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Review of the geology and the apatite distribution of the carbonatite in the Lillebukt Alkaline Complex, Stjernøy Northern Norway

NGU
Norges geologiske undersøkelse
Geological Survey of Norway

Geological Survey of Norway
NO-7491 Trondheim, Norway
Tel.: 47 73 90 40 00
Telefax 47 73 92 16 20

REPORT

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Title:
Review of the geology and the apatite distribution of the carbonatite in the Lillebukt Alkaline Complex, Stjernøy Northern Norway

Authors:	Client:
Håvard Gautneb	NGU, with financial support from FeFo
County:	Commune:
Finnmark	Alta
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Summary:

This report gives an overview of the geology, the history of investigations and all previous data (now in digital form) on the distribution of P_2O_5 and apatite in the Lillebukt Alkaline Complex (LAC) and some selected adjacent areas. The LAC is situated on the southern central part of the island Stjernøy in the Altafjord 45 km NW of Alta. The complex comprises an area of about 13 km^2 where the main rocks: hornblende clinopyroxenite, alkali syenite and carbonatite occur in a crudely concentric pattern. In addition, large intrusions of nepheline syenite occur in the southern part of the complex. All these rocks are post-dated by nepheline syenite pegmatites and by several generations of mafic dykes. We have a data set of 280 bulk rock analyses. The bulk of the samples are from the carbonatite and the hornblende clinopyroxenite, the two rocks units in which significant contents of apatite are found. The carbonatites (218 analyses) have an average P_2O_5 content of 2.33%, with a maximum value of 6.45%, but only 23 samples have levels above 6% P_2O_5. The pyroxenites (56 analyses) have an average P_2O_5 content of 2.35 and a maximum value of 13.49%. 4 samples have P_2O_5 above 8%. All our data combined give an average P_2O_5 of 2.38% equal to 5.62 weight % of apatite. In well-exposed and well-sampled areas of about 300x300 meters, the spatial distribution of samples gives an average P_2O_5 of 3.00% in the carbonatite. The contents of heavy metals such as As and Cd are below their detection limits of 10ppm.

We believe that our dataset is sufficiently large and representative that it gives accurate information on the P_2O_5 and apatite contents of the relevant rocks within the Lillebukt Alkaline Complex on Stjernøy.

A CD with the total analytical data is included together with this report

Keywords:	Nepheline syenite	Mineral deposit
Industrial minerals	Carbonatite	Alkaline rocks
Apatite	Pyroxenite	

Norsk sammendrag

Denne rapporten gir en oversikt over geologien og sammenstiller alle tidligere undersøkelser, som gjelder fordelingen av fosfor og apatitt, i Lillebukt alkaline kompleks (LAK) på Stjernøy i digital form. LAK ligger på den sydlige-sentrale del av Stjernøy. Komplekset har en størrelse på 13 km^2 der hovedbergartene er: pyroksenitt, syenitt og karbonatitt som opptrer i en konsentrisk fordeling, i tillegg finnes det nefelinsyenitter i den sørlige delen. Vi har en database med 280 kjemiske bergartsanalyser, der resultatene kan oppsummeres som følger: Karbonatittene har et gjennomsnittlig P_2O_5 innhold på 2.33% med en maksimalverdi på 6.45 %. Pyroksenittene har et gjennomsnittlig P_2O_5 på 2% med en maksimalverdi på 5%. Alle prøvene, samlet, har et gjennomsnittlig P_2O_5 innhold på 2.38%. Dette tilsvarer et apatittinnhold på 5.62%. Innenfor et grundig undersøkte område av karbonatitten på 300x300 meter finner vi et gjennomsnitt på 3% P_2O_5. Innholdet av giftige elementer slik som arsen og kadmium er begge under analytisk påvisningsgrense.

Gehaltene av P_2O_5 og apatitt er lavere enn det som det er gruvedrift på i dag andre steder.

Vår database antas å være representativ når det gjelder sammensetningen av bergartene i Lillebukt alkaline kompleks.

Sámegiel čoahkkáigeassu

Dát raporta addá bajilgova geologiijas ja buohtastahttá buot ovdalaš iskkademiid digitála hámis, mii guoská fosfora ja apatihta juohkáseapmái, i Lillebukt alkaline kompleks'as (LAK'as) Stiertnás. LAK lea lulli-guovddáš oasis Stiertnás. Komplekset lea sturrodat lea 13 km^2 man váldogeađgešlájat leat: pyroksenihtta, syenihtta ja karbonatihtta main lea konsentralaš juohkáseapmi, dasa lassin gávdnojit nefelinsyenihtat mátta oasis. Mis lea diehtobása mas leat 280 kjemiske báktešládjaanaliissat, maid bohtosiid sáhttá čoahkkágeassit dainna lágiin: Karbonatihtaid gaskamearálaš P_2O_5 sisdoallu lea 2.33% man bajemusárvu lea 6.45 %. Pyroksenihtaid gaskamearálaš P_2O_5 lea 2% man bajemusárvu lea 5%. Buot iskkademiin oktiibuot lea gaskamearálaš P_2O_5 sisdoallu 2.38%. Dát vástida apatihttasisdoalu mii lea 5.62%. Siskkobealde vuđolaččat iskkaduvvon 300x300 mehtára karbonatihtas gávdnat mii gaskamearálaččat 3% P_2O_5. Mirkoávdnasiid sisdoallu nugo arsena ja kadmiuma leat goappašagat analyhtalaš gávdnanráji vulobealde .

P_2O_5 ja apatihtta sisdoallu leat unnit go dat mas lea ruvkedoaibma odne.

Min diehtobása jáhkkojuvvo leame ovddasteaddjin go guoská báktešlájaid oktiibidjui Lillebukt alkaline komplex'as.

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ENCLOSURE

Geological map of the Lillebukt Alkaline Complex
CD rom with this report and the analytical data in digital form

1. Introduction

This report is a compilation and review of the results from investigations of the Lillebukt Alkaline Complex (LAC) on Stjernøy Northern Norway. We review data collected by various people from 1951 up to the 1980s, and presents a compilation of our own data from 1992 to 2009. The work has, during these years, been sponsored or directly financed by a number of organizations which include:

The Geological Survey of Norway
Landsdelsutvalget for Nord Norge og Namdalen
Finnmark fylkeskommune
Finnmarkseiendom (FeFo)

Logistical supported has been provided by North Cape Minerals (NCM, Lillebukt Stjernøy)
This report gives a quite detailed review of the geology, but emphasis is put on the occurrence of apatite and variation in the distribution of phosphorus.

A CD with the total analytical data is included together with this report

When converting from weight % P_2O_5 to weight % apatite we use the following relationship throughout this report.

$$\text{Apatite} = P_2O_5 \times 2.3595$$

2. Geographical setting

The LAC is situated on the southern central part of Stjernøy, situated in Altafjord, about 45 km NW of Alta. The island of Stjernøy has a very rough topography with steep mountain sides down to the sea with steep peaks up to about 1000 m. a.s.l. In addition the the internal part of the island is dissected by several deep valleys that are difficult to traverse to the sea. However, apart from the steep ascent from the sea, most of the LAC is fairly easily accessible. (Figure 1).The LAC has a surface dimension of about 6 x 2 km^2 (Figure 2 and 3) and can be followed from Lillebukt in the south to the central part of Finndalen in the north. The easiest access is either by helicopter, or by making arrangements with NCM for transport to the top of Nabbaren, from which there is an easy walk downhill to the central part of the complex. It can also be accessed by walking northwards from Lillebukt through a narrow valley; 1.5-2 hours walk from sea level to the central part of the complex.

Figure 1 Panorama over the central part of the Lillebukt Alkaline Complex, to the right is the lake Saravann, the central of the picture, just to the left of the lake is the high-grade apatite area of the carbonatite, see Figure 11 and 12.

