Mineralogy, petrology and geochemistry of soils of the Alnö Carbonatite Complex, Sweden

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1   Introduction

The research area is Alnö Island, which is located to the northeast of the town Sundsvall, Sweden. In this area, the main type of rock is migmatitic gneiss. In the northern part of the island, there is a special geological phenomenon – an intrusion of carbonatites and alkaline rocks, which took place through repeated intrusive episodes in the early Proterozoic to early Cambrian during 80 Ma, whereas the main intrusion was emplaced at around 546 Ma BP (Morogan & Lindblom, 1995). The main types of intruded rocks are pyroxenites, carbonatites, ijolites, urtites and lamprophyres, like the alnöite, which was named after the island. Furthermore, the host rocks were altered by fenitization (alkalimetasomatosis) at the contact zone to the intrusion of carbonatites and alkaline rocks (von Eckermann, 1948; Aspden, 1980; Morogan & Lindblom, 1995).

The opportunity for this research work in the carbonatite complex of Alnö Island came by chance during a field trip in 2001, when we sampled podzols in the southern part of the island to study chronosequences of soil formation. Dr. Ulla Lundström, our collaborator from Sweden, who lives on Alnö, mentioned a 'special geological phenomenon' in the northern part of the island. When walking along a transect in the forest southeast of the village Pottäng it became obvious, that in some areas of the spruce forest the ground vegetation seemed to be different to that of a normal spruce forest on acidic (gneissic) parent material, which is the main type of host rock on Alnö Island. Plants which indicate these acidic rocks, e. g. cowberry (*Vaccinium vitis-idaea*), were missing completely. These areas seemed to be very narrow – only some metres wide. We concluded, that this could be due to the special parent material in this area. We decided to dig soil profiles to see, whether we would really find different parent material. The first soil profile was dug near the road southeast of the village Pottäng, where we presumed - from the vegetation assemblage – to find rocks different to the 'normal' gneisses.

Finally, we excavated six soil profiles, in three we found different types of alkaline and carbonatitic rocks, in two we found the original host rock – gneiss – and one showed both types of parent material. It was also obvious, that the soils partially showed a different kind of soil formation. Whereas the profiles on the alkaline/carbonatitic parent material could be classified as cambisol, the two profiles on gneiss were already developing towards podzols. However, the podzolization process was weaker than could be expected from the approximate age of the soils and after comparison with the podzols in the southern part of the island on the same elevation above sea level.

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Therefore, we concluded, that those soils were also influenced by the surrounding alkaline rocks. In general, the whole transect seemed to have undergone solifluction, which partially mixed the parent materials. However, the overall soil characteristics were nevertheless preserved. It was then decided to start an interdisciplinary project about how those different rocks affect the soil formation, chemical parameters, the vegetation assemblage and eventually the growth of the main type of tree in this transect – Norway spruce. The aim of this doctoral thesis was to characterize the soil and geological parameters in the six chosen soil profiles in detail.

This research work also gave the opportunity, to study differences in soil development on carbonatites and alkaline rocks. Up to now, carbonatites and related rocks have been investigated from a petrological or an economic point of view with respect to their anomalous trace and rare earth element content. The examination of carbonatites and alkaline rocks from a soil scientific view point seems to have been neglected so far. This thesis may help to elucidate the effects of carbonatites and alkaline rocks on the mineralogy and geochemistry of soils as well as the differences in soil development in comparison with soils on the host rocks, the gneissic migmatites.

2   Geography and geology of the research area

2.1   Geography and physiography of Alnö Island

Alnö Island is the largest of a group of islands situated in the Baltic Sea east of the town Sundsvall and between the outlets of the two big rivers Indalsälven and Ljungaälven. It is located between 17°22' and 17°30'E and between 62°21'and 62°29N'. It is separated from the mainland by a narrow but rather deep sound. Alnö shows a rather uniform topography with fairly level rock-plateaus, largely covered by glacial drift, i. e. coarse, glaciofluvial deposits, glacial silt and clay, post-glacial clay and coarse delta sediments, which were deposited during the uplift of the land (von Eckermann, 1948; Agrell, 1979). The average height above sea level is about 80 metres, whereas heights of 128 and 102 metres are attained in the southern and northern part, respectively (von Eckermann, 1948).

2.2   Geology of Sweden

2.2.1   Pre-Quaternary geology of Sweden

The Swedish bedrock comprises three major units (Lundqvist & Bygghammar, 1994):
- the *Precambrian crystalline basement*: it is older than 570 million years (Ma) and belongs to the Baltic Shield, which extends from the Kola Peninsula to SW-Norway
- the *Caledonides*: they formed during the Caledonian Orogeny (510 to 400 Ma) and extend to Great Britain and Ireland
- the *sedimentary bedrock outside the Caledonides*: was formed during the Cambrian to Tertiary and overlies the Precambrian basement.

The Baltic Shield comprises ten major geological units, which are divided by their bedrock, the age of the bedrock and important geological events (Lundqvist & Bygghammar, 1994)

The research area Alnö Island is located in the *Svecofennian Area*, which belongs to the Svecokarelian Province. The main types of bedrock in the Svecofennian Area are metamorphosed sedimentary rocks (e.g. greywacke) and volcanic rocks (with rhyolitic composition). Usually the rocks are between 1880 and 1870 Ma old. Partial melting of the rocks led to the formation of migmatitic gneisses in depths at about 10 to 15 km and at temperatures between 500 – 650 °C (Lundqvist & Byghammar, 1994).

Alnö Island is also one of the locations in Sweden which shows a special geolocical phenomenon – igneous rocks of alkaline composition. Except on Alnö Island alkaline igneous rocks can be found at Norra Kärr, Almunge (Uppland), Särna (Dalarna) and in the Kalix Archipelago. Alkaline and carbonatitic intrusions – particularly that of the research area - will be discussed in detail later (Lundqvist & Bygghammar, 1994).

