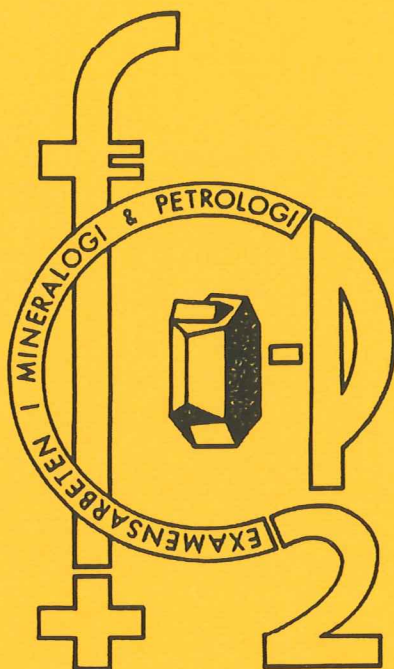


EXAMENSARBETE I GEOLOGI VID LUNDS UNIVERSITET

Mineralogi och petrologi

LUNDS UNIVERSITET
GEOBIBLIOTEKET
PERIODICA



Proterozoic hydrothermal alteration and mineralization along the Protogine Zone in southern Sweden

Daniel Larsson

Lunds univ. Geobiblioteket



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"Gold is where you find it"

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Abstract

Occurrences of high alumina rocks constituted by quartz, kyanite, rutile and Al-phosphates are spatially related with the Protogine Zone, a system of ductile and brittle deformation zones within the Proterozoic crust of southern Scandinavia. A hydrothermal origin has been proposed for high alumina rocks at Västanå, based on the chemistry of these rocks, while gradual transitions between magmatic rocks and high alumina rocks at Hökensås and Hålsjöberg suggest a similar origin. These rocks are characterised by very low alkali/aluminum ratios, caused by hydrolytic leaching whereby alkalis and other rock forming elements have been leached, leaving a residual rock mainly composed of high alumina minerals and quartz. A partly amphibolitised dolerite cuts the high alumina rock at Hålsjöberg and clearly postdates this hydrothermal event. Textural relations and considerations of the ductile-brittle transition in the crust furthermore suggest that hydrolytic leaching occurred before or during prograde metamorphism at a temperature below c. 400°C. Character of alteration and geological setting indicate that solutions causing hydrothermal alteration derived from a magma of acid or intermediate composition, which also served as heat source for convection in a brittle, near surface environment. The occurrence of rare Al-phosphates in high alumina rocks at Hålsjöberg and Hökensås suggests a temporally related origin of hydrothermal leaching and formation of some of the Al-phosphates. Rare Al-phosphates at Västanå; on the other hand, seem to be restricted to hematite mineralization, indicating a simultaneous origin of hydrothermal leaching and Fe-, Mn-mineralization. Comparison of high alumina rocks world over and consideration of plate tectonic setting favour formation in a subduction related environment rather than in an intracontinental rift setting.

1 Introduction

In southern Sweden, small deposits of rare Al-phosphates, rutile and abundant kyanite occur at Västanå, Hökensås, Hålsjöberg, and Diksberg (Fig. 1). All these occur along a foliated and fractured lineament, called the Protogine Zone (PZ), extending from southernmost Sweden to northern Värmland and into Norway, underneath the Caledonian nappes.

The alignment of these mineralizations along the PZ strongly suggests that their genesis and/or preservation are somehow linked to the tectonic evolution of the zone.

Geijer (1963) considered that titanium and phosphorus in these deposits were added by magmatic fluids, possibly related to intrusion of dolerite. Wise and Loh (1976) suggested that similar high alumina deposits in the western USA (e.g. White Mountain, California) characterised by the assemblage Quartz + Al-silicate + Al-phosphate + rutile, formed by hydrolysis of metavolcanic rocks; a process whereby the rock minerals take up hydrogen ions and water and release cations to the transient fluids (Hemley and Jones 1964; Meyer and Hemley 1967; Montoya and Hemley 1975). Wise and Loh (1976) showed, by using standard hydrothermal techniques that the presence of Al-phosphates in this kind of deposits could be due to phosphoric acid in the hydrolyzing fluid. This genetic model was adopted by Andréasson and Stanfors (1988) and Ek and Nysten (1990). The latter authors also inferred that hydrothermal alteration at Hålsjöberg and Hökensås could have taken place in a hot spring environment, where supracrustal rocks were altered to an Al-rich residual phosphate-bearing rock which during later regional metamorphism was converted to a kyanite-bearing siliceous rock. At Hålsjöberg they estimated peak metamorphic conditions at $P > 2 \text{ kb}$ and $T < 575^\circ\text{C}$. This kyanite-bearing rock or "quartzite" as well as mica schist at Hålsjöberg and Västanå have been considered to be of sedimentary origin (Bäckström 1897; Geijer 1963; Lundegårdh 1995). However, as described in this paper, a granite-"quartzite" transition occurs at Hålsjöberg, where the granite appears to have been altered to a "quartzite" rich in kyanite. At Hökensås, granite seems to grade into a similar kyanite bearing "quartzite" (Rodhe and Andréasson 1992) which earlier has been interpreted to be of sedimentary origin (Ek and Nysten 1990). The close association of granites at these localities has led to the assumption that most, if not all of the "quartzite" at Hökensås, and at least part of the "quartzite" at Hålsjöberg derived from granitoid rocks. In the Västanå area, Kornfält and Bergström (1983) likewise reinterpreted a tectonized "metasedimentary rock" as a volcanic rock which had been leached from Na and Ca by hydrolyzing fluids. The quartzite hosting the high-alumina-phosphorus-assemblage at Västanå is still considered to be of sedimentary origin, due to obvious sedimentary structures (Andersson 1975; Kornfält and Bergström 1983).

In this study, a mineralogical description of the granite-"quartzite" transition at Hålsjöberg is made, as well as a discussion of the physicochemical conditions prevailing during the alteration. High-alumina rocks formed by hydrothermal processes are frequently associated with ore-mineralization which motivates an investigation of associated sulfides at Hålsjöberg and Hökensås with respect to base metal content, trace elements and possible anomalies of Au and Ag. At Västanå, where sulfides are scarce, emphasis has been made on investigating the relation between hematite concentrations and high-alumina assemblages. In this paper, quartzitic rocks will be called quartzites only if the sedimentary origin is ascertained. When uncertainties remain about the protolith, the name quartz-kyanite rock or high-alumina rock is used. The word Protogine Zone is used, not to denote any

lithotectonic boundary, but rather as a name of a zone with brittle and ductile deformation, whatever its exact genesis or extent.

In addition to examining the genesis of the high-alumina assemblages, the purpose of this paper is to make comparisons with geochemically similar deposits described in the literature, in order to shed some light on the tectonic evolution of the PZ.

2 Geological setting

2.1 Bedrock geology of southern Sweden

The Proterozoic crust of southern Sweden was accreted to the Baltic shield during the Middle Proterozoic. Several tectonic zones form boundaries between segments of crust with different tectonic evolutions. One of these zones is the Protogine Zone (PZ) which could have been

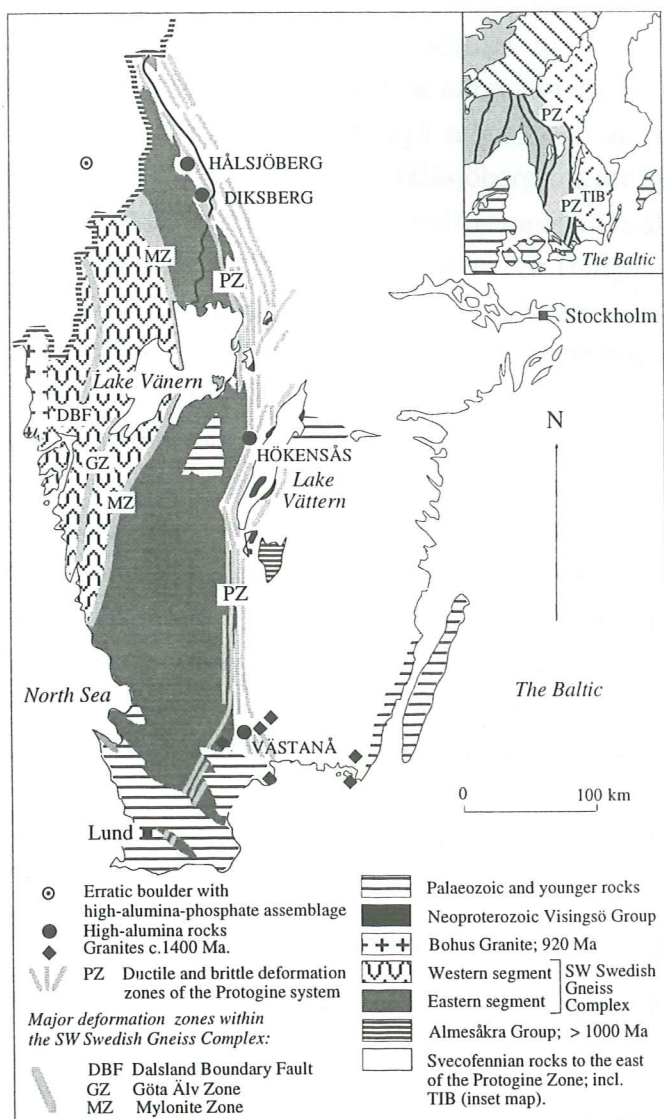


Fig. 1. Map of southern Sweden, showing main geological provinces and occurrence of high-alumina rocks along the Protogine Zone. TIB = Transscandinavian Igneous Belt (see inset map). Modified after Andreásson and Dallmeyer 1995.

established already when the Svecofennian crust (1,90-1,86 Ga) was intruded by granites of the Transscandinavian Igneous Belt (TIB) (1,83-1,65 Ga; Fig. 1)(Gorbatshev 1980; Gaa'l and Gorbatshev 1987). The PZ is today a tectonic belt of anastomosing ductile and brittle deformation zones forming the approximate easternmost limit of terranes affected by the Grenvillian-Sveconorwegian orogen (1250-900 Ma). However, the TIB and possibly Svecofennian rocks occur on both sides of the PZ. The continuity of the PZ north of lake Vättern has been questioned since it occurs within the eastern segment of Sveconorwegian orogen and thereby only corresponds to the boundary between semi penetratively and more or less penetratively deformed TIB rocks. (Wahlgren et al. 1994). However, as mentioned above, the PZ may have had its origin before the Sveconorwegian orogen which was initiated at c. 1250 Ma and was coming to an end at c. 900 Ma, when crustal slices were thrust over from the west and stacked on top of each other causing granulite facies metamorphism in south western Sweden. Subsequent exhumation uncovered these granulites while the PZ evolved into a c. 30 km wide zone of steep faults separating the high grade granulitic terrane in the west from the lower grade

terrane in the east (Gaa'l and Gorbatshev 1987; Gorbatshev and Bogdanova 1993). Mafic dyke swarms intruded at and along the PZ at the final stages of crust formation c. 1500 Ma ago (Johansson and Johansson 1990, Sm-Nd age) and at three occasions during the Sveconorwegian event, as a response of extensional tectonic regimes. Mafic dyke swarms intruded at 1220 Ma and c. 1180 Ma as a response of incipient break up of the shield. Younger dyke swarms of tholeiitic affinity intruded at c. 900-800 Ma when rejuvenation of the PZ occurred due to rapid uplift of the western crustal segment (Patchett 1978) or as a response to Neoproterozoic continental break up (Solyom et al. 1992).

2.2 Hålsjöberg area

Hålsjöberg is located 20 km NE of Torsby (Fig. 1). Quartz-kyanite rock is here associated with mica schist of supposed sedimentary origin, a feldspar-porphyry of dacitic composition which locally grades into a phyllonitic rock and a gneissic granite which in similarity to the dacite locally grades into a highly deformed rock (Gorbatshev 1971; Lundegårdh 1995). The northernmost quartz-kyanite outcrop (Figs. 2 and 3) is almost totally hosted by a gneissic granite which is the dominating bedrock in the region, although subordinate at Hålsjöberg. Dolerite sills/dykes, called hyperites constitute the youngest rock at Hålsjöberg and are like the quartz-kyanite bodies dipping between 30-50° E. The dolerite has been altered to amphibolite along its margins, a feature which is very common in southern Sweden and not restricted to Hålsjöberg. Dykes of granite resembling Filipstad type granite cut the dacitic rock (Fig. 4). A few meters wide border zone of muscovite-bearing rock, frequently occurs between the quartz-kyanite bodies and the surrounding host rocks. Part of the quartz-kyanite rock has a banded texture with quartz-rich bands interlayered with kyanite-rich bands. This structure has been interpreted as a primary sedimentary feature (Lundegårdh 1995). The major part of the quartz-kyanite rock occurs as a massive rock where quartz and kyanite is evenly distributed. Al-phosphates and rutile occur almost exclusively in both varieties of quartz-kyanite rock while the magmatic rocks are mainly barren of these.

Late N-S trending faults occur near the eastern margin of the locality; these are however unrelated to the hydrothermally altered rocks (Kjell Gustafsson, Terra Mining, pers. comm.).

LKAB has been prospecting in the area, with the intent of mining the rock for its aluminum. Average chemistry and mineralogy of the quartz-kyanite rock are presented in Tables 1 and 2.

Table 1. Average chemistry of quartz-kyanite rock at Hålsjöberg (Bida 1985).

SiO ₂	70-80 %
Al ₂ O ₃	18-24 %
TiO ₂	0.25-0.70 %
Fe ₂ O ₃	0.8-2.0 %
K ₂ O	0.10-0.40 %
P ₂ O ₅	0.1 %

Table 2. Average mineralogical composition of quartz-kyanite rock at Hålsjöberg (Bida 1985).

Quartz	55-70 %
Kyanite	25-40 %
Rutile	0.3-0.7 %
Muscovite	3-4 %
Fe, Ti-oxides	
Pyrite	
Al-phosphates	

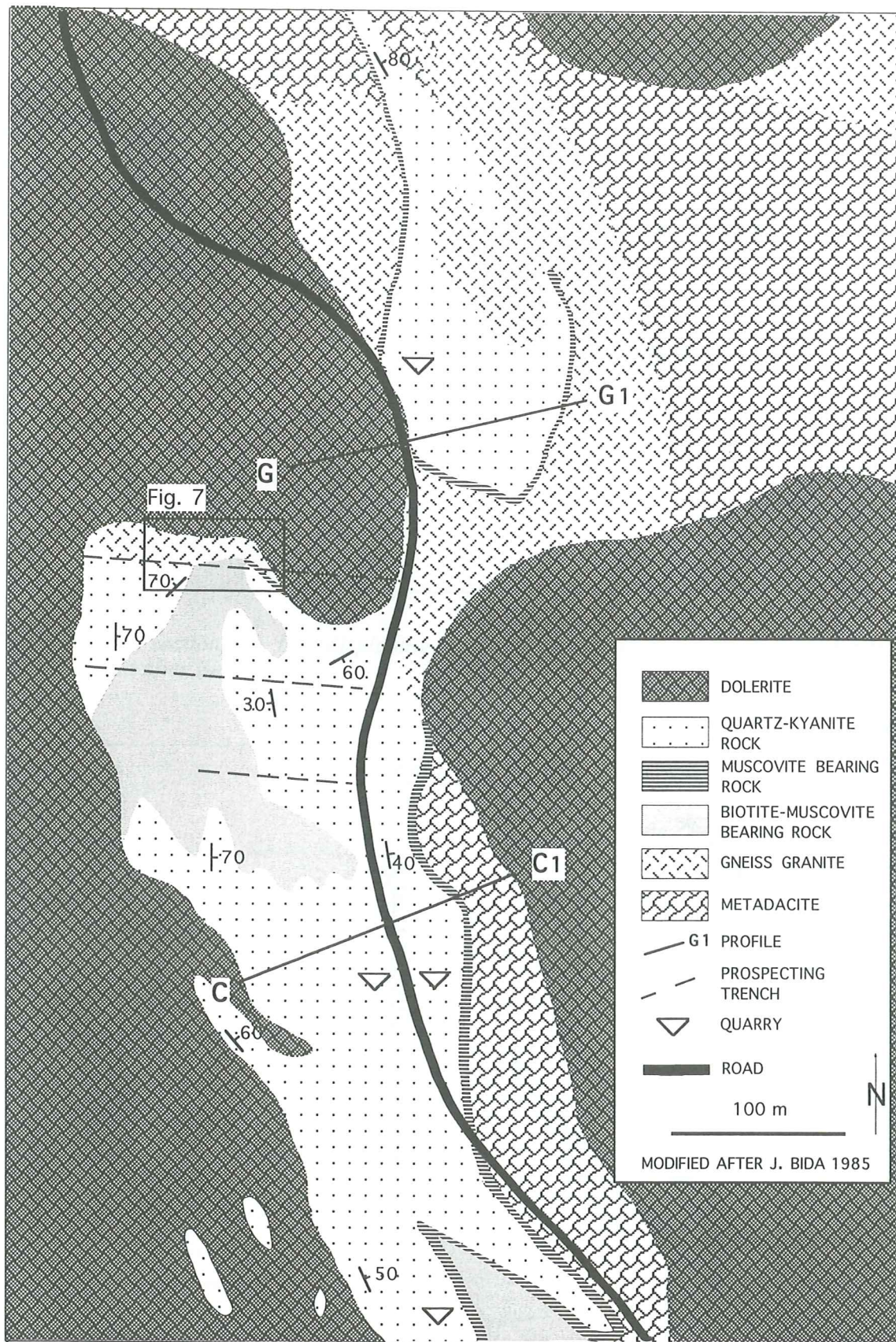


Fig. 2. Geological map of the occurrence of high-alumina rocks at Hålsjöberg. Modified after Bida (1985).

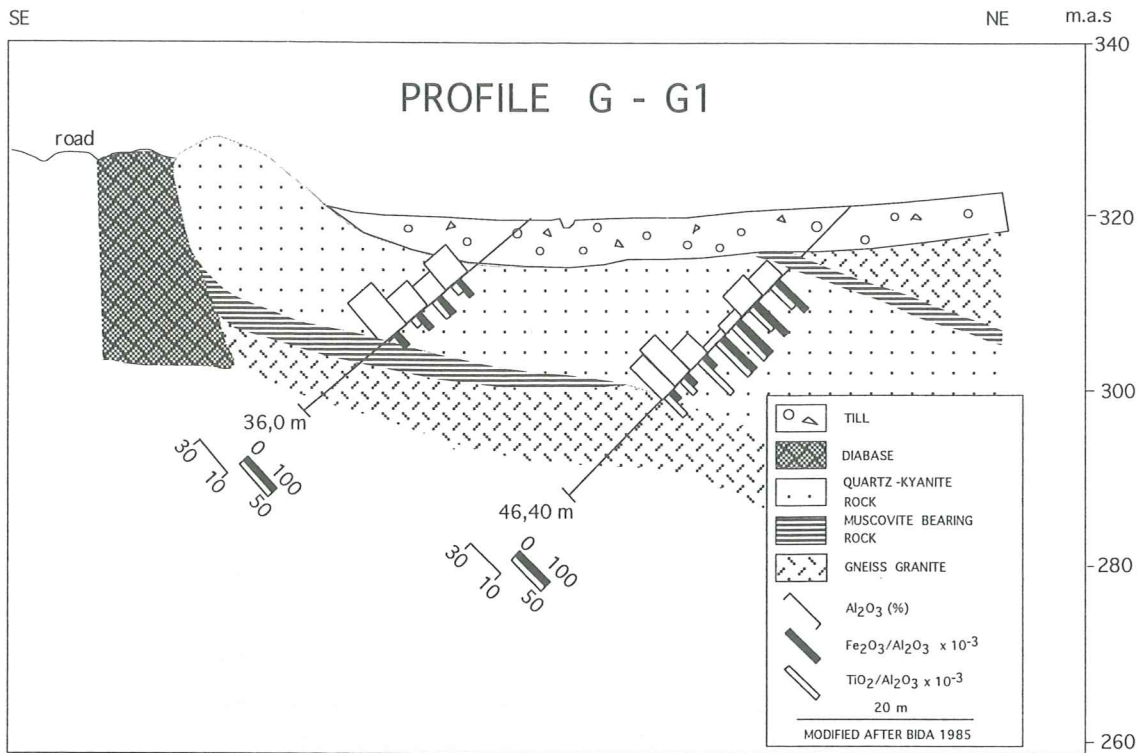


Fig. 3. Cross section G - G1, displaying intrusive contact between dolerite and quartz - kyanite rock. Modified after Bida (1985).

