Sm−Nd and Rb−Sr ages of hornblende clinopyroxenite and metagabbro from the Lillebukt Alkaline Complex, Seiland Igneous Province

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Apatite-rich hornblende clinopyroxenite from the Lillebukt Alkaline Complex, Stjernøy, has yielded Sm−Nd and Rb−Sr internal isochron ages of 540 ± 39 Ma (MSWD = 0.21) and 521 ± 22 Ma (MSWD = 0.00) respectively, interpreted as intrusion ages. εNd[H] of +4.00 ± 0.55 and εSr[L] of −11.21 ± 0.34 suggest a moderately depleted mantle source. The metagabbro host, which was deformed before emplacement of the hornblende pyroxenite dykes, gives Sm−Nd and Rb−Sr internal isochron ages of 517 ± 61 Ma (MSWD = 1.64) and 534 ± 8 Ma (MSWD = 4.60) respectively. Both probably date metamorphic recrystallization of the host metagabbro that took place before the initiation of the alkaline magmatism.


The Lillebukt Alkaline Complex is part of the Seiland Igneous Province (Fig. 1), which comprises gabbros, ultramafites, diorites, nepheline syenite, alkali syenite, carbonatite and swarms of mafic dykes (Robins & Gardner 1975) emplaced into paragneisses of the Eidvågeid Supracrustal Sequence and metasediments belonging to the Sørøy Group. The magmatic rocks occur in the uppermost nappe of the Kalak Nappe Complex, which itself belongs to the Middle Allochthon of the Scandinavian Caledonides (Ramsay et al. 1985; Roberts & Gee 1985). The development of the Seiland Province has been regarded as synorogenic with respect to the Finnmarkian Phase of the Caledonian Orogeny (Sturt et al. 1967, 1978), or the Finnmarkian Orogeny (Ramsay & Sturt 1986), which was believed to have occurred between 540 and 490 Ma. The existence of the Finnmarkian Orogeny, as previously defined, has been questioned by several authors (e.g. Krill & Zwaan 1987; Townsend & Gayer 1989).

The age of the Sørøy Group and its deformation in relation to the intrusion of different magmatic rocks is central in establishing a relative time scale for events in the region. The Sørøy Group has been regarded as synorogenic with respect to the Finnmarkian Phase of the Caledonian Orogeny (Sturt et al. 1967, 1978), or the Finnmarkian Orogeny (Ramsay & Sturt 1986), which was believed to have occurred between 540 and 490 Ma. The existence of the Finnmarkian Orogeny, as previously defined, has been questioned by several authors (e.g. Krill & Zwaan 1987; Townsend & Gayer 1989).

The age of the Sørøy Group and its deformation in relation to the intrusion of different magmatic rocks is central in establishing a relative time scale for events in the region. The Sørøy Group has been assumed to be of Late Precambrian to Cambrian in age (e.g. Roberts 1968; Ramsay et al. 1985). However, recent investigations have shown that metasediments correlated with the Sørøy Succession are intruded by ca. 800 Ma old gneissoids (Daly et al. 1991). The Hasvik Gabbro, believed by Sturt, Pringle & Ramsay (1978) to have been emplaced during the peak of Finnmarkian regional metamorphism (at about 525 Ma), has also been shown by Sm−Nd internal isochrons to be about 700 Ma old (Daly et al. 1991). These data suggest that the Sørøy Succession and the older intrusives in the Seiland Province are Precambrian, but Rice (1990) believes that the Hasvik Gabbro is emplaced into the Eidvågeid Supracrustal Sequence rather than the Sørøy Succession.

Zircons from nepheline syenite pegmatites, which are amongst the youngest magmatic rocks in the Seiland Province, have yielded Cambrian U−Pb ages of 531 ± 2 and 523 ± 2 Ma (Pedersen et al. 1989).