2.2.2   The Quaternary of Sweden and Quaternary deposits

Sweden was influenced by three major glaciations during the Quaternary – the Weichselian, the Saale and the Elster glaciation. The thickness of the ice sheet was about 3000 m during the climax of the glaciations. The largest extension of the ice sheet was attained in the two older glaciations (Elster and Saale), where it reached to the northern borders of the German low mountain range, the Sudeten mountains and the Carpathians, and in Russia to the rivers Dnjepr and Don (Faupl, 2000).

The Weichselian glaciation started at about 115 ka years BP, and was interrupted twice by interstadials: the Brörup Interstadial (100 ka – 90 ka years BP) and the Odderade Interstadial (80 ka – 70 ka years BP). The earliest stage of the glaciation started at about 50 ka years BP and had its maximum extension at about 20 ka years BP, where the ice margin was south of Berlin (Lundqvist & Robertsson, 1994). It has been calculated, that the advance of the ice sheet was between 100 and 150 m/year during the growth from the central area of glaciation to the maximum extent at about 20 ka BP (Donner, 1995).

The landscape of Sweden is largely influenced by the latest glaciation - the Weichselian - and its recession. In the Holocene, the landscape has been reformed by isostatic uplift and wave-washing of the shores at that time (Fredén, 1994a).

Most of Sweden is covered by Quaternary deposits, only a small area exposes bedrock (Agrell, 1979). Very few pre-Weichselian deposits can be found (Hättestrand, 1998; Persson, 1994), because their traces have been removed to a large extent by later glaciations (Fredén, 1994b).

Along the east coast of Sweden, there are many small hills and joint-aligned valleys running in NW-SE direction, e. g. the valley of the river Indalsälven near Sundsvall. Only small amounts of till are found here, but mostly wave-washed sediments (gravel and sand) in connection with glaciofluvial deposits. Clays on the east coast are

dominantly varved glacial clay, with thicknesses of 10 m or more. In places with granitic bedrock, there are areas with abundant boulders (Agrell, 1979).

2.3   Geology of Alnö Island

2.3.1   Introduction to alkaline rocks and carbonatites

2.3.1.1   Alkaline rocks

The term 'alkaline rock' refers to rocks containing feldspathoidal minerals or rocks not necessarily containing a feldspathoid but with low SiO_2 and high alkali contents (Edgar, 1987). Alkaline rocks are a very diverse group of continental rocks, which occur in the interior regions of continents, far from the orogenic belts of convergent plate boundaries. Although some alkaline rocks are associated with continental rifting, many of them have no distinctive tectonic environment. Alkaline rocks all have in common, that they appear in widely differing settings. Therefore, it is easier to group the alkaline rocks according to their compositions, rather than their geologic relations (McBirney, 1993).

2.3.1.2   Carbonatites

Although they occur worldwide, carbonatite complexes are rare geological phenomena, comprising only 1 % of all igneous rocks (Le Bas, 1987). Carbonatites complexes are usually located in stable, intra-plate regions, often within the Precambrian Shield or continental platform areas (U.S. Geological Survey, 1998).

According to Streckeisen (1980), carbonatites are defined as igneous carbonate rocks with more than 50 % modal carbonate minerals. There are four main groups of carbonatites:

- Calcite-carbonatite with the subtypes *sövites* (coarse-grained) and *alvikites* (medium- to fine-grained)
- Dolomite-carbonatite (*beforsite*)
- Ferrocarbonatites, which are composed of iron-rich carbonate minerals
- Natrocarbonatites: Na-K-Ca-carbonatites, which are only known as extrusive products of the Oldoinyo Lengai volcano in Tanzania

As accessories, biotite, pyroxene, apatite, magnetite, melanite and Ti- and Nb-bearing minerals, such as perovskite and pyrochlore, can occur in the carbonatites. Carbonatites with 50 – 70 % of silicate minerals are called *silicosövites*. *Sövitepegmatites* consist of calcite and pyroxene (with apatite, magnetite etc.) (Kresten, 1990).

Carbonatites are composed largely of carbonates of Ca, Mg, Na and Fe. K-rich carbonatites have not been reported up to now. Typical accessories are apatite, magnetite and rare minerals such as monazite and pyrochlore (McBirney, 1993). In the carbonatite nomenclature, characteristic contents of other minerals are indicated by prefixes; e.g. apatite-pyrochlore-carbonatite (Woolley & Kempe, 1989). In high

concentrations, those minerals are sources for rare earth elements (REE) and several rare metals. Carbonatites are usually poor in SiO_2 (McBirney, 1993).

Carbonatites and related rocks have been investigated petrologically/magmatically or from an economic point of view with respect to their anomalous trace and rare earth element content. ·Carbonatite deposits which are suitable for mining purposes, range in size from 6 to 300 million tons (U.S. Geological Survey, 1998).

There are several environmental signatures, which mark the presence of carbonatites. Soils and sediments associated with carbonatites are characterized by anomalous contents of Fe, P, Nb and REE as well as Th, U, Ti and Ba. Fluviatile sediments downstream from carbonatite deposits usually show anomalous contents of Th, Ba, Nb and REE (La, Ce, Nd and Sm). Furthermore, in some carbonatite complexes there are high concentrations of magnetic minerals, which produce positive magnetic anomalies.

The mining of carbonatites is usually carried out in large open-pit quarries. The high amounts of U and Th in the waste associated with the mineral processing are potential environmental risks with respect to their radioactivity (U.S. Geological Survey, 1998).

Furthermore, carbonatites are used as sources for carbonate and phosphate, e.g. in the Eastern Rift Valley of Kenya (van Straaten, 2002). There have also been investigations of the potential of powdered carbonatites to improve the fertility of soils with high acidity and low natural fertility (Costa, 2001).

