Slope Processes of Linnédalen, Spitsbergen: Sedimentation through Avalanching

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Introduction:

During late July and the beginning of August 2010 a field study on slope processes was developed in Linnédalen, central Spitsbergen (figure 1). The aim of this project is to analyze slope processes in the region focusing primarily on snow avalanching as a function of sedimentation. The study will combine and correlate meteorological data, time-lapse camera imagery and prior studies in the area. The objective is to gain an understanding of the valley wall sedimentation and the significance of snow avalanching as a means of clast transport in Linnédalen. A focused study will be conducted on the eastern and western flanks of Griegaksla with a comparative analysis of slope characteristics with regards to rock type, grain size and slope features. The study also involves mapping the clast size distribution of five talus cones in the Linné valley using Arc GIS. Avalanche activity will be determined through time lapse photo imagery and Tinytag shock logger activity. Avalanche periods will also be compared to meteorological data. Twelve natural sediment traps are monitored between the eastern and western flanks of Griegaksla indicating yearly sedimentation. This study focuses on whether snow avalanching the predominant mechanism in the regional sedimentation, and what factors control sedimentation. The project will also try to hypothesize how slope processes evolved through time and what will happen in the future.

-Geography (location, relief)-

Svalbard is an archipelago located in between the Arctic Ocean, the Barents Sea and the Greenland Sea spanning from 76° - 81° north of the equator. The size of the group of islands is 61,022 km^2 while the larges and only settled island, Spitsbergen is 37,673 km2. The main island Spitsbergen directly translated means “spiked mountains” emphasizing that much of the island is mountainous and high relief. The western coast is dominated by high alpine summits, while the peaks to the central and eastern domains stand as plateau like with steep face walls and flanks but flat tops.

The study area is located on the northwestern coast of central Spitsbergen, Kapp Linné. The region is dominated steep alpine peaks that rise up out of incised “U” shaped valleys that have undergone large scale glacial and fluvial erosion (Humlum, 2002). Mountains (~750m ASL) proximal to the coast rise up rapidly and exhibit a wide range of knife edge narrow ridge lines to more plateau-style summits. This is function of bedrock geology and unique tectonic histories.

Due to Svalbard’s positing above the Arctic Circle, the region undergoes a period of midnight sun and a period of polar night. This is experienced in Longyearbyen from April 20th until the 23rd of August, and the 26th of October until the 17th of February respectively (figure 2). Dates are similar at Kapp Linné. These extreme conditions place a significant role in the seasonality of the region and unique climate. According to Hjelle (1993) the region is defined as a peri-glacial environment due to present climate, geomorphology processes and features exhibited. Kapp Linné’s location on the ocean moderates temperature extremes and also brings more precipitation generally experienced at similar latitudes (Humlum et al., 2003; Åkerman, 2005).

Linnédalen is a ~18 km long valley on the west coast of central Spitsbergen oriented N/S. It is a home to a glacial-fluvial-lacustrine system that has run off into Isford for the last ~9kyrs. Around 9600yrs ago Linnéfjorden was sealed and formed Linnévatnet (Svendsen et al. 1989). Linnévatnet is boarded by Griegfjellet (781m) and Griegaksla (478m) to the west, an alpine ridge forming the northwestern domain of Linnédalen. The northeastern flank of the valley is bracketed by Vardasen (567m) and Vardebourg (588m), large cliff-faced peaks with more of a plateau styled summit (figure 3).

-Bedrock Geology-

Svalbard is an exposure of the north western domain of the Eurasian continental plate which was uplifted by late Mesozoic and Cenozoic crustal activity. The archipelago exhibits a range of rocks recording back to the Precambrian up until present day. During the Precambrian Eon the Archipelago was located near today's South Pole. During this period Svalbard experience several mountain building events that today are exhibited on Spitsbergen's north and west coast (Ingolfsson, 2008). Paleo-magnetic dating show that the islands where subequatorial pre Devonian and over time have migrated north (Worsley et al., 1986). Svalbard drifted from an equatorial zone to roughly 45°N from the early Carboniferous to Cretaceous period during which sandstone and limestone deposition was experienced on the south and eastern regions of Spitsbergen (Ingolfsson, 2005). Towards the end of the Tertiary period Svalbard reached its present day location and extensive glaciations began and continue through today (Ingolfsson, 2008).

Bedrock starting at Isfjord Radio (the outer coast of Central Spitsbergen) and moving eastward to Grønfjorden rises in stratigraphic column going upward in the original depositions of the layers (figure 4). The ages of bed layers have been determined according to presence of different fossils, sedimentary structures and the degree of metamorphism and deformation.

The western flank of Linnévatnet to the west coast is formed of Precambrian Heckla Hoek rocks consisting of diamictites, carbonate rocks and phylites. The western flank of Griegaksla (the knife edge ridge between Linnévatnet and the strandflats) is comprised of mid-Proterozoic arno-argillaceous phylites of the St. Jonsfjorden sequence (Åkerman, 1980; Hjelle & Lauritzen, 1982; Ohta et al., 1992). Worsley et al., (1986) believed that the ridge represents a local branch of the Caledonian fold belt. The valley has formed in the metamorphicaly weakened lower- Carboniferous quartzite of the Billefjoden group (Åkerman, 1984; Ohta et al., 1992). The eastern flank of Linnévatnet and in general the region is dominated by the Carboniferous Billefjorden Group of sedimentary rocks, including limestone and dolomite as well as small coal seams (Dallmann et. al. 1992).

-Surface Geology-

The archipelago is 60% ice covered leaving much of the underlying bedrock blanketed. Ground that is exposed is predominantly loose rock and cliffs (30%) where vegetation only makes up a small percent of ground cover (<10%) (Ingolfsson, 2005). Svalbard exhibits continuous Permafrost ranging from roughly 100 m near the coast, down to as much as 500 m thick at higher altitudes with an active layer ranging from 0-3meters (avg. 1m) (Humlum et al., 2003). A permafrost environment has an effect on the snowpack temperature due to the variation in the ground's thermal regime (Eckerstorfer and Christiansen, submitted a). Although permafrost on Svalbard is continuous, (Humlum et al., 2003) Kapp Linné probably exhibits a unique permafrost/active layer due to its proximity to the ocean (Gulf Stream) and geothermal ground hydrology.

Exposed sediment surfaces display active frost shattering and sorting leading to the presence of active layer features and processes occurring above the permafrost like ice wedge polygons, sorted/unsorted circles, and stripes all (Ackerman, 1980, 1996). Frost shattering drives the production of clasts, where sedimentation from the valley walls is driven by slope processes like avalanches, rock falls, debris flows that carry particles out in colluvial/alluvial fans and solifluction lobes. Free-face valley walls stand above talus cones, alluvial fans, rock glaciers and glaciers (Figure 5). Lower laying bedrock along the Nordenskioldkystn strandflat is overlain by Quaternary marine shore deposits. Surficial geology in the Kapp Linné region is composed of a range from marine muds, strandflats, beach cobbles on the lowlands to scree and talus on the slopes, to bedrock free-face slope walls on the upper peaks.

-Climate/Snow Climate-

In relation to the archipelagos extreme northern latitude (74° - 80° N) Svalbard experiences a relatively mild climate with a mean annual air temperature (MAAT) at sea level of -3.8°C in 2009 (met.no data). The MAAT recorded at Isfjorden Radio Station from the period 1912-1975 is -4.8°C. (Norsk Meteorlogisk Institutt, Oslo, Steffensen 1969, 1982, Forland et al. 1997). Spitsbergen's climate is controlled in large part by the interaction of air and water masses of different thermal regimes, the winter sea ice extent as well as its position in a cyclone track. In particular the winter cyclones cause large air temperature variations on daily and weekly basis resulting in rain on snow events as well as snowstorms.

Precipitation rates vary largely throughout the Archipelago. While Longyearbyen at sea level only receives only ~190mm water equivalent higher altitudes alpine regions especially further south experience much higher rates. Precipitation rate in Kapp Linné usually range around 450mm at sea level annually. There is a significant vertical component to precipitation rates in hand with altitude, but little is known as to the exact affect (Humlum, 2002).

Due to the lack of large vegetation and the persistent strength, wind is the most important factor controlling snow depths and redistribution in the region. The annual dominant wind direction is SE but differs locally due to a channeling effect midst the topography (Humlum, 2002). Wind speeds in Linnédalen followed trend with a dominant southeast direction and rates often above 20 m/second (figure 6a). Gusts from 2008-2009 frequently exceeded 30 m/s (figure 6b). The extreme and complex High Arctic Maritime environment results in characteristic highly stratified snowpack. Eckerstorfer and Christiansen (submitted a) found that the snowpack is thin, hard and cold, with wind slab layers, ice layers and a persistent weak base.