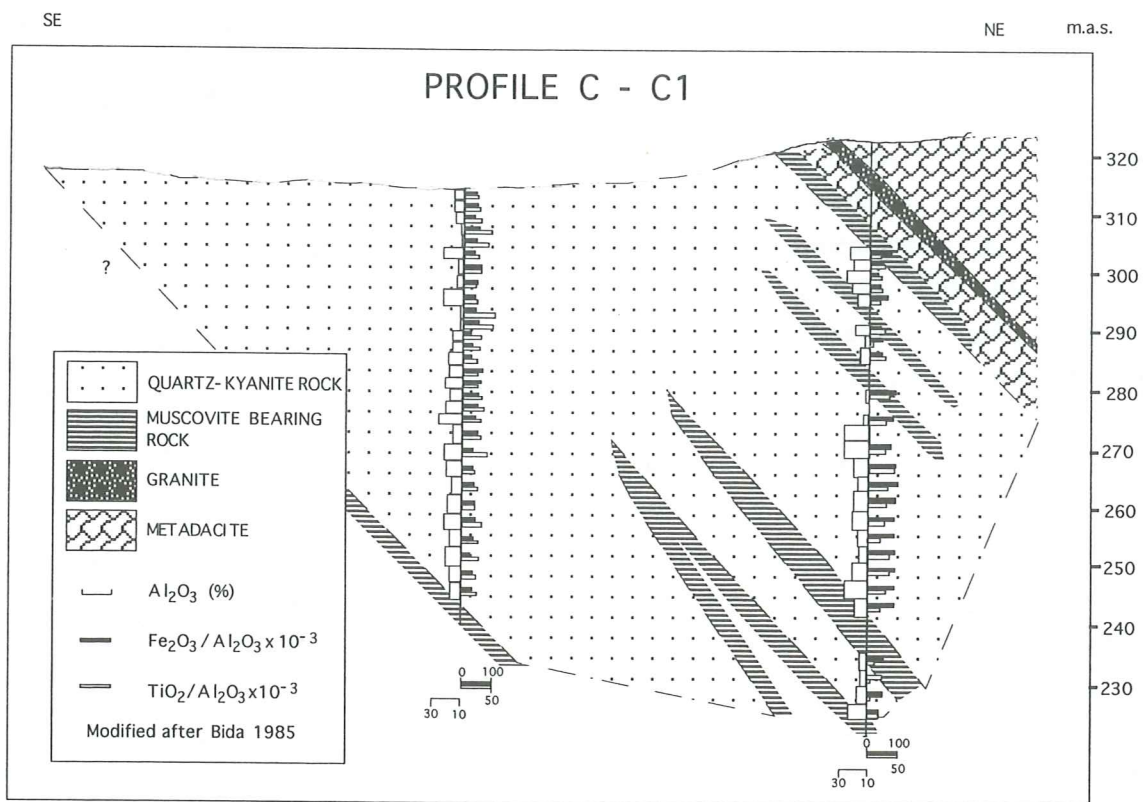


Fig. 4. Cross section C - C1, showing a dyke of granitic rock (upper right) and occurrence of muscovite - bearing rock within the quartz - kyanite rock. Modified after Bida (1985).

Today the quarry is run by Hålsjöberg Kyanit AB and the rock is quarried for its ornamental value.

An erratic quartzitic boulder consisting of c. 40 % kyanite and accessory rutile, lazulite and svanbergite has been found c. 80 km west of Hålsjöberg at Storsjön in Norway, which suggests a continuation of bedrock-occurrences of high alumina rocks northwest of Hålsjöberg (Bryn 1962).

Igelström (1854) discovered an isolated outcrop at Diksberget c. 60 km south of Hålsjöberg (Fig. 1) constituted by quartz, kyanite, lazulite, rutile, pyrite and apatite (Geijer 1963). However, this outcrop has not been refound since (Lundegårdh 1995).

2.3 Hökensås area

The Hökensås deposit, located at Björnåsen c. 12 km SE of Tidaholm (Fig. 1), comprises white mica schists, chloritoid-muscovite bearing rocks as well as a quartz-kyanite rock which in similarity to Hålsjöberg is the host for the characteristic Al-phosphate - rutile assemblage (Fig. 5).

White mica schists pass into a protomylonitic granite within N-NNE trending shear zones. The granite occurs in an unaltered state to the east and is considered to belong to the Transscandinavian Igneous Belt (TIB) (Rodhe and Andréasson 1992). Rocks of volcanic origin occur in the area. Most notable is a small outcrop of a somewhat foliated and mineralized metavolcanic rock at Krigskullen c. 1 km south of Björnåsen. The Hökensås area is a horst which borders the lake Vättern graben, hosting the Neoproterozoic Visingsö group.

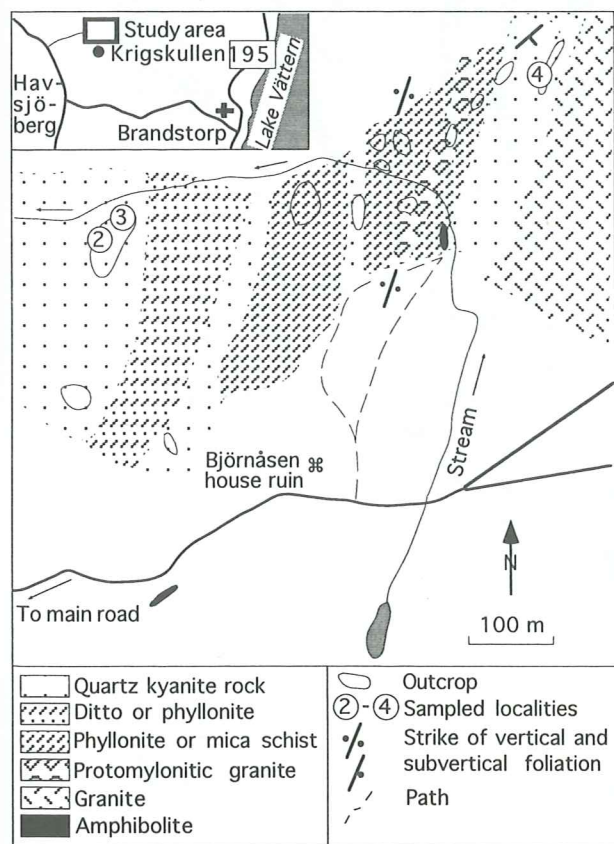


Fig. 5. Geological map showing occurrences of high - alumina rocks in the Hökensås area Modified after Rodhe and Andréasson (1992).

2.4 Västanå area

The Västanå deposit is situated 20 km NE of Kristianstad (Fig. 1). The assemblage Al-phosphates+Al-silicates+hematite is confined to a small abandoned iron mine, hosted by a quartzite of sedimentary origin, which forms a c. 5 km long and c. 0,5 km wide belt (Fig. 6). Crossbedding as well as conglomerates indicate a high energy sedimentary environment during deposition of the protolith of the quartzite. The mine is today waterfilled and is approximately 2 meter wide and 30 meter long, situated close to the underlying metarhyolite. This is the type locality for the rare Al-phosphates trolleite and attakolite, which were described by Blomstrand (1868) who found them in the tailings of the abandoned mine. The stratigraphy is tilted to the west and the transition to the overlying altered and foliated mica schist is gradual and diffuse. Layers of quartzite and conglomerate occur intercalated. This mica schist is in places andalusite- and/or kyanite-bearing. Due to its

relatively low Al-content and the sporadic presence of feldspar phenocrysts in this mica schist, it has been interpreted to be a volcanic rock which at a later stage was leached from alkalis. Except lazulite, mostly occurring as fracture fillings, no Al-phosphates and no noteworthy amount of hematite have been found in it (Bäckström 1897; Andersson 1975; Kornfält and Bergström 1983).

The mica schist mentioned above is of greenschist facies grade while surrounding gneisses of unknown origin are of amphibolite facies grade. Metavolcanic rocks and gneisses were intruded by granites of the Karlshamn group. A granite of this group has been dated at c. 1350 Ma. (Åberg et al. 1985, Rb-Sr whole rock methods). A dolerite dyke dated at c. 930 Ma (Johansson and Johansson 1990, Sm-Nd isochron), cuts the foliated mica schist slightly north of the Al-silicate-bearing micaschist.

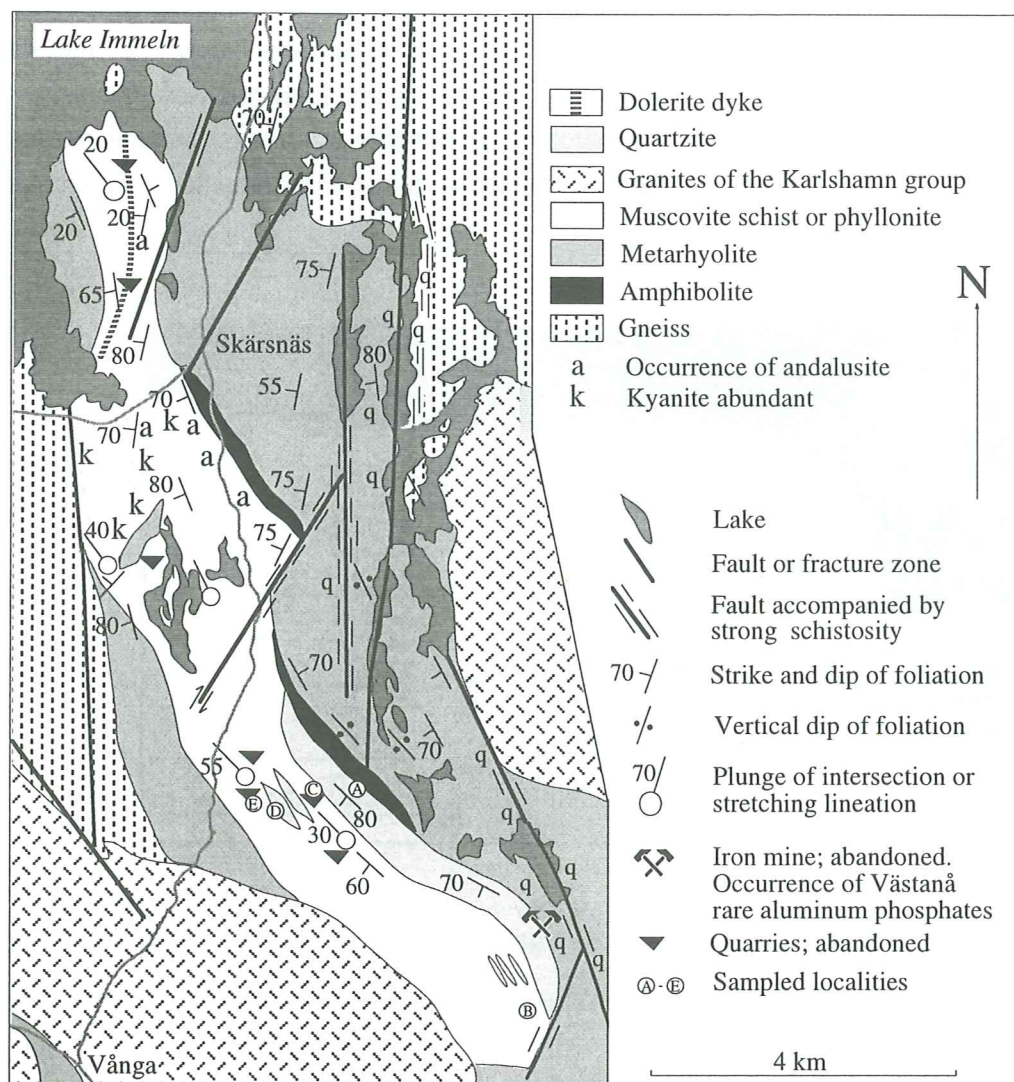


Fig. 6. Geological map of the Västanå area. Sampled localities are indicated. Modified after Andreásson and Dallmeyer (1995).

3 Methods

3.1 Field work

At Hålsjöberg, field work was concentrated to rock sampling and mapping of a prospecting trench across a transition zone between granite and quartz-kyanite rock (see inset, Fig. 2). Reconnaissance of the quarry and surroundings was also made. Samples were taken at close interval from a c. 1 meter wide transition zone (see inset, Fig. 7) where a muscovite-rich granite grades into a kyanite-dominated rock. Samples were also taken from the surrounding granite and the dolerite dyke and its amphibolitized margin as well as from a sulfide bearing quartzitic rock, situated near the granite. At Hökensås, samples were taken from three outcrops, with the main purpose to determine contents of trace elements, base metals and noble metals, in order to assess the source of fluids and crustal depth of alteration and sulfide mineralization. Two of the outcrops are characterised by relatively high contents of sulfides (2-10%) in quartz-kyanite rock. The third outcrop, c. 1 km south of Björnåsen ruin, at Krigskullen, is a sulfide bearing metavolcanic rock.

Although the Västanå area has been thoroughly investigated, uncertainty remains as to the timing of hydrothermal alteration and hematite-mineralization. Rock samples were taken from the quartzite to determine whether it has been affected by hydrothermal alteration or not. Special attention has been paid to hematite mineralization and its relation to sedimentary processes or/and hydrothermal activity,

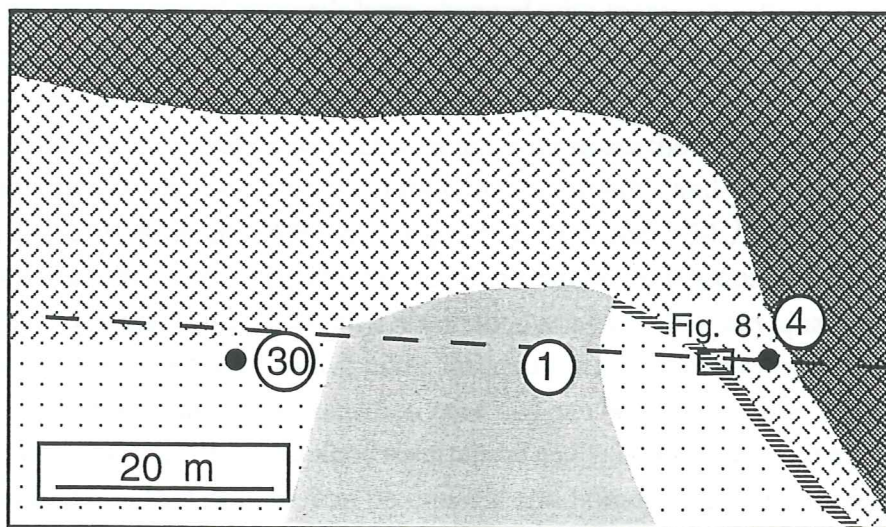


Fig. 7. Sampled sites along the prospecting trench, referred to in the text. For legend, see fig. 2.

since hematite in addition to other heavy minerals define sedimentary structures as crossbedding in the quartzite as well as occur in quartz veins.

Approximately forty samples were selected for thin section preparation. Of these, 12 were taken from the transition zone between muscovite-rich granite and kyanite-dominated rock at Hålsjöberg. Samples of granite interpreted as being more or less unaffected by secondary alteration were taken at short distance from this alteration zone (samples 87-1, 93-1 and 4, Fig. 7 and 8) and will be called

unaltered granite in this paper. The granite within the zone is extensively sericitised and unaltered granite, if any, is covered by Quarternary cover. It is assumed that the unaltered granite sampled constitutes the protolith of the altered granite within the above mentioned transition zone.

3.2 Laboratory work

3.2.1 Modal analysis

Modal analysis of 14 samples from the transition zone and surrounding granite were made (appendix). Etching with sodium hexanitrocobaltate was performed on some thin sections to differentiate K-feldspar and plagioclase. Petrographical analysis was supplemented by electron microprobe analysis to determine anorthite content in plagioclase and for identification of accessory minerals.

3.2.2 XRD

X-Ray Diffraction (XRD) was used with the main purpose of identifying minerals which are difficult or impossible to identify by optical microscopy. Among these are minerals occurring as earthy material, e.g. clay minerals, hematite and some Al-phosphates. The Al_2SiO_5 -polymorphs, kyanite and sillimanite are sometimes difficult to distinguish from each other by optical methods.

Eight samples from which thin-sections had been prepared were selected for XRD-analysis to determine how the proportions of minerals have changed with increasing alteration in the transition zone at Hålsjöberg. A full scan was done for most of the samples, to select suitable peaks. The most important requirements are that no interference with other peaks exists and that peaks are sufficiently strong. Muscovite, quartz and kyanite were chosen since these are the major phases in the transition zone. Two suitable peaks were selected for muscovite and quartz, and one peak was selected for kyanite (for muscovite 10,00 Å and 4,00 Å, for quartz 4,26 Å and 1,54 Å and for kyanite 1,34 Å). A special program was then used whereby the scanner searches and stops at the selected peaks to measure the intensity during a time interval. This method does not give any quantitative data, since no internal standards have been used, but it gives information about increasing or decreasing trends of the selected mineral phases along the transition zone and can be considered as a complement to the modal analysis. The advantage of this method over modal analysis is that a relatively large amount of material, as compared to a thin section, can be crushed and homogenized and thereby get a sample that is more representative. The drawbacks of XRD are that the intensity of a peak is not only dependent on the proportion of a certain mineral but also of the chemistry of the sample and especially the content of feric minerals. Grain size of the grinded sample is of course another important factor to consider, as well as the preferential orientation of the mica minerals, especially in samples where the mica content is very high.

3.2.3 Geochemical analysis

Samples for chemical analysis were crushed, weathering rinds removed, and sent to ACME Analytical Laboratories LTD, a Canadian laboratory in Vancouver, specialised in ore analysis. To

determine geochemical zonation in the above mentioned transition zone at Hålsjöberg, a whole rock analysis was performed by ICP, whereby contents of altogether 11 main elements and 7 trace elements were determined. Sample sizes were between 300 and 1000 gram, except for sample 23 (*Quartz rock*) which weighed c. 70 gram. This last sample was still considered as a representative sample due to the homogeneity and small grainsize of the rock. A so called geochemical extraction analysis was also performed. This is a partial leach technique based on dissolution by waterdiluted aqua-regia solution followed by ICP-analysis, whereby contents of base metals and noble metals was determined. It should be noted that the last mentioned analytical technique is a partial leach method which does not dissolve silicate minerals. Total leach is only accomplished for some of the elements which are almost exclusively present in sulfides and oxides. Gold contents were determined separately by aqua-regia digestion followed by graphite furnace atomic adsorption, with a detection limit at 1 ppb. Samples from Hökensås and Västana were only analysed with the geochemical extraction technique and not with the whole rock technique.