2.3.1.3   Fenites and fenitization

The process of fenitization refers to metasomatic changes which bring a host rock into compositional equilibrium with an alkali silicate (e.g. ijolite) or a carbonatite intrusive complex (Morogan, 1989). The outer zones and the host rocks are strongly altered by volatile-rich fluids. The process of fenitization was first described in the Fen Complex in Norway, where carbonatites and alkaline rocks intruded Precambrian gneisses (McBirney, 1993; Mitchell & Brunfelt, 1975). Fenitization produces syenitic rocks, which tend to be nepheline-rich close to the intrusion and progessively more silica-saturated outward. On the very border of the fenites, the host rocks are fractured, but otherwise unaltered (McBirney, 1993).

Fenitization comprises multiple processes. The alterations during the fenitization process are influenced by several parameters, i. e. (Le Bas, 1987):
- the geochemistry of the metasomatising magma
- the characteristics of the fluids of the magma
- the depth profile of the magma, since different reactions occur at different depths
- the porosity and structure of the host rocks being fenitized
- the mineralogy and geochemistry of the host rocks
- the water-rock interaction

2.3.1.4   Rare earth elements in fenites and carbonatites

The analysis of REE in fenites and carbonatites is important because the distribution of the REE in ultramafic and alkalic rocks as well as in carbonatites could serve as an important geochemical indicator of the physicochemical conditions of mineral formation (Möller et al., 1980). Carbonatites contain the highest contents of REE and the highest LREE:HREE (La:Lu) ratios of any igneous rocks. The contents of La and Ce are highest in the ferrocarbonatites. On the whole, the ferrocarbonatites are also richer in REE compared to the other types of carbonatites (Woolley & Kempe, 1989).

Morogan (1989) reports from research on fenites from Båräng and Stornäset, that during fenitization, CaO, Na_2O and K_2O as well as Fe_2O_3 are continuously introduced. SiO_2 and Al_2O_3 show little changes in lower grade fenites, but are depleted in higher grade fenites. P_2O_5 increases significantly in high grade fenites and near the contact with sövite. These changes in element concentrations with increasing fenitization of the host rocks could be a result of transport of material into and out of the system during fenitization or of volume changes (Morogan, 1989).

With increasing grade of fenitization, the REE distribution shows an enrichment in LREE with respect to HREE. Sodic fenites show higher absolute REE concentrations compared with potassic fenites, whereas intermediate fenites are enriched in Ce. There are several factors which influence the different distribution patterns of REE during the fenitization process, e. g. the REE concentrations of the reacting minerals or the REE abundance in the fenitizing fluid. The higher content of LREE in high grade fenites could be due to changes of temperature and pH (Morogan, 1989).

2.3.2   The carbonatite complex of Alnö Island

The occurrence of limestones on Alnö was probably known locally as far back as the 17th century and the deposits were quarried fairly extensively during the 18th and 19th century. The limestones were used as mortar or were shipped unburned as flux-stone to small ironworks along the coast of the Baltic (von Eckermann, 1948).

As early as 1895, Högbom provided evidence for the existence of an alkaline complex in the northern part of Alnö. He stated that the carbonatites have crystallized from nepheline-syenitic magmas. The rocks of the alkaline complex have also been subject to studies by F. Hoppe from the Swedish Geological Survey in 1881, who discovered a melilite-bearing dike-rock. Högbom (1895) named the rock "alnöite", which has made Alnö famous in the petrological world. From then on, Alnö was known for this 'striking dike-rock', as von Eckermann (1948) puts it.

During time, the term 'alnöite' was used for several types of lamprophyric dyke rocks. In the classic locality at Stornäset on the east coast of Alnö, the alnöite is made up of biotite, melilite and some carbonates as main minerals and perovskite, chromite, garnet and pyrrhotite as accessories. Furthermore the alnöite contains big phenocrysts of biotite or anomite with diameters of several cm and also smaller phenocrysts of augite, olivine, titanomagnetite and apatite (von Eckermann, 1948).

Kresten (1979) states, that because the alnöites of Alnö Island show wide variations with respect to composition and texture, a re-definition of the term seems necessary.

Kresten uses the term alnöite for lamprophyric rocks, with phenocrysts of phlogopitic mica, titanomagnetite and one or more of the following minerals: olivine, diopsidic pyroxene, calcic amphibole (edenite/hastingite). The matrix of the alnöite consists of phlogopite, calcite, titanomagnetite, perovskite and apatite. There are also varieties, which contain melilite, andradite, picotite or chromite. Olivine-rich alnöites grade into the kimberlitic rocks, with increased melilite contents into melilitolites and those with increased calcite contents into alvikites.

The alkaline and carbonatite complex of Alnö Island belongs to the best known complexes in the world, due to the extensive work and resulting classic memoir of the "The alkaline district of Alnö Island" by Harry von Eckermann (1948).

The complex is exposed in the northeast of Alnö and comprises pyroxenites, urtites, ijolites, carbonatites and fenites (Aspden, 1980). The alkaline and carbonatitic intrusions can also be found on the islands north of Alnö, with the most important occurrence at the island Långarsholmen. The complex was emplaced in the migmatitic and gneissic host rocks in the early Proterozoic to early Cambrian. The complex formed through repeated intrusive episodes during 80 Ma. The main complex at the northeast of Alnö Island was emplaced around 546 Ma. The northern ring complex of Långarsholmen was emplaced at about 600 Ma (Morogan & Lindblom, 1995).

The protoliths in the alkaline area of Alnö are mainly Archean migmatitic gneiss-granites (von Eckermann, 1966) with a relatively constant mineralogy of quartz, microcline, oligoclase and biotite, with different contents of chlorite and muscovite. As accessory minerals zircon, apatite and titanite can occur (Morogan, 1995).

The carbonatite intrusion of Alnö Island comprises two main centres (Kresten, 1980; Morogan & Lindblom, 1995):
1. The main intrusion (Alnö Island s.s.) consists of four series of plutonic rocks: pyroxenite, melteigite-ijolite-urtite, nepheline syenite and carbonatite (sövite). It is roughly circular with a diameter of about four kilometres.
2. The ring intrusion of Långarsholmen with pyroxenite, sövite and ijolite.

