THE ENLARGEMENT OF SISIMIUT'S HARBOUR

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INTRODUCTION

The municipal harbour is one of the most important features of Sisimiut. Since the city is the second largest one in Greenland, its port has become one precious spot due to the prawn industry, commercial activities and tourism. This is the reason why the city has grown up around it.

The problem which is taking place nowadays is the difficulty that the port's facilities are having at the time of handling the growing number of passengers and quantities of goods seen in recent years.

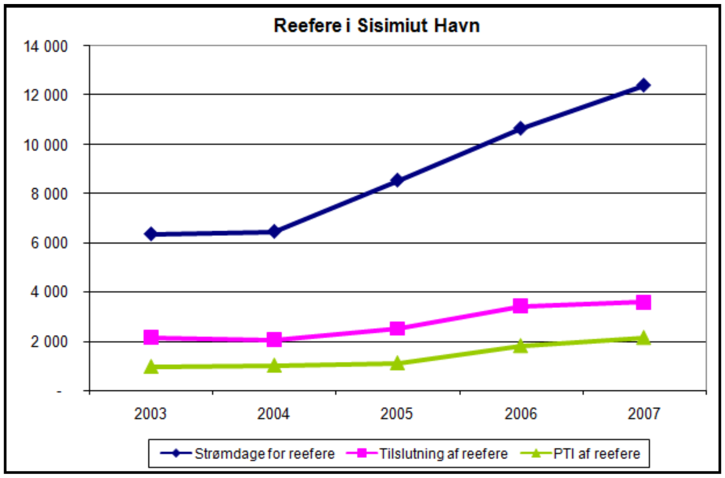

Figure 1. Number of trawlers.

As Figure 1 shows, Sisimiut Harbour has doubled the number of trawlers in between 2004 and 2006, and has even increased the cruise ships arrivals during the last few years.

This has happened at the same time as the freight quantities have also increased. The increased numbers of trawlers catching prawns outside Sisimiut gives more landings with the frozen catch. Therefore, there is also a need to secure more space for reefers on the harbour.

Thus, our task would be related on improving the harbour facilities in Sisimiut in August. More specifically, our work will be focused on the extension of this port in order to make it capable to cope with these latest needs.

State-of-the-art

This is the most northerly harbour in Greenland which is open and ice-free all year round. The harbour is a centre of active fishing and both large trawlers and smaller fishing vessels are native to the town.

Two different harbours are actually in use in Sisimiut, they're called as Atlantic and Fishery respectively. Besides the quays of the last one there's also a public jetty for smaller boats and a private marina, as well as an offshore quay.

Concerning the Atlantic quay, it handles the passenger ships serving the whole of Greenland's west coast and is where more than 50 cruise liners call in to the town each year. Each week it receives large, ocean-going supply ships and from here there's further shipping to Qanaaq and Kangerlussuaq.

Figure 2. Harbours situation

But, the problem is that its quay is no longer than 50 meters long, and so, allows just a draught of between 8 and 13 meters. Atlantic's length does not seem sufficient to operate both vessels passenger and larger trawlers.

In the present circumstances there is however an unfortunate confusion of container and public access to passenger and warehousing which provides a high risk for accidents. In the shorter term there should be a separation of traffic at the port area. The current confusion of driving with containers and private traffic to and from the warehouses are very uncomfortable from a security point of view.

In the longer term there should be an extension of dock areas, and there shall be allocated space on port area or elsewhere in the city for facilities to operate the larger trawlers.

Harbour's facilities include:

- Container terminal
- Cold stores
- Vessel telephones
- Fresh water plant
- Forklift trucks

- Refrigeration stores
- Storage areas
- Fuelling with petrol or diesel
- Heated and non-heated storehouses
- Tractors
- Shipyard with a slipway for 250 tons

Royal Arctic Line is actually responsible for the daily operation of the harbour and it's also the one which sails all along the Greenlandic coast with freight goods. In addition, parts of Greenland's southern and western coasts are sailed by passenger ships. Royal Arctic Bygdeservice is sailing freight routes, too.

Interesting project

Since it is a rapidly growing harbour due to the impending oil exploration in the Davis Strait and the continually rising quantities of goods freighted by Royal Arctic Lines' supply vessels; our field of study will let the port growing up and becoming sufficient for the actual and future needs.

One solution was initially proposed for the extension needed; the enlargement of the Atlantic Harbour. Finally, Greenland's Home Rule and Sisimiut Municipality have thus jointly proposed the expansion of the existing fishing quay to the west, in order that two large deep-draught vessels can dock at the harbour at the same time (see Figure2).

The reason for the change was that it wasn't believed there could be more ships if the large Atlantic harbour was extended. At least if the ships are considered as big as the trawlers and cruise ships tend to be.