Snow conditions in the High Arctic in Svalbard are unlike other regions in the world. Thus the common snow climate classification (McClung & Schaerer, 1993) does not properly represent Svalbard's High Arctic environment (Eckerstorfer Christiansen, submitted a) In comparison to other nival regions, the High Arctic has undergone very little snow stability research; leaving a large amount still unknown about the unique snowpack. A better understanding of the High Arctic snowpack is not only important for insight to the mechanisms that control the formation of slab avalanches, the sedimentation rate correlated with the slope process and their characteristics, but the topic is also gaining importance in today's changing world.

-Avalanche Mechanics-

Snow avalanching can be driven by various triggering mechanisms. Sedimentation can occur in cornice, slab and loose snow avalanches. A slab avalanche is an event when a package of snow (slab) detaches from the surrounding snowpack on a weak interface and gravity carries the unit down slope. A fracture occurs in the snowpack initiated by loading that then proceeds to propagate through a weak interface and travel down slope with gravity. Avalanches events can be natural or human induces and are often a function of loading of the snowpack that produces the fracture. This loading event can be directly related to a cornice collapse. Cornices are built up masses of snow and ice deposited from wind redistribution. They often form on the lee sides of mountains, plateaus, or ridges. A loose snow avalanches or slough avalanches frequently form on slopes exhibiting steeper inclinations and are not characteristic of the cohesion visible in a slab avalanche.

Avalanche starting zones often are on slopes with inclinations between 30-45° and run out to flatter, lower angle terrain. Slopes prone to avalanching cannot be too steep, allowing for snow accumulate and load. Avalanche slopes are not too gentle either allowing for a low normal force component while the parallel and gravitational force components are higher and working in conjunction.

Snow stability correlates directly with weather and is driven by winds, temperature, and precipitation. Many other factors play roles in avalanche activity. Inclination, altitude, exposure, aspect, slope form and topography are all key variables in the avalanche process. Slab avalanches can occur on the scale of tens to hundreds of meters long/wide and be composed of units of snow anywhere from 10 cm to 10 m thick.

Altitude role driving stability and stratigraphy is tightly correlated with weather events. Different altitudes will experience different temperatures, amounts of precipitation, kinds of precipitation, and winds. Variable exposures will results in varying snowpack stratigraphy and stability with respect to wind scouring and redistributing. Depending on the hemisphere and time of year different slope angles will experience different amounts of sun light. The formation of sun crusts and also the ripening of the snow can initiate avalanche activity. Slope form (convex/concave) can also hinder snow stability, by irregular strain and stress components. The influence of local topography on avalanche activity is not well understood, but certainly plays a part in the snow stratigraphy and stability. Avalanches on Svalbard have been recorded throughout the year on (Cryosphere). Slab, cornice and loose snow avalanches have all been seen in Linnédalen.

-Talus Cones/Sedimentation-

Talus cones are features that draped valley walls. They are formed by gravitational forces acting on the bedrock free-face walls, the sediment source and often correspond with avalanching (figure 7). Degradation of the free-faces occurs with erosional weathering overtime, but is intensified as temperatures exhibit extreme fluctuations. Freeze thaw deformation or frost shattering is the process that predominantly drives the production of clasts in Svalbard. Frost shattering is the mechanical weather process induced by the freezing and thawing of H_20 in rock fissures and cracks. The process is driven by volumetric expansion, as water experiences a nine percent expansion as it freezes (Mastuoka & Murton, 2008). Frost shattering and the degradation of bedrock/clasts is more extensive in spring, summer and fall where water is able to freeze and thaw on a more frequent cycle (diurnally).

Methodology:

In order to gain a better understand of the slope processes in Linnédalen and on the Griegaksla ridge various methods were utilized. The study incorporated mapping particle size and distribution on five different talus cones in the valley region. The measuring of all long axes was conducted and recorded by photo analysis and Arc GIS (figure 8). MATLAB was also utilized to produce box and whisker plots of the particle distribution across the cones. A comparative analysis of slope characteristics was conducted on two different talus cones on the Griegaksla ridge, one on the eastern and one on the western flank with regards to rock type, grain size and slope features. The project also involved geomorphic mapping on both eastern and western slopes of Griegaksla, highlighting the different geomorphic features on the ridgeline.

Sedimentation rates were studied by monitoring twelve different established natural sediment traps located on various talus cones on both flanks of Griegaksla. These data were also compared to records accumulated over the past five years from the same traps. Sediment traps present sedimentation rates that have occurred at that one site over the course of the year and do not necessarily correspond with snow avalanching. But most sediment traps were accompanied by Tinytag Shock loggers. Shock loggers are small instruments that record maximum acceleration events every hour, continuously. They affectively record slope activity perpendicular to placement up to 5g throughout the year.

All results are compared and combined to valley weather data from the main station south of Linnévatnet. Temperature, precipitation rates, wind intensity are used to interpret the active of slope process and in turn the driving mechanism in sedimentation. Many of the valley walls also appear in diurnal time lapse imagery during the light season, recording and bracketing large events. By combining these data it is possible to highlight sedimentation events and possible avalanche cycles throughout the season that might corresponded with sedimentation.

Results:

-Sediment Traps-

Sediment traps were established on Griegaksla in 2005 and have been monitored annually in the end of August. The 2009-2010 year's sedimentation exceeds rates recorded over the past five years, with 6/12 traps collecting sizable quantities of clasts (table 1). Traps are located between the lower half to the bottom of the talus cones and exhibit a surface area of ~150cm. The surfaces of the traps all stand up off the slope face ~30cm. The sediment trap surfaces held a combined weight of 22.75kg almost 15kg more than ever recorded. Indicated by the **, trap 13 also "trapped" two other sizable clasts on the uphill slope of it weighing 2.8 and 7.9kg respectively. Although these two particles were not necessarily sitting on top of the sediment trap, they were supported by (caught in) the sediment trap. Trap 13 exhibits the site with the most sedimentation recorded, not only this year but over the past five years in comparison to all traps. Sediment traps 3, 7, 8, 11, and 12 have trapped little two no particles over the past five years representing the low end of sedimentation. Most important to note is that sediment traps recording the larger amounts of particles this season (traps 5 and 6), are frequently snow covered in August during the monitoring rounds both experiencing multiple burial years. All clasts recorded in the traps were blocky and often accompanied by finer particles.

It is also important to note that couple clasts were seen on the slope with very fresh chipped faces exhibiting rough/sharp edges (figure 9a). These clasts left a trail of small fractures upslope of them and were not supported by the sediment traps (figure 9b). These will be not referred to as dry sedimentation.

-Meteorological & Tinytag Shock Logger Data-

The annual meteorological data from the main station in Linnédalen exhibits drastic temperature swings, and over the course of the year experiences temperatures that range from a high spike at 13.7°C and drop down to -23.44°C over a few different short periods (figure 10). Both freezing temperatures are experienced in summer months where over freezing temperatures are recorded during winter months. Wind speeds in the valley are recorded as high as 16m/s with gust that surge up to 38m/s and generally trend SE (figure 11). Although the valley is relatively dry the region can experiences extreme precipitation events. Precipitation is possible all year round but is most often accompanied by warmer packages of air so the driest weather is experienced during February, March and April during the coldest part of the year. All these extreme events can be experiences both in dark and light seasons. This last year recorded various storms but the most significant storm bringing the largest amounts of precipitation and highest winds was experienced in late January (figure 12a & b).

The Tinytag shock logger data exhibits high activity on the Griegaksla slopes. Some shock loggers recorded higher amounts then others, but all responded strongly and almost simultaneously during two specific events. These events both occurred during the dark season, one on December 18th – 19th and the second January 27th – 28th (Shock logger plots in power point 1) Combining meteorological data with the shock logger results it is very likely that this slope activity is due to two major avalanche cycles. Both events follow significant precipitation periods that were activated by extreme wind storms. These two events were preceded by warmer temperatures where activity began to take place as temperatures dropped in the valley. The weather that built up to the slope activity began almost as early as a week prior to the events. Each cycle exhibited activity of ~24hrs and ~38hrs respectively.

-Time Lapse Imagery-

Time lapse photographs are directed at four different regions in the valley. From south to north they are as follows glacier up (cirque), glacier down (Little Ice Age Moraine), plume (Linnéelva inlet) and lake down (Linnévatnet outlet). Two photographs a day beginning in the end of April. Photo imagery data does not overlap well with Shock logger data while no large events appear near the end of the season and slopes are relatively bare at the mouth of the valley by the time sunlight exposes valley walls. The automatic cameras do show several things thing. The photographs display how warm temperatures work up through the valley, with snow melt beginning at the mouth of Linnédalen and slowly running up the valley to Linnébreen. By the end of the season (the final images) the cirque walls are still predominantly snow covered. Annual sedimentation is also visible as the snowpack thins on avalanche fans exposing clasts carried down the slope that season (white snow dirties). This is visible in all four regions but is experienced last at the glacier cirque.