4 Results

4.1 Mineralogical and geochemical zonation at Hålsjöberg

The following description concerns a zone where a *granite* passes into a bluish kyanite dominated rock (Fig. 8). Results from modal analysis and geochemical analyses are presented in Figs. 9 and 10 (see also appendix).

The *unaltered granite*, which is slightly deformed and recrystallised has anhedral microcline and

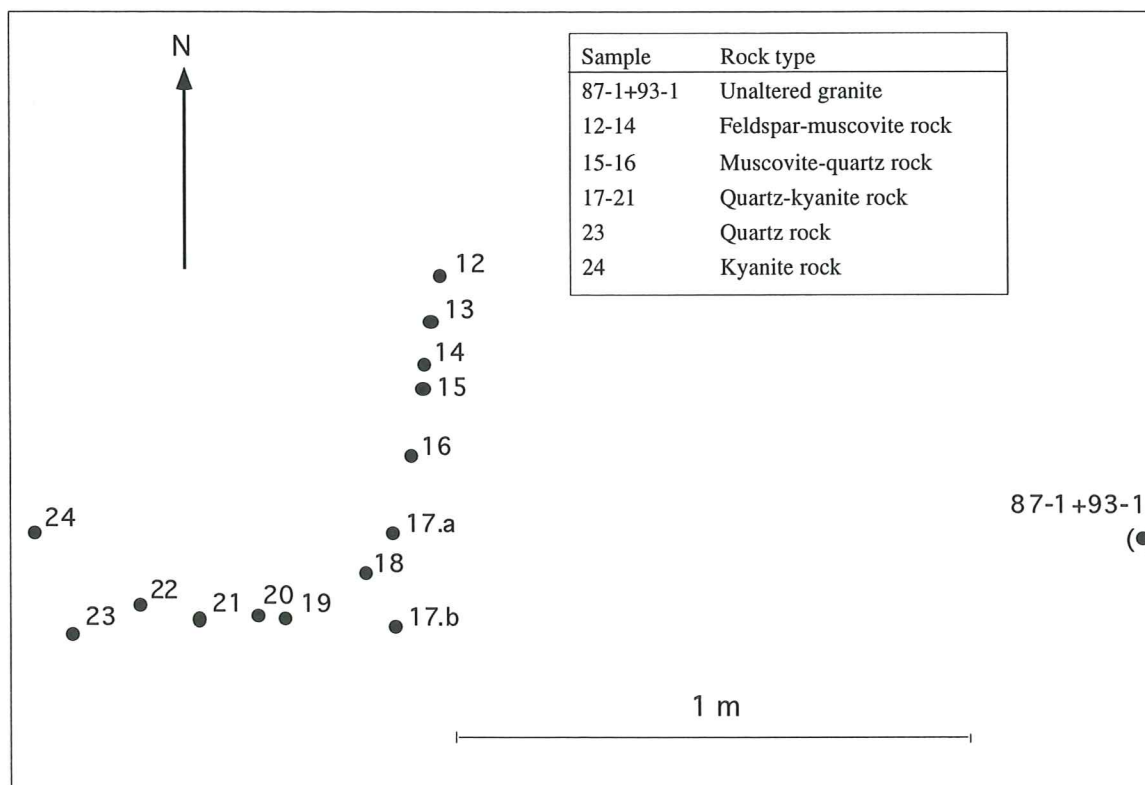


Fig. 8. Samples taken along a transition - zone between granite and kyanite - dominated rock at Hålsjöberg, used for modal, XRD and chemical analysis. Approximate location of samples 87-1 and 93-1.

oligoclase phenocrysts rimmed by fine grained aggregates of feldspar and quartz (Fig. 11). Albite twinning is common in both phenocrysts and matrix plagioclase. Crosshatched twinning of microcline is similarly present both in phenocrysts and smaller grains. The granite has a red colour which to some extent may be due to hematite pigment within the finegrained aggregates surrounding the phenocrysts and within microcline phenocrysts. The modal content of brown biotite is about 10% and it occurs in slightly chloritized aggregates of a size up to a few mm, together with zircons and hematite with exsolution laminae of ilmenite. Pyrite is present as a few small idiomorphic crystals, rimmed by limonite. Small amounts of fresh idiomorphic magnetite which seems unrelated to the biotite occur as well. Muscovite/sericite occurs as randomly oriented crystals in the plagioclase but also as independent small muscovite crystals. Myrmecitic textures are present although scarce. A few euhedral apatite crystals have been noted.

The granite passes into a *feldspar-muscovite rock* where the K-feldspar seem to have been altered to plagioclase and muscovite. Remnants of microcline are present in albite-oligoclase phenocrysts where the cross hatched twinning has been replaced by muscovite and albite twins forming a checked pattern (Fig. 12), whereas K-feldspar only remains as small domains within the plagioclase. The primary plagioclase is strongly sericitised. Biotite is partially replaced by muscovite while hematite, ilmenite and zircons remain largely unaffected. Magnetite has not been noted.

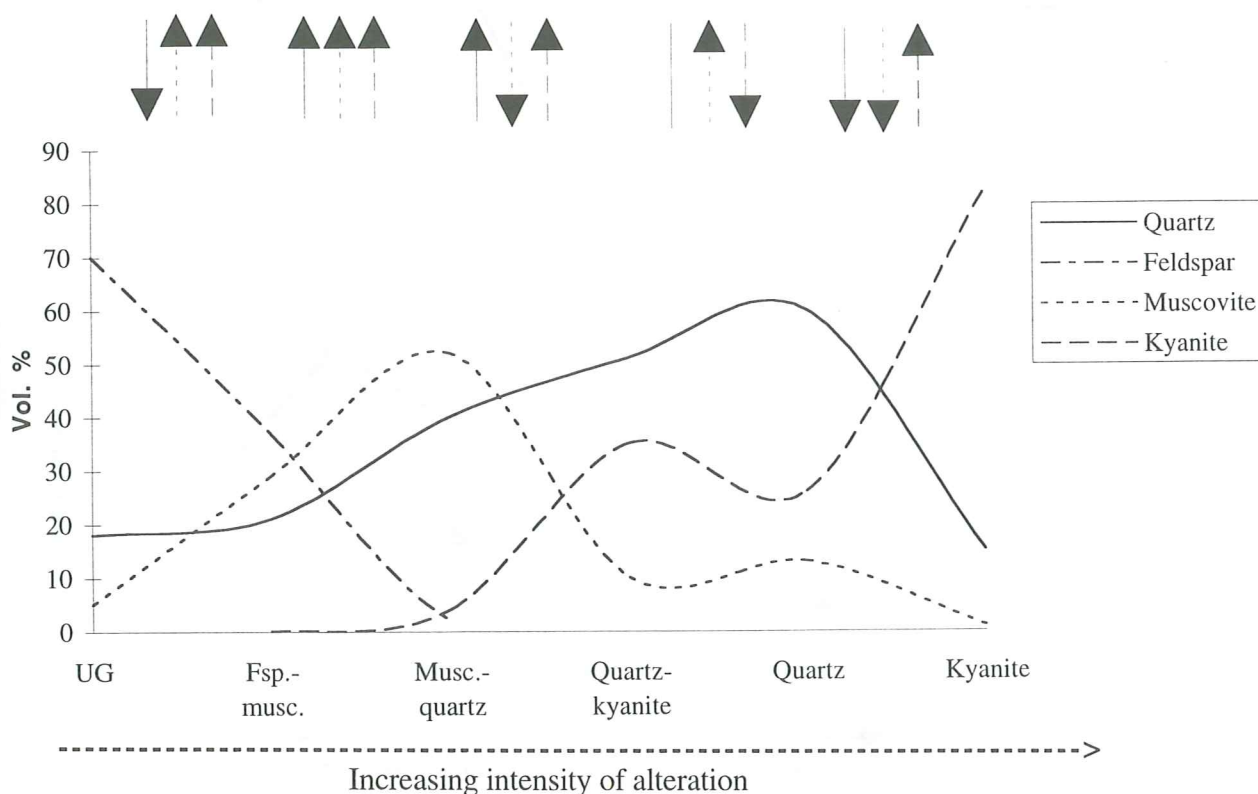


Fig. 9. Variation in abundance of minerals indicative of alteration in the transition zone at Hälsjöberg. Based on modal analyses of 12 thin-sections. UG = Unaltered Granite (average of samples 4 and 87-1). Fsp.-musc. = Feldspar muscovite rock (average of samples 12, 13, 87-2 and 14). Musc.-quartz = Muscovite-quartz rock (sample 15). Quartz-kyanite rock (average of samples 18, 19, and 21). Quartz rock (sample 23). Kyanite rock (sample 24). Arrows show decreasing or increasing trend of mineral content, as determined by XRD-analysis. (See also appendix).

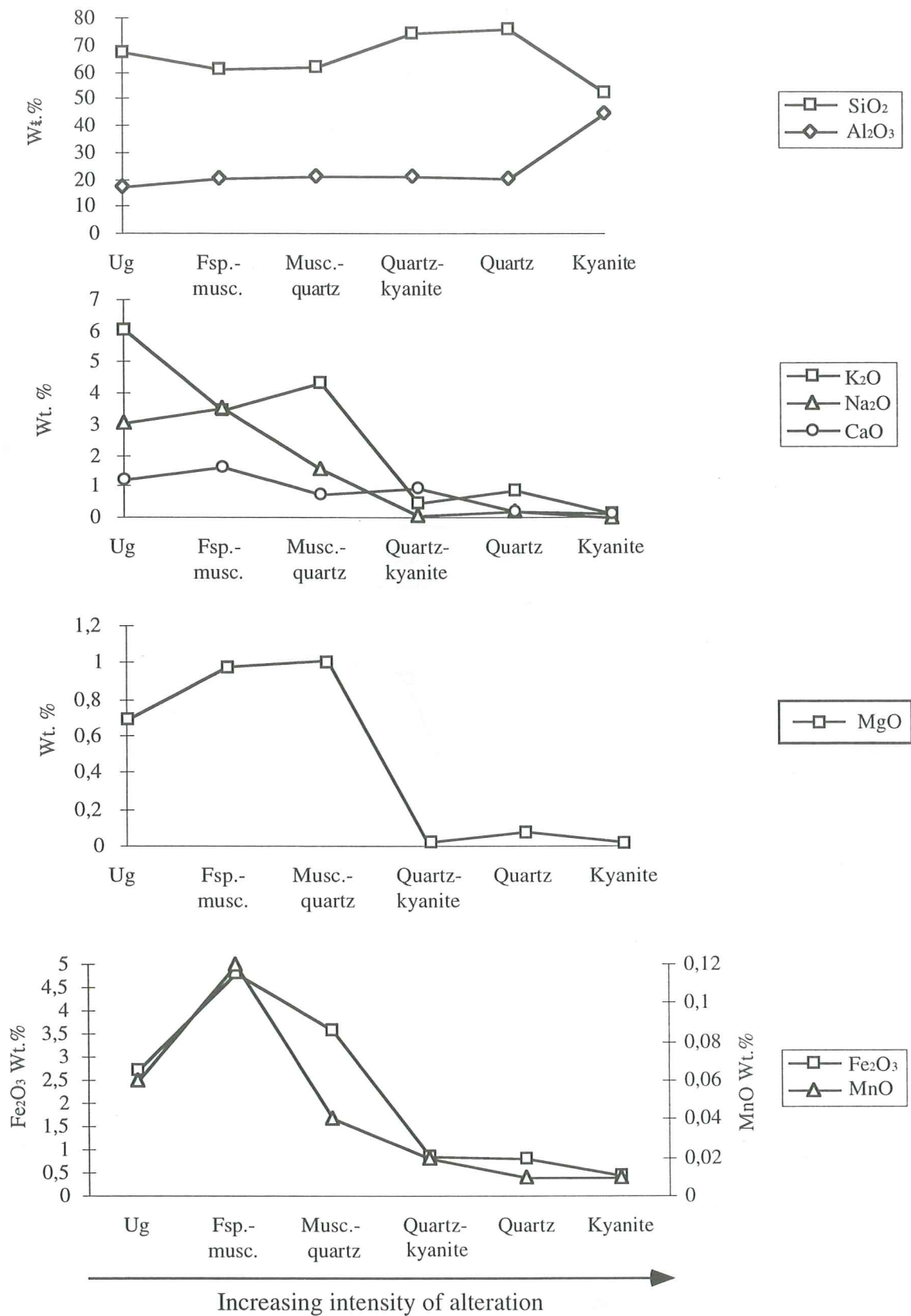


Fig. 10. Chemical variation with increasing intensity of alteration along the transition zone at Hålsjöberg. Based on 9 samples. Unaltered granite (average of samples 4, 93-1 and 87-1). Feldspar-muscovite rock (average of samples 87-2 and 12). Muscovite-quartz rock (sample 15). Quartz-kyanite rock (sample 19). Quartz rock (sample 23). Kyanite rock (sample 24). (See also appendix)

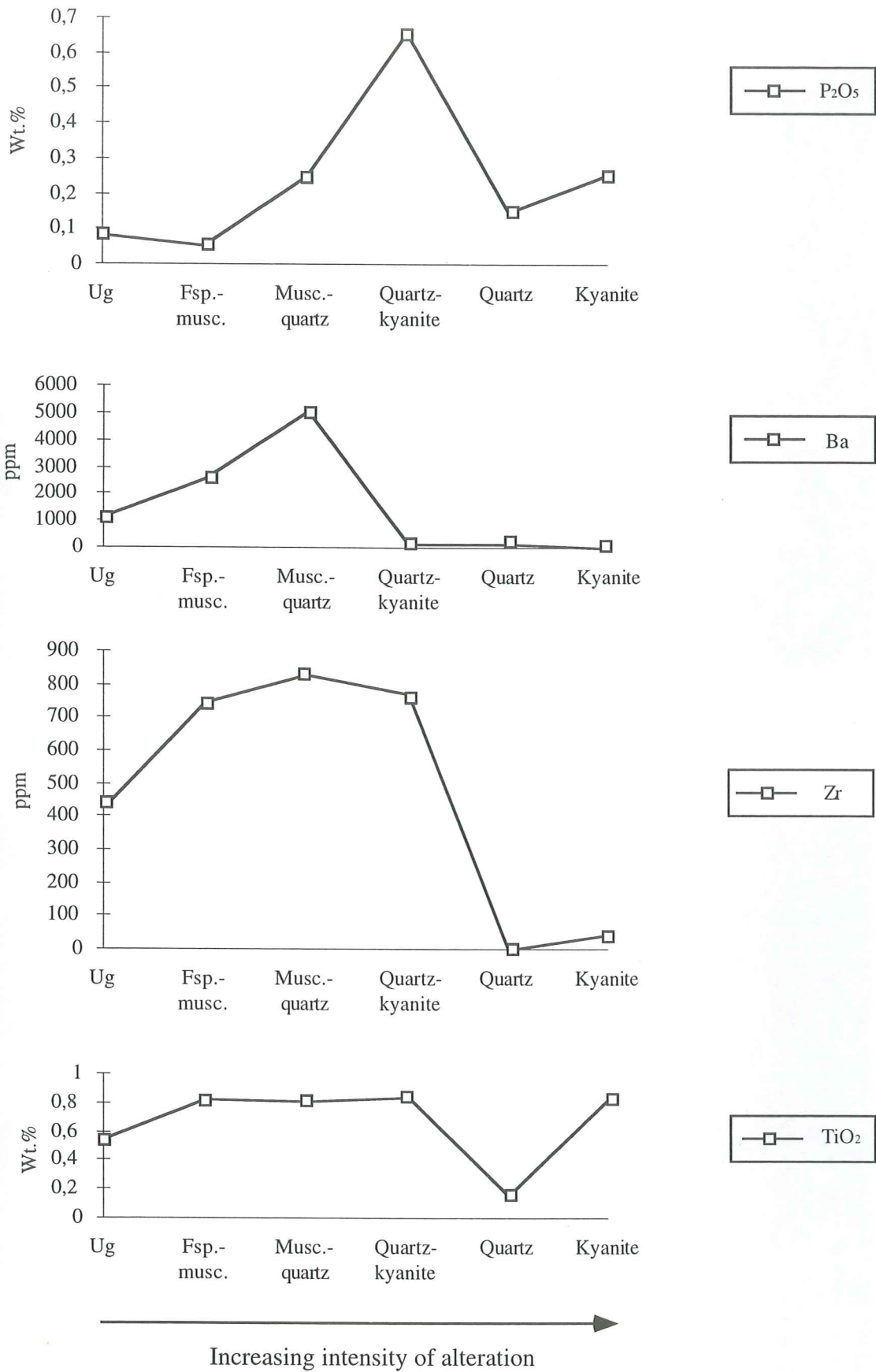


Fig. 10. Cont..