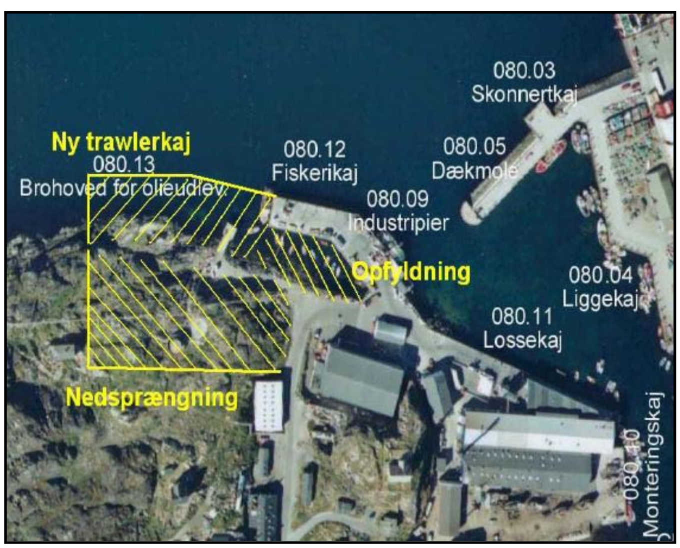

Figure 3. Harbour´s enlargement prediction.

Two different fields to study

The enlargement project of the harbor strongly involves two different topics: the geology and soil mechanics on one side and the waves' behavior concerning to the coast.

These are the reasons why some field measurements are needed, and they'll be carried out on site.

From one side, the bottom of the sea will be mapped by ecosounder, some samples of sediments will be taken and analyzed as well as the waves data will be studied.

From the other side, the terrain is going to be examined by geophysical methods.

Regarding to the results obtained, it is expected to be able to decide the following features:

-Position/shape and height of the new quay.

-Methodology of construction.

HARBOUR DESIGN

In harbours' design there are two different typologies for the berth structure: solid and open berth. Both of them provide a vertical front where ships can berth safely.

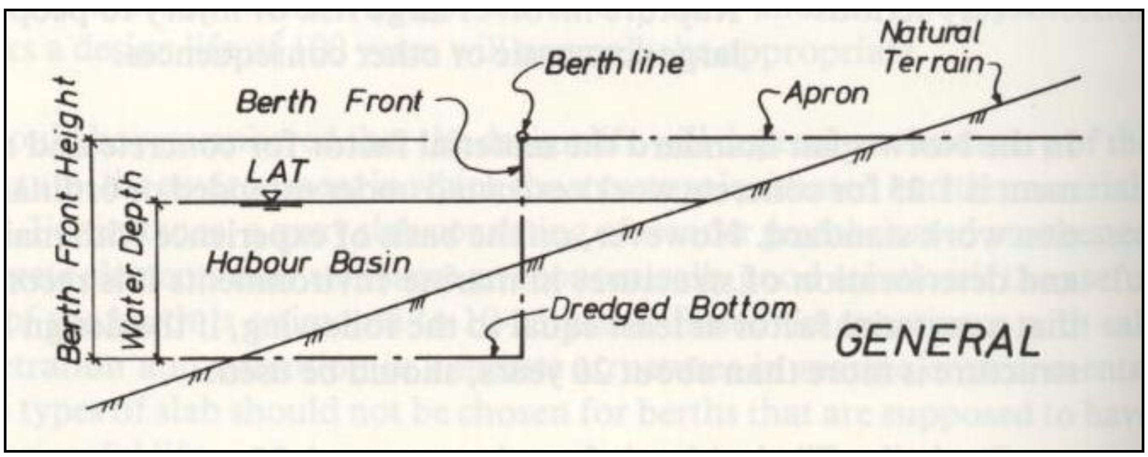

Figure 4. Berth structure parts nomenclature

The first one is filled right out to the berth front where a vertical front is constructed to resist the horizontal load from the fill and a possible useful load.

The second one is differenced because the quay slab is placed on dredged slope on a piled structure.

