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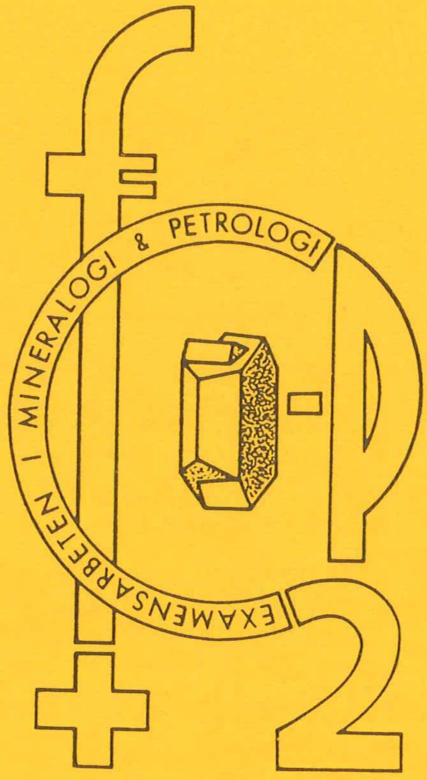

Structural and U-Pb isotopic age constraints on the tectonothermal evolution at Glassvik, Halland.

Ulf Söderlund

Lund 1990 **NR 47**

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Abstract

The topic of this paper include an attempt to interpret the mutually timing of the tectonothermal events at Glassvik, considered to constitute a key locality in the southern part of the Southwestern Granulite Provinve (SGP). The province is characterized by numerous occurrences of mafic granulites and charnockites as well as high-grade gneisses of a polymetamorphic origin.

Three different distinguishable types of granitic dykes and segregates have been studied. A thick pegmatitic dyke was sampled and dated by the U-Pb zircon method. The upper intercept age is 1510 Ma and is interpreted as the intrusion age, while the significance of the lower intercept age of c. 630 Ma is unclear.

Three planar structures are distinguished by differences in mineralogy, deformational textures and structural relationships to intrusive pegmatitic dykes and segregates. The intrusion of the pegmatitic dykes postdates the formation of the compositional banding (S1) exposed in the amphibolites, and predates a high-grade event D2. During this event (D2), migmatitic gneisses were formed and pre-existing fabrics and intrusive dykes were reworked. Retrogression of the high-grade metamorphic assemblages in amphibolitic S3-lenses is interpreted to be associated to late or post-Sveconorwegian uplift.

Ulf Söderlund
Geologiska Institutionen
Avd. för Mineralogi & Petrologi
Sölvegatan 13, S-223 62 Lund, Sweden.

Contents

1 Introduction

The objective of this study is to evaluate the relative timing of tectonothermal events, in the southern part of a geologically complex region, referred to as the Southwestern Granulite Province (SGP) (Fig.1).

High-grade rocks occur in large areas in southwestern Sweden. The metamorphic and structural evolution of these are largely unknown. In an attempt to clarify the tectonothermal history of the region several key localities have recently been investigated. This paper treats one of these key localities, Glassvik, in the province of Halland, southwestern Sweden (Fig. 2). At this locality numerous pegmatitic dykes and segregates occur, that based on mineralogy, deformational textures and structural relationships, can be separated into three major types.

A generation of thick pegmatitic dykes were sampled for a U-Pb zircon dating. The aim was to obtain age brackets for the previous as well as the subsequent tectonothermal events. Complementary studies concerning deformational processes in high-grade rocks, metamorphic petrology and information from previous investigations nearby Glassvik, have made it possible to present age-constraints of the Proterozoic tectonothermal events, that affected this part of the SGP.

2 Geological setting — crustal regions and boundaries

The Southwest Scandinavian Domain includes southwestern Sweden and southern Norway, forming the south-western margin of the Baltic Shield. The Swedish part of the domain (Fig. 1) is usually referred to as the Southwest Scandinavian Gneiss Complex (SGC; Lindh 1987) and is mainly composed of rocks of 1.75-1.50 Ga in age (Gáal & Gorbatschev, 1987). The SGC comprises a western and an eastern segment that are separated by the Mylonite Zone (MZ). In the east, the SGC is delimited by the Protogine Zone (PZ), a tectonic boundary located along the western margin of the Transscandinavian Granite-Porphyry Belt (TGPB). The Svecofennian rocks, 1.90-1.75 Ga in age, are located to the east of the TGPB and include most of the rest of Sweden, apart from an Archean nucleus in the northeast.

The Southwestern Granulite Province constitutes the southern part of the eastern segment of the SGC (Fig. 1). The northern boundary of the SGP is unknown. In fig. 1, a preliminary boundary is marked with a line between Ulricehamn and Borås, coinciding with the northernmost known outcrop of granulite facies rocks (Johansson et al. 1991).