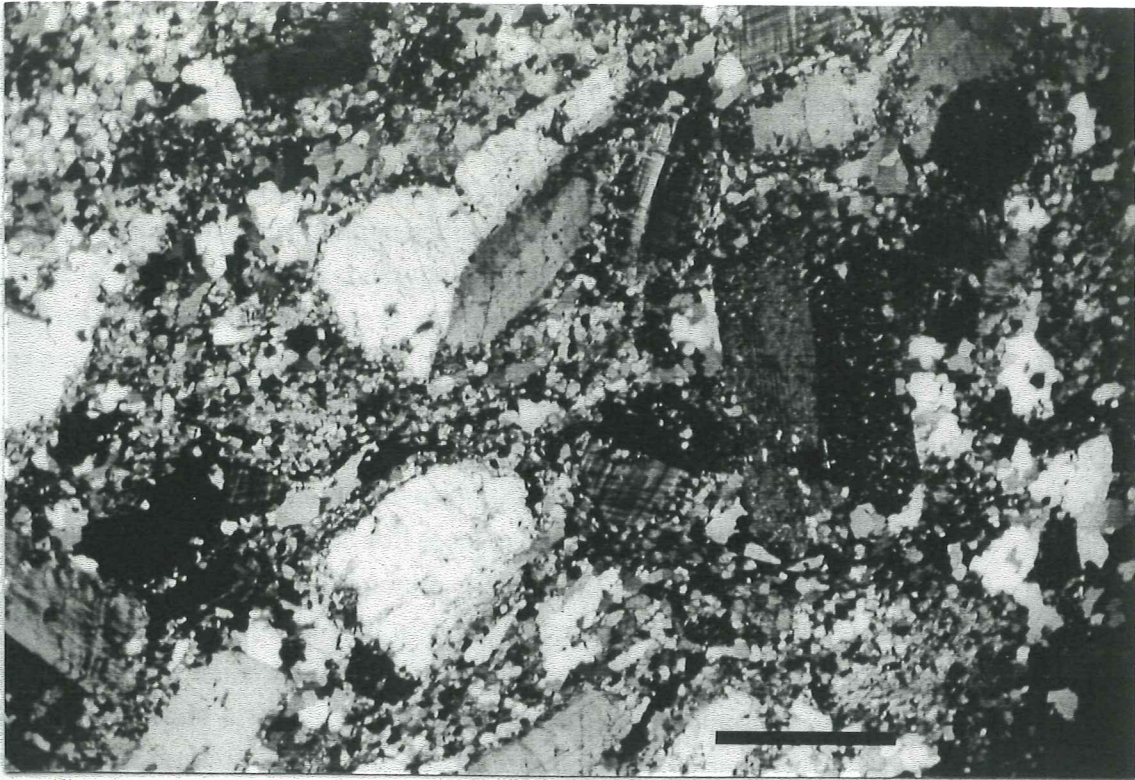


Fig. 11. Granite with oligoclase- and microcline-phenocrysts surrounded by finegrained aggregates of quartz and feldspar. (Scale is 2 mm, crossed nicols, sample 4)

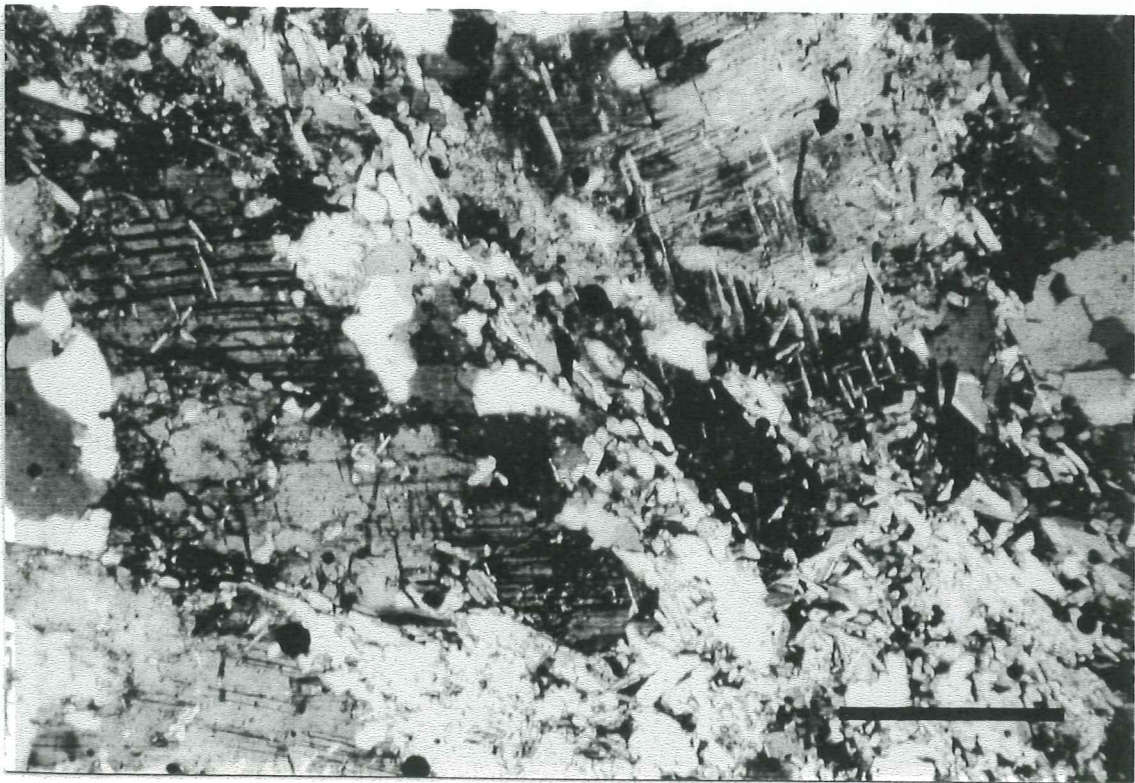


Fig. 12. Feldspar-muscovite rock dominated by albite-oligoclase phenocrysts with albite twins forming crosshatched pattern and with local enrichments of muscovite. (Scale is 0,5 mm, crossed nicols, sample 87-2)

Subidiomorphic garnets appear, in amounts between 1 and 2%, mostly grown on muscovite which occurs as inclusions within the garnet. Pressure shadows are present but only seen around a few crystals and are weakly developed. Chlorite is present as an alteration product of biotite and muscovite, and constitutes no more than c. 2% of the rock. Fine grained hematite is common as inclusions within garnets. The colour of the rock has changed to a light yellow tint due to the disappearance of microcline and hematite pigment. The granitic texture remains and the bimodal grainsize caused by deformation is discernable also in this rock. It should be noted that the extent and spatial distribution of this rocktype is uncertain due to Quarternary sediments and soil cover. The most notable chemical change as compared to the fresh granite is a lower content of SiO_2 and K_2O , and a higher content of Ba, CaO, Na_2O and Al_2O_3 (Fig. 10).

The *feldspar-muscovite rock* passes into a *muscovite-quartz rock* where muscovite approaches a modal content of c. 50% and clusters of small unoriented anhedral as well as needle-formed kyanite crystals begin to appear in the muscovite. Biotite has been extensively altered to muscovite although hematite, ilmenite and zirkon still seem to be relatively unaffected. Pyrite occurs as small idiomorphic crystals with thin rims of limonite. Very small grains of opaques, hard to identify, are present in some of the muscovite as well as the kyanite. Garnets are only present in amounts less than 0.5%, where some of those remaining, have inclusions of small prismatic crystals of kyanite. A few small feldspar crystals are still present in amounts up to about 2 %, but none of the large primary phenocrysts remain. Granitic texture is still discernable, in spite of the almost total disappearance of primary minerals. Feldspar phenocrysts have been pseudomorphosed by muscovite which in turn is rimmed by quartz aggregates similar to the primary granitic texture (Fig. 13). The colour has attained a grey tint, probably because of the disappearance of feldspar and the increase of muscovite and

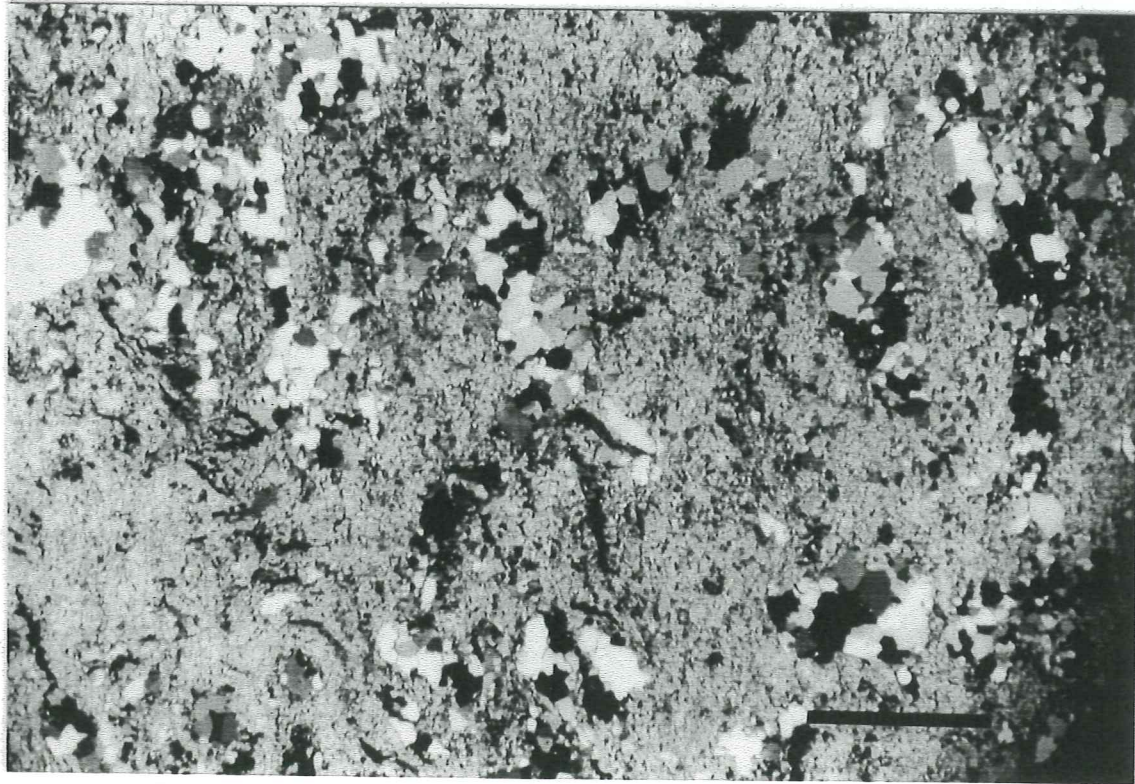


Fig. 13. *Muscovite-quartz rock, dominated by muscovite, which has almost totally replaced feldspar. Quartz aggregates are mainly unaffected and have the same appearance as in the granite. (Scale is 2 mm, crossed nicols, sample 15)*

quartz. This rock is characterised by an increase of Ba and K₂O as well as decrease of Na₂O and CaO (Fig. 10).

This assemblage passes into an almost bimodal *quartz-kyanite rock*. Kyanite has almost totally replaced muscovite, occurring as small anhedral crystals within or totally replacing small grained muscovite aggregates. Somewhat larger kyanite crystals form pseudomorphic aggregates with diamond shaped cross sections (Fig. 14). Kyanite also appears as thin needles in the quartz, radiating from some of the larger kyanite crystals, forming "rosette" textures. These kyanite needles look like sillimanite, although no sillimanite has been confirmed by XRD. Biotite is not to be found, while rutile occurs at the former site of it and is possibly an alteration product of ilmenite and biotite, although hematite and ilmenite remain largely unaltered. Zircons appear together with these opaques in similar amounts as previous rock. Garnet is not present. Fluor-apatite occurs in amounts up to about 1,5% as medium grained anhedral crystals, mostly in association with rutile, but also as fracture fillings. Apatite is not widespread in this rock-type, probably only related to fractures. Trace of pink-blue tourmaline within quartz are also present in this rock. The granitic texture is still evident although muscovite has been almost totally replaced by fine-grained kyanite. The amount of SiO₂ is much higher compared to previous rocks and contents of Na₂O and K₂O are lower (Fig. 10).

The transition of the *quartz-kyanite rock* to *quartz rock* is marked by a nearly total textural change while the mineral assemblage remains similar, except for a change of proportions between phases (Fig. 15). Quartz and muscovite contents are higher while the content of kyanite is lower. Grainsize is fairly even and, compared to previous rock, more fine grained. Kyanite occurs mostly as colourless, unoriented fine needles, but a few "rosette" textures are also present. Muscovite is evenly

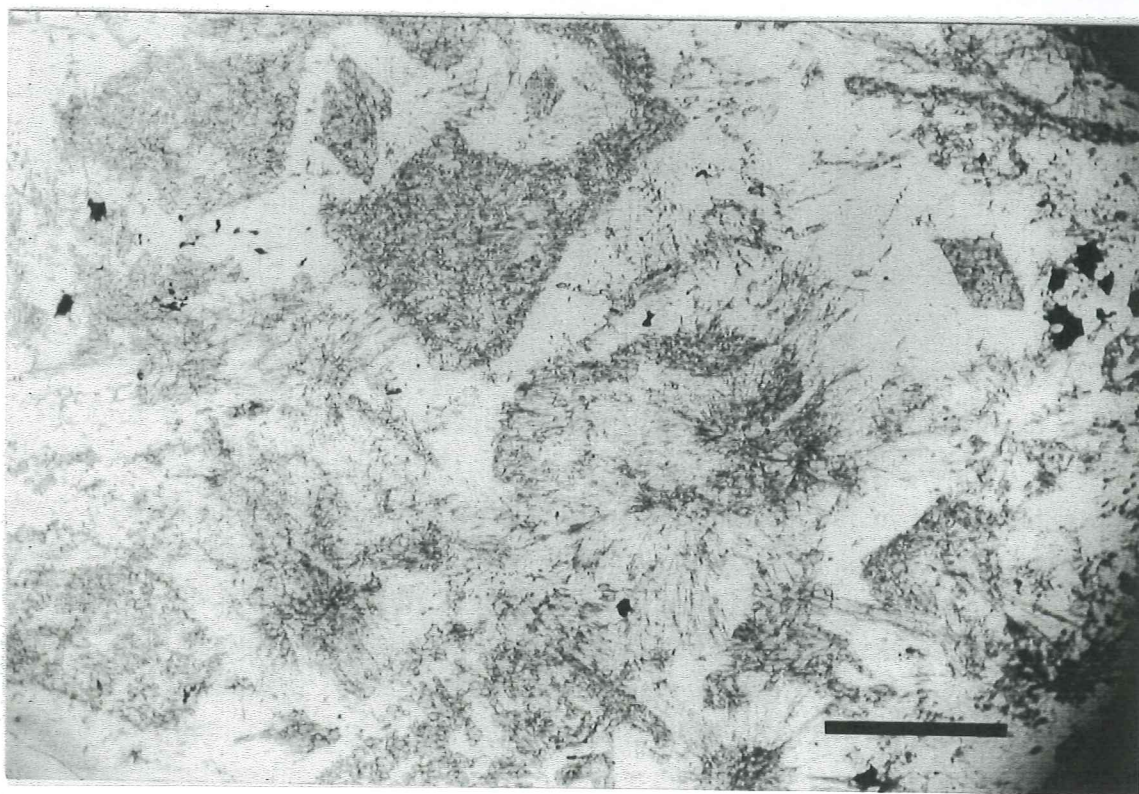


Fig. 14. *Quartz-kyanite rock with euhedral aggregates mainly constituted by kyanite. The large aggregates resemble feldspar phenocrysts while diamond shaped aggregates may be replacements of andalusite. Also note the clusters of acicular kyanite, forming "rosette" textures. (Scale is 2 mm, plane-polarized light, sample 21)*

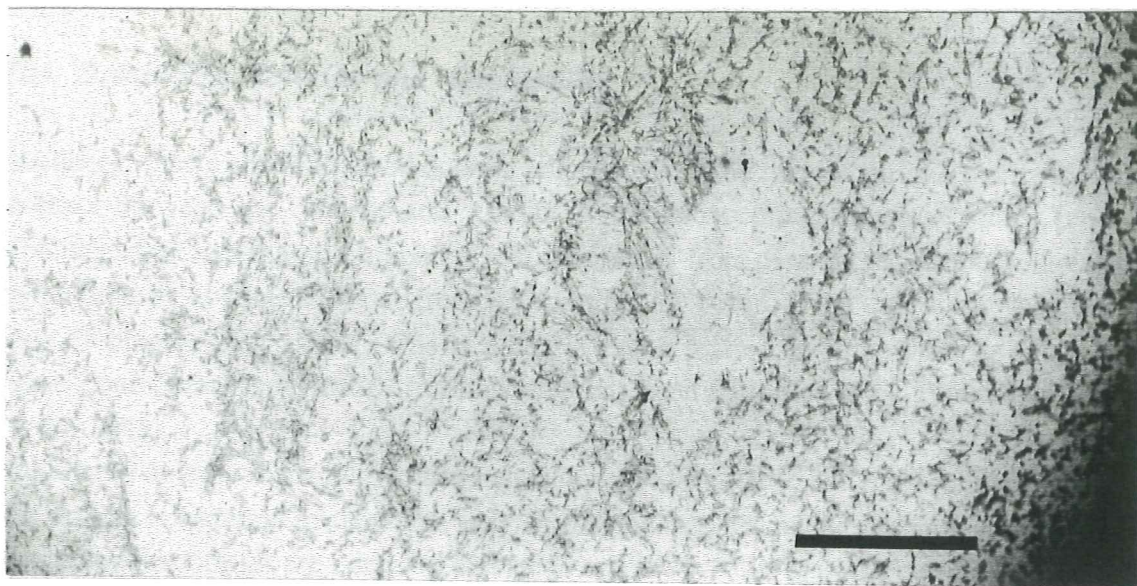


Fig. 15. Quartz rock with evenly dispersed, finegrained kyanite and muscovite. (Scale is 2 mm, plane-polarized light, sample 23).

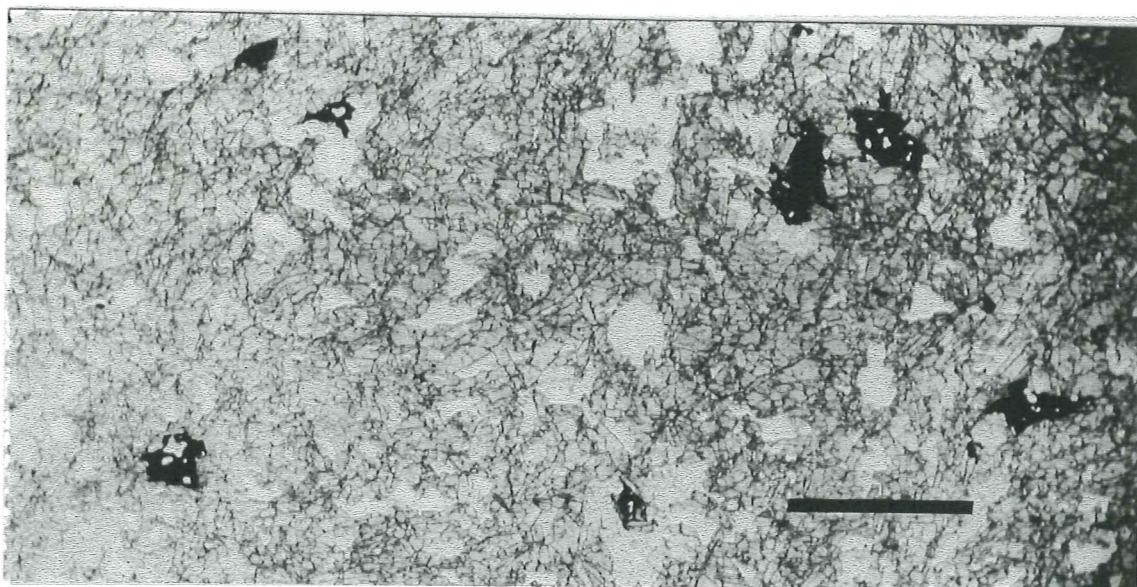


Fig. 16. Kyanite rock with c. 80% kyanite. The dark mineral is rutile. (Scale is 2 mm, plane-polarized light, sample 24)

dispersed, unoriented and similarly finegrained. Rutile is present but in very small amount and zirkons as well as opaques are absent. The colour of the rock is light green, probably due to dispersed kyanite. TiO_2 and especially Zr is much lower than for previous rocks.

The transition to *kyanite rock* is abrupt and is marked by a sudden increase in grainsize of kyanite. Kyanite is more abundant (c. 80%) while quartz content is markedly lower (c. 20%). Kyanite is present as unoriented, large, light blue, lath shaped crystals (Fig. 16). Rutile is common as large anhedral crystals and lazulite appears as small anhedral disseminated patches in association with the kyanite. No zirkons have been found and opaques are restricted to a few small idiomorphic limonite-rimmed pyrite crystals.

The result from the XRD-analysis is largely in accordance with the result from the pointcounting, except that no increasing trend of quartz content between *quartz-kyanite rock* and *quartz rock* was

revealed by XRD (Fig. 9).

4.2 The Hålsjöberg dolerite and amphibolite

At Hålsjöberg, partly amphibolitised dolerite sills/dykes cut the granite and the quartz-kyanite rock. The contact between the dolerite and granite in the prospecting trench is sharp, and foliated amphibolite passes into massive amphibolite further away from the contact. Amphibolite also occurs within the dolerite at some distance from the margins. In outcrop, the dolerite is very dark due to clouding of plagioclase crystals. This is a characteristic feature of some dolerite dykes along the Protogine Zone (Johansson 1992). In Skåne this has been attributed to Fe-Ti-oxides (Wikman and Bergström 1983).

The unaltered dolerite is medium grained and dominated by augite and plagioclase, forming ophitic texture. Augite is clouded in the same way as plagioclase. Magmatic ilmenite and magnetite with biotite-amphibole coronas are common and small amounts of olivine with coronitic texture can also be found, where the inner rim consists of colourless pyroxene and the outer rim of amphibole. Small amounts of chalcopyrite and pyrrhotite are present as well as symplectite of ilmenite and probably pyroxene.

In the amphibolite, plagioclase crystals have lost the clouding and the rock is dominated by hornblende. Idiomorphic garnets are common and quartz occurs in about equal amounts to plagioclase. Small amounts of brown biotite and opaques without corona textures are also present.