There are some other very small intrusions on or near Alnö Island, i. e. the Bäräng intrusion, a breccia vent with carbonate lapilli tuffs on Sälskar island and a small intrusion with sövite and melilitolite at Söråker.

A schematic block diagram of the intrusion pattern of the different rock types in the alkaline complex of Alnö Island is shown in Fig. 2..
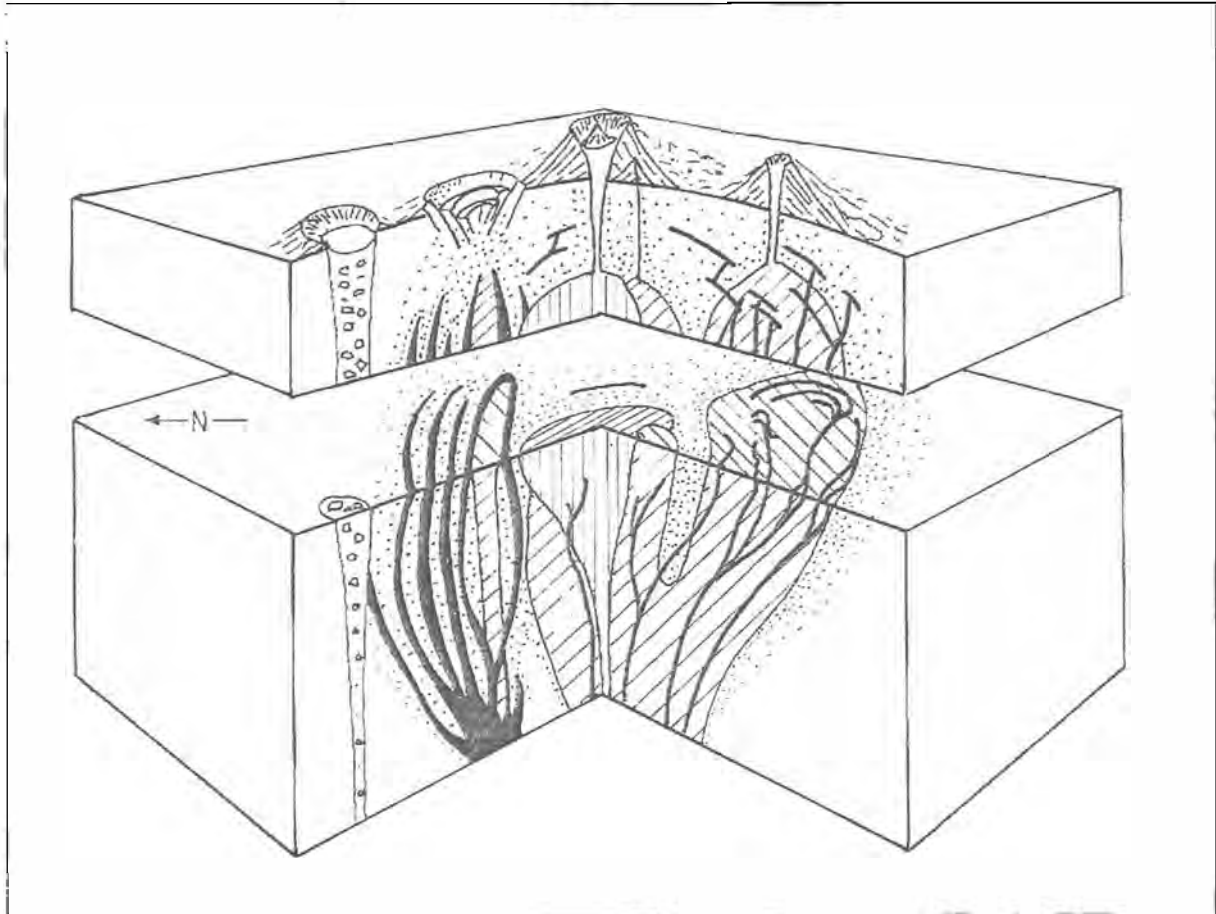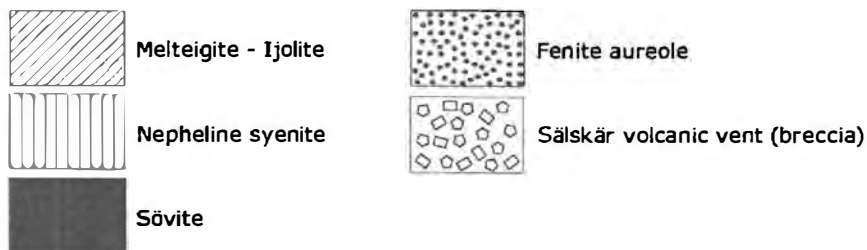
Fig. 2.1: Block diagram of the Alnö Complex (modified from: Kresten, 1990)

Melteigite - Ijolite

Nepheline syenite

Sövite

Fenite aureole

Sälskär volcanic vent (breccia)

The chronology of the intrusive events on and around Alnö Island can be summarized as follows (Morogan & Lindblom, 1995):

1. Intrusion of pyroxenite, sövite and ijolite at Långarsholmen together with fenitization of host rocks (see next paragraph)
2. Intrusion of pyroxenite and ijolite at the main complex, fenitization and emplacement of nephelinite and phonolite dykes
3. Intrusion of nepheline syenite at the main complex with emplacement of tinguaite and trachyte dykes
4. Intrusion of sövite at the main complex
5. Båräng intrusion
6. Emplacement of alnöite, alvikite and beforsite dykes

The aureole of fenitization extends to 500 – 600 m around the carbonatite .centre, where the host rocks have been altered to fenite. During the process of fenitization,

several mineral changes occured in the protolith. The quartz, feldspars, biotite and chlorite of the host rocks have been replaced by alkali pyroxene and amphibole, and new generations of feldspars, calcite, titanite, fluorite and apatite (Morogan & Woolley, 1988).

