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INVESTIGATIONS IN THE VÄSTERVIK AREA, SOUTHEASTERN SWEDEN

1. Structural geology and genesis of the "younger" granites.

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ABSTRACT

A geological map, short description and general petrological discussion is given of a small part of the Svecofennian in SE-Sweden.

The problems concern a relatively small sedimentary complex and surrounding granite-gneisses, hybride diorites, migmatites and associated "younger" granites.

Structural analysis has revealed that deformation has taken place in at least two phases. The first phase is characterized by isoclinal folding of the bedding plane with horizontal axial plane and generation of axial plane schistosity of newly formed mica. The second and dominant deformation phase is characterized by parallel, often plastic, folding with vertical axial plane. The metamorphism linked with this second phase is characterized by the crystallization of andalusite and sillimanite in sediments of appropriate composition. Moreover, this deformation is accompanied by extensive migmatization and the intrusion of granite dikes, the so-called "younger" granites. A mushroom-like interference pattern of superposed folds from both phases is extensively discussed.

A new geochemical test is applied to establish the depth of intrusion of the "younger" granites. This test is based on the variation of the eutectic composition of a granitic melt at varying pressures, as determined experimentally by von Platen and Höller (1966). The results suggest a rather shallow depth of intrusion, which corresponds to the type of the broadly contemporaneous metamorphism of the associated sediments.

Results of the analysis of trace elements of the "younger" granites, especially the low K/Rb-ratio, indicate an anatectic origin of these granites.

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I INTRODUCTION

Since 1963 several islands in the central part of the Västervik area have been investigated by a small team of the department of mineralogy and petrology of the Free University, Amsterdam (Holland), under the leadership of Prof. W. Uytenbogaardt. This research takes place in concert with the department of mineralogy and petrology of the University of Stockholm. In the present paper some of the results are given.

Isotopic age determinations have been carried out by the Z.W.O. Laboratorium voor Isotopen-Geologie (Amsterdam) and will be discussed in a second paper (by Priem et al. this issue).

II GEOLOGICAL SETTING

General

The Västervik area (about 40 sq. km) is a slightly NW-SE elongated complex of metasedimentary rocks, the Västervik formation, surrounded by various types of granite-gneisses. Outliers of the metasediments occur as far as 100 km south of Västervik.

The granite-gneisses of the area form part of the so-called Småland granites extending to the west and to the south of the area in question. An adjacent few km wide belt – referred to as Loftahammar granites – running NW-SE, is found just northeast of the metasediments.

Furthermore, a large number of distinctly younger basic dikes and massifs occur in the metasediments

and in the granite-gneisses.

Still younger dikes and small massifs, consisting of medium-grained equigranular granites, have invaded the metasediments, granite-gneisses and basic rocks.

The general structural direction in the area is NW-SE.

The part of the Västervik area investigated by the present authors covers the Västervik formation from its topographical centre on the island Lilla Rätö up till its contact with the augen-gneisses of the Loftahammar region on the island Björkö. (see geological map).

Metasediments

Features of the Västervik formation have been described by A. Gavelin (1904, 1910), S. Gavelin (in: Gavelin and Lundegårdh, 1960) and S. Gavelin and Russell (1967). According to S. Gavelin the lower part of the formation consists of homogeneous quartzites, at least 1.800 m. thick. Meta-arkoses and meta-graywackes are the main rock types in the upper part of the formation. Carbonaceous and tuffaceous rocks have not been observed.

Sedimentary structures such as cross-bedding, ripple marks and graded bedding are preserved at several localities (Gavelin and Russell, 1967; Russell, 1967).

The main constituents of the sedimentary rocks are: quartz, plagioclase (albite-andesine), microcline, biotite and colourless mica. Locally, andalusite and/or sillimanite occur (Loberg, 1963). Meta-arkoses and meta-graywackes are distinguished by relatively high feldspar and mica contents.

In the investigated area sillimanite has been found on the islands Stora Rätö, Vinökalv, Hultö and Björkö. It is mostly associated with relatively large quantities of biotite. The paragenesis sillimanite-andalusite occurs in flecky gneisses (amply discussed by Loberg, 1963) on the islets Lilla and Stora Boholmen.

Granitic rocks

Practically all granitic rocks in the area have the same mineralogical composition, microcline, oligoclase, quartz and biotite being the main constituents. However, the textural variation is considerable. The main types are: (I) granite-gneisses, coarse grained augen-gneisses with augen up to 5 cm. (Loftahammar granite) and: (II) equigranular, medium-grained granites with locally developed schistose fabric, referred to as "younger" granites and occuring as dikes and small massifs. The equigranular medium grained granites show little petrographical variations. Moreover, quantitative analyses of several samples of the "younger" granite on Lilla Rätö have revealed that this granite is mineralogically and chemically rather homogeneous.

Furthermore, granitic material occurs as leucosomes of migmatites. The migmatites occur as veined gneisses in the meta-sedimentary series and as agmatites derived from basic intrusives.

The relation between the Loftahammar granite and the Västervik formation is a problem, which has been discussed in several papers. Holmquist (1905a, b) argued that the Loftahammar granites are intrusive in the metasedimentary complex because sedimentary xenoliths occur in the augen-gneisses. A. Gavelin (1904) originally put forward the idea that the Loftahammar granite could be the basement on which the Västervik sediments had been deposited. Later Gavelin (1910) agreed with the theory of Holmquist but he made restrictions with respect to the evidence. Magnusson favours the original idea of A. Gavelin (Magnusson et al., 1963).

To the opinion of the present authors both the Småland granites and the Loftahammar granites are intrusive in the Västervik series. Parts of the Småland granites resemble exactly the augen-gneisses of Loftahammar and probably belong to the same granite generation. Moreover, recent isotopic age determinations on augen-gneisses of both the Loftahammar and Småland granite areas indicate the same late Svecofennian age (Welin, 1966; Priem et al, this issue). The non-schistose types of the Småland granites seem to be younger than the augen-gneisses and can possibly be correlated with the younger granites in the mapped area.

Granitic quartzites

A. Gavelin (1910, p. 108-110) gives an extensive description of white feldspar rich quartzitic rocks with rock types transitional to the Loftahammar granite, mostly occurring in a transitional zone between the quartzite-leptite series (Västervik formation) and the Loftahammar granite. These white, quartzite-like rocks locally seem to behave intrusively, both with respect to the metasediments and to the

Loftahammar-granite. Gavelin concludes that these rocks are of metamorphic origin and genetically related to but younger than the quartzite-leptite series.