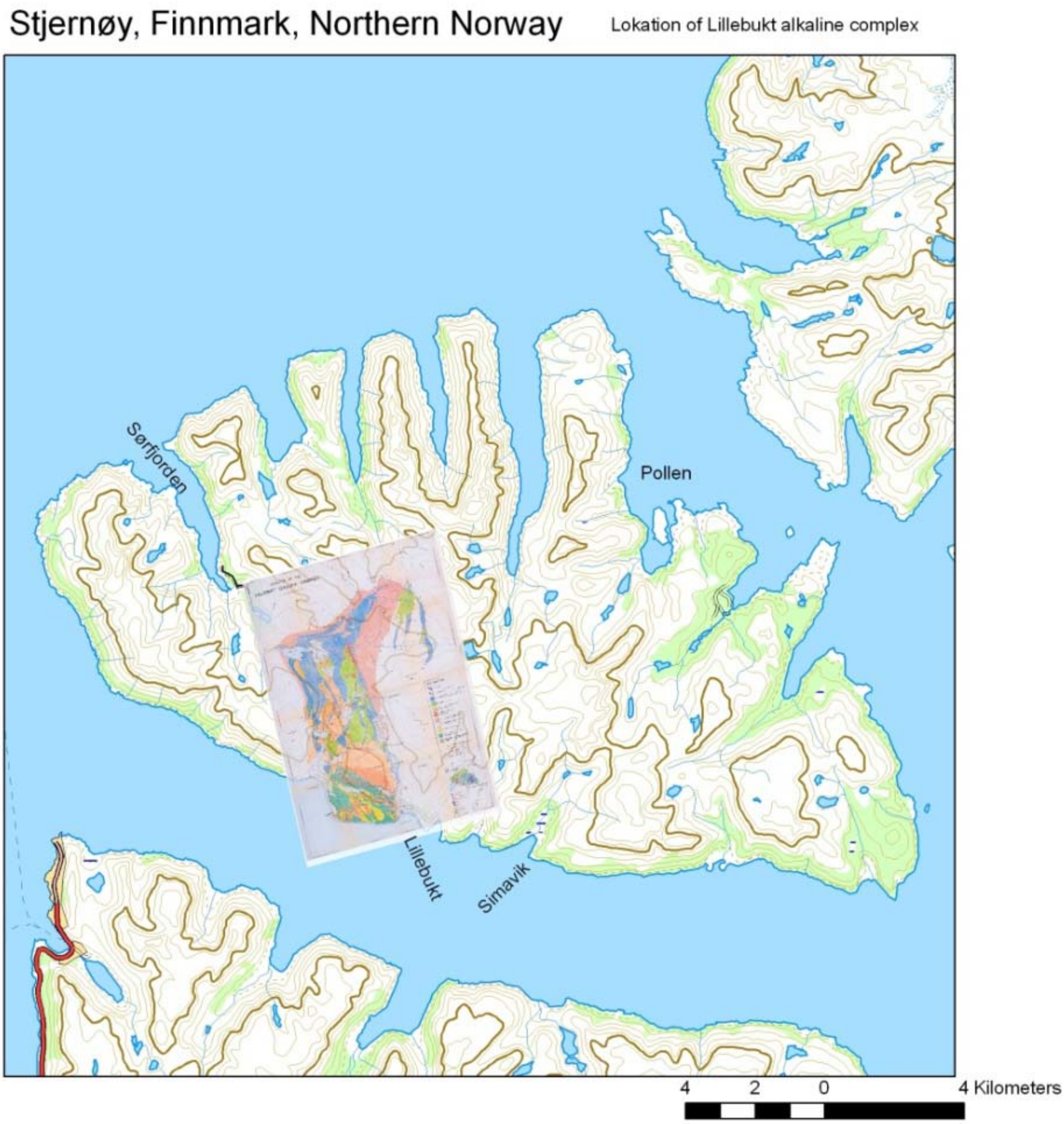


Figure 2 Map of Stjernøy, with the location of the Lillebukt alkaline Complex and location other areas discussed in the text (se also map enclosure)

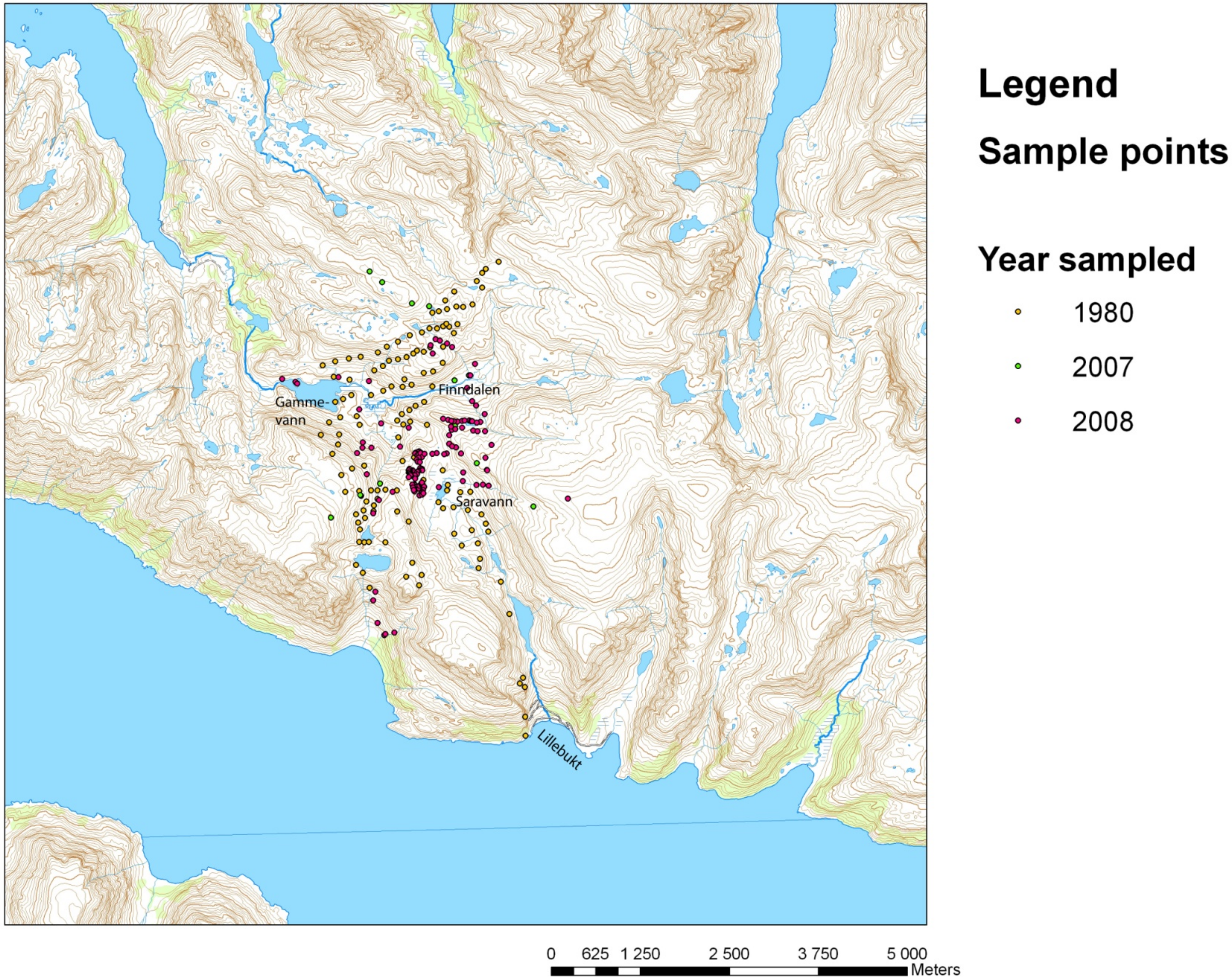


Figure 3 Map showing the sampling points

2.1 North Cape Minerals nepheline syenite production

Several companies and now North Cape Minerals have, since the beginning of the 1960s had a mine in active production (Fig 4). The focus of the operation is a nepheline syenite body comprising the central part of the mountain Nabbaren. The nepheline syenite is currently being produced from an open pit at the top of Nabbaren. The nepheline syenite is upgraded through several steps of magnetic separation, in which mafic minerals are removed. The final product is a K-feldspar- and nepheline-enriched product used as raw material in the glass and ceramic industries.

Figure 4 North Cape Minerals nepheline syenite factory, with Mount Nabberen in the background

3. History of investigations and compilation of older data

This report comprises and compiles data from many different sources from 1951 up to the present.

The earliest descriptions of the rocks from the LAC were published by Strand (1951). Strand visited the area and sampled outcropping carbonatite in the Finndalen valley, east and north of Gammevann (Figure 5).

He published modal content and the first chemical analysis of the carbonatite Table 1 and 2.

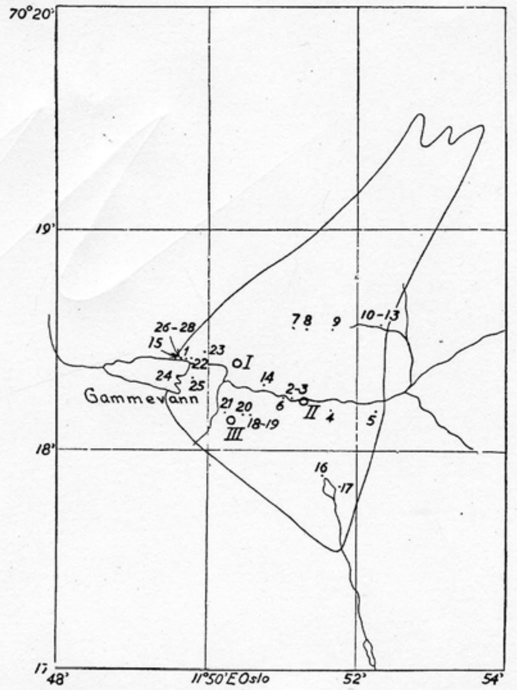
Table 1 Modal composition carbonatite rocks (data from Strand 1951)

Sample	3	4	15	13	28	5	9	19
Calcite	75.3	62.8	56.2	56	34.4	52.2	45.5	44
Biotite	20.5	24.3	29.7	32.7		14.4	42	36.4
Hornblende						24	2	
Albite		0.8		3.4	2.4		6.5	9.4
Nepheline			2.5		4			
Apatite	3.8	10.8	7.4	4.2	4	6.7	2.4	6.1
Opaque	0.4	1.3	4.2	3.7	3.2	2.7	1.6	4.1

Sample	**22**	**26**	**12**	**23**	**10**	**25**	**Average**
Calcite	43.6	42.5	41.6	40	31.9	23.5	**46.4**
Biotite	41.9	54.8	50.1	50.2	53.8	39.9	**37.7**
Hornblende							**13.0**
Albite		0.5			6		**4.1**
Nepheline	8.1					35	**12.4**
Apatite	1.4	1.8	7.1	2.8	2.5	1.1	**4.4**
Opaque	5	0.4	1.2	7	5.8	0.5	**2.9**

Table 2 Average chemical composition of 7 samples from the carbonate (data from Strand 1951)

Average of 7 samples	
SiO_2	18.93
TiO_2	2.76
Al_2O_3	8.81
Fe_2O_3	3.37
FeO	13.67
MnO	0.32
MgO	4.05
CaO	22.47
BaO	0.6
Na_2O	0.44
K_2O	4.54
P_2O_5	1.91
CO_2	16.27
S	0.25
F	0.12
H_2O-	0.23
H_2O+	1.24



Kartskisse over søvittfeltet i Fjellfinndalen.
I—III. Lokaliteter for store prøver uttatt etter anvisning av statsgeolog Poulsen, 1—28. lokaliteter for forfatterens håndstykker.

