

# **Correlation between microtextures and mechanical strength**

**Sala-Heby, central Sweden**

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## **Correlation between microtextures and mechanical strength Sala-Heby, central Sweden**

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### **Abstract**

Microtextures in thin section, but also textures at hand specimen scale, affect the strength (resistance to abrasion and fragmentation) of rocks. The first objective of this thesis is to see if correlation exists between studied textures and mineral assemblages and technical analyses. When correlation exists the next approach is to see which textures/mineral assemblages result in good or poor rock strength i.e. good or poor resistance to abrasion and fragmentation. The metamorphic scenario, in the Sala-Heby area, set by Delin and Söderman (2005) will be tested through the comparison of the geographical locations of samples with granodioritic composition and textures which result in good or poor rock strength. It is also important to see which one of the three rock types in the investigated area generally show better rock strength than the others and why.

Hand specimen and thin sections from the Sala-Heby area, Sweden, with granitic-, granodioritic- or tonalitic composition have been studied visually and through an optic microscope in order to identify the current textures and mineral assemblages. Point counting was carried out on thin sections to receive the rock composition of all samples, so comparison with technical values could be made.

Gneiss texture, compositional banding (in hand specimen), type of grain boundaries, preferred orientation formed by amphibole, relative directions of different types of foliations (in thin section) and biotite content (a mineralogical texture) affects the strength of the rocks considering abrasion. Rocks with granitic composition show best resistance to abrasion when considering the studied textures and mineral assemblages.

The ability of rocks to resist fragmentation is widely affected by augen-, gneiss texture (in hand specimen), preferred orientation formed by amphibole and biotite and the relative directions of different types of foliation (in thin section).

*Key words:* Microtextures, Sala-Heby, Studded tyre test, Los Angeles analyses, point counting, biotite content, abrasion, fragmentation, dimensional preferred orientation, crystallographic preferred orientation

## **Correlation between microtextures and mechanical strength Sala-Heby, central Sweden**

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### **Sammanfattning**

Mikrotexturer i tunnslip, men även texturer i handstuff, påverkar bergarters hållfasthet/kvalité (motståndskraft mot nötning och fragmentering). Det första syftet med denna rapport är att se om det finns samband mellan studerade texturer/mineralogier och tekniska hållfasthetsanalysvärden. Nästa ansats, när korrelation finns, är att ta reda på vilka texturer/mineralogier som ger bra eller dålig bergkvalité dvs. bra eller dålig motståndskraft mot nötning och fragmentering. Genom att jämföra de geografiska platserna för prover med granodioritisk sammansättning med de texturer som resulterar i bra eller dålig hållfasthet kan man testa det metamorfa scenariot som finns i Sala-Heby området enligt Delin och Söderman (2005). Det är också viktigt att ta reda på vilken av de tre bergartstyperna, vilka finns i undersökningsområdet, som generellt visar bättre bergkvalité än de andra och varför.

Handstuff och tunnslip med granitisk-, granodioritisk- eller tonalitisk sammansättning från Sala-Heby området, Sverige, har undersökts okulärt och genom ett optiskt mikroskop så att identifiering av aktuella texturer och mineralogier kunde utföras. Punkträkning utfördes på tunnslipen för att få ut bergartssammansättningen för varje prov. Detta gjordes för att provens sammansättning skulle kunna jämföras med de tekniska hållfasthetsvärdena.

Gnejs textur, kompositionsbandning (texturer i handstuff), typ av korngräns, föredragen orientering bildad av amfibolkristaller, relativa riktningar mellan olika typer av foliationer (texturer i tunnslip) och biotithalt (mineralogisk textur) påverkar bergarters hållfasthet med avseende på nötning. Bergarter med granitisk sammansättning visar bäst motståndskraft mot nötning när man tar hänsyn till de studerade texturerna och mineralogierna.

Bergarters förmåga att motstå fragmentering påverkas till stor del av ögon-, gnejs textur (i handstuff), föredragen riktning på amfibol- och biotitkristaller och relativa riktningar mellan olika typer av foliationer (i tunnslip).

*Nyckelord:* Mikrotexturer, Sala-Heby, Kulkvarnanalyser, Los Angelesanalyser, punkträkning, biotitinhåll, nötning, fragmentering, dimensionell föredragen riktning, kristallografisk föredragen riktning

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# 1. Introduction

## 1.1 Objectives

Rock samples, both hand specimens and thin sections, from the Sala-Heby area, Sweden were studied according to mineralogy and certain textures. The first approach of this project is to compare these textures and mineral assemblages with technical strength values, i.e. rock strength, to see if correlation exists. The technical strength values were supplied by Sträng et al. (2007). Another objective of this project was to determine, when correlation exists, which textures and mineral assemblages result in good or poor rock strength. When this has been established, it is possible to compare samples with granodioritic composition with the textures resulting in good or poor rock strength. The result can be connected to the geographical location of the samples and the metamorphic scenario for this type of rock in the Sala-Heby area, set by Delin and Söderman (2005), can be tested. It is also important to see which one of the three rock types (granite, granodiorite and tonalite), in the investigated area, generally shows better rock strength than the others and why.

## 1.2 Granite, granodiorite and tonalite

Granite, granodiorite and tonalite show high silica content and are called felsic rocks. These types of rocks form when crust material remelts and form plutons. A QAP ternary diagram is used to classify felsic plutonic rocks. Granite consist of quartz (20-60 vol. %), alkali feldspar (30-75 %), plagioclase (20-50 %) and colored minerals such as biotite and amphibole (7-10 % of the total). Tonalite contains the same amount of quartz as granite but shows higher content of plagioclase. Minor amounts of alkali feldspar are characteristic for tonalite. Granodiorite show an intermediate composition between granite and tonalite. (Wenk and Bulakh 2004)

## 1.3 Preferred orientation

*Preferred orientation* (p.o.) is statistical alignment of mineral grains, which can be applied to shape, *dimensional preferred orientation* (d.p.o.), and/or crystal axes, *crystallographic preferred orientation* (c.p.o.), (Vernon 2004). Mica such as biotite forms c.p.o., due to the alignment of crystal axes in the same direction which results in foliation. Quartz forms d.p.o. because the foliation is the result of elongated grains, not necessarily corresponding to their crystallographic long axis. (Lennart Björklund, personal communication).

## 1.4 Hypothesis

### 1.4.1 Textures

*Grain boundary migration* (GBM) is a type of recrystallization process, where atoms in a grain with higher strain energy migrate, by diffusion, and are added to the surrounding grains with lower strain energy. *Subgrain rotation* (SR) is another recrystallization process where dislocations are free to creep from one lattice plane of one subgrain to another and are thereby added to the neighboring subgrain. Sutured *grain boundaries* (g.b.) are the result of these two processes (Winter 2001). Sutured g.b. are interlocked and can resist more strain than straight g.b. The result is that the former type is stronger than the latter and also improves rock strength.

Cleavage is a type of foliation, and the presence of such foliation in a rock permits the rock to split up more easily (Davis and Reynolds 1996). Logically thinking, material which shows penetrative foliation, both in hand specimen and thin section, ought to be weaker (easier to split up) than material which shows less penetrative foliation. This statement has been applied to d.p.o. and c.p.o. where the most penetrative foliation is represented by bands of crystals (type 4) and no foliation by clusters (type 1).

Gneiss texture and compositional banding are types of foliation and are the result of recrystallization of igneous or sedimentary rocks during metamorphism (Davis and Reynolds 1996). These textures are found in hand specimen. If they are present they weaken the material, which will split up more easily than if these textures were absent.

When more than one type of foliation exists, and their relative directions are the same, logically thinking this will result in a more penetrative foliation than if the relative directions were different. The penetrative foliation will weaken the material which will break up more easily (poor rock strength). This has been applied to the *relative directions of dimensional preferred orientation* and *crystallographic preferred orientation* formed by quartz, amphibole and biotite (d.p.o./c.p.o.) and the *relative orientations of crystallographic preferred orientation* formed by biotite and amphibole respectively (c.p.o./c.p.o.).

Alteration affects the hardness and the properties of minerals (Nesse 2000) and the result is a weakening of the material. Higher degree of alteration weakens the material more than a lower degree of alteration does. This approach has been applied to plagioclase crystals in the studied samples.

#### **1.4.2 Mineralogy**

Biotite is a mica mineral which is built up by tabular sheets stacked on top of each other. On Mohs scale of hardness biotite shows a hardness of 2-3, which represents a soft material. Biotite forms very good cleavages, which can work as slip planes (Davis and Reynolds 1996), and the result is an elastic foliation (Nesse 2000). The softness and elastic character of biotite makes it resistant to fragmentation but not to abrasion. This approach has been applied to the biotite content in the studied samples.

Chlorite is built up in a similar way as biotite and shows the same hardness on Mohs scale of hardness (2-3). Very good cleavage can be formed, but does not make the foliation elastic, only flexible (Nesse 2000). Since chlorite is soft and form good cleavage it has the tendency to weaken its host rock. The same approach as for biotite content has been applied for both primary and secondary chlorite content in the studied samples.

Microcline, belonging to the feldspar group, forms very good cleavages in a brittle manner and shows a hardness of 6-6,5 on Mohs mineral scale of hardness (Nesse 2000). Since microcline forms good cleavage the mineral can easily split up and therefore shows low resistance to fragmentation. Due to the hardness of microcline it shows good resistance to abrasion. This statement has been applied to augen texture studied in hand specimen.

## 1.5 Earlier work

Figure 1. contains two maps which lie on top of each other. The bottom map is the bedrock map where the different rocks are displayed in various colors. The topmost map (semitransparent) is restricted to the sampled area and shows rock quality class 1-3, set by Sträng et al. (2007), where class 1 is the best. The sampled area (Figure 1.) extends both across and along the main strike of the bedrock formations. The geographical locations and spatial relations between the 12 sample locations where Sträng et al. (2007) collected all the material used in this project can be seen. Technical analyses such as *Studded tyre tests* (STT) and Los Angeles tests were carried out on the samples. Delin and Söderman (2005) studied an area of the bedrock which range from just north of Heby and northward to where the sampled area (rock quality map made by Sträng et al. 2007) do not extend any further. The southern part of the sampled area (south of Heby) is not included in the investigation, even though a trend could be seen. The granodiorites in the north showed to be more recrystallized than the ones in the south, which indicates that the degree of metamorphism in the granodiorites gets more intense to the north (Delin and Söderman 2005 and references therein).