The glacier cirque camera exhibits three different small events on the upper walls. The period of the morning of May 21st to the morning of May 23rd in the cirque displays precipitation then direct action avalanching that follows shortly after. The June 10th – 12th displays another sizable event and sedimentation become visible for the first time on the valley walls. Sedimentation also becomes visible on the western cirque valley walls during activity from the June 22nd - 24th. The glacier-down imagery exhibits loose snow avalanches and snowmelt from the morning of June 21st – afternoon of the 22nd also. The plume camera shows active slopes during two different periods in June, the afternoon of 12th – 15th in the morning and the morning of June 21st – the morning of the 22nd. Slope activity is visible in Linnévatnet outlet imagery during a warming event from morning of June 19th – 21st in the afternoon. All events correspond with temperature swings, and precipitation events (auto cam events in power point 2).

-Griegaksla-

Griegaksla is the ridge at the northwestern domain of Linnédalen and directly to the west of Linnévatnet. Bedrock geology on the eastern and western flanks vary in lithology and dip (strike is similar). The western (strandflat) exposure, both free face and slopes are composed of phylite that varies in color from greenish bluish, to a dark tanish grey. Bedding is consistently dipping ~80°W but ranges from 70° – near vertical. The eastern (Linnévatnet) side is dominated by a grayish quartzite that dips ~60°E. The mean particle size at the slope base of the eastern flank is 20-50cm where the western flank clasts range 2-10 cm (Ackerman, 1980). The western flank of Griegaksla is exposed in developed talus cones cut by minor debris flow levee systems. It also exhibits numerous small rock glaciers at the cone toes. West Griegaksla is also wet and vegetated with both moss and lichen growth covering particles. The eastern flank of Griegaksla is made up of talus cones coalescing with talus sheets. Unlike the east side, there is minor evidence of fluvial channels (with the exception of one major debris flow scour/levee system) and only two rock glaciers that have formed at the toe of two cones (figure 13). The western flank is much drier and only exhibits a small amount of lichen cover.

-Talus Cones-

Mapping the talus cones produced a better understanding of the processes that take place to in the development of the feature. Five different talus cones in Linnédalen were photographed and analyzed to better visualize clast size distribution (from north to south; VB, GW, GE, K1 and K2) (PHOTO). All talus cones varied slightly in lithology, displayed different inclinations and sizes. All cones displayed a coarsening from peak to toe, were clast size averages were doubled and often tripled from top to bottom (figure 14a). Clast size also fined near the centers of the cones and coarsened in a skirt like fashion (figure 14b). Box plots from the upper slopes and center cones display more uniform clast size while box plots from the outer edges of the talus cones exhibit larger variations. In the Arc GIS photograph analysis smaller finer clasts allowed for greater sample sizes in the analysis and inversely smaller samples in the outer/lower regions of the cones. Some cones displayed unique features in both vertical and horizontal box plot (figure 15).

Discussion:

Although it is clear that the majority of significant activity is present in the winter months and the snow climate/meteorology cater to snow avalanching the effect of sedimentation through avalanching is not exactly quantitative. The traps in a sense act as small windows that can provide a view of sedimentation, but deposition in surrounding areas is unclear and can only be extrapolated. The high exposure of the trap surfaces decreases likelihood of material stranded on the trap arriving in any other fashion than carried down in matrix suspension (of snow). The sediment trap data displays relative snow avalanche sedimentation at that exact time and location (as long as clasts are not extensively chipped and fractured indicating another form of deposition as seen in figure 9a&b). Having sediment traps under snow cover late in the season is not necessarily ineffective while the avalanche sedimentation with me deposited in lobe of snow and ice. This larger more compressed deposit of snow will not melt as fast at the normal snowpack, hence can provide a good site to effectively see sedimentation.

The Tinytag shock loggers are effective in displaying slope activity, but could possible provide more information with a better understanding of their sensitivity. The shock logger graphs present that majority of significant events during the winter months. Because it is unclear how sensitive the loggers are to rain events, wind exposure, and the possible snowpack insulation significant events were interpreted as slope activity that resulted in maximum acceleration (5g) in the shock loggers simultaneously. This means that the majority of the loggers would have to detect a high acceleration at relatively the same time to negate for local events, unique exposures and minor background disturbances. It would be interesting to study how proximity to activity is a function of detecting intensity.

The meteorological data shows that the winter climate could initiate snow avalanches in the valley. The extreme temperature swing, and intense precipitation events followed by high wind storms creates a region optimal for snow avalanching. Also the frost shattering erosive process creates a proactive source area and initiates valley sedimentation. Combining valley weather data with shock logger data allowed for the interpretation of two major avalanche cycles. The two different avalanche periods were driven by severe storms as the sum of multiple meteorological factors. Linnédalen's extreme meteorological data suggests that snow avalanches play a substantial role in valley sedimentation, but it cannot completely prove or quantitatively show how substantial of a role it takes. It is difficult to prove that the two major avalanche cycles are definitely the causing factor that led to the deposition of sediments recorded in the traps, but events triggered by the most extreme meteorological period and causing the most intense slope activity is not a bad hypothesis for the cause of deposition.

Time lapse photo imagery although can be very effective in bracketing avalanche events, is not ideal in Linnedalen, due to half of the avalanche season being hidden from imagery in the dark and a large percentage even if darkness was not a factor, high precipitation rates and strong winds make avalanche path visibility nearly impossible. The time lapse imagery from the spring of 2010 effectively captured the surge of avalanche activity that occurs as the snowpack ripens in the spring and the slopes become alive with loose snow avalanches. It would be very interesting to compare imagery of large scale avalanche cycle events to that of the slides captured in the loose snow spring events.

The eastern and western flanks of Griegaksla exhibit different properties despite their proximity to one another. The variability of vegetation, geomorphic features, talus morphology, slope processes and mean clast size are all function of bedrock lithology and flank exposure. Griegaksla experiences unique climates on either side of the ridge. Linnedalen can be calm and warm sunny while the western flank of Griegaksla on the strandflats is cold, windy and getting pounded by heavy fog and precipitation. On the other hand it is also possible that Linnedalen is holding weather and the valley is experiencing snow while Kapp Linné is under clear skies. Most prominent in distinguishing the two different flanks is the geology. The phyilte from the western side of the ridge exhibits different properties like cleavage, erosional resistance, and free-face structure than the quartzite on the eastern flank for Griegaksla. Although both sides exhibit unique characteristics (so extreme that it would not be clear if they were part of the same ridge if not for aerial imagery) they have both managed to withstand the extreme climate of Kapp Linné for well over the age of Linnévatnet.

All talus cones mapped displayed a common structure with a coarsening toward the outskirts. This is probably the function of two main processes. An object with more mass (larger clast) will have more momentum than an object with less mass (smaller clast) when acting under the same kinematic force (gravity = $9.8m/s^2$). Apart from larger clasts possessing more energy and traveling further down the slope; larger clasts travel down the talus cone and hammer rocks in their path. Clast degradation is another function of a fining upwards on talus cones, as more activity occurs above the particles they will deteriorate. Avalanche debris exhibits similar characteristics with large particles carrying further and remaining on the surface due to the physical effect of “inverse segregation”. Gray & Chugunov (2006) construct a model for particle-size segregation and diffusive remixing of different size particles in a “shallow gravity-driven free-surface flow” that quantitatively rationalized the segregation that occurs in snow avalanching. Their results complemented the work of Kern et al., (2001) in the study of new avalanche rescue techniques based on inverse segregation. The combination of momentum, particle hammering in the transport path and the segregation of particles in avalanching all contribute to the common structure scene in talus cones and their course grained skirts (figure 16).

All talus cones did not map exactly the same though. There are variations in mean clast size due to lithology and some talus cones might be larger than others due to source areas. Variations in talus cones were visible in the horizontal cross-sections through the finger prints of other slope processes. Griegaksla west (GW) exhibited an irregular package of large clasts to the left of center in the horizontal transect (figure 15). This trend is seen in the box plots was visible on the slope itself. The GW talus cone had been scoured / leveed on the left side by a large fluvial event (figure 17). The event seemed to be relatively fresh (the last 5-10yrs) due to lack of settling that had taking place. The levee/scour system was over 2m deep in some regions and ~4m wide in some regions. A feature this extreme is not common in Linnedalen and stood out as an extreme event by a possible debris flow, or even a slush avalanche. Unlike the other talus cones that were packed and compressed through time, the debris around the flow was loose and not dense/uncompressed. Other similar debris levee systems were visible on other talus cones in the area but seemed to be older and smaller scale events.

Another possible method in studying slope activity in the region might be through lichen and vegetation coverage on the talus cones. It could be expected that slopes that are more active and have a higher frequency of sedimentation will support less vegetation than a talus cone in a relic or dormant state. Determining a rock-wall retreat rate for the valley would also provide incite as to the slope processes active in the development of the valley, and whether active was linear or not. It would also be beneficial to compare sedimentation rate in Linnedalen to those around Longyearbyen. Although both experience relatively similar climates it would be interesting how bedrock geology affects sedimentation. Expanding sedimentation rates to other regions at similar latitudes might also provide incite as to how climate drives the rate of sedimentation. The most quantitative and simple addition to providing a better understanding of the sedimentation rate in Linnedalen would be the monitoring of more sediment traps. And also the marking (painting) of rocks to gain a more precise understanding of the processes that particles undergo while travel from the free-faces into the base of the valley overtime.