Sketch-map of the sövite area in Fjellfinndalen.
I—III and 1—28, localitites of samples.

Figure 5 Map showing the sample localities for samples listed in Table 1 from Strand (1951).

Table 2 shows that Strand found an average apatite content of 4.5 wt % in the carbonatite.

Heier (1961) made a general overview of the different rock types in the Lillebukt area, He presented the first geological map and chemical analyses of different rock types with special emphasis on the nepheline syenite. He also presented the first mineral analysis of apatite (Table 3).

Table 3 Composition of apatite from the carbonatite (data from Heier 1961)

Element	Wt%
Cl	0,06
H_2O	0,00
CO_2	0,60
Refractive index No	1,642

This corresponds to an apatite end member shown in Table 4.

Table 4 Apatite end members calculated from Table 3 (data from Heier 1961), see also Table 3.

	Apatite end members
Cl-apatite	1%
CO_2- apatite	10%
Oxyapatite	71%
F-apatite	18%

Elkem-Spigerverket carried out exploration for apatite on Stjernøy in late 1976, including stream-sediment geochemistry and bedrock sampling. Apart from a brief unpublished report (Berthold 1976) no other information is publically available today. During this work the apatite-rich pyroxenite on the eastern margin of the LAC was found. Berthold (1976) reports the following apatite content in the pyroxenite (Table 5).

Table 5 Apatite contents of the pyroxenite on the eastern margin of Lillebukt alkaline complex (based on XRF P_2O_5 analyses Berthold 1976)

Sample	Wt% apatite
14001	4
14002	6
14003	14
14004	20
14005	17
14006	8
14009	11
14010	8
14011	24
14012	27
14013	11
14013	6
14015	8
14016	9
14033	8
average	12

In the early 1980s, professor Brian Robins of the University of Bergen supervised a series of students who investigated the LAC and the Pollen carbonatite (Bruland 1980, Skogen 1980, Kjøsnes 1981, Strand 1981 Robins & Tysseland 1983). The geological map (Enclosure no. 1) and our knowledge of the geology of the LAC are largely based on the results of these workers. We have digitalized all relevant analytical data including 133 bulk rock analyses of the carbonatite from Strand (1981). He also presented a mineral analysis of apatite. (Table 6)

Table 6 Mineral analysis of apatite, compiled from Strand 1981, location of sample unknown.

	Average apatite
CaO	55.09
FeO	0.18
MgO	0.08
MnO	0.05
Na_2O	0.39
SrO	0.67
Ce_2O3	0.31
SiO_2	0.05
P_2O5	41.22
SO_3	0.03
F	1.66
Sum	99.73
Sr	4391
Ba	1146
Y	219
La	546
Ce	1011
Pr	254
Nd	1187
Sm	216
Gd	113
Dy	64
Ho	21
Er	57
Yb	3.5

In 1985 Renate Cadow, started a Ph.D. study on the apatite mineralization in the pyroxenites of the LAC. The study was unfortunately never completed and no results or data are available.

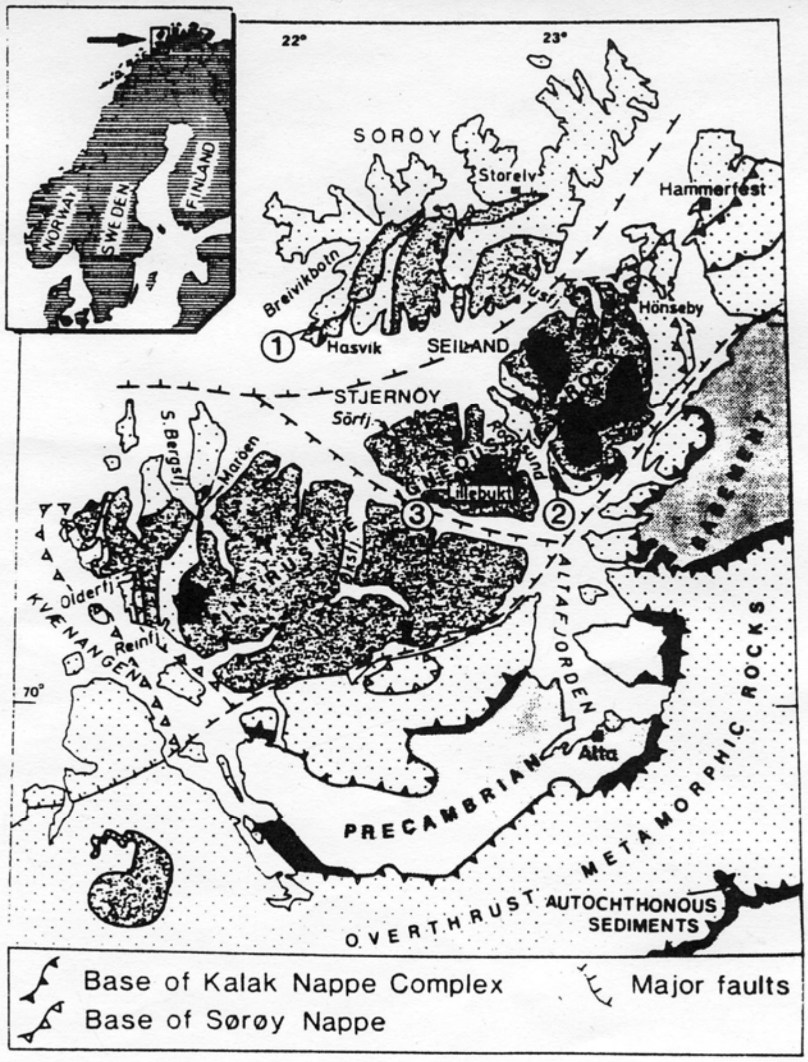
In the early 1990s the carbonatite of the LAC got renewed interest as fertilizer in organic farming (Gautneb & Bakken 1995, Bakken et al. 1997 a and b). Dust and tailings from the nepheline syenite production and crushed carbonatite were tested as fertilizer both in greenhouses and in outdoor growth experiments. The results can be summarized as follows: In short term greenhouse experiments the carbonatite gave a crop yield of about 40% of that of KCl fertilizer and a comparable crop yield when compared to KCl in a 3-year outdoor growth experiment.

With the large increase in the price of rock phosphate and DAP (Di-ammonium-phosphate) that occurred internationally from 2006 until the middle of 2008, scientists from NGU and UMB (Norwegian University of Life Science) started to investigate the economical potential of the LAC again. With financial support from the Government Property Administration of Finnmark (FeFo) field work and sampling was done in 2007 and 2008 and these results are included in this report.

4. Geological setting and field description

The LAC is part of the Seiland Igneous Province and Robins (1996) gives the most up to date and comprehensive geological review.

The Seiland Igneous Province (Figure 6) is part of the Sørøy Nappe of the Kalak Nappe Complex (KNC) which constitutes the Middle Allochthon of the Caledonides of Northern Norway. The KNC were thrust from the WNW into its present position above early Paleoproterozoic basement rocks or late Precambrian to Cambrian sediments during scandian orogeny (Roberts & Gee 1985).



Simplified geological map showing the main features of the Seiland Province. Numbers refer to 1. Hasvik Gabbronorite; 2. Rognsund Intrusion; 3. Lillebukt Alkaline Complex. Ultramafic complexes are in black.

Figure 6 Geological map of the Seiland Igneous Province (Robins 1996)

The magmatic evolution of the Seiland Igneous Province was prolonged and included intrusion of numerous gabbroic plutons, calc-alkaline intrusions, ultramafic complexes nepheline syenite and syenite alkaline rocks, carbonatites and swarms of mafic dykes.

Syenite rocks, carbonatites and mafic dykes are clearly the youngest igneous rocks in the province. They are believed to be related to nephelinitc magmatism. Field relationships at the LAC and elsewhere demonstrate that nepheline syenite pegmatites represent the latest phase of magmatic activity. The alkaline magmatism has been dated by U-Pb on zircons to 531+/-2 and 523+/-2 Ma (Pedersen et al. 1989)

The alkaline rocks of Seiland Igneous province all have a miaskitic (as defined by Sørensen 1974) chemistry (Robins 1996), i.e. they have molecular proportions of (the agpaitic index AI):

$$AI = \frac{Na_2O + K_2O}{Al_2O_3} < 1$$

This is an important chemical feature and results in the rocks being corundum normative, contrary to rocks with AI > 1 which are acmite normative. Miaskitic alkaline rocks are generally low in REE (Sørensen 1974).

4.1 The Lillebukt Alkaline Complex (LAC)

The LAC occupies a N-S elongated area of about 13 km^2 (Heier 1961, Robins 1996). The main rock types includes hornblende clinopyroxenites, syenites and carbonatites occur in a crudely concentric pattern (see map enclosure). Carbonatites form the core of the complex and are surrounded by, and intrudes hornblende clinopyroxenite in the northern part and nepheline syenites and minor alkali syenites in the southern part of the complex. The intrusive sequence of the rocks is: Perthositic syenite (oldest), hornblende clinopyroxenite, syenite and nepheline syenite and carbonatites. The latter are postdated by syenite and nepheline syenite pegmatite dykes. All these rocks are pre- and post-dated by mafic dykes. The host rocks that makes up large part of Stjernøy are metagabbros. Locally intense metasomatic alteration during intrusion led to the formation of fenites.

4.1.1 The Carbonatites

The mineralogy and petrochemistry of the carbonatites were investigated by Strand (1981). The carbonatites of the complex has, in general, the composition of silico-carbonatitite with about 40% of strontian calcite. Biotite is the main mafic minerals but in areas hornblende may be dominant and has led to the mappable distinction between biotite carbonatite and hornblende carbonatite (see map enclosure). Nepheline, feldspar and apatite are common constituents but have an irregular distribution. The former two are most common near the contacts of nepheline syenites and xenoliths of nepheline syenite pegmatites (Figure 7 and 8). Fe-Ti oxides are common locally. The carbonatite was investigated with respect to Th, U and REE by Heier (1962) and Gautneb (2008) but no enhanced content of REE minerals or radioactive elements have been detected

The mineralogical and chemical variations of the carbonatite result from many processes, including metasomatic reaction with the country rock, fractional crystallization, accumulation of liquidus minerals and lastly, mechanical redistribution and recrystallization during syn- and postmagmatic deformation and metamorphism (Strand 1981).