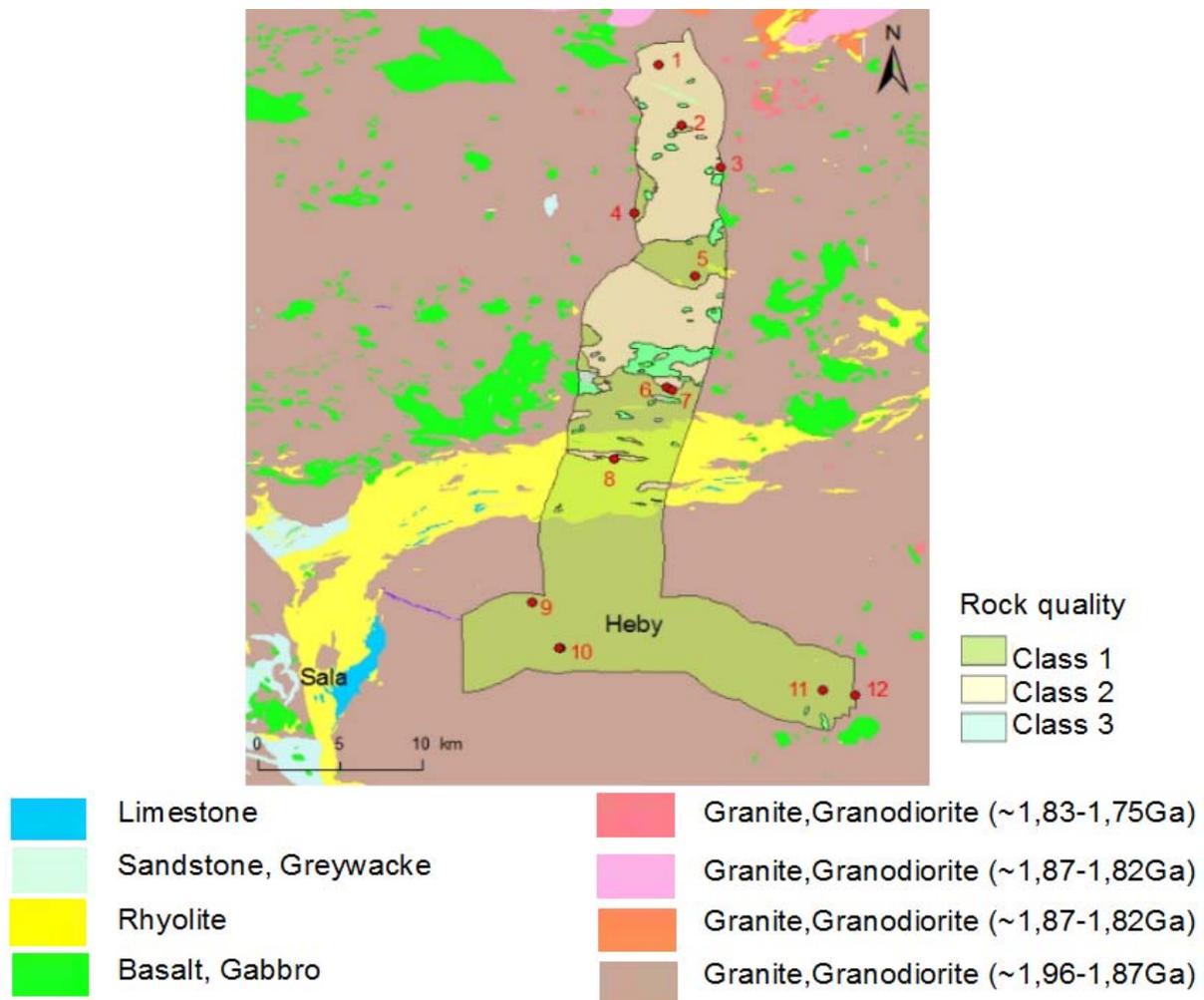


Figure 1. Geographical map of the investigated area, Sala-Heby, Sweden, which shows the geographical location for all samples used in this project. The figure is composed of two maps which lie on top of each other. The topmost (semitransparent) is restricted to the sampled area and shows rock quality class 1-3. The bottom map shows the rocks which makes up the bedrock. (From Sträng et al. 2007)

## **2. Methods**

### **2.1 Sträng et al. (2007)**

The *Geological Survey of Sweden* (SGU) supplied material used in this project, which correspond to 12 hand specimens and thin sections from the Sala-Heby area, Sweden. The materials were cut perpendicular to the foliation, if present. Also maps and information were supplied by the SGU.

#### **2.1.1 Point counting**

Point counting was used in the petrographic analyses to receive the modal composition of the thin sections. Approximately 500 counts/ thin section were made on a 24x20mm area.

#### **2.1.2 Technical analyses**

From every sample location in the sampled area Sträng et al. (2007) took 50-70 kg rock material to be able to carry out the technical analyses STT and Los Angeles.

Studded tyre test value is a measurement of the rock's abrasion resistance. The analyses were carried out by *Mark Radon Miljö konsult AB* (MRM AB) in Luleå according to FAS Metod 259-02 specifications. First the material was crushed in a rotating jaw crusher (30mm grains were received) and then it went through a laboratory jaw crusher (16mm grains were received). Coarse and fine sieving was carried out with a machine shaker and shaking table respectively, according to FAS-metod 221-02. The analyzed fraction was 11, 2-16 mm. (Sträng et al. 2007)

Los Angeles value is a measurement of rock's resistance to fragmentation. The analyses were carried out by MRM AB in Luleå according to SS-EN 1097-2. Crushing and sieving were carried out in the same way as for STT. The analyzed fraction was 10-14 mm. (Sträng et al. 2007)

Results from STT and Los Angeles analyses are good tools for determining the quality, strength and the suitability of material as building material (road, railway and concrete). Low STT values and Los Angeles values represent material with best resistance to abrasion and fragmentation respectively.

A third technical analysis, MicroDeval, is not considered in this paper because only 3 out of 12 samples showed values from this analysis.

## **2.2 This project**

In this project thin sections and hand specimens of granite, granodiorite and tonalite from the Sala-Heby area, Sweden, were studied in respect to texture and mineralogy.

### **2.2.1 Qualitative analyses**

Investigation of all 12 hand specimen a pair of textures were chosen for the qualitative analyses. The investigated textures were visible foliation, augen-, gneiss textures and compositional banding.

A set of textures had to be selected when studying the thin sections. Textures studied were grain boundaries (g.b.) between quartz grains, dimensional preferred orientation (d.p.o.) formed by

quartz, crystallographic preferred orientation (c.p.o.) formed by biotite and/or amphibole, relative directions of different types of foliations d.p.o./c.p.o. and c.p.o./c.p.o.. All textures were classified and graded according to a qualitative scale 1-2, 1-4 or class S or D.

### **2.2.2 Point counting**

It was decided, already from the beginning of this project, to delay the study of the mechanical qualities of the rocks until after studying their petrographic properties. The interpretation and selection of petrographic properties would thus not be biased.

The modal compositions (based on the main components in each sample) of the thin sections, and thereby the rocks, were established through point counting. A digital point counter and PetrogLite version 2.41 software were used. The total area of each thin section was 32x24mm and investigated with a fixed point counting distance. Altered minerals, such as biotite, were first and foremost counted as partially chloritized biotite while altered plagioclase was counted as plagioclase. In the former case the purpose of the analysis was to separate primary chlorite (single crystals) from partially chloritized biotite (secondary chlorite). To decide the degree of alteration of plagioclase crystals a qualitative scale, 1-4, was selected.

Textures and mineral assemblages studied in this project are good prospecting tools which makes it easier to determine the quality of the material before making technical analyses such as STT- and Los Angeles.

### 3. Results

#### 3.1 Sträng et al. (2007)

##### 3.1.1 Point counting

Sträng et al. (2007) carried out point counting on all samples, and the results are shown in Figure 2.

Sample	ID	Qz	FIs	PI	Bt	Chl
1	HLD020910A	30,2	7,4	52,8	6,8	0,6
2	HLD020742A	26,6	5,2	42,2	17,4	-
3	MAL010035A	24	2,6	46,8	11,6	0,4
4	AEN010210A	41,2	22,4	25,6	5,4	-
5	AEN010163A	44	0,2	49,8	5,6	-
6	HLD020838B	39,6	2,6	42	14,2	-
7	HLD020837A	38	16,4	43,4	1,8	-
8	HLD010328A	26,4	5,8	44	13,4	0,2
9	DLA030002A	26,8	19,4	40	6	-
10	MPA040040A	29	18,2	34	10,6	-
11	CMR030099A	44	23,8	29,4	2,2	-
12	MPA040039A	30,8	31,8	33,2	2,4	0,4

Figure 2.

The table shows the results received from the point counting carried out by Sträng et al. (2007). The numbers represent volume % of minerals in the sample. ID= sample name, Qz= quartz, FIs= feldspar, PI= plagioclase, Bt= biotite, Chl= chlorite. The full extent of this table is found in Appendix. (From Sträng et al. (2007))

A QAP ternary diagram, Figure 3. (Le Maitre 1989) was made for all 12 samples supplied by the SGU to give a better visual picture of their relative compositions (based on the main minerals quartz, feldspar and plagioclase in each sample). Figure 3. is based on results by Sträng et al. (2007) (Figure 2.). Figure 3. shows that samples 3, 5 and 6 have a tonalitic composition while samples 1, 2, 7, 8, 9 and 10 show a granodioritic composition. Granitic compositions are shown by samples 4, 11 and 12.

