an upper limit of hardness measurements that is lower than the stated 1000 kPa.

5.4.3 Layer variability in Hemsedal 2

The hardness variability of layers along a full transect was investigated using the tracked layers from Hemsedal 2 (Feil! Fant ikke referansekilden.). The main factors controlling the observed hardness variations are believed to be snow variability, the manual tracking of layers and the accuracy of measurements. No obvious spatial trends were found for any of the layers, though layer **h** shows signs of gradual changes in hardness (**0**). For this analysis, eventual trends were considered negligible and thus the variation to be randomly distributed. Of 16 layer boundaries recorded in the manual snow cover profile, 10 were identified in the SP2 profiles. One layer (**f**) was not identified manually, but was found in 19 of the 20 transect profiles and therefore included.

Some simplifications were done when tracking the layers. No consistent layer boundaries were found above the thin crust layer **c**. This section is therefore treated as one layer (**b**), which, except for meltforms near the surface and the presence of free water, was fairly homogenous. Another major simplification was to ignore the transition zones around the layer boundaries. A typical boundary in snow is found to be 0.5-5 mm thick and not sharper than a single grain diameter (Kronholm et al., 2004). The boundary found in a penetrometer profile also includes the effect of the tip gradually entering the new layer (Kronholm et al., 2004; Satyawali et al., 2009). In SP2 profiles, the transitions are expanded even more by the re-sampling to mm-scale. We found the lengths of transition zones to be highly variable, but usually larger than 5 mm. Not looking at them separately has the consequence that some mm's of too high or low values are added to each layer. For thin, soft layers, this might have a major impact on the average hardness, thus the layer boundaries were set closer to the softer layers.

The average hardness of a weak layer has been found to be an indicator of stability (Pielmeier & Schweizer, 2007). This means that valuable information on the structural properties of a weak layer might be available also in averaged SP2 signals, if measured accurately. No critical weak layer was present in the Hemsedal 2 transect, but layer **j** had recently been one and still had a noticeable faceted character. Looking at the measurements of each profile in **Figure 4.19**, one of the twenty samples has values about ten times higher than the average. The rest have fairly consistent means, shown by the relative standard error of 27 % (**Table 4.2**). A mean coefficient of variation of 57 % might represent the locations of the layer boundary more than the hardness variations measured inside the layer itself. The average thickness was measured to be 13 mm (**Table 4.1**), which means that the samples consist of relatively few measurements and that means and dispersions are easily affected by boundary placements.

This leads to a necessary clarification of what the calculated layer parameters mean in this thesis compared to the ones used to classify snow from SMP measurements. Satyawali et al. (2009) used the mean, the standard deviation and the coefficient of variation to identify snow class from penetrometer signals. The parameters are calculated per mm depth, which means they are based on 250 measurements. Layer properties are obtained by taking the average of all the values calculated inside the layer. Mean layer hardness obtained from SP2 measurements is comparable to mean layer hardness based on SMP measurements. The difference, excluding all measurement uncertainties, is the number of measurements they are based on. That is not the case for the standard deviation and the CV. These are the parameters describing the variations in micro-structural resistance found per mm depth in SMP signals, variations that are not available in the already averaged SP2 signals. The standard deviation and CV are here calculated on the basis of a layer, and only describe the variation in hardness per mm in that layer.

The by far highest variation inside a layer is found for the "merged" layer b (**Figure 4.21**). Considering the relatively large part of the layer that was manually classified as rounded snow of hand hardness 1F-P, the mean layer hardness is surprisingly low and the mean CV surprisingly high (**Table 4.2**). Looking at the profiles (Feil! Fant ikke referansekilden.), variability, both vertically and laterally, is high and seems randomly distributed. We assume that the high water content observed in this layer might play a role here. This could cause tip freezing like suggested earlier for measurements where water is present, and also probably have a significant impact on the compaction and deformation around the probe tip. Techel (2010) found that the penetration resistance increases at liquid water content up to 3 vol.%, corresponding to moist snow, in non-persistant layers, using the SMP and artificially introducing liquid water into the snow cover. This was explained by rapid clustering of grains that are kept together by capillary forces. Layer **b** was recorded as wet to very wet, which means that the water content probably was over 3 vol.%. Increased liquid water content will at some point, as the capillary forces are reduced, reduce the strength of grain bonds and probably reduce penetration resistance.

5.4.4 Comparison to hand hardness profiles

The manual snow cover profile is the most used and thereby the most important method for identification of snow layers. Discriminating layers using hand hardness is subjective and suffers from limited vertical resolution, but is a fast way of evaluating the important characteristics of a snow cover for a trained observer. When comparing a hand hardness profile to a penetrometer profile, the most striking difference is the resolution. **Figure 4.22** shows one of the better matches we have between a manual profile and a SP2 profile, where the main structures match well between the two. In some of the other transects it was hard to find any matching structures at all. This is, however, not surprising, as there are some uncertainties involved.

Pielmeier and Schneebeli (2003) compared snow cover profiles obtained from hand hardness, Rammsonde and SMP to the detailed stratigraphy observed in planar sections. The hand hardness profile contained 80 % of the layers, the Ram-profile 60 % and the penetrometer profile all layers. As relatively unexperienced observers, a fair amount of uncertainty has to be assigned to our manual snow cover profiles. The numerous melt-freeze crusts, ice lenses and variable presence of water made layer identification challenging, and we found that the profiles from the most vertically variable snow covers were the hardest to correlate. When comparing a transect profile to the hand hardness profile, the distance between the two is also a source of error. The hand hardness was collected at one of the transect ends, which means SP2 profiles are up to 220 cm away.

In Hemsedal 2, there were both manually recorded layers that were not found in SP2 profiles, and a layer (**f**) found in SP2 profiles that was not identified in the field. Layer **f** was actually found to be a consistent, thin and fairly soft layer in 19 of the 20 transect profiles (**Figure 4.20**; Feil! Fant ikke referansekilden.). This means that we might have missed a layer potentially important to stability, which the SP2 detected. The high resolution in both depth and hardness of a penetrometer profile makes detailed information on hardness differences available. In general, our impression is that for dry and fairly homogenous snow that is not too soft, the SP2 might be able to detect interfaces and layer boundaries that are hard to identify manually, and by that adding valuable nuances to the manual recordings. In variable snow full of large hardness contrasts, we found it difficult to extract the important hardness differences from the profiles, and even more difficult to correlate them to a hand hardness profile. Depth errors are also a big part of this problem.

5.5 Usability

5.5.1 Use of a high-resolution penetrometer in the Systematic snow cover diagnosis (SSD)

In **Table 5.1**, we present an overview of the main steps of the Systematic snow cover diagnosis where we also suggest how the use of a penetrometer can be implemented. Manually testing, analyzing and evaluating the weak layer will still have to be the key elements, considering the amount of certain information available from penetrometer signals. What a penetrometer probably can do, is to significantly increase the efficiency and precision of the analysis. Assuming the penetrometer reliably detects most types of potential weak layers, digging may be limited to slopes where, and after, such layers are identified. Exact pit location can also be optimized by verifying weak layer depth and hardness before digging.

The most valuable improvement may still be the opportunity to verify spatial changes in the slab and weak layer properties on the go. Hardness and depth information is available at any point, a test taking only a few seconds. Three out of five unfavorable properties can be tracked directly, making a continuous evaluation of the slab and the weak layer possible. Adding information on weak layer hardness, which also can be used to estimate fracture character, means both the physical presence and the strength of the weak layer can be assessed without the need of digging.

Table 5.1. Steps of stability evaluation based on the Systematic snow cover diagnosis (Kronthaler et al., 2013; Müller et al., 2015) and how the use of a penetrometer can be implemented.

Step	**Methods**	**Penetrometer improvement**
Find and test the most prominent weak layer	Choose location and perform a small block test. Classify the ease of weak layer failure by applied force - while excavation - gentle tapping - moderate tapping - hard tapping and the structure of the fracture plane - plane (Q1) - rough (Q2) - stepped (Q3)	Use hardness profiles to detect potential weak layers and optimize pit location
Analyse the weak layer	Identify grain shape, size, formation processes and state of metamorphism of the weak layer	Measure correct hardness of thin weak layers
Evaluate the weak layer	Summarise unfavourable properties of the weak layer and the overlaying slab. Weak layer: - Easy failure: while excavation/gentle tapping and Q1-Q2 - Thickness < 2 cm - Grain size > 1,25 mm - Depth < 1 m - Grain type: Persistent (SH, DH, FC) Slab: - Cohesive but soft: 4F-1F	
Extrapolate to nearby slopes	Estimate if and how the identified properties change with elevation and aspect by considering the formation processes. Verify estimates by adding more pits.	Verify estimates and observe spatial changes adding point observations on the go. Properties directly readable from hardness profiles: - weak layer thickness - weak layer depth - weak layer and slab hardness

5.5.2 Weak layer detection

This study has not been concerned with stability measures. A description of weak layer detection are therefore based on manual snow cover profiles and a general definition of a weak layer as a relatively less cohesive layer beneath a relatively more cohesive layer (Tremper, 2008). Structural instability indices of weak layers, often referred to as "lemons" or "yellow flags", were introduced by McCammon and Schweizer (2002) and Jamieson and Schweizer (2005), and indicate the likelihood of fracture initiation and propagation from the weak layer properties. The "unfavourable properties" proposed by Kronthaler et al. (2013) are based on similar indices, and also includes the slab hardness and the fracture character obtained from a block test.

The purpose of a weak layer detection is to effectively identify slopes of interest for stability evaluation, which might be as much about the absence as the presence of unfavourable snow cover properties. At this initial stage, however, this should be based on a few simple criteria that leave little room for subjective assessment. If a layered structure is detected, where a relatively thin and soft layer is present below a layer of bounded (cohesive) snow, this should lead to further investigations. Quantified criteria might be the least critical class for weak layer depth and thickness, as given in the "unfavourable properties" classification scheme by Kronthaler et al. (2013), combined with the "lemon" hardness transition (Jamieson & Schweizer, 2005)

- Weak layer depth < 1 m
- Weak layer thickness < 10 cm
- Hardness difference between slab and weak layer < 1

The SP2 was found to measure absolute depths to less than actual depths, with an average miss of ~9 cm in the range 50-100 cm (**Table 4.1**). Combined with surface signals observed at over 20 cm below the defined surface, the depth to the weak layer might be underestimated by an amount exceeding 30 cm. As a result, more layers might fall into the < 1 m category, and, more importantly, slabs might appear much thinner and less harmful than they actually are. This illustrates the importance of objective criteria that takes possible measurement errors into account.

Measured thickness of thin, soft layers are observed to vary within a range of ± 1 cm and have means close to the actual thickness (difference < 1 cm). The uncertainties related to snow variability and layer tracking are, however, considerable for layers this thin. A general tendency of the thickness of soft layers being underestimated is probably irrelevant compared to the uncertainty of estimating layer thickness from the displayed profile.

The next question is how thin a layer might be and still be detectable. This is especially relevant for non-persistant weak layers and interfaces in dry snow, often found to be a few mm’s thick and almost invisible to the naked eye. We have found that high penetration rate might reduce the chance of detecting very thin layers, but the detection of weak interfaces in dry snow has not been specifically tested. Measurements in more or less homogenous rounded snow of one finger to pencil hardness at Filefjell 1, show that the SP2 is able to reproduce relatively small hardness contrasts in succeeding profiles (Figure 5.2). The vertical extent of the weaker zones marked in the figure has, however, not been verified.

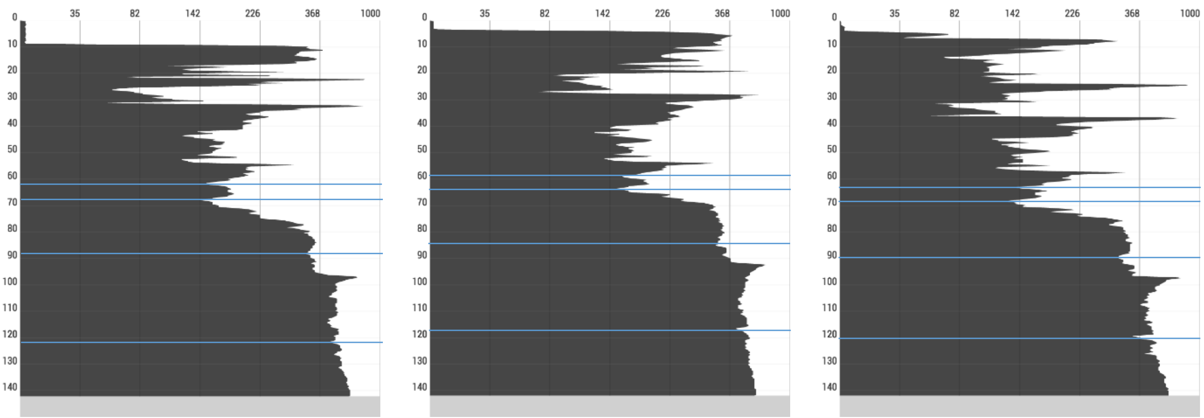

Figure 5.2. p19, p20 and p21 from Filefjell show measurements in dry, rounded snow of 1F to P hardness below depth ~50 cm. The lines mark some of the small, weaker zones that are reproduced in all three profiles.

A relative hardness difference of minimum one hand hardness step is in this context a relatively vague criteria, since the hand hardness is a coarse and subjective measure. Introducing precise and absolute hardness measurements to field observations brings the opportunity to refine the existing or specify new instability indices. Interpreting SP2 hardness in terms of hand hardness steps is not straight forward, though the profiles are graphed using an exponential scale which resembles the non-linear hand hardness scale as quantified by (Colbeck, Akitaya et al., 1990) and (Höller & Fromm, 2010). The SP2 scale is shown with six sub-divisions which might be intended to correspond to hand hardness steps. If the SP2 profiles are to be used along with manual profiles and interpreted on the basis of existing hardness criteria, however, the scale and the graphing have to be further investigated.

The challenges with relating coarse hand hardness measures to high-resolution penetrometer measurements are seen in **Figure 4.23**, where SP2 hardness is plotted against the corresponding hand hardness. Though this is based on data from one transect and therefore only one manual profile, the range of hardness measurements related to each hand hardness step clearly shows that relating hand hardness to absolute hardness involves uncertainties. The purpose of using this measure is also more about describing relative hardness differences, than the absolute hardness itself.

Overall, the SP2 seems to resolve hardness differences at a high vertical resolution. The average hardness of layers tracked along a transect has also been found to preserve the main structures of the snow cover. Although soft (F) surface snow was detected at Svartholten (**Figure 4.15**), we believe this might have been due to compaction of moist, cohesive snow in front of the probe tip. Accuracy in soft snow has not been sufficiently tested in this study, but Hagenmuller et al. (2016) found that the SP2 was unable to detect a weak layer of loose, new snow under a slightly wind-packed slab, indicating that it might struggle with identifying non-persistent weak layers. When it comes to distinguishing critical hardness differences from the less critical, this has to be further researched. A part of this is the graphing itself, which due to its scale and plot format enhances hardness contrasts by an amount that depends on the hardness.

5.5.3 Quantification of weak layer hardness

The hardness of a layer is directly related to its structural properties. After a weak layer is detected and analyzed, reliable hardness measurements can thus detect spatial changes in the weak layer properties. Pielmeier and Schweizer (2007) found that weak layer hardness and the difference in hardness between the slab and the weak layer, measured with the SMP, were indicators of instability. Later, Floyer and Jamieson (2009) predicted fracture character from SABRE-signals, also using non-microstructural properties. This shows that the SP2 signal, if accurate, might be used to assess not only the presence of a weak layer, but also structural properties relevant for stability.

We found that the SP2 measured the mean hardness of a faceted, 2 cm thin layer with a relative standard error of 27 % along a 2 m transect. Assuming that several profiles are collected at each location, significant changes in weak layer hardness might be detectable. However, manually extracting the mean hardness of a layer in profiles as shown on the SP2 screen is hardly possible. If the observable minimum hardness is a useful approximation is not investigated. Results also suggest that hardness measurements are less repeatable in wet snow covers (**Figure 4.16**), and that absolute hardness accuracy in soft snow might be unreliable (**Figure 4.14**).

5.5.4 Tracking of unfavorable properties

The detection of unfavourable properties has now been discussed in detail, and this section will focus on reviewing more practical issues related to the tracking of these. A recent study by Hagenmuller et al. (2016) evaluated the functionality of the SP2 in avalanche forecasting, comparing SP2-profiles to Rammsonde- and SMP-profiles. They suggested that for the SP2 to correctly reveal the snow stratigraphy, several profiles need to be collected at each location and then matched to one representative profile. Hagenmuller and Pilloix (2016) have developed a numerical method for matching penetrometer profiles, which might be considered implemented in future high-resolution penetrometers. Looking at **Figure 5.3**, it seems clear that measurement variability combined with spatial variability of snow layers can result in profiles that are hard to correlate, even when profiles are collected less than 2 m apart. Scrolling back and forth between profiles to manually assess what might be a representative profile reduces the objectivity and increases the chance of misinterpretations.

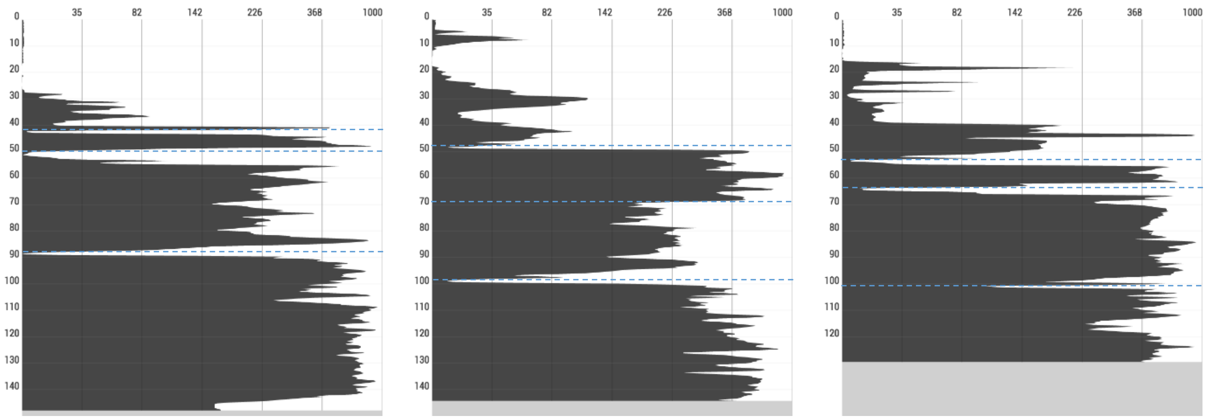

Figure 5.3. Comparison of p60, p49 and p41 from the Hemsedal 2 transect. Corresponding layers are marked with dotted lines, showing that correlating profiles might be challenging.

The character of the snow cover is also found to have an influence on the usability of the SP2. In vertically variable old snow, the profiles contain a large number of hardness transitions potentially important for stability assessment. To identify the critical ones, or track certain transitions, might be difficult. Also, assessment of the strength of thin crust layers compared to the weakness of layers below and the overlaying weight, based on their relative appearance, has to be done with great care, considering the accuracy found for depth measurements and the possible overestimation of crust thickness.