Although sedimentation through avalanching is not the only form of slope processes driving sedimentation in the region it seems to be the dominant process making up for the majority of the slope activity. There are clearly other slope processes that occur in the valley and contribute in the valley sedimentation. Although it appears that these take place less frequently and during rare extreme events opposed to the seasonal snow avalanching. As meteorology is a key mechanism in the control of snow avalanching, a changing snow climate will directly affect snow avalanching and indirectly affect sedimentation in Linnedalen. As the climate that controls slope processes in Linnedalen evolve what does this mean for slope processes. If the climate is experiencing a warming trend, what effect is that having on winds or precipitation? Are temperatures more apt to fluctuate? A figure from Ole Humlum displaying mean annual air temperatures from Longyearbyen over nearly the last century exhibits large winter temperature variations (figure 18). These temperature data presented from the Longyearbyen region are most likely sharing a similar weather record with Linnedalen. If the mechanisms driving avalanches continue but at a greater frequency does that correlate with high sedimentation rates in Linnedalen? Do variable winter temperatures correspond with more common extreme events driving other slope processes (debris flows) and eventually reform the slope morphology of the valley. The slope morphology is always a function of the bedrock that it is comprised of and the climate that surrounds it.

Conclusion:

Linnedalen exhibits a wide range of slope processes and peri-glacial features. The slope walls represent the region's composition and the climate it is exposed to. A combination of snow avalanching along with other slope processes combine to make up the Linnedalen slope wall sedimentation budget. Avalanching is not the solo form of slope wall sedimentation but the most consistent comprising of a larger factor of valley sedimentation and overall rock wall retreat. Mapping talus cones is an affect means of better understanding snow avalanching activity, processes and sedimentation.

Meteorology is a key mechanism in the control of snow avalanching, and a changing snow climate will directly affect snow avalanching and indirectly affect sedimentation in Linnedalen. Better understanding of tomorrow's climate will help better understand the slope processes and activity that face us.

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Figure 1: Aerial Image of Linnédalen, Central Spitsbergen. Linnévatnet bordered by Griegaksla to the west and Vardeborg to the north east.

Figure 2: Displays seasonal daylight in Longyearbyen, Svalbard's main settlement (also central Spitsbergen)

Figure 3: Aerial imagery of Linnédalen, displaying the northern extent of Griegaksla to the toe of Linnébreen. Sediment traps and Tinytag shock loggers are located on eastern and western flanks of Griegaksla. The main weather station is located just south of Linnévatnet. Lake Kongress is located just south east of Linnévatnet.

Figure 4: The Bedrock map of Kapp Linné region.

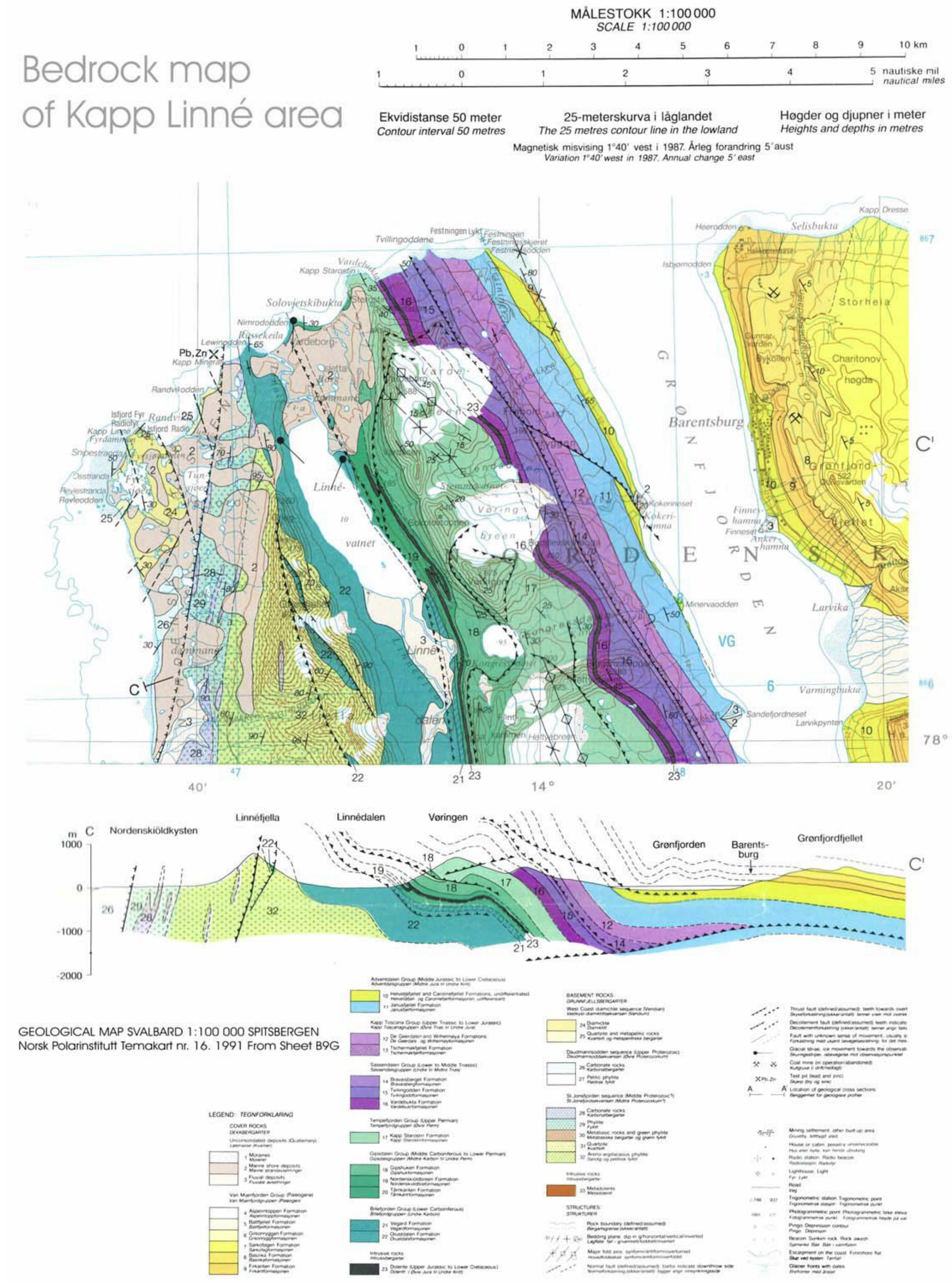
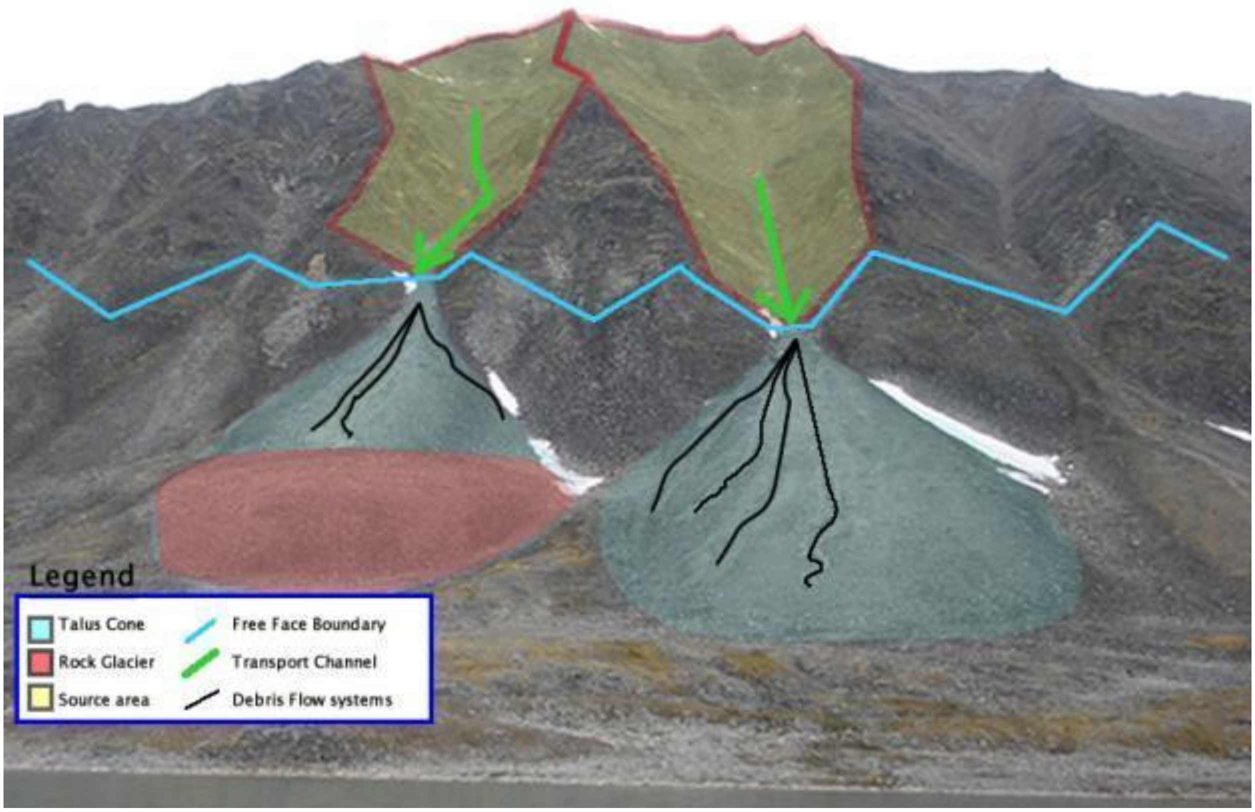
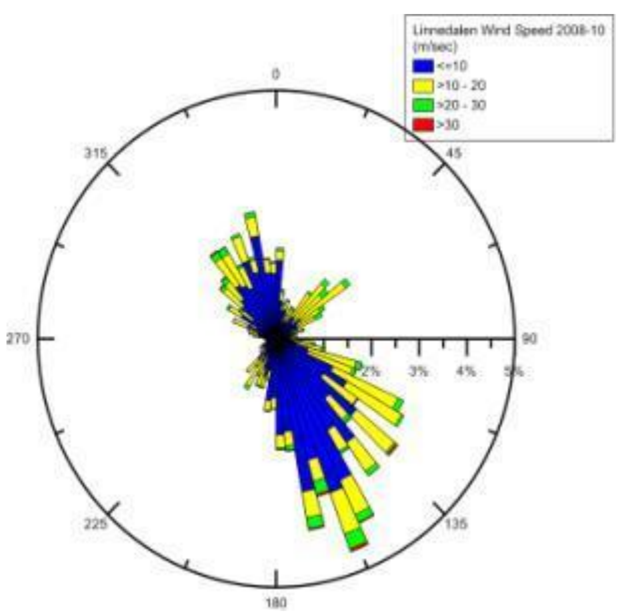