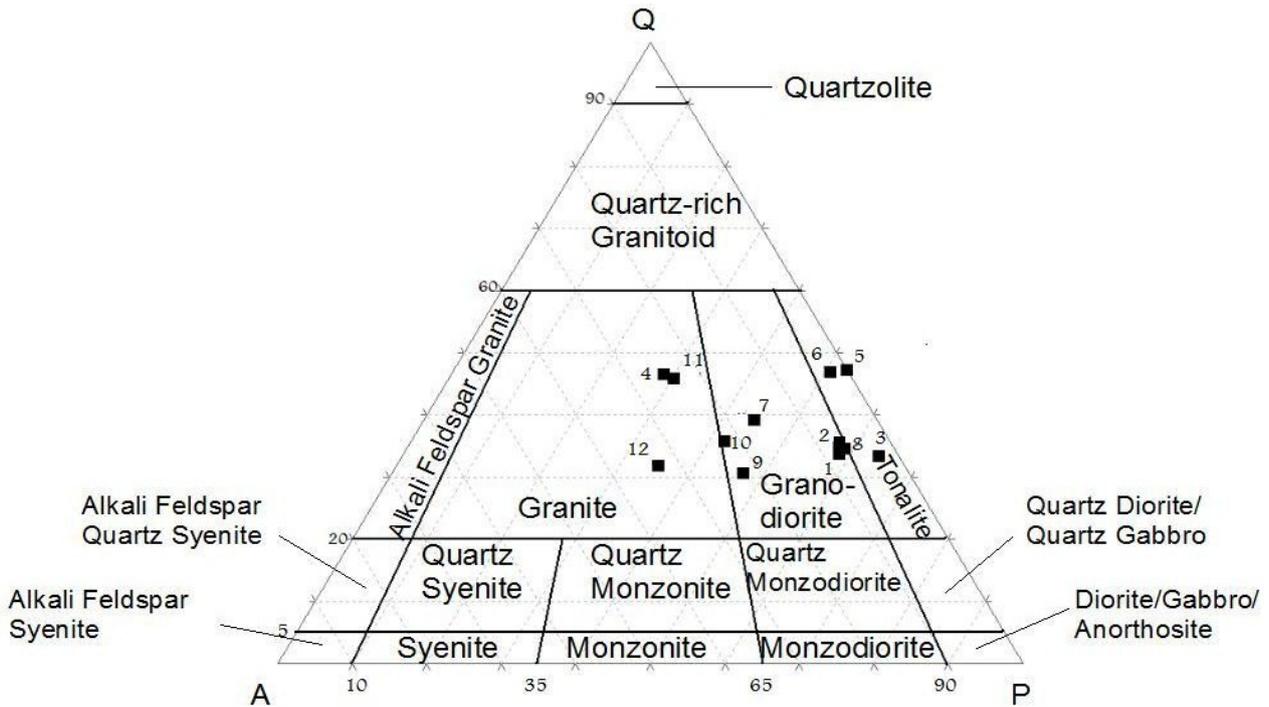


Figure 3.

QAP ternary diagram shows the relative amounts of quartz, feldspar and plagioclase for the 12 samples, based on the point counting by Sträng et al. (2007) (Figure 2.) (From Le Maitre 1989)

The highest biotite contents, >10 %, were found in samples 2, 6, 8, 3 and 10, see Figure 4. Sample 7 shows the lowest content which correspond to 1,8 %.

Chlorite was only found in samples 1, 3, 12 and 8, see Figure 5. Sample 1 shows the highest content (0,6 %) while sample 8 displays the lowest content (0,2%). The chlorite content is not specified to be primary or secondary. Both Figure 4. and 5. are based on the point counting by Sträng et al. (2007) (Figure 2.).

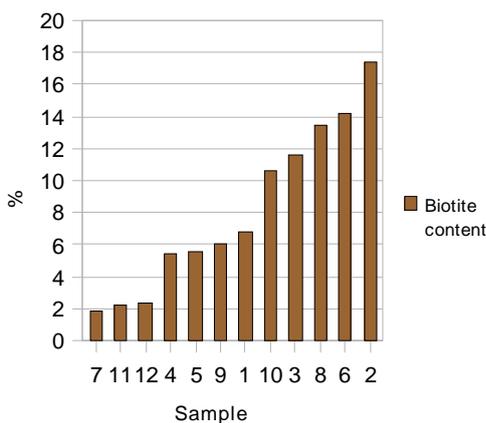


Figure 4.  
Total biotite content for all 12 samples.

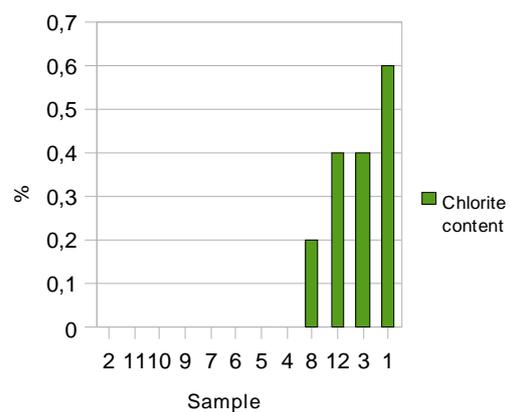


Figure 5.  
Total chlorite content for all 12 samples.

### 3.1.2 Technical analyses

The results of the technical analyses carried out by Sträng et al. (2007) are shown in Figure 6.

Sample	ID	Kk	LA
1	HLD020910A	11,3	21,1
2	HLD020742A	9	16,2
3	MAL010035A	12,2	19,6
4	AEN010210A	7,4	16,1
5	AEN010163A	9,4	19,4
6	HLD020838B	13,9	22,5
7	HLD020837A	8,7	20,8
8	HLD010328A	13,5	18,1
9	DLA030002A	9	15,9
10	MPA040040A	9,5	16
11	CMR030099A	10,2	24,4
12	MPA040039A	6,7	16,5

Figure 6.

The table shows the results of the technical analyses from Sträng et al. (2007). The results are expressed as %. ID= sample name, Kk= Studded tyre tests value, LA= Los Angeles value. (From Sträng et al. (2007))

Studded tyre tests were made for all samples. According to Figure 7. samples 6, 8, 3, 1 and 11 show the highest STT values (poorest resistance to abrasion), >10 %. The lowest and best value (6,7 %) is represented by sample 12. The rest of the samples (2, 4, 5, 7, 9 and 10) have STT values between the highest and the lowest values.

Los Angeles analyses were made on all samples. The highest values (poorest resistance to fragmentation) , >20 %, are represented by samples 11, 6, 1 and 7 while the lowest and best value, 15,9 %, was shown by sample 9, see Figure 8. All other samples have values between these values. The results shown in Figure 7 and 8. are based on the results by Sträng et al. (2007) (Figure 6.).

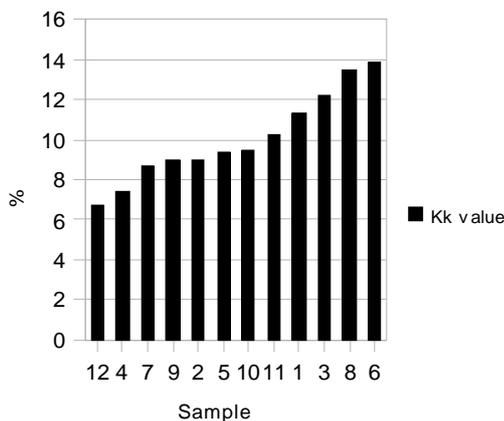


Figure 7.

Studded tyre test values for all samples, where the lowest value represent the most abrasion resistant sample.

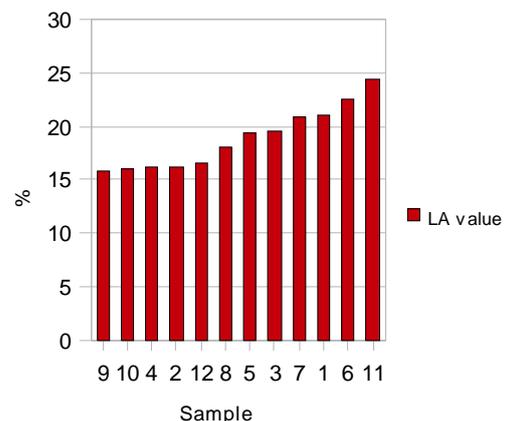


Figure 8.

Los Angeles values for all samples, where low values represent samples with good resistance to fragmentation.

## 3.2 This project

### 3.2.1 Ocular studies

Ocular classification was carried out in hand specimen for all samples regarding textural factors. Figure 9. shows which textures occur in which samples.

Sample	ID	F	Augen	Gneiss	Comp band
1	HLD020910A	Yes	Yes	Yes	Yes
2	HLD020742A	Yes	-	Yes	Yes
3	MAL010035A	Yes (weak)	-	-	-
4	AEN010210A	Yes (weak)	-	-	-
5	AEN010163A	Yes	-	-	-
6	HLD020838B	Yes	-	Yes	Yes
7	HLD020837A	Yes	Yes	Yes	-
8	HLD010328A	Yes	-	Yes	Yes
9	DLA030002A	-	-	-	-
10	MPA040040A	Yes (weak)	-	-	-
11	CMR030099A	-	Yes	-	-
12	MPA040039A	-	Yes	-	-

Figure 9.

The table shows textures studied in hand specimen. ID= sample name, F= visible foliation, Augen= augen texture, Gneiss= gneiss texture, Comp band= compositional banding

### 3.2.2 Thin section studies

Classification of textural properties in all thin sections was carried out and qualitative scales, 1-2, 1-4 or class S or D, were chosen. This approach facilitates the interpretation of textures which occur in thin section.

Grain boundaries (g.b.) between quartz grains were the first texture studied in thin section. A qualitative scale, 1-2, was chosen where type 1 represents sutured g.b. and type 2 straight g.b., see Figure 10. and 11. respectively.

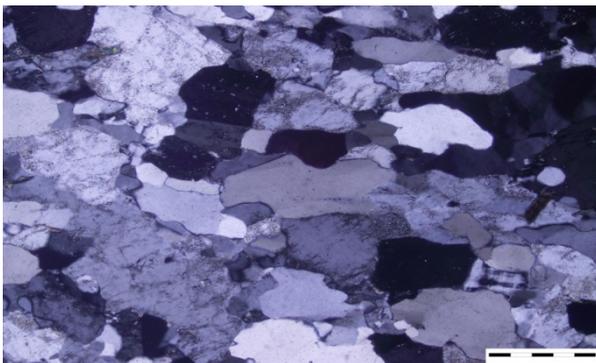


Figure 10.  
Grain boundary (g.b.) type 1 (sutured) from thin section HLD020837A. Scale=0,5mm. Crossed polarizers.



Figure 11.  
Grain boundary (g.b.) type 2 (straight) from thin Section HLD020910A. Scale=0,5mm. Crossed polarizers.

The second texture studied was dimensional preferred orientation (d.p.o.) formed by quartz grains. A qualitative scale, 1-4, was selected where type 1 represents no d.p.o. (Figure 12.) and type 2 shows weak d.p.o. (Figure 13). Type 3 represents a visible d.p.o. which can be seen in 40-50 % of the quartz grains, see Figure 14. When >50 % of the quartz grains show d.p.o. they are classified as type 4, see Figure 15.