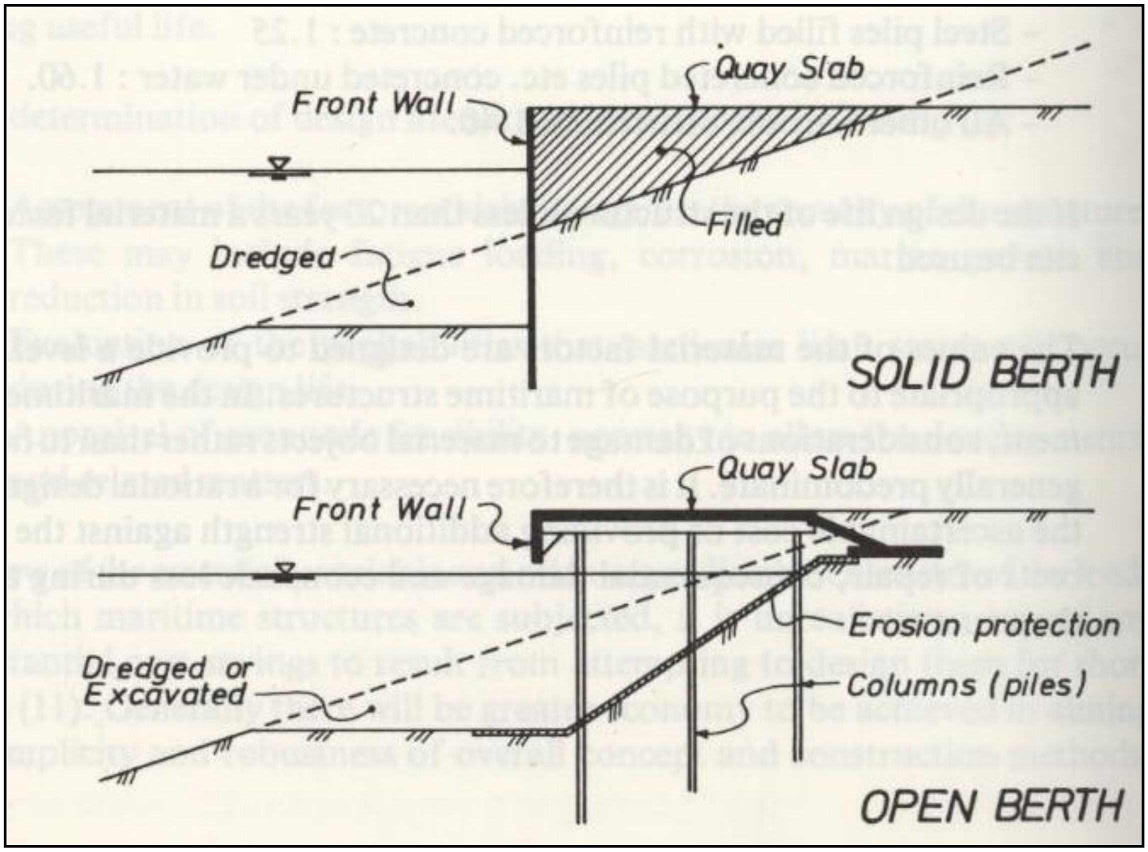

Figure 5. Berth structures terminology

Solid berth is so-called *quay* as the berth structure type, as well as the *open berth* is the *pier*. There is a classification depending on their way of construction:

- SOLID BERTH
  - Gravity wall
    - Block wall
    - Caissons
    - Celles
  - Sheet pile wall
    - Simple sheet pile wall
    - Solid platform
    - Semi-solid platform

- OPEN BERTH
  - Lamella
  - Columns
  - Piles

To be able to choose the most favourable one, economically and technically speaking, there are some factors to take in consideration.

Berth structures should be designed and constructed to resist vertical loads from trucks, cranes, etc. As well as horizontal loads from ship impacts, wind, fill behind the structure, etc.

Normally solid berths are considered more resistant than open ones because of its self-weight which constitutes a greater part of the total structure weight, and it is a stabilizing load. On the other hand in the case of open berths, a greater safety factor is applied. An exception is the open quay on wooden piles where the whole structure is flexible and yields when ships come alongside, sufficiently to absorb a substantial part of the impact energy.

Factors affecting the choice of structures

Several factors take importance at the time of choosing the correct structure for the harbour's design. They are classified in ten different issues: soil conditions, underwater work, wave action, design experience, construction equipment, materials, construction time, future extensions, expansion joints and constructions costs.

The type of soil or rock located in there should be useful to consult the suitable type of foundation; so if for example there is loose soil, of course a solid berth structure would not be chosen, but an open one.

Since the foundations and the berth structure itself will be found inside the water, the work is tried to be carried out from above the sea, as much as possible for simplicity. Thus, for this aspect sheet pile structures and structures made of steel pipe piles are ideal.

Due to open berth structures has a much smaller front wall against the wave action, these are the most favourable to reflect the incoming loads.

Of course previous experience is relevant to choose the type of structure. Most of the construction work takes place in connection with water and therefore working techniques, plant and machinery are to considerable extent different from those applied in construction on land. So, if the project is an extension of an existent harbour, a look in the past will be very useful.

When designing a berth structure it has to be taken into account which types of machinery and construction plant can be procured for the site in question.

Timber, concrete and sheet are the materials which can be used for the structure construction, either using one of these alone or together by combining them. The choice of these will depend on the properties suitable for the purpose wanted and also on the economic considerations. The durability of these materials will be regarded with special attention due to the aggressive environment in which the structure will be placed.

Regarding to construction time, the main problem would be if the new berth is to be built on the same place as an old one, which is still in operation, or a new berth structure is going to be erected close to an existent one where operation would be hampered during the construction period. A time-saving construction method should be emphasized even if its construction cost is higher.

At the time of constructing a new berth structure some provisions should be made for possible future extensions of the berth in one or more directions. Also the depth along the front has sometimes to be increased due to the changing size on the ships which are currently coming to and from the port.

The soil condition and the temperature variations require the erection of expansion joints. Moreover in places where ice takes place sometime over the year, or the temperature varies largely, shrinkage and yielding of the foundations are probable to occur.

Finally nearly the factor which is taken the most into account at the time of construction is its cost. Unit prices of the materials, machinery and working hand are the ones which will increase the total amount on the bill. For this, one should keep in mind that a number of contractors ought to be able to procure them so that true competition is secured and prices are lowered.

GEOLOGY

Since it has been justified the importance of the soil conditions factor, it has been thought necessary an introduction an description of the terrain conditions in Sisimiut.

Starting to contextualize the whole country, a description of Greenland's geology has been carried out.