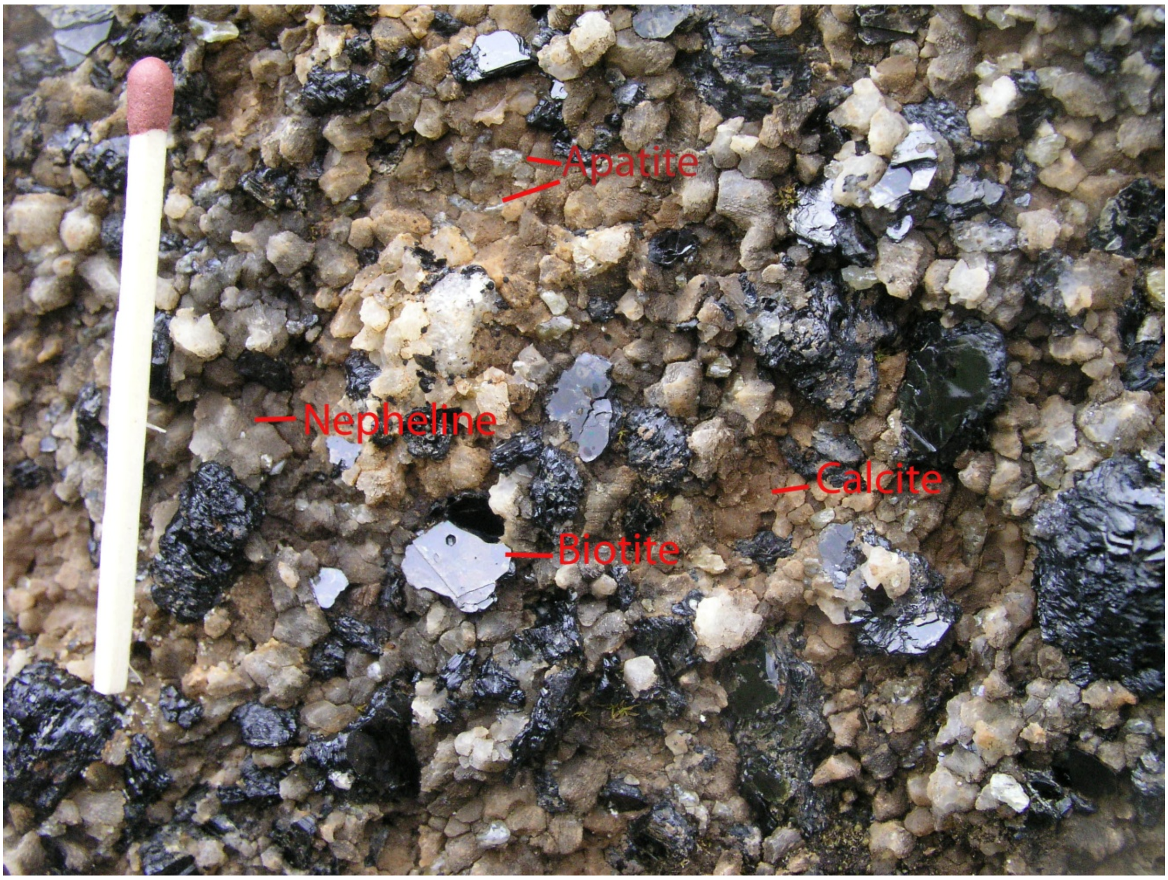


Figure 7 Close-up picture of carbonatite, with the main minerals indicated


Figure 8 Banded carbonatite, with inclusions of deformed dykes.

4.1.2 Apatite-rich hornblende clinopyroxenites

On the northern and eastern margin of the complex there is an area of hornblende clinopyroxenites (in this report pyroxenite or alkali pyroxenite, for simplicity, when appropriate). According to Kjøsnes (1980) and Robins (1996) they form a 50-600 meter wide and 11 km long belt of subparallell and steeply dipping coarse-grained to pegmatitic dykes. Individual dykes are, in general, 50-100 cm wide and are separated by screens of gabbroic host rocks that are fenetized. Fenetized gabbro makes up about 40% of the rock volume in this zone (Robins 1996). Dykes up to 10 m wide have been observed. They lack chilled margin and commonly show an inward directed comb-structure growth of clinopyroxene and hornblende up to 50 cm large, as well as up to 10 cm large skeletal apatite crystals (Robins 1996).

These rocks can be unusually rich in apatite, as already observed by Berthold (1976) Apatite contents up 32 wt% have been detected. However, due to the large variation of the apatite mineralization and the variable amount of fenetized gabbroic screens between the apatite-rich dykes the aerial extent and volume of economic apatite mineralization is very difficult to estimate. Kjøsnes (1981) showed that the pyroxenites of the LAC have a mineralogy identical to jacupirangites (nepheline-bearing clinopyroxenites). The term alkali pyroxenites was used in his descriptions and he presents the following average composition (Table 7).

Table 7 Average composition hornblende (alkali) pyroxenite according to Kjøsnes (1981)

SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	H_2O
36.02	11.7	2.84	8.88	8.72	8.58	16.77	1.05	1.18	0.26	2.64	0.66

Kjøsnes concluded, based on the comparison between the composition of nephelinites, their crystallization sequence, texture and mechanism of emplacement, that the alkali pyroxenites originated from fractional crystallization of an olivine-nephelinitc magma that was depleted in alkalies and enriched in P_2O_5 and H_2O. Crystallization of pyroxenes, amphiboles, Fe-Ti oxides and apatite took place on the walls of dykes; thus the alkali pyroxenites can be regarded as cumulates.

4.1.3 Fenitization (CO_2- and alkali-metasomatism)

The fenitization and metasomatic reactions between the mafic rocks and carbonatites was studied in detail by Kjøsnes (1981) and according to him; depending on the rock types, pyroxenites, nepheline-syenites or carbonatites and their mutual contact with each other or country rock, each case led to the formation of fenites of individual character. Again depending on rock type the dominating process was eighter CO_2- or alkali-metasomatism or both. Thus Kjøsnes (1981) found that fenitization in the LAC was not restricted only to carbonatites, involved also other rock types such as pyroxenites and nepheline syenites. This is supported by work elsewhere (Le Bas 1977, Robins & Tysseland 1983) If we exclude the fenites formed in xenoliths we have the following occurrences of fenites in the LAC:

a) Dark mafic veins throughout the nepheline syenite gneiss
b) Area north and south of Saravann in which hornblende clinopyroxenites are intensively intruded by carbonatite
c) Screens separating hornblende clinopyroxenite dykes throughout the area mapped as alkaline pyroxenite (see map enclosure)
d) Fenites associated with nepheline syenite, in the southern part of the complex.

Only the fenites in association b and c occur in areas that have been the target for our investigation of the apatite potential.

Fenites associated with pyroxenites are distinguished from unaffected pyroxenites by being granular, medium- to coarse-grained banded dark rocks, whereas the unaffected pyroxenites are coarse-grained to pegmatitic and highly variable in modal composition. The pyroxenites are, in addition, much more weathered and the fenites stand out in the landscape. The fenites show little remnants of the original texture. At well exposed localities, the changes in the rock due to fenitization are clearly visible (Figure 9) but most often overburden make the distinction between fenite and country rock less obvious (Kjøsnes 1981).

4.1.4 Mineralogical and chemical changes during fenitization

According to Kjøsnes (1981) the most characteristic feature during fenitization of gabbro, is the disappearance of plagioclase. Typical modal compositions in surrounding gabbro are 50% plagioclase, 25 % clinopyroxene and 15 % amphibole. During fenitization this is converted to a rock comprising 90% pyroxenes + amphiboles and about 10% of Fe-Ti oxides (Kjøsnes 1982)
Fenitiaztion of the layered mafic rocks surrounding the LAC result in the following changes in chemistry:

Si: a distinct but highly variable reduction,
Al: distinct reduction and decrease in variability, thus a homogenization occurs
Ti: a marked increase and lowered variability
Mg: this is the element which displays the most significant increase, due to its presence both in pyroxenes and amphiboles
Ca: Increases
Na: decreases, due to breakdown of plagioclase
K: shows a small increase
P: increases during fenitization. this has been attributed to high activity of P_2O_5 in the fenitizing fluids

In areas where the carbonatites are in well exposed contacts with its country rocks (north and south of Saravann and where minor carbonatite intrusions occur elsewhere). The following changes in chemistry are observed (Kjøsnes 1981):
Si, Al and Na show a marked decrease, Ti Fe, Ca and P show higher concentrations than the unaffected layered mafic rocks. The changes in major elements reflect the differences in mineralogy between carbonatites and silicate rocks. Mineralogically, fenitization associated with carbonatite intrusion is associated with a pervasive decomposition of plagioclase, with removal of Si, Al and Na, and formation of clinopyroxene and amphibole (Kjøsnes 1981).

Figure 9 Carbonatite veins(light colour) intruding into gabbro resulting in formation of fenite (dark color) with a clear contact to gabbro (grey colour).

4.2 Deformation

The deformation of the LAC is strong and hetrogenously distributed. The nepheline syenite shows a strong foliation. The fenites and gabbros show a strong tectonic fabric associated with intense folding folding. The carbonatite is strongly deformed and locally folded, as indicated by bands of variable biotite contents, numerous tectonic inclusions and deformation of cross-cutting dykes. The carbonatite has undergone at least two phases of folding (Robins 1996). The hornblende clinopyroxenites are the least deformed rocks. Skogen (1980) interpreted the LAC as initially representing an alkaline ring complex (See Fitton & Upton 1987 for review). Our data does not permit any detailed discussion of the deformation and tectonic development of the LAC.