On the mountain scale, the effectivity of mapping spatial variability using penetrometer profiles depends in part on the degree of variability. The same main stratigraphic features have to be present, and they have to be recognized, for a direct comparison of two profiles to be useful. **Figure 5.4** show the difference in character between profiles in Hemsedal 1 and 2, collected at the bottom and at the top of the same slope. Profiles from Filefjell 1 and 2 are compared in **Figure 5.5**, collected at similar aspects and a few hundred meters apart. The examples show that the visual task of identifying certain familiar structures might be challenging. If no matching features are identified comparing two or more profiles, a new pit is the only option.

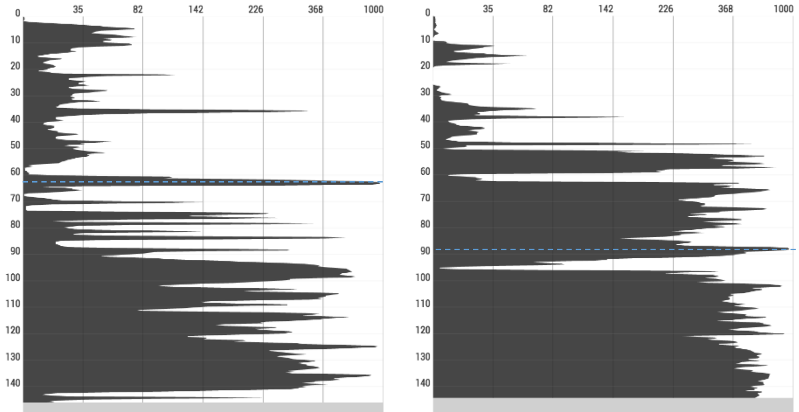

Figure 5.4. Comparison of p11, Hemsedal 1, and p57, Hemsedal 2. The profiles are collected at the bottom and at the top of the same slope. The dotted lines mark the same crust layer, with the most prominent weak layer identified just below in both profiles.

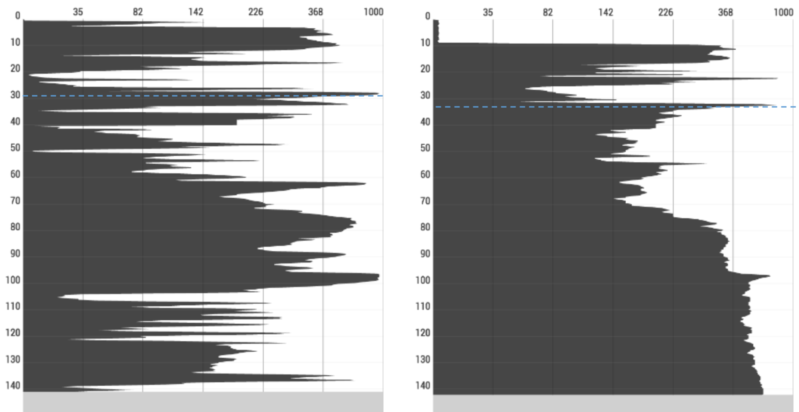

Figure 5.5. Comparison of p52, Filefjell 2 and p19, Filefjell 1. The profiles are collected at similar aspects a few hundred meters apart and with a difference in elevation of around 100 m. Dotted lines mark the same crust layer. Below this, variable meltforms were found at Filefjell 2. At Filefjell 1, this part consisted of dry, rounded snow.

6 Conclusions

The aim of this study was to assess the reliability and possible use of the SP2 snow penetrometer. We conducted 110 field tests, along with detailed stratigraphic records, on five different locations, and performed lab tests to further improve interpretation of hardness profiles. Data was analyzed to quantify the accuracy and precision of measurements. Finally, we looked at how the use of a high resolution penetrometer can be implemented in the Systematic snow cover diagnosis, and how the SP2 fits the requirements of a functional tool.

Our results show that the SP2 is able to reproduce the main stratigraphic sequences, but lacks accurate depth measurements. Layer depths tend to be underestimated in the upper part of the snowpack, making it look as though these layers are shallower than observed in the manual profile. Uncertain determination of the surface level is found to give varying lengths of air measurements and also leads to missing data at the top of profiles. Variable scaling of layers and full profiles is observed, and video analysis of lab tests have shown that penetration rate can influence the distribution of hardness with depth. Accuracy increases with depth, but the overall level of uncertainty seems to exceed the average errors stated by Avatech.

Hardness measurements are found to be consistent in dry snow, but are less repeatable in snow where free water is present. Mean hardness of 10 tracked layers was consistently measured along a 2 m transect, indicated by relative standard errors between 3,5 and 27 %. A stratigraphic profile based on average layer depths and hardness from the same transect was found to resemble the manually recorded hand hardness profile, but also to suffer from inaccurate layer depths.

In the framework of avalanche forecasting and the Systematic snow cover diagnosis, we considered effective detection of weak layers, quantification of weak layer hardness and spatial tracking of unfavorable properties to be valuable benefits of implementing the use of a high resolution penetrometer. The SP2 was observed to reliably detect a persistent weak layer, and stratigraphic hardness differences are well contrasted in profiles. The main concerns are that depth errors and scaling might complicate comparison of profiles, and that the ability to detect soft snow and non-persistent weak layers might be insufficient.

By assessing accuracy and precision of measurements, we have learned how the SP2 may perform in variable old snow, wet snow and firm dry snow. Our results are limited by the snow conditions during our fieldwork, which did not facilitate measurements of a typical dry snow stratigraphy or of an active weak layer. The absolute accuracy of hardness measurements is not verified, as we had no comparable objective measure. Usability of the SP2 is discussed in terms of functionality in avalanche forecasting, with the same limitations related to snow conditions.

Our findings are in line with other recent studies of the SP2. Avatech is soon releasing a new model, in which the depth accuracy and the soft snow sensitivity is expected to be significantly improved. High-resolution penetrometers will probably grow increasingly popular among avalanche observers as well as recreationists, as the functionality and ease of use are further developed. For these tools to be able to live up to their potential, we suggest that future developments include instability indices based on absolute hardness parameters, implementation of methods for matching profiles and user interfaces that allows layer tracking and analysis on the go.

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Appendix A Maps

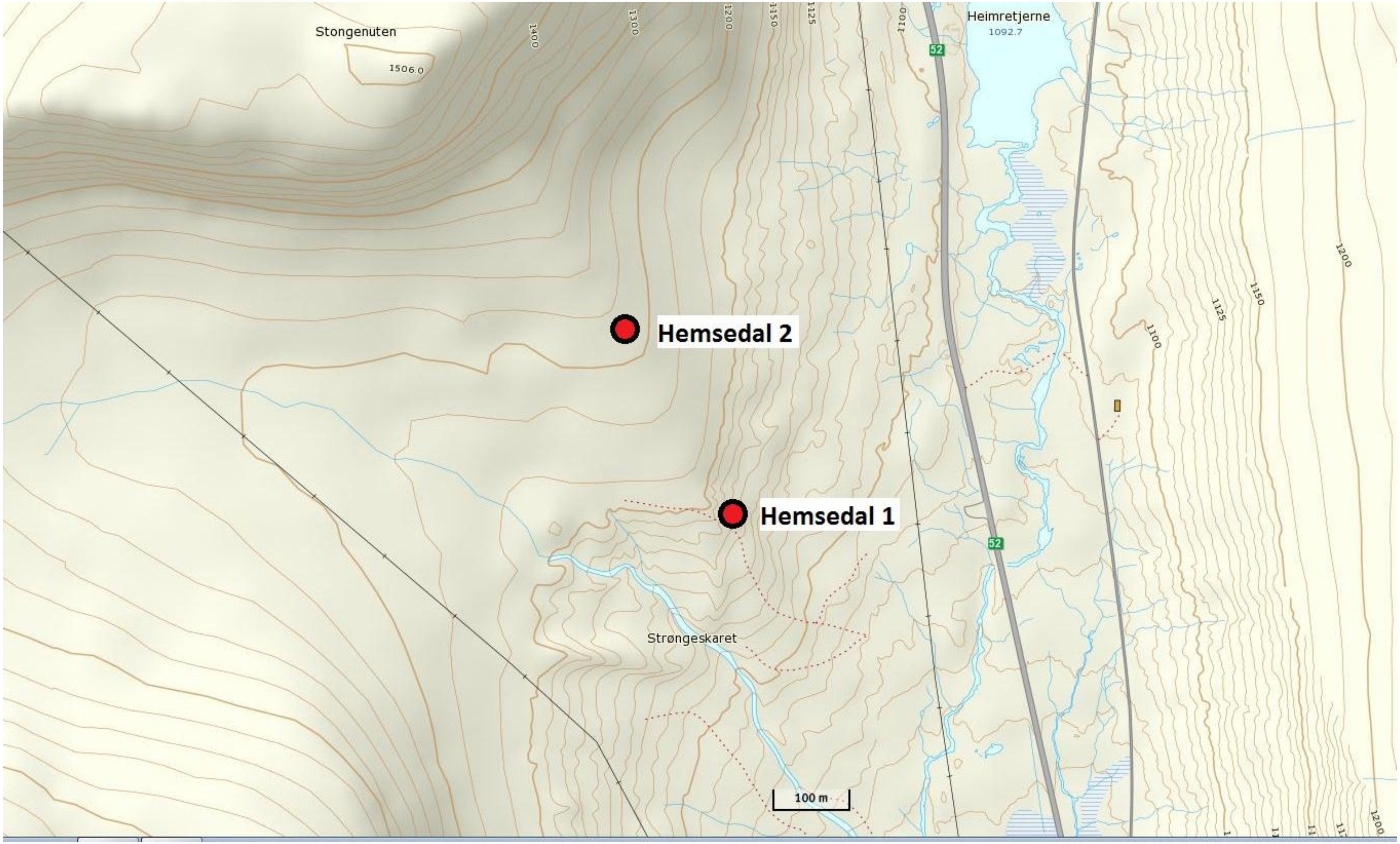


Figure A. 1. Map over the test sites in Hemsedal.

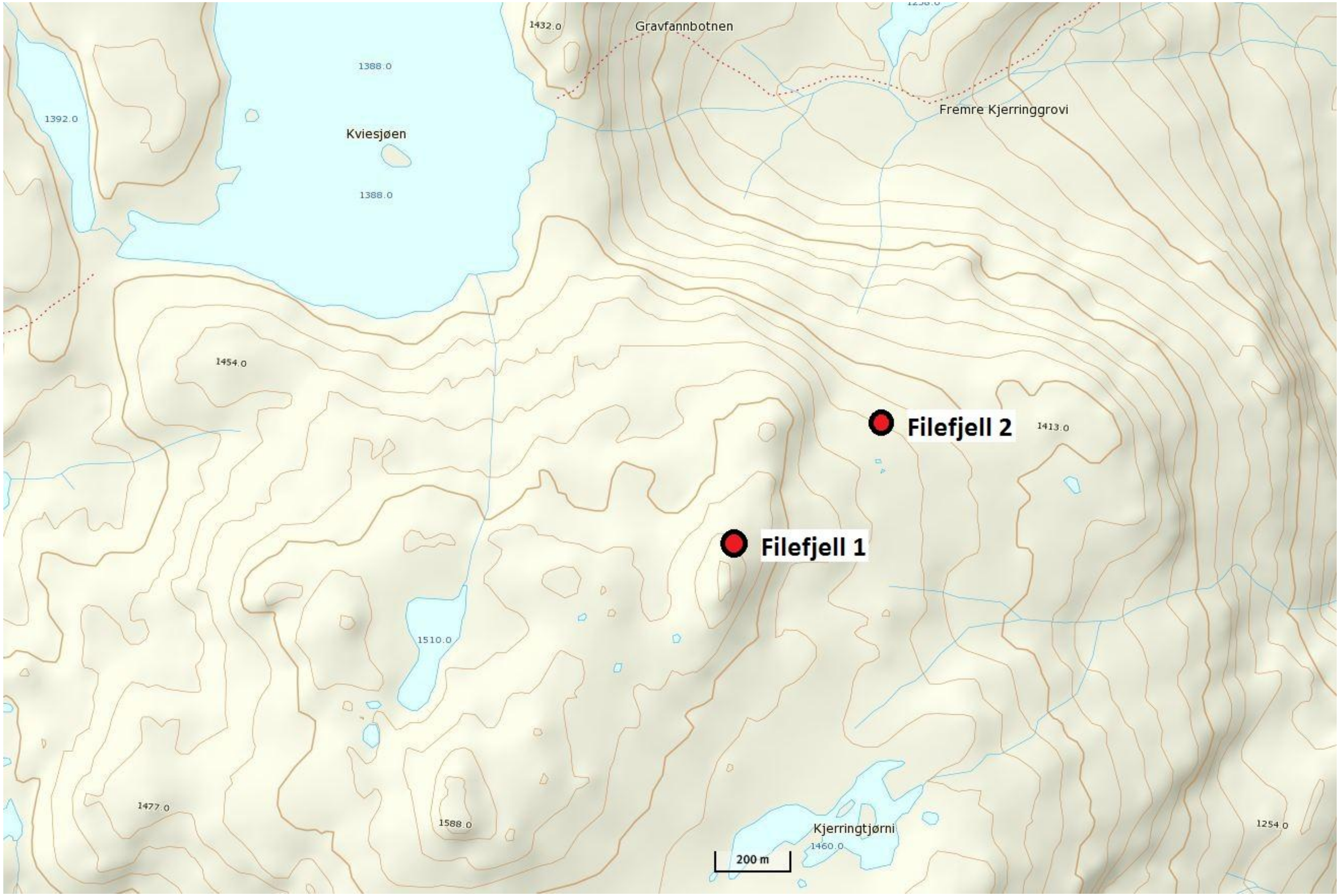


Figure A. 2. Map over the test sites in Filefjell.

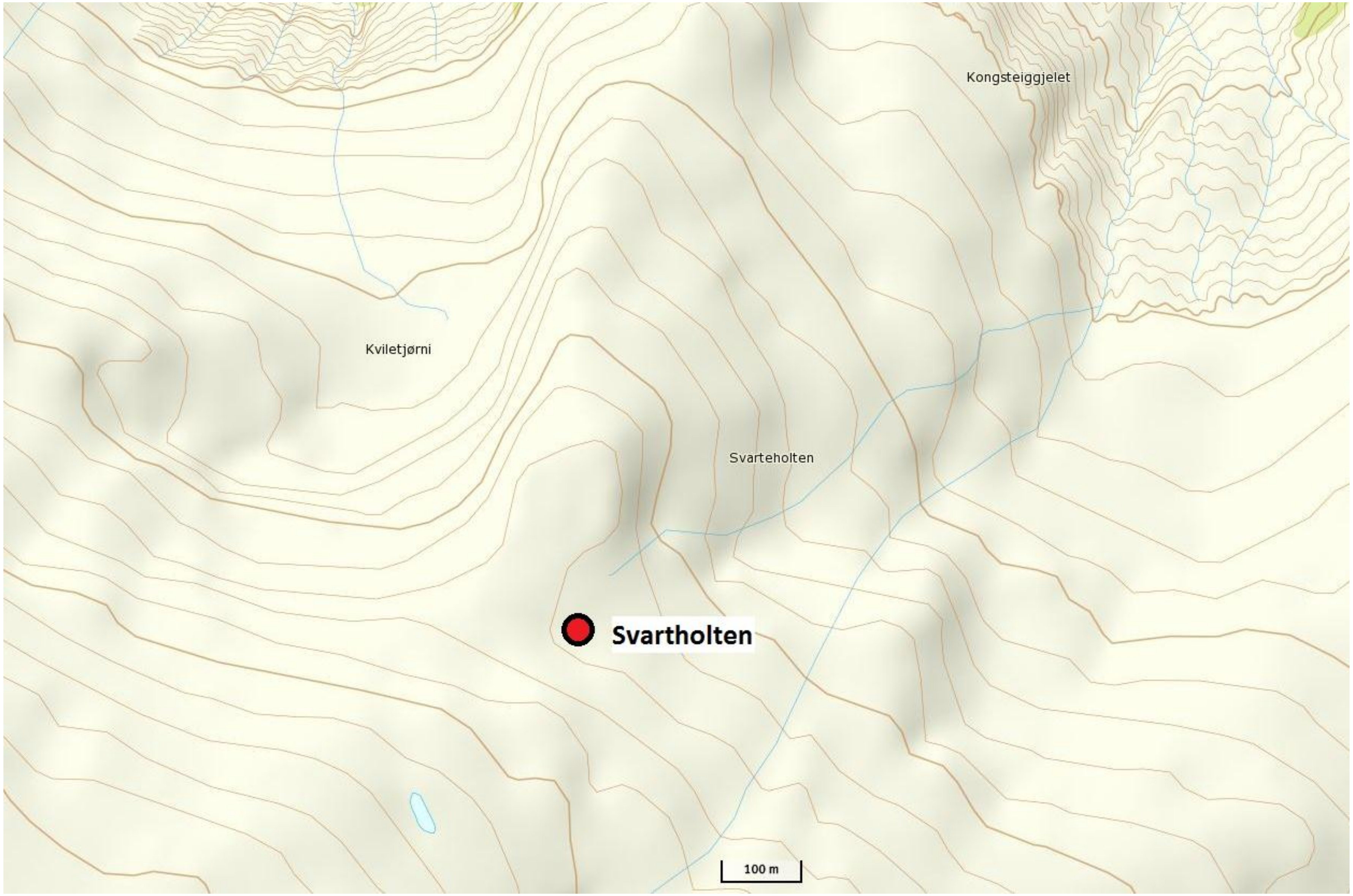
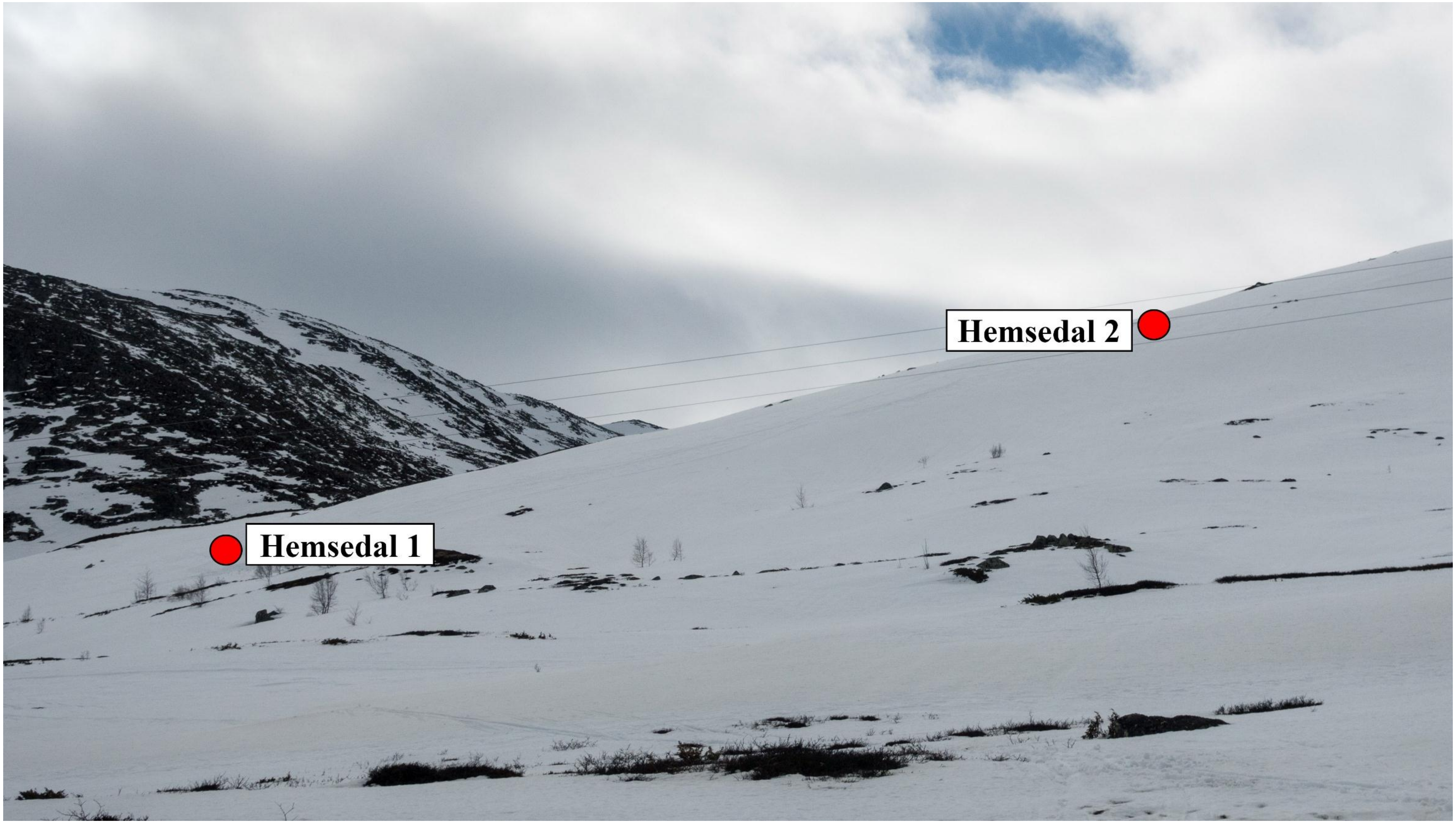


Figure A. 3. Map over the test site at Svartholten.