3 Methods

3.1 Field

The six sampled profiles were chosen along a transect in a forest SSW of the village Pottäng on Alnö Island. The choice of the six sampling sites was made with the help of an assessment of the vegetation in the transect, which seemed to reflect the underlying parent material quite well. Sites with an assumably alkaline or carbonatitic parent material showed a slightly different vegetation assemblage than the sites with acidic parent material with its typical vegetation assemblage. The aim was to sample three soil profiles with the original gneisses of this area (Alkaline 2, 4 and 5) and three profiles with alkaline or carbonatitic parent material (Alkaline 1, 3 and 6). According to the geological map (Kresten, 1986), only two types of parent material occur in the transect – fenites and sövites. When excavating the soil profiles, it became clear very quickly, that the assumptions about the position of "alkaline" or "gneissic" soil profiles were rather good. However, the three soil profiles on the toe of the slope (Alkaline 1, 2 and 3), also contained parent material of the upper three soil profiles (Alkaline 4, 5 and 6). The soil profiles were classified according to the World Reference Base for Soil Resources (FAO, ISRIC & ISSS, 1998).

3.2 Laboratory

The following methods were used:

- Mineralogy of parent material, fine soil and < 2 μm-fraction by X-ray diffractometry (XRD) and additional IR-spectroscopy and Simultaneous Thermal analysis for the < 2 μm-fraction
- Characterization of rocks by thin section analysis, scanning electron microscopy and microanalysis
- Geochemistry of rocks, fine soil and < 2 μm-fraction by X-ray fluorescence (XRF) and Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS) including major, trace and rare earth elements (REE)
- Physical soil parameters (particle size distribution)
- Chemical soil parameters (pH, electrical conductivity, pedogenic oxides, organic carbon, cation exchange capacity)

4   Results

4.1   The soil properties and parent material of the six soil profiles

4.1.1   Profile Alkaline 1 (A1)

The parent rock for profile A1 is a **Calcite Melanite Ijolite** with the mineral components nepheline, calcite, phlogopite, pyroxene, F-apatite, melanite, magnetite, sphene (titanite), pyrite, perovskite and baryte.

The minerals in the fine soil, which derived from the weathering of the calcite melanite ijolite, are mainly phlogopite and vermiculite. Vermiculite is a product of the weathering of the phlogopite. Other minerals are calcite, pyroxenes and quartz. The 2 μm-fraction is dominated by secondary chlorite and illite. Furthermore, smectite, vermiculite and traces of mixed-layer minerals occur.

Profile (A1) was classified as **Episkeletic Cambisol**. It is located at the toe of the slope and is the most shallow of all profiles, with only 33 cm depth. It is dominated by gravel and sand with clay contents under 5 %. The vegetation indicates acidic as well as alkaline soil properties.

4.1.2   Profile Alkaline 2 (A2)

Like mentioned above, concerning the parent material, profile A2 is a mixed profile, where two types of rocks can be found. The first one is obviously influenced by fenitization and can be classified as **fenitized gneiss** or **syenitic fenite**. The second type of rock present in this profile is completely unaltered **gneiss**.

The mineral components of the **syenitic fenite** are plagioclase, Alkali-Feldspar, quartz, phlogopite, chlorite, fluorite, pyroxene, hematite and melanite (?).
The mineral components of the **gneiss** are plagioclase, quartz, phlogopite, monazite, xenotime, zircon, orthoclase, chalcopyrite, rutile, pyrite, apatite and magnetite.

The mineralogy of the fine soil is dominated by quartz, K-feldspar, plagioclase, vermiculite, mica and chlorite from the weathering of the gneiss and the syenite fenite.
The clay fraction shows vermiculite and secondary chlorite as predominant clay minerals. Furthermore, smectites, various amounts of illite and mixed-layer clay minerals occur.

Profile A2 was classified as **Episkeletic Cambisol**, like profile A1, whereas profile A2 showed even higher gravel content – between 62 and 73 % in the uppermost horizon. When excavating this profile and particularly when interpreting the geochemical results, it became very clear, that profile A2 is a 'mixed' profile, where different types of rocks and therefore subsequently different soil properties can be found. The vegetation around profile A2 also stresses the mixed properties of profile A2.

4.1.3   Profile Alkaline 3 (A3)

In profile A3 the main type of parent rock is a ***pyroxenite ijolite syenite*** with sharp intrusive contacts between the three rock types. Furthermore, gneisses, granite-gneisses and borengites – consisting nearly entirely of K-Feldspar – occur.

The mineralogy of the Pyroxenite Ijolite Syenite is:
Syenite (red part):
K-Feldspar (Orthoclase), albite, pyrite, hematite, perovskite and pyrochlore
Ijolite (red/black part):
Nepheline, pyroxene, K-Feldspar, phlogopite and hematite
Pyroxenite (black part):
Pyroxene, phlogopite, nepheline (micro-dyke), rutile and calcite

The fine soil contains mainly K-feldspar and plagioclase from the weathering of the syenite, ijolite and borengite. Furthermore, pyroxenes, apatite, vermiculite and mica occur from the weathering of the pyroxenite and the other rocks in this profile.
The clay mineralogical assemblage is dominated by secondary chlorite and illite as well as various amounts of smectite and vermiculite and traces of mixed-layer minerals.

Profile A3 was classified as ***Hyperepiskeletic Cambisol*** or ***Leptosol***, respectively. This profile has by far the highest rock content of all profiles, often over 90 %, which would be necessary for the classification as Leptosol. Profile A3 is located right under the plateau, where profiles A4 and A5 are located at an 'edge', before the hill becomes a little bit steeper towards profiles A2 and A1. It seems, that most boulders and rocks got caught at this 'edge', leading to the extremely high rock content in this profile.