5. Analytical results

5.1 Analytical data and methods

Analytical data are compiled from the the following sources:

1) Digitalized sampling map of Strand (1981) with 133 XRF analyses.
2) Data collected from several periods of investigation including:
    a) 1990 -1993 (Gautneb & Bakken 1995)
    b) 2007-2008, which were financially supported by FeFo. The samples were collected as hand specimens, dust drilling with portable a Pioneer drill and by blasting out up to 1 ton of rock and homogenization of this material

All together 280 bulk rock analyses from the LAC and adjacent areas have been conducted.

Since our database represents a compilation of data collected over a large time span and analyzed at different labsoratories there is a difference in the number of trace elements analyzed for the different batches.

Strand (1981) analyzed his samples using standard XRF techniques at the University of Bergen. The 2007 and 2008 data was analyzed by XRF and the facilities of NGU. For the samples collected by NGU we used duplicates and international standards for quality checking. Such control is not available for the Strand (1981) data.

133 sample points from Strand (1981) was transferred manually from his sample map to a digital map, which calculated UTM coordinates This transfer may result in an error of up to maximum 200-300 meters both in the X and Y directions.

A CD with the total analytical data is included together with this report.

The distribution of the samples and the locations of the subareas are shown on Figure 3.

In detail one sees that in some areas there is a very irregular distribution of sampling points, due to overburden and steep, inaccessible areas.

5.2 Lillebukt alkaline complex, chemical variations with emphasis on the distribution of phosphorus

This chapter will discuss the chemical variation of the rocks and their average composition. Since sampling has not been done with the goal of discussing the petrogenetic evolution of the rocks discussions are focused on the variation in phosphorus contents. In accordance with the main lithologies in the LAC and adjacent areas the rocks are divided into the following main groups.

1) Nepheline syenite
2) Pyroxenite
3) Carbonatite with biotite and/or hornblende
4) Fenites
5) Gabbros

Due to the nature of the mode of formation of the rocks and the metasomatic processes a large, overlapping chemical variation between the rocks types can be expected.

The chemical variations in the rocks are summarized in Table 8, 9 and 10 with the apatite-rich carbonatite and pyroxenites in Table 8. Histograms and the main statistical data are shown in Figure 14.

Unless other wise stated the content of apatite and calcite are always calculated from the analysed values of P_2O_5 and CO_2 with these conversion factors:

Apatite = P_2O_5 x 2.3595
Calcite = CO_2 x 2.2748

The chemistry of the rocks can be summarized as follows:

The carbonatites show the CO_2 content varying from 2.5 to 37.81 with an average of 17.63 %, equal to a calculated calcite content from 5.12 to 86,01 with an average of 40.10%. The content of P_2O_5 varies from 0.45 to 6.45 with an average of 2.33, which is equal to calculated apatite contents from 1.06 % to 15,22%, with an average of 5.50%. The carbonatites are enriched in the alkali earth elements (Ba, Sr) and the light rare earth elements (LREE ,La Ce Nd). Undesired toxic elements such as As and Cd are all below their detection limits (<10ppm)

The pyroxenites can be quite calcitic with a maximum measured CO_2 content equal to 8.29 %, which equals 18,85 % calcite, but the average calcite is only 1.27 %. The P_2O_5 content varies from 0.21% to 5% with an average of 5%.

Nepheline syenites (mainly late crosscutting dykes) were sampled when they occurred along our traverses. They all have a low contents of CO_2 and P_2O_5, the latter with values from 0.016 to 0.823 with an average of .013% P_2O_5. This is equal to a variation in apatite content from 0.047% to 0.87% with an average of 0.31%.

The fenites show a very large spread in values variation as expected from their mode of formation as metasomatically altered rocks. The apatite content varies from 1.4% to 3.56%, with an average of 2.48%. Similar, to the carbonatites the fenites show an extreme enrichment in alkali earth elements and LREE, with >1% of Ba and 0.07% of Ce and almost 0.6% of Sr.

The gabbros have compositions that are more undersaturated in SiO_2 that what what was anticipated. This due to the fact that rocks which in the field have classified as gabbros, may be transitional to what, petrographically, should be classified as pyroxenites or dunites. Some samples may also been influenced by metasomatism from fenitizating fluids. This is evident from the CO_2 variations in the gabbros which corresponds to calcite contents that varies from 0 to 6.23%. The apatite content vary from 0.07 to 5.64 with an average of 1.72% apatite.

Figure 14 shows histograms for the P_2O_5 distributions in the sample collection, with individual plots for the carbonatites and the pyroxenites. The samples with the highest grade represent single rock samples.

Table 8 Chemical variation of the carbonatites and hornblende clinopyroxenites

	Carbonatites	n= 216			Pyroxenites	n= 79		
Sample	$\bar{X}$	max	min	median	$\bar{X}$	max	min	median
SiO_2	19.36	45.30	1.59	18.82	36.17	44.57	27.40	36.51
Al_2O_3	7.65	23.06	1.75	7.40	10.91	14.80	6.45	11.37
Fe_2O_3	9.70	25.90	0.94	7.46	15.31	32.00	8.17	13.45
TiO_2	2.61	8.79	0.55	2.69	2.87	5.29	1.80	2.64
MgO	3.75	8.68	0.79	3.63	9.00	13.90	3.56	9.18
CaO	25.05	48.00	5.28	24.19	17.78	28.26	1.10	17.60
Na_2O	1.12	13.52	0.00	0.65	1.50	3.36	0.82	1.42
K2O	2.74	5.87	0.45	2.87	1.42	5.91	0.08	1.30
MnO	0.33	0.50	0.12	0.34	0.20	0.39	0.11	0.17
P_2O_5	2.33	6.45	0.45	1.97	3.24	5.00	0.21	3.00
LOI	16.43	34.30	2.18	17.10	0.98	7.66	-0.01	0.80
SUM	86.79	99.63	67.76	82.97	98.96	100.31	97.05	98.86
S	0.07	0.35	-0.02	0.06	0.11	0.85	-0.02	0.03
CO_2	17.63	37.81	2.25	17.71	0.56	8.29	-0.26	0.33
Ag	-9	31	-10	-10	-8	20	-10	-10
As	-3	3	-10	1	-9	11	-10	-10
Ba	4510	15600	793	3785	864	4860	167	657
Cd	-10	-10	-10	-10	-10	-10	-10	-10
Ce	521	1040	66	524	180	435	38	162
Co	31	55	6	28	52	105	30	51
Cr	1	68	-4	-4	35	266	-4	12
Cu	11	34	-2	8	68	306	-2	49
Ga	12	19	2	12	16	25	9	15
La	315	640	79	306	74	227	19	66
Mo	2	5	-1	2	2	4	-1	2
Nb	74	257	0	67	60	362	12	46
Nd	242	440	37	245	82	196	-10	81
Ni	1	82	-20	-2	17	142	-20	3
Pb	-3	17	-3	-3	3	35	-3	-3
Rb	142	300	3	155	37	185	3	15
Sb	-15	-15	-15	-15	-15	-15	-15	-15
Sc	4	25	-5	6	28	61	-5	26
Sn	-10	14	-10	-10	-10	-10	-10	-10
Sr	4582	8590	1510	4424	604	1860	224	550
Th	11	24	-4	12	7	21	-4	8
U	13	26	3	13	0	12	-2	-2
V	89	223	11	84	424	831	126	364
W	-4	6	-5	-5	-5	-5	-5	-5
Y	71	143	20	70	29	76	8	27
Zn	152	246	35	150	81	222	38	77
Zr	94	388	15	46	249	600	17	225

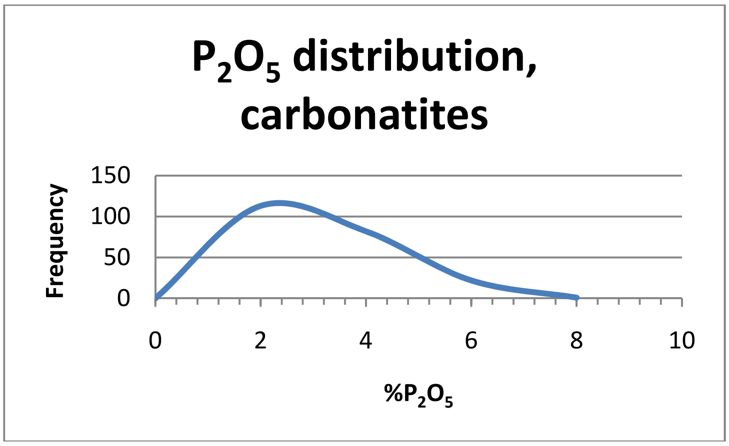
- Negative values are below detection limits,