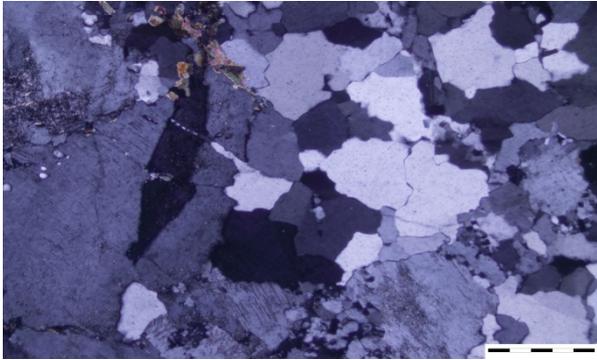


Figure 12.  
Dimensional preferred orientation (d.p.o.) type 1 (none) from thin section AEN010163A.  
Scale=0,5mm. Crossed polarizers.



Figure 13.  
Dimensional preferred orientation (d.p.o.) type 2 (weak) from thin section MAL010035A.  
Scale=0,5mm. Crossed polarizers.

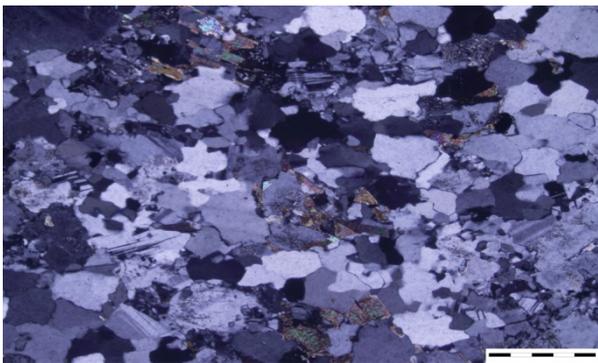


Figure 14.  
Dimensional preferred orientation (d.p.o.) type 3 (semi evident) from thin section AEN010210A.  
Scale=0,5mm. Crossed polarizers.

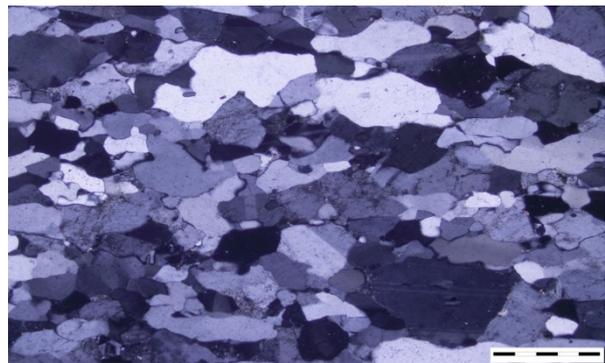


Figure 15.  
Dimensional preferred orientation (d.p.o.) type 4 (evident) from thin section HLD020837A.  
Scale=0,5mm. Crossed polarizers.

The occurrence of biotite and amphibole crystals was the third texture studied and a scale, 1-4, was chosen. These crystals form different degrees of crystallographic preferred orientation (c.p.o.) in rocks. Type 1 represents none while the intensity of c.p.o. increases towards type 4. Type 1 represents the occurrence of biotite/amphibole as clusters, see Figure 16. Type 2 equals randomly distributed biotite/amphibole crystals with different orientations (Figure 17a, b). Randomly distributed crystals of biotite/amphibole, with the same orientations, fulfill the criterion for type 3, see Figure 18a, b. The occurrence of biotite/amphibole crystals as bands represent type 4, Figure 19a, b.

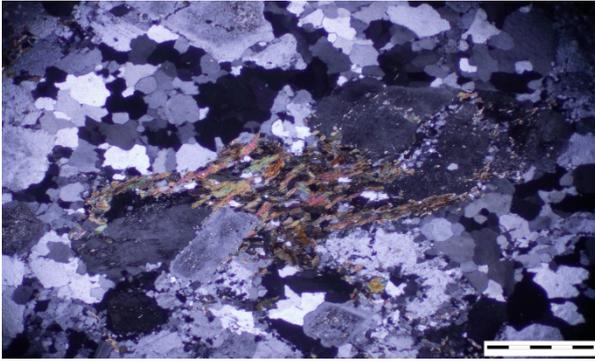


Figure 16.  
Crystallographic preferred orientation (c.p.o.) type 1 (cluster), formed by biotite, from thin section AEN010163A. Scale=1mm. Crossed polarizers.

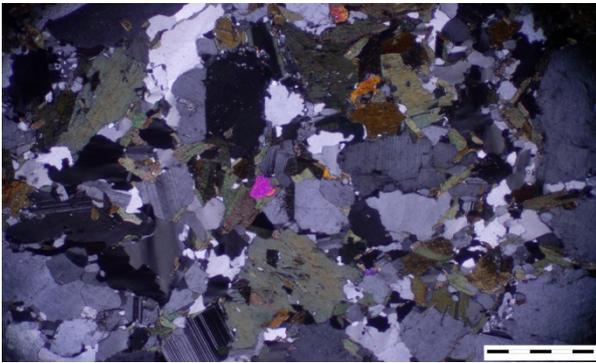


Figure 17a.  
Crystallographic preferred orientation (c.p.o.) type 2 (randomly distributed crystals with different directions), formed by amphibole, from thin section MAL010035A. Scale=1mm. Crossed polarizers.

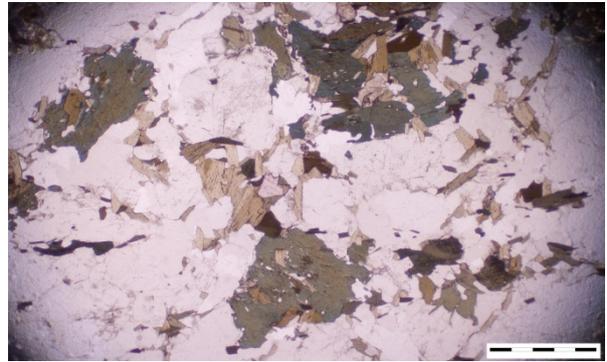


Figure 17b.  
Crystallographic preferred orientation (c.p.o.) type 2 (randomly distributed crystals with different directions), formed by amphibole, from thin section MAL010035A. Scale=1mm. Plane polarized light photo.

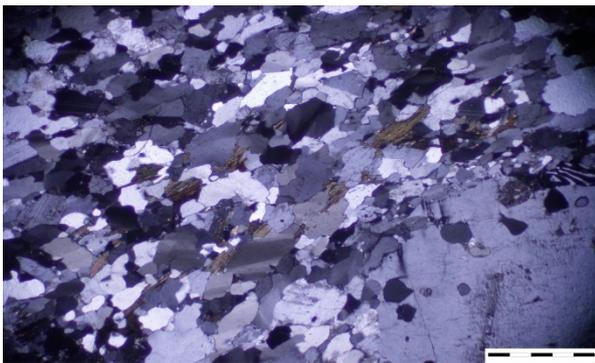


Figure 18a.  
Crystallographic preferred orientation (c.p.o.) type 3 (randomly distributed crystals with the same directions), formed by biotite, from thin section HLD020837A. Scale=1mm. Crossed polarizers.

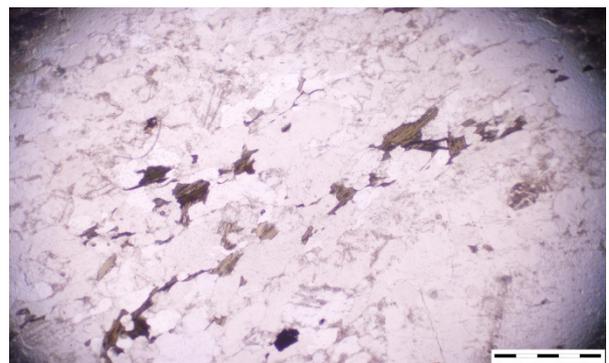


Figure 18b.  
Crystallographic preferred orientation (c.p.o.) type 3 (randomly distributed crystals with the same directions), formed by biotite, from thin section HLD020837A. Scale=1mm. Plane polarized light photo.

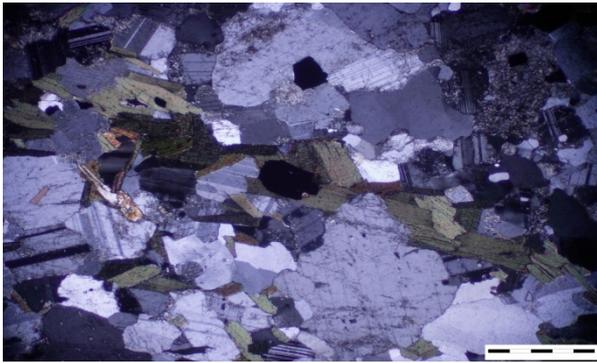


Figure 19a.  
Crystallographic preferred orientation (c.p.o.) type 4 (bands), formed by biotite, from thin section HLD020910A.  
Scale=1mm. Crossed polarizers.

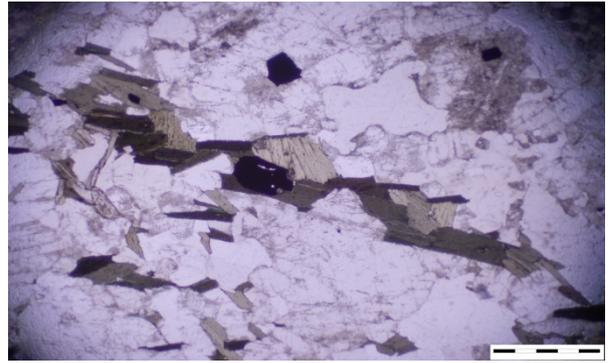


Figure 19b.  
Crystallographic preferred orientation (c.p.o.) type 4 (bands), formed by biotite, from thin section HLD020910A.  
Scale=1mm. Plane polarized light photo.

The relative directions of crystallographic preferred orientation (c.p.o./c.p.o.) formed by biotite and amphibole respectively, is the fourth texture investigated. A classification was made which divides the texture c.p.o./c.p.o. into class S or D. When c.p.o./c.p.o. show the same orientations they represent class S, see Figure 20a, b. If c.p.o./c.p.o. show different orientations they represent class D (Figure 21a, b).