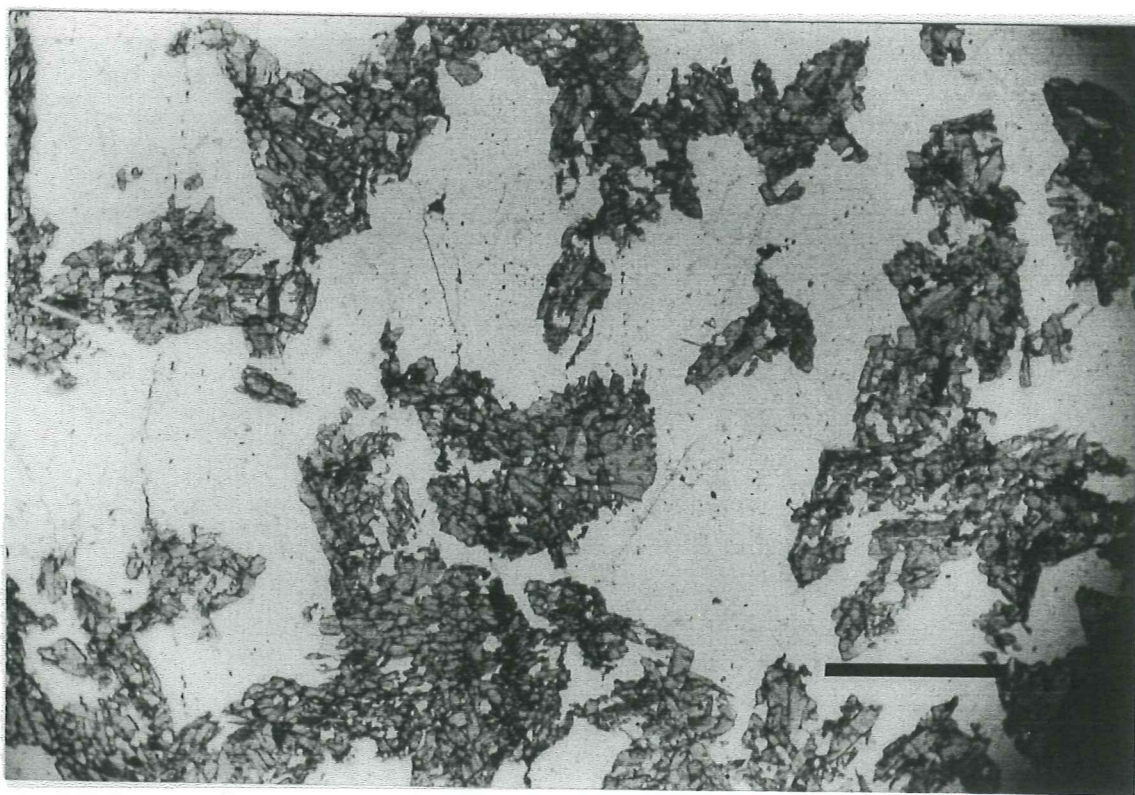


Fig. 17. Aggregates of kyanite resembling feldspar phenocrysts. Note the difference in grain size compared to quartz-kyanite rock in the alteration zone (Fig.14). (Scale is 2 mm, plane-polarized light, sample 30)

4.3 Hydrothermal alteration and sulfide mineralization at Hålsjöberg and Hökensås

It should be noted that the *quartz-kyanite rock*, *quartz rock* and *kyanite rock* described above are similar to the mineralogical composition of the dominating rock type at Hålsjöberg, which has been called "kyanite quartzite" (Sjögren 1877; Geijer 1963; Lundegårdh 1995). The banded texture which is characteristic for the "Hålsjöberg quartzite" is not to be found in the trench. An outcrop 5 meter south of the trench (Sample 30, Fig. 7) consists of massive quartz-kyanite rock without the bimodal banded character, occurring as the coarse grained, kyanite rich rock with a "granitic" texture where aggregates of kyanite have outlines resembling feldspar phenocrysts (Fig. 17).

Dykes or fracture-fillings with the same mineralogy as the wall rock cut the banded quartz-kyanite rock at Hålsjöberg (Fig. 18.), although the proportions of kyanite, quartz and rutile are probably different. These minerals are coarse in central parts and considerably more fine grained in the margins of the dykes/fracture-fillings, which distinctly cut the banded texture of the wallrock. A selection of rock chips from the transition zone and dyke/fracture-filling, are displayed in fig. 19.

A small outcrop of dark quartzitic rock is located in the prospecting trench (Sample 1, Fig. 7, Table 3). It is medium grained and dominated by anhedral quartz while muscovite and kyanite are subordinate. Fluor-apatite occurs in association with muscovite. Hematite with ilmenite laminae, sometimes together with euhedral pyrite occurs in the same manner as in the granite (Fig. 20). A very small amount of chalcopyrite is also present. Pyrite also occurs as colloform banding together with marcasite, deposited within cavities, and as idiomorphic crystals which have crystallised later than colloform pyrite (Fig. 21). The colloform textures are within c. 1 mm cavities and are not related to



Fig. 18. A dyke or fracture-filling at Hålsjöberg, consisting of quartz, kyanite and rutile, which cuts a banded rock of the same mineralogy.

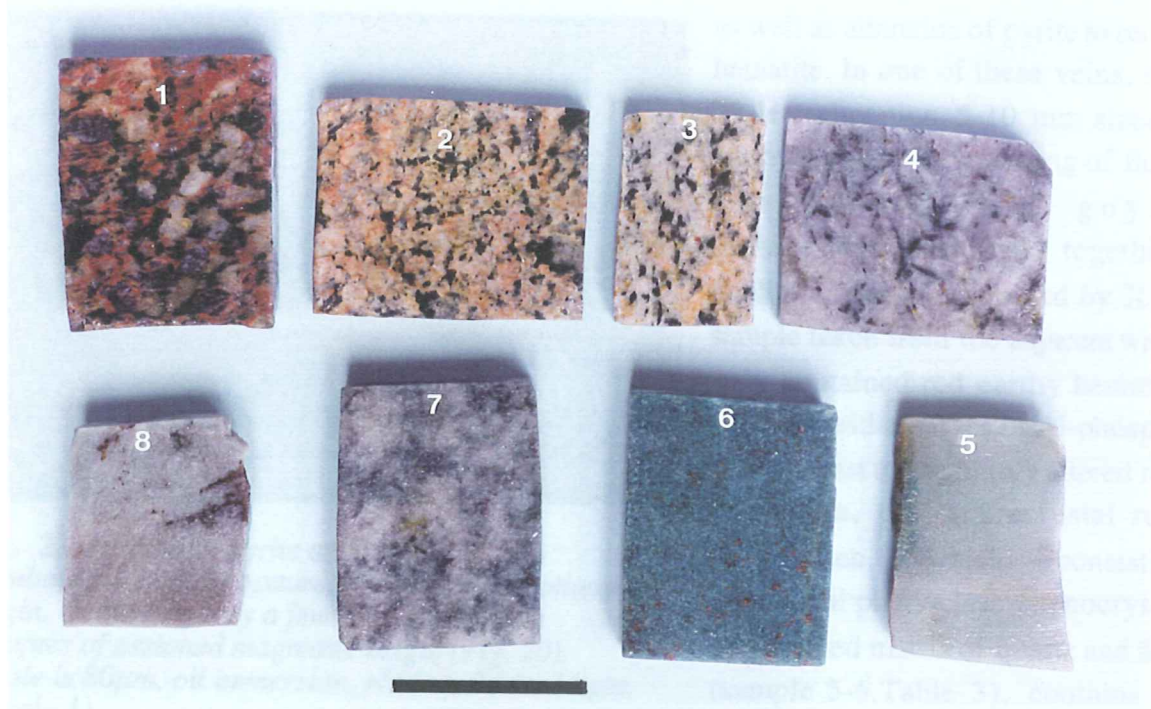


Fig. 19. Rock chips from the alteration zone at Hålsjöberg: 1 = Unaltered granite, 2 = Feldspar-muscovite rock, 3 = Muscovite-quartz rock, 4 = quartz-kyanite rock, 5 = Quartz rock, 6 = Kyanite rock, 7 = dyke or fracture-filling. Following sample is from Hökensås: 8 = Quartz - kyanite rock with rutile and pyrite (Scale is 2 cm).

fractures. Marcasite has been deposited later than pyrite in the cavities, and mostly constitutes the inner rim of the colloform texture. Marcasite is also present as independent anhedral grains. Recrystallised framboidal-looking pyrite occurs, where the "framboids" have coalesced to form homogeneous pyrite, but with the framboidal-looking texture remaining as dark rings within the pyrite.

The analysed samples of sulfide bearing quartz-kyanite rock from Björnåsen at Hökensås (sample 2-4, Fig. 5, Table 3). contained c. 2-5 % pyrite which is the only sulfide, occurring as disseminated

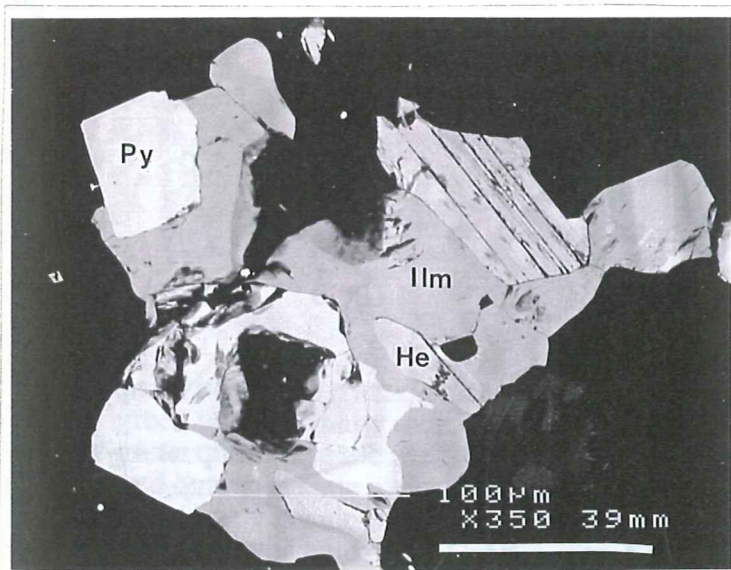


Fig. 20. Aggregate of pyrite and hematite with ilmenite laminae, displaying typical magmatic texture. (Electron microprobe, scale is 100 μm , sample 1)

idiomorphic crystals. Rutile is common although not as conspicuous as pyrite and is associated with zircons and hematite which contains irregular blebs of exsolved ilmenite. The chemical analyses of these rocks did not reveal any consistent anomalies, except sample 4 which contains a small anomaly of bismuth (47 ppm) and gold (30 ppb).

Thin, highly deformed discordant quartz veins occur in sulfide bearing quartz-kyanite rocks at Björnåsen. These veins were together with the host rock affected by weathering or a late hydrothermal event leading to alteration of kyanite to pyrophyllite or muscovite and kaolinite

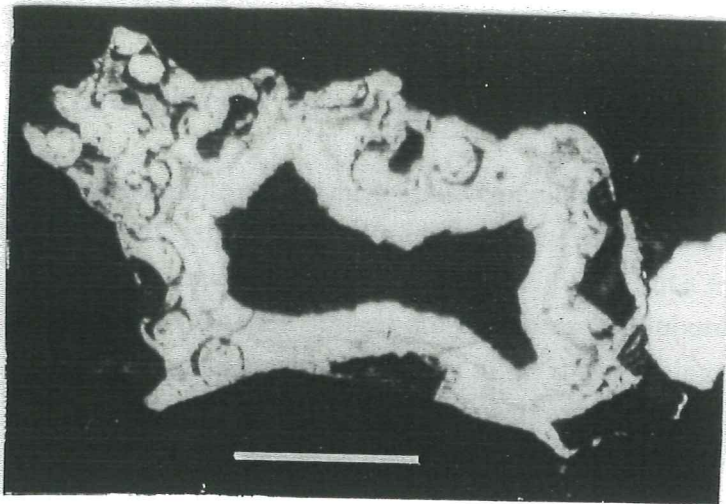


Fig. 21 Colloform pyrite and marcasite with framboidal - looking texture, of obvious hydrothermal origin. Occurring only a few millimeters from opaques of assumed magmatic origin (Fig. 20). (Scale is 80µm, oil immersion, plane-polarized light, sample 1).

amount of pyrite, while only trace of hematite has been found. Alteration of this rock is restricted to sericitisation near thin quartz veins. The chemistry of this rock with respect to ore elements does not

as well as alteration of pyrite to red earthy hematite. In one of these veins, affected by late alteration, 5-10 mm sized white earthy aggregates consisting of florencite (appendix) or goyazite ($\text{SrAl}_3(\text{PO}_4)_2(\text{OH})_5 \cdot \text{H}_2\text{O}$) together with kaolinite, were determined by XRD. A sample taken from the adjacent wall rock only contained red earthy hematite and kaolinite without trace of Al-phosphates.

In contrast to the highly altered rocks at Björnåsen, the supracrustal rock at Krigskullen, which consists of occasional plagioclase phenocrysts in a fine grained matrix of quartz and feldspar (sample 5-6. Table 3), contains c. 5% magnetite together with about equal

Table. 3. Chemical analyses of sulphide bearing samples from Hålsjöberg and Hökensås. Contents in ppm.

Sample	1	2	3	4	5	6
Mo	7	20	22	86	39	2
Cu	43	3	4	46	13	11
Pb	35	15	6	27	9	10
Zn	55	1	2	4	11	52
Ag	0,6	<0,3	<0,3	0,4	0,5	<0,3
Co	1	8	23	20	97	14
As	4	<2	<2	5	18	8
U	<5	<5	<5	5	<5	<5
Th	9	32	6	3	4	6
Cd	<0,2	<0,2	<0,2	<0,2	0.4	<0,2
Sb	<2	<2	<2	5	<2	3
Bi	6	2	4	47	<2	4
V	82	2	3	6	18	25
Au*	0,001	0,005	0,011	0,030	0,009	0,004

1. Dark quartzite. C. 5% pyrite + marcasite. Hålsjöberg.
2. Gray-green quartz-kyanite rock. C. 2% pyrite. Björnåsen (Hökensås).
3. Gray-green quartz-kyanite rock. C. 5% pyrite. Björnåsen (Hökensås)
4. Gray -red quartz-kyanite rock. Slightly oxidized. C. 5% pyrite. Björnåsen (Hökensås).
5. Dark gray meta volcanic rock . C. 10% pyrite. Krigskullen (Hökensås)
6. Dark gray meta volcanic rock . C. 5% pyrite. Krigskullen (Hökensås)

ICP - 0.500 gram sample digested with 3 ml. 3 - 1 - 2 HCl - HNO₃ - H₂O at 95 deg. C for one hour and diluted to 10 ml. with water.

Au* analysis by acid leach/AA from 10gm. sample.

differ much from the altered rocks sampled at Björnåsen.

4.4 *Hydrothermal alteration and hematite mineralization at Västanå*

Massive quartzite occurring near the amphibolite (sample A, Fig. 6) displays sedimentary textures in the form of cross bedding and conglomerate horizons. Heavy minerals forming laminae in the quartzite are mainly hematite, ilmenite and rutile, but a few rounded zircons and a mineral interpreted as hercynite (Mg-rich spinel) are also present. Subordinate anhedral kyanite occurs in elongated aggregates together with the heavy mineral assemblage. Quartz occurs in amounts exceeding 90% and forms a polygonal equidimensional texture. The appearance of hematite, ilmenite and rutile is similar or even identical to the occurrence in the Hålsjöberg transition zone even if there can be no doubt about the detrital origin of the hematite with ilmenite in the crossbedded Västanå-quartzite (hematite in the mine excluded). Rutile occurs in close association with hematite and is frequently attached to it without any zoning visible between the minerals. Ilmenite occurs as irregular blebs within the hematite without any tendency of lamellar texture. Lazulite, although scarce, is present as large anhedral grains and is not associated with the heavy mineral laminae. The conglomerate horizons contain pebbles which are flattened and consist of the same quartzitic material as the matrix although a few pebbles of pure white quartz also occur.

Conglomerate pebbles in the mica schist (sample B, Fig. 6) display the same heavy mineral laminae as the quartzite of sedimentary origin described above. The mineral assemblage within the laminae are the same although some of the rutile crystals are elongated in contrast to the almost spherical zircons. The pebbles have a serrated texture and green tourmaline occurs as small disseminated anhedral grains. Green tourmaline is also present together with heavy minerals within the muscovite-matrix between the pebbles.

Quartz veins and associated minerals are common in the Västanå formation within the altered mica schist as well as in the metavolcanic rock underlying the quartzite and the amphibolite. Quartz veins within the altered volcanic rock have been sampled at three localities (Sample C-E, Fig. 6). Most of these veins occur as fracture fillings cutting the foliation, although some veins seem to be parallel to foliation. Relatively large, cm-sized nodules of massive hematite occur within discordant quartz veins in the above mentioned conglomerate. In a prospecting pit (Sample C, Fig. 6.), a quartz vein seemingly parallel to foliation and c. 30-40 cm wide contains 1-2 cm wide streaks of fine grained green tourmaline. In the same vein a small amount of specular hematite occurs at the contact to the micaceous wallrock. Quartz stringers within a banded quartzitic rock (Sample D, Fig. 6) similarly contains streaks of tourmaline and also some lazulite, but no hematite has been noted. The veins are parallel to, as well as crosscutting, the banded texture. A horizon of pelitic or altered volcanic material composed of muscovite, quartz and anhedral brown andalusite porphyroblasts are cut by these quartz veins without any visible alteration zoning in the wall rock. Andalusite porphyroblasts are cut by thin quartz veins without showing any related alteration.

Thin quartz veins with abundant lazulite and some streaks of tourmaline occur in a quarry (Sample E, Fig. 6). These veins are up to c.10 cm wide and are slightly discordant to the foliated mica schist, which also contains some disseminated lazulite. In the dump of the Västanå mine, pieces of vein quartz with specular hematite have been found although blocks of hematite-ore in the dump generally seem to be poor in quartz. These veins are generally discordant to the "schistosity" of the ore and

seem to be associated with pyrophyllite. A sample taken from an erratic boulder near the iron mine containing a thin concordant dark blue lens within mica schist was analysed for its vein material by XRD and was confirmed to be a mixture of scorzalite and quartz. Scorzalite is the Fe-rich endmember in the lazulite-scorzalite serie and has not been reported from the Västana formation before, although it is common within the quartz-kyanite rock at Hålsjöberg together with other Al-phosphates (appendix).

Two samples taken from the dump at the Västana mine were analysed with the chemical extraction technique (Table 4). These analyses reveal relatively high contents of Ca (>0,55%), Sr (>877 ppm), P₂O₅ (>0,258%) in a hematite rich sample containing at least 70 % hematite. Analyses of a sample with considerably less hematite (10-25%) mainly constituted by pyrophyllite/muscovite and kyanite did not reveal equally high contents of the same elements. Two samples resembling those which were analysed are displayed in fig. 22.

Table. 4. Chemical analyses of hematite-bearing samples from Västana mine. Contents in ppm, unless anything else is stated.

Sample	V1	V2
Mo	<1	<1
Cu	6	4
Pb	16	10
Zn	2	4
Ag	<0.3	<0.3
Co	<1	2
As	3	<2
U	<5	11
Th	11	37
Cd	0.4	<0.2
Sb	<2	<2
Bi	5	8
V	46	23
Mn	415	44
Sr	877	537
La	30	101
Au*	<0.001	0.001
Fe (%)	16,50	5,76
K (%)	0.14	0.07
Ca (%)	0.55	0.02
P (%)	0.258	0.041

V1. >70% hematite.
V2. 10-25% hematite.