Detailed mapping on Björkö has revealed the presence of an extensive, heterogeneous complex of more reddish quartz – K-feldspar rocks, ranging in composition and texture from quartzites and meta-arkoses to granites and augen-gneisses.*

Together with larger bodies of augen-gneisses (Loftahammar-granite) these so-called granitic quartzites are present in a large domeshaped body which practically covers the whole of southern Björkö. It seems highly probable that the outlines of southern Björkö have been determined by this dome.

The schistosity in the surrounding metasediments follows roughly the contact with the granitic quartzite complex, deviating from the overall NW-SE trend. The schistosity in the complex itself has a rather irregular fold-like pattern. Close to the contact it generally shows a creep-like sharp bend tending parallel to the schistosity of the surrounding metasediments (meta-graywackes).

All structural and petrographical evidence hitherto obtained lead to the hypothesis that this complex is the product of granitisation and/or partial anatexis accompanied by mobilisation of metasediments and intercalated augen-gneisses to a plastic, still highly viscose rock mass. This rock mass could have behaved more or less intrusively forming a dome-shaped body in the directly surrounding metasediments.

A genetical relation between the white quartzite-like rocks described by A. Gavelin and the so-called granitic quartzites of Björkö has to be accepted in view of the structural evidence.

Basic rocks

Basic rocks occur as small dikes and as larger massifs within the mapped area.

The cores of the larger dikes and massifs have a basic to ultra-basic composition, characterized by the paragenesis olivine, ortho- and clinopyroxene, green amphibole and labradorite. The smaller dikes and the outer zones of the larger bodies have a dioritic composition with pale green to blue-green amphibole, andesine, biotite, quartz, epidote and, locally, scapolite.

* J. Hoeve, private communication.

The origin of the dioritic rocks is still questionable. According to A. Gavelin (1910) the changing composition of the basic rocks is due to the degree of assimilation of quartzitic or granitic material by the gabbroic magma. S. Gavelin (1960) regards the dioritic rocks as metabasites.

The dioritic rocks are normally penetrated by narrow granitic veins forming a network pattern. Consequently, these rocks generally have an agmatite-like appearance with a basic paleosome and a granitic to granodioritic neosome. Where basic rocks are in contact with the medium-grained equigranular granite, the neosome is a continuation of the granite.

The origin of the granitic veins in the diorites has been discussed previously. According to Holmquist (1905a, b) they have originated by intrusion from the Loftahammar granite. A. Gavelin (1910) thought that they were the result of assimilation of granitic or quartzitic material by the gabbroic magma. In his view, this assimilated material formed acid rest melts which solidified in the contraction joints of the cooling basic rocks.

According to Sederholm (1907) the formation of the agmatites resulted from regional melting during metamorphism, followed by intrusion.

S. Gavelin (1960), discussing the granitic veins in the diorites ("metabasites"), speaks of "patterns between metabasite and siliceous sediments".

With some generalisation the question is whether the leucosome originated in situ with some mobilisation (A. Gavelin; S. Gavelin), or by intrusion of granitic material (Holmquist; Sederholm).

According to the present authors, the origin of the leucosomes of the agmatites is genetically connected with the medium grained, equigranular "younger" granites. Main field evidence for this opinion is:

(1) Where agmatites are in contact with "younger" granites, the leucosomes are direct continuations of the granites without sharp contacts or changing composition.
(2) Transitions from "younger" granites to typical agmatites often occur in one and the same outcrop.

The evolution of these hybride, basic and intermediate rocks has been complicated, most probably, by metamorphism. To what extend any of the three processes, mentioned above, has contributed to the present situation is one of the main problems under investigation.

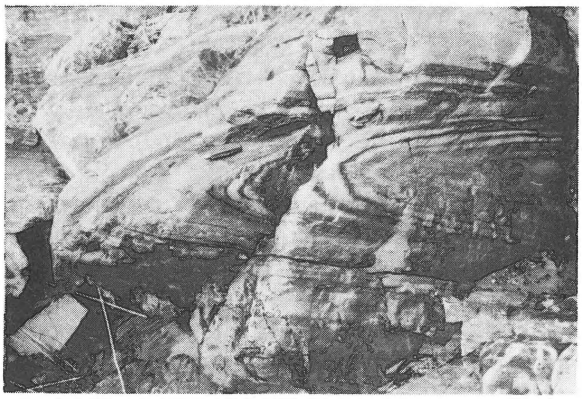


Fig. 1
First phase fold, similar style. Locality: Stora Gråskär.

III STRUCTURAL ANALYSIS (F.J. Elbers)

General

A striking phenomenon in the studied area is the constancy of strike and dip of the schistosity plane in the metasediments. This schistosity plane, formed by planar arrangement of tabular minerals, strikes NW-SE and has mostly a steep position. Where the rock has a banded character, the schistosity is generally concordant with the banding. In most cases the banding, characterized by the alternation of light and dark bands, respectively poor and rich in biotite, is believed to represent the original bedding of the sediments. This idea is supported by the occurrence of sedimentary features in the banded units such as cross-bedding and ripple-marks.

Two types of folds can be distinguished in the studied area, which are believed to represent at least two successive phases of deformation during the Svecofennian orogenesis. The first type is generated during a phase of isoclinal slip folding of the bedding plane, with development of axial plane schistosity. The second type is formed by flexural-slip folding of this schistosity plane. In the second type of folds no new axial plane schistosity has been developed.

First deformation phase (F_1)

Folds of bedding, generated by the first deformation phase have the following characteristics:
1. isoclinal and recumbent,
2. axial plane schistosity,
3. similar form,
4. monoclinic symmetry,
5. relatively small scale (decimeter to meter).

The figures 1 and 2 give examples of F_1 folds. The biotite fabric in figure 3 illustrates the axial plane

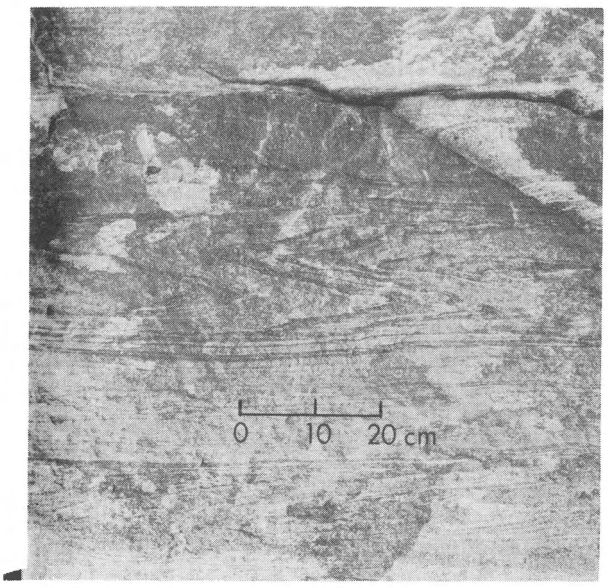


Fig. 2
First phase fold, intrafolial style. Locality: Kriksholmen.