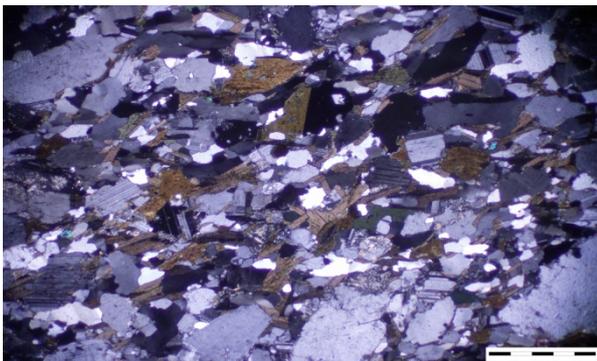


Figure 20a.  
Class S, (same directions) for c.p.o./c.p.o. from thin section HLD020742A.  
Scale=1mm. Crossed polarizers.

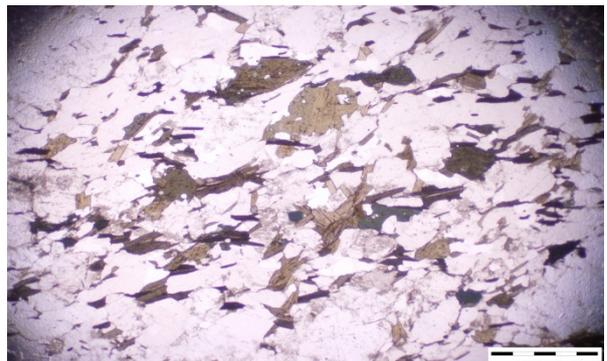


Figure 20b.  
Class S (same directions) for c.p.o./c.p.o. from thin section HLD020742A. Scale=1mm.  
Plane polarized light photo.

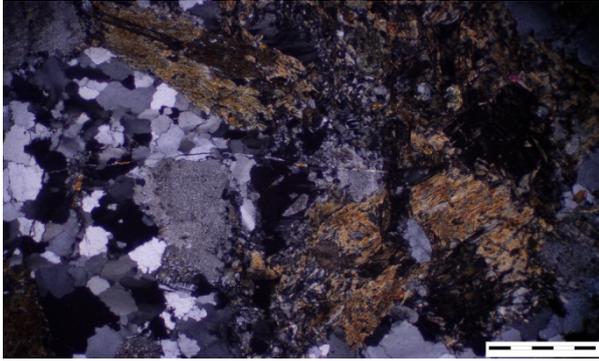


Figure 21a.  
Class D, (different directions) for c.p.o./c.p.o.  
from thin section DLA30002A. Scale=1mm.  
Crossed polarizers.

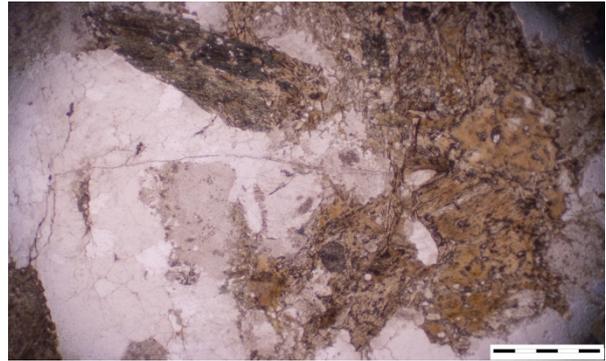


Figure 21b.  
Class D, (different directions) for c.p.o./c.p.o.  
from thin section DLA30002A. Scale=1mm.  
Plane polarized light photo.

The relative directions of dimensional preferred orientation (formed by quartz) and crystallographic preferred orientation (formed by biotite or amphibole) (d.p.o./c.p.o.) is the fifth studied texture in thin section. A classification was made which divides the texture in class S or D (the same classification as for the fourth texture studied). When d.p.o./c.p.o. show the same orientation they fulfill the criteria for class S, see Figure 22a, b. Class D represent different orientations of d.p.o. (quartz) and c.p.o. (biotite/amphibole) (Figure 23a, b).

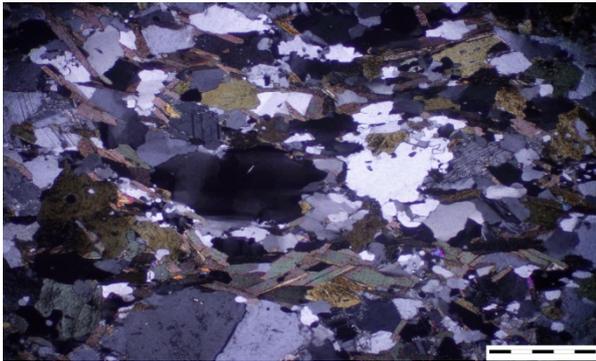


Figure 22a.  
Class S, (same directions) for d.p.o./c.p.o.  
from thin section HLD010328A.  
Scale=1mm. Crossed polarizers.

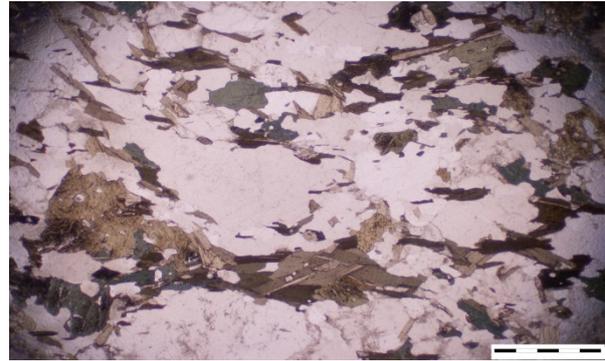


Figure 22b.  
Class S, (same directions) for d.p.o./c.p.o. from  
thin section HLD010328A. Scale=1mm.  
Plane polarized light photo.

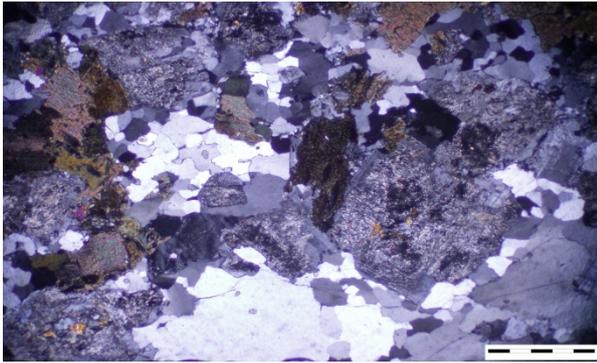


Figure 23a.  
Class D (different directions) for d.p.o./c.p.o.  
from thin section MPA040040A. Scale=1mm.  
Crossed polarizers.

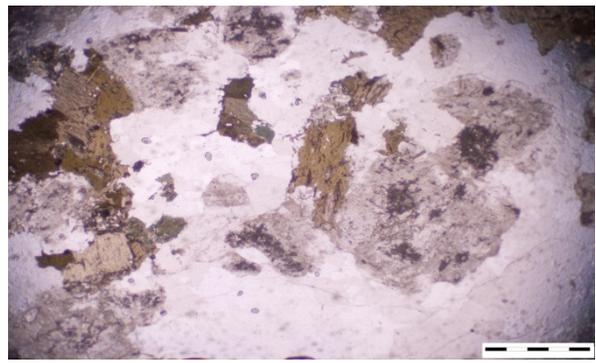


Figure 23b.  
Class D (different directions) for d.p.o./c.p.o.  
from thin section MPA0400400A. Scale=1mm.  
Plane polarized light photo.

The degree of alteration of plagioclase crystals is the sixth and last texture studied in thin section. To determine the degree of alteration a qualitative scale, 1-4, was selected. Type 1 represents unaltered plagioclase crystals, see Figure 24. Crystals with low alteration and good crystal shape equal type 2 (Figure 25). Type 3 represents a medium alteration of plagioclase crystals which results in more diffuse crystal shapes, see Figure 26. Type 4 equals severe alteration of plagioclase crystals (Figure 27).

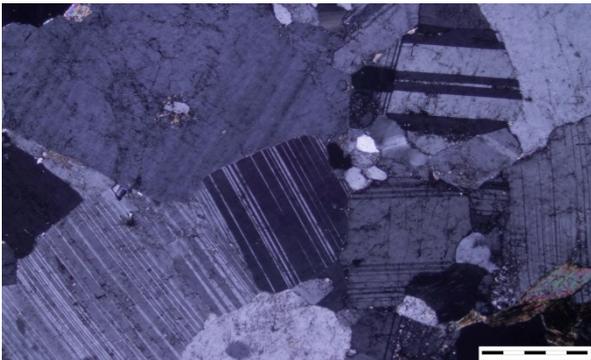


Figure 24.  
Plagioclase crystal type 1 (no alteration) from  
thin section HLD020910A. Scale=0,5mm.  
Crossed polarizers.

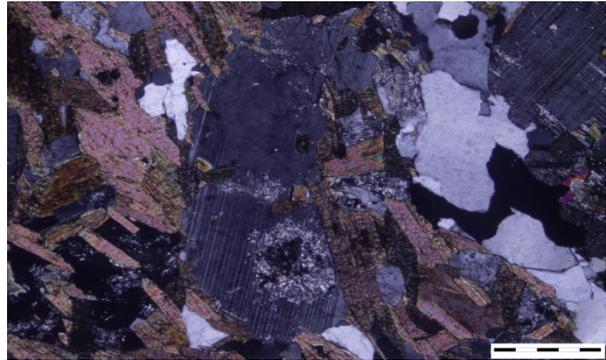


Figure 25.  
Plagioclase crystal type 2 (low alteration)  
from thin section HLD020838B. Scale=0,5mm.  
Crossed polarizers.

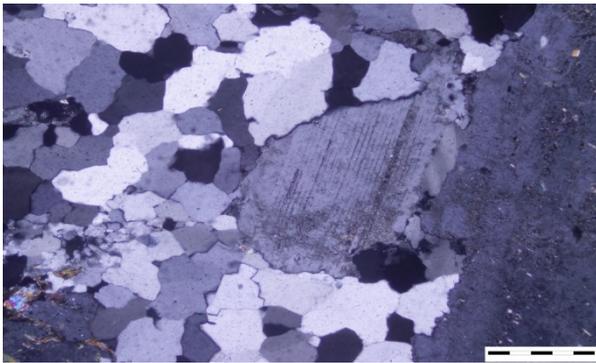


Figure 26.  
Plagioclase crystal type 3 (medium alteration)  
from thin section AEN010163A. Scale=0,5mm.  
Crossed polarizers.