Greenland's geology

Greenland is the largest island in the world within 80% of its surface covered by the Inland Ice. Its major geological units show continuity with North America, eastern Canada and northern Europe having rocks from similar ages and lithology, but their disposition and character strengthen the idea that Greenland is a single North Atlantic land mass.

In Figure 6 the most important geological features are shown:

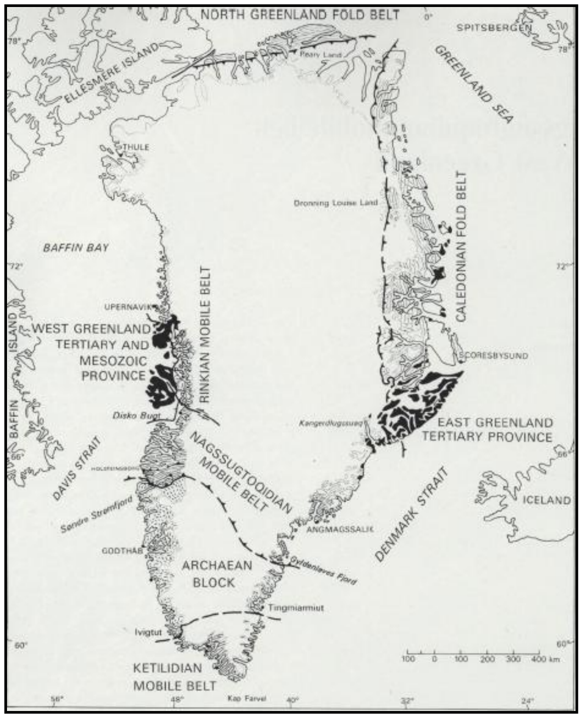

Figure 6. Structural divisions of Greenland [see Ref.9]

The Rinkian mobile belt, the Nagssugtoqidian mobile belt, the Archaen gneiss complex and the Ketilidian mobile belt together are forming the *Precambrian Shield*. The *Paleozoic Fold Belts* include both the East and North Greenland fold belts. Finally, the *Platform Areas* are classified as: South, North and North-West, East, West, the Tertiary volcanic province and the Quaternary and Glaciation.

As it is indicated in the map, the Archaen block is the geological column with the oldest rocks (to be more rigorous, the oldest reliable isotopic ages of any terrestrial rock has been found in the Isua region of central West Greenland), which are from the Archaen age, followed by Proterozoic, Paleozoic and Mesozoic sedimentary and magmatic provinces. Late Phanerozoic continental-scale magmatism appears along the west, east and northern coasts. Then, also late Proterozoic-Palaeozoic basins have been formed into extensive fold belts along the northern and eastern coasts.
Sedimentary basins, from the Upper Proterozoic to Tertiary (from 65 million to 1.8 million years ago), are associated with default tectonics. They represent a 30% of the exposed rock in Greenland. The remaining 70% is formed of crystalline rocks of the Precambrian Shield, which are in the ice-free area.

In order to be able to place the ages that are being mentioned in the right way, here there is a diagram of the geologic eras from 4500 million years B.C. (The second timeline is a subsection of its preceding timeline).

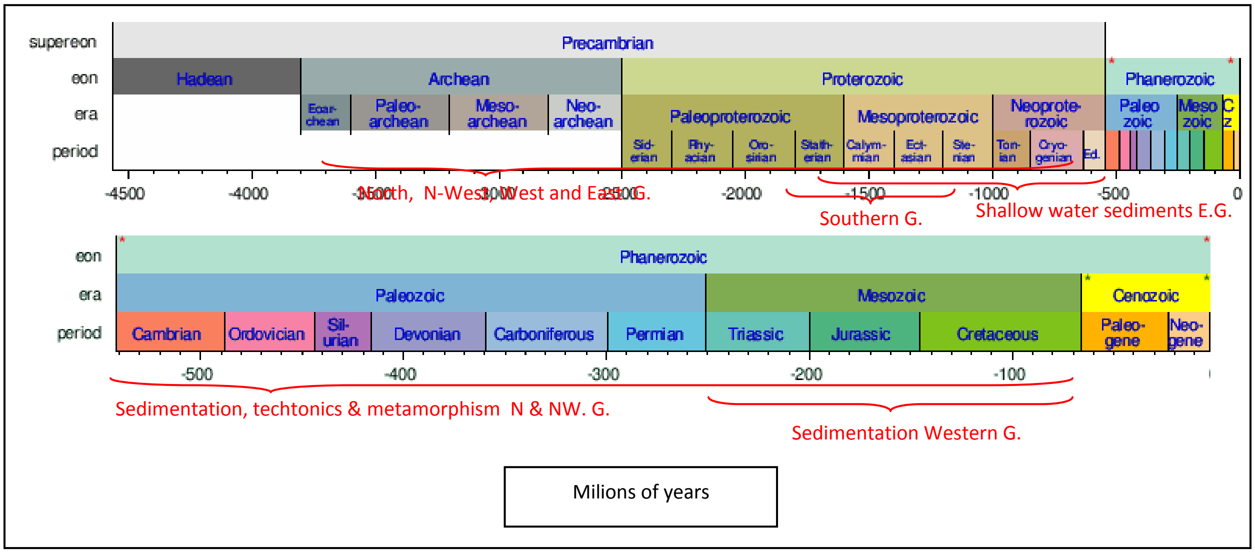

Figure 7. Geologic eras diagram [see Ref.5]

Before focusing deep into Sisimiut's area, an overview of Greenland's geology is given to have a clear idea of which are the predominant rocks and minerals.