Hemsedal 2
Hemsedal 1

Appendix B Snow cover profiles

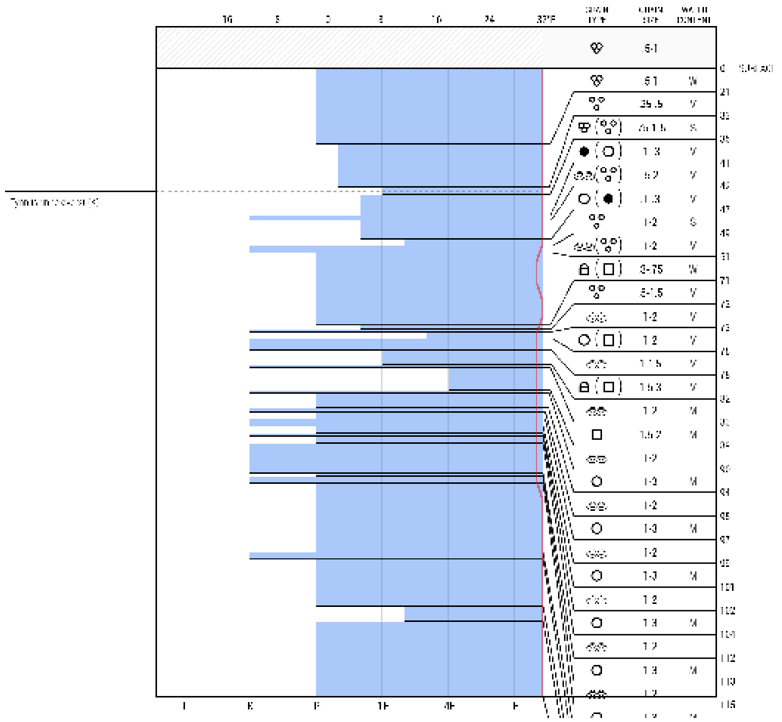
Appendix B.1 Hemsedal

Avanet SNOW PROFILE — Hemsedal 1

Organization: –

Location: Strøngeskaret, Buskerud Date: 2017-03-27 Snowpit depth: 174 cm
Lat/Lng: 60.94804, 8.16492 Observer: Åsmund Skancke Karlsnes Snowpack depth: 174 cm

Elevation: 1,128 m Wind: Moderate, –
Slope: 21° Blowing snow: None, –
Aspect: 105° EbS Precipitation: No Precipitation
Air temp.: 39°F Foot Pen. (PF): –
Sky: ◯ Few Ski Pen. (PS): –



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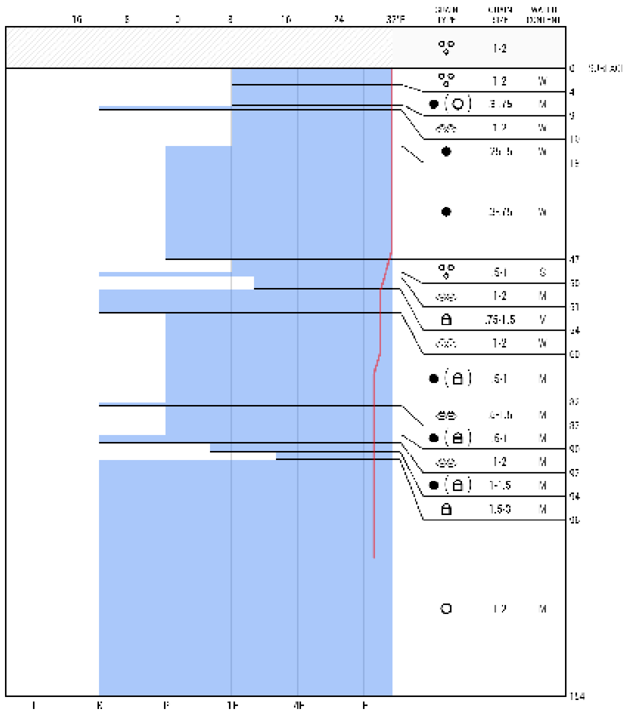
Avanet SNOW PROFILE — Hemsedal 2

Organization: –

Location: Stangenuten, Buskerud Date: 2017-03-27 Snowpit depth: 154 cm
Lat/Lng: 60.94999, 8.16192 Observer: Åsmund Skancke Karlsnes Snowpack depth: 215 cm

Elevation: 1,196 m Wind: Moderate, –
Slope: 20° Blowing snow: None, –
Aspect: 100° EbS Precipitation: No Precipitation
Air temp.: 36°F Foot Pen. (PF): –
Sky: ◯ Few Ski Pen. (PS): –



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Appendix B.2 Filefjell

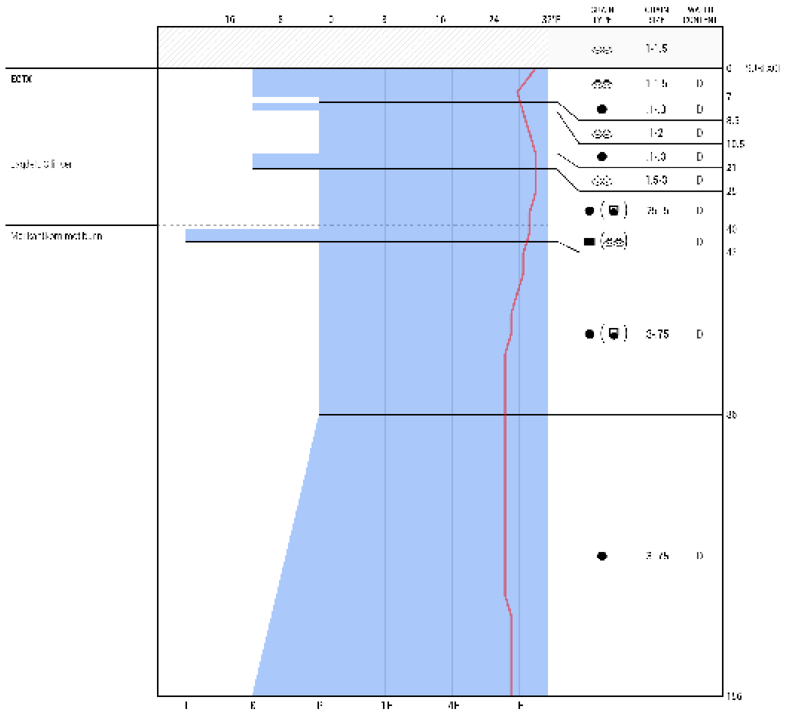
Filefjell 1

Avanet SNOW PROFILE

Organization: –

Location:	Salen,øvre, Sogn og Fjordane	Date:	2017-03-27	Snowpit depth:	156 cm
Lat/Lng:	61.11342, 7.96131	Observer:	Åsmund Skancke Karlsnes	Snowpack depth:	156 cm

Elevation:	1,531 m	Wind:	Calm, –
Slope:	22°	Blowing snow:	None, –
Aspect:	80° EbN	Precipitation:	No Precipitation
Air temp.:	33°F	Foot Pen. (PF):	–
Sky: ⦵	Overcast	Ski Pen. (PS):	–



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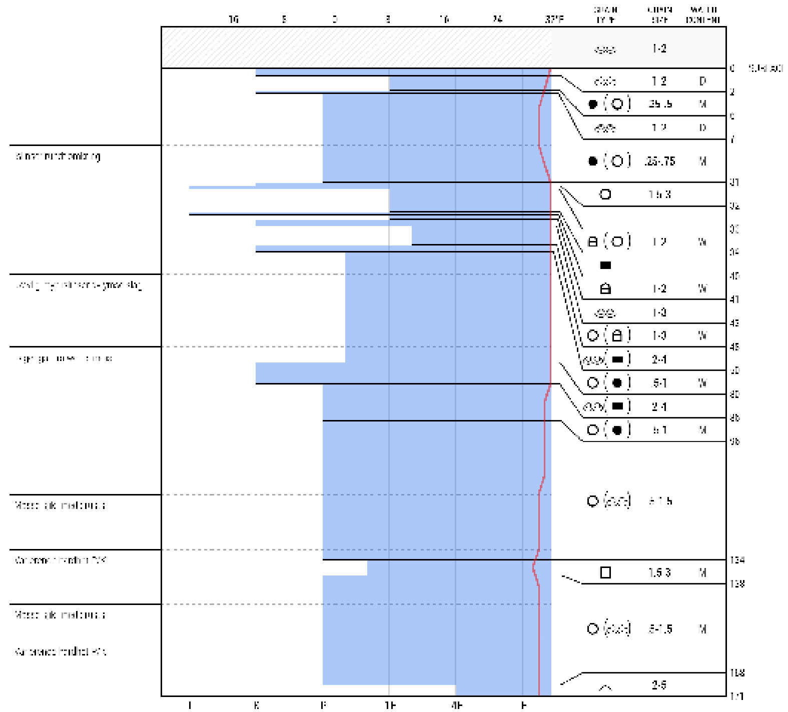
Filefjell 2

Avanet SNOW PROFILE

Organization: –

Location:	Salen,øvre, Sogn og Fjordane	Date:	2017-03-28	Snowpit depth:	171 cm
Lat/Lng:	61.12201, 7.97826	Observer:	Åsmund Skancke Karlsnes	Snowpack depth:	171 cm

Elevation:	1,436 m	Wind:	Calm, –
Slope:	22°	Blowing snow:	None, –
Aspect:	5° N	Precipitation:	No Precipitation
Air temp.:	35°F	Foot Pen. (PF):	–
Sky: ⦵	Overcast	Ski Pen. (PS):	–



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Appendix B.3 Svartholten

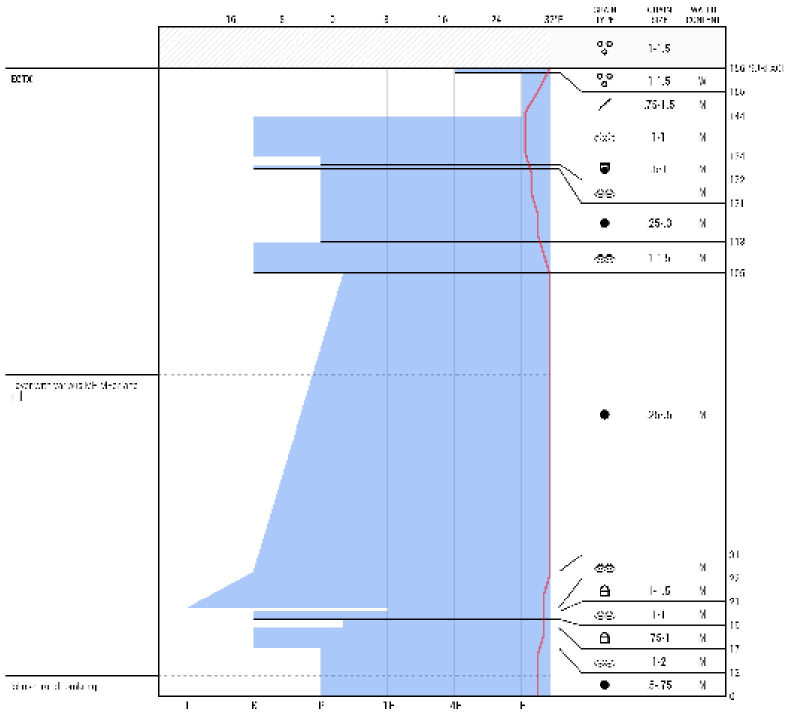
Svartholten

Avanet SNOW PROFILE

Organization: –

Location:	Svarteholten, Sogn og Fjordane	Date:	2017-03-31	Snowpit depth:	156 cm
Lat/Lng:	61.30406, 6.92454	Observer:	Åsmund Skancke Karlsnes	Snowpack depth:	213 cm

Elevation:	1,131 m	Wind:	Calm, –
Slope:	17°	Blowing snow:	Light, –
Aspect:	78° EbN	Precipitation:	Rain - Very Light
Air temp.:	39°F	Foot Pen. (PF):	–
Sky:	Overcast	Ski Pen. (PS):	–



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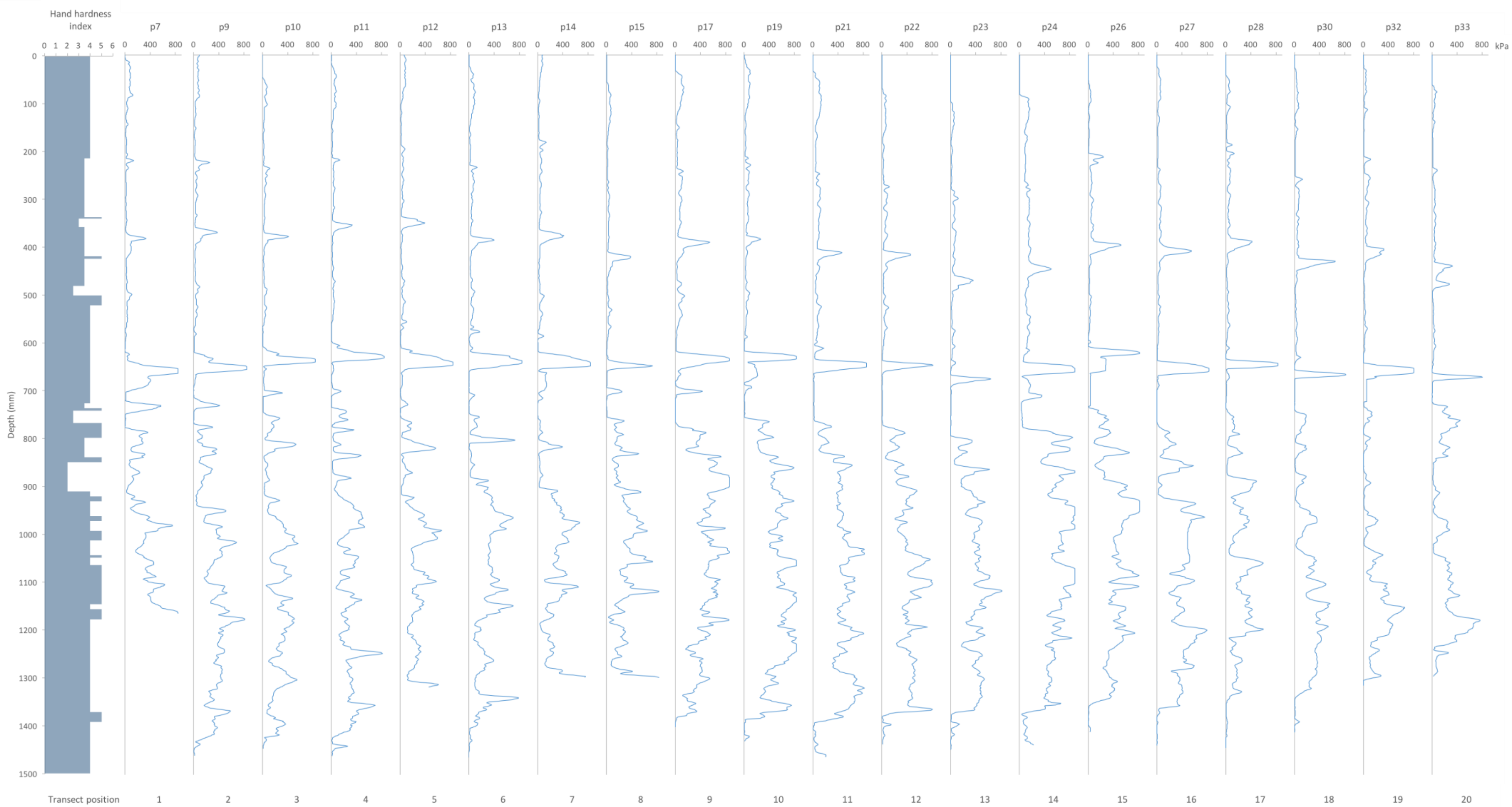
Appendix C SP2 Profiles

Appendix C.1.1 Hemsedal 1



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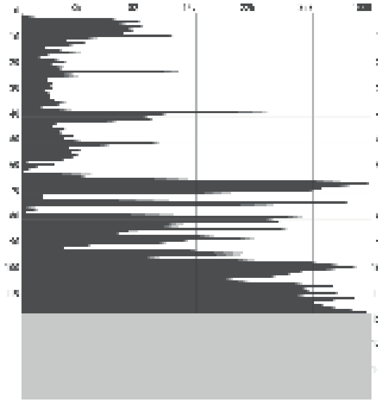

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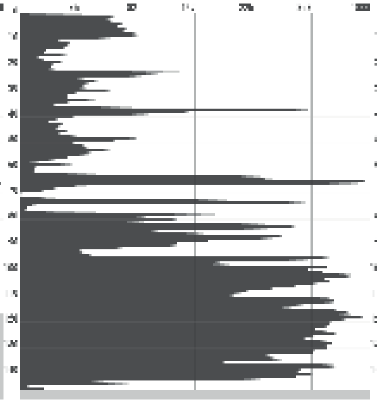