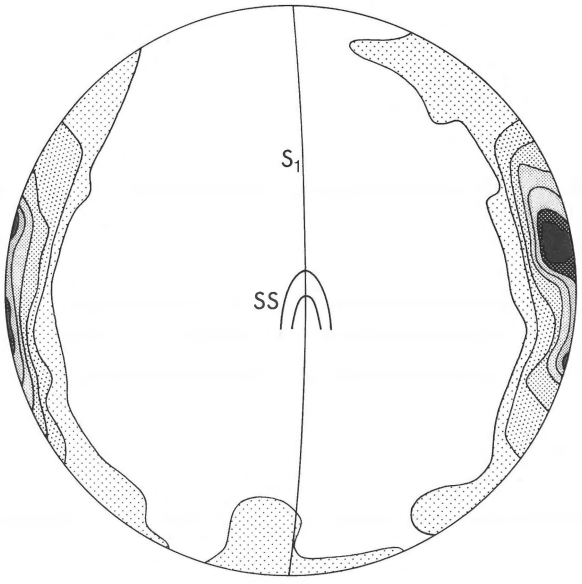


Fig. 3
Stereogram showing 200 poles of [001] in biotite in the core of the F_1 fold in figure 1. Contours, 14%, 12%, 10%, 8%, 6%, 4%, 2% per 1% area.

schistosity.

Restoration of F_1 folds to their original position indicates that the F_1 axial plane was horizontal before younger deformation became active. The trend of the b-axis of first phase folds denote that the tectonic B-axis of the first deformation phase was oriented in NNE-SSW direction, in a horizontal plane. The A-axis, horizontal too, had a WNW-ESE direction and indicates the direction of tectonic transport. The C-axis had a vertical position perpendicular to the horizontal AB plane. An example of restoration of a F_1 fold to original position will be discussed extensively in the review of the F_2 deformation.

According to the classification of Whitten (1966) the F_1 folding is of the slip type. The simple shear movement responsible for the deformation had a dominating horizontal component. The asymmetry of the folds gives an indication about the movement direction during the deformation. The schistosity may have been developed during this simple shear movement by crystallisation of the platy minerals in the horizontal plane of movement. Examples of F_1 folds in the field are rare. Until now, F_1 folds have only been observed on mesoscopic scale, nevertheless, macroscopic folds may be expected.

The simple shear movement is indicated, besides the asymmetric recumbent folds with axial plane schistosity, by another phenomenon in the meta-sediments. On several locations, tension fissures occur which are arranged in 'en echelon' fashion (fig. 4). These joints develop during a simple shear movement perpendicular to the maximum elongation (Ramsay, 1967, p. 88), and indicate the direction of the movement couple. Cross-bedding in the neighbourhood of tension fissures on Lilla Boholmen gives the possibility to restore these tension joints to original position. This position revealed that during the first deformation phase slip has occurred from NW to SE. The asymmetry of first phase folds supports this result.

Second deformation phase (F_2)

The second type of folds which can be recognised in the meta-sediments of the Västervik area has the following characteristics:

1. variation from open gentle folds to tight isoclinal folds,
2. axial plane schistosity has not been developed,
3. parallel form,
4. orthorhombic symmetry,
5. occurrence on meter to decameter scale,
6. axial planes mostly subvertical with NW-SE strike.

The figures 5 and 6 illustrate the difference in style between two typical F_2 folds. The tight plastic folding (fig. 6) occurs always in the neighbourhood of "younger" intrusive granites and migmatites. It seems, therefore, likely that the plastic folding was caused during synkinematic granite intrusion and migmatization. According to de Sitter and Zwart (1960) the type of folding in a particular

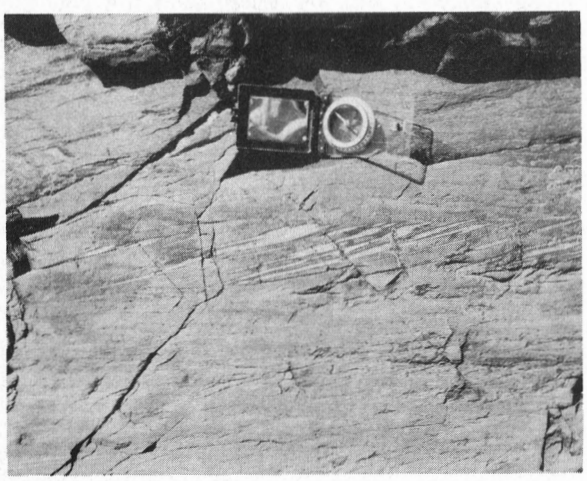


Fig. 4
Tension fissures in meta-graywacke. Locality: western shore of Björkö.

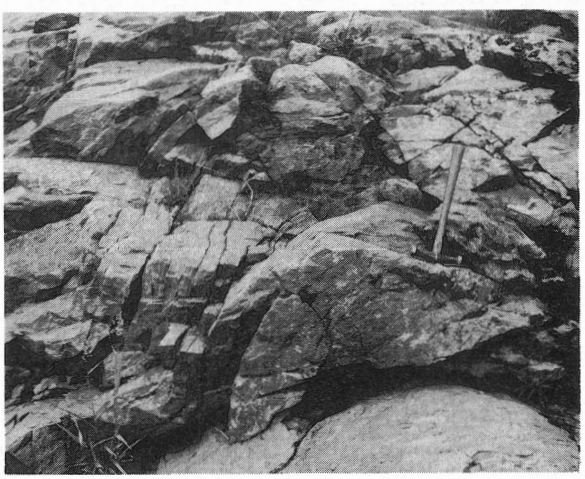


Fig. 5
Second phase fold, concentric style. Locality: western shore of Björkö.



Fig. 6
Second phase folds, tight, plastic style. Note granitic material in the upper limb of the main fold. Locality: Stora Gråskär.

layer can change by decrease of the rock resistance for instance through heating or introduction of water.