The present work was initiated to constrain the age of apatite-rich hornblende clinopyroxenite in the Lillebukt Alkaline Complex, and its metagabbro host by Sm−Nd and Rb−Sr internal isochrons. An additional aim was to characterize the source regions of the parental magmas of both rock types.

Geology of the Lillebukt Alkaline Complex

The Lillebukt Alkaline Complex (Heier 1961; Robins 1980, 1985) forms a N−S elongated area covering ca. 13 km² (Fig. 2). Along its eastern margin the alkaline complex is emplaced in metagabbro in which relict modal layering has a steep dip. To the north and west the alkaline complex is bounded by coarse-grained hornblendite or amphibolite.

The outcrop pattern within the alkaline complex is crudely concentric with an outer swarm of apatite-rich hornblende clinopyroxenite dykes along the eastern, northern and northwestern margins. The southern part of the complex is occupied by sheets and lensoid intrusions of nepheline syenite and syenite that were emplaced into mafic rocks and perthositic syenite, now strongly metasomatized. All these rock units were intruded by calcite carbonatite that forms the core of the complex together with metasomatized mafic rocks. The alkaline activity ended with the intrusion of syenite and nepheline syenite pegmatite dykes (Robins 1980). Swarms of mafic
alkaline rocks and carbonatite
plutonic rocks
allochthonous metamorphic rocks
autochthonous sediments
Precambrian basement

base of Kalak Nappe Complex
other thrust planes
major faults

0 km 500 km

LOPPHAVET
ØKSFJORD-HALVØYA
STJERNØYA
STJERNSUND
ALTEFJORD

70°
Geology and petrography of the hornblende clinopyroxenite

Hornblende clinopyroxenite was emplaced as steeply dipping dykes with a strike roughly parallel to the outline of the alkaline complex. The main occurrence of hornblende pyroxenite is along the eastern margin of the alkaline complex, where the dyke swarm is up to 750 m wide. Individual dykes are a few centimetres to several metres wide and occupy about 60–70% of the area where they occur. Locally, the hornblende clinopyroxenite dykes are cut by dykes of syenite pegmatite, nepheline syenite pegmatite and carbonatite.

Fluids associated with crystallization of hornblende clinopyroxenite caused intense metasomatism of the gabbroic host rocks. In a 20–30 m wide zone along the margin of the alkaline complex and between the individual hornblende pyroxenite dykes, gabbro was altered into medium- to coarse-grained, granular ultramafic rocks mineralogically similar to the hornblende clinopyroxenite (Kjøsnes 1981; Robins 1985).

Hornblende clinopyroxenite consists of very aluminium-rich diopside (Ca$_{51-53}$Mg$_{30-33}$Fe$_{15-19}$Al$_{20-23}$O$_{7}$8.5–10.2 wt%), pargasitic to hastingsitic hornblende, apatite, ilmenomagnetite, ilmenite and minor amounts of calcite. It does not contain any feldspar or feldspathoid. In places the hornblende clinopyroxenite consists almost exclusively of pyroxene, while hornblende dominates locally. The most characteristic feature of the rock is the high apatite content, averaging ca. 5–10%, but reaching 60% in places. Apatite occurs as acicular, euhedral to skeletal crystals or as xenomorphic granular aggregates. Calcite is only a minor constituent and is usually associated with apatite. Ilmenomagnetite and associated ilmenite can vary from ca. 1% to ca. 40% with an average of about 5–10%.

The dykes are coarse-grained to pegmatitic. In some dykes pyroboles and apatite are elongated normal to the dyke margins over the whole width of the dyke. More rarely, crystals are oriented parallel to dyke margins. In many dykes there is no preferred orientation. Chilled margins are absent. In contrast to similar dykes on Seiland (Robins 1974), the hornblende clinopyroxenite dykes of the Lillebukt Alkaline Complex are neither mineralogically nor texturally zoned. The hornblende clinopyroxenites are believed to be cumulates generated by plating of the walls of conduits occupied by flowing nephelinite magma (Kjøsnes 1981).