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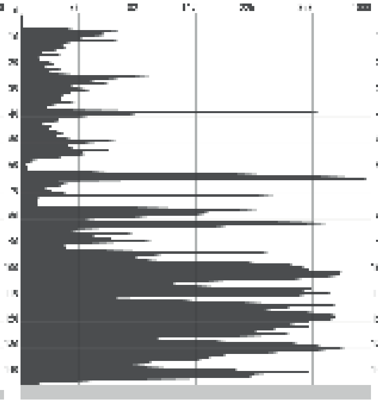

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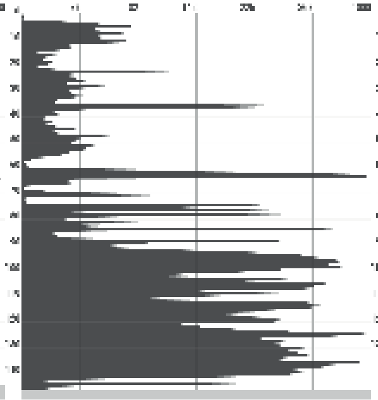

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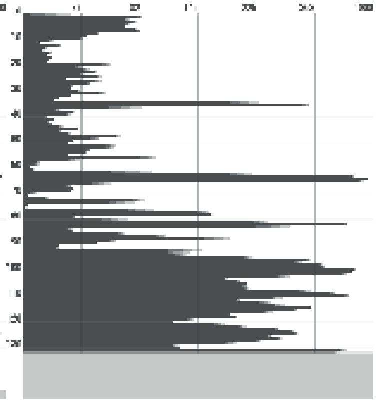

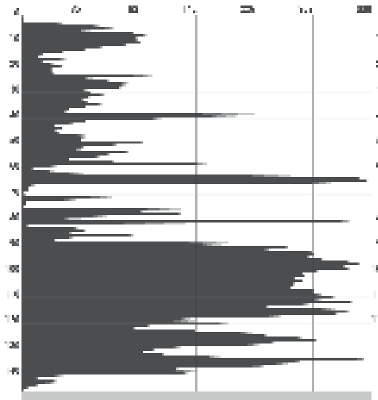

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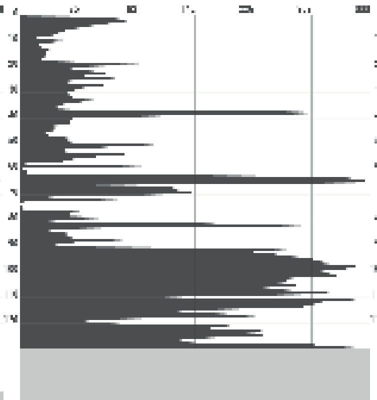

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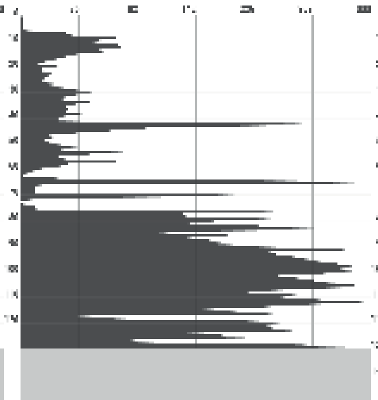

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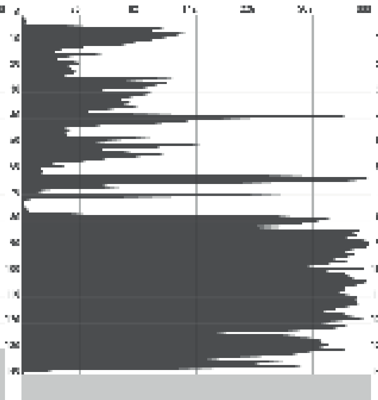

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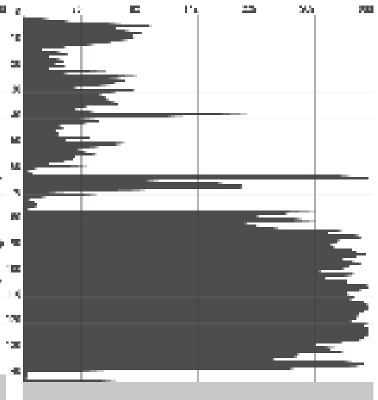

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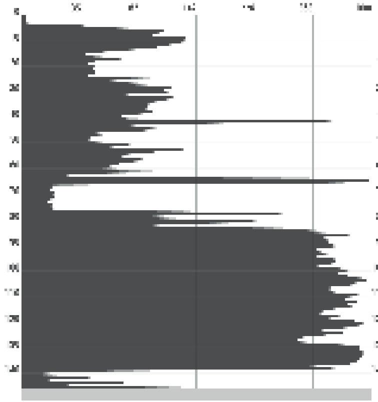

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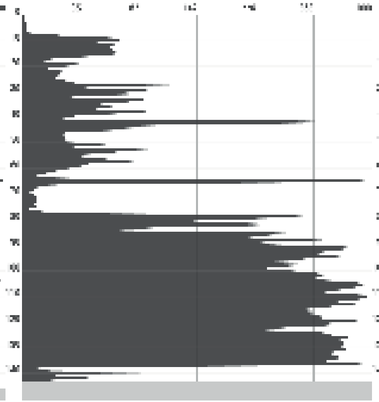

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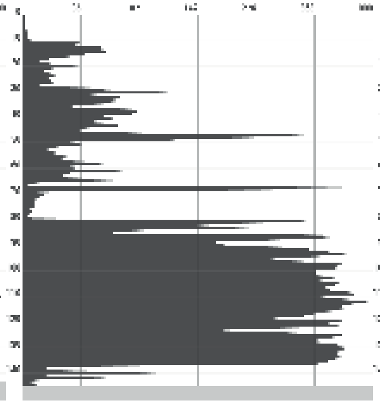

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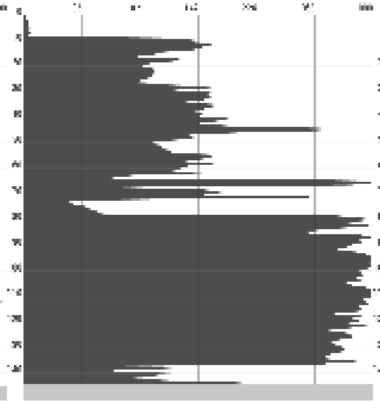

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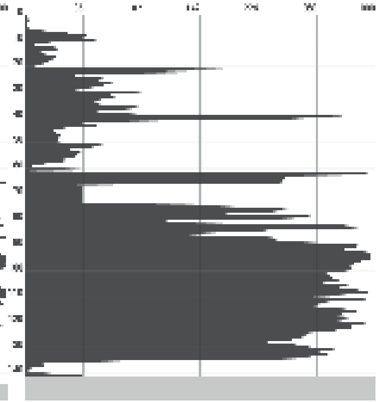

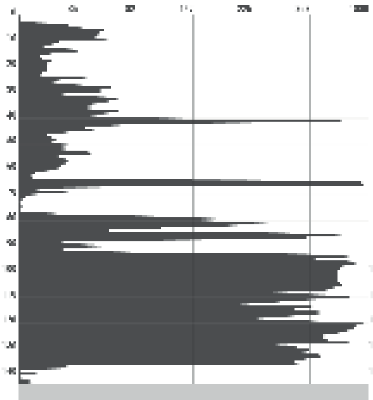

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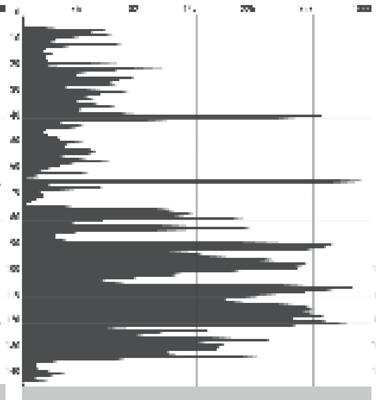

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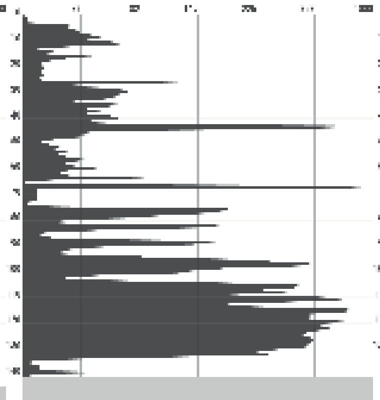

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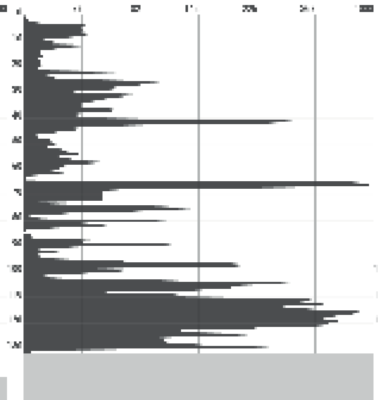

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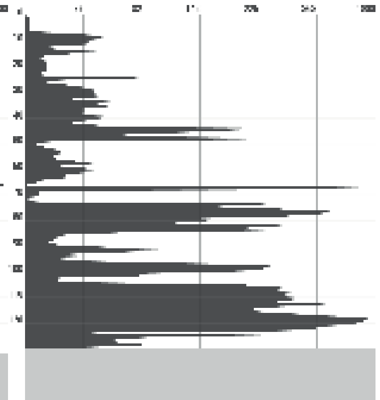

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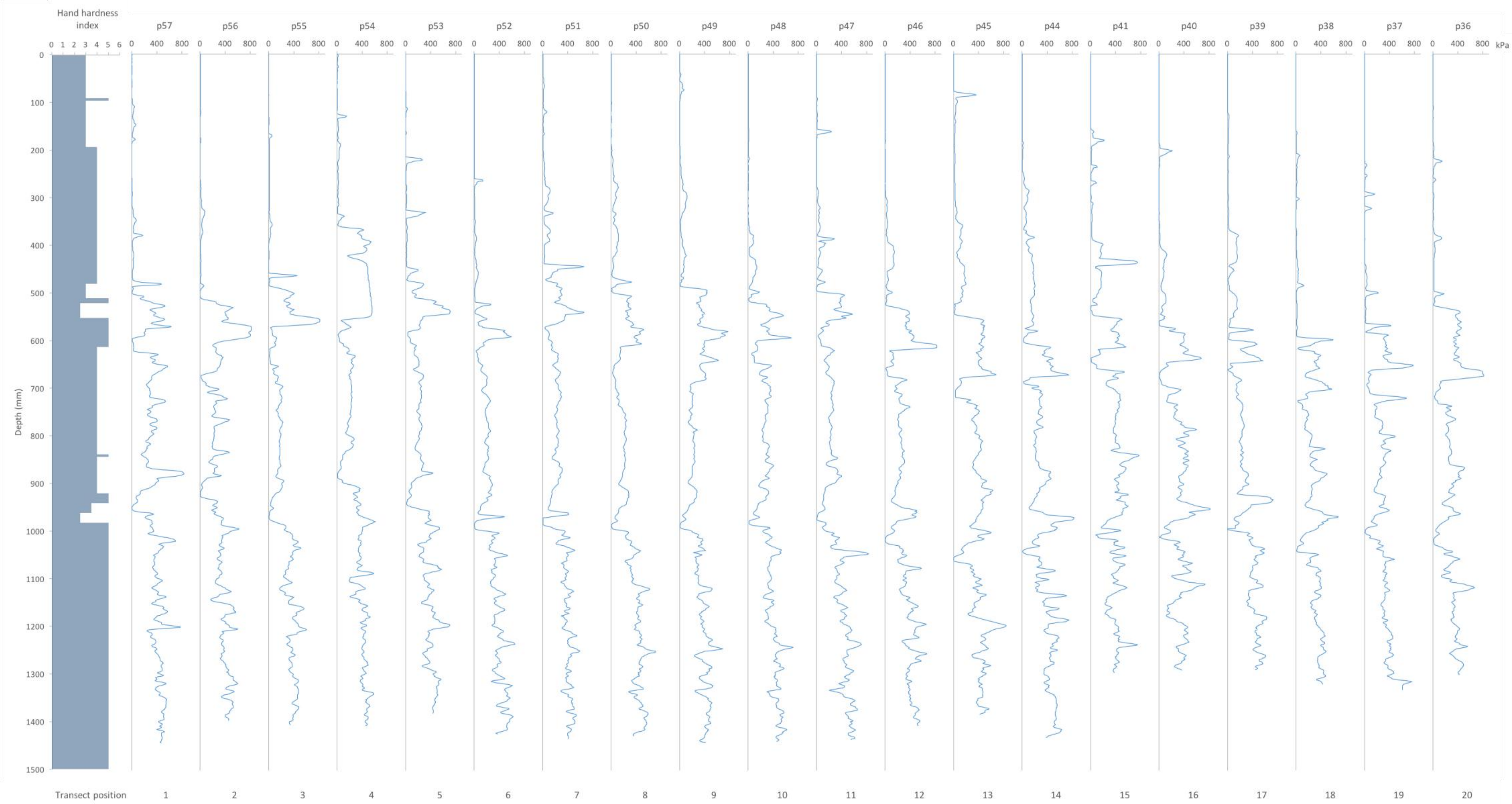
Appendix C.1.2 Hemsedal 2



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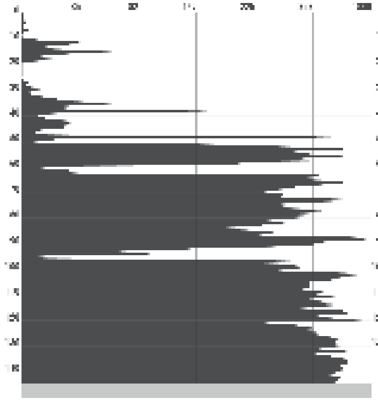

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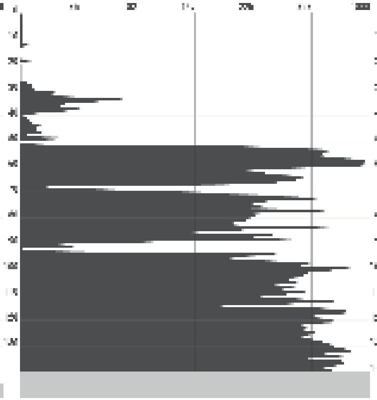

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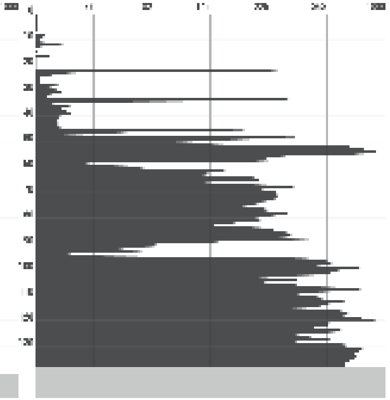

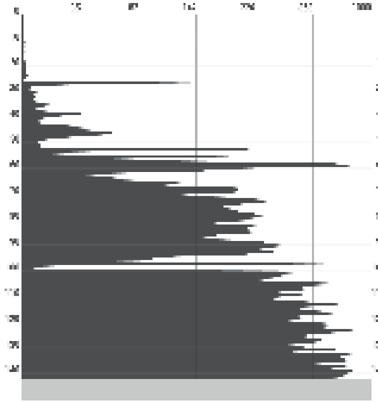

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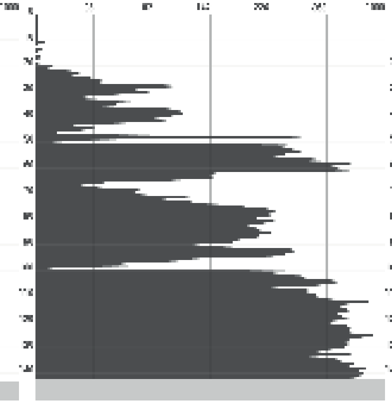

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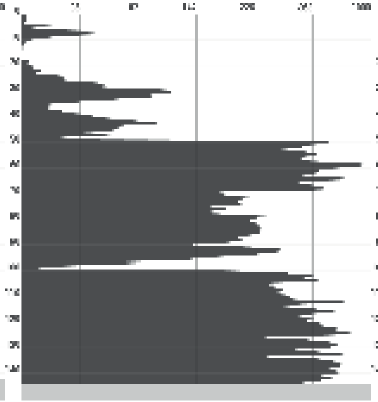

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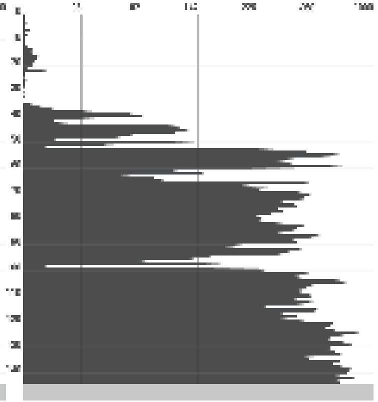

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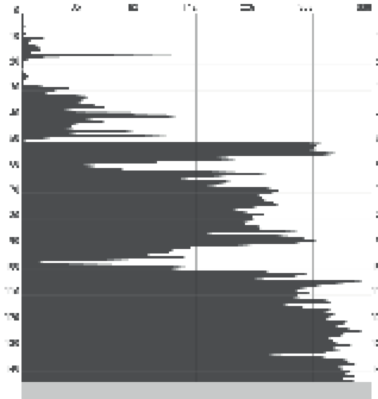

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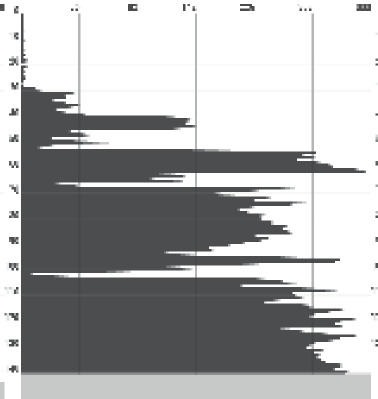

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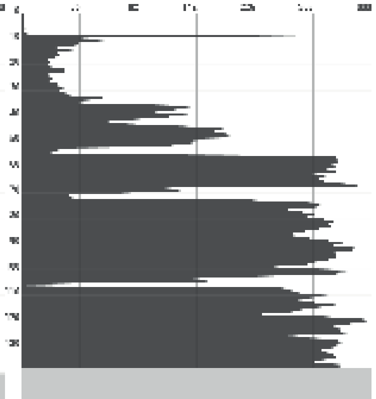

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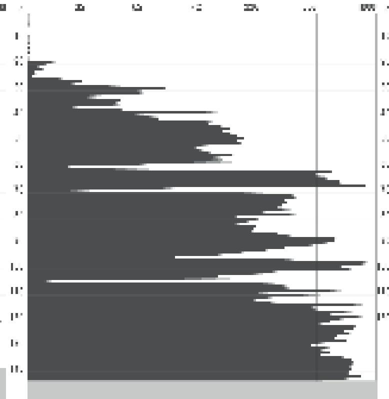

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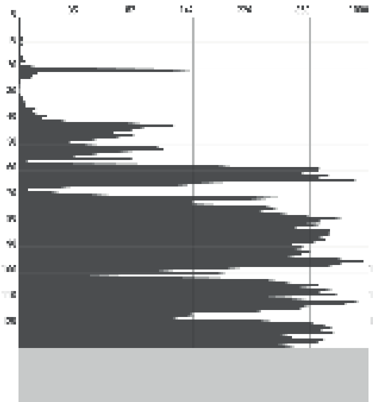