SISIMIUT

Here there is a detailed map of Sisimiut area and its surroundings. The brownish-yellow colour corresponds to gneissic lithology while the dark strips are mainly amphibolites, with some blue intrusions related to marble rock. The brown colour shows the areas where there are shales. The pink zone, near Sisimiut has granitic presence.

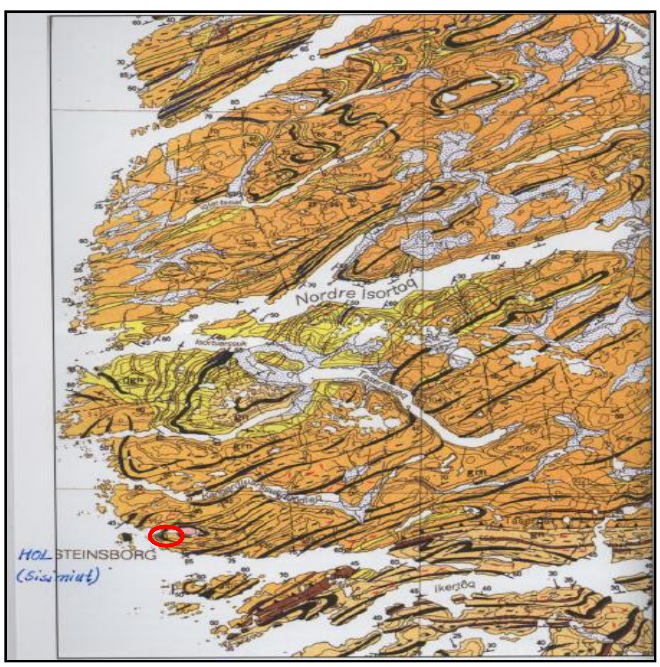

Figure 8. Overview of the geology in Sisimiut's area.[see Ref.8]

As the map shows, gneiss is the rock which mainly covers the entire zone. Southern mountainous areas are affected by shearing process, suffered downwards the city. These formations were created under amphibolites facies. Because of the process mentioned, there was foliation in the direction of the fault as well as intrusions of dolerite and marine sediments along the crack length. Regarding to these intrusions, there is a visible transition of volcanic dolerite into amphibolites as the length is followed to the east.

Going to the north, a patchwork of many coloured gneiss, granite, pegmatite rocks can be seen; this image persists along 200km to the east. Again to the north, brownish, yellow, rusty gneissic bands appear together with several evidences of mica slates, marble and sulphide schists. Some of the slates scenes are much undulated, with steeply sloping. Still in the north, where sulphide crumbly layers are found, mica, pyrite, pyrrhotite and graphite appear.

Now, getting approached to Sisimiut, it suddenly becomes darker due to granite intrusion. Specifically charnockite (orthopyroxene-bearing granite, composed mainly of quartz, perthite or antiperthite and orthopyroxene) is placed in the deeper part of the bedrock area’s formation, from dark grey to olive green. Immediately east of the city, there is pale reddish fine-grained granite in the charnockite atmosphere.

Finally, in the coastal areas, the bedrock structure is adamant with relief cracks in special directions and patterns. Main mountain formations have several scenes with rusty bands containing sulphides and granites.

Having reached this point, the last paragraph explains the reason why weathering is going to be studied in this project. First of all, it’s going to be described and classified the different weathering effects of rock material.

Since Greenland’s rock mass has been heavily weathered over the years; it has been thought necessary to analyze how weathering can affect to rock mass properties particularly in Sisimiut.

WEATHERING

Definition

Weathering is defined as the breakdown or decomposition of rocks and minerals at or near the Earth´s surface. Most rocks and minerals are formed deep within the Earth´s crust where temperatures and pressures differ greatly from the surface.

It has to be differenced weathering from erosion. The first one occurs “in situ”, without movement, while the other one involves the movement of rock and minerals by agents such as water, ice, wind and gravity. Weathering is the first step for a number of other geomorphic and biochemical processes. The products of weathering are a major source of sediments for erosion and deposition.

According to the International Standard *ISO 2003*, there are four different terms to describe weathering of rock materials. The following classification is general and focused on the external appearance of the rock sample. So it should be used for a first identification of the phenomenon studied:

Description

Fresh: This term is used when the rock presents no visible alteration. Thus, apparently no weathering has affected the sample yet.

Discoloured: As the word means, the colour of the material has become lighter and now weathering effects are pretty clear. The shade got after the alteration should be specified for further classification. Furthermore if this modification has been caused for mineral changes, it has also to be mentioned.