Figure 7 shows the biotite fabric of a F_2 fold. The difference with fig. 3 (biotite fabric of a F_1 fold) is that the biotite is distributed in a great circle with b_2 as axis. Possibly crystallisation during F_2 was more at random then during F_1. Only in one case a slight crenulation cleavage is observed in the hinge of a large F_2 fold.

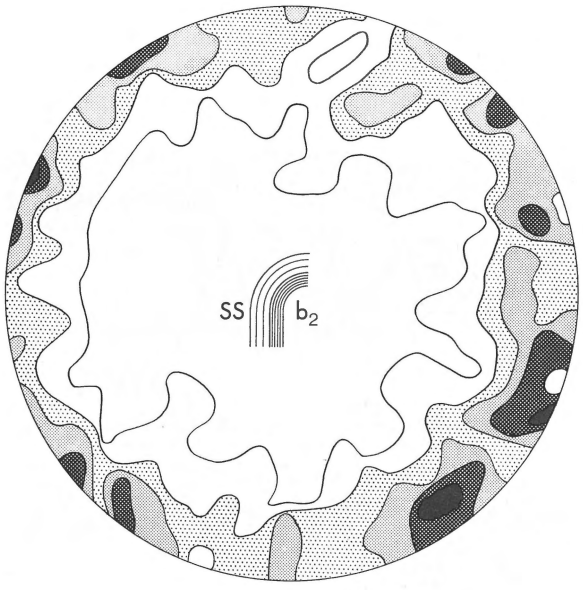


Fig. 7
Stereogram showing 200 poles of [001] in biotite in the core of a concentric F_2 fold. Contours, 4,5%, 3,5%, 2,5%, 1,5%, 0,5% per 1% area.

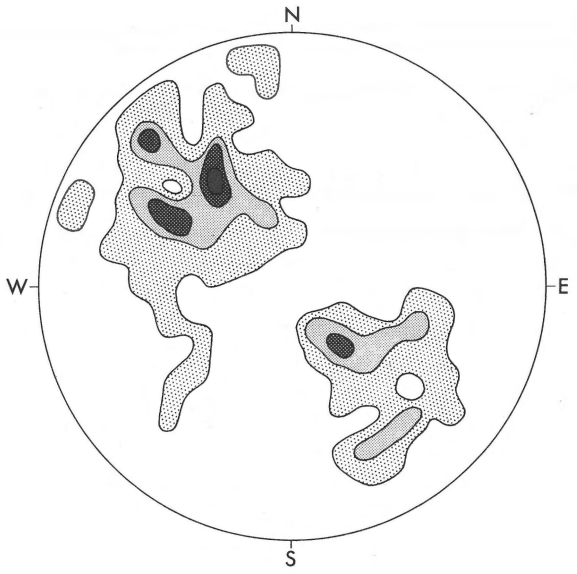


Fig. 8
Stereogram showing 42 b_2 fold axes. Contours, 4%, 3%, 2%, 1% per 1% area.

The second deformation phase is responsible for the steep position and NW-SE strike of the sediments in the larger part of the studied area. This can be concluded from the tight style of the F_2 folds, the vertical position of the axial plane and the NW-SE trend of the b_2 fold-axis. Figure 8 illustrates the trend of the b_2 axis in the region. The difference in plunge direction may be caused by a still younger, not yet well known deformation. According to Gavelin & Russel (1967) and Russel (1967) the folding in the NW part of the Västervik area seems to have a more open style.

According to the classification of Whitten (1966), the F_2 folding is of the flexural-slip type. A strong compression with NE-SW direction has been responsible for the deformation. The orthorhombic symmetry and the vertical position of the axial plane of the F_2 folds indicate that the two components of compression have been roughly equal. The tectonic B-axis of the second deformation phase was oriented in NW-SE direction, and had a horizontal position. The A-axis was vertical and the C-axis horizontal, perpendicular to the vertical AB plane. On Stora Rätö a mushroom-like interference pattern of a F_1 and a F_2 fold has been found. This denotes, according to Ramsay (1967, p. 525-531), that the angle be-

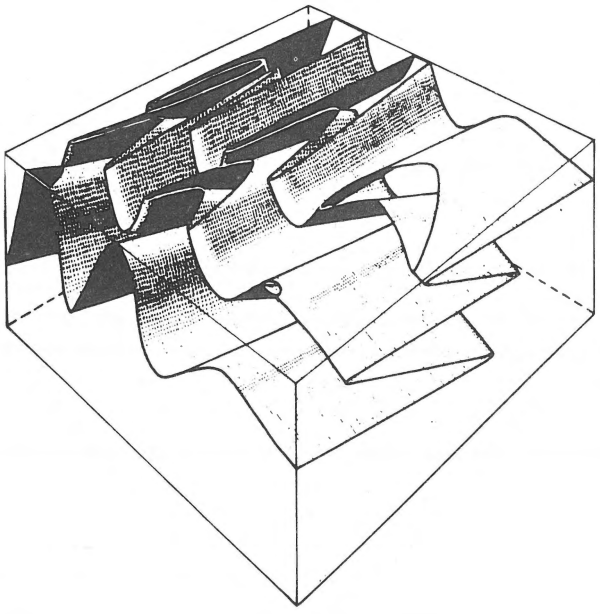






Fig. 9
Mushroom interference patterns produced by two successive fold phases.
(a) Three dimensional picture produced by superposition of two fold phases with fold axes and axial planes perpendicular to each other, the axial plane of the first phase fold being horizontal (After Ramsay, 1967, 527).
(b) Two dimensional interference pattern produced when the fold axis of the first and the second phase fold cross each other at an angle of about 50°. (After Ramsay, 1967, 531).
(c) Mushroom outcrop pattern on horizontal plane in meta-graywacke. Outlines drawn on photograph. Note the conformity with (b). Locality: Stora Rätö.

tween the first axial surface a_1 and a_2 is 0°, and the angle between b_1 and b_2 between 0° and 90° (see fig. 9). Because of the vertical position of the axial plane of the F_2 fold, a_1 must have been horizontal. The mean trend of the first fold hinge can be determined by finding the direction of the join of the ends of the 'prongs' of the lobate outcrop shapes where they occur at the same topographic level (R a m s a y, 1967, p. 529-530). Therefore b_1 must have had roughly a NNE-SSW direction.