The mineral assemblage and textures of the hornblende clinopyroxenite are generally magmatic. Some
hornblende appears to have replaced clinopyroxene and may possibly be metamorphic in origin. Locally, metamorphic recrystallization of all minerals is well advanced.

Geology and petrography of the metagabbro
The metagabbro to the east of the Lillebukt Alkaline Complex is part of a large intrusion that is similar to several plutons in the Seiland Province in being characterized by olivine gabbro lacking primary orthopyroxene (Robins & Gardner 1974). Typical for the metagabbro is a penetrative metamorphic foliation parallel to relict modal layers. Since the foliation is cut at high angles by the hornblende clinopyroxenite dykes as well as syenite and nepheline syenite pegmatites, deformation appears to have preceded the initiation of the alkaline magmatism. The gabbro has also suffered high-temperature metamorphism (Kjøsnes 1981). The main minerals in the metagabbro are plagioclase (labradorite to andesine), Ca-rich pyroxene, hastingsitic amphibole and Fe-Ti oxides. Olivine is generally absent, having been replaced by pyroxene-hercynitic spinel symplectites or intergrowths of Ca-poor pyroxene and Fe-Ti oxides. Plagioclase is generally in the form of equigranular aggregates of normally zoned grains. Inclusions are rare but some crystals are crowded with small, elongated grains of hercynitic spinel and, rarer, euhedral corundum. Plagioclase crystals of this type are believed to have been derived from contact-metamorphosed pelitic metasediments, which are found within the gabbro as large rafts. Ca-rich pyroxene occurs as recrystallized aggregates of crystals that commonly contain lamellae of magnetite and lesser ilmenite. The brown, granular to oriented amphibole appears to have developed at the expense of pyroxene and plagioclase.

The metagabbro includes frequent, large rafts of hornfelsed psammitic and pelitic metasediment as well as calc-silicate. That the metasediments were intensely deformed prior to the intrusion of the gabbro is shown by the complex fabrics and folds preserved in the xenoliths (Kjøsnes 1981).

Sample descriptions and analytical techniques
A sample of hornblende clinopyroxenite (LAC 20 RC) was collected from a ca. 50 cm wide dyke on the eastern side of the alkaline complex ca. 200 m east of the carbonatite plug and ca. 300 m west of the metagabbro contact (Fig. 2). It consists of about 40% pyroxene, 35% hornblende, 15% apatite and 10% ilmenomagnetite and ilmenite. The texture is predominantly igneous. Hornblende and clinopyroxene contain exsolved Fe-Ti oxide needles. The apatite occurs as euhedral, acicular crystals, some of which are bent and partly recrystallized.

A sample of granular metagabbro (LAC F40 KK), used to determine an internal isochron, was collected by Kjøsnes (1981) approximately 400 m east of the margin of the alkaline complex (Fig. 2). Another sample of metagabbro (LAC 102 RC) was taken a few metres away from the metasomatized zone along the eastern margin of the alkaline complex. Only the whole-rock Nd isotopic ratios were determined in this sample.

Apatite, hornblende and clinopyroxene were extracted from the hornblende clinopyroxenite, and plagioclase, hornblende and clinopyroxene were separated from the metagabbro, in both cases using a Frantz magnetic separator.

Isotopic analysis was carried out at the Mineralogical-Geological Museum, University of Oslo on a Vacuum Generators 354 fully-automated, 5-collector mass spectrometer. The samples were prepared following the procedure described by Mears (1986). Nd isotopic ratios are normalized to 146Nd/144Nd = 0.7219. Sr isotopic ratios are normalized to 86Sr/88Sr = 0.1194. The decay constants used were 6.54 × 10^-12 a^-1 for the decay of 143Sm to 144Nd and 1.42 × 10^-11 a^-1 for the decay of 87Rb to 86Sr. εNd(CHUR) and εNd(T) were calculated assuming present-day ratios of 147Sm/144Nd = 0.1967, 143Nd/144Nd = 0.512647 (Jacobsen & Wasserburg 1984, normalized to 146Nd/144Nd = 0.7219), 87Rb/86Sr = 0.0827 and 87Sr/86Sr = 0.7045 (DePaolo & Wasserburg 1976).