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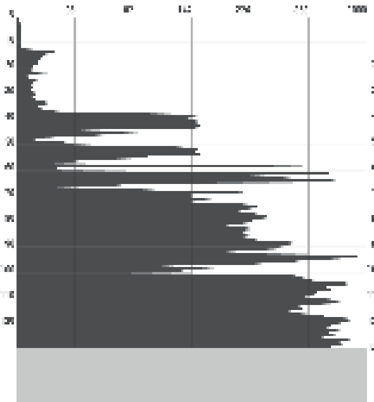

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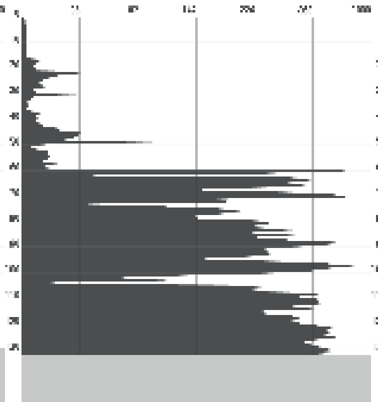

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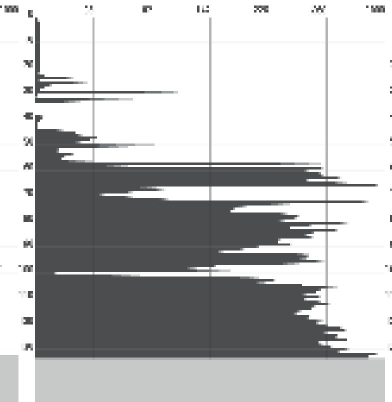

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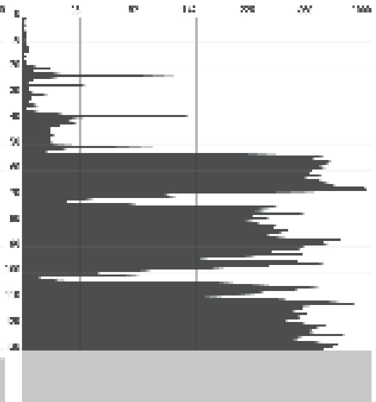

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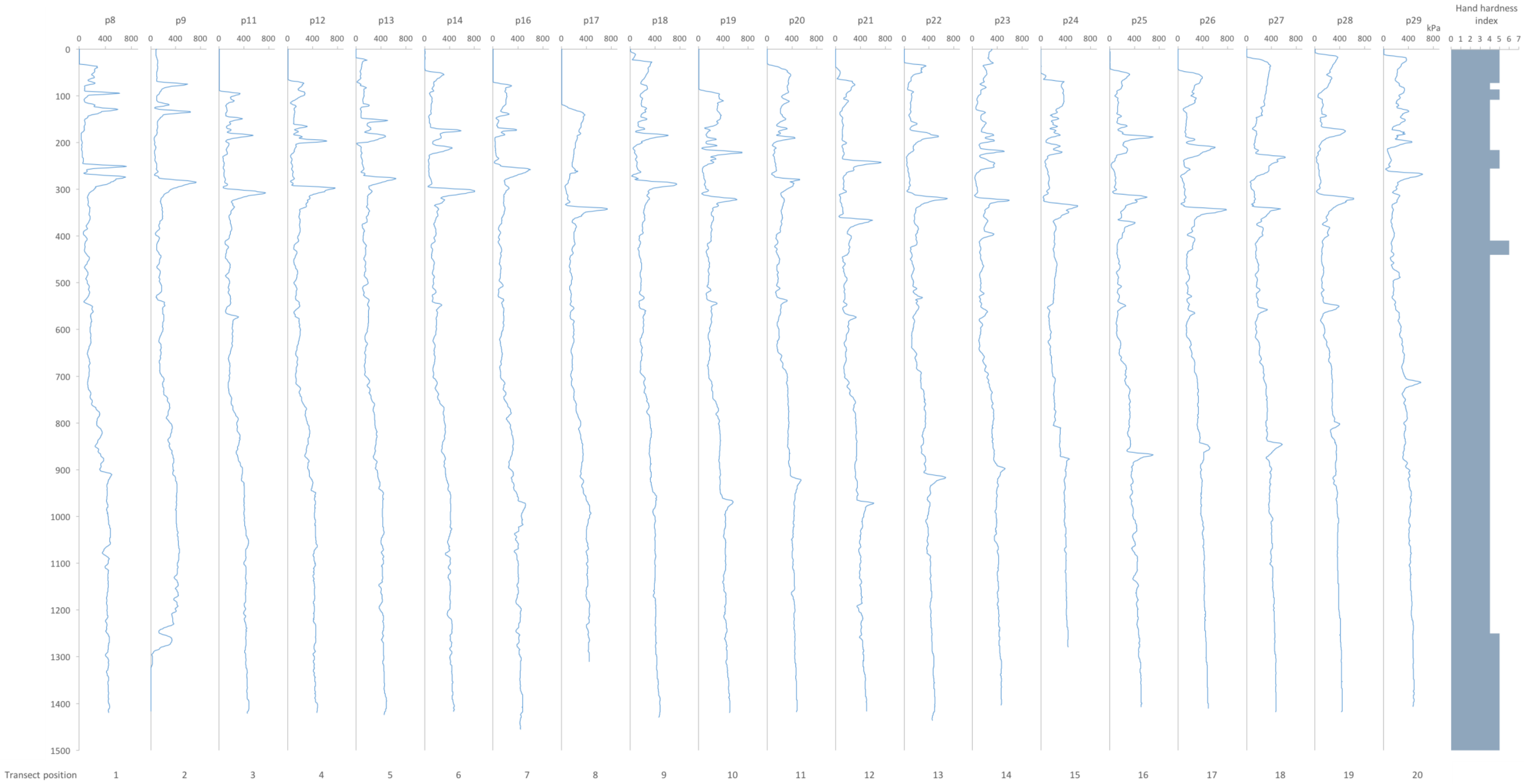
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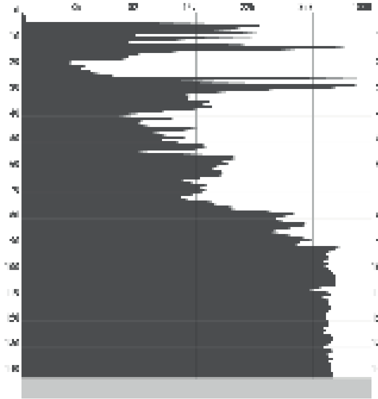

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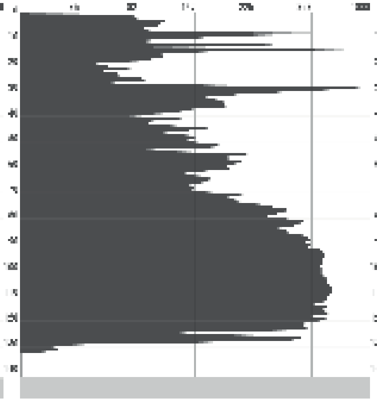

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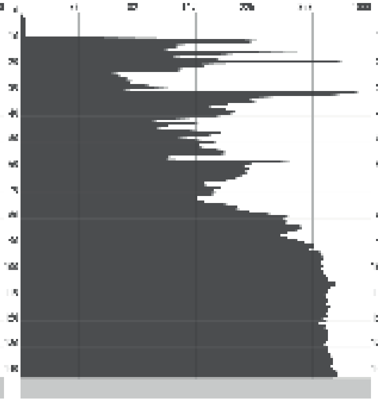

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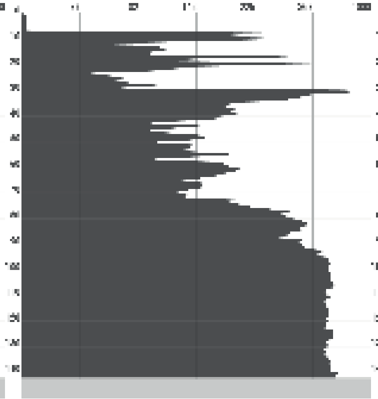

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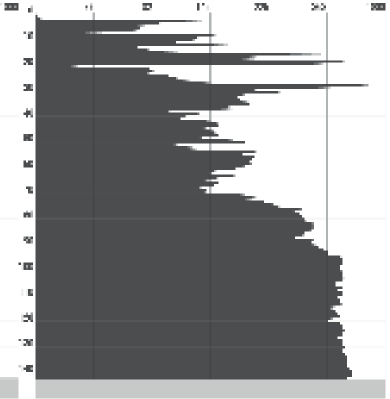

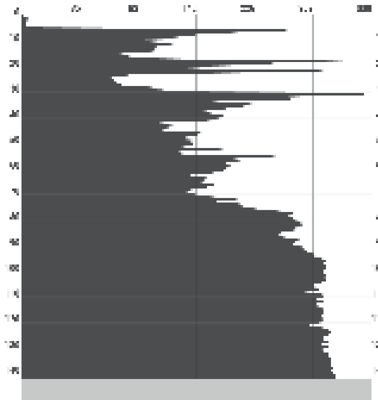

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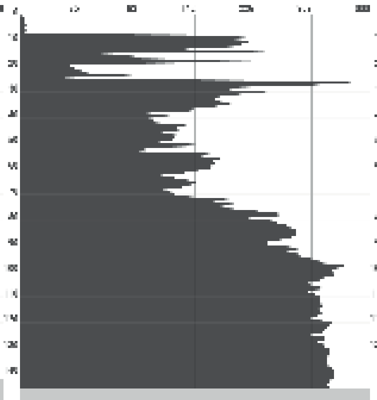

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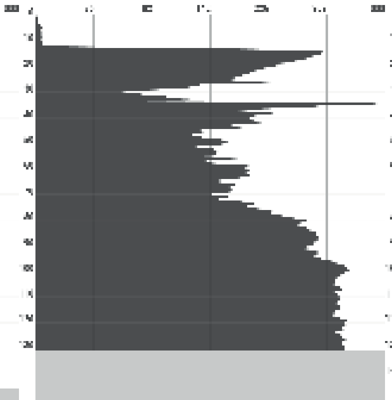

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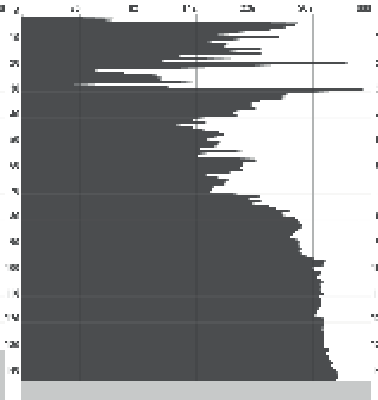

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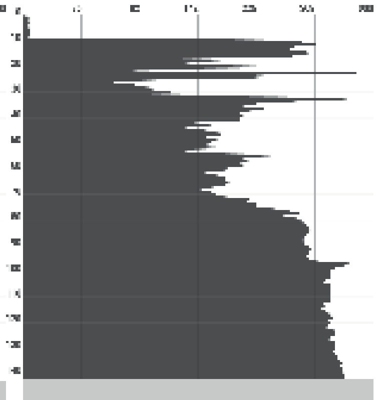

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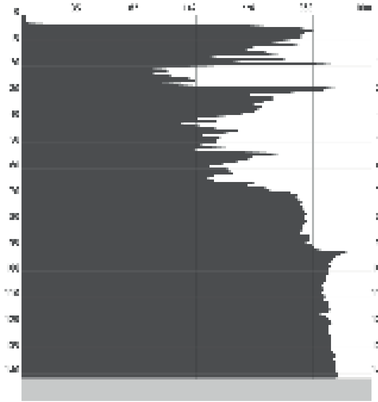

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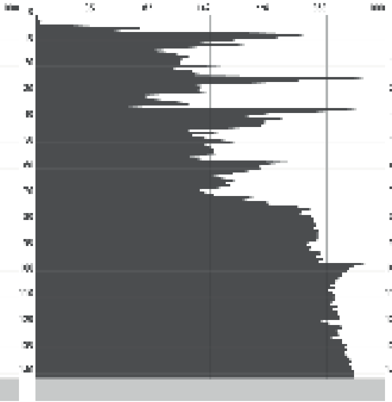

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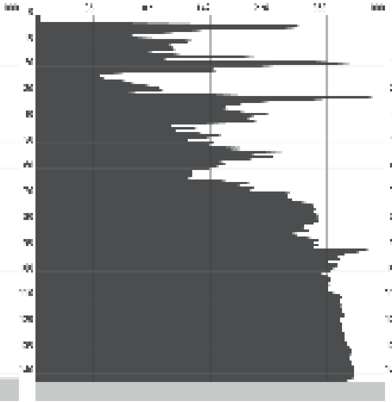

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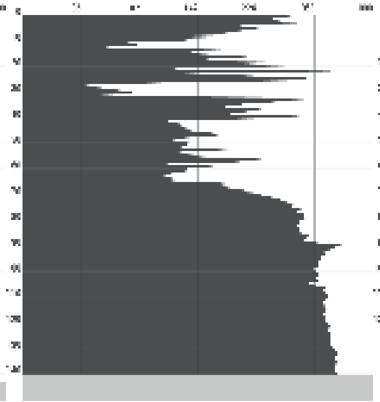

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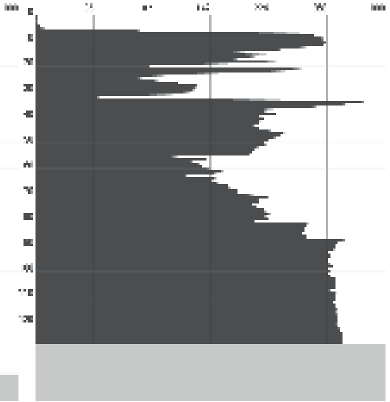

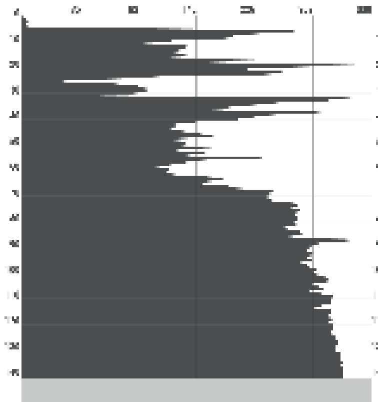

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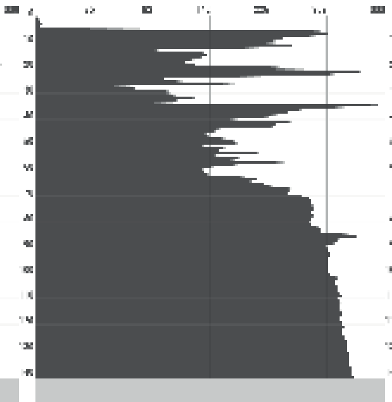

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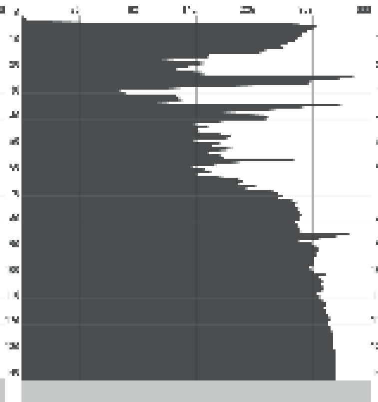

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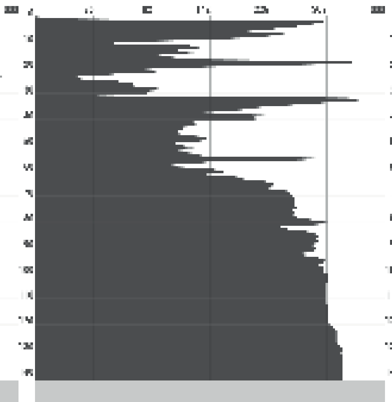

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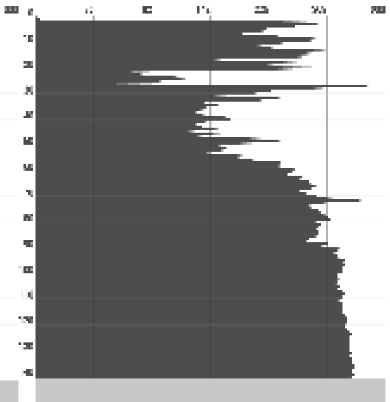

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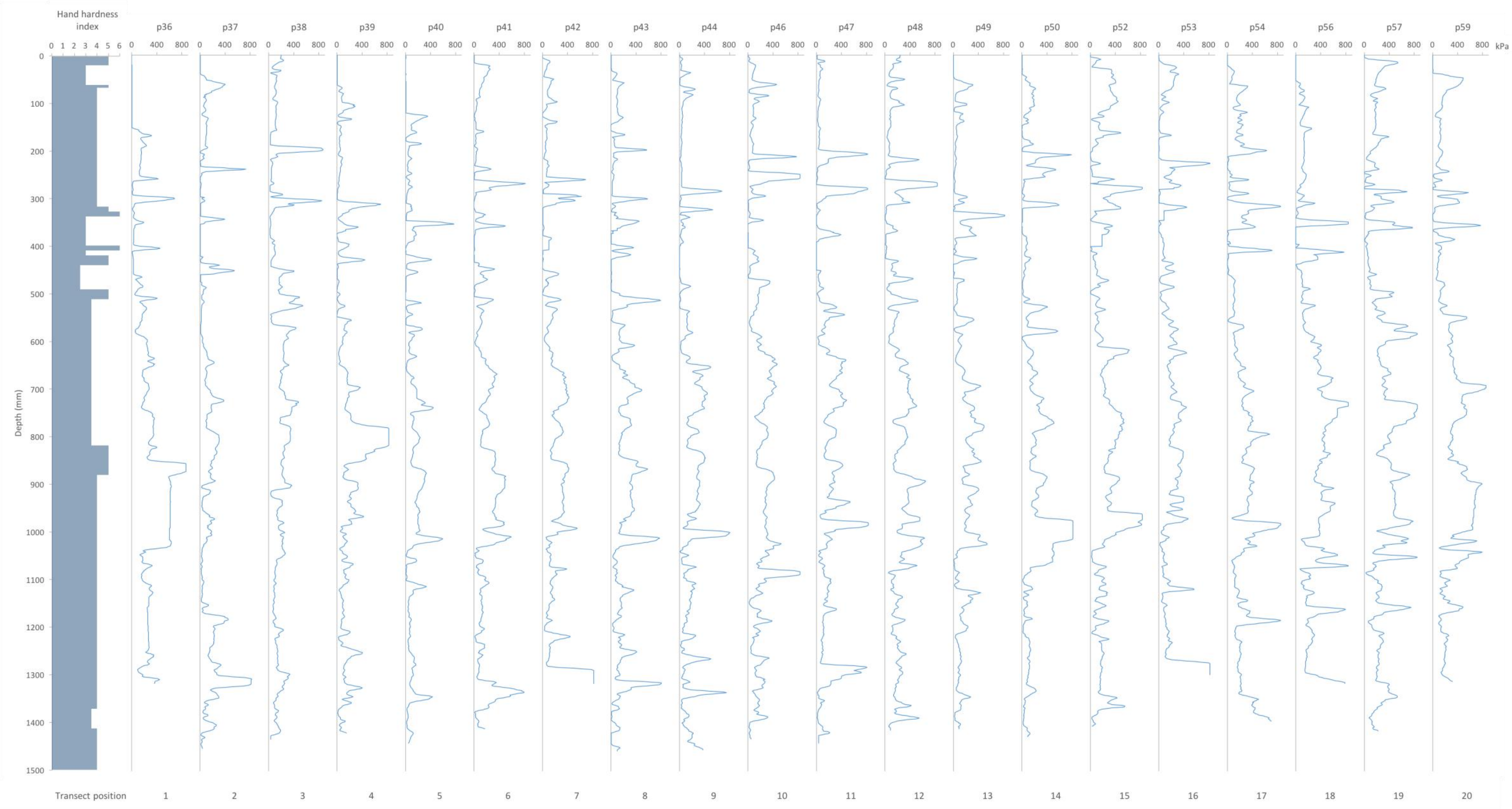
Appendix C.1.4 Filefjell 2