R u s s e l l (1967) performed paleocurrent analysis in the Västervik area. He assumed that folding over the measured area has taken place around only one important axis with a NW-SE trend. According to Russell large scale gentle folding seems to be characteristic of the tectonic style of the Västerik area. It seems very likely that Russell only recognised the flexural-slip folding of the second deformation phase. Assuming that the F_1 deformation has been active on a regional scale, any attempt to reconstruct the original position of sedimentary features must reckon with composite folding. According to R a m s a y (1961), in unfolding a combination of flexural and shear folding it is necessary to know (1) the amount of shear, (2) the amount of compression, and (3) the flexural rotation. In the case of the paleocurrent analysis in the Västervik area by Russell only the last condition has been fulfilled.

Metamorphism and migmatization in relation to deformation

The metamorphism during the first deformation phase is not yet well known. Up to now no relictic index minerals have been found which are clearly related to the first deformation phase. It seems unlikely, however, that metamorphism during this phase exceeded meso-conditions.

High-grade metamorphic minerals, such as sillimanite and andalusite, occur in the more argillaceous beds. They are found together in the so-called flecky gneisses described by L o b e r g (1963). According to this author (p. 80) the flecks are elongated in a b-axis direction, which is NW-SE (p. 33). This indicates that the flecks are formed in the F_2 stress-field. It is, therefore, probable that the thermo-metamorphism, which caused the growth of the flecks with andalusite and sillimanite, is synkinematic F_2. Moreover sillimanite occurs in migmatitic rocks suggesting that the top of the metamorphism and the migmatization took place simultaneously.

As already mentioned, several granite intrusions and veined gneisses are accompanied by plastic F_2 folding. They are, therefore, considered as synkinematic F_2. Granites and leucosomes of migmatites cutting through F_2 folds must be younger. Sometimes they have a biotite foliation parallel to the axial plane of the fold, which suggests that the granitic melt crystallised in the F_2 stress field. Consequently, the intrusion of younger granites and the migmatization is considered as syn- to late-kinematic F_2.

The younger granites and the augen-gneisses (Loftahammar granite) can be distinguished on the following characteristic structural features. The younger granites intrude the basic dikes which in turn intrude the augen-gneiss. The younger granite cuts through F_2 folds while the augen-gneiss is folded itself in a characteristic F_2 manner. The younger granite is medium to fine grained and has sometimes a slight foliation, the augen-gneiss has a distinct schistosity.

The schistosity in the augen-gneiss is concordant with the schistosity in the metasediments and shows F_2 folds. The schistosity in the augen-gneiss can, therefore, be considered as s_1. The age of the Loftahammar granite is, for that reason, pre-F_1. Inclusions of Loftahammar granite in the gabbro massif of Grundemar (outside the mapped area), which are protected against the influence of the deformations, denote that the original texture of the Loftahmmar granite was porphyritic. It seems possible that the alkali-rich feldspar phenocrysts became flattened and augen-shaped during the first deformation phase. The occurrence of xenoliths of metasediment in the Loftahammar augen-gneiss points in the direction of a prekinematic intrusion of Loftahammar granite in the metasedimentary complex. The granitic quartzite - augen-gneiss complex of southern Björkö has been mentioned above. The emerging of this plastic mass of meta-sediments and augen-gneisses is tentatively considered as late-kinematic F_2. The plastic and irregular F_2 deformations of the schistosity of the complex must have been generated during a state of low competency. The bending to concordant position of the schistosity of the granitic quartzite near the contact with the banded graywackes is considered as the result of creep of the plastic mass along the contact during the uplift. Locally the granitic quartzite has even intruded the banded graywackes.

The deformation of basic dikes

A. G a v e l i n (1910) studied the relation between the Loftahammar granite and the basic intrusive rocks and concluded that the latter intrude the former. According to Gavelin the folding of the basic dikes in the augen-gneisses and the origin of the schistosity in the gneiss belong to the same process. Evidence of this assumption, which implicates a pre F_1 age of the basic intrusions, is found by the present authors on the presence of slip folds (F_1) in small basic veins and dikes, which occur in the metasediments. In contrast to the smaller dikes and veins a distinct schistosity in the larger massifs is lacking.

Diorite sills on Stora Rätö show macroscopic fold structures (see the geological map). Measurements of the schistosity of metasediments underlying the bended diorite revealed that the sediments are folded in a way similar to the macroscopic fold form of the diorite. This indicates that, during F_2, the diorite was folded in an open way together with the schistosity in the sediments.

It seems likely that most dioritic dikes and sills intruded prekinematically and suffered both orogenic phases. Apart from the folded diorites straight discordant basic dikes also occur which are apparently younger.

The megascopic structure of the Västervik area

The Västervik area can be considered as a wedge of sediments which is compressed by broadly folded granite massifs of the Småland and Loftahammar regions. Three arguments speak in favour of this hypothesis, namely:

(1) In virtue of petrological data and radiometric dating it is probable that the granite-gneisses of Småland and Loftahammar originally formed one complex.

(2) The strike of schistosity, both in the augen-gneisses and in the metasediments, and the strike of the eastern and western contacts between the augen-gneisses and the metasediments have the same NW-SE direction. The present position of the sediments, therefore, is originated during the second deformation phase.

(3) The deformation of the sediments is caused by a compression with roughly equal components in NW-SE direction. This compression can only be wielded by the granite massifs on either side of the sediments.

In this respect the experimental results of R a m s a y (1967, p. 382-383) are interesting. This author investigated the behaviour of two unlike rock types suffering a progressive compressive strain parallel to the boundary surface. The boundary surface became folded in a characteristic way: broad, rounded antiforms, separated by narrow pinched synforms. According to Ramsay large scale geological examples of this type of structure can be found at the unconformable contacts of basement and cover when they suffer a common period of orogenic activity. The Västervik area seems to present a good example of this phenomenon.

IV ORIGIN OF THE "YOUNGER" GRANITES
(W.S. Sijperda)

General

Theoretically, the following modes of origin of the "younger" granitic rocks, equigranular granites as well as quartzitic migmatites and basic agmatites (cf. Ch. 2), are possible: (1) metasomatic processes and/or metamorphic differentiation (cf. L o b e r g, 1963); (2) partial melting in situ, accompanied by mobilization on a local scale (i.e. intrusion of granitic material into the basic rocks); (3) intrusion from larger depths.

One of the problems involved has been chosen for investigation, namely the origin of a small granite outcrop of the "younger" granite type on the islet Lilla Rätö. Questions to be answered relate to (1) the origin of the granite (i.e. intrusion or origin in situ); (2) the depth of origin of the granite melt and the level of intrusion; and (3) the origin of the granite melt (i.e. anatexis or differentiation of basic magma).