Line-fitting and correlated errors were determined as recommended by York (1969). Age and intercept errors are quoted at the 2σ level (expanded 2σ where MSWD exceeds 1).

Results
Results are presented in Tables 1 and 2 and Figs. 3, 4 and 5. The Sm–Nd mineral-whole rock isochron age of the hornblende pyroxenite sample is 540 ± 39 Ma (MSWD = 0.21), with an initial 143Nd/144Nd of 0.512157 ± 0.000028. εNd(440) is +4.00 ± 0.55, suggesting

![Fig. 3. Sm–Nd isochron diagram for samples of hornblende clinopyroxenite and metagabbro.](image-url)
Table 1. Nd isotopic data for a hornblende clinopyroxenite (LAC20RC) and two samples of metagabbro from the Lillebukt Alkaline Complex.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fraction</th>
<th>Sm ppm</th>
<th>Nd ppm</th>
<th>Sm/Nd</th>
<th>147Sm/144Nd ± %</th>
<th>143Nd/144Nd ± 2σ x 10^-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAC20RC</td>
<td>wr</td>
<td>16.2</td>
<td>100.2</td>
<td>0.1618</td>
<td>0.0985 ± 0.025</td>
<td>0.51250 ± 0.014</td>
</tr>
<tr>
<td></td>
<td>cpx</td>
<td>6.1</td>
<td>28.3</td>
<td>0.2156</td>
<td>0.1312 ± 0.025</td>
<td>0.51262 ± 0.018</td>
</tr>
<tr>
<td></td>
<td>hbble</td>
<td>7.2</td>
<td>36.5</td>
<td>0.1985</td>
<td>0.1208 ± 0.025</td>
<td>0.51258 ± 0.014</td>
</tr>
<tr>
<td></td>
<td>ap</td>
<td>95.1</td>
<td>633.1</td>
<td>0.1302</td>
<td>0.0873 ± 0.025</td>
<td>0.51246 ± 0.018</td>
</tr>
<tr>
<td>LACF40KK</td>
<td>wr</td>
<td>4.9</td>
<td>21.2</td>
<td>0.2327</td>
<td>0.1417 ± 0.025</td>
<td>0.51265 ± 0.018</td>
</tr>
<tr>
<td></td>
<td>cpx</td>
<td>4.5</td>
<td>15.9</td>
<td>0.2833</td>
<td>0.1725 ± 0.025</td>
<td>0.51276 ± 0.014</td>
</tr>
<tr>
<td></td>
<td>hbble</td>
<td>7.7</td>
<td>30.3</td>
<td>0.2543</td>
<td>0.1548 ± 0.025</td>
<td>0.51272 ± 0.014</td>
</tr>
<tr>
<td></td>
<td>plag</td>
<td>8.4</td>
<td>48.5</td>
<td>0.1723</td>
<td>0.1052 ± 0.025</td>
<td>0.51254 ± 0.016</td>
</tr>
<tr>
<td>LAC102RC</td>
<td>wr</td>
<td>5.7</td>
<td>24.8</td>
<td>0.2328</td>
<td>0.1417 ± 0.025</td>
<td>0.51269 ± 0.018</td>
</tr>
</tbody>
</table>