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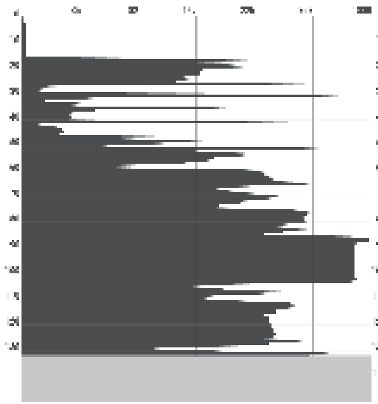

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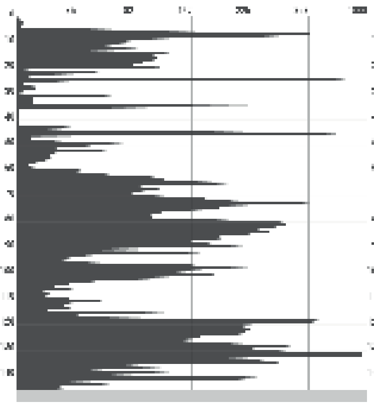

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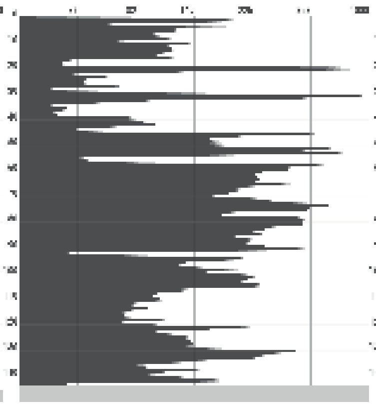

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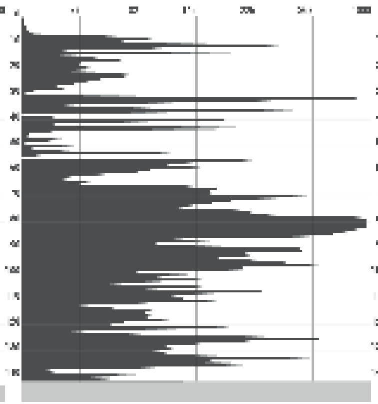

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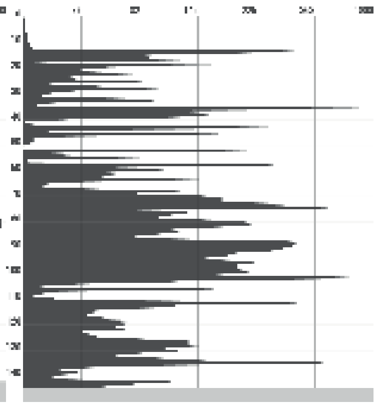

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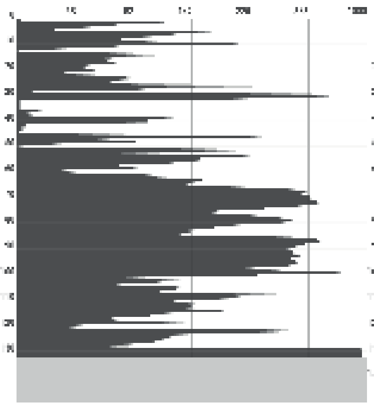

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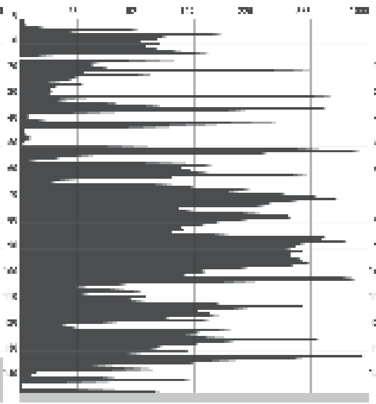

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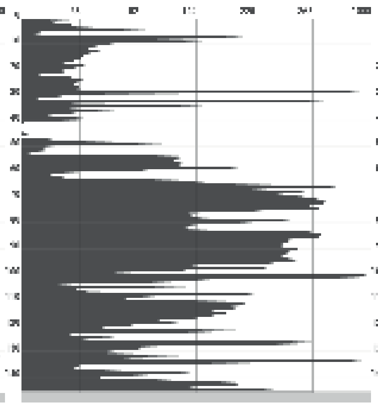

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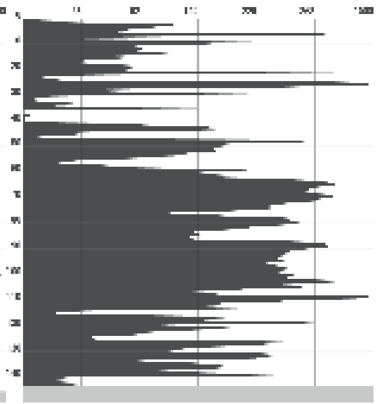

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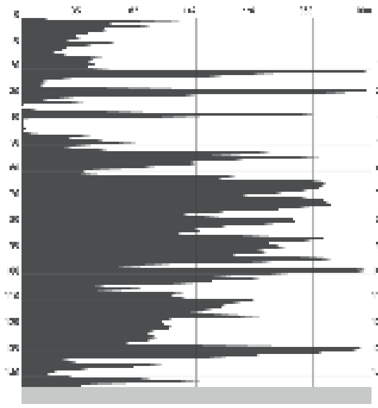

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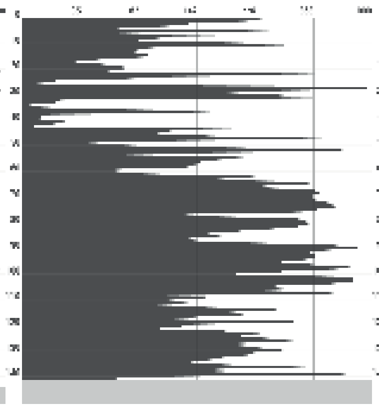

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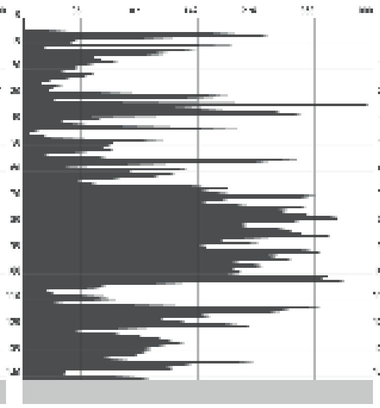

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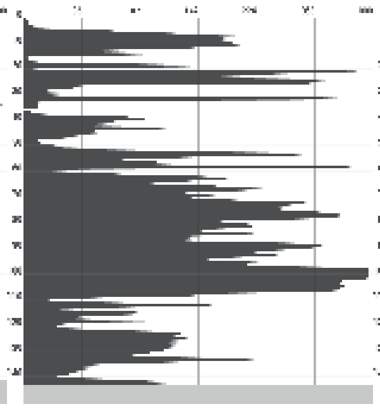

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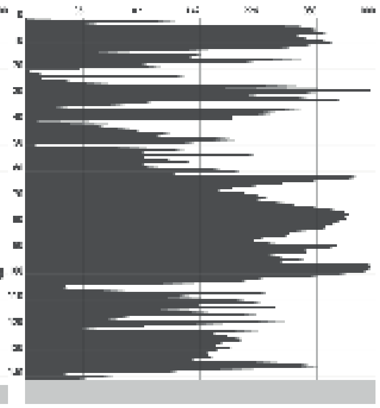

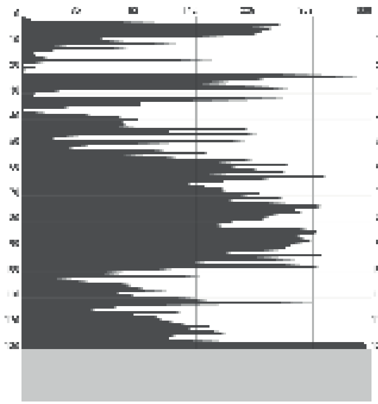

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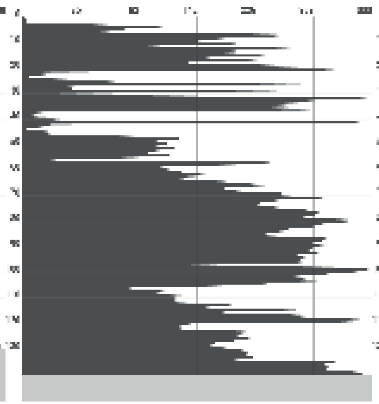

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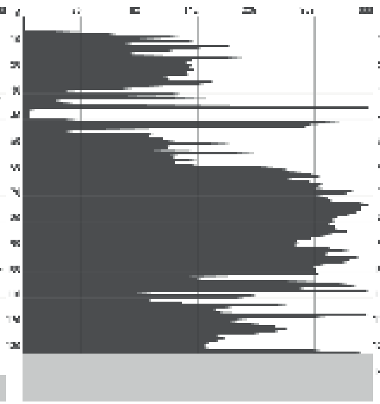

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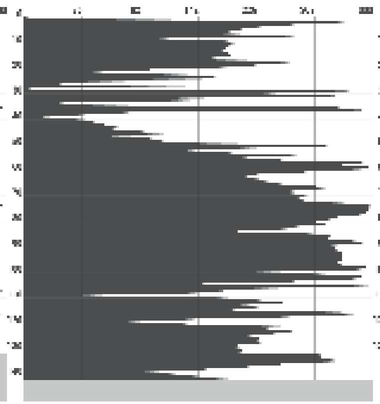

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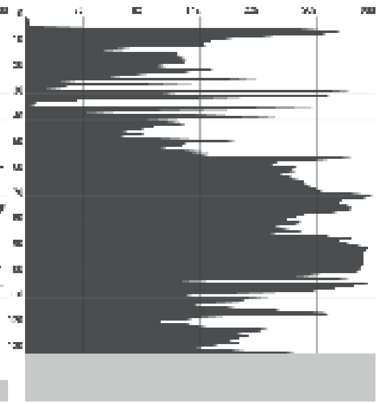

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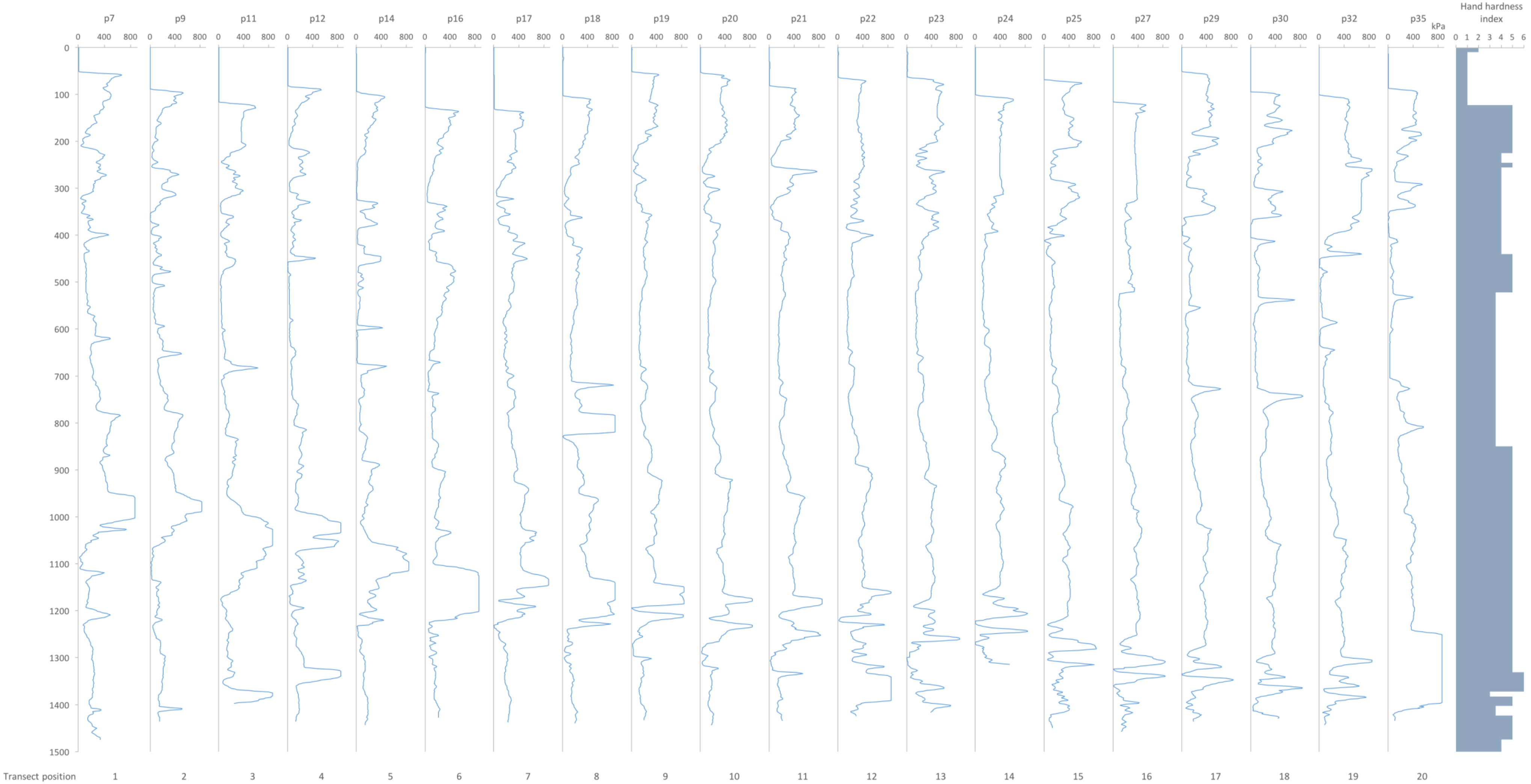
Appendix C.1.5 Svartholten



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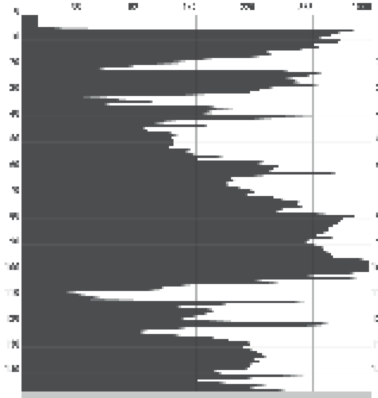

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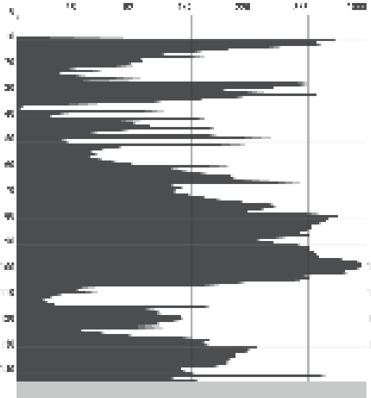

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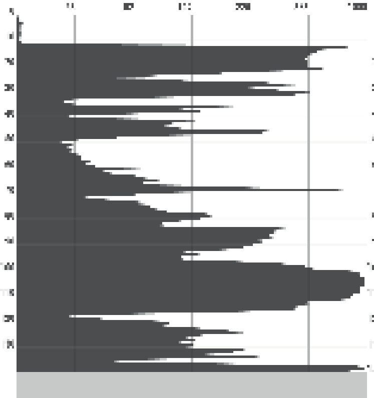

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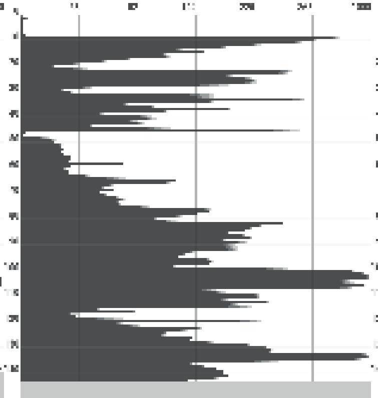

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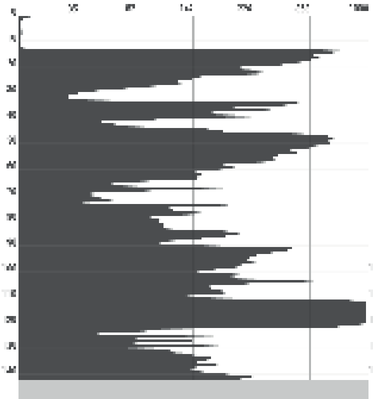

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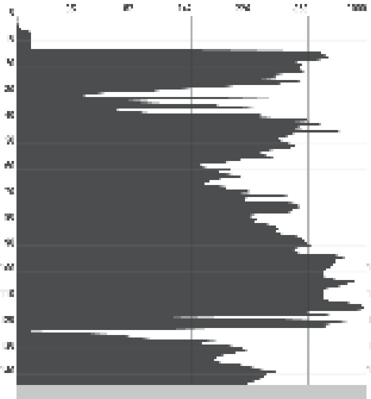

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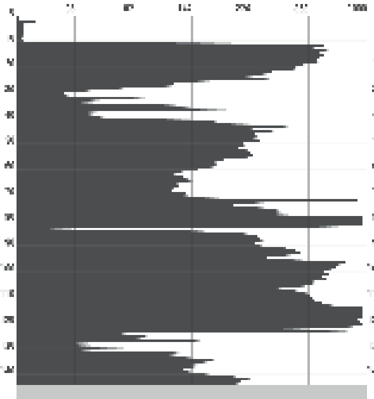

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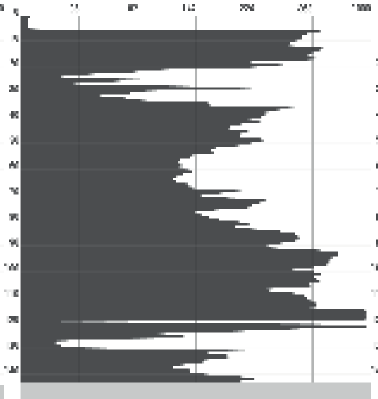

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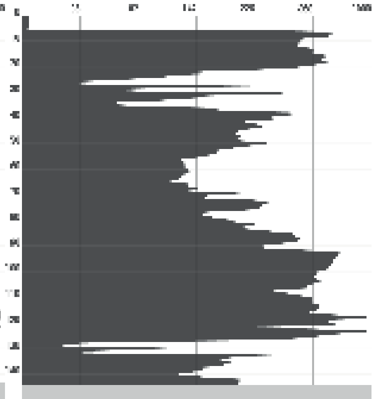