Analysis and analytical results

The problem was tackled by the investigation of the chemical variations within the relative outcrop, especially at the contact with the surrounding quartzite. Elements studied were: silicon, sodium, potassium, aluminum, iron, manganese, scandium, cobalt, rubidium and cesium. Sample preparation and analytical methods are extensively discussed by S i j p e r d a (1968).

The bulk composition of the rather homogeneous granite approaches that of an alkali granite, according to the in geochemical literature commonly used classification of N o c k o l d s (1954): 73.8 wt. %

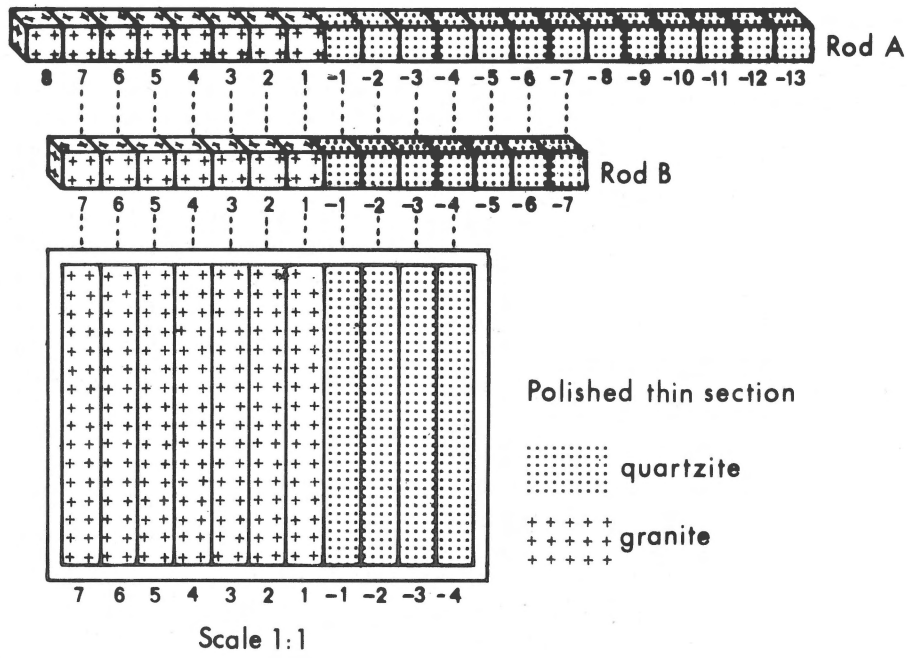


Fig. 10
Preparation of the cubes of rods A and B, showing the corresponding zones in polished thin section.

(SiO_2), 12.9% (Al_2O_3), 3.27% (Na_2O), 5.78% (K_2O), 1.68% FeO (total); 85 ppm Mn, 3.2 ppm Sc, 2.1 ppm Co, 275 ppm Rb and 1.6 ppm Cs.

The composition of the adjacent quartzite is: 90.8% SiO_2, 1.92% Al_2O_3, 0.35% Na_2O, 0.76% K_2O, 0.19% FeO (total), 2.7 ppm Mn, 0.7 ppm Sc, 6.0 ppm Co, 23 ppm Rb and 0.2 ppm Cs.

In order to study the contact between granite and quartzite in more detail, two rods (A and B) were cut perpendicularly to the contact. The dimensions of these rods were ½ x ½ x 11 and ½ x ½ x 7 cm. respectively. The rods were sawn into equal pieces of ½ x ½ x ½ cm. each, numbered as indicated in figure 10.

The rock cubes were used for neutron activation analysis.

Furthermore, a polished thin section was prepared, measuring 5.5 x 4.0 cm., the granite-quartzite contact running parallel to the shorter edge at a distance of 3.5 cm (fig. 10). The polished thin section has been used for electron microprobe analysis.

The figures 11a to 11d show the analytical results for SiO_2, Al_2O_3, Na_2O and K_2O, obtained both by neutron activation analysis and microprobe analysis. The amounts of the respective elements are represented in relation to the distance from the contact. In these figures the average composition of the granite is plotted at point *gr.* of the abscissa: that of the quartzite at the contact at q_1 and that of the adjacent quartzite at q_2.

Strikingly, the respective curves for the cubes of rods A and B correspond rather well, in spite of the fact that the distance between teh rods was 65 cm. (The polished thin section was located intermediately.)

Discussion

As to the increase of the potassium and silicon contents and the decrease of the sodium content in the contact zone, the results obtained by von Platen and Höller (1966) are elucidatory. These authors performed experimental anatexis on a banded gneiss with a bulk chemical composition approximating that of an average clay.

Runs were carried out at 2000, 4000 and 7000 bars H_2O pressure. On the basis of these results data for anatexis at 10.000 bars were extrapolated. When a pressure of 2000 bars was applied, melting began at 695°C; the temperature of the beginning of melting decreased with rising H_2O-pressure to 645°C at 10.000 bars. The initial melt at 2000 bars had a Q (quartz) : Ab (albite) : Or (orthoclase) ratio of