4.1.4   Profile Alkaline 4 (A4)

The parent rock for profile A4 is a coarse-grained, nearly completely unaltered ***gneiss***, which shows very weak signs of alteration by fenitization.
The mineralogical assemblage of this rock consists of quartz, mica, K-feldspar, plagioclase and zircon.

The mineralogical assemblage of the fine soil is absolutely dominated by the weathering products of the gneiss – quartz, K-feldspar, plagioclase, chlorite, vermiculite, mica and hornblende.

The predominant clay minerals are accordingly primary and secondary chlorite, illite, kaolinite and various amounts of smectite and vermiculite. Furthermore, high amounts of in I/V-mixed layer occur in the lowermost horizon.

Profile A4 was classified as ***(Weakly podzolized) Cambisol***. This soil is a Cambisol, but shows clear signs of beginning podzolization. Profile A4 and A5 are the only two profiles, where cowberry (*Vaccinium vitis-idaea*) occurs, which is a indicator for strongly acidic soil properties.

4.1.5   Profile Alkaline 5 (A5)

The parent rock for profile A5 is a fine grained, very homogeneous **gneiss**, which seems to be completely unaltered and not affected by fenitization.

Like in profile A4, the fine soil in profile A5 is dominated by the minerals, which derive from the weathering of the gneiss – quartz, K-feldspar, plagioclase, vermiculite, mica and hornblende.
The clay mineralogical assemblage is likewise dominated by partially very high amounts of secondary chlorite as well as primary chlorite, illite, kaolinite and various amounts of smectite and vermiculite. Like in profile A4, high amounts of a mixed-layer mineral – either an I/V- or an I/C/V-mixed layer - can be found in the lowermost horizon.

Profile A5 was classified as **(Weakly podzolized) Cambisol**. This profile is dominated by the sand and silt fractions. The gravel and the clay content is very low.

4.1.6   Profile Alkaline 6 (A6)

There is a big variety of rocks found in this profile.
Alnöite with the mineral components calcite, phlogopite, apatite, magnetite, chlorite, pyroxene, Cr-spinel and quartz.
Calciocarbonatite (sövite) with the mineral assemblage calcite, phlogopite, apatite, pyroxene, K-feldspar, quartz, baryte, sphalerite, parisite-(Ce)/synchisite-(Ce), thorite and monazite.
Feldspathic ijolite with the mineral assemblage calcite, mica, pyroxene and analcime.

The mineralogy of the fine soil shows the importance of biotite/phlogopite in all of the parent rocks as weatherable mineral. The predominant mineral is vermiculite as well as mica (biotite). Furthermore, mostly low amounts of quartz, K-feldspar, pyroxene, apatite and magnetite can be found in this profile. In the two lowest horizons, garnet can be found in the fine soil.

The clay mineralogical assemblage of this profile is the most outstanding of all. It nearly entirely consists of trioctahedral smectite and illite. Additionally, corrensite occurs in different amounts, mainly in the lowermost horizon. The smectites show some untypical characteristics in the XRD-analysis upon saturation with different chemicals as well as in the STA-analysis. This can be seen in connection with the special parent rocks of this profile. As the characteristics of the clay minerals of this profile are not yet fully understood, they will be subject of further research.

Profile A6 was classified as **Episkeletic Cambisol**. However, even if this profile has very alkaline parent rocks, like carbonatite, the vegetation assemblage, besides the indicator plants for alkaline soils, contains some indicators for acidic soil properties, e.g. *Linnaea borealis* and *Frangula alnus*. Profile A6 is located at a small hill, which is rather exposed to wind, leading to increased litter erosion. Therefore, the nutrient input is less with subsequent topsoil acidification and a development of the Cambisol towards 'acidic Cambisol' and eventually to a podzol. However, these processes can still not be seen in the chemical and physical properties, like migration of pedogenic oxides or clay. The vegetation reacts very sensitive to changes in the soil profile by

changes in its assemblage. In the case of profile A6, the vegetation shows the beginning of the topsoil acidification.

4.2 Comparison of the six soil profiles

All six soil profiles can be classified – according to the WRB – as Cambisols, whereas the biggest differences concern the rock content and the degree of podzolization. Four of the six sampled soil profiles – A1, A2, A3 and A6 - show big differences in the parent material, whereas the two sites on the more or less unaltered host rock - the migmatitic gneisses, i. e. Alkaline 4 and Alkaline 5, show rather uniform mineralogy. Due to the very different parent material and the small-scale mass movements, which obviously have taken place in this transect, a comparison is very difficult. Furthermore, due to these deposition processes it is hard to judge, what the 'real' bedrock of the soil profiles is.

Fig. 3.1 is a sketch of the sampled transect, where the profiles are presented and summarized. Following, the depositional trends downwards the slope are discussed for the profiles from the uppermost (A6) to the lowermost profile (A1), following the slope of the transect.