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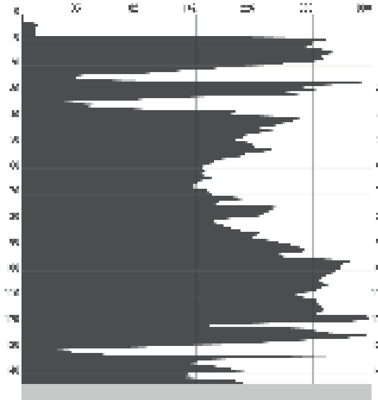

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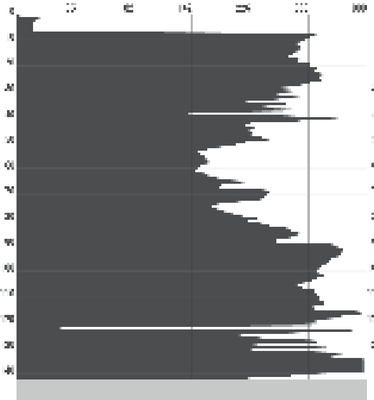

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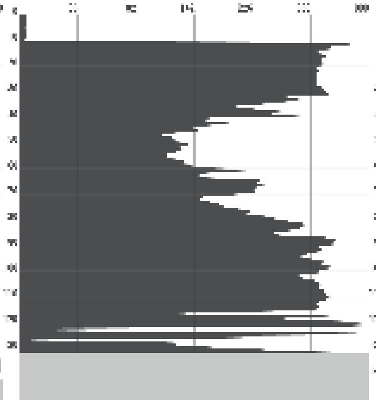

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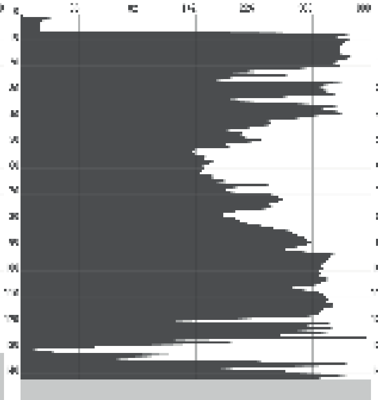

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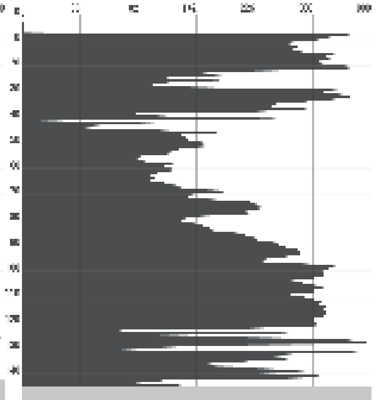

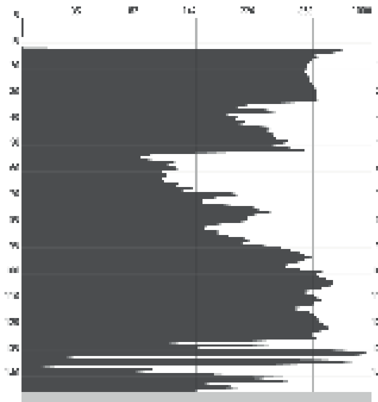

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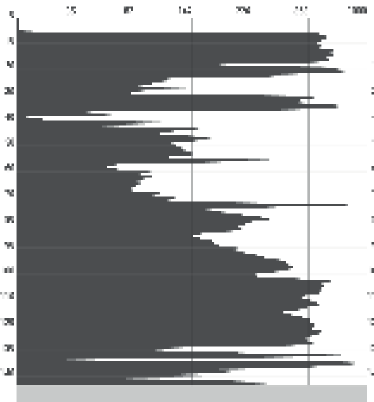

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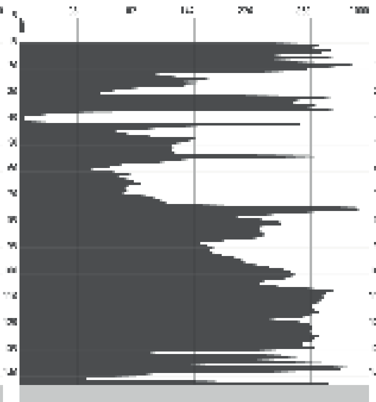

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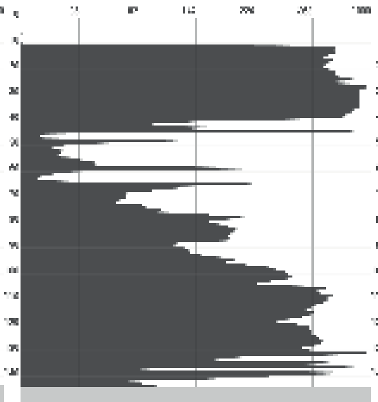

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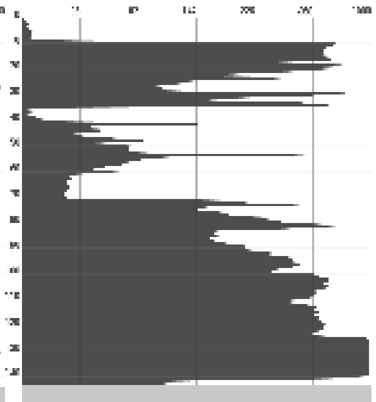

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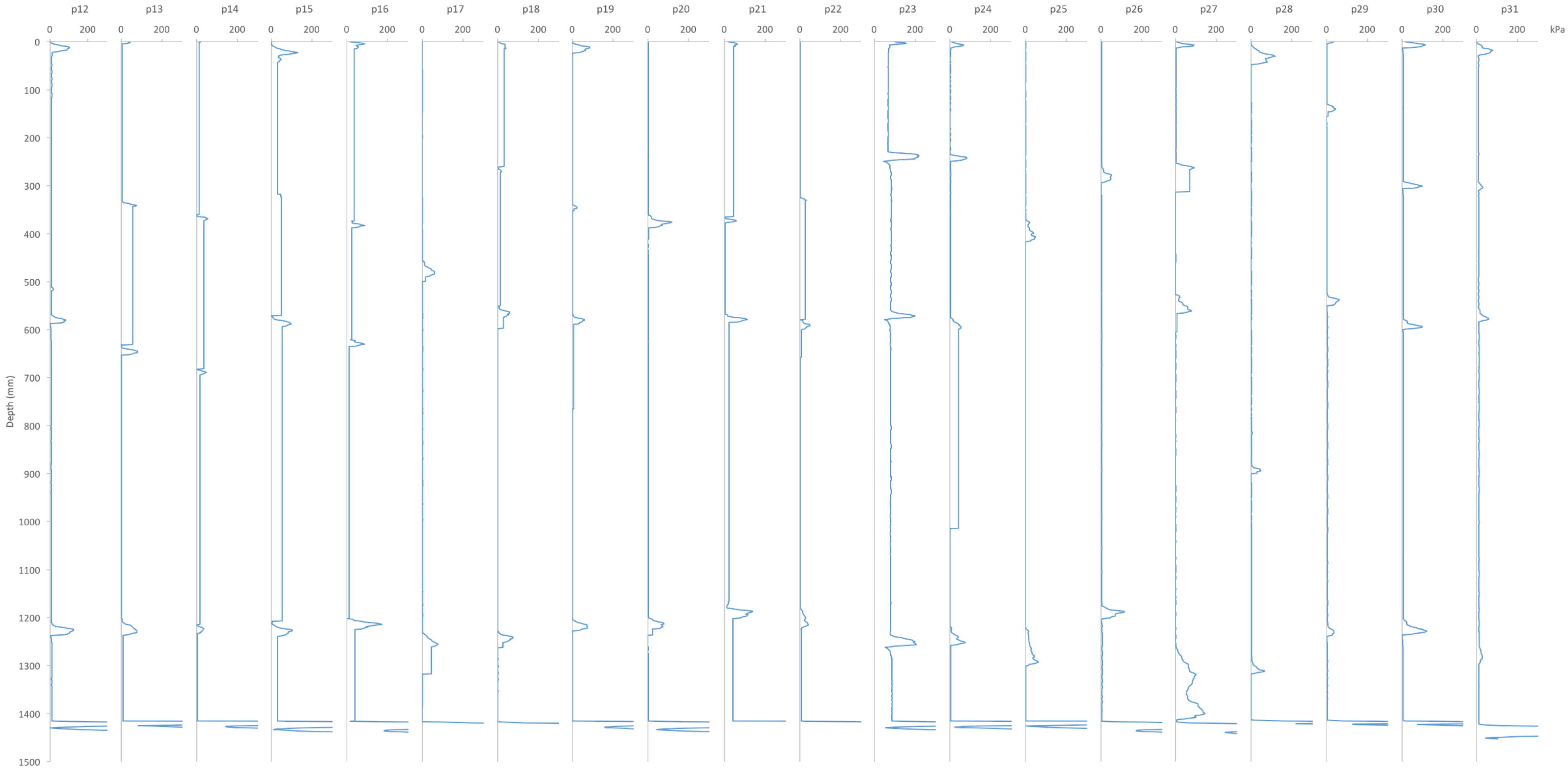
Appendix C.1.6 Lab 4 transect



Appendix D Depth measurements

Appendix D.1 Tracked layers in Hemsedal 2

Avanet SNOW PROFILE

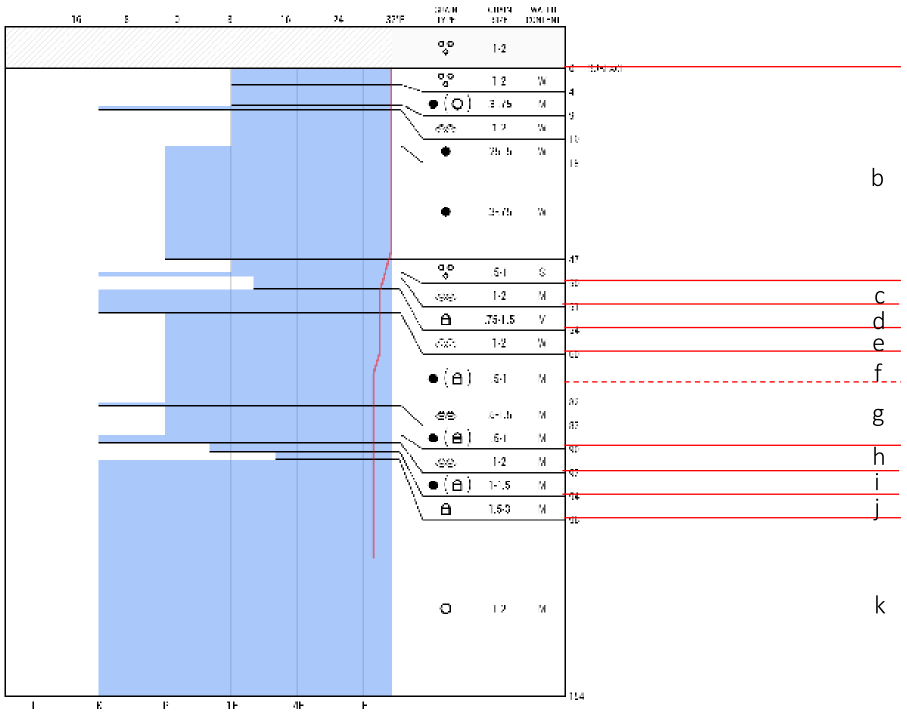
Organization: –

Location: Støngenuten, Buskerud | Date: 2017-03-27 | Snowpit depth: 154 cm

Lat/Lng: 60.94999, 8.16192 | Observer: Åsmund Skancke Karlsnes | Snowpack depth: 215 cm

Elevation: 1,196 m
Slope: 20°
Aspect: 100° EbS
Air temp.: 36°F
Sky: ◯ Few

Wind: Moderate, –
Blowing snow: None, –
Precipitation: No Precipitation
Foot Pen. (PF): –
Ski Pen. (PS): –



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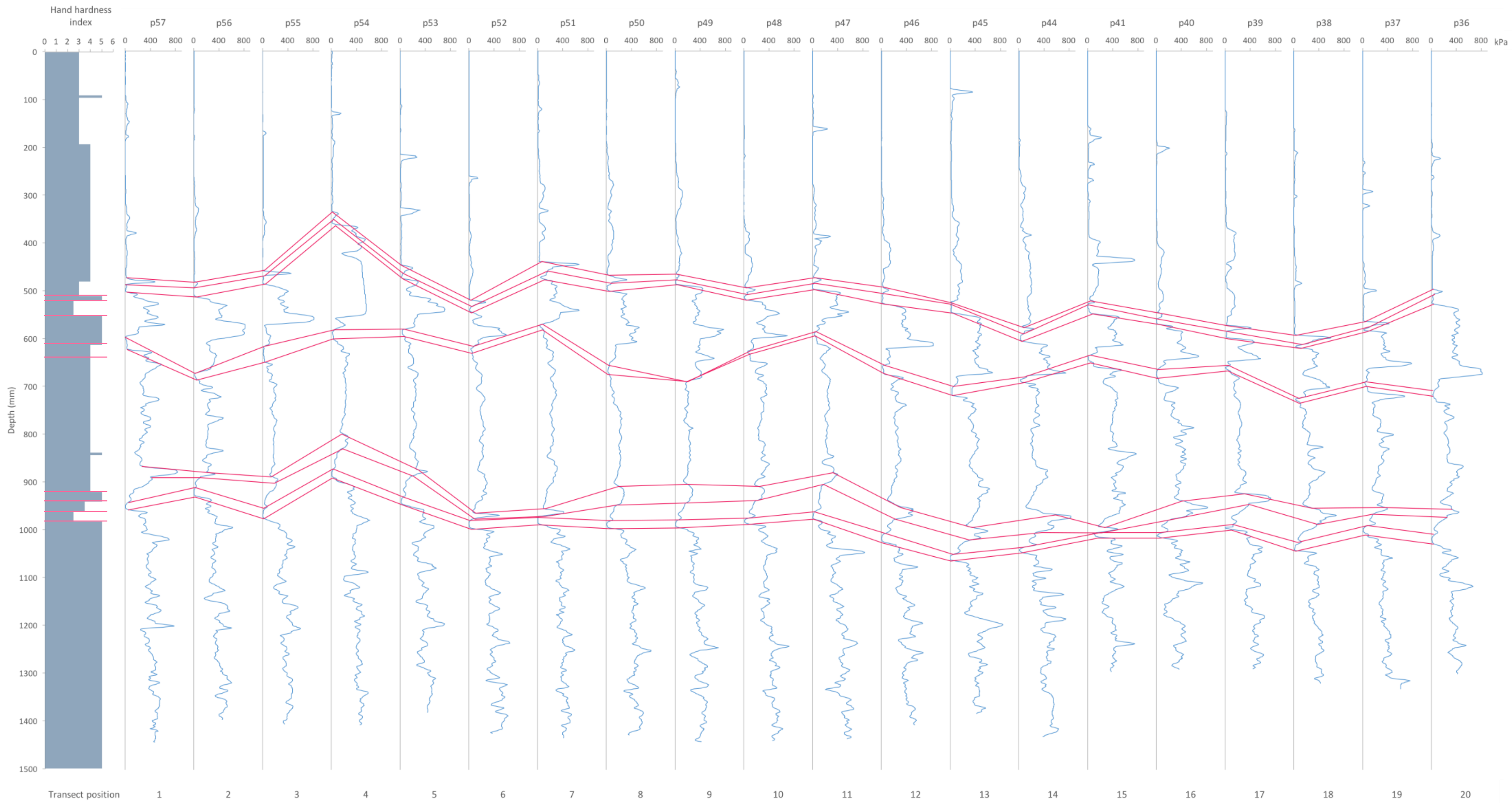
Powered by AVATECH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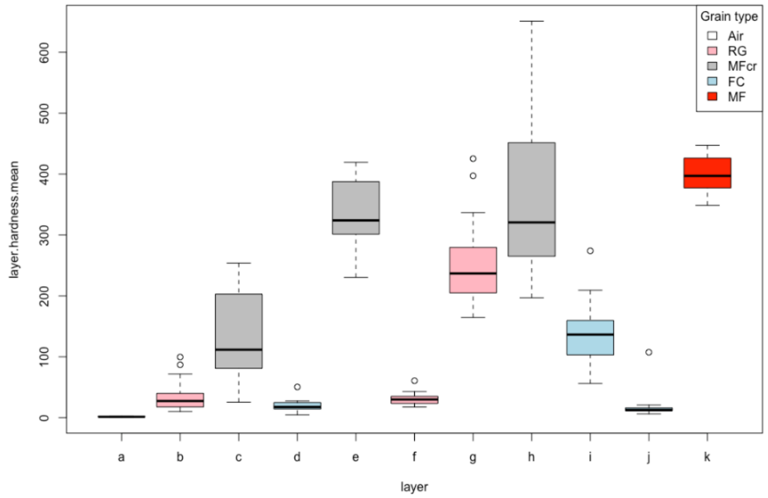
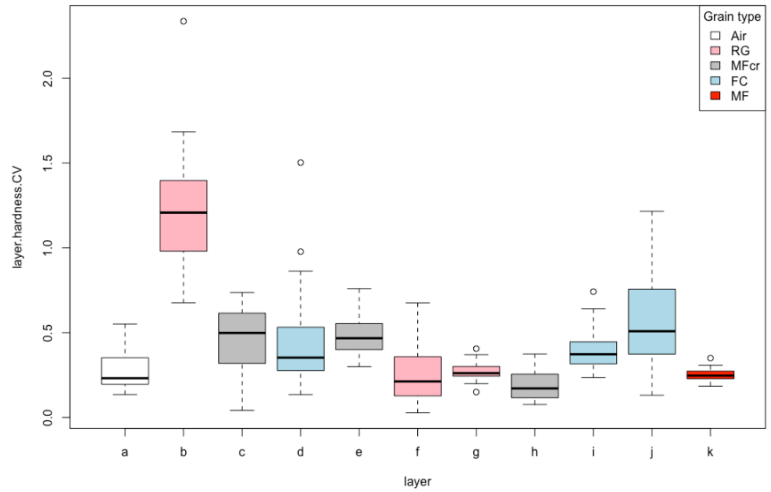
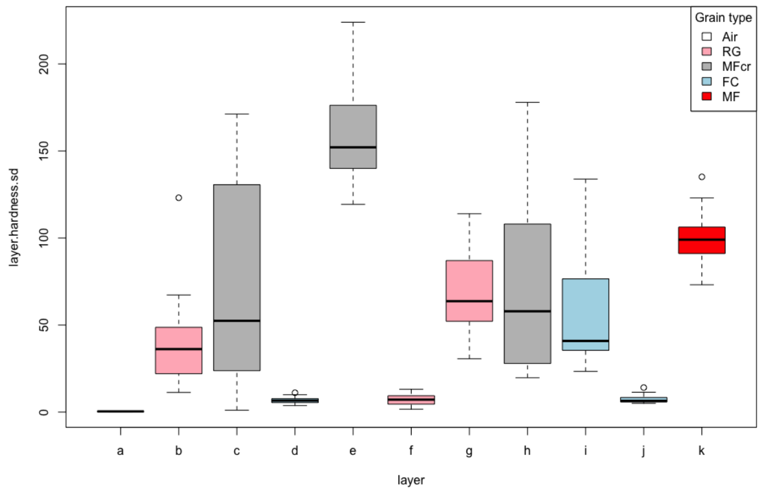
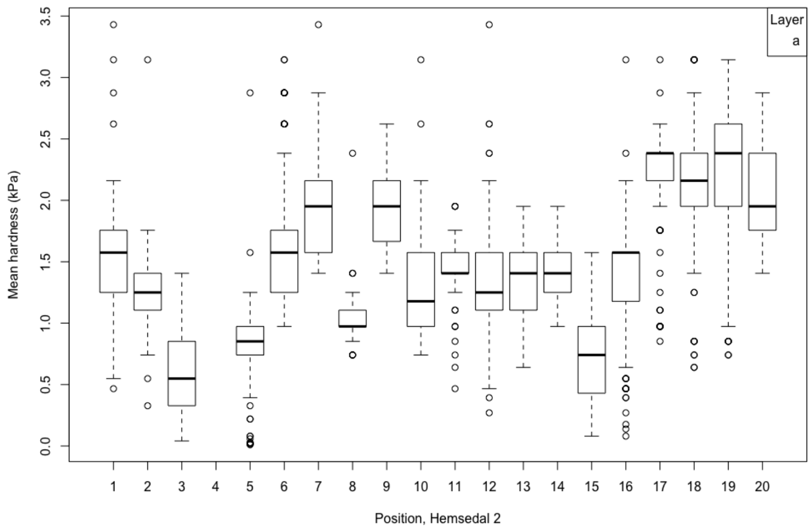
p57
p56
p55
p54
p53
p52
p51
p50
p49
p48
p47
p46
p45
p44
p41
p40
p39
p38
p37
p36
0 400 800
kPa
Depth (mm)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
Transect position
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