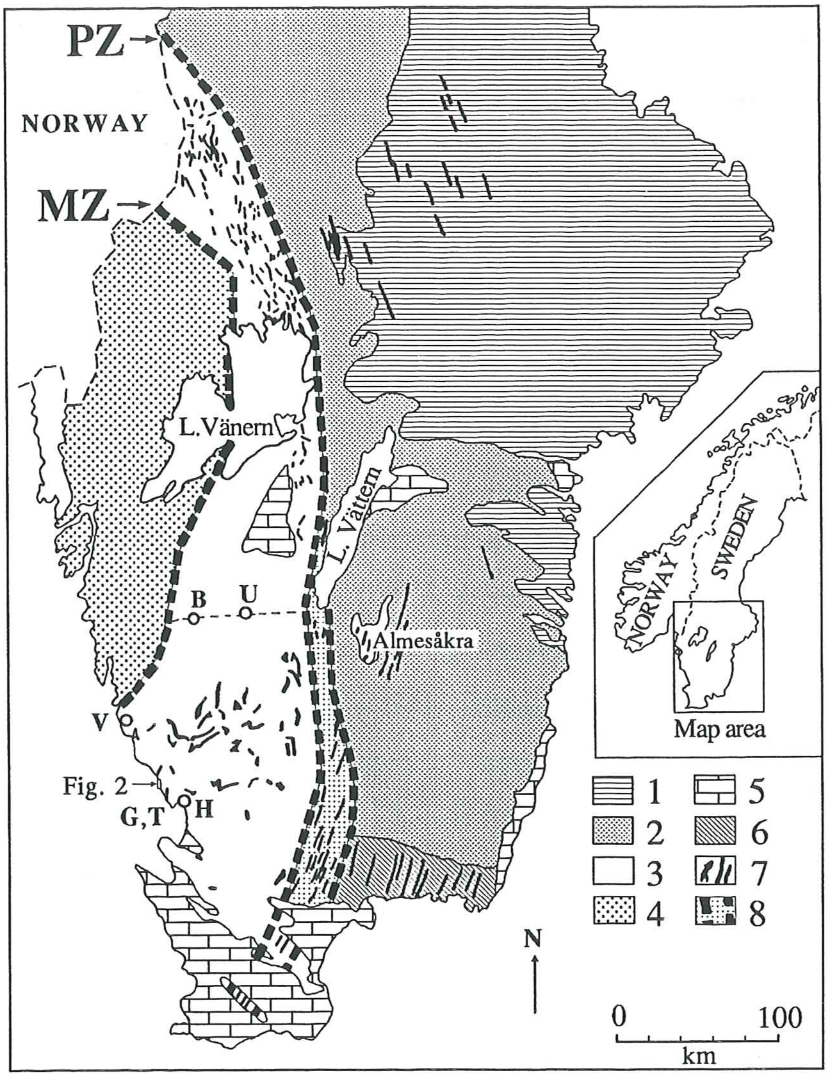


Figure 1. Geological map of south Sweden showing the major provinces. Key:
(1) Svecofennian Province;
(2) Transscandinavian Granite-Porphyry Belt (TGPB);
(3) Eastern segment of the Southwest Scandinavian Gneiss Complex (SGC);
(4) Western segment of the Southwest Scandinavian Gneiss Complex (SGC);
(5) Phanerozoic cover;
(6) Blekinge Province;
(7) Undifferentiated mafic rocks including amphibolites, gabbros, dolerite dyke swarms, etc;
(8) Southern part of the Protogine Zone.
Tectonic boundaries: MZ= Mylonite Zone, PZ=Protogine Zone. Towns and localities referred to in the text: B=Borås, U=Ulricehamn, V=Varberg, T=Tylösand, G=Grötvik, H=Halmstad.

Recent work (Johansson et al. 1991; Johansson & Kullerud, in press) have indicated that the SGP was considerably more affected by the Sveconorwegian-Grenvillian orogeny (1250-900 Ma) than previously thought. High-grade metamorphism occured during a late stage of this orogeny. Sm-Nd geochronology on minerals from mafic granulites yielded late Sveconorwegian ages of 907 ± 12 and 916 ± 11 Ma for the high-grade metamorphism (Johansson et. al. 1991).

Even though large efforts have been made to clarify the geodynamic role of the MZ and the PZ, respectively, this issue is still debated. Johansson et. al. (1992) demonstrated that the MZ was active around 920 Ma by U-Pb dating of titanite from a mafic lens in the tectonic zone. This age was interpreted to date the uplift of the eastern segment, which is in accordance with the fact that these zones represent important breaks in metamorphic grade and structural style (Johansson 1990; Johansson et. al. 1991).

3 Glassvik

The rocks at the Glassvik locality consists essentially of grey gneisses and amphibolites (Caldenius et al. 1966). These rocks form a compositionally banded unit with amphibolite layers varying from a few meters to several tens of meters in thickness (Fig.2). A common feature of these rocks is the occurrence of granulite facies mineral assemblages. Generally, the high-grade metamorphic minerals have been more or less retrograded into lower metamorphic assemblages. Due to a varying degree of recrystallisation a poorly defined preferred mineral orientation is locally developed.

In some amphibolites, a somewhat diffuse compositional (0.03-0.5 m) S1-banding can be observed (Fig. 7), representing an early bedding or foliation. The dominating trend of