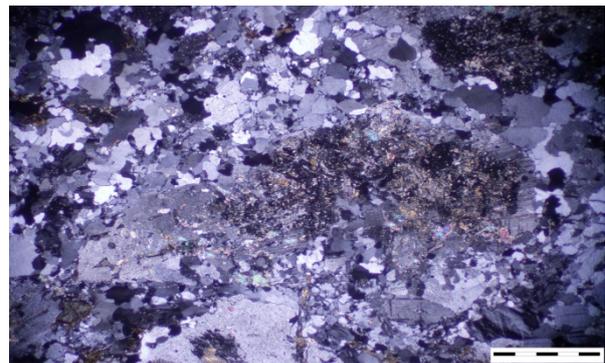


Figure 27.  
Plagioclase crystal type 4 (severe alteration)  
from thin section MPA040039A. Scale=1mm.  
Plane polarizers.

Figure 28 shows the different textures seen in thin section and in which samples they occur.

Sample	ID	g.b.	d.p.o.	c.p.o. Bt	c.p.o. amf	c.p.o./c.p.o.	d.p.o./c.p.o.	altered Pl
1	HLD020910A	- 2	- 2 - -	1 - 3, 4	- - 3 -	S	S	1,2 - -
2	HLD020742A	1 -	- - - 4	- - - 4	- - 3 -	S	S	- 2,3 -
3	MAL010035A	1,2	- 2 - -	- 2 ,3,4	- 2 - -	S	S	1,2 - -
4	AEN010210A	1 -	- - 3 -	- 2 - -	-	-	D	- 2,3,4
5	AEN010163A	1 -	1,2 - -	1 - - -	-	-	D	- - 3,4
6	HLD020838B	1,2	1,2 - -	1 - - 4	- - 3 -	S	S	- 2 - -
7	HLD020837A	1 -	- - - 4	- - 3 -	-	-	S	- 2,3,4
8	HLD010328A	1 -	- - 3 -	- - - 4	- - 3 -	S	S	- 2,3,4
9	DLA030002A	1 -	- - 3 -	1 - - -	- 2 - -	D	D	- - 4
10	MPA040040A	1 -	- 2,3 -	1,2 - -	1,2 - -	S,D	D	- - 4
11	CMR030099A	1 -	- 2,3 -	1,2 - -	-	-	D	- - 3,4
12	MPA040039A	1 -	- 2,3 -	- 2 - 4	-	-	D	- - 3,4

Figure 28.

The table shows results for the textures seen in thin section. ID= sample name, g.b.= grain boundaries between quartz grains, d.p.o.= dimensional preferred orientation formed by quartz, c.p.o. bt= crystallographic preferred orientation formed by biotite, c.p.o. amf= crystallographic preferred orientation formed by amphibole, c.p.o./c.p.o.= relative directions of crystallographic preferred orientation formed by biotite and amphibole, d.p.o./c.p.o.= relative directions of dimensional preferred orientation (formed by quartz) and crystallographic preferred orientation (formed by biotite and/or amphibole), altered Pl= degree of alteration in plagioclase.

### 3.2.3 Point counting

The results of the point counting, i.e. the modal composition of the thin sections, are shown in Figure 29.

Sample	ID	Qz	Pl	Fls	Bt	Pr Chl	Sec Chl
1	HLD020910A	32,6	45,9	10,9	4,0	0,6	4,3
2	HLD020742A	34,5	27,3	17,9	17,9	-	0,5
3	MAL010035A	31,6	37,3	5,8	13,1	-	0,1
4	AEN010210A	49,4	17,8	23,4	4,9	-	-
5	AEN010163A	42,8	50,6	1,1	5,3	-	0,1
6	HLD020838B	27,4	39,1	8,8	14,3	-	0,4
7	HLD020837A	43,1	21,3	32,8	0,9	-	0,5
8	HLD010328A	30,5	33,5	10,9	12,3	-	0,5
9	DLA030002A	32,6	27,9	27,1	4,4	0,1	3,4
10	MPA040040A	31,1	21,4	31,4	8,5	-	0,5
11	CMR030099A	37,0	21,3	38,0	2,9	-	0,5
12	MPA040039A	40,1	16,4	39,3	3,6	-	0,5

Figure 29.

The table shows the results of point counting carried out in this project. The numbers represent the modal % of minerals. ID= sample name, Qz= quartz, Pl= plagioclase, Fls= feldspar, Bt= biotite, Pr Chl= primary chlorite, Sec Chl= secondary chlorite. The full results in this table are found in Appendix.

The relative composition of all 12 samples (based on their main minerals: quartz, plagioclase and feldspar) can be seen in a QAP ternary diagram (Le Maitre 1989), Figure 30. Results of the point counting (for quartz, plagioclase and feldspar) in this project, see Figure 29., are plotted in Figure 30. Sample 5 is the only one with tonalitic composition, while samples 1, 3, 6 and 8 have granodioritic composition, see Figure 30. The rest of the samples (2, 4, 7, 9, 10, 11 and 12) show granitic composition.

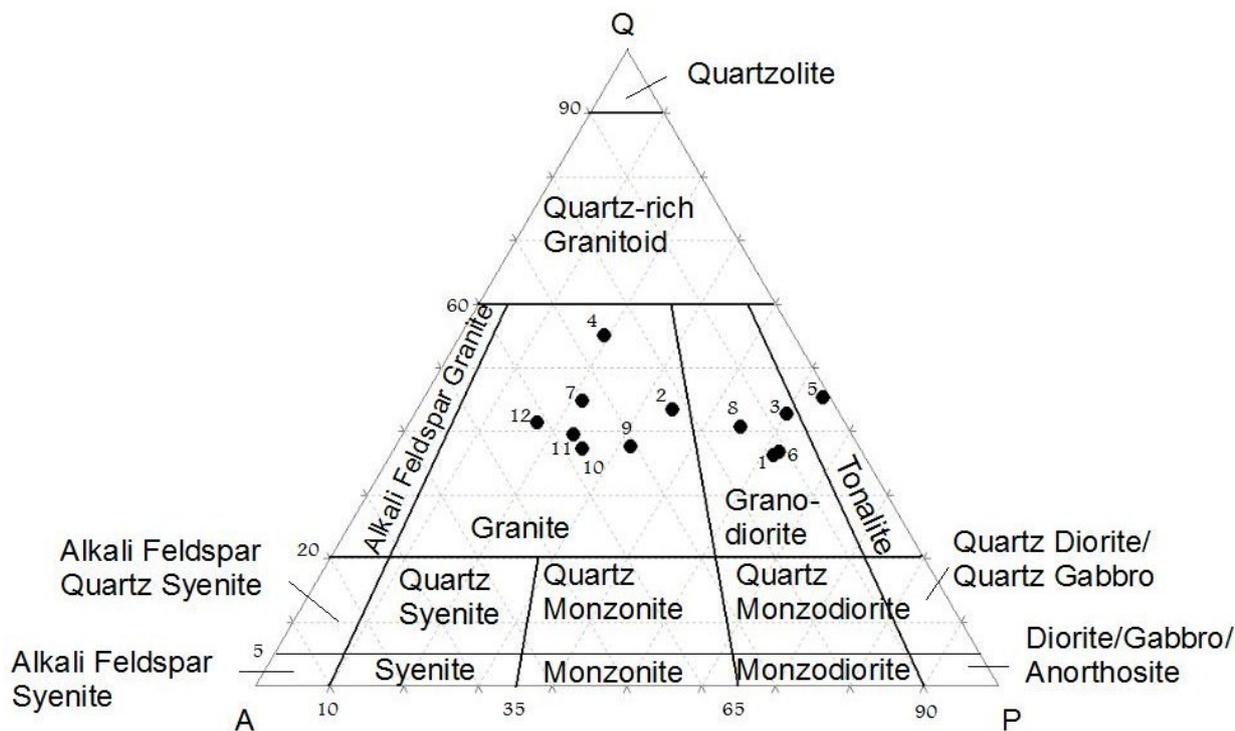


Figure 30.  
The QAP ternary diagram is based on point counting carried out in this project (Figure 29.) (From Le Maitre 1989)

According to Figure 31. samples 2, 6, 3 and 8 contain the highest amount of biotite, >12 %. It can also be seen that sample 7 contains the lowest amount of biotite which corresponds to 0,9 %.

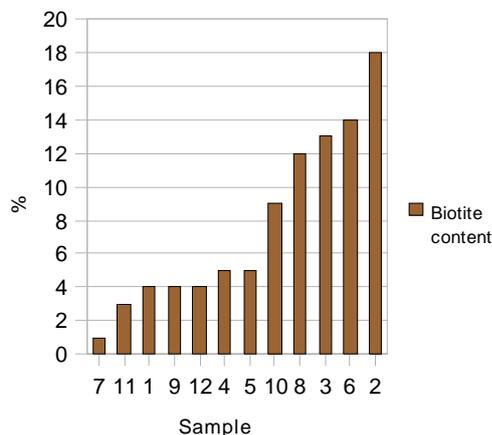


Figure 31.  
Total biotite content in all 12 samples.

Primary chlorite could only be found in samples 1 and 9, see Figure 32. Sample 1 shows the highest value, 0,6 %, while sample 9 displays a value of 0,1 % .

The highest amounts of secondary chlorite, >3 %, were found in samples 1 and 9, see Figure 33. Samples 5 and 3 contain the lowest amount of secondary chlorite (0,1 %) while sample 4 do not

contain any at all. Figure 30., 31., 32. and 33. are based on the results of point counting carried out in this project, see Figure 29.

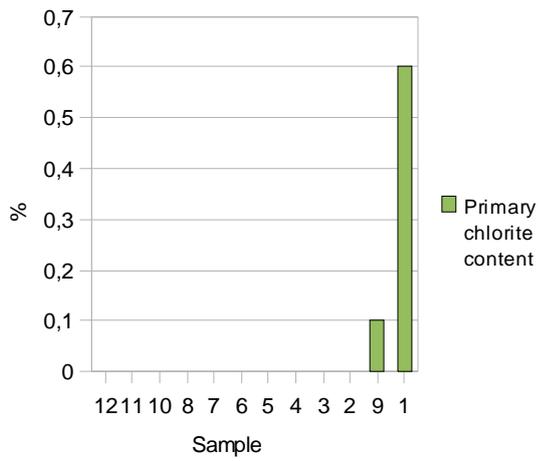


Figure 32.  
Total primary chlorite content in all 12 samples.