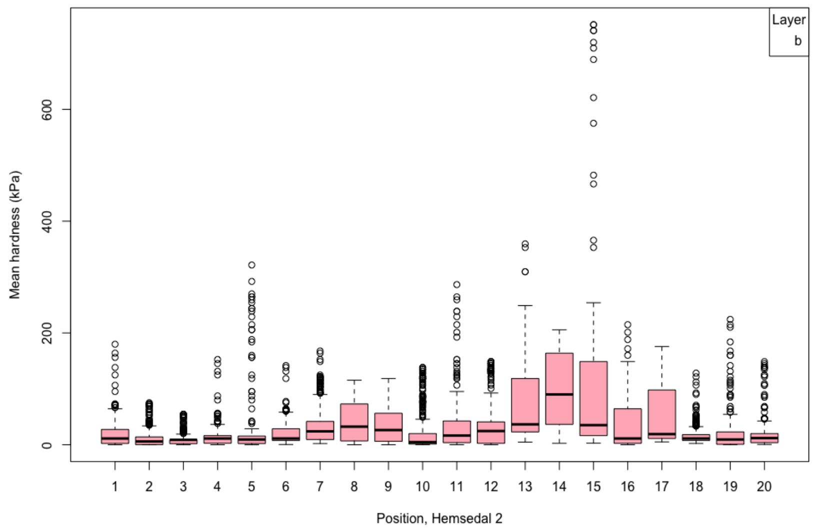
Appendix E Hardness measurements

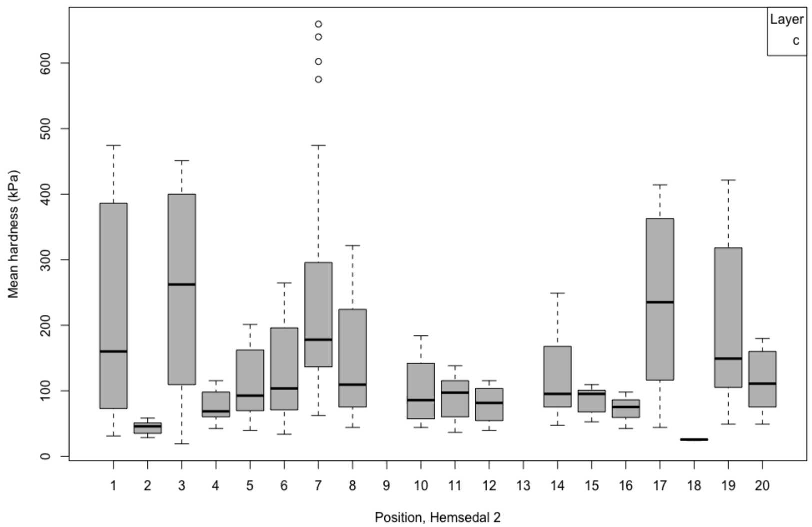


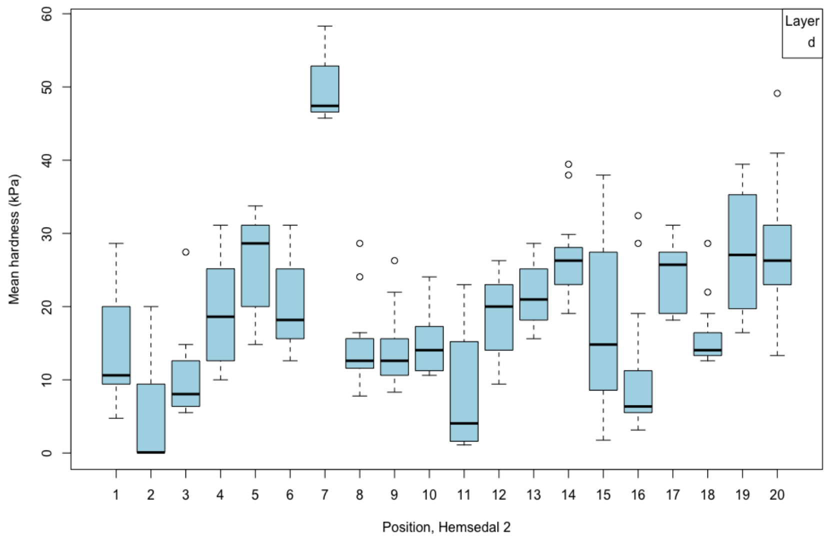


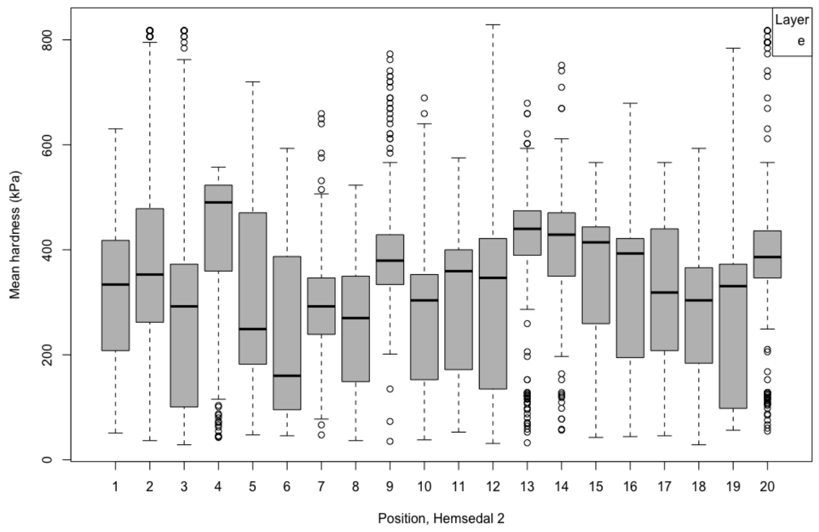


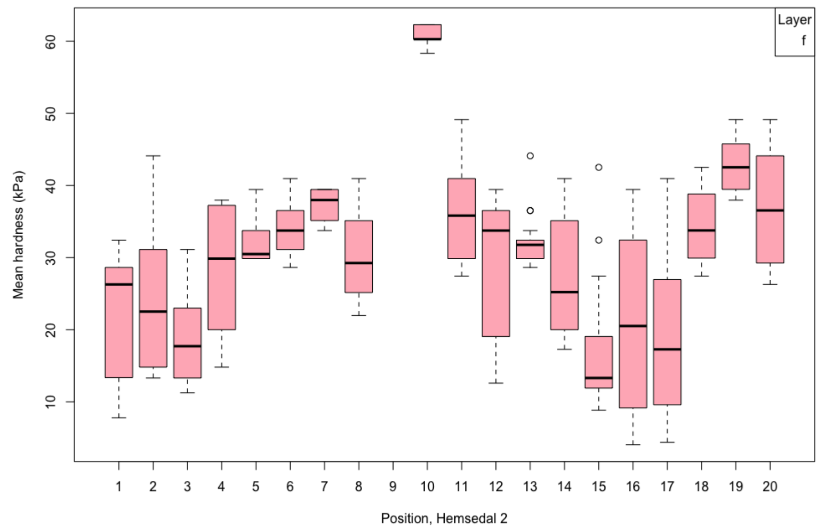

Layer
a
Mean hardness (kPa)
Position, Hemsedal 2

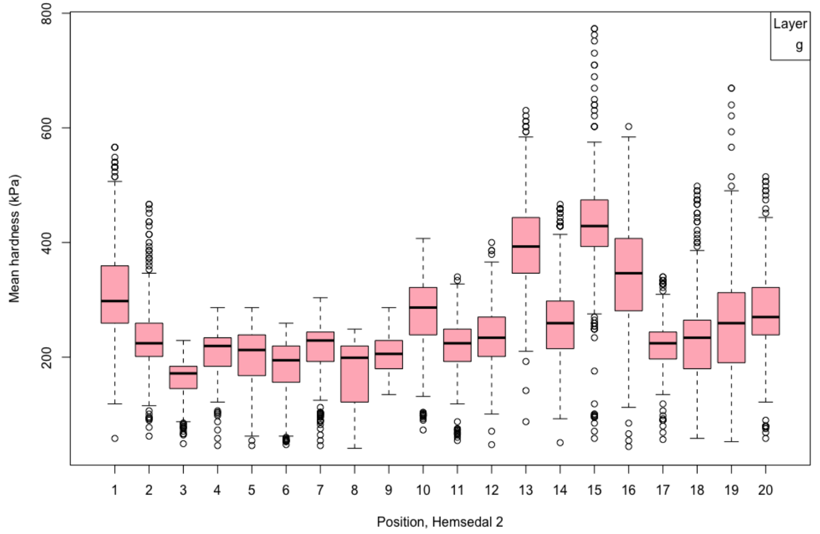

Layer
b
Mean hardness (kPa)
Position, Hemsedal 2

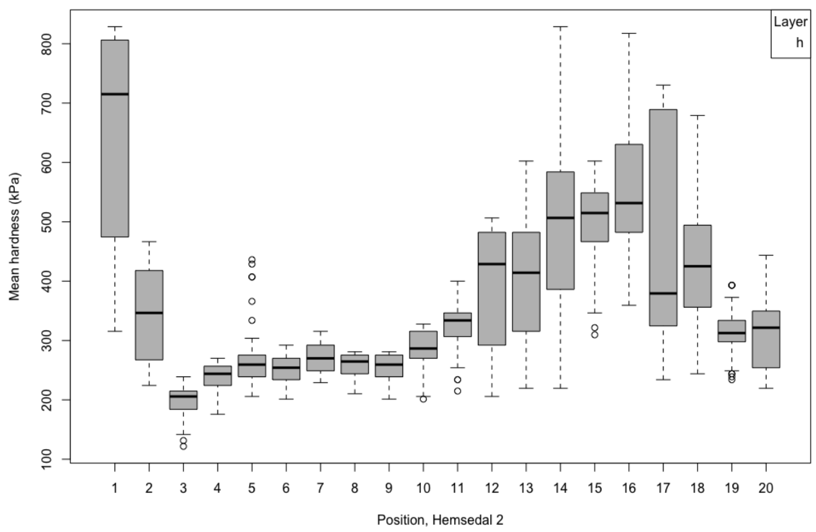

Layer
c
Mean hardness (kPa)
Position, Hemsedal 2

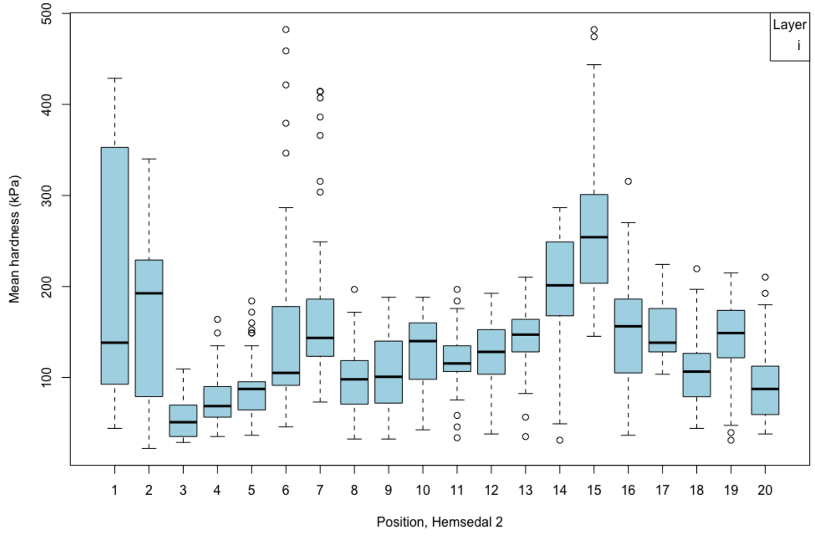

Layer
d
Mean hardness (kPa)
Position, Hemsedal 2

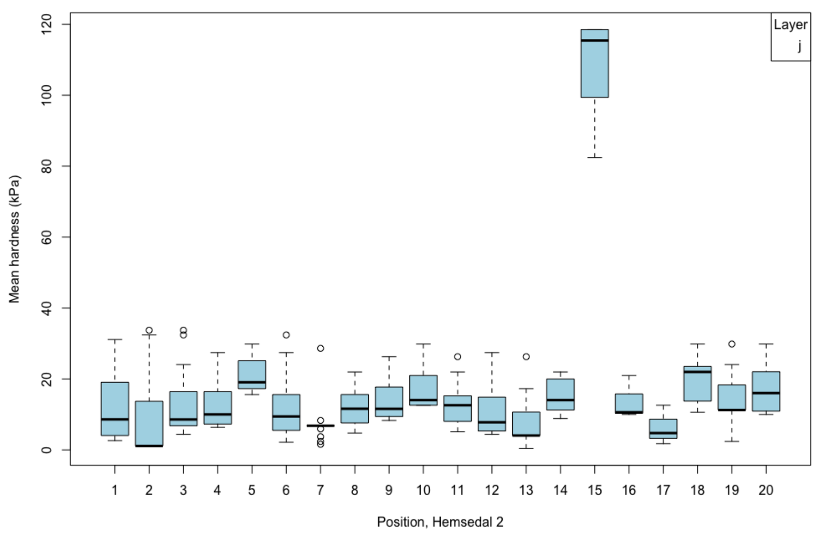

Layer
e
Mean hardness (kPa)
Position, Hemsedal 2

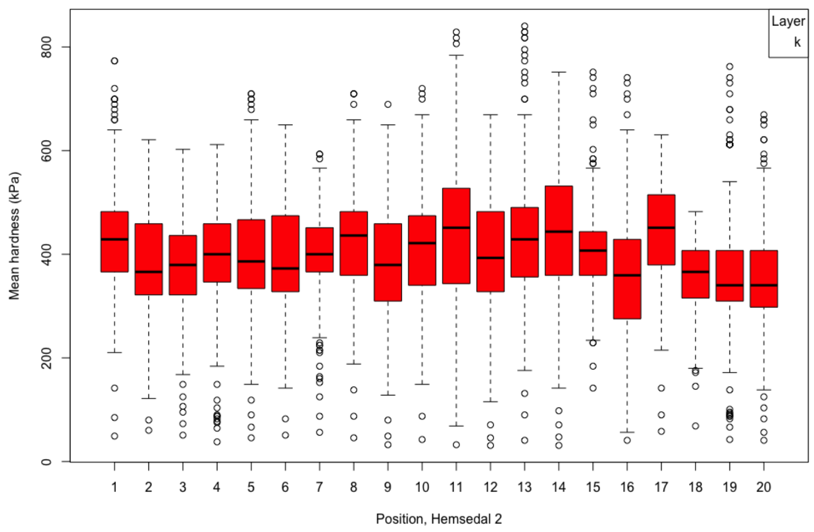

Layer
f
Mean hardness (kPa)
Position, Hemsedal 2


Layer
g
Mean hardness (kPa)
Position, Hemsedal 2


Layer
h
Mean hardness (kPa)
Position, Hemsedal 2


Layer
i
Mean hardness (kPa)
Position, Hemsedal 2


Layer
j
Mean hardness (kPa)
Position, Hemsedal 2


Layer
k
Mean hardness (kPa)
Position, Hemsedal 2

Appendix E.1 Correlation to grain type

A simple correlation is shown for SP2 hardness measurements and primary grain type. The distributions indicate significantly higher hardness measurements for meltforms than rounded and faceted grains.

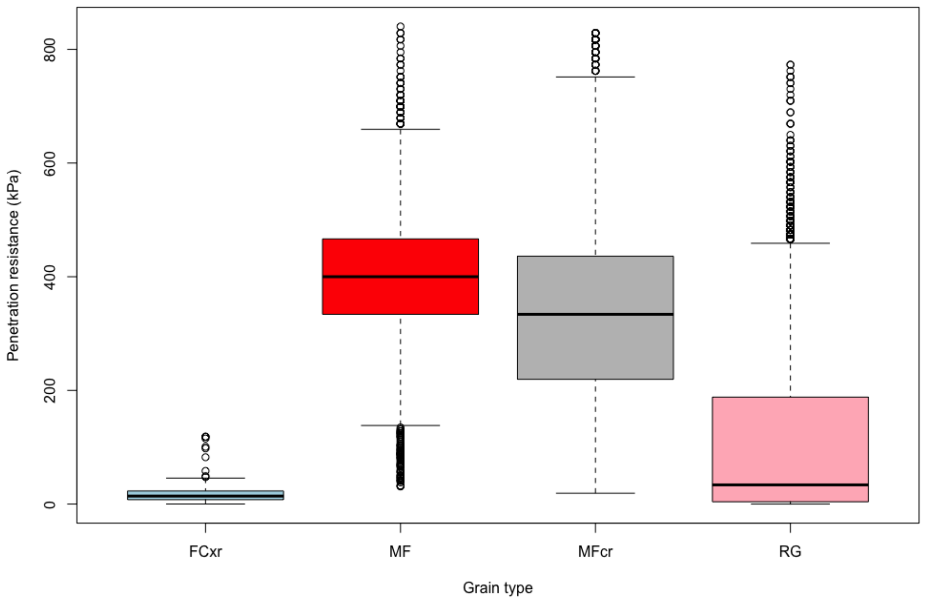


*Figure 7.1. Hardness measurements plotted by primary grain type for identified layers in the Hemsedal 2 transect. Lines represent the median and boxes span the interquartile range (IQR). Whiskers extend to the maximum and minimum values, but maximum 1.5*IQR away from the median. Values further away are defined outliers, shown as small circles.*

Appendix E.2 Profile from Lab 4