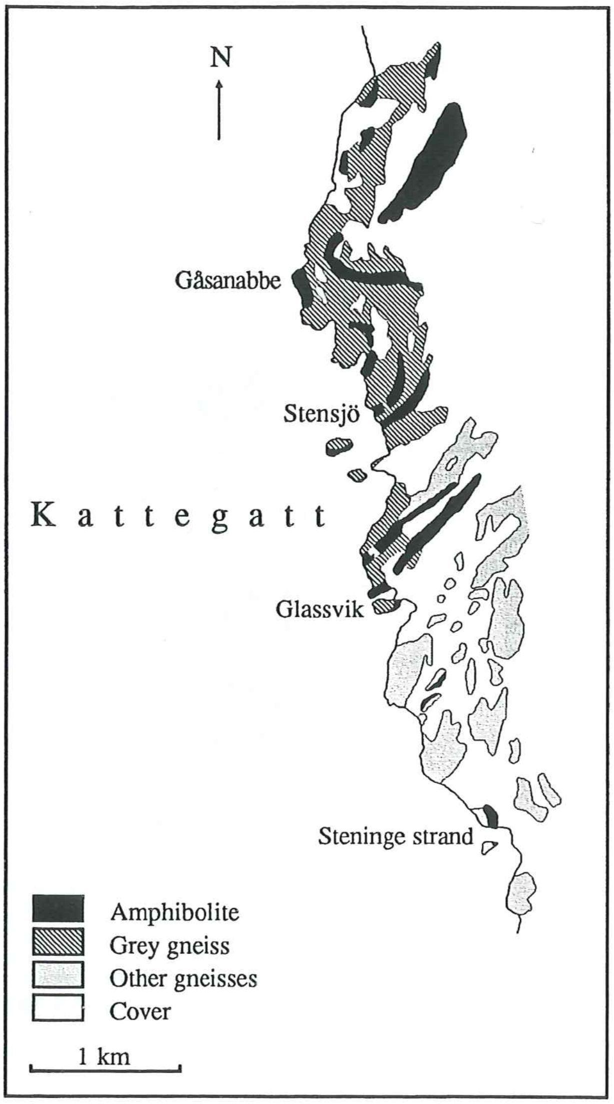


Fig 2. Geological map of the studied area. (Caldenius et al. 1966).

planar and linear fabrics is approximately E-W, subparallel to the regional gneissosity (S2), which is attributed to the major tectonothermal event, D2 (Fig. 17).

3.1 *Grey gneisses*

The grey migmatitic gneisses are fine to medium grained and consist of plagioclase, quartz, alkali-feldspar, hornblende and biotite. The dominance of plagioclase among the feldspar and the presence of biotite give the rock a grey colour. Muscovite, garnet, apatite and zircon occur as accessory minerals. The gneissosity (S2), is a compositional banding of felsic and mafic minerals, respectively.

3.2 *Amphibolites*

The amphibolites are black to dark grey, fine to medium grained with plagioclase, hornblende and garnet as the main minerals. Alkali-feldspar, biotite and pyroxene occur in minor amounts and sometimes porphyroblastic remnants of clinopyroxene can be seen.

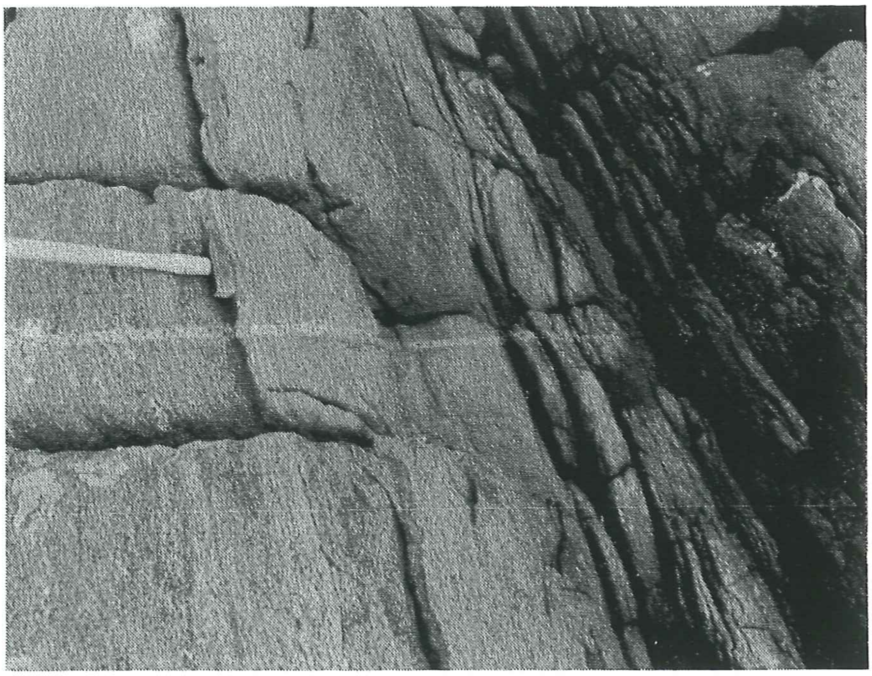


Figure 3. Distinct transition zone between S2 (from center to the left) and S3 (to the right). A thin pegmatitic vein (type 3) truncates both of the foliations at high angle.

In the amphibolites E-W-trending zones occur, being less massive in appearance (Fig. 3). Where strongly deformed, a more pronounced schistosity (S3) can usually be distinguished. Within the S3 foliation planes a lineation (L3) (defined by preferred growth of hornblende) can be seen. Garnet in particular, but also hornblende, have been retrograded and replaced by plagioclase and biotite, resulting in a dark brown colour.

3.3 *Felsic intrusions and segregates*

Pegmatitic rocks occur in vast amounts in the gneisses. The felsic intrusions and segregates are always coarser grained than the neighbouring rocks. The term ”pegmatitic” is used in a wide sense including also medium grained rocks.

The majority of the pegmatitic rocks were emplaced prior to the deformational event D2. As deformation proceeded during this event, the felsic mobilisates were deformed. The final morphology of a dyke or segregate, undergoing deformation, is largely dependent on their orientation relative to the direction of shearing as well as the physical properties of the surrounding rocks. One and the same generation of pegmatitic rocks therefore display large differences in shape depending on if it occurs in mafic or felsic host rocks.

Three types of dykes and segregates have been recognised. A short morphological and mineralogical description of these is given below.

3.3.1 *Type 1a dykes*

This type of dykes comprises 0.3-10 m wide pegmatitic dykes, trending parallel/sub-parallel to the regional gneissosity S2 (Fig. 5). The contacts to the gneisses are sharp and planar along their observed length (200-300 m). The composition is alkali-granitic, with alkali-feldspar, quartz and albitic plagioclase as the most common minerals. Subordinate Fe-Mg minerals are biotite and dark reddish garnet, the latter occurring preferentially along the contact to the gneisses. Apatite, magnetite, pyrite and zircon are accessory minerals.