ICP - 0.500 gram sample digested with
3 ml. 3 - 1 - 2 HCl - HNO₃ - H₂O at 95 deg. C.
for one hour and diluted to 10 ml. with water. Au* with
GF/AA.

index consistently higher than 3. In the alteration zone investigated at Hålsjöberg this value is attained within the *muscovite-quartz rock* where kyanite begins to appear (Fig. 23), and with increasing kyanite content the ratio increases considerably. The apatite which is present in the *quartz-kyanite*

5 Discussion

5.1 Physico-chemical character of alteration

An important criteria in determining whether a rock containing high-alumina assemblages is a hydrothermal product due to leaching of alkalis, is the aluminum to total alkali ratio, defined as Al₂O₃ / CaO + Na₂O + K₂O (A / CNK) (Ririe 1990). Since aluminum is considered to be considerably less mobile than alkalis, this ratio has been used as an alteration index. Rocks with high-alumina minerals formed in a hydrothermal environment are usually not all abnormally high in aluminum and do not differ much from the protolith in this respect. The depletion of alkalis is furthermore mostly compensated by addition of silica (Pirajno 1992), which results in a relatively even distribution of aluminum within altered and unaltered rocks. In zones of unusually high fluid flow, it can be expected that aluminum is mobilized and thereby making the index invalid. Based on geochemical analyses of altered rocks in the Paleozoic Carolina slate belt and Norseman-Wiluna greenstone belt, Ririe (1990) concluded that altered rocks containing high alumina minerals have an alteration

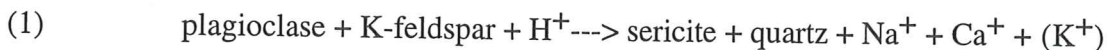


Fig. 22. Samples taken from the tailings of the Västanå mine. Sample to the left is mainly constituted by muscovite/pyrophyllite while hematite is subordinate. Sample to the right is dominated by crenulated specular hematite. (Scale is 3 cm)

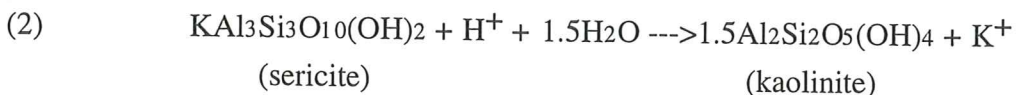
rock is a late product since it occurs as fracture fillings and would normally not be stable during the process of acid leaching. Due to the Ca content in the apatite, the A/CNK ratio is somewhat too low for this rock and the content of phosphorus is considerably higher than for the other rock types in this zone.

Reactions causing feldspar destruction by hydrolysis (Fig. 24) have been called *sericitic alteration* when sericite is the main alteration-product.

A general form of reaction caused by the circulation of acid fluids is:

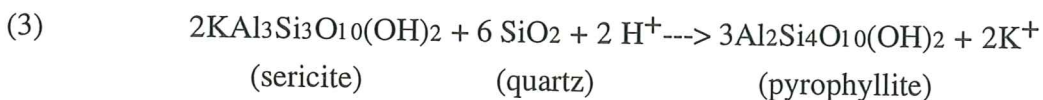


Whether potassium is released or consumed is dependent on host rock. While alteration of dacitic rocks needs addition of potassium for the sericite, alteration of rhyolitic rocks requires removal of potassium. Sodium and calcium are depleted in both cases (Wojdak and Sinclair, 1984). When this alteration is more intense, causing decomposition of sericite and the temperature is below 300°C, sericite becomes unstable:



When all feldspar is decomposed and the major part of the sericite is altered to clay minerals, it is called *advanced argillic alteration* (Meyer and Hemley, 1967).

If temperature exceeds 300°C during alteration, pyrophyllite becomes the stable phase instead of kaolinite:



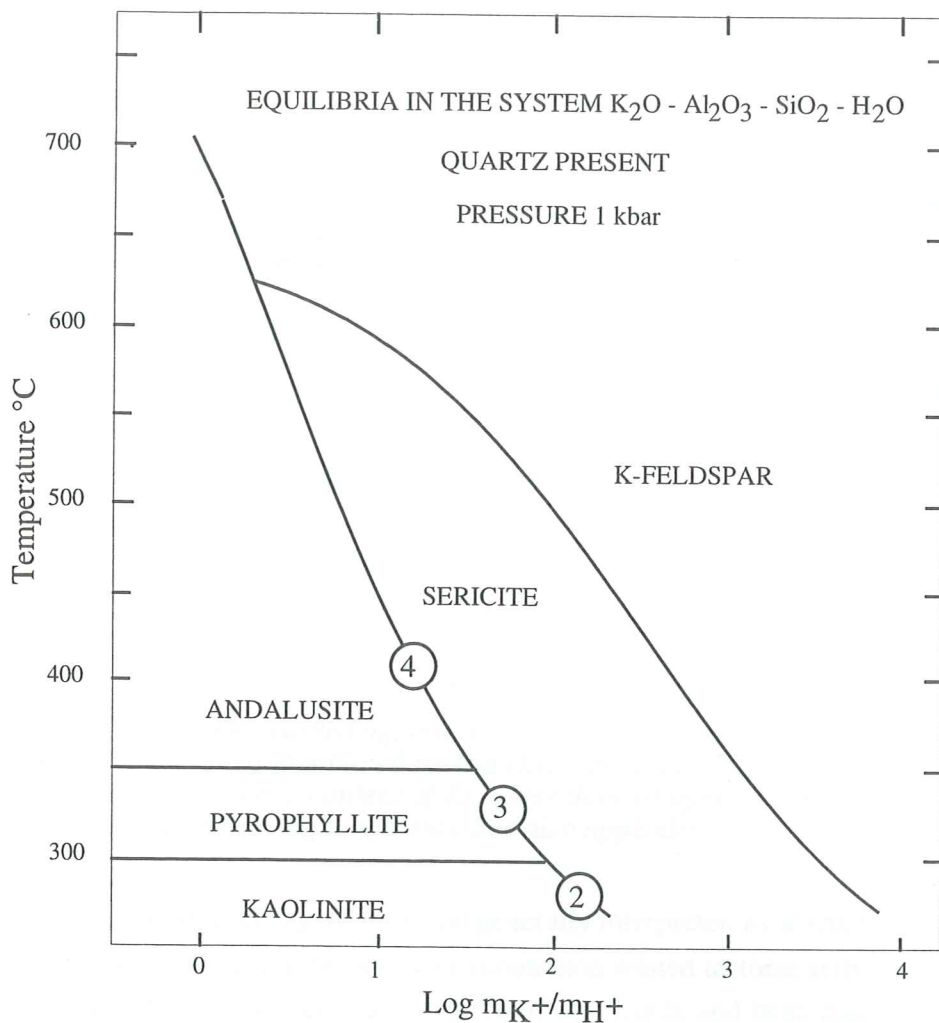


Fig. 24. Equilibria in the system $K_2O + Al_2O_3 + SiO_2 + H_2O$, with stability-fields of aluminosilicates which form as a result of hydrolysis when quartz is present. Numbers refer to reactions in the text. (After Wojdak and Sinclair 1984)

further indicated by Zr/TiO_2 and Al_2O_3/TiO_2 ratios of the two most altered samples in the transition zone, which differ markedly from the ratios of the less altered samples, suggesting that these elements were mobilized during hydrolysis (Fig. 25). Even if no distinct lithological boundary is visible between *quartz-kyanite rock* and *quartz rock* it can not be excluded, however, that the protolith of the *quartz rock* differed considerably from the composition of the granite before hydrothermal alteration. The same applies to *kyanite rock* which also have a Zr/TiO_2 ratio different from the granite. However, the very high content of aluminum in this rock indicates that aluminum has been mobilized. In high-alumina deposits in the Carolina slate belt, the occurrence of rutile is widespread and usually present in amounts between 0,5 to 1%. Even at Graves Mountain, known for its large rutile crystals in the size of several centimetres, the bulk-content of rutile in the quartz-kyanite rock does not exceed 1% (Espenhade and Potter 1960). It is possible that titanium has been mobilized to a certain extent but that such mobilization was restricted to rocks affected by the acid fluids, i.e. a redistribution within the altered protolith instead of addition from an external source. This would also be the case at Hålsjöberg where rutile locally occurs in high amounts and its formation probably linked to the breakdown of biotite and ilmenite which have served as sources of

The hydrothermal alteration at Hålsjöberg is of an advanced character, whereby even less mobile elements like Al, Ti and Zr locally may have been mobilised. This is exemplified by the highly irregular distribution of these elements in quartz-kyanite rock at Hålsjöberg, where dm-wide aggregates of rutile can be found while the bulk content of Ti is rather low. The bulk content of phosphorus is likewise surprisingly low although lazulite and scorzalite are often found in dm-sized aggregates. Thus, the conspicuous occurrence of rutile and Al-phosphates does not necessarily imply that titanium and phosphorus were added from an external source. This is

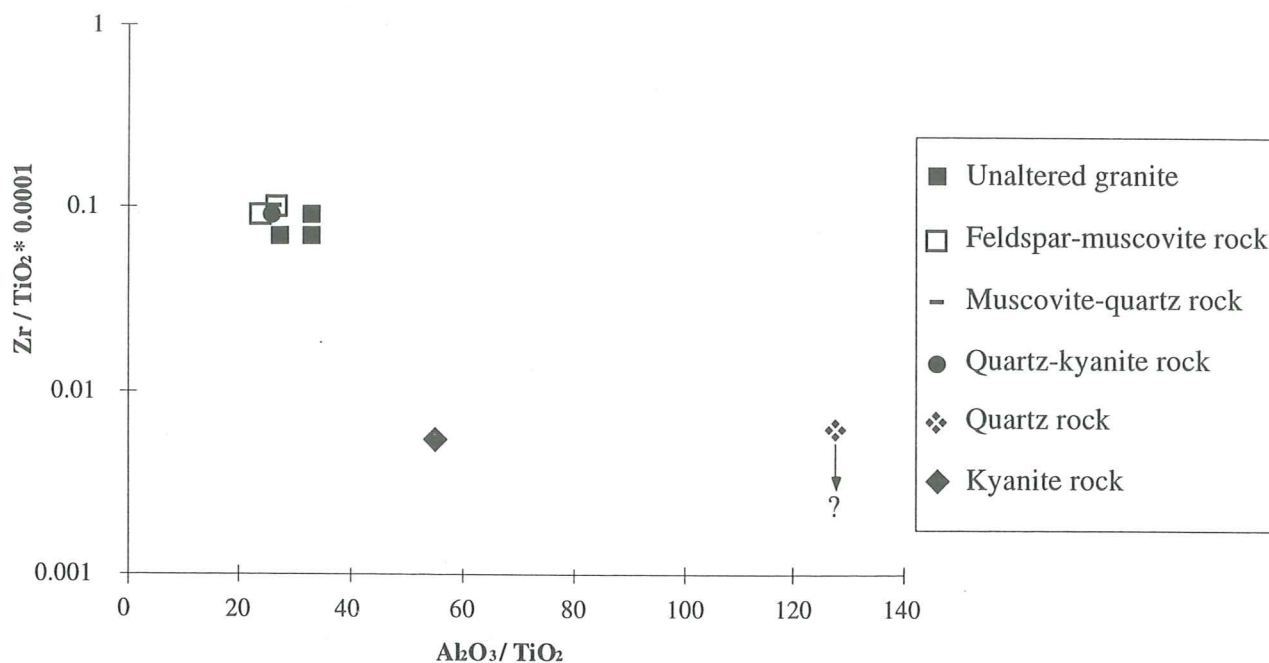


Fig. 25. Zr / TiO_2 plotted against Al_2O_3 / TiO_2 for rocks in the investigated transition zone between granite and kyanite-dominated rock at Hålsjöberg. Zr / TiO_2 ratio for quartz-rock is marked as a maximum-value since content of Zr is less than 10 ppm, i.e. below detection limit. (Zr in ppm, Al_2O_3 and TiO_2 in weight percent). See also appendix.

titanium.

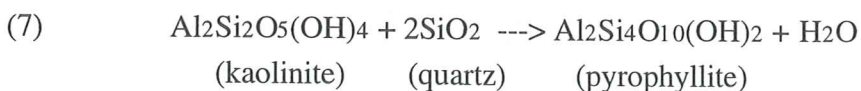
Intense acid leaching of rocks is generally interpreted as a shallow crustal (epithermal, <1,5km) phenomena, occurring presently in subduction related tectonic settings. Shallowly intruding felsic or intermediate magmas serve as a source of acid fluids and heat, maintaining vigorous convection of magmatic-metamorphic fluids in an environment characterised by a high geothermal gradient and fumarolic or hot spring activity. In areas of uplift and high relief, these occurrences are quickly eroded. Mesozoic and Cenozoic deposits are common (eg. western USA) in areas where erosion has been limited, but Paleozoic and especially Precambrian high alumina rocks are rare. The Enåsen gold deposit (~1,8-1,9 Ga) in central Sweden has been interpreted as a metamorphosed Proterozoic counterpart to recent epithermal gold deposits. The bulk mineralogy is constituted by 95 % quartz and sillimanite. The composition of this rock was obtained by hydrothermal alteration causing strong leaching and intense silicification (Hallberg 1994). Similar occurrences have been identified in Carolina slate belt in USA and in Precambrian greenstone belts, such as Norseman-Wiluna greenstone belt in Australia (Ririe 1990).

5.2 Metamorphism of high alumina rocks

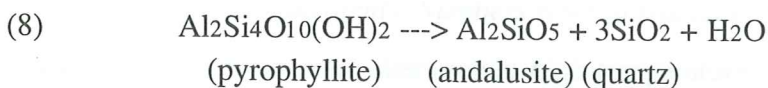
The majority of high alumina rocks with kyanite as the predominant Al-silicate have been interpreted as formed by metamorphism of rocks hydrothermally altered at low pressure. Some of these have not until recently been questioned and reinterpreted as metamorphosed epithermal products. Gresens (1971) described Precambrian pegmatite and kyanite rocks at Big rock in northern New Mexico and suggested that kyanite bearing high alumina rock formed by hydrolysis (hydrogen metasomatism) of a metarhyolite during metamorphism at high temperature and pressure. This was reinterpreted by Schreyer (1987) who by support of textural indications suggested that alteration was pre-

metamorphic. Schmidt (1985) suggested that kyanite bearing high alumina rock at Brewer mine in Carolina slate belt was of hydrothermal origin. This was questioned by Ririe (1990) who interpreted kyanite in Brewer mine to be of metamorphic origin. He also suggested that gold-bearing high alumina rocks in Archean Norseman-Wiluna greenstone belt are metamorphosed equivalents to recent epithermal hydrothermal deposits.

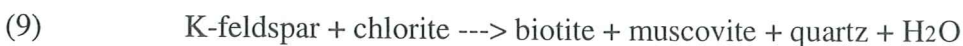
In assessing whether high alumina rocks are synmetamorphic or premetamorphic in origin, it is important to consider possible metamorphic reactions expected if the alteration occurred before regional metamorphism at low pressure and temperature. Minerals like kyanite, garnet, staurolite and chloritoid are in general not stable in the epithermal environments discussed above. Pyrophyllite and andalusite are stable in the epithermal environment but can also be products of metamorphism postdating the hydrothermal event. At increasing temperature kaolinite will be dehydrated to pyrophyllite:



while pyrophyllite at even higher temperatures will be altered to andalusite or kyanite by the reaction:



Temperatures and pressures of metamorphic reactions which can be expected are presented in Fig. 26. Chloritoid which occurs in the Västana area is characteristic of upper greenschist facies, while kyanite which is present at all three localities described in this paper, is characteristic for upper greenschist facies as well as amphibolite facies. Garnet and staurolite occurs at Hålsjöberg and is an indicator of upper greenschist facies or amphibolite facies. Chlorite is a common alteration product during weak acid hydrolysis, and at prograde metamorphism chlorite can react with K-feldspar:



This reaction can explain the absence of K-feldspar and the relatively high amount of biotite in the *feldspar-muscovite rock* in the Hålsjöberg transition zone. It should be noted however that a relatively large difference of K₂O content between the fresh granite (c. 6% K₂O) as compared to the *feldspar-muscovite rock* (c. 3% K₂O) indicates hydrothermal leaching as a cause of K-feldspar destruction rather than a metamorphic reaction in a closed system.

Garnet can form during metamorphism by a continuous reaction such as:



Garnet is not present in the fresh granite and must thereby be of metamorphic origin. This is also confirmed by its textural relation with muscovite which formed at an earlier stage.

The pseudomorphs consisting of kyanite crystals forming cubic or diamond shaped cross sections in *quartz-kyanite rock* at Hålsjöberg might be replacements of andalusite which formed as a primary

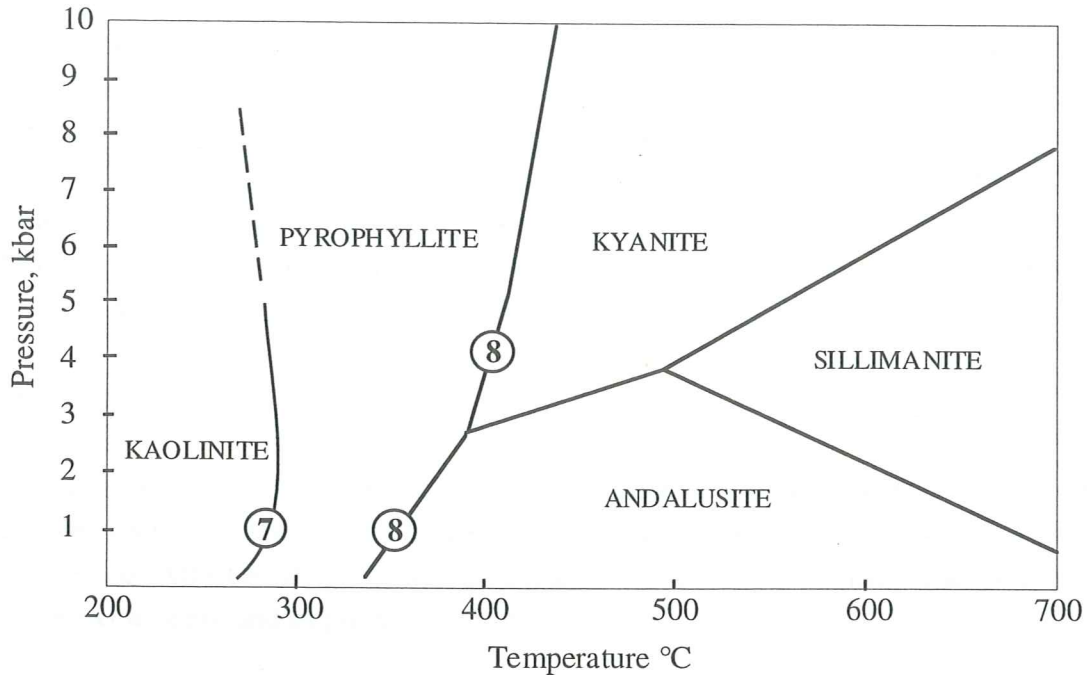


Fig. 26. *Stability-field of aluminosilicates expected to occur in rocks affected by hydrolysis, and their metamorphic equivalents. Numbers refer to reactions in the text. From Ririe (1990).*

phase during hydrothermal alteration at high temperatures in near surface environments (Schreyer 1987; Ririe 1990). Kyanite will form when temperature and pressure reach c. 380° C. and c. 2,5 kbar (Fig. 26.), which is within the brittle-ductile transition in the crust. This transition occurs at 370-400°C. in subvolcanic and tectonic active settings as confirmed by drilling in regions with hydrothermal activity (at Lardarello, Italy, at Nesjavellir, Iceland and at the Geysers, California) (Fournier 1991). At this temperature permeability will be restricted, due to increased plasticity of rocks, causing any open fractures to be sealed and fluid pressure will thereby approach lithostatic pressure. It is therefore likely to assume that acid hydrothermal leaching is limited at the stability conditions of kyanite. In addition, the reaction line (Fig. 24) between Al-silicates and muscovite is displaced to lower ratios of K⁺/H⁺ at increased temperature. Optimal conditions for hydrothermal leaching would consequently be at fairly low temperatures and brittle conditions, allowing a free bodily flow of solutions, through open fractures at hydrostatic pressure or through sediments and volcanics with high porosity and permeability.