Table 2. Sr isotopic data for a hornblende clinopyroxenite (LAC20RC) and two samples of metagabbro from the Lillebukt Alkaline Complex.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fraction</th>
<th>Rb ppm</th>
<th>Sr ppm</th>
<th>Rb/Sr</th>
<th>87Rb/86Sr ± %</th>
<th>87Sr/86Sr ± 2σ x 10^-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAC20RC</td>
<td>wr</td>
<td>8.8</td>
<td>590.0</td>
<td>0.0150</td>
<td>0.0433 ± 0.025</td>
<td>0.7034 ± 0.018</td>
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<tr>
<td></td>
<td>cpx</td>
<td>0.4</td>
<td>182.2</td>
<td>0.0020</td>
<td>0.0057 ± 0.025</td>
<td>0.7031 ± 0.018</td>
</tr>
<tr>
<td></td>
<td>hbble</td>
<td>21.2</td>
<td>571.8</td>
<td>0.0370</td>
<td>0.1070 ± 0.025</td>
<td>0.7039 ± 0.018</td>
</tr>
<tr>
<td></td>
<td>ap</td>
<td>0.0</td>
<td>2679.2</td>
<td>0.0000</td>
<td>0.0000 ± 0.025</td>
<td>0.7031 ± 0.018</td>
</tr>
<tr>
<td>LACF40KK</td>
<td>wr</td>
<td>6.7</td>
<td>577.9</td>
<td>0.0116</td>
<td>0.0336 ± 0.025</td>
<td>0.7031 ± 0.018</td>
</tr>
<tr>
<td></td>
<td>cpx</td>
<td>0.6</td>
<td>56.3</td>
<td>0.0114</td>
<td>0.0331 ± 0.025</td>
<td>0.7031 ± 0.018</td>
</tr>
<tr>
<td></td>
<td>hbble</td>
<td>22.5</td>
<td>234.3</td>
<td>0.0961</td>
<td>0.2779 ± 0.025</td>
<td>0.7050 ± 0.020</td>
</tr>
<tr>
<td></td>
<td>plag</td>
<td>3.2</td>
<td>1432.6</td>
<td>0.0011</td>
<td>0.0655 ± 0.025</td>
<td>0.7029 ± 0.018</td>
</tr>
<tr>
<td>LAC102RC</td>
<td>wr</td>
<td>8.8</td>
<td>579.6</td>
<td>0.0151</td>
<td>0.0438 ± 0.025</td>
<td>0.7032 ± 0.030</td>
</tr>
</tbody>
</table>

A relatively depleted mantle source. The pyroxenite has an initial Nd isotopic composition fairly similar to that of three carbonatites from the Lillebukt Alkaline Complex (εNd530 = +4.1 to +4.9, Aitcheson 1989), but higher than a syenite and a nepheline syenite from the same complex (εNd530 = +3.3 and +2.6, Aitcheson 1989). The age of separation of the parent magma from the depleted mantle reservoir of DePaolo (1981) is 729 Ma, while the model age relative to the depleted Baltoscandian mantle of Mearns et al. (1986) is 577 Ma (Fig. 5).

The Rb–Sr age of the same sample and separates is 498 ± 33 Ma (MSWD = 4.24). Omitting apatite, which has a slightly high 87Sr/86Sr ratio, an isochron with a much improved fit yields an age of 521 ± 22 Ma (MSWD = 0.00) with an initial 87Sr/86Sr of 0.703096 ± 0.000024. The initial Sr isotope ratio falls into the range (0.7027–0.7031) defined by three carbonatites, a syenite and a nepheline.
syenite from the Lillebukt Alkaline Complex reported by Aitcheson (1989).

The Sm–Nd isochron age of metagabbro F40 based on whole rock, clinopyroxene, hornblende and plagioclase is 517 ± 61 Ma (MSWD = 1.64), with an initial 

$$^{143}Nd/^{144}Nd = 0.512187 ± 0.000059, \varepsilon_{\text{Nd}}^{143} = +4.02 ± 1.15.$$  

The 

$$^{143}Sm/^{144}Nd$$

ratios of the two metagabbro samples are almost equal, but the 

$$^{143}Nd/^{144}Nd$$

ratio of LAC 102 is higher, so that it does not lie on the isochron defined by the whole rock and minerals of F40 (Fig. 3). The Sm–Nd model ages relative to the depleted mantle reservoirs of DePaolo (1981) and Mearns et al. (1986) are 830 Ma and 606 Ma respectively (Fig. 5) for sample F40 and 771 Ma and 538 Ma for sample 102.