The dykes are vertical or dip steeply to the south. The relationship between the contacts of the dykes and the regional gneissosity is characterised by a low-angle discordance, which is transformed continuously into concordance when approaching the contacts of the dykes. In an approximately 5 cm wide zone along the contacts the gneissosity undulates parallel with the pinch and swell structures of the pegmatitic dykes (Fig. 4). Pinch-and-swell-structures, boudins and an internal foliation in the pegmatites are evidence of post-intrusive deformation. The internal foliation is parallel/subparallel to S2.

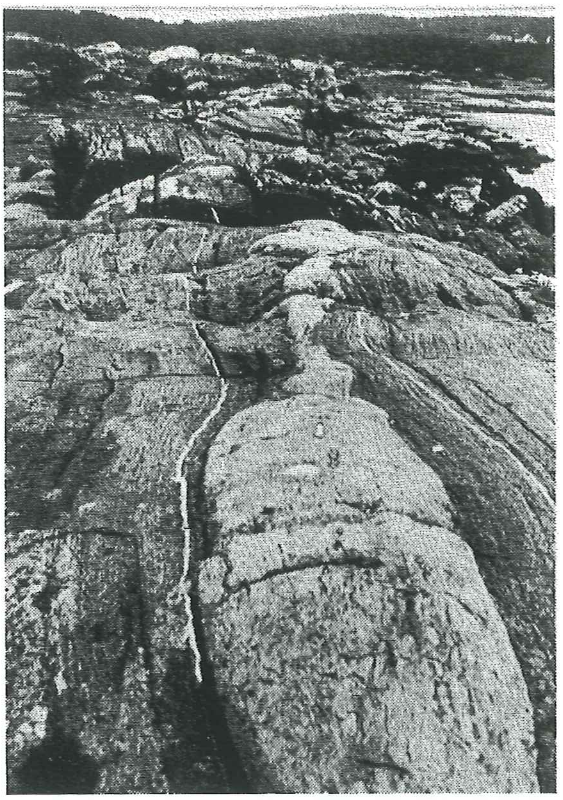


Figure 4. Type 1a pegmatite dyke embedded in the amphibolite, exposing well developed pinch and swell structures. On each side of the dyke a foliation plane have been marked by a chalk in purpose to elucidate the low-angle discordancy between the attitude of the dyke and the S2 fabric.

3.3.2 *Type 1b dykes*

These felsic dykes are up to a few tens of meters long. They differ from the type 1a dykes by being narrower (5-15 cm) and distinctly discordant to the regional gneissosity S2. Locally, the dykes are almost perpendicular to S2. Further, the type 1b dykes, are more intensely deformed than the type 1a dykes, the former commonly occuring as isoclinal folds, Z-folds or rootless folds

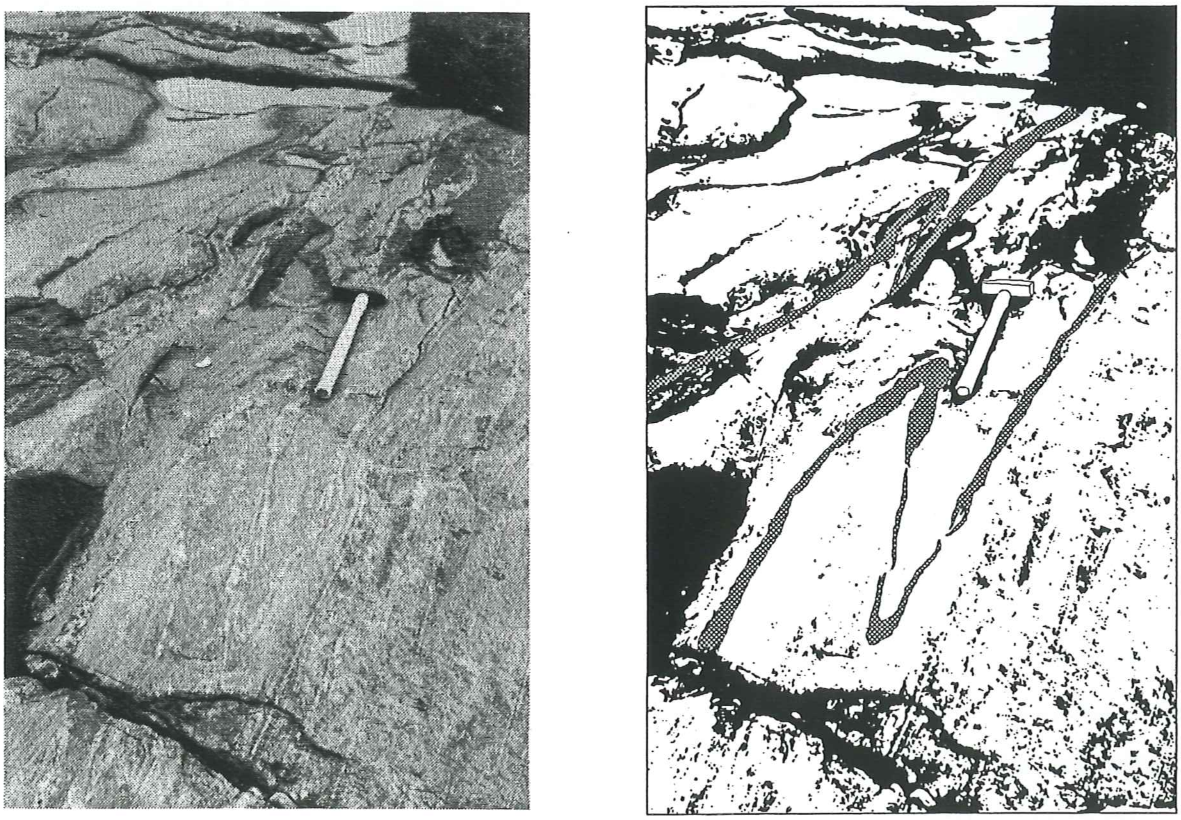


Figure 6. Intensily deformed and folded (Z-folds) type 1b dykes in grey gneiss.