Figure 5: The eastern flank of Griegaksla with geomorphic features highlighted.



Figures 6a + b: Two rose-plot diagrams that represent wind speed and wind gust in relation to orientation from 2008-2010. All rates are in meters per second and generally trend SE.

A)



B)

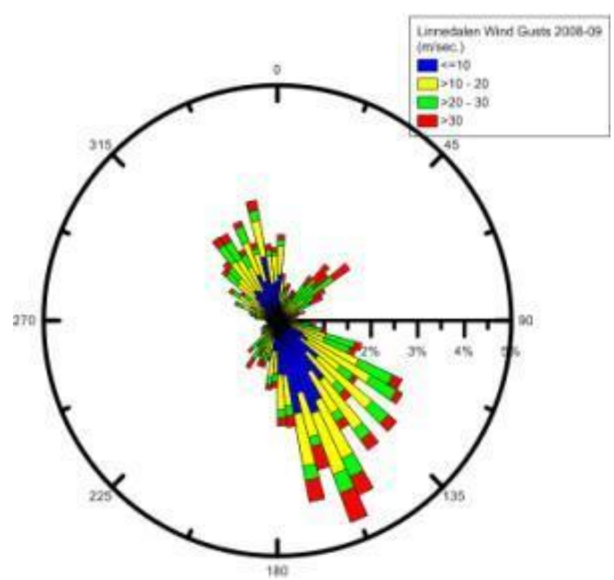


Figure 7: Talus cones of Griegaksla east from the other side of Linnévatnet

Figure 8: Two images that display the process of photo analysis used in the mapping of the talus cones. Each yellow dot represents a photograph point in the vertical transect (blue points are photos on the horizontal). The lower right photo is an example of what was analyzed at every point (w/scale bar)

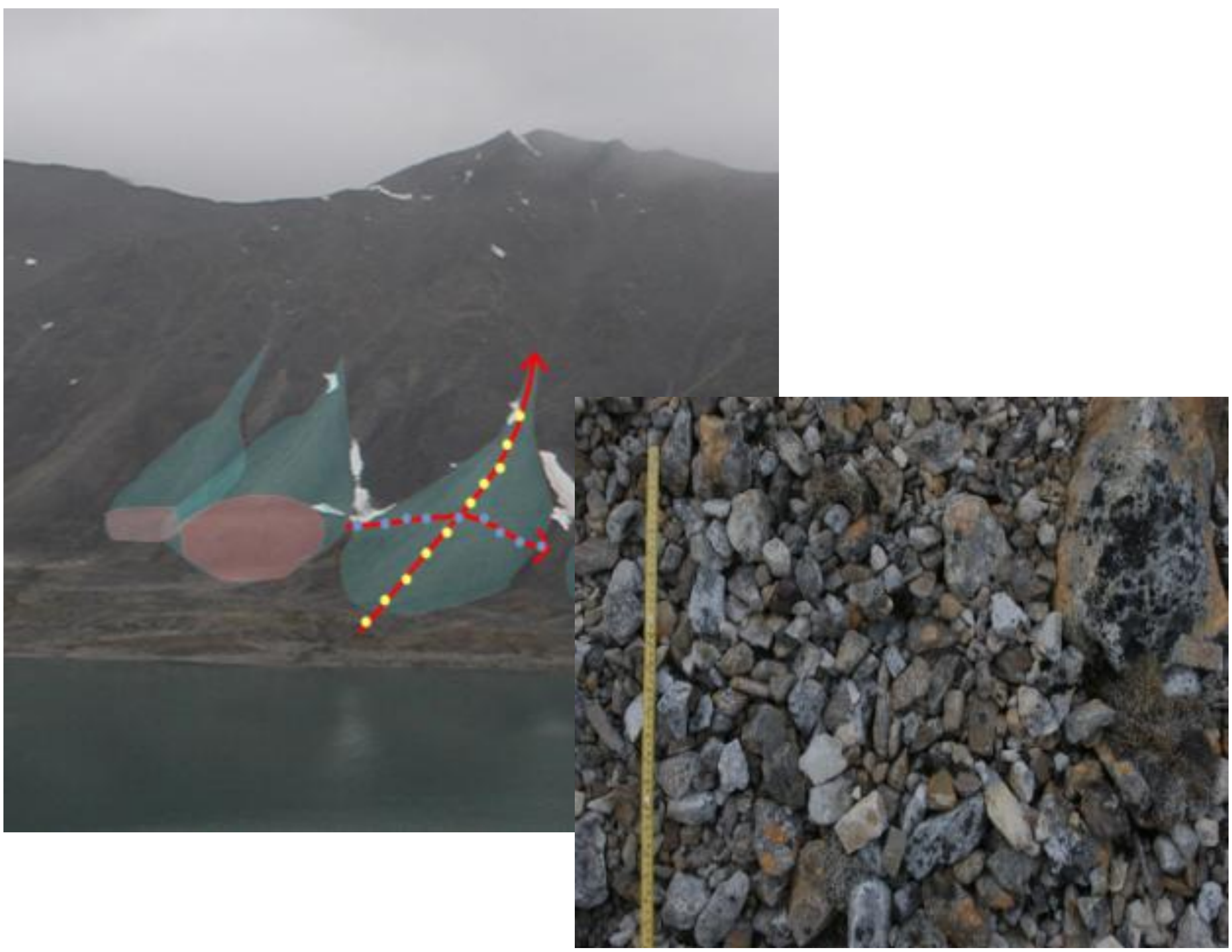


Figure 9a & 9b: Image of chipped dry sedimentation seen on a Griegaksla talus cone. Small fracture placed for reference (ski pole for scale).

Figure 10: Main Station temperature and precipitation (09-10)