Table 9 Chemical variation of nepheline syenites and fenites

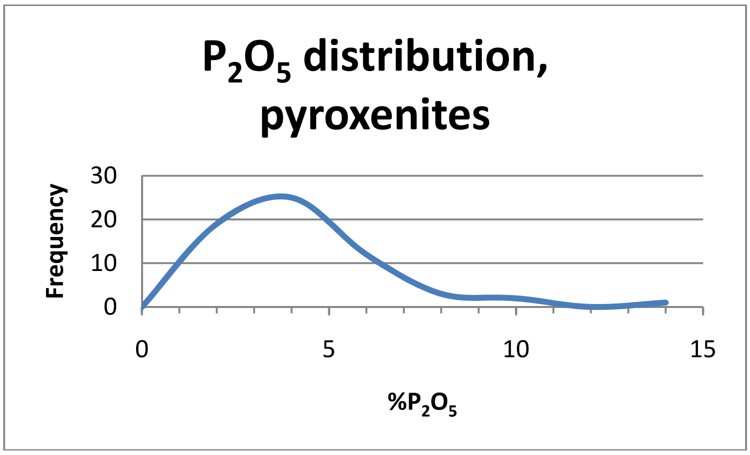
	Nepheline syenites	n= 5			Fenites	n= 5		
Sample	X̄	max	min	median	X̄	max	min	median
SiO_2	57.22	61.40	54.00	58.10	21.48	28.50	14.70	22.40
Al_2O_3	20.76	23.40	18.40	20.80	9.21	14.90	3.88	8.55
Fe_2O_3	4.53	6.01	3.50	4.52	15.32	18.00	8.32	17.00
TiO_2	0.76	1.00	0.63	0.73	2.92	3.87	1.12	3.11
MgO	0.65	0.94	0.21	0.70	2.73	3.37	2.06	2.79
CaO	0.93	1.81	0.50	0.88	20.78	37.42	9.17	19.20
Na_2O	9.45	11.10	8.19	9.29	2.17	4.90	0.67	1.53
K_2O	3.45	4.71	1.98	3.56	2.68	4.08	0.54	3.52
MnO	0.07	0.09	0.05	0.06	0.29	0.33	0.26	0.29
P_2O_5	0.13	0.37	0.02	0.09	1.05	1.51	0.59	1.06
LOI	1.06	2.01	0.27	0.82	19.45	34.00	9.55	13.90
SUM	99.01	99.93	97.88	98.96	92.65	98.34	71.83	97.76
S	-0.01	0.02	-0.02	-0.02	0.11	0.18	0.03	0.12
CO_2	0.96	1.70	0.51	0.92	16.23	27.25	9.75	13.96
Ag	-10	-10	-10	-10	-10	-10	-10	-10
As	-10	-10	-10	-10	-10	-10	-10	-10
Ba	3362	6190	1770	2010	6261	10600	856	8010
Cd	-10	-10	-10	-10	-10	-10	-10	-10
Ce	14	62	-20	24	545	719	426	518
Co	8	11	5	8	36	43	29	37
Cr	-1	5	-4	-4	4	10	-4	6
Cu	2	7	-2	4	21	34	12	20
Ga	17	24	13	17	12	14	10	13
La	10	34	-10	14	301	429	231	273
Mo	0	2	-1	-1	3	4	2	2
Nb	39	68	14	43	113	153	73	119
Nd	-4	19	-10	-10	181	233	134	179
Ni	-2	-2	-2	-2	-4	6	-20	-2
Pb	-3	-3	-3	-3	-3	-3	-3	-3
Rb	69	74	60	72	142	218	38	156
Sb	-15	-15	-15	-15	-15	-15	-15	-15
Sc	-5	-5	-5	-5	5	9	-5	6
Sn	-10	-10	-10	-10	-10	-10	-10	-10
Sr	2470	3910	1130	1990	5066	5930	4130	5110
Th	0	6	-4	-4	9	12	7	9
U	7	11	4	6	12	15	10	12
V	25	33	15	26	112	183	44	111
W	-2	8	-5	-5	-2	6	-5	-5
Y	5	12	1	4	77	124	54	67
Zn	46	60	30	48	179	268	138	155
Zr	32	48	13	36	98	193	41	95

Table 10 Chemical variation of the gabbros

	Gabbros		n = 17	
Sample	$\bar{X}$	max	min	median
SiO_2	38.87	46.30	32.20	40.11
Al_2O_3	11.34	14.70	7.33	11.45
Fe_2O_3	13.35	25.30	5.59	11.62
TiO_2	2.93	4.81	1.70	2.87
MgO	11.42	19.80	5.06	11.35
CaO	15.37	19.90	12.00	15.40
Na_2O	1.36	2.53	0.69	1.31
K_2O	2.10	3.84	0.38	2.02
MnO	0.17	0.37	0.08	0.14
P_2O_5	1.33	3.97	0.05	0.24
LOI	0.85	2.39	0.10	0.69
SUM	99.01	99.65	98.26	99.03
S	0.02	0.16	-0.02	0.00
CO_2	0.65	2.74	0.00	0.41
Ag	-10	-10	-10	-10
As	-10	-10	-10	-10
Ba	1482	4010	378	1095
Cd	-10	-10	-10	-10
Ce	135	453	22	80
Co	53	72	39	52
Cr	107	659	-4	17
Cu	89	371	3	57
Ga	12	19	7	13
La	53	197	-10	31
Mo	2	3	1	2
Nb	48	151	20	38
Nd	57	190	-10	40
Ni	101	354	-2	61
Pb	6	39	-3	-3
Rb	62	157	8	23
Sb	-15	-15	-15	-15
Sc	44	75	16	49
Sn	-10	-10	-10	-10
Sr	484	1940	140	379
Th	2	21	-4	-4
U	-1	5	-2	-2
V	321	609	86	307
W	-4	6	-5	-5
Y	24	57	8	20
Zn	63	191	25	42
Zr	182	411	67	150



$\%P_2O_5$	*Frequency*
0	0
2	113
4	82
6	22
8	1
Average	2.33
Max	6.45
Min	0.45
Median	1.97
Stdev.	1.15



$\%P_2O_5$	*Frequency*
0	0
2	19
4	25
6	12
8	3
10	2
12	0
14	0
Average	2.00
Max	5.00
Min	0.21
Median	3.00
Stdev	3.00

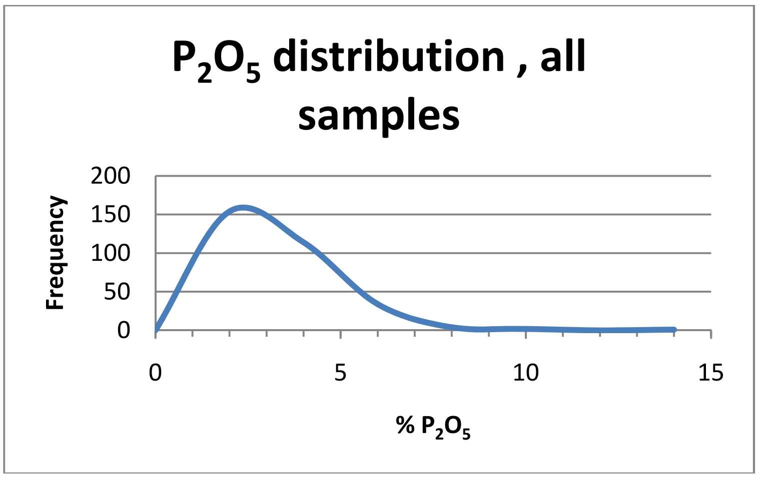


Figure 10 Histograms and statistical data for the P_2O_5 distribution Stjernøy rocks

$\%P_2O_5$	*Frequency*
0	0
2	154
4	114
6	34
8	4
10	2
12	0
14	1
Average	2.38
Max	6.34
Min	0.02
Median	2.01
Stdev	1.60

5.2.1 Spatial chemical variation

Figure15 shows the spatial distribution of P_2O_5 derived by applying geosoft Target for ArcGis In the carbonatite there is a high-grade area that stretches from south of lake Saravann and northwards for about 3 km. NE of lake Saravann there are several high-grade areas, mainly in pyroxenites on the eastern rim of the Lillebukt complex. Areas with nepheline syenite and fenite are generally of low grade. The area to the north side of the contoured map, gives the impression that the sampling stopped too early. This is an artifact of kriging[1]
This area is outside the LAC, and the descriptions given above show that they contain low levels of P_2O_5

The spatial distribution can be illustrated in more detail by selecting one area, carbonatite, where detailed sampling has been conducted in an area that are fairly easy accessible.

This area is shown on Fig 12. It lies about 200 north west of Saravann. This is a well-exposed area suitable and consisting only of carbonatite (it is also shown on the picture in Figure 1). The variation in P_2O_5 is large, from almost 0.092 to 6.46% P_2O_5,with an average of 3.00 %. This value corresponds to apatite contents that vary from 0.22 to 15.24%. the average is 7.07%.

[1] Kriging is a statistical method that can be used for widely and uneven scattered sampling points on an irregular surface. It uses linear regression techniques, where the properties of an unsampled location is estimated from the values from its neighbouring locations. See Davis 2002 for a general description of this method.