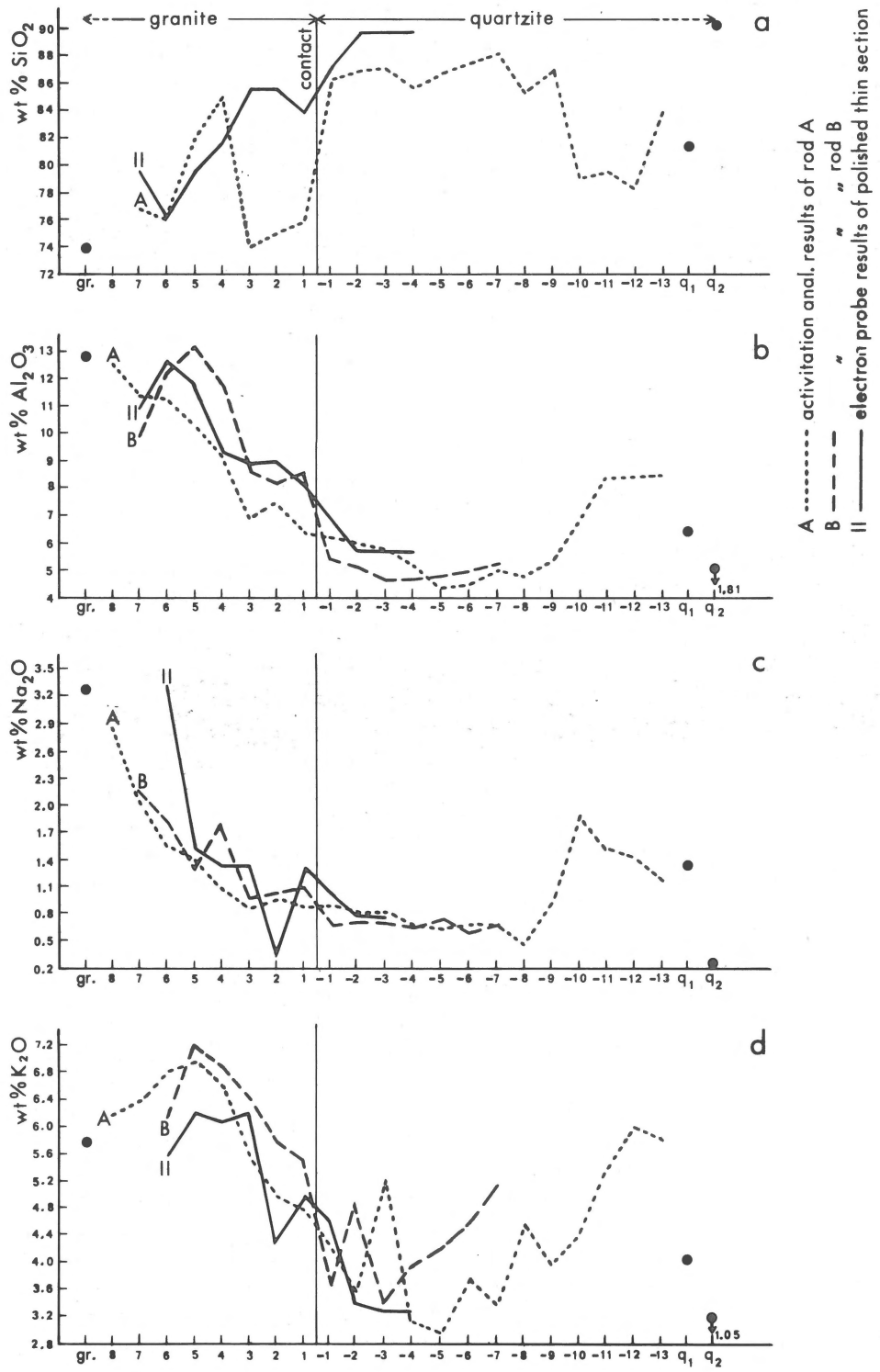


Fig. 11a-11d.
SiO_2, Al_2O_3, Na_2O and K_2O contents (wt%) in granite and quartzite as related to the distance from the contact.

44 : 19 : 37. Higher pressure brought about a change in composition of the initial melt; it was successively enriched in Ab-component and depleted in Q- and Or-component.

The following reasoning is in agreement with the data obtained by von Platen and Höller (1966):

Suppose at a certain depth an anatectic melt is formed. The composition of the initial melt depends on the Ab/An ratio of the starting material and the prevailing pressure. Where this melt intrudes to higher levels, its composition will not suit the new conditions any longer. Because of the lower pressure at the level of intrusion, the melt tends to become richer in Q- and Or-component and poorer in Ab-component. This will occur only near the contact – where exchange of material with the wall-rock is possible –, provided conditions are not beyond the limits set by the chemical composition of the wall-rock. Consequently, the contact zone will be characterized by a higher content of potassium and silicon and a lower sodium content as compared with the average composition of the granite. The same reasoning holds for granitic melts which originate by differentiation of a basic magma: at a certain depth the degree of differentiation is limited, of course, by the prevailing temperature and pressure. Thus, in intrusive granites differentiation will proceed in the contact zone, involving enrichment in silicon and potassium and impoverishment in sodium. The difference in composition between the contact zone and the rest of the granite will depend on the difference between the level of origin of the granite melt and the level of intrusion and, in case of an anatectic origin of the melt, the Ab/An ratio of the source rock. The influence of these two factors can be estimated quantitatively from figure 12. In this figure the eutectic points are plotted in agreement with the determinations by von Platen (1965) for constant pressure and varying Ab/An ratio (points A-D) and by von Platen and Höller (1966) for constant Ab/An ratio and varying pressure (points 1-4). In this "coordinate system" the pressure under which anatexis took place and the Ab/An ratio of the source rock can be determined from the position of the point representing the central portion of an intrusive granite of anatectic origin. Furthermore, from the point which represents the composition of the granite in the contact zone the pressure at the level of intrusion can be inferred. Thus, when pressures are "translated" into levels, the depths of origin and intrusion of a granite melt can be established.

The above reasoning implies the following suppositions:

(1) The use of the curves in figure 12 as a "coordinate system" for reference involves the assumption that the curves for varying Ab/An ratio at different (constant) pressures, and also those for varying pressure at different (constant) Ab/An ratios, would be parallel.

(2) The melt has eutectic composition at the level of origin; or, in other words, the temperature has not risen to a considerable extent above the eutectic temperature.

(3) The fluid phase consists of H_2O only. When the acidity of the fluid phase is high (caused by addition of HCl and/or HF) the eutectic melts associated with it are richer in Or-component as compared with eutectic melts associated with a fluid phase of low acidity (von Platen, 1965).

(4) In the contact zone chemical equilibrium has been reached.

According to this reasoning, the pressure at the level of intrusion can be estimated now from the position – in a normative Q-Ab-Or diagram – of the point representing the average composition of zones 3 to 5 (figs. 11a, 11c and 11d). Likewise, the pressure at the depth of origin of the melt can be inferred. In figure 12 point P and Q represent the central part and the contact zone (zones 3 to 5) of the granite, respectively. Experimentally obtained eutectic points for starting material with varying Ab/An ratio at constant pressure (von Platen, 1965) are also given (A-D), while points 1-4 represent the eutectic points for constant Ab/An ratio and varying pressure (von Platen and Höller, 1966). From the position of point P in this "coordinate system" it follows that the pressure at the level of origin of the melt must have been approximately 4500 bars. The corresponding depth is approximately 15 km. The Ab/An ratio in the source rock has been roughly 4.0, provided anatexis was involved. By extrapolation for point Q a pressure of approximately 500 bars (corresponding depth: approximately 3.5 km) at the level of intrusion is obtained.