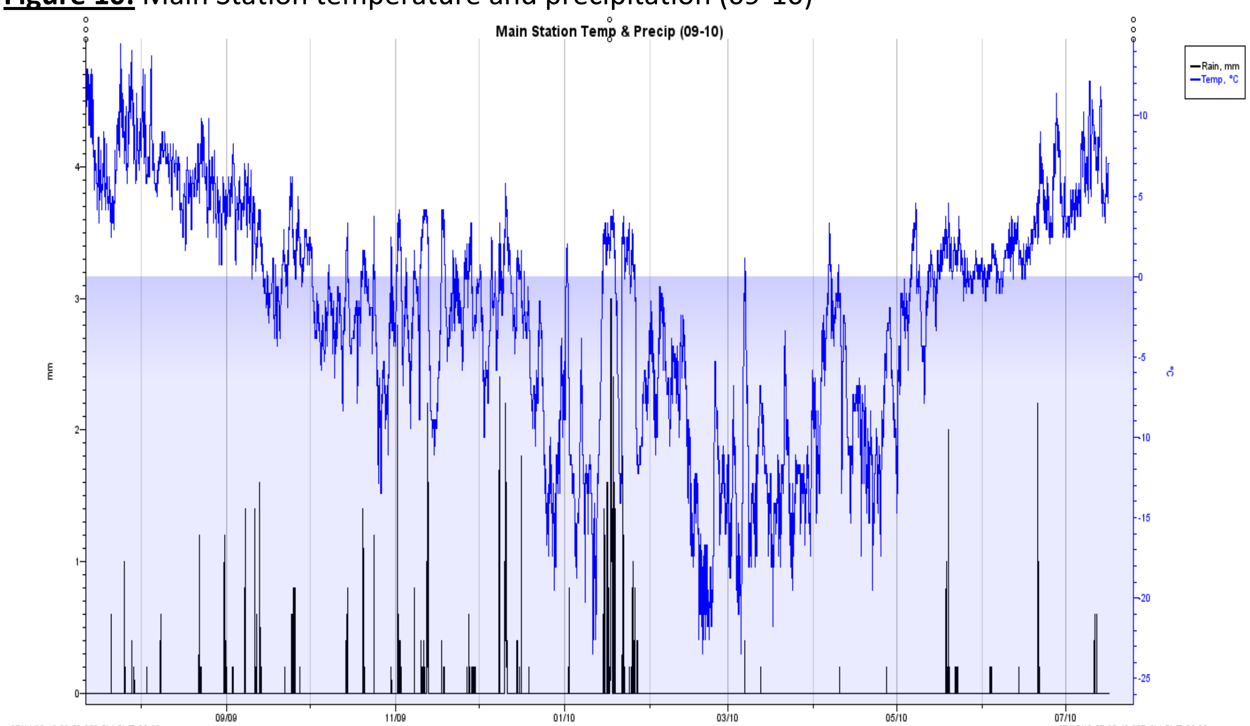


Figure 11: Main Station wind speeds and gusts (09-10)

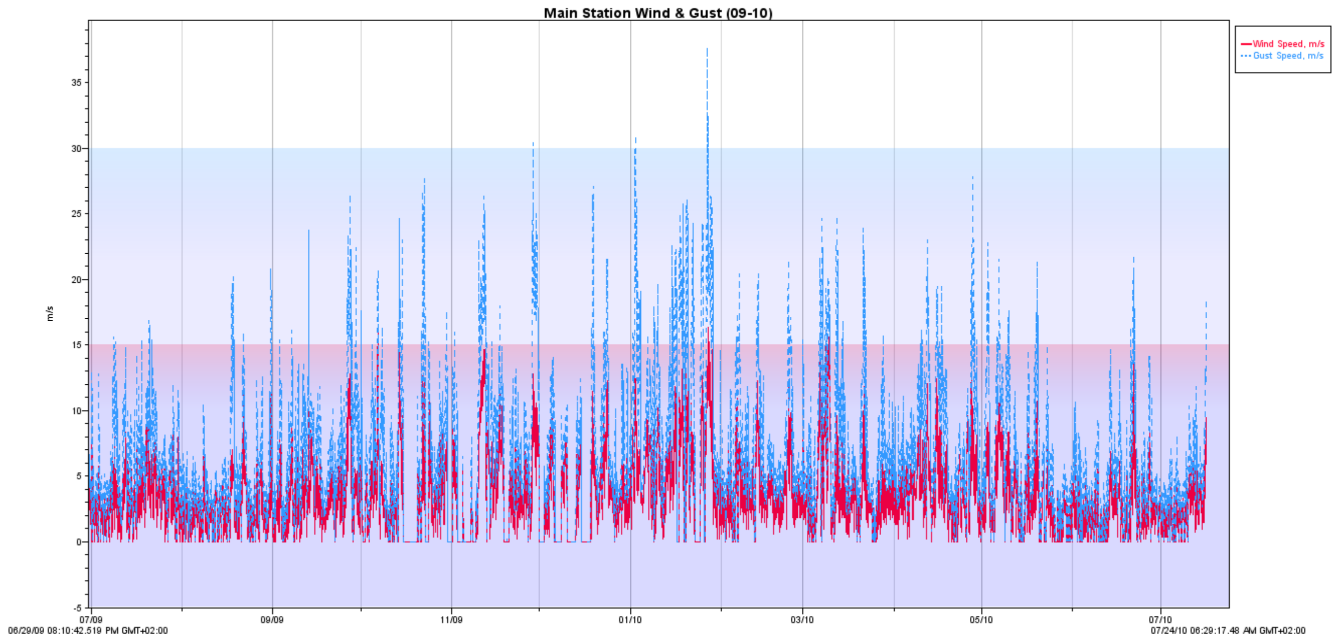


Figure 12a &12b: Late January storm: temperature/ precipitation and winds

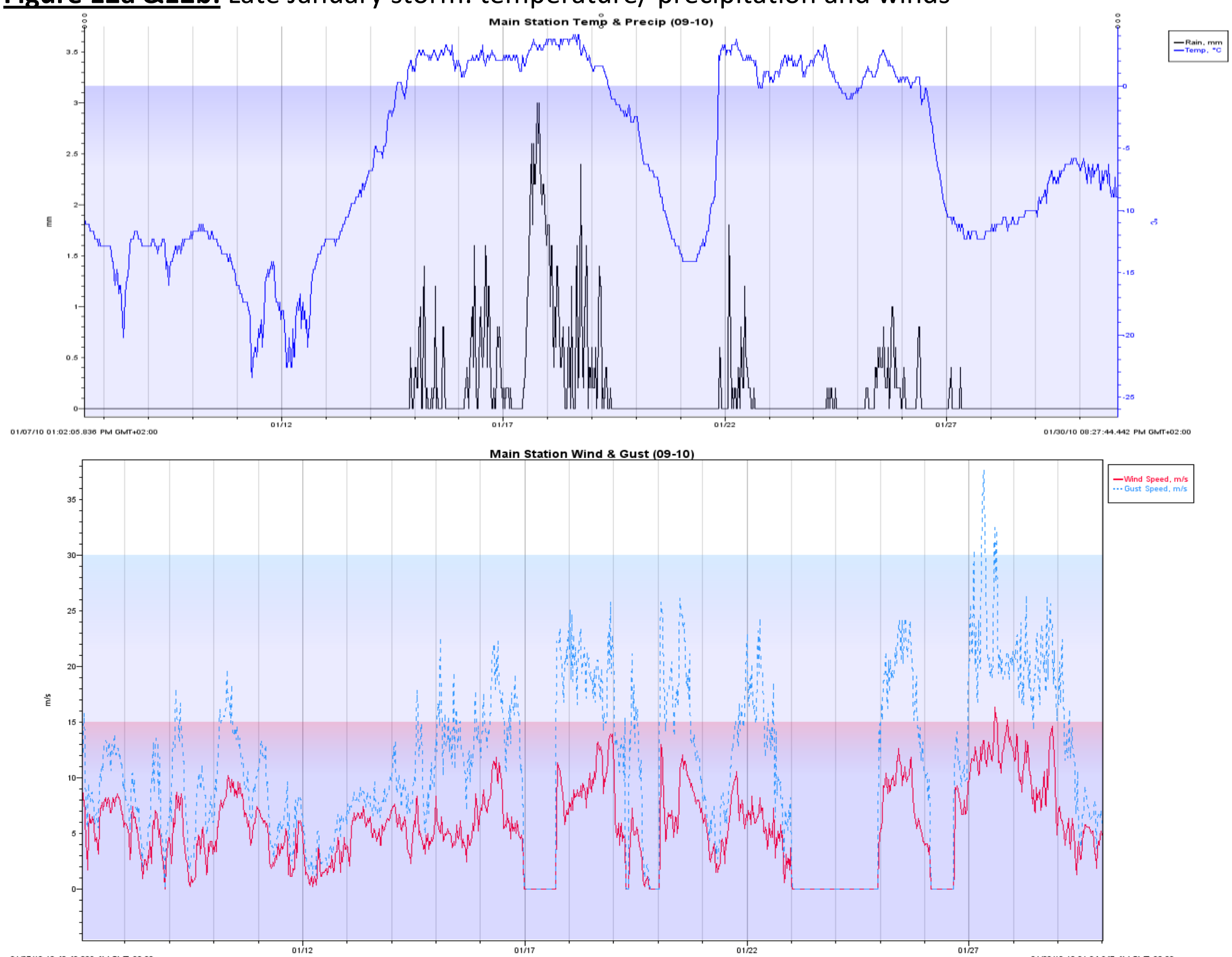


Figure 13: Geomorphic map of Griegaksla region.