(Fig. 6). In the amphibolites, remnants of 1-4 cm large porphyroblastic pyroxenes occur in some of these veins. Type 1b veins are in places cross-cutting the S1 foliation (Fig. 7).

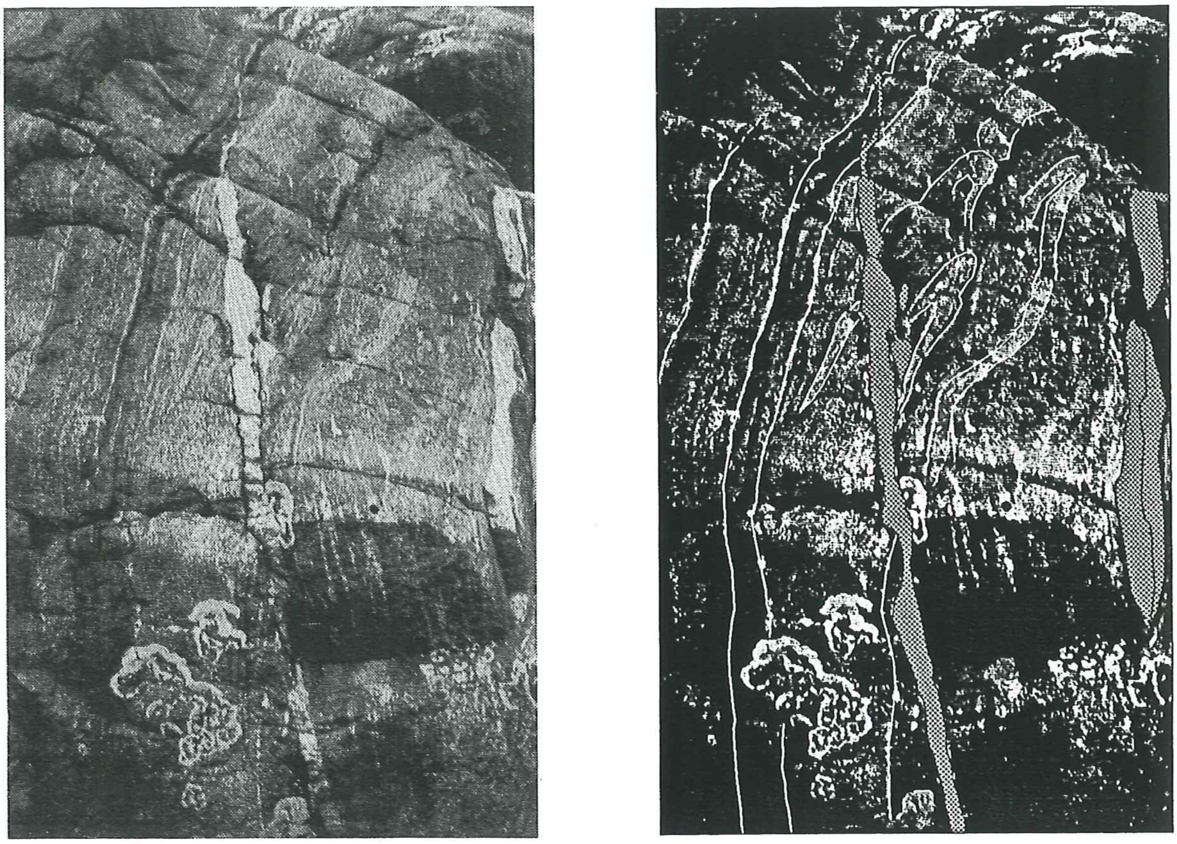


Figure 7. S1-foliation, truncated by a 10 cm thick dyke (type 1b). The pegmatitic dyke as well as the S1 trend subparallel to S2.

3.3.3 *Type 2 segregates*

Small-scale leucosome segregates are widespread in the amphibolites. No mobilisates with similar morphology, occur in the grey gneisses. Due to their wide range in shape and other characteristics, they are divided into the following subgroups.

3.3.3.1 *Type 2a segregates:* These segregates, that are predominantly planar, gives the amphibolites a mottled appearance. The length of the segregates is usually less than 20 cm with an average thickness of 1 cm. Some of the segregates are folded, displaying both concordant and discordant relations to S2 (Fig.8)

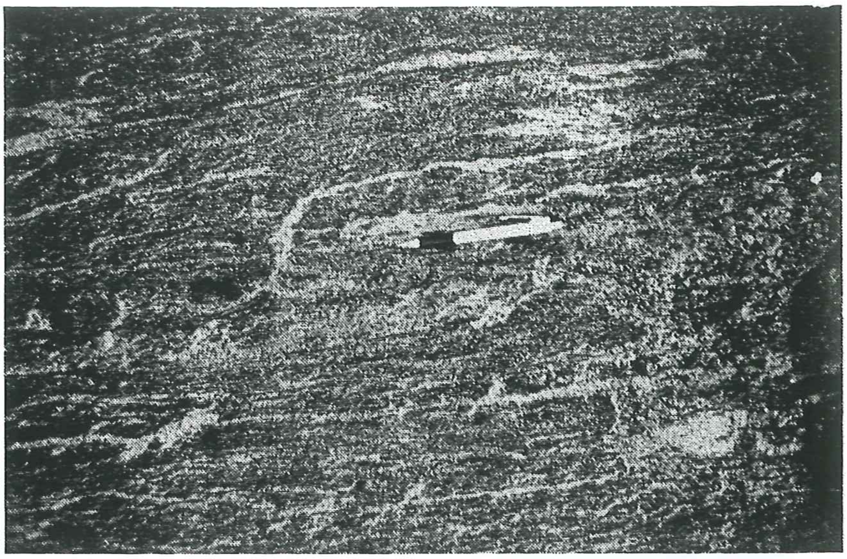


Figure 8. Planar and S-shaped veins (2a), indicating a possible syn-D2 origin.