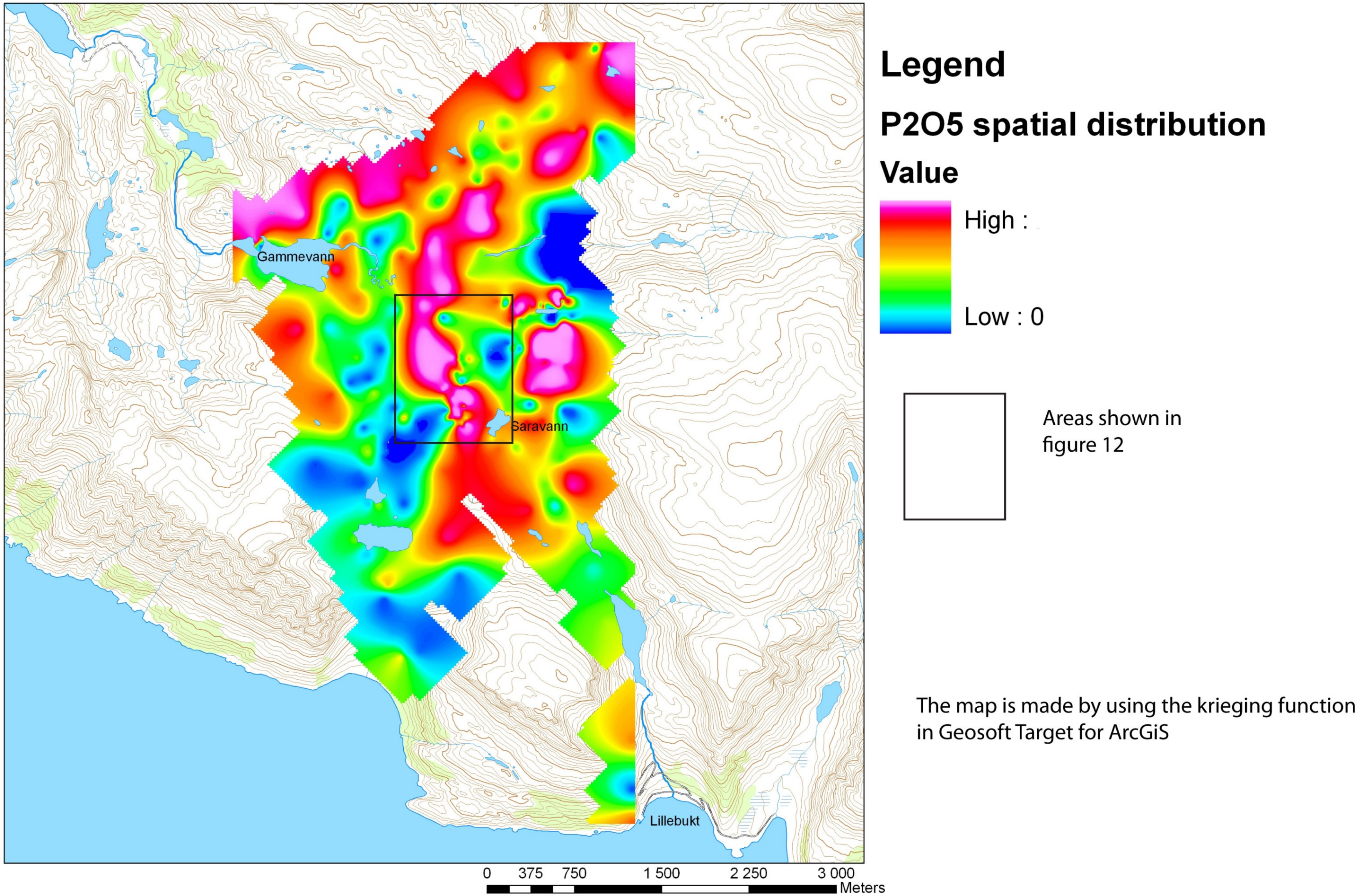


Figure 11 Spatial distribution of P_2O_5: the area along the northern edge of map is outside the LAC (see text for discussion)

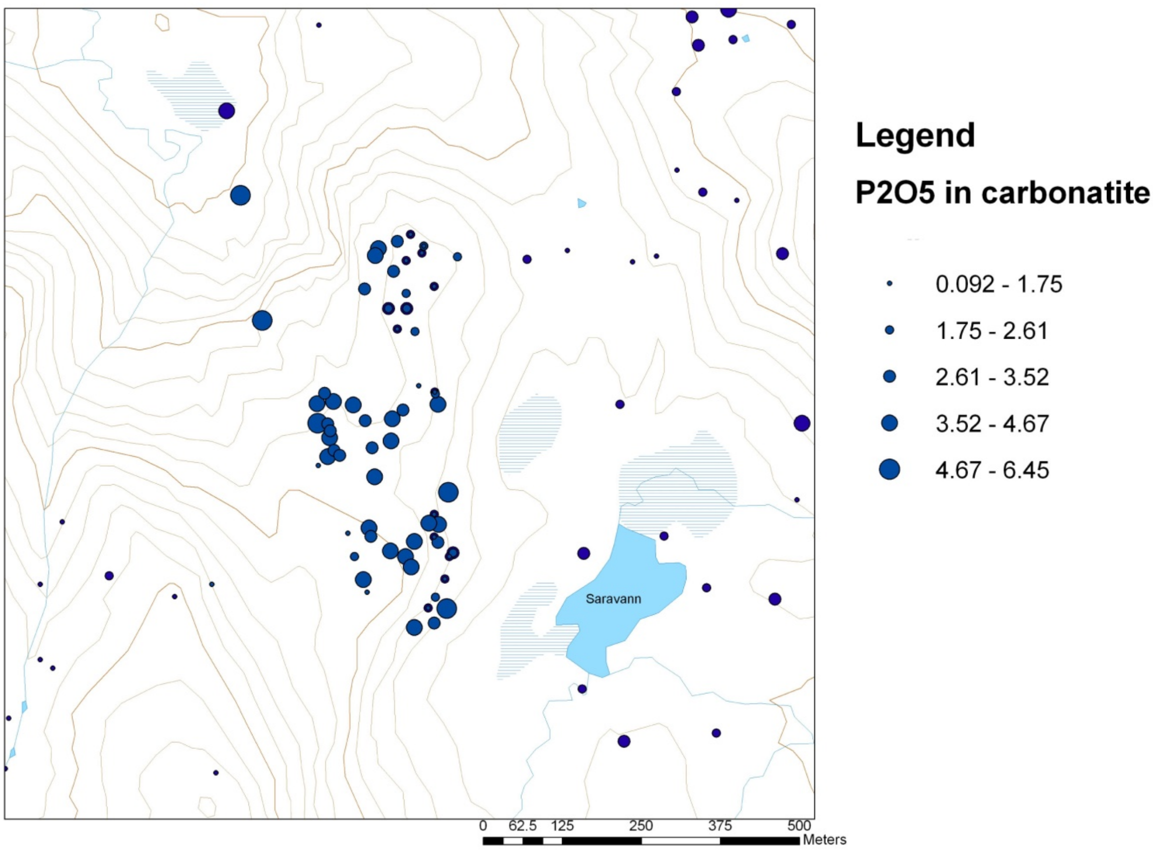


Figure 12 The distribution of P_2O_5 in carbonatite in the area north west of Saravann.

This well sampled area show an average of 3.00. It is probably realistic to believe that an average grade of about 3% P_2O_5 or about 7% apatite can be achieved over areas of about 300x300 m^2. Neither in the carbonatite nor in the pyroxenite is it possible to find areas of any significant size (> 300 x 300 meters) where the grade is higher than 10% apatite.

6. Petrography of selected rocks

The petrographic descriptions are limited to rocks where significant levels of P_2O_5 are found, namely the carbonatites and pyroxenites.

6.1 Carbonatite

Apart from large crystals of biotite, the carbonatites are fairly homogenous rocks. The dominant minerals are calcite, biotite, nepheline, apatite and Fe-Ti oxides. Crystal sizes vary from 0.1 mm 2-3 mm, with some large biotite crystals that can be several cm long (Figure 18). The grain boundaries of the calcite crystals are straight, giving the rock a granoblastic texture indicating that the calcite has been totally re-crystallized during a metamorphic overprint. The crystal size of the individual apatite grains varies from 0.1 to about 1 mm in length. The apatite grains are homogenous and without any inclusions. They show an undulating extinction, indicative of deformation.

The modal vol% estimations made by Strand (1951), see Table 1, appear to give a representative overview of the mineral content of the carbonatite, with an average apatite content of 4.4 vol%. Strand (1981) reports that the carbonatite contains from 2 to 6 vol% apatite.

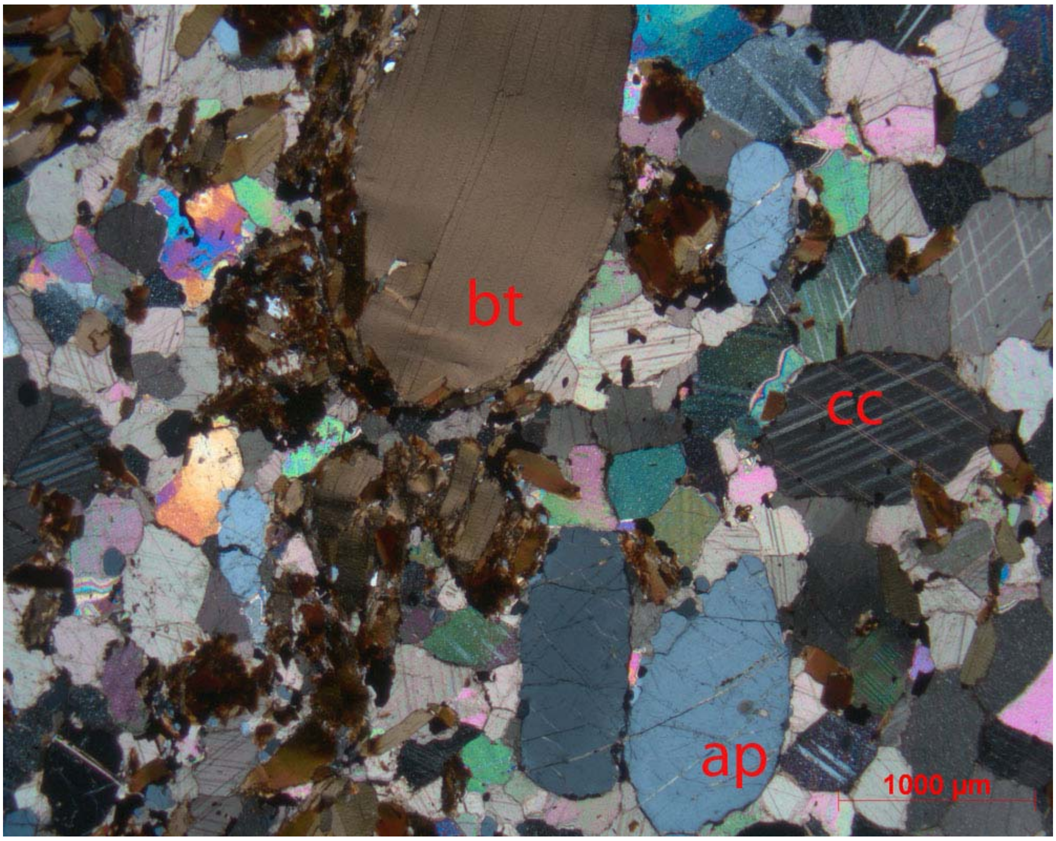


Figure 13 Microphotograph of carbonatite, with the important minerals marked, bt= biotite, cc= calcite and ap= apatite

6.2 Pyroxenite

The pyroxenites, particularly the non-fenitized varieties are very coarse grained rocks, commonly with a crystal size of several cm on average. The grain boundaries are irregular and fresh non-fenetized varieties show less signs of being recrystallised compared to the carbonatites. The dominant minerals are colourless clinopyroxene, brown hornblende, apatite and locally significant amounts of Fe-Ti oxides. The amount of hornblende can be equal to the amount of clinopyroxene, and the term hornblende clinopyroxenite would be the accurate rock name. Systematic measurements of the modal mineral content has not been done by previous workers nor by us. The rock is too coarse grained to give a precise measurement of the modal proportions from a standard thin section.