Disintegrated: This step begins to be critical since the rock has suffered a loss of cohesion and so it has been transformed into soil conditions. Although having this effect, the structure of the initial material has been maintained. Finally in this grade of weathering just the rock is altered, but the minerals are not. This weathering mechanism is known as physical one.

Decomposed: Now, chemical weathering is affecting the rock material. Mineral grains are changed into soil condition, but the structure of the initial material is still preserved. In this case, mineralogy has been altered in the way of decomposition of its grains.

The definitions above aren't enough to describe the grade of alteration of the rock material. The second term should be accompanied by adjectives such as partially, wholly or slightly. Moreover the three last terms should be used in combination.

This first classification is what can be used in the field at the time of the rock analysis. Thus, basing the analysis of this project on the master thesis done in 2003 – *Bedømmelse af fjeldkvalitet i Sisimiut og Utoqqaat* some pictures are available to have a first contact with the real rock material.

First of all, the main feature which should be considered at the time of describing the alteration suffered is the climate: temperature, ice and oxygen.

Focusing to **Sisimiut**, some gneiss can be distinguished on the surface, as Figure 9 shows.

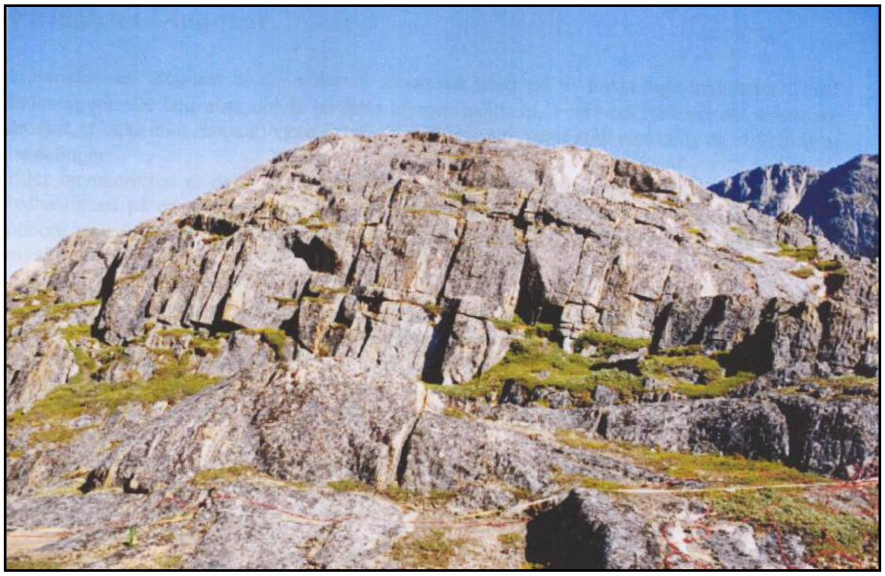

Figure 9. Rock structure in Sisimiut [see Ref.1]

In this region the Nagssugtoqidian shear-deformation was accompanied by a strong recrystallisation in the amphibolites facies, which might be very well governed by the distribution of water at the time of the metamorphism, the brownish hypersthenes gneisses being retrogressed to light grey biotite-hornblende gneisses. Thus, the visual analysis helps to guess that weathering should be defined as slightly discoloured and partially disintegrated.

Starting from the point that the rock mass has been altered mainly by the ice, the temperature and pressure at the time of its formation and also recrystallization, physical weathering is the solution thought. This area has suffered frost wedging; it occurs when water within the pore structure or cracks freezes to ice. It could expand between 8-11%, which increases the internal pressure. This increase together with thaw cycles is what produces micro-fissures, cracks, flacking and spalling. Also mineralization changes and pressure release affected the area because of the folding activity and the displacements of the Nagsugtoqidian mobile belt.

Having a look at Figure 7, and focusing on the fracturing, classification from *RockLab* software has been used for description (see Figure 8). The rock structure in this case could be classified as blocky with good-fair surface conditions.

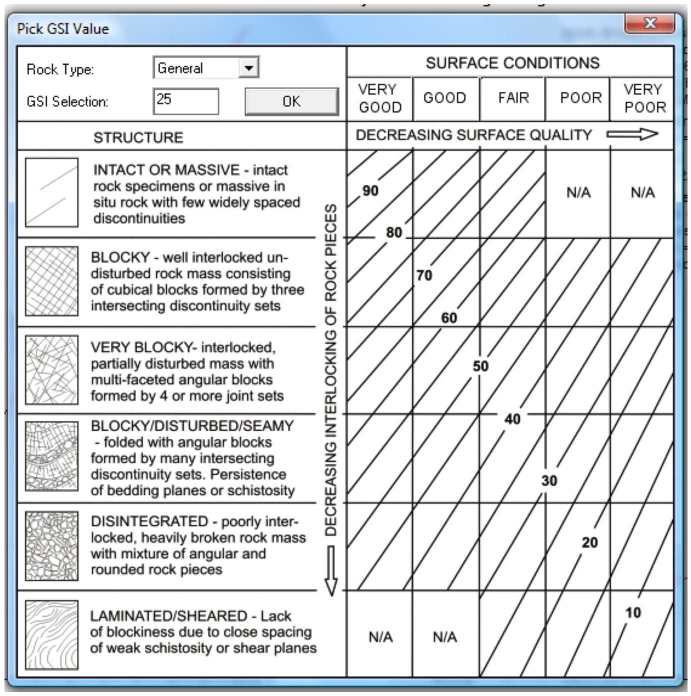

Figure 10. RockLab GSI classification

Later in this assignment the behaviour of the rock material defined will be compared with others maintaining the same structure but with very good and very poor surface conditions.