3.3.3.2 *Type 2b segregates:* Undeformed, 5-20 cm in size and irregulary shaped segregates can be found, as well. These segregates are generally surrounded by a dark rim (melanosome) of hornblende and biotite (Fig. 9).

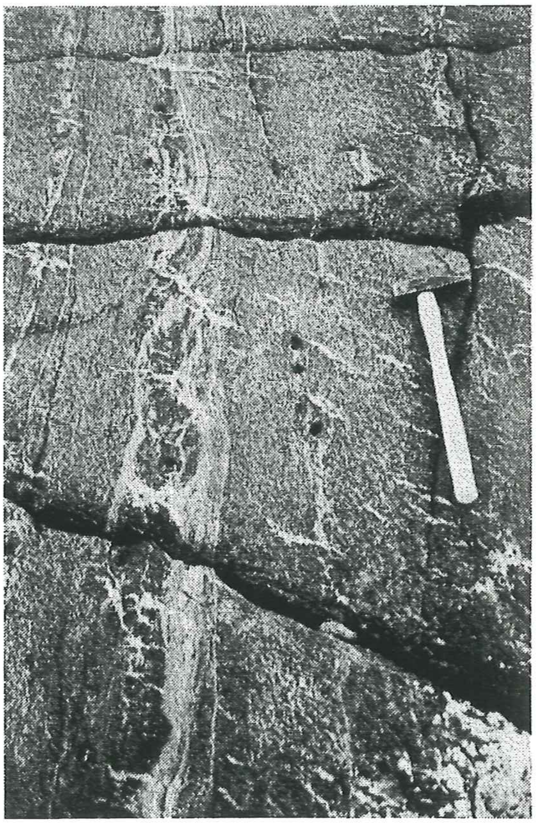


Figure 9. Leucosome 2b-segregates in amphibolite, with no signs of later deformation. In the center to the left a light S1-layer is truncated by irregulary shaped segregates.

3.3.4 *Type 3 veins*

A generation of young, undeformed and thin (< 0.1 m) felsic veins occur sparsely at Glassvik (Fig.3). These veins truncates the regional gneissosity, S2, and the older generations of dykes and moblisates (type 1a, 1b, 2a and 2b). High-grade metamorphic assemblages are absent.

4 Zircon morphology

The central part of a c. 5 m wide pegmatitic dyke of type 1a was sampled for U-Pb dating of zircons (Fig. 10). The zircons from the dyke, vary in colour, length-width ratios and shape. Numerous zircons display cracks, often radiating from the centres of the grains.

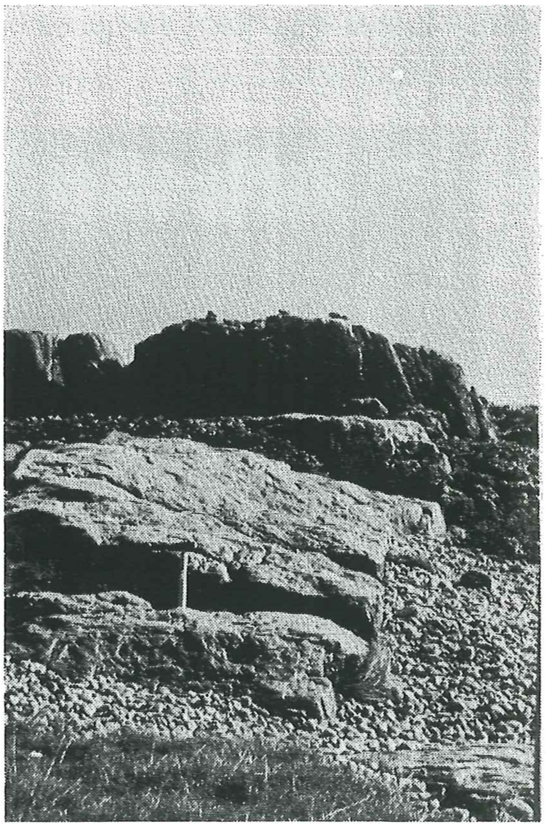


Figure. 10. The dyke sampled for U-Pb systematics.

In order to check the crystal´s internal structures, the zircons were mounted in epoxi and polished. The zircons were then examined in a scanning electron microscope. No typical growth zoning pattern or inherited cores were found. However, in some of the zircons, darker and lighter domains could be observed. When using a semi-conductive back-scatter electron detector, minor amounts of Ca, Al and Hf were detected in the darker domains. The polished thin-sections were also studied under the petrographic microscope after treatment of hydrofloric acid, revealing a vague magmatic zoning in some of the crystals.

Two main types of zircons could be distinguished. The most common type (Fig. 11A) is characterised by being sub- to euhedral in shape. Their long-prismatic shape indicates a magmatic origin. The average length to width ratio is about 3:1, and the colour is yellow to brown. Fractures are frequent in the zircons, explaining the large amounts of angular zircon fragments in the concentrate. Two zircon populations of this type were analysed, 106-150 μm and >150 μm (Table 1).