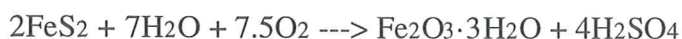
5.3 Source and movement of acid fluids

Fluids causing acid sulfate alteration, which is a form of *advanced argillic alteration*, are generally characterised by a high concentration of H₂SO₄. These fluids cause leaching of alkalis and other rock-forming elements and ultimately the formation of the assemblage alunite + kaolinite + quartz + pyrite. Models based on thermodynamic considerations and stable isotope analysis (Brimhall and Ghiorso 1983; Rye et al. 1992; Rye 1993; Hedenqvist and Lowenstern, 1994) have been presented. These models also treat environments where PO₄-analogues to alunite (KAl₃(SO₄)₂(OH)₆) form and in general, these models are restricted to geologic environments with felsic or intermediate magmatism within the upper crust, where vigorous convection of fluids are possible due to high

permeability. Cathles (1983) modelled the evolution of massive sulfide deposits and concluded that hydrothermal flow through intrusions at temperatures above 350°- 400° C is severely restricted due to ductile conditions. The rate of grain dissolution, causing closure of open fractures becomes significant already at temperatures above c. 300° C. This has also been confirmed by Smith and Evans. (1984) who in the laboratory observed extensive crack healing in quartz, at a temperature of 400° C. The brittle-plastic transition marks the limit for downward convection of meteoric fluids in tectonically active regions, which was taken into consideration by Rye et.al. (1992), who delineated three different environments for the formation of acid sulfate alteration. These are denoted as: supergene, steam heated and magmatic hydrothermal.

1. Supergene environment

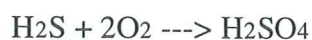
In this environment, acid fluids are generated by the oxidation of sulfide minerals (weathering) and the resulting alteration gives rise to assemblages containing alunite, kaolinite, halloysite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) or allophane ($\text{Al}_2\text{SiO}_5 \cdot n\text{H}_2\text{O}$) as well as hematite or goethite. A summary reaction to produce a hydrous iron oxide phase and sulphuric acid is described as:



This alteration is largely constrained by earlier mineralization and usually does not extend deeper than hundred meters from the surface. The occurrence of gossan and secondary enrichment horizons are unique features of this environment.

2. Steam heated environment

The mineralogical characteristics of the steamheated environment is similar to the supergene and usually occurs in the upper parts of hydrothermal systems (Fig. 27). However, in steam heated waters sulphuric acid is produced at and above the water table by oxidation of H_2S which is distilled from the underlying hydrothermal system. A summary reaction can be written:



A typical attribute of this environment is the presence of extensive silica-sinter deposits, which have formed at the paleosurface. Although the acid fluid is formed above the watertable at temperatures at 100°C or below, these fluids may descend to greater depths where higher temperatures are encountered.

3. Magmatic hydrothermal environment

Fluids causing acid sulfate alteration in this environment are derived from crystallizing magmas and the meteoric component may be absent or, as in some instances, considerable. Fluid flow is usually structurally controlled and veins of quartz and alunite frequently form, with alteration zoning outward from these veins. Aluminum is mobilized if alteration is very intense, giving rise to "vuggy silica"

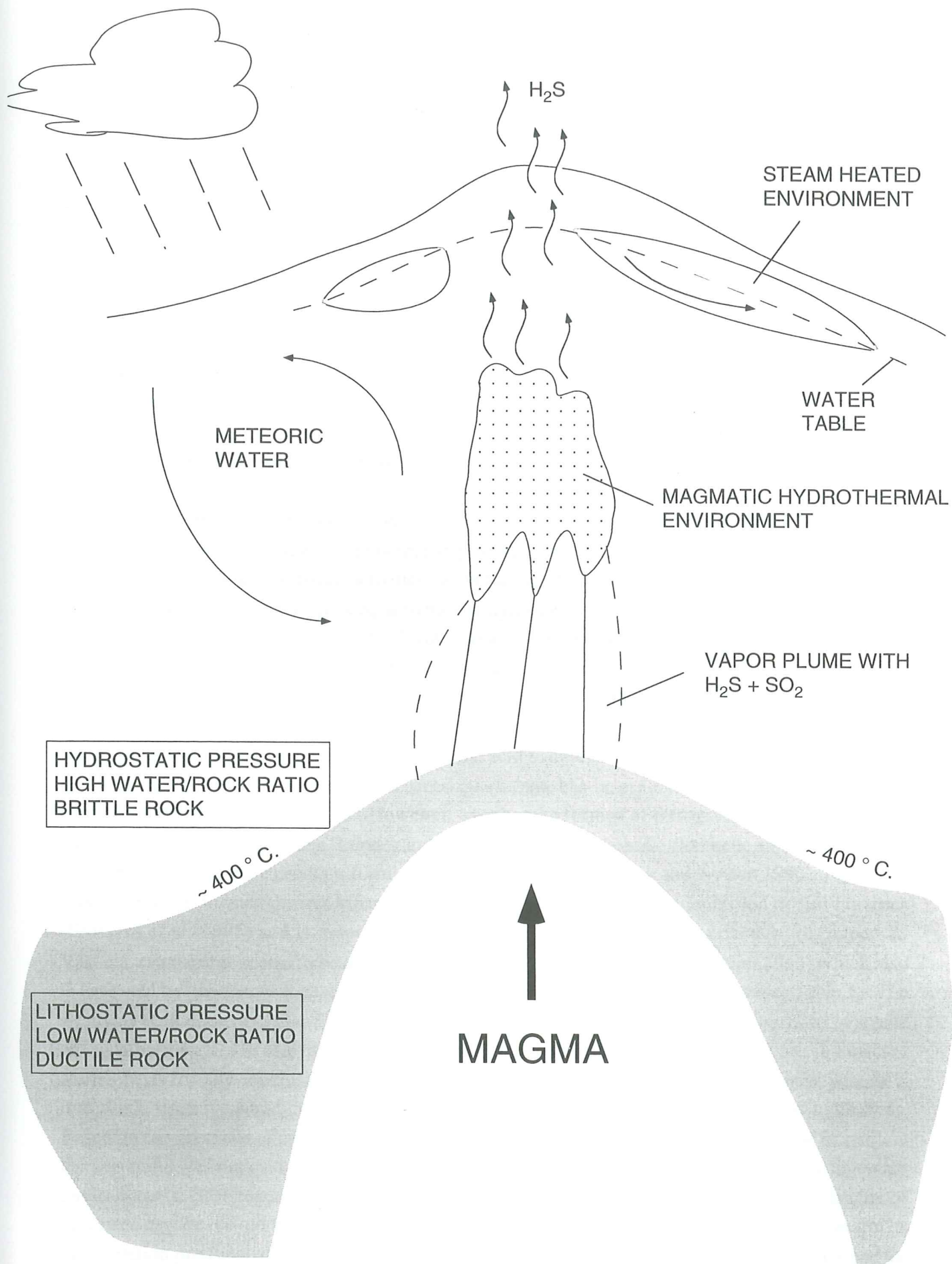
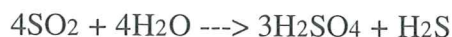


Fig. 27. Model showing a hydrothermal system above the ductile - brittle transition, with steamheated environment overlying magmatic hydrothermal environment.

with voids produced by total leach of feldspar phenocrysts. It is during magmatic hydrothermal alteration alunite with high contents of PO₄ forms, and it is even considered to be a unique attribute of this environment (Rye et. al. 1992). PO₄ analogues to alunite have been discovered in some of these deposits together with alunite. Sulphuric acid is produced at temperatures below 400°C, when magmatic vapours begin to condensate, with increasing amounts of H₂SO₄ and H₂S produced as the temperature decreases:



It should be noted that SO₂ is not the only component except H₂O present in magmatic vapours, but also HCl and HF, which contribute to the acidity. Magmatic hydrothermal fluids may alter rocks over a considerable vertical range and there might be a transition to steam heated environment at more shallow depth (Fig. 27). Some of the magmatic hydrothermal acid sulfate systems are known to overlie deeper porphyry copper-molybdenum deposits.

5.4 Significance of specific minerals

Alunite (KAl₃(SO₄)₂(OH)₆) is considered to be a good indicator of *advanced argillic alteration* since this mineral usually is present in epithermal deposits affected by intense hydrolysis. Alunite is even more dependent of high hydrogen activities for its formation than kaolinite, pyrophyllite or andalusite (Hemley et al., 1969). At decreasing activities of hydrogen, potassium and SO₄ in the fluids or an increase in temperature above c. 400 °C (at 1 kbar), alunite becomes unstable and is replaced by muscovite or Al₂SiO₅ (Schreyer 1987). Important in this context is that the Al-phosphates svanbergite (SrAl₃(PO₄)(SO₄)(OH)₆), woodhouseite (CaAl₃(PO₄)(SO₄)(OH)₆) and florencite (CeAl₃(PO₄)₂(OH)₆) (appendix) are isostructural to alunite (Wise 1975). Alunite sometimes contains some phosphorus and svanbergite occurs in some acid sulfate deposits, as at Summitville, Colorado (Stoffregen, 1987) where an intensely leached quartz latite has been altered to vuggy quartz, alunite, kaolinite and traces of svanbergite. However, svanbergite formed at retrograde conditions together with pyrophyllite at Hålsjöberg (Lundegårdh 1995), while at Hökensås, florencite similarly has been interpreted as a late stage product, forming at retrograde conditions (Ek and Nysten 1990). Florencite may even have formed during Mesozoic weathering, since it has been identified in soil-horizons (Frossard et al. 1995) and is associated with kaolinite at Hökensås, as described in this paper. At Västanå, svanbergite seems to be associated with hematite (Bäckström 1897; Geijer 1963) which also is indicated by geochemical analysis of the two samples taken from the old iron mine (Table 5). The relatively high content of Ca, Sr and P in the hematite rich sample may reflect the presence of apatite and svanbergite. These analyses only give a hint about the chemistry of the hematite ore and can not form a basis for any conclusions. However, the relatively high contents of Ca in the same sample is intriguing, since it contradicts the idea that svanbergite would be a product of intense acid hydrolysis. Based on the presence of apatite at the Västanå mine Andersson (1975) suggested that the hematite at the iron mine was deposited in a neutral pH environment since apatite is unstable in acid sedimentary environments. Stoffregen and Alpers (1987) concluded that apatite is unstable at conditions of *advanced argillic alteration* at temperatures of 250° C and that svanbergite or woodhouseite would be the alteration products of apatite, although a high initial activity of PO₄ in the fluid would extend the

stability field of apatite to somewhat higher acidities. However, the very high content of hematite in association with the phosphate-minerals limited to the ore body, suggests an environment of deposition, possibly followed by an episode of leaching.

Wise and Loh (1976) determined the stability of Al-phosphates (augelite- $\text{Al}_2\text{PO}_4(\text{OH})$, berlinite- AlPO_4 and trolleite- $\text{Al}_4(\text{PO}_4)_3(\text{OH})_3$) in the temperature range of 350° to 600° C and concluded that these Al-phosphates are far more stable than any Al-silicate during hydrolysis if a component of phosphoric acid is present in the fluid. This is in accordance with the presence of these phases in association with Al-silicates and quartz in high alumina deposits.

Colloform marcasite within cavities in quartzitic rock at Hålsjöberg has most likely been deposited by the same acid fluids which caused the hydrothermal alteration of the host rock, since marcasite chiefly occurs as a low temperature mineral formed from highly acid fluids (Roberts et al. 1990). The colloform texture of marcasite and pyrite is an evidence of high porosity and permeability of the host rock during mineralization, which further supports a near surface environment.

5.5 Timing of alteration

A sharp contact between dolerite and quartz-kyanite rock is exposed at an outcrop close to the southernmost quarry at Hålsjöberg (Fig. 2). Close to the margin the dolerite has been altered to amphibolite, consisting of hornblende, feldspar, garnet, mica and quartz, while the quartz-kyanite rock remains unaffected (Sjögren 1877). This is the same assemblage as in the amphibolite in the trench, where it is in contact with the granite. Since no large tectonic movements have taken place, causing displacement of the dolerite, the conclusion must be that the intrusion of the dolerite postdates the hydrothermal activity which would have caused almost total leach of alkalis from parts of the dolerite. The amphibolitisation of the dolerite is thereby also a much later process which caused no significant loss of alkalis. Since the amphibolite possibly corresponds to peak metamorphism of the area, i.e. a minimum temperature of 520° C and $P > 2$ kb, based on the presence of the assemblage of staurolite and garnet (Ek and Nysten 1990), it can be assumed that the hydrothermal alteration predates this peak metamorphism. This is further supported by the occurrence of late garnets in the *feldspar-muscovite rock* in the above described alteration zone, where the garnets have crystallised on muscovite of hydrothermal origin and thereby postdate hydrothermal alteration. A dolerite located c. 20 km north west of Hålsjöberg has been dated at 1550 Ma (Welin et. al. Rb-Sr Concordia, 1980) an age which corresponds to intrusion age, and a whole rock-mineral Rb-Sr isochron age of 975 Ma corresponding to a metamorphic event. Dating of a similar flat lying dolerite, near Ölme in Värmland yielded a Sm-Nd age of 1512±98 Ma (Johansson and Johansson 1990). It can not be excluded, however, that the dolerite at Hålsjöberg belongs to a younger generation.

Since metamorphic fluids capable of causing *advanced argillic alteration* have not, to the best of my knowledge, been documented, a magmatic source should be considered. A dolerite dyke dated at c. 930 Ma (Johansson and Johansson 1990) is present within the PZ near Västanå, indicating magmatic activity and tectonic unrest. Some dolerite dykes belonging to the same generation have been emplaced in the upper part of the crust, as indicated by xenolithic fragments of feldspathic sandstone within some of them (Rodhe 1988). However, mafic magmas giving rise to fluids causing hydrothermal alteration and mineralization are usually strongly differentiated, alkaline and

volatile rich. Exsolution of a separate volatile phase would take place as a result of depressurization or to concentration of volatiles in a residual melt-phase (White and Hedenquist, 1990; Richards 1990). The dolerite at Västana is of tholeiitic affinity, while *advanced argillic alteration* is typically related to intermediate and acid volcanic activity.

In the Västana formation, late quartz veins are mostly parallel to the foliation while some are cutting the foliation. The veins described in this paper, containing tourmaline (dravite) and lazulite are clearly postdating the event which caused extensive leaching of volcanics and no observations confirming a relation between quartz veins and leaching of wall rocks have been reported by earlier workers. Bäckström (1868) noted that some of the conglomerate pebbles were mineralized with tourmaline and hematite and concluded that this mineralizing event predated the formation of the conglomerate. This can not be considered as an evidence for an early timing of mineralization since both tourmaline and hematite are present in the matrix between the conglomerate pebbles as well as in late quartz veins.

Even if granites have been affected by alteration at Hökensås and Hålsjöberg it is important to consider the presence of supracrustals of both sedimentary and volcanic origin at Hålsjöberg and Västana, as well as the presence of volcanics at Hökensås, since hydrothermal alteration causing extensive leaching of mobile elements is a phenomena expected in a near surface volcanic environment. Berger and Bonham (1990) emphasized the importance of deep continental rifting for the formation of gold-silver deposits related to *advanced argillic alteration* in the western United States, where fracture systems controlled and served as conduits for magmas as well as meteoric fluids. These considerations together with the suggestions that hydrothermal alteration in the PZ-deposits occurred at temperatures below c. 400° C, before peak metamorphism and before intrusion and amphibolitisation of dolerite dykes/sills makes it more plausible that the hydrothermal event causing leaching of rocks from mobile elements was an early phenomena, probably occurring in a presveconorwegian environment characterised by volcanic activity, subsidence and sedimentation. A possible setting is a back-arc rift of a continental magmatic arc overlying a subduction zone.

If alteration is of magmatic hydrothermal or steam heated origin, intrusions corresponding to the same age as the alteration event must have been present in the vicinity of altered rocks. It is possible that these intrusions at Hålsjöberg, Hökensås and Västana belonged to the same generation or at least formed in the same tectonic environment as the rocks affected by alteration. Granite plutons near the Västana formation has been dated at c. 1360 Ma (Patchett, 1978, Rb-Sr) and c.1350 Ma (Åberg et al., 1985, Rb-Sr), while no plutonic rocks of these ages have been identified in the vicinity of Hålsjöberg and Hökensås, where the granites probably belong to the Transscandinavian Igneous Belt, which is considerably older (1,83-1,65 Ga).

A steam heated or supergene origin implies that alteration took place at the paleosurface, which is possible, when considering that the Västana formation is solely constituted by supracrustals, while altered granites at Hålsjöberg and Hökensås rather indicate a deeper, structurally bound, magmatic hydrothermal origin. The supergene origin would not require an environment with magmatic activity and hydrothermal convection of fluids, although it would necessitate a preceding event of sulfide mineralization. At Hökensås, sulfides are present in unaltered supracrustals at Krigskullen as well as in quartz-kyanite rock at Björnåsen, indicating that sulfides were stable during hydrothermal alteration or formed after this event. Since the transport of leached elements is limited in this environment, zones of supergene enrichment would form below the watertable, a feature not recognized at Hålsjöberg, Hökensås or Västana.

5.6 A modern example of hydrothermal alteration and mineralization

Shallow submarine deposits of Fe-rich muds (30-45 % Fe₂O₃) are forming today nearby the active calcalkaline volcanoes of Santorino and Nea Kameni, which lie on the southern Aegean volcanic arc c.130 km north of Crete. Here, active geothermal systems are depositing hydrated ferric oxide gels and goethite within embayments of a shallow submarine environment. Oxidation of H₂S released by crystallising magmas at depth give rise to fluids with H₂SO₄ (steam heated environment), which cause extensive leaching of Fe from volcanic rocks. When these fluids reach the seafloor, a rapid increase of pH and redox potential oxidise the ferrous iron in solution and hydrated ferric oxide gels and goethite form, while manganese oxides are precipitated at some distance from the hydrothermal vent due to the higher stability of manganese complexes (Smith and Cronan 1983; Boström and Widenfalk 1984). Boström and Widenfalk (1984) noted a positive correlation between phosphorus and iron, which in part may be due to the presence of vivianite (Fe₃(PO₄)₂·8H₂O). The phosphorus content of the Fe-rich mud is between 0,1 and 0,5 % (Puchelt et al., 1973).

Considering that the Västana formation consists of acid metavolcanics and quartzites of sedimentary origin, it can be assumed that the environment were in certain aspects similar to the present volcanic setting in the Aegean sea. Acid fluids with high activity of PO₄, Fe and other base metals (e.g. Mn, Pb) mixing with seawater or meteoric water could explain the local enrichment of these elements within the quartzite at Västana. The andalusite-kyanite bearing mica schist, which formed at some distance from the hematite (specularite) deposit, is low in iron and manganese as compared to unaltered metavolcanics in the area (Kornfält and Bergström 1983), indicating that not only alkalis were leached from the rocks. Acid fluids causing hydrothermal alteration by hydrolysis is a normal near surface feature in regions of acid and intermediate volcanism. Metal deposits forming by mixing of fluids or sudden release of pressure due to boiling is also an expected feature in this environment.