Finally, the last step should be establishing a grade on the weathering stages scale, regarding again to the *ISO 2003* rules. Here there is the table recommended:

Tabla 1. Scale of weathering stages of rock mass [see Ref.1]

Term	Description	Grades
Fresh	No visible sign of rock material weathering; perhaps slight discoloration on major discontinuity surfaces.	0
Slightly weathered	Discoloration indicates weathering of rock material and discontinuity surfaces.	1
Moderately weathered	Less than half of the rock material is decomposed or disintegrated. Fresh or discoloured rock is present either as a continuous framework or as core stones.	2
Highly weathered	More than half of the rock material is decomposed or disintegrated. Fresh or discoloured rock is present either as a discontinuous framework or as core stones.	3
Completely weathered	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact.	4
Residual soil	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported.	5

Thus, considering the table above, the description in terms of weathering scale should be *slightly-moderately weathered*, grade 1-2.

RockLab ANALYSIS

In order to see the influence of weathering processes in rock material properties, some tests have been done with the help of RockLab program. The most representative rock materials, mentioned in the previous section, have been chosen for this analysis. The comparison has been done between gneiss and amphibolite in 3 different grades of fracturing state, and also with a highly weathered or altered rock.

At the time of the implementation of the data in the program, some other considerations, apart from the rock type, are taken. The Uniaxial Compressive Strength (sigci), the Geological Strength Index (GSI), the Intact Rock parameter (mi) and the Intact Modulus (Ei) are chosen as the rock parameters. The second one is the one it has to be modified depending on the fracturing state of the rock. Concerning the civil work that is going to be carried out in the field, there are some other parameters which have to be set. They are the Disturbance factor (D), the Slope Height and the Unit Weight; the last one is already fixed by default. These two first factors are chosen considering the harbour construction, with good blasting (due to hard rock) and assuming a slope height of 15m.

With these inputs, some theories such as Hoek-Brown and Mohr-Coulomb are used to give some results which can be interpreted to understand the differences between the samples chosen. In this case, Mohr-Coulomb and the Rock Mass Parameters are the ones taken into account for the following analysis.

How are rock properties influenced by fracturing?

Here there are the input-output results obtained by RockLab:

Tabla 2. RockLab results

		Gneiss			Amphibolite			Highly-weathered rock
	Parameters	**Very Good**	**Good-Fair**	**Very poor**	**Very Good**	**Good-Fair**	**Very poor**	**Poor-Very poor**
Hoek-Brown Classification	**sigci [MPa]**	150	150	150	100	100	100	3
	GSI	90	50	20	90	50	20	25
	mi	30	30	30	26	26	26	6
	D	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	MR	525	525	525	450	450	450	400
Hoek-Brown Criterion	**mb**	17.318	1.923	0.370	15.009	1.667	0.321	0.097
	s	0.235	0.001	0.000	0.235	0.001	0.000	0.000
	a	0.500	0.506	0.544	0.500	0.506	0.544	0.531
Failure Envelope Range	**sig3max [MPa]**	0.478	0.426	0.388	0.459	0.408	0.371	0.257
	Unit Weight [MN/m3]	0.027	0.027	0.027	0.027	0.027	0.027	0.027
	Slope Height [m]	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Mohr-Coulomb Fit	**c [MPa]**	7.140	0.453	0.143	5.107	0.356	0.119	0.022
	phi [deg]	68.105	64.863	51.722	66.338	61.958	47.847	15.884
Rock Mass Parameters	**sigt [MPa]**	-2.033	-0.056	-0.004	-1.564	-0.043	-0.003	-0.001
	sigc [MPa]	72.654	3.842	0.274	48.436	2.561	0.183	0.009
	sigcm [Mpa]	98.621	27.280	9.557	62.638	16.931	5.895	0.101
	Em [MPa]	45329.90	8448.45	2089.01	25902.80	4827.68	1193.72	36.269

Mohr-Coulomb characteristic values have been plotted for a better understanding of the influence of the alteration suffered in the rock material due to weathering processes.