The estimation of the relevant pressures presupposes an eutectic composition of the melt at the level

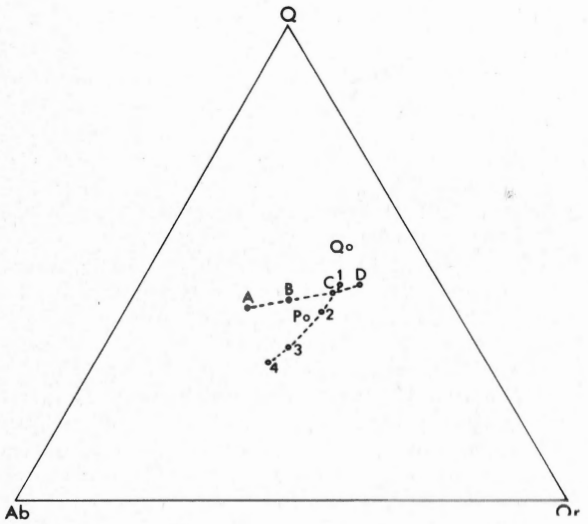


Fig. 12
The composition of the alkali granite at the centre (point P) and at the contact (point Q), with reference to experimentally obtained eutectic points for starting materials with varying Ab/An ratio at constant pressure (A-D), and starting materials with constant Ab/An ratio at varying pressure (1-4).

of origin (i.e. the absence of a marked rise in temperature above the eutectic value). From the fact that the curves P-Q and 4-1 are parallel, or approximately so, it follows that such a superheated condition of the melt cannot have occurred indeed. Secondly, the fluid phase is supposed to have consisted of H_2O only. Furthermore, it is assumed that in zones 3 to 5 chemical equilibrium has been reached.

The intrusive character of granites does not necessarily refer to anatexis or differentiation of a basic magma. Comparison of the trace element contents of the alkali granite studied with those of well-documented differentiates of a basic magma (with similar major element composition), may be conclusive in this respect. Such differentiates have approximately the following trace element composition: manganese: 500 ppm; chromium: 1 ppm; scandium: 5 ppm; cobalt: 1 ppm; rubidium: 500 ppm; and cesium: 4 ppm (Nockolds and Mitchell, 1948; Wager and Mitchell, 1951; Nockolds and Allen, 1953; Taylor, Emeleus and Exley, 1956; Tauson and Stavrov, 1957; Bowler, 1958; Sen, Nockolds and Allen, 1959; Fröhlich, 1960; Fryklund and Fleischer, 1963; Norman and Haskin, 1968). Comparison with the trace element data obtained shows that the alkali granite from Lilla Rätö is conspiciously lower in manganese (85 ppm), rubidium (275 ppm) and cesium (1,6 ppm) and higher in chromium (4,1 ppm) and cobalt (2,1 ppm).

Especially the low rubidium and cesium values are interesting. It has been demonstrated repeatedly that the behaviour of these elements can be described adequately by the rules of Goldschmidt. (For a review, see Taylor, 1965). Potassium is the only major element of a size comparable to that of rubidium (10 per cent difference). Furthermore, the electronegativities and ionization potentials of both elements are very similar. The difference in ion size is effective under conditions of extreme fractionation; so progressive enrichment of rubidium in residual magmas can lead to amounts of 500 ppm or more in late stage granites. Cesium is the largest cation and can substitute for potassium only. However, the K-Cs coherence is not very marked because cesium is much larger than potassium (26 per cent difference). So cesium is enriched considerably in the last differentiates.

The alkali granite under investigation does not show any appreciable enrichment in rubidium and cesium.

Rubidium enrichment in late stage granites results in K/Rb ratios below the "normal" range of 150-300. Indeed, in granites of the relevant major element composition values of roughly 100 would result (Taylor, Emeleus and Exley, 1956; Taylor and Heier, 1958; Heier and Taylor, 1959; Bowler, 1958). Contrastingly, the K/Rb ratio of the alkali granite studied is 175, even in the contact zone. As trace element contents and K/Rb ratio in the alkali granite of Lilla Rätö do not stand comparison with those of late stage differentiates of basic magmas (with similar major element composition) it seems evident that the granite is anatectic.

Conclusions

1. To decide whether a granite is intrusive or not, data on the behaviour of silicon, sodium and potassium in a 2 to 3 cm. zone at the contact suffice. In intrusive granites this zone is characterized by enrichment of silicon and potassium and depletion of sodium. The granite studied appeared to be intrusive.

2. When the compositions of contact zone and central part of an intrusive granite are known, the pressures at the level of origin and intrusion of the melt can be estimated. The Ab/An ratio of the

starting material of anatectic melts can be inferred as well. For the granite studied the relevant pressures were 4500 and 500 bars, respectively (corresponding depths: 15 and 3.5 km.). The Ab/An ratio of the source rock was 4.0.

3. As regards trace element content and K/Rb ratio, the alkali granite outcrop of Lilla Rätö deviates considerably from late stage differentiates of basic magmas with similar major element composition. This suggests that anatexis is involved.

V GEOLOGICAL EVOLUTION

Summarising the data at present available and assuming that extrapolation of data from the investigated area to the whole Västervik area is justified, the geological evolution of the Svecofennian orogen in this area can be tentatively reconstructed.

(1) Development of a large shallow basin. Deposition of clastic sediments: sandstones, arkoses and graywackes.

(2) Regional scale intrusion of huge batholiths of porphyritic granites (Småland) and Loftahammar granites).

(3) Local intrusion of basic and ultrabasic dikes, sills and larger massifs.

(4) First deformation phase characterized by slip folding with horizontal axial plane. Synkinematic mesometamorphism and generation of axial plane schistosity. Transformation of porphyritic granites to augen-gneisses.

(5) Paroxysm of the orogene. Second deformation phase characterized by plastic flexural slip folding with vertical axial plane and NW-SE fold axis. Synkinematic high-grade metamorphism, migmatization and local intrusion of equigranular granites of anatectic origin.

Variations in the composition of an equigranular "younger" granite suggest intrusion at a relatively shallow level. Moreover, as the widespread occurrence of andalusite and/or sillimanite points to the development of a steep geothermal gradient, also metamorphism took place at a relatively shallow level.

The granitic "younger" rocks and the analusite-sillimanite paragenesis are formed during the same orogenic phase and locally directly associated. Conclusively, the Västervik area shows all the characteristics of the Hercyno-type orogen, according the classification of Z w a r t (1967).

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