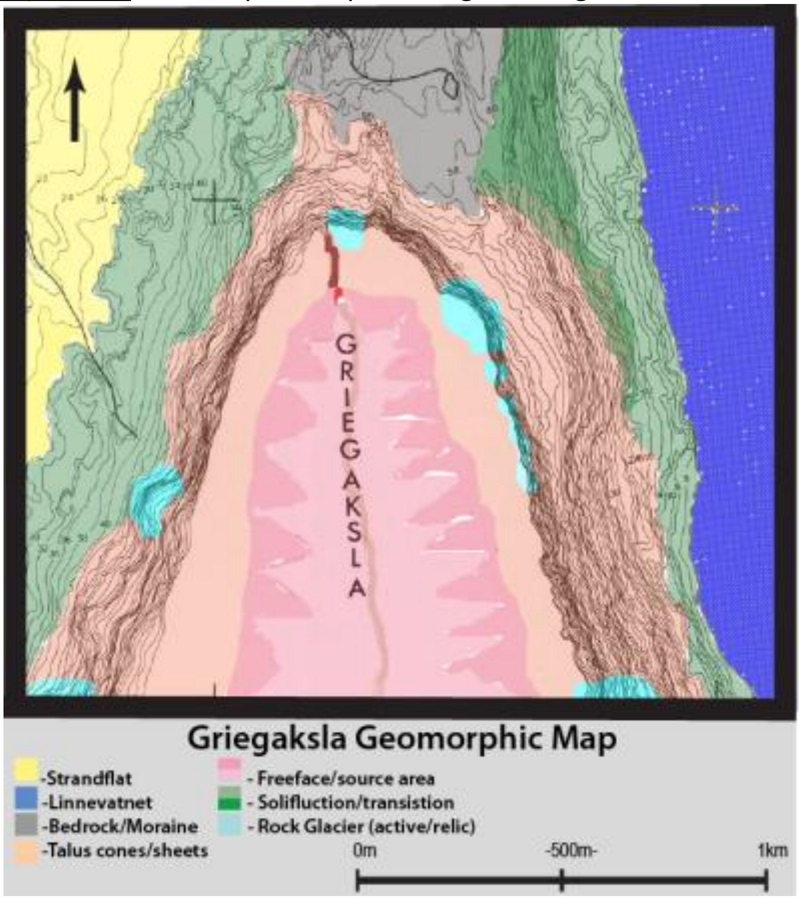
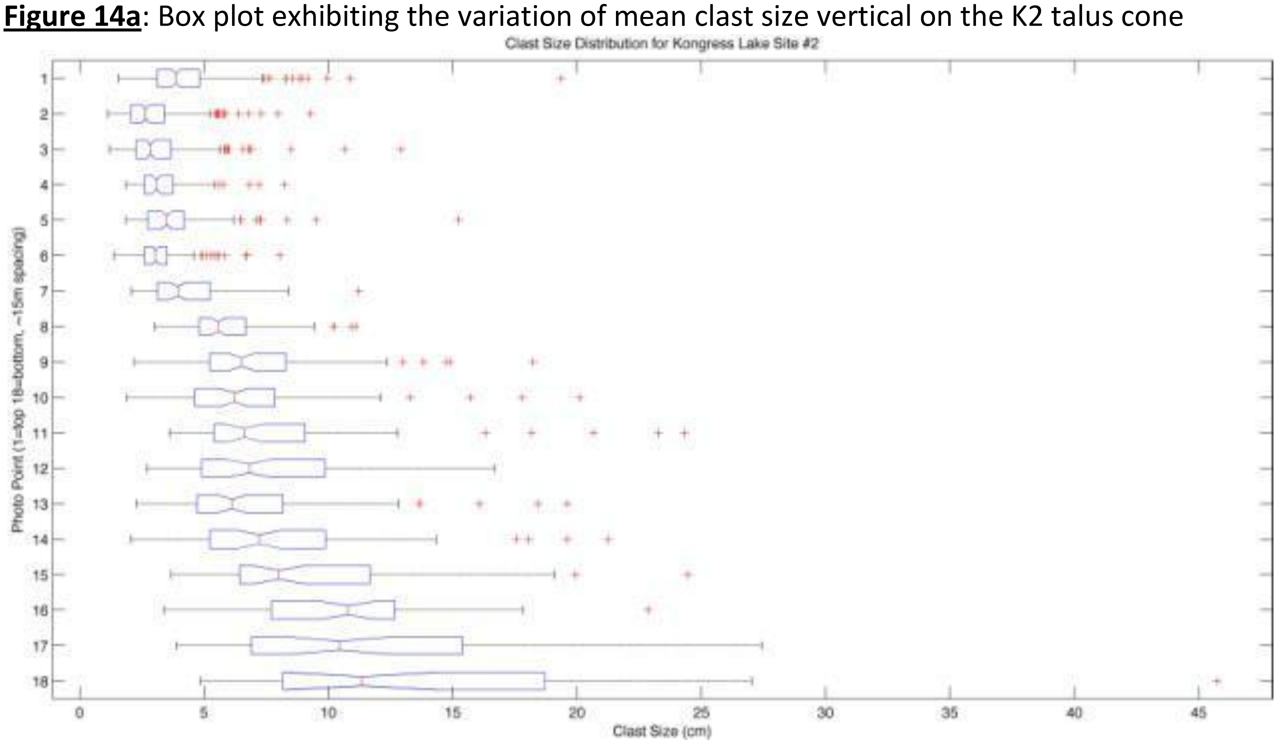


Figure 14a: Box plot exhibiting the variation of mean clast size vertical on the K2 talus cone



<u>Figure 14b</u>: Box plot exhibiting the variation of mean clast size horizontally on the K2 talus cone

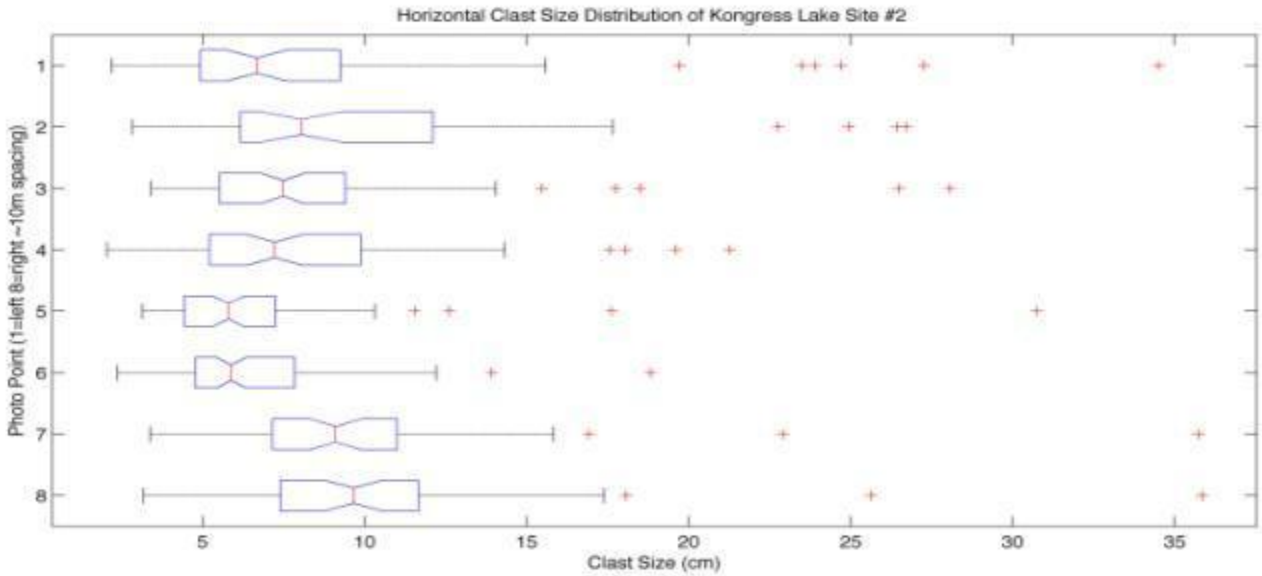
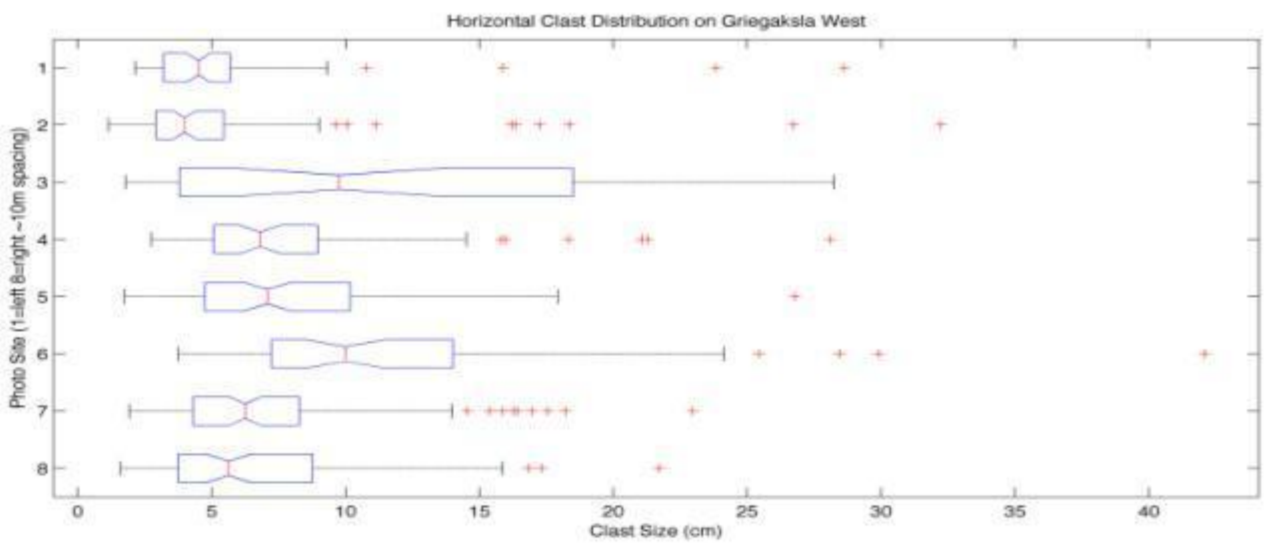


Figure 15: Box plot exhibiting the irregular clast size variation horizontally on GW talus cone



<u>Figure 16:</u> The K2 talus cone mapped out displaying the course particle skirt at the toe (in purple). The K2 cone also exhibits multiple tongues (possible due to variations in bedrock source, or a hiatus in sedimentation).