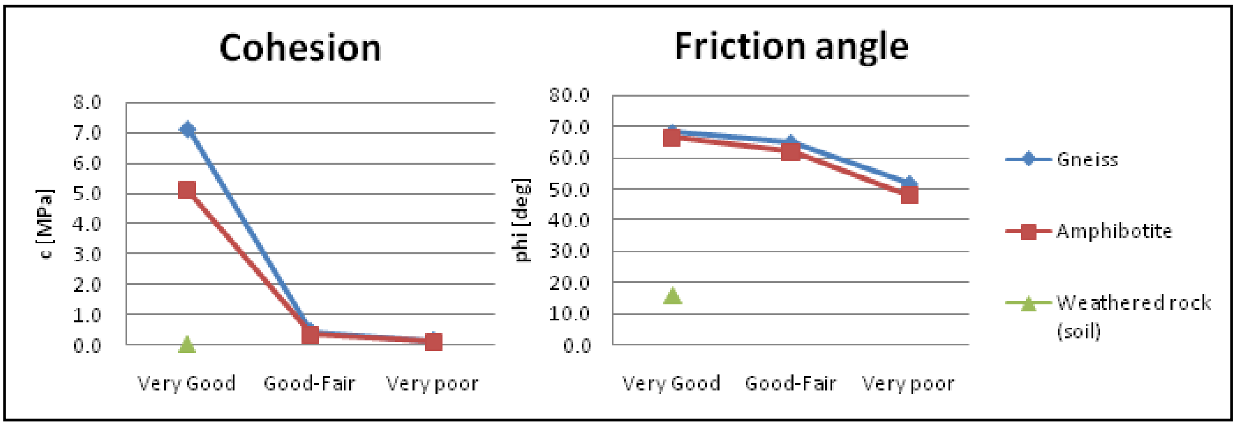

Figure 11. Cohesion and Friction angle respresentation.

As it can be seen in the hard rock results (Gneiss and Amphibolite), Mohr-Coulomb properties have a clear tendency to decrease. This tendency matches the grade of fracturing of the rock structure and its surface appearance when becoming more and more visible and diminished.

The cohesion is the parameter which is influenced the most by a decrease of the Geological Strength Index. Both cohesion and friction angle influence on the strength of the rock structure in front of shear forces. Figure 10 shows the theoretical equation which relates the three mentioned factors, by Mohr-Coulomb criterion.

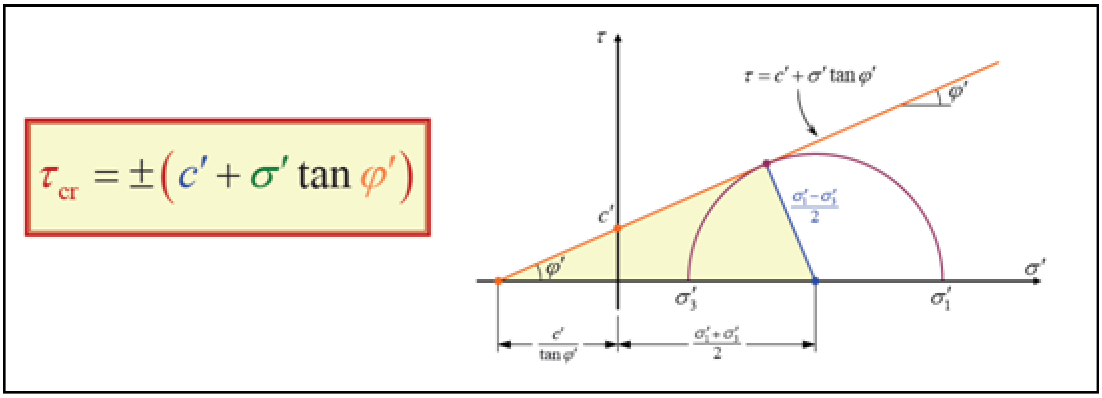

Figure 12. Mohr-Coulomb Criterion. [see Ref.6]

Thus, with this knowledge, it can be stated that with less cohesion and friction angle the rock material is not able to suffer such high shear stresses, since the area below the line is decreasing at the same time. It is proved that in hard rocks, the influence of physical weathering such as frost wedging is really noticeable. This would be the example of the rock structure in Sisimiut.

Focusing on the Rock Mass Parameters, it’s visible that all, tensile strength, uniaxial compressive strength, global rock mass compressive strength and deformation modulus, rapidly decreases with the structure deterioration approaching to soil values.

CONCLUSION

Focusing to the harbour's contruction, which was the main purpose of this project, it can be concluded that in Sisimiut, rocks as gneiss and charnockite with amphibolites intrusions, are placed in the coast.

Over the years this material has suffered several processes such as folding, frost wedging, pressure increases and mineralization changes which resulted in cracks, micro-fissures and spalling of the initial structure.

As mentioned in the corresponding point, it is finally defined as slightly-moderated weathered material.

This fact influences quite a lot in the rock characteristic parameters, in the way of decreasing the final stability of the rock settlement.

It has to be taken in consideration at the time of civil works in that area. This is the case in which nowadays there is some trouble. Once the necessary parameters are obtained, and the extension dimensions are decided, it might be calculated if the rock material is capable to cope with the forces which will appear on it.

The previous section gives the understanding of how can weathering influences on the stability of a hard rock material such as gneiss, granites or amphibolites. So, is a matter of interest to spend some time focusing on this analysis before starting working in the field in a civil project, although having a theoretical exceptional lythology.

For the future Master Thesis a study of different alternatives will be done taken in consideration the important factors mentioned and explained in the "harbour design" section. Also the field work would be used in order to determine these necessary factors at the time of the choice.

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  Charnockite

  Amphibolite facies

  Sulphide

  Pyrite

  Pyrrothite

  Oxidation

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