In *profile A6*, most of the rocks found in the profile are alnöites, sövites and ijolites. It is hard to judge, whether these alkaline rocks really reflect the alkaline dyke, which must be located under profile A6 with intruded alnöite, sövite and ijolite, or, if these rocks have been deposited from a nearby dyke by short-distance deposition. Nevertheless profile A6 is an alkaline profile, due to the predominance of alkaline rocks. This constitutes the main influence for the soil formation processes. In *profiles A5 and A4*, the lower parts consist of very homogeneous sands with gneissic boulders in the upper part of the profiles. Most interesting concerning profile A4 and A5 is the rather low degree of podzolization. The soil formation of profile A4 and A5 seems to be influenced by the surrounding alkaline rocks in the sense of a slowing of the podzolization process. *Profile A3* has the highest rock content and is dominated by big, angular to subangular boulders of the pyroxenite ijolite syenite and smaller rocks of the borengite. Furthermore, some rocks of gneissic material can also be found in this profile, still, the alkaline rocks predominate. The gneisses seem to have been deposited from profiles A4 and A5. Downwards profile A3, the transect becomes rather 'steep' towards profiles A2 and A1. *Profile A2* is the most mixed profile of all the profiles. Mostly, it contains syenitic fenite, but also big amounts of gneisses. The geochemical results of profile A2 show, that the lowermost horizon always groups with the horizons of profile A4 and A5, which have developed on gneiss. The upper three horizons always group with the horizons of the alkaline profiles A1, A3 and A6. Therefore, it can be concluded, that profile A2 has developed on gneiss, but was also largely influenced by syenitic fenite, which makes this profile an intermediate profile between alkaline and gneissic. Syenitic fenite could only be found in this profile. Therefore it is likely, that the original gneiss was both left unaltered and influenced by fenitization. *Profile A1*, as the relatively youngest profile, is also the most shallow and has the calcite melanite ijolite as parent material. This makes profile A1 a true alkaline profile. Gneisses can be found in the vicinity of profile A1, but not in the profile. Therefore, it can be concluded, that the gneisses
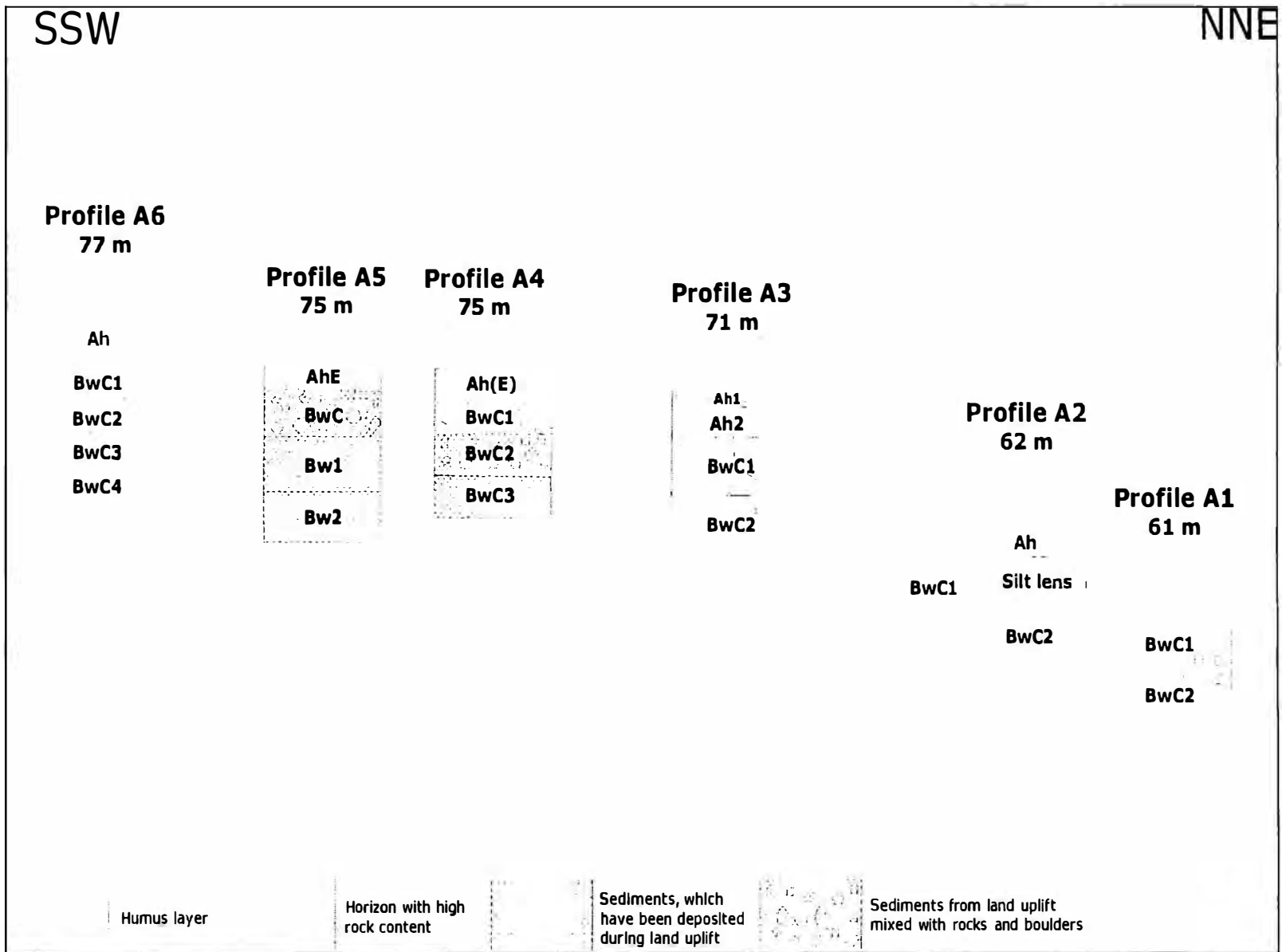
have been deposited recently and not during postglacial deposition. Therefore they were also not included in the soil formation of profile A1.

SSW

NNE

Profile A6
77 m

Ah

BwC1

BwC2

BwC3

BwC4

Profile A5
75 m

AhE

BwC

Bw1

Bw2

Profile A4
75 m

Ah(E)

BwC1

BwC2

BwC3

Profile A3
71 m

Ah1

Ah2

BwC1

BwC2

Profile A2
62 m

Ah

Silt lens

BwC2

BwC1

Profile A1
61 m

BwC1

BwC2

| Humus layer | Horizon with high rock content | Sediments, which have been deposited during land uplift | Sediments from land uplift mixed with rocks and boulders |

Fig. 3.1: Sketch of the transect

4.3   Geochemistry

The geochemical results showed very well, the partially very unusual contents of otherwise rare elements in the alkaline rocks. The correlations of the single elements in the fine soil showed, that the alkaline profiles A1, A3 and A6 form one group and profiles A4 and A5 the other. Profile A2 is – concerning geochemistry – a mixed or intermediate profile, where the lowermost part belongs to the 'acidic group' of A4 and A5, whereas the upper part belongs to the alkaline profiles A1, A3 and A6. This cluster formation was also observable with the rocks, but partially there were outliers, which showed extremely high contents of single elements.