The second type (Fig. 11B) is rounded to ellipsoidal, and the grain surfaces are generally smooth. Irregularly shaped grains are abundant as well. These zircon crystals display a large number of crystal faces, some with high crystallographic indices. Fractures are less abundant, explaining the high transparency and the almost gem quality lustre. The colour is similar to that of the first type. Three zircon fractions of this type were selected and analysed; <150, 74-106 and 106-150 µm (Table 1).

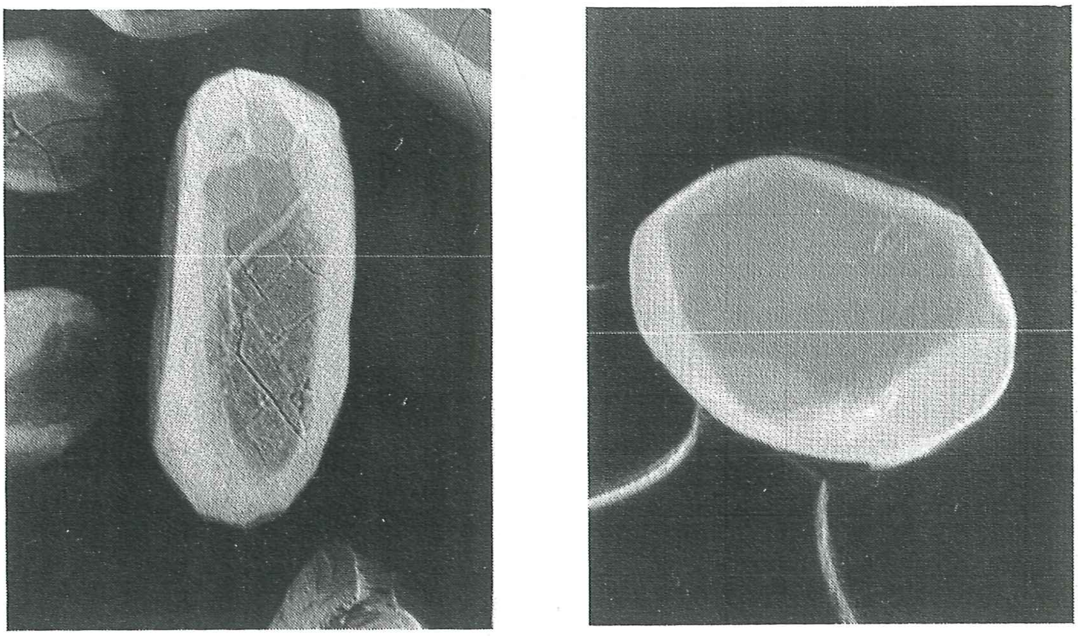


Fig 11. Scanning electron microscope photograph of zircons from the type 1a pegmatitc dyke. **A.** Microphotograph showing sub-eudral zircon grain (120 µm in length) in the center of the picture, referred to as the prismatic type in the text. Notice the large amounts of cracks. **B.** SEM photograph of a rounded zircon (80 µm across). Note the absence of fractures.

5 **Analytical procedure**

The sample preparation and analyses were made in Stockholm at the Laboratory of Isotope Geology of the National Museum of Natural History.

The zircons were separated using conventional procedures described by e.g. Schouenborg (1988). Chemical preparation followed the methods of Krogh (1973). The uranium as well as the lead analyses were made on a MAT 261 masspectrometer.

The age calculations followed the procedure of Ludwig (1980) and the analytical errors are given at the 2 sigma confidence level. The decay constants used are those of Steiger & Jäger (1977), and the lead analyses were corrected for a initial common lead contamination of 0.0090 ng by applying the model of Stacey & Kramers (1975); $^{206}Pb/^{204}Pb=18.5$, $^{207}Pb/^{204}Pb=15.6$ and $^{208}Pb/^{204}Pb=38.5$.

6 Results

Five zircon size-fractions between ~30 to >150 µm were analysed. The fractions define a discordia line with an upper intercept of 1510 ± 32 Ma and a lower intercept of 631 ± 64 Ma. The MSWD-value is 0.16 (Fig. 12). No systematic difference in discordancy between the two types of zircons were found. The least discordant data point is discordant by 38 %, and the uranium content is high, varying between 500 to 3000 ppm (table 1).

Table 1. U and Pb analytical data for zircons from the type 1a pegmatitic dyke. a) Corrected for blank and mass spectrometer fractionation. b) Corrected for common lead, blank and mass spectrometer fractionation. P = prismatic and R = rounded

	Measured ratios				Sample	Concentrations (ppm)			Age
Sieve fraction (µm)	$\frac{^{206}Pb}{^{204}Pb}^{a}$	$\frac{^{206}Pb}{^{238}U}^{b}$	$\frac{^{207}Pb}{^{235}U}^{b}$	$\frac{^{207}Pb}{^{206}Pb}^{b}$	weight (mg)	U	Pb_{rad}	Pb_{com}	$\frac{^{207}Pb}{^{206}Pb}$
1. >150 P	1326	0.19448	2.31946	0.0971	1.23	2083	388.4	19.7	1348
2. 106-150 P	1072	0.20240	2.44528	0.1001	0.30	2958	568.6	36.1	1373
3. 106-150 R	3118	0.16658	1.85930	0.0844	0.07	414	65.7	1.4	1219
4. 74-106 R	1197	0.19691	2.36073	0.0986	0.55	1950	365.9	20.7	1358
5. <50 R	1189	0.19709	2.35743	0.0985	0.32	1927	360.8	20.6	1354