Since detrital hematite in the quartzite contains ilmenite and is accompanied by rutile, in contrast to the hematite at the iron mine where no ilmenite and very small amounts of rutile have been found, it can be assumed that a hydrothermal process instead of a sedimentary process is responsible for the formation of this deposit. This was also concluded by Geijer (1963) who noted the scarcity of other heavy minerals than hematite in the iron mine and that it does not have a detrital shape. He also inferred that the close association of hematite ore and Al-phosphates suggests a common origin.

It is well known that goethite (FeO(OH)) and especially ferrihydrite (Fe₁₀O₁₅·9H₂O) adsorb phosphorus at acid conditions (Frossard et al. 1995). This is an important consideration, since it may give an explanation to the correlation between hematite and phosphorus contents. Another important feature of the iron ore in the Västana mine is that the ore in addition to hematite contains muscovite, kyanite, pyrophyllite and phosphates rather than quartzite or vein quartz and that some of the minerals as apatite and attacolite (Ca,Mn)₃Al₆(PO₄,SiO₄)₇·3H₂O are manganiferous. The occurrence of manganiferous silicates like Mn-andalusite and Mn-chloritoid (ottrelite) in the mica schist further indicates an exhalative origin in similarity to the modern Mn-Fe-rich sediments at Santorini and other volcanic environments. It is justified to assume that the specular hematite, Al-silicates and some of the phosphates would form during diagenesis and metamorphism. Some hematite, even in the form of specularite, occurs in vein quartz found in the mine tailings and in the surroundings. This might be explained by a late formation of specularite and vein quartz during

metamorphism, unrelated to the hydrothermal event which originally introduced iron and phosphorus.

5.7 Similar occurrences in the geological record, a comparison.

5.7.1 *Champion mine, White Mountains, California.*

Champion mine is located in central California close to the Nevada border and situated within the White mountains fault zone. The latter is up to 1,6 km wide and is composed of sheared blocks of metavolcanics and metasedimentary rocks of Permian to Jurassic age. Dikes of Cretaceous aplite and pegmatite cut the fault in the northern part of the range and granitic rocks of similar age occur within 3 km from the deposit. A genetic connection with the andalusite deposit, which itself is hosted within metarhyolite, has been proposed for this granite (Wise 1977).

The deposit has been mined for andalusite which constitutes the bulk of the rock, together with quartz. Quartz also occurs as vuggy veins together with tourmaline, muscovite, lazulite and woodhouseite. Pyrophyllite also occurs in these veins and is widespread as a replacement product of andalusite in the wall rock. Rutile which locally occurs as large crystals is disseminated throughout the area and constitutes about 0,5 % of the rock. The phosphate minerals, augelite, trolleite, woodhouseite and svanbergite (appendix) are later than the andalusite and have formed almost exclusively along two shear zones. Augelite also occurs as euhedral crystals together with trolleite in fractures and miarolitic cavities in the andalusite rocks. Wise (1977) suggested that the andalusite rock formed by hydrolysis (hydrogen metasomatism) of rhyolite rocks whereby also rutile formed as an alteration product of titanite and a component of phosphoric acid in the fluid would convert andalusite to Al-phosphates.

5.7.2 *Hillsborough pyrophyllite mine, North Carolina, U.S.*

Hillsborough pyrophyllite mine occurs within andesitic and dacitic metavolcanics which have been correlated with rocks of the Carolina slate belt, dated as Lower Paleozoic (c. 560-570 Ma) and extending from central Georgia to southern Virginia. Hillsborough pyrophyllite deposit is one out of at least 40 large bodies of high alumina rocks hosted by metavolcanics and metaepiclastic rocks that have undergone greenschist facies metamorphism. The "slate belt" has been interpreted as a continental margin arc (Rogers 1982) or an oceanic arc on a continental fragment similar to modern New Zealand (Glover and Sinha 1973; Feiss et al. 1993). Feiss et al. (1993) further elaborated these models and suggested that the volcanic slate belt was formed in a rifted arc, containing hot springs, causing epithermal alteration and mineralization which were preserved due to rapid transition to submarine conditions. Pyrophyllite occurs as fracture fillings in a lenticular body about 205 m long and 15 to 60 m wide constituted by andalusite-topaz-rock which is parallel to the regional structural trend. The deposit formed by hydrothermal leaching of andesitic to dacitic rocks before regional metamorphism in a geothermal hot spring system whereby kaolinite was formed, which later during metamorphism was converted to andalusite and topaz at a temperature between 400° and 450° C and a pressure > 2 kbar. At a later event silica rich fluids reacted with andalusite and topaz whereby pyrophyllite formed (Sykes and Moody 1978). Schreyer (1987) interpreted andalusite as an early

product of hydrothermal alteration based on textural evidence and the common opinion that andalusite in other similar deposits in Carolina slate belt are of hydrothermal origin and not a product of regional metamorphism. Intrusions in Carolina slate belt are predominantly felsic and have the same range of age as the supracrustals (550-705 Ma). In discussing the origin of the Hillsborough deposit, Sykes and Moody (1978) excluded the possibility that weathering would be the origin of this deposit with the argument that tropical soils like laterite and bauxite did not appear in the geologic record until Devonian time. Although the bulk chemistry of the Hillsborough deposit as well as other similar deposits in Carolina slate belt are normal as regards to phosphorus content, Al-phosphates and especially lazulite has been reported from some of these. At Hillsborough, the occurrence of solid solution of florencite-woodhouseite-svanbergite was studied by Schreyer (1987)(appendix). These Al-phosphates are present as a multitude of minute grains included within quartz or as large crystals. Their genesis has been attributed to the simultaneous presence of sulphuric and phosphoric acids in the fluids during the premetamorphic hydrothermal event. The absence of apatite in these rocks are explained by the unusually low ratio of Ca/Al (Schreyer 1987).

5.7.3 *Kiawa Mountain, New Mexico, U.S.*

The Kiawa Mountain formation is a Precambrian metasedimentary unit which mainly consists of quartzite and muscovite-quartz-schist. This unit contains an aluminous quartzite, well known for its occurrence of the rare mineral viridine (manganiferous andalusite) (Heinrich and Corey 1959) which also occurs at Västana, together with ottrelite, pink manganiferous muscovite and kyanite. At Kiawa mountain viridine appears together with quartz, kyanite, muscovite, specular hematite and rutile in a banded quartzitic rock in which crossbedding and conglomerate can be identified. This rock displays many similarities to rocks in the Västana formation, although no volcanics have been identified. Heinrich and Corey (1959) suggested that the protholith had been a Mn- and Fe-bearing kaolinitic sandstone, but did not discuss the genesis. A near surface origin is to be assumed, whether it be in a steam-heated (Volcanic Santorini-type) environment or in a supergene (weathering) environment.

6 Conclusions

1. High-alumina rocks discussed in this paper originally formed as a consequence of convecting acid fluids causing extensive leaching and transport of alkalis and other mobile elements. Later metamorphism converted these rocks to the present mineralogy.
2. Exsolution of volatiles from acid or intermediate magmas gave rise to acid fluids by condensation and/or mixing with oxidised meteoric fluids. These magmas also served as heat sources for convection.
3. Textural and structural relations as well as considerations of the ductile-brittle transition in the crust, indicate that this alteration took place before or during prograde metamorphism at a temperature below c. 400°C
4. An early hydrothermal event at Västana, occurring during sedimentation in a near surface volcanic environment and causing leaching of volcanics as well as mineralization, is suggested. A late hydrothermal event at Västana is probably related to deformation during retrograde metamorphism and did not cause any considerable leaching of alkalis.

Acknowledgement

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APPENDIX

Appendix

Rock Sample	Unaltered granite PZ-87-1	Fsp. - musc. 12	13	PZ-87-2	14	Musc. - quartz 15
Quartz (Vol. %)	20	14	20	27	22	40
Plagioclase	29	39?	49?	30?	28?	2
K-feldspar	39	+?	+?	+?	+?	0
Muscovite	4	31	24	30	32	52
Biotite	5	12	2	9	13	1
Garnet	0	1	+	2	1	0
Chlorite	0	+	2	0	0	+
Kyanite	0	0	0	0	0	4
Kaolinite	0	0	0	0	+	0
Rutile	0	0	0	0	0	0
Zirkon	+	+	+	+	+	+
Opagues	1	1	2	2	2	1
Apatite	+	0	0	0	0	0
Tot.	98	98	99	100	99	100
Points counted	1500	2000	2000	2000	2000	2000
Rock Sample	16	17	18	19	20	21
Quartz (Vol. %)	50	58	49	49	54	60
Plagioclase	0	0	0	0	0	0
K-feldspar	0	0	0	0	0	0
Muscovite	32	24	22	5	4	13
Biotite	0	0	2	0	0	0
Garnet	0	0	+	0	0	0
Chlorite	0	0	+	0	0	0
Kyanite	11	12	24	42	40	26
Kaolinite	6	5	+	0	0	+
Rutile	0	+	0	1	+	+
Zirkon	+	+	+	+	+	+
Opagues	1	+	2	1	+	0
Apatite	0	0	0	2	0	0
Tot.	100	99	99	100	98	100
Points counted	2000	2000	2000	2000	2000	1500
Rock Sample	16	17	18	19	20	21
Quartz (Vol. %)	50	58	49	49	54	60
Plagioclase	0	0	0	0	0	0
K-feldspar	0	0	0	0	0	0
Muscovite	32	24	22	5	4	13
Biotite	0	0	2	0	0	0
Garnet	0	0	+	0	0	0
Chlorite	0	0	+	0	0	0
Kyanite	11	12	24	42	40	26
Kaolinite	6	5	+	0	0	+
Rutile	0	+	0	1	+	+
Zirkon	+	+	+	+	+	+
Opagues	1	+	2	1	+	0
Apatite	0	0	0	2	0	0
Tot.	100	99	99	100	98	100
Points counted	2000	2000	2000	2000	2000	1500

+ Occur in amounts less than 0.5 %.

XRD

mineral	d-value	4 (Ug)	12(Fsp.-musc.)	15(Musc.-quartz)	16 (Musc.-quartz)
Muscovite	10,00	527	2192	2308	1997
Muscovite	4,00	282	1224	1406	1171
Quartz	4,26	566	301	550	890
Quartz	1,54	369	287	466	619
Kyanite	1,34	173	242	385	575
mineral	d-value	20(Quartz-ky.)	22(quartz-ky.)	23(Quartz)	24(Ky.)
Muscovite	10,00	491	470	1386	124
Muscovite	4,00	306	309	921	109
Quartz	4,26	1282	1331	1345	593
Quartz	1,54	944	1012	902	431
Kyanite	1,34	1184	2290	1600	2449

Appendix

Rock		Metadacite	Unaltered granite			Fsp.-musc.
Sample		PZ-93-5	4	PZ 93-1	PZ 87-1	PZ 87-2
SiO ₂ (%)	ICP/W	64.93	69.88	67.67	66.95	62.2
TiO ₂	ICP/W	0.5	0.5	0.63	0.53	0.83
Al ₂ O ₃	ICP/W	16.46	16.27	16.99	17.17	19.49
Fe ₂ O ₃	ICP/W	4.36	1.98	3.35	2.79	4.66
MnO	ICP/W	0.08	0.08	0.05	0.07	0.13
MgO	ICP/W	1.67	0.47	0.73	0.65	1
CaO	ICP/W	1.49	1.03	1.07	1.48	1.85
Na ₂ O	ICP/W	4.13	2.89	3.38	2.89	2.83
K ₂ O	ICP/W	5.18	6.28	5.04	6.91	4.11
P ₂ O ₅	ICP/W	0.15	0.08	0.07	0.1	0.06
Cr ₂ O ₃	ICP/W	0.006	0.002	<.001	<.001	0.003
LOI		1.4	0.8	1	0.6	2.4
Total		100.7	100.55	100.3	100.46	100.16
Ba (ppm)	ICP/W	1559	1023	1173	1310	2236
Ni	ICP/W	18	44	23	24	28
Sr	ICP/W	471	335	404	356	519
Zr	ICP/W	136	471	443	372	684
Y	ICP/W	12	14	25	31	25
Nb	ICP/W	<10	13	12	<10	<10
Sc	ICP/W	<10	<10	10	<10	<10
Mo (ppm)	ICP/AR	0.6	2.3	1.2	1.7	1.6
Cu	ICP/AR	76	2.8	5.3	3.6	5.7
Pb	ICP/AR	4.6	5.4	8.6	5.1	7.3
Zn	ICP/AR	73.2	73	49.8	41.4	57.6
Ag	ICP/AR	124	0.07	0.031	0.125	0.036
Co	ICP/AR	10	2	4	6	5
As	ICP/AR	2.4	3.6	1.3	1	1.5
U	ICP/AR	<5	10	<5	<5	<5
Th	ICP/AR	11	25	30	26	41
Cd	ICP/AR	0.11	0.17	0.13	0.04	0.19
Sb	ICP/AR	0.3	0.3	0.4	0.5	0.5
Bi	ICP/AR	0.3	0.1	0.1	0.1	<0.1
V	ICP/AR	65	12	13	15	15
Tl	ICP/AR	0.2	0.2	0.2	0.2	0.2
Hg	AA	0.027	0.028	0.021	0.025	0.021
Se	ICP/AR	<0.3	<0.3	<0.3	<0.3	<0.3
Te	ICP/AR	<0.1	0.3	<0.1	<0.1	<0.1
Au	AA/GF	0.003	0.004	0.004	0.008	0.005

Analytical technique: ICP/W = Whole rock analysis - LiBO₂ fusion - ICP. Ba is sum as BaSO₄ and other metals are sum as oxides.

ICP/AR = Partial analysis - Aqua Regia digestion - ICP.

AA/GF = Atomic Adsorption / Grafite Furnace

Appendix

Rock		Fsp.-musc.	Musc.-quartz	Quartz-kyanite	Quartz	Kyanite
Sample		12	15	19	23	24
SiO ₂ (%)	ICP/W	60.6	62.29	74.26	76.47	52.17
TiO ₂	ICP/W	0.8	0.81	0.84	0.16	0.82
Al ₂ O ₃	ICP/W	20.98	21.25	21.34	20.53	44.88
Fe ₂ O ₃	ICP/W	5.03	3.58	0.85	0.82	0.46
MnO	ICP/W	0.12	0.04	0.02	0.01	0.01
MgO	ICP/W	0.94	1.02	0.02	0.08	0.02
CaO	ICP/W	1.43	0.74	0.98	0.2	0.16
Na ₂ O	ICP/W	4.19	1.58	0.09	0.17	0.02
K ₂ O	ICP/W	2.89	4.36	0.48	0.86	0.13
P ₂ O ₅	ICP/W	0.05	0.25	0.66	0.15	0.26
Cr ₂ O ₃	ICP/W	<0.001	0.015	<0.001	0.007	0.017
LOI	ICP/W	3	3.6	0.8	1	1.5
Total		100.7	100.54	100.48	100.49	100.47
Ba (ppm)	ICP/W	2852	5066	133	119	30
Ni	ICP/W	<10	<10	<10	22	65
Sr	ICP/W	602	226	98	73	43
Zr	ICP/W	805	829	770	<10	46
Y	ICP/W	25	24	16	<10	<10
Nb	ICP/W	14	11	12	<10	10
Sc	ICP/W	11	10	10	<10	<10
Mo (ppm)	ICP/AR	1.8	1.5	0.8	1.1	0.3
Cu	ICP/AR	7.6	3.1	3.1	5.8	1.6
Pb	ICP/AR	6.4	3.1	1.6	2.1	2.4
Zn	ICP/AR	79.5	53.6	<1	6.4	2.1
Ag	ICP/AR	0.053	<0,030	<0,030	<0,030	<0,030
Co	ICP/AR	3	4	<1	1	<1
As	ICP/AR	4.4	6.3	2.8	1.2	2.5
U	ICP/AR	22	15	<5	<5	<5
Th	ICP/AR	39	18	1	<1	1
Cd	ICP/AR	0.12	0.09	0.18	0.06	0.09
Sb	ICP/AR	0.2	0.2	<0,2	0.3	<0,2
Bi	ICP/AR	<0,1	0.1	0.1	0.2	<0,1
V	ICP/AR	12	4	1	3	<1
Tl	ICP/AR	0.1	0.1	<0,1	0.1	0.1
Hg	AA	0.029	0.039	0.041	<0,005	0.027
Se	ICP/AR	<0,3	<0,3	<0,3	<0,3	<0,3
Te	ICP/AR	0.4	0.1	0.1	<.1	0.1
Au	AA/GF	0.002	0.001	0.001	not det.	0.001

Analytical technique: ICP/W = Whole rock analysis - LiBO₂ fusion - ICP. Ba is sum as BaSO₄ and other metals are sum as oxides.

ICP/AR = Partial analysis - Aqua Regia digestion - ICP.

AA/GF = Atomic Adsorption / Grafite Furnace.

		Västanaå	Hökensås	Hålsjöberg	Ch.m.	Hill.
Trolleite	$Al_4(PO_4)_3(OH)_3$	*		*	*	
Angelite	$Al_2PO_4(OH)_3$	*	*	*	*	
Berlinite	$AlPO_4$	*		*		
Svanbergite	$SrAl_3(PO_4)(SO_4)(OH)_6$	*		*	*	*
Woodhouseite	$CaAl_3(PO_4)(SO_4)(OH)_6$		*		*	*
Crandallite	$CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$		*	*		
Florencite	$CeAl_3(PO_4)_2(OH)_6$		*			*
Lazulite	$MgAl_2(PO_4)_2(OH)_2$	*	*	*	*	
Scorzalite	$FeAl_2(PO_4)_2(OH)_2$	*	*	*		
Souzalite	$(Mg, Fe+2)_3(Al, Fe+3)_4(PO_4)_4(OH)_6 \cdot H_2O$			*		
Bjarebyite	$(Ba, Sr)(Mn, Fe, Mg)_2Al_2(OH)_3(PO_4)_3$	*				
Childrenite	$(Fe, Mn)Al(PO_4)(OH)_2 \cdot H_2O$	*				
Gatumbaite	$CaAl_2(PO_4)_2(OH)_2 \cdot H_2O$			*		
Wyllite	$Na_2Fe_2Al(PO_4)_3$			*		
Wicksite	$NaCa_2(Fe, Mn)_4MgFe(PO_4)_6 \cdot 2H_2O$			*		
Apatite	$Ca_5(PO_4)_3(F, Cl, OH)$	*	*	*	*	
Wagnerite	$(Mg, Fe+2)_2PO_4F$			*		
Attacolite	$(Ca, Mn, Sr)_3Al_6(PO_4, SiO_4)_7 \cdot 3H_2O$	*				
Burangaitite	$(Na, Ca)_2(Fe, Mg)_2Al_{10}(PO_4)_8(O, OH)_{12} \cdot 4H_2O$	*				
Millisite	$NaCa(Al, Fe)_6(PO_4)_4(OH)_9 \cdot 3H_2O$	*				

Illustration of confirmed occurrences of phosphate minerals at Västanaå, Hökensås, Hålsjöberg, Champion mine (Ch.m) and Hillsborough pyrophyllite deposit (Hill.)

Tidigare skrifter i serien "Examensarbeten i Geologi vid Lunds Universitet":

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