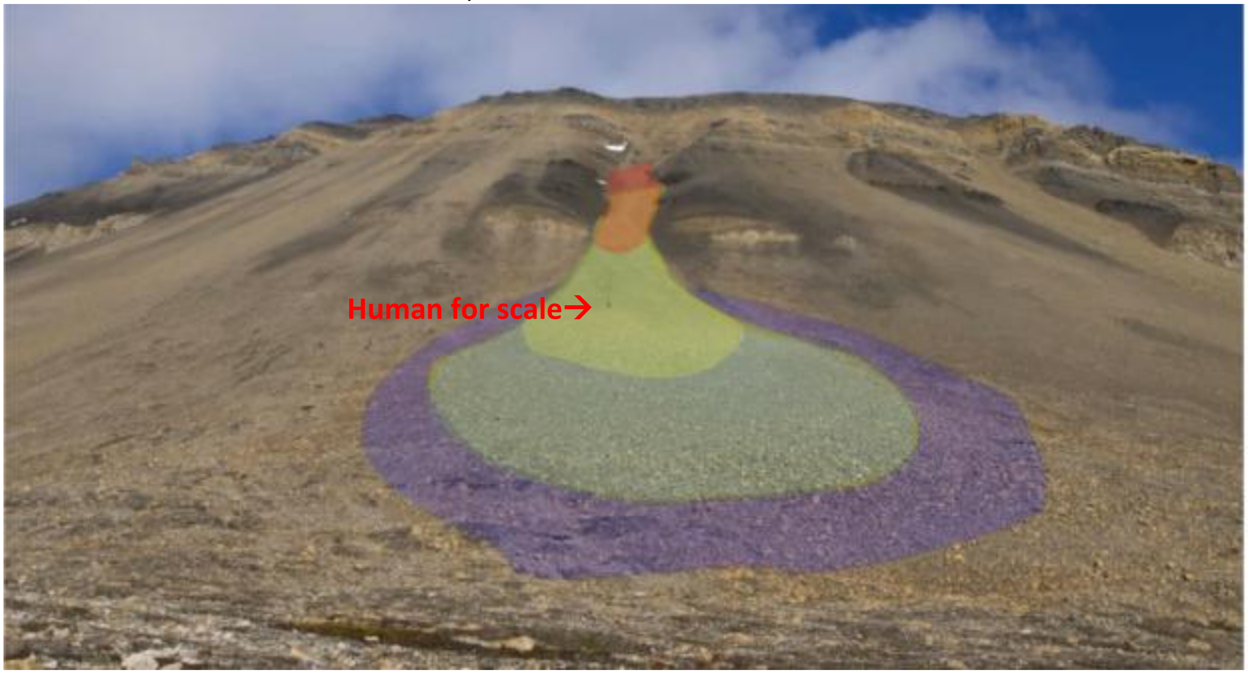


Figure 17: Scour/Levee system on GW (cause for spike in mean clast size)

<u>Figure 18:</u> Variations in summer temperatures in Longyearbyen over past century **(O, Humlum)**

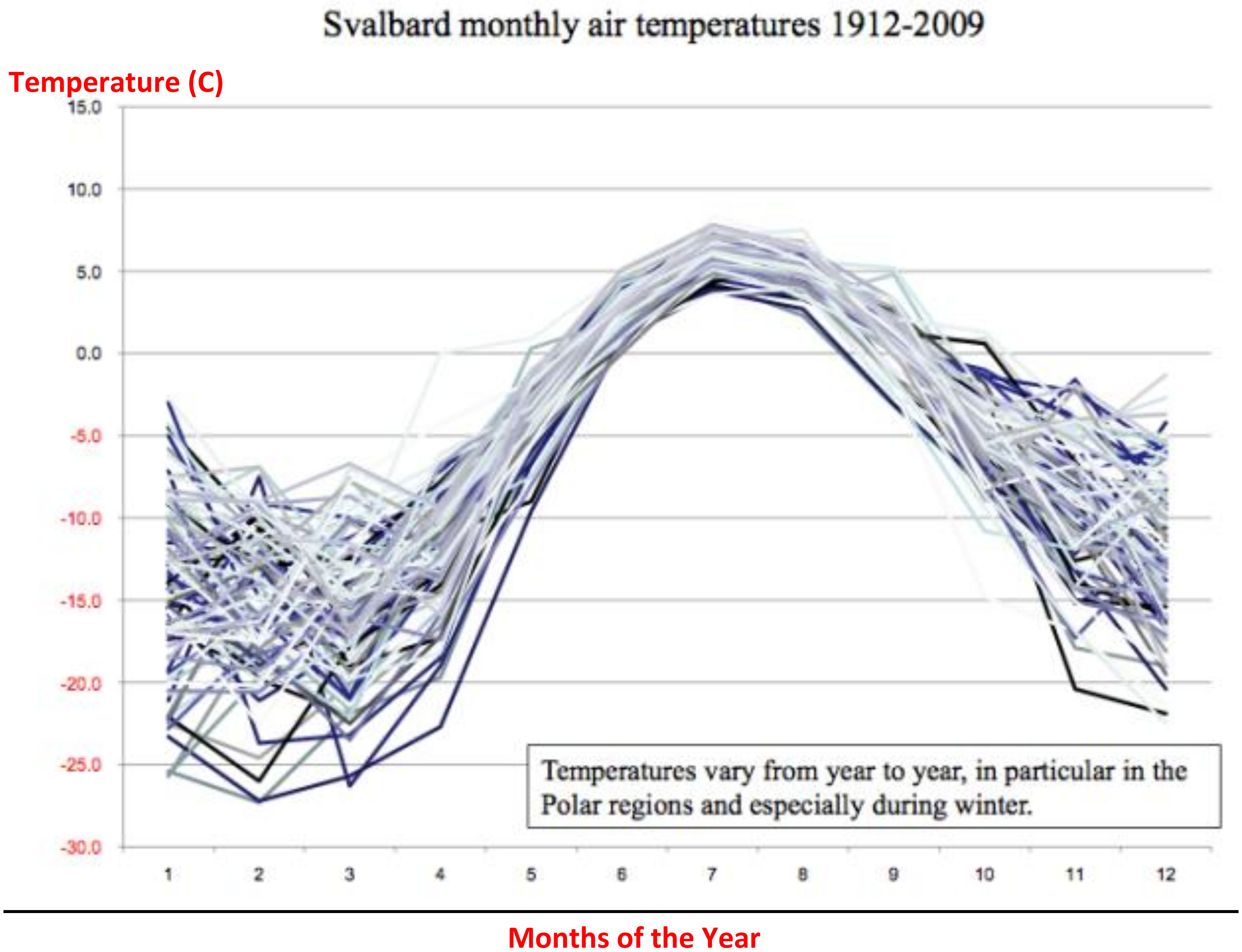


Table 1:

Sediment Traps Kapp Linne

Name of trap	2005	2006	2007	2008	2009	2010
Moni 2 (UTM 33X 0470558,8663311)	0	0	320g	0	0	100g
Moni 3 (UTM 33 x 0470604,8663310)	0	0	0	0	0	0
Moni 4 (UTM 33X 0470590, 8663334)	0	100g	0	0	0	175g
Moni 5 (UTM 33X 0470614, 8663377)	0	snow	snow	snow	0	400g
Moni 6 (UTM 33X 0470612, 8663380)	0	20g	30g	snow	snow	475g
Moni 7 (UTM 33X 0470593, 8663745)	0	0	30g	0	0	0
Moni 8 (UTM 33x 0470604, 8663768)	0	0	5g	0	0	0
Moni 9 (UTM 33X 0471437,8663764)	0	0	0	0	760g*	350g
Moni 10 (UTM 33X 0471439,8663766) area 0.66 m2	0	0	0	220g	0	0
Moni 11 (UTM 33X 0471450, 8663752)	0	0	0	0	0	0
Moni 12 (UTM 33X 0471448, 8663741)	0	0	5g	0	0	0
Moni 13 (UTM 33 X 0471434, 8663738)	0	0	not found	0	0	775g**

* on area of 130*160 cm
** +one block (30*40*50 cm) + on photo point rock (2.8 kg + 7.9 kg + one block (40*12*15 cm)