From our chemical analyses it is possible to give an estimate of the vol% of apatite from the following relationship (Hutchison 1975):

$$volume\ \%\ apatite = \frac{weight\ \%\ apatite}{1.265}$$

Thus the calculated volume % of apatite is 20% less than the calculated weight %, if other parameters are kept equal. The mutual relationship between apatite and other minerals shows that the crystallization of apatite took place throughout all stages of cooling, except for the very latest stages where Fe-Ti oxides crystallized. Later deformation has given the apatite an undulating extinction.

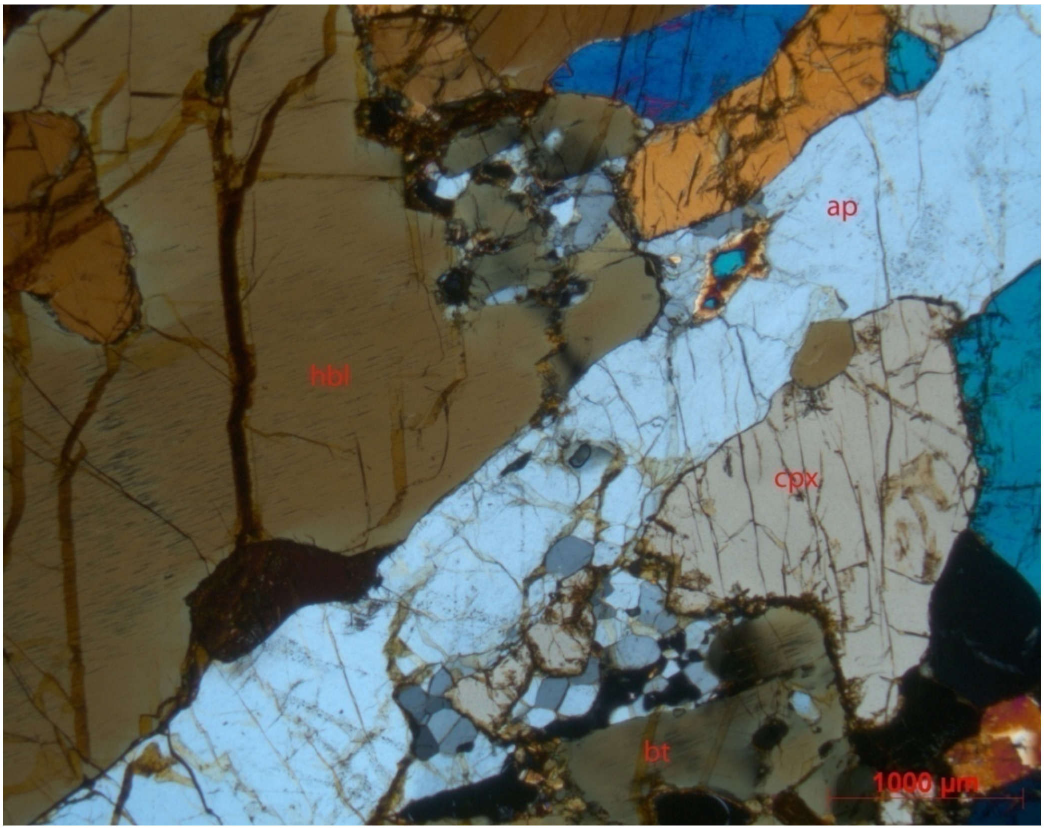


Figure 14 Microphotograph of pyroxenite, with the main minerals marked. Note the large apatite crystal crossing the photo from upper right to lower left, hbl= hornblende, cpx= clinopyroxene, bt= biotite, ap = apatite.

Our petrographical examinations conclude that the apatite occurs with a grain size and purity that meet the requirements for beneficiation,but the grades are lower than apatite ore mined today.

7. Concluding remarks

This report presents an overview of all investigations done on the LAC. It comprises a compilation of all data presently available, regarding the content and distribution of phosphorus and apatite, including 280 bulk chemical analyses.

Two rock types within and adjacent to the LAC contain P_2O_5 in significant amounts. These are the carbonatites which makes up the core of the complex, and hornblende clinopyroxenite dykes that occur along the eastern margin of the complex.

Combining all analyses an average P_2O_5 content of 2.38 %, can be calculated with a maximum value of 6.45 %. However of 280 samples only 7 have contents higher than 8%.

Samples of the carbonatite gives an average of 2.33 % P_2O_5. However, within a well-exposed and densely sampled area of about 300 x 300 meters an average of 3.0% P_2O_5 can be determined.

Correspondingly, for the hornblende clinopyroxenite the average P_2O_5 content is 2 %, with a maximum value of 5.00%.

The LAC appear to be only area on Stjernøy where the contents of P_2O_5 reach interesting levels.

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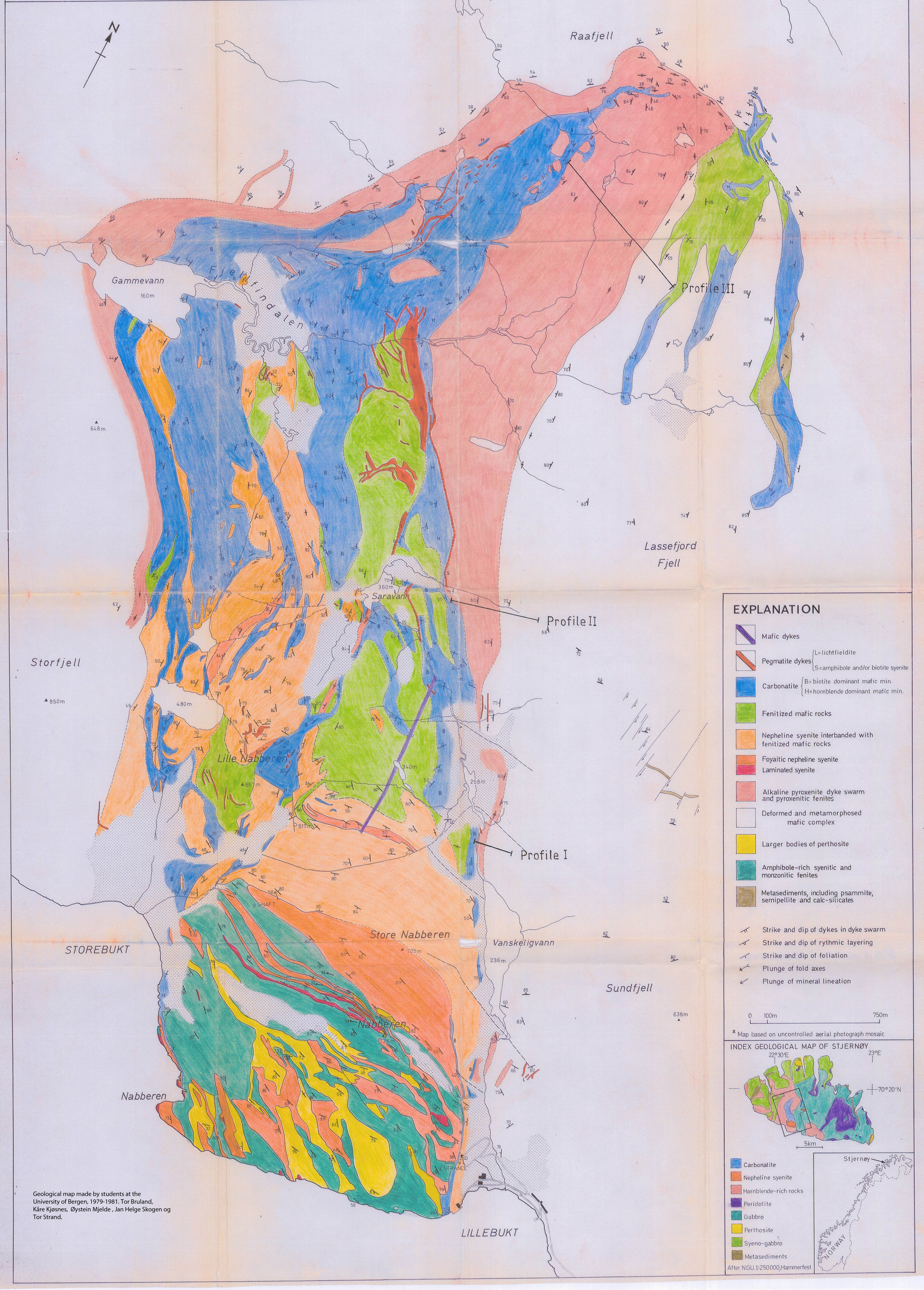
GEOLOGY OF THE
LILLEBUKT ALKALINE COMPLEX



Geological map made by students at the University of Bergen, 1979-1981. Tor Bruland, Kåre Kjøsnes, Øystein Mjelde , Jan Helge Skogen og Tor Strand.