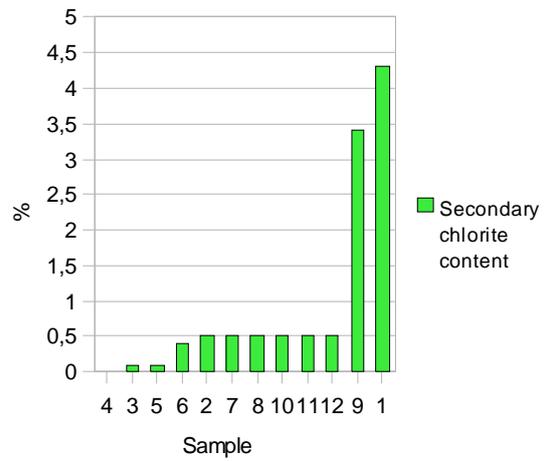


Figure 33.  
Total secondary chlorite content in all 12 samples.

## **4. Discussion**

First a clear correlation between studied textures and mineral assemblages and good or poor technical analysis values, has to be determined. Since the studied textures and mineral assemblages are based on certain hypothesis, when a clear trend exists, correlation between textures and mineral assemblages and good or poor rock strength can be established.

### **4.1 Studded tyre test values vs. studied textures and mineral assemblages**

Comparing the textures and mineral assemblages studied in this project (Figure 9, Figure 28. and Figure 29) with the strength values received from Studded tyre tests (STT) (Figure 7.), it gets evident that some of the textures and mineral assemblages show more influence on the abrasion resistance of rocks than others.

Figure 7. shows that samples 1, 3, 6 and 8 display the poorest STT values while samples 4, 7, 9 and 12 show the best values (lowest). This is visually displayed in Figure 34. where blue circles represents good- and red circles represents the poorest STT values of all samples. Comparing the STT values for these 8 samples with textures and mineral assemblages studied in hand specimen, thin section and point counting in this project, correlation, if present, becomes evident.

#### **4.1.1 Hand specimen**

Gneiss texture and compositional banding correlates with poor STT values and therefore they affect the ability of rocks to resist abrasion in a negative manner. Other textures studied in hand specimen (visible foliation and augen texture) do not show correlation to the STT values of the samples.

#### **4.1.2 Thin section**

Sutured grain boundaries (type 1 g.b.) correlates with good STT values and is the only texture in thin section which improves the resistance to abrasion of the material. Type 3 amphibole (randomly distributed crystals with the same directions) and class S for c.p.o./c.p.o. and d.p.o./c.p.o. (same directions for different types of foliation) shows correlation to poor STT values and thereby weakens the material. Other textures studied in thin section do not correlate with the STT values.

#### **4.1.3 Point counting**

Biotite content correlates with poor STT values. The higher biotite content the lower the abrasion resistance of the material. The rest of the textures studied in thin section (primary and secondary chlorite content) do not correlate with the STT values.

Samples showing the best STT values (4, 7, 9 and 12) have granitic composition while samples 1, 3, 6 and 8 with granodioritic composition displays the poorest STT values, see Figure 34. Correlation between good STT values and granitic composition are showing.

Type 1 g.b. (sutured grain boundaries) is responsible for the good STT values of samples 4, 7, 9 and 12. Gneiss texture and compositional banding explain the poor STT values samples 1, 6 and 8 are showing. Sample 3 have poor STT value due to high biotite content and class S for c.p.o./c.p.o. and d.p.o./c.p.o..

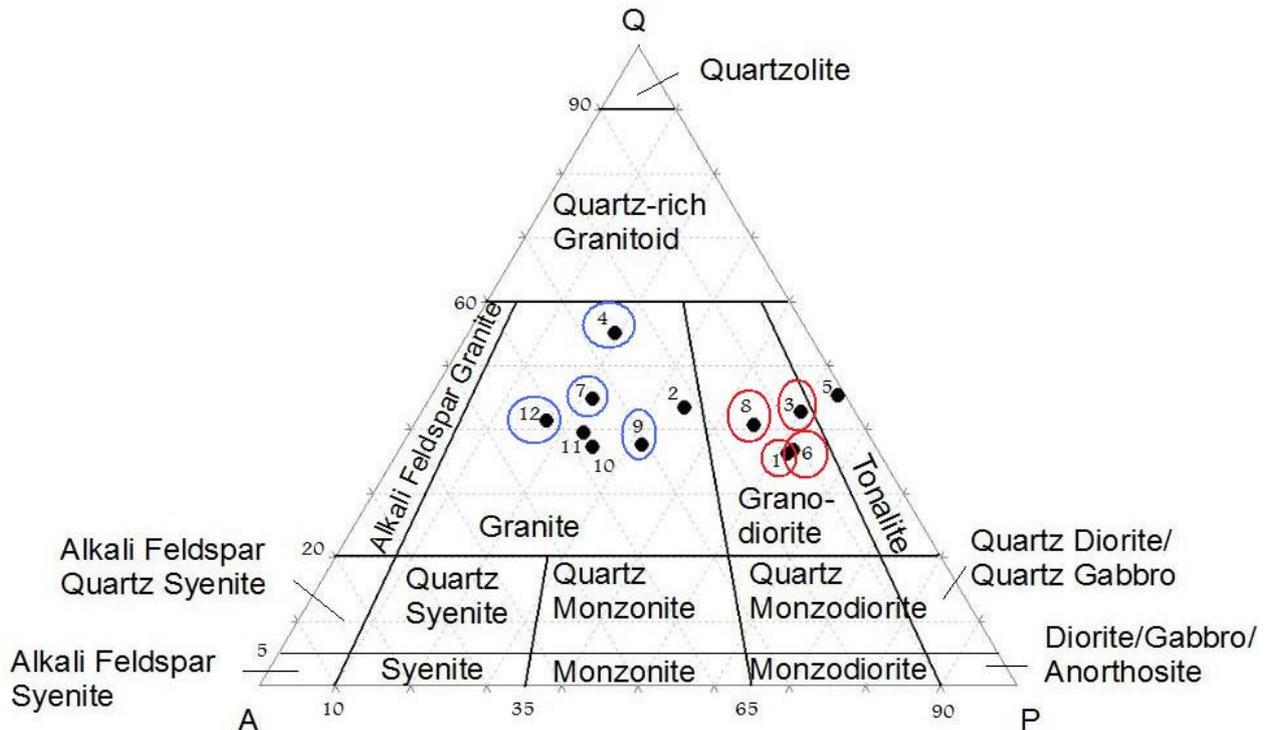


Figure 34.

Samples showing the best STT values are circled with a blue circle. A red circle reveals which samples show the poorest STT values. (From Le Maitre 1989)

## 4.2 Los Angeles values vs. studied textures and mineral assemblages

Comparing studied textures and mineral assemblages in this project (Figure 9., 28. and 29.) with strength values received from the Los Angeles analyses (Figure 8.), it gets evident that some textures and mineral assemblages influences rocks resistance to fragmentation more than others.

Figure 8. shows that samples 1, 6, 7 and 11 display the poorest Los Angeles values while samples 2, 4, 9 and 10 show the best values (lowest). This is visually shown in Figure 35. where blue circles represents good- and red circles represents the poorest Los Angeles values of all samples.

Comparing the Los Angeles values for these 8 samples with textures and mineral assemblages studied in hand specimen, thin section and point counting in this project, correlation, if present, becomes evident.

### 4.2.1 Hand specimen

Augen- and gneiss texture correlates with poor Los Angeles values and thereby they lower the ability of the material to resistance fragmentation. Other textures studied in hand specimen (visible foliation and compositional banding) do not show correlation to the Los Angeles values.

### 4.2.2 Thin section

Type 1 and 2 amphibole (clusters and randomly distributed crystals with different directions) correlates with good Los Angeles values and strengthen the material. The opposite effect comes from type 3 biotite (randomly distributed crystals with the same orientations) and class S for

d.p.o./c.p.o. (same directions of dimensional and crystallographic preferred orientation) which makes the material less resistance to fragmentation. The rest of the textures studied in thin section do not correlate with the Los Angeles values.

### 4.2.3 Point counting

No textures studied through point counting (biotite-, primary and secondary chlorite content) affects the ability of the material to resist fragmentation.

Samples 2, 4, 9 and 10 have granitic composition and are showing the best Los Angeles values, see Figure 35. The poorest Los Angeles values are displayed by samples 1, 6, 7 and 11 which have granitic- or granodioritic composition. No correlation between rock type and the ability of the material to resist fragmentation is showing.

Good Los Angeles values of samples 2, 4, 9 and 10 are explained by the absence of augen- and gneiss texture in the 2 former samples and the presence of type 1 and/or 2 amphibole in the two latter samples. Augen-, gneiss texture, type 3 biotite and class S for d.p.o./c.p.o. are responsible for the poor Los Angeles values samples 1, 6, 7 and 11 are showing. Figure 9. and 28. shows which samples contain which textures.

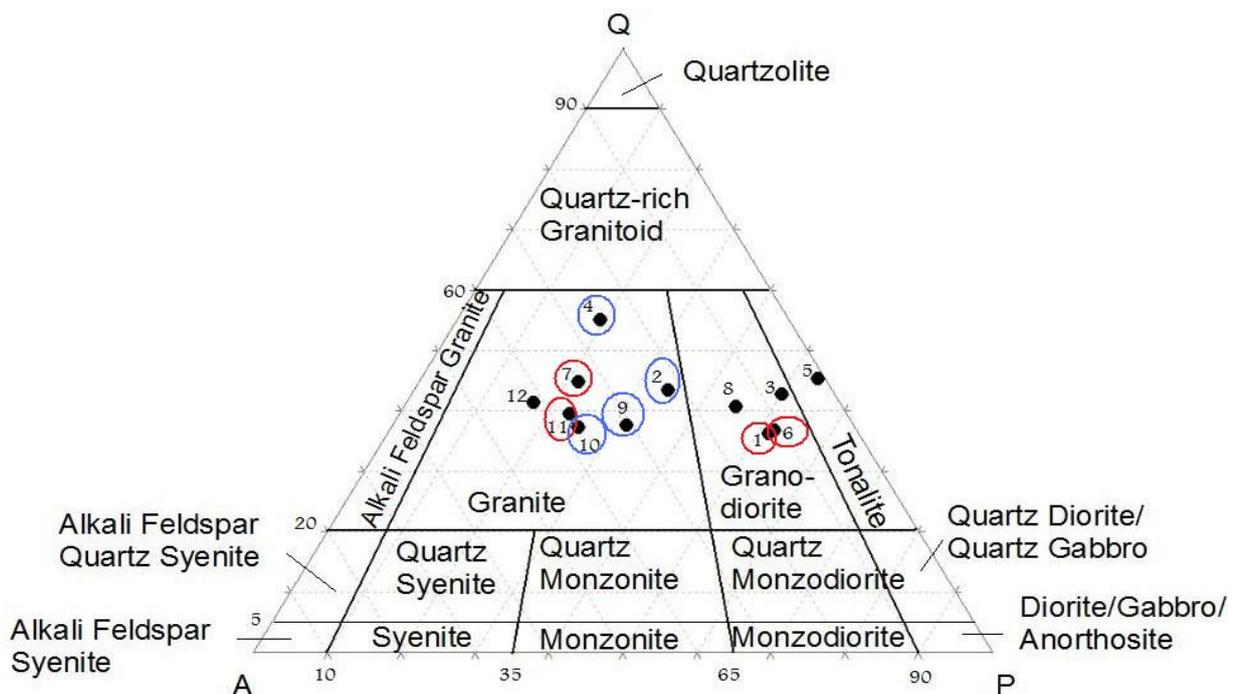


Figure 35.