The Rb–Sr isotopic data for metagabbro F40 do not define an isochron, because of the anomalous data for plagioclase (Table 2, Fig. 4). Excluding plagioclase, the data give an age of 534 ± 8 Ma (MSWD = 4.60), indistinguishable from the Sm–Nd age, and an initial 

$$^{87}Sr/^{86}Sr$$

of 0.702892 ± 0.000019.

Conclusions

The Sm–Nd age of the apatite-rich hornblende pyroxenite from the Lillebukt Alkaline Complex as determined by an internal isochron is 539 ± 39 Ma. The Rb–Sr isochron age for the same rock and separates (excluding apatite) is 521 ± 22 Ma. In view of the igneous mineralogy and texture of the analysed hornblende clinopyroxenite they are interpreted as intrusion ages. Taking into account the U–Pb age of 523 ± 2 Ma on zircon from a nepheline syenite pegmatite in the Lillebukt Alkaline Complex (Pedersen et al. 1989), and the observation that such pegmatites cut the hornblende clinopyroxenite dykes, intrusion of the hornblende clinopyroxenite probably took place between about 543 and 523 Ma.

As the host metagabbro was deformed and recrystallized before the emplacement of the hornblende clinopyroxenite dykes, it is probably significantly older than the alkaline magmatism. This is not unambiguously reflected in the isotopic data. The metagabbro yielded Sm–Nd and Rb–Sr ages of 517 ± 61 Ma and 534 ± 8 Ma respectively. This appears to be younger than the Sm–Nd internal isochron age of 612 ± 33 Ma for a weakly metamorphosed gabbro from the same pluton at Kvafljord, NE Stjernsøy (Daly et al. 1991), but is not distinguishable from the ages of 604 ± 44 Ma (Daly et al. 1991) and 502 ± 28 Ma (Mørk & Stabel 1990) for metagabbros from Storvik on the Øksfjord peninsula. All of these samples, which have been dated earlier, were collected from what is believed to be the same large intrusion (the Stjernsund gabbro of Robins & Gardner 1974). In view of the deformation and recrystallization which this intrusion has suffered and the complex tectono-thermal history of the Seiland Province in general, there can be some uncertainty as to the interpretation of these internal isochron ages. Daly et al. (1991) postulated that 604 ± 44 Ma is an intrusion age for the Storvik magagabbro, while Mørk & Stabel (1990) presented evidence that the 502 ± 28 Ma isochron from the same intrusion dates metamorphic recrystallization. Mørk & Stabel (1990) note that a two-point isochron based on relict igneous Ca-rich pyroxene from the same sample and the whole-rock data gives an age of 620 ± 43 Ma, identical within error with the age reported by Daly et al. (1991). On the basis of these earlier results and the metamorphic texture of the dated sample, it is considered most probable that the Sm–Nd and Rb–Sr isochron ages for the Lillebukt metagabbro date its recrystallization and not its emplacement.

The hornblende clinopyroxenite was derived from a mantle source that was depleted, but not as severely as the model depleted mantle of DePaolo (1981). The Nd and Sr isotopic compositions support derivation of the magmas which crystallized the host olivine gabbro and the hornblende clinopyroxenite and carbonatite belonging to the Lillebukt Alkaline Complex from isotopically similar sources.

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References


DePaolo, D. J. & Wasserburg, G. J. 1976: Inferences about magma sources and mantle structure from variations of 

$$^{143}Nd/^{144}Nd.$$  


Mearns, E. W., Andersen, T., Mørk, M. B. E. & Morvik, R. 1986: 

$$^{143}Nd/^{144}Nd$$

evolution in depleted Baltoscandian mantle (abstract). Terra Cognita 6, 247.