Generally, it can be said, that the alkaline rocks and soil profiles are enriched in the following elements: Ti, Fe, Mn, Ca, P, Ba, F, Nb, S, Sr, Th, U, Zn and Zr.
Some rocks or profiles addtionally showed high amounts of: Cl, Co, Cr, Cu, Ni, V and Y.

For illustration of the difference in geochemistry, the average contents of Ti, Fe and Ca as well as Ba, F and Nb in the fine soil of the alkaline and the gneissic profiles were plotted in Fig. 3.2 and 3.3. Profile A2 was excluded from the calculations, because of its characteristics of an intermediate profile concerning the geochemistry.
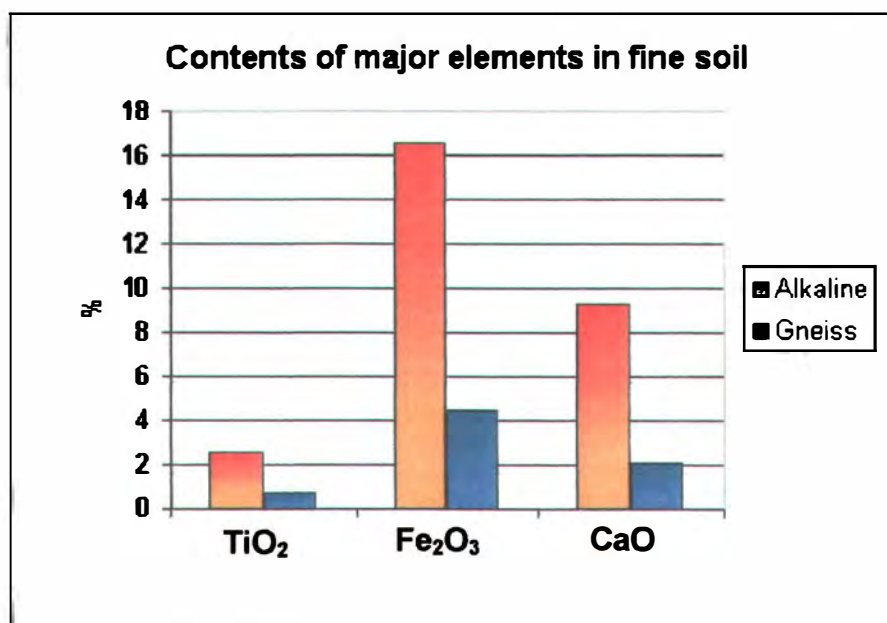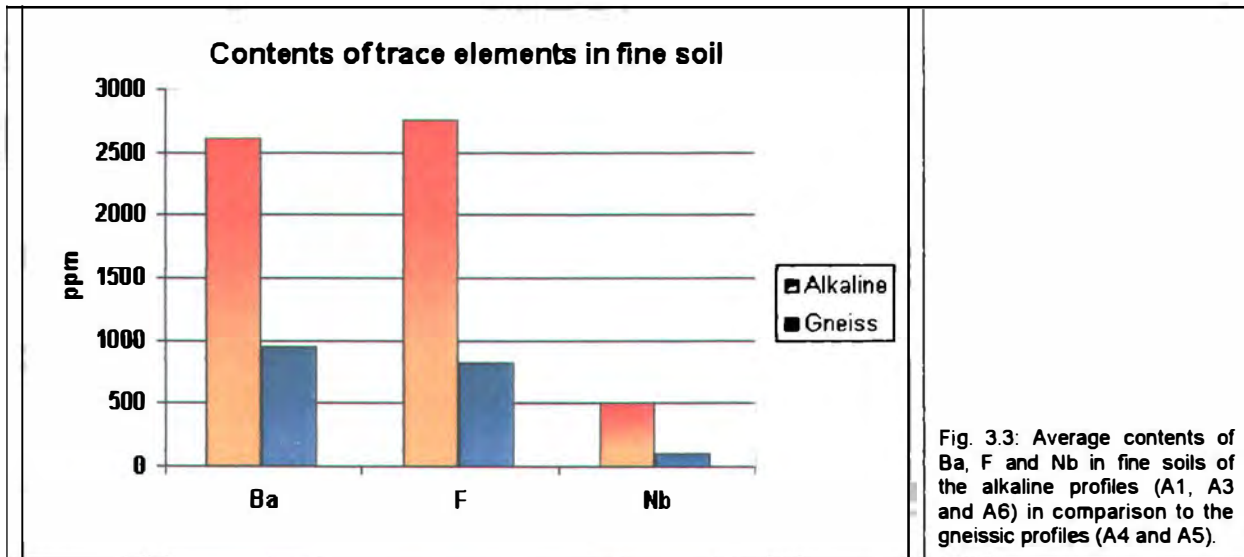

Fig. 3.2: Average contents of Ti, Fe and Ca in fine soils of the alkaline profiles (A1, A3 and A6) in comparison to the gneissic profiles (A4 and A5).

Fig. 3.3: Average contents of Ba, F and Nb in fine soils of the alkaline profiles (A1, A3 and A6) in comparison to the gneissic profiles (A4 and A5).

5 Conclusions

- **There are significant differences in mineralogy and geochemistry between alkaline and acidic parent material and soil profiles**
- **The soil formation processes are the same, but differ in progress due to the different age of the soil profiles. The soils on gneissic parent material already show signs of podzolization, whereas the podzolization processes seem to have been ,slowed down' by the influcence of the alkaline rocks.**
- **The soil profiles on gneiss are rather uniform in mineralogy and geochemistry**
- **The alkaline rocks and soil profiles differ strongly among one and another due to the different types of alkaline rocks**
- **The vegetation reflects the parent material very well**

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