Samples showing the best Los Angeles values are circled with a blue circle. A red circle reveals which samples show the poorest Los Angeles values. (From Le Maitre 1989)

### **4.3 Comparing point counting results from Sträng et al. and from this project**

Comparing compositions set by Sträng et al. (2007) (Figure 3.) with compositions for all samples set in this project (Figure 30.), is showing that the same sample can have different composition depending on who classified it.

In this project the composition classification of all samples, according to their main components (quartz, plagioclase and feldspar), is more feldspar rich than the results received from Sträng et al. (2007). This difference might be due to different amount of counts/thin section. Another cause might be that a digital point counter, with fixed counting distance, was used in this project while the type of point counting equipment Sträng et al. (2007) used is unknown. Possible misclassification of feldspar in thin section can be a factor which affects the definition of the composition of the samples.

Comparing results from point counting, considering biotite content, from Sträng et al. (2007) (Figure 4.) with results in this project (Figure 31.) it gets clear that the classifications are similar. Both classifications show that samples 2, 3, 6 and 8 have the highest biotite content and sample 7 the lowest. The biotite content of the other samples (1, 4, 5, 9, 10, 11 and 12) are similar between the two parts and ranges from 2,2-10,6% for Sträng et al. (2007) and 2,9-8,5% in this project.

The results from point counting carried out by Sträng et al. (2007) (Figure 5.), considering the chlorite content, cannot be compared with results in this project (Figure 32. and 33) due to absence of information if the chlorite is primary or secondary.

### **4.4 Degree of metamorphose in the sampled area**

According to Delin and Söderman (2005) the degree of metamorphism in granodiorites in the sampled area increases to the north (Delin and Söderman 2005 and references therein). Comparing samples with granodioritic composition (samples 1, 3, 6 and 8) in this project with studied textures, which shows good or poor rock strength values (STT and Los Angeles), the geographical metamorphic scenario set by Delin and Söderman (2005) can be tested.

Textures such as type 1 g.b. (sutured grain boundaries), type 1 and 2 amphibole (clusters and randomly distributed crystals with different directions) correlates with good rock strength i.e. good STT- and Los Angeles values. Due to the absence of a geographical trend considering studied textures in the samples (1, 3, 6 and 8) no correlation between good STT- and good Los Angeles values and the metamorphic degree in granodiorites is showing.

Gneiss texture and class S for d.p.o./c.p.o. (same directions of different foliations) correlates with poor STT- and Los Angeles values. All samples contain both textures except sample 3 which lacks gneiss texture, therefore no correlation between poor STT- and poor Los Angeles values and the metamorphic degree in granodiorites is showing.

The theory of geographical metamorphic scenario set by Delin and Söderman (2005) in the Sala-Heby area have been tested in this project but no approach which have been investigated have supported the theory of Delin and Söderman (2005). An explanation to this might be that the number of samples (only four) investigated to test the theory was too few for any variation to be visible. Textures which have not been dealt with in this project might be another factor which can explain the metamorphic scenario.

## **5. Conclusions**

### **5.1 Textures and mineral assemblages studied in hand specimen and thin section**

Sutured grain boundaries (type 1 g.b.) strengthen the material while textures such as gneiss texture, compositional banding, type 3 amphibole (randomly distributed crystals with same directions), class S for c.p.o./c.p.o. and d.p.o./c.p.o. (same directions of different types of foliation) and high biotite content lower the ability of the material to resist abrasion.

Type 1 and 2 amphibole (clusters and randomly distributed crystals with different directions) strengthen the material while augen-, gneiss texture, type 3 biotite (randomly distributed crystals with same directions), class S for d.p.o./c.p.o. S (same directions for the different type of foliation) weaken the material and makes it more vulnerable to fragmentation.

Samples with granitic composition combined with good STT (studded tyre test) values show best resistance to abrasion. Considering the resistance to fragmentation none of the three rock types (granite, granodiorite and tonalite) show better resistance than the others.

The textures and mineral assemblages studied in this project can explain the good and poor STT and/or Los Angeles values for all samples.

### **5.2 Metamorphic grade in granodiorites**

The theory of geographical metamorphic scenario set by Delin and Söderman (2005) in the Sala-Heby area have been tested in this project but no approach which have been investigated have supported the theory. The number of samples (only four) investigated to test this theory was too few for any variation to be seen and/or other textures which have not been dealt with in this project might be factors which can explain this situation.

### **5.3 Sources of error**

Source of error might be the analyses made in this project, which are based on subjective observations of one person and has not been considered from another angle of perspective. Due to this, misidentification and/or misclassification might be the result in certain cases and will not be discovered.

### **5.4 Applicability**

Results received in this project, considering good and poor properties of textures and different mineral assemblages can be applied and act as helping tools when the most suitable rock material, such as concrete-, railway and/or road material, shall be selected. They can also be used as prospecting tools to determine the quality of the material before technical analyses are made.

### **5.5 Limiting factors**

This project represents 10 weeks of full time work, therefore time has been a limiting factor. All samples from the sampled area have not been considered in this project, this limits the extent of the results received in this project.

## **5.6 Further work**

Further work can be done to make it possible to grade the textures, so one can be able to see which extent each and one of the textures are affecting the rock strength. A favorable approach would be to analyze samples of the same rock type with more pronounced variation of the textures and mineral assemblages with the assistance of multivariate analyses.

## **6. Acknowledgements**

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## 8. Appendix

Sample	ID	Qz	Fls	Pl	Bt	Musk	H	Px	Chl	Ep	Pr	Opaque	Other
1	HLD020910A	30,2	7,4	52,8	6,8	-	0,4	-	0,6	0,2	0,4	0,6	0,6
2	HLD020742A	26,6	5,2	42,2	17,4	-	7,8	-	-	0,6	-	-	0,2
3	MAL010035A	24	2,6	46,8	11,6	-	13,4	-	0,4	0,2	0,4	0,2	0,4
4	AEN010210A	41,2	22,4	25,6	5,4	3,6	-	-	-	0,8	-	1	-
5	AEN010163A	44	0,2	49,8	5,6	0,4	-	-	-	-	-	-	-
6	HLD020838B	39,6	2,6	42	14,2	-	-	-	-	0,6	0,2	0,4	0,4
7	HLD020837A	38	16,4	43,4	1,8	-	-	-	-	-	-	0,4	-
8	HLD010328A	26,4	5,8	44	13,4	-	8,6	-	0,2	1	-	-	0,6
9	DLA030002A	26,8	19,4	40	6	-	2,4	-	-	2	3,2	0,2	-
10	MPA040040A	29	18,2	34	10,6	-	7,2	-	-	0,6	0,4	-	-
11	CMR030099A	44	23,8	29,4	2,2	0,4	-	-	-	0,2	-	-	-
12	MPA040039A	30,8	31,8	33,2	2,4	0,8	-	-	0,4	0,6	-	-	-

The table represent the full extent of Figure 2. and show the results received from pointcounting carried out by Sträng et al. (2007). ID= identification name for each sample, Qz= quartz, Fls= feldspar, Pl= plagioclase, Bt=biotite, Musk=muscovite, H=hornblend (amphibole), Px=pyroxene, Chl=chlorite, Ep=epidote, Pr=phrenite, Opaque=opaque minerals, Others= other minerals than the ones mentioned above. (From Sträng et al. 2007)

Sample	ID	Qz	Pl	Fls	Bt	Musk	Pr Chl	Sec Chl	Amf	Ep/Tit	Opaque
1	HLD020910A	32,6	45,9	10,9	4,0	0,1	0,6	4,3	0,1	0,3	1,2
2	HLD020742A	34,5	27,3	17,9	17,9	-	-	0,5	0,3	0,8	-
3	MAL010035A	31,6	37,3	5,8	13,1	-	-	0,1	10,5	1,5	-
4	AEN010210A	49,4	17,8	23,4	4,9	2,3	-	-	-	0,9	1,5
5	AEN010163A	42,8	50,6	1,1	5,3	-	-	0,1	-	0,1	-
6	HLD020838B	27,4	39,1	8,8	14,3	-	-	0,4	8,6	1,5	-
7	HLD020837A	43,1	21,3	32,8	0,9	-	-	0,5	-	2,6	1,1
8	HLD010328A	30,5	33,5	10,9	12,3	-	-	0,5	9,8	2,6	-
9	DLA030002A	32,6	27,9	27,1	4,4	-	0,1	3,4	2,5	2,0	-
10	MPA040040A	31,1	21,4	31,4	8,5	-	-	0,5	6,4	0,3	-
11	CMR030099A	37,0	21,3	38,0	2,9	-	-	0,5	-	0,4	-
12	MPA040039A	40,1	16,4	39,3	3,6	0,1	-	0,5	-	-	-

The table represent the full extent of Figure 29. and show the results received from pointcounting carried out in this project. ID= identification name for each sample, Qz= quartz, Pl=plagioclase, Fls=feldspar, Bt=biotite, Musk=muscovite, Pr Chl=primary chlorite, Sec Chl= secondary chlorite, Amf=amphibole, Ep/Tit=epidote/titanite, Opaque=opaque minerals.