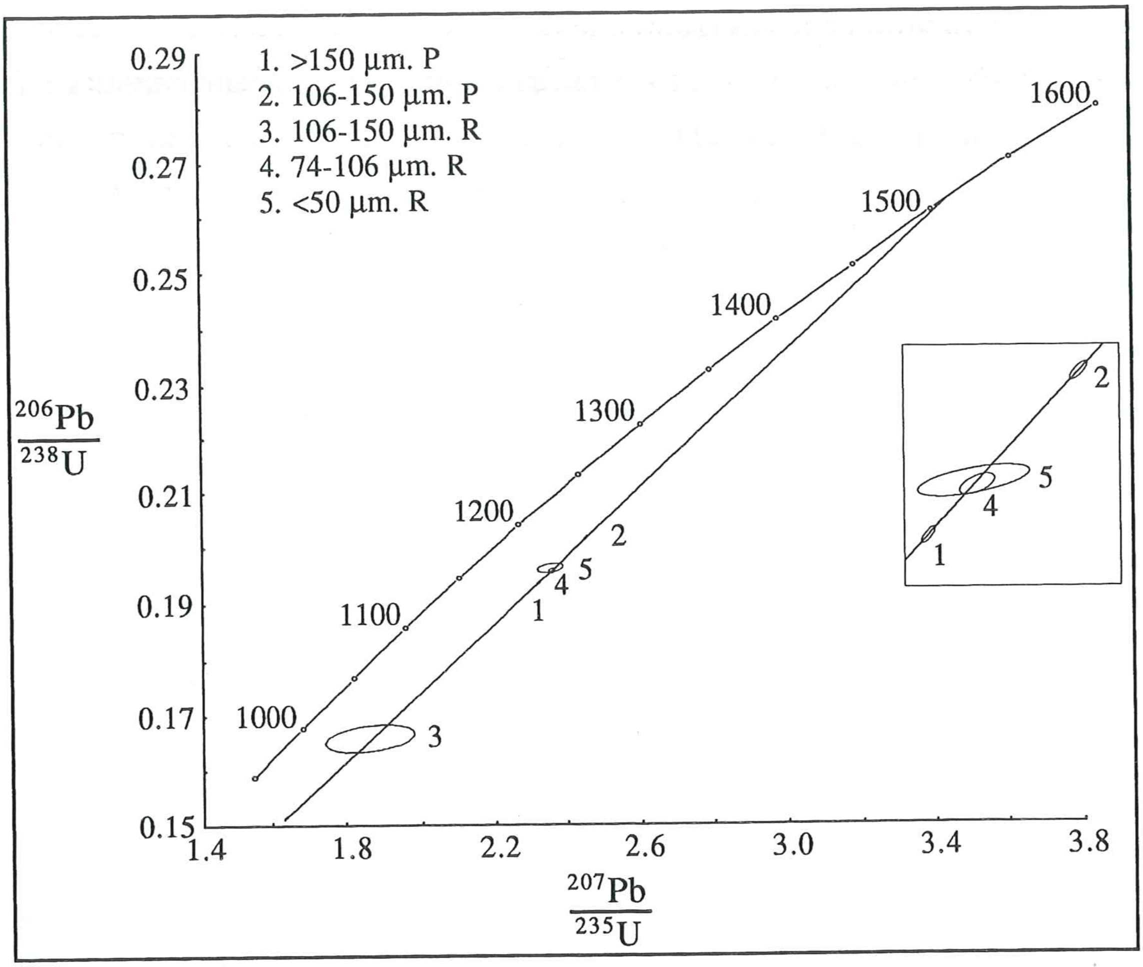


Fig 12. U-Pb concordia diagram for the zircons of the type 1a pegmatite with 2 sigma error ellipsoids. P=Prismatic and R=Rounded.

7 Discussion

7.1 *Interpretation of the isotopic results*

The upper intercept age of 1510 Ma is interpreted as the intrusion age of pegmatitic dykes of type 1a.

The physical properties of the abundant prismatic type of zircons is typical for zircons of magmatic origin, while the second type have features possibly indicating a metamorphic overprint. The difference in uranium content (Table 1) between the prismatic and the rounded zircons is constistent with the results of e.g. Pidgeon & Aftalion 1972, Grauert & Wagner 1975 and Schenk 1980, indicating that zircons from granulites generally are rounded and have lower uranium content than prismatic zircons of magmatic origin (Pidgeon 1991; Chiarenzelli et al. 1993).

Table 2.

Location	**Rocktype**	**Age (Ma)**	**Method**		**References**
Skåne (Scania)					
Vägasked	Grey gneiss	1611±6	U-Pb	Zircon	Å. Johansson 1991
Romelåsen	Aplitic gneiss	1557+32/-28	U-Pb	Zircon	Å.Johanssson 1991
Beden	Granodiorite	1449+23/-11	U-Pb	Zircon	Å. Johansson 1991
Skäralid	Gneissic granit	1575+78/-62	U-Pb	Zircon	Å. Johansson 1991
Kullaberg	Gneissic granit	1497+47/-34	U-Pb	Zircon	Å. Johansson 1991
Örkelljunga	Charnockite	1452+348/-47	U-Pb	Zircon	Å. Johansson 1991
Hinneryd	Granit	1548±10*	U-Pb	Zircon	See below
Stenberget	Aplitic vein	1395**	U-Pb	Monazite	Welin & Blomqvist 1966
Halland					
Varberg	Charnockite	1420±52**	Rb-Sr	W.r	Welin & Gorbatschev 1978
Torpa	Granite	1379±7	U-Pb	Zircon	Åhäll et al. 1992
Värmland					
Sunne	Granite	1612+58/-46	U-Pb	Zircon	P-O Persson 1986
Forshaga 1	Granite	1647+24/-22	U-Pb	Zircon	P-O Persson 1986
Forshaga 2	Granite	1486+86/-43	U-Pb	Zircon	P-O Persson 1986
Nilsby	Granite	1612±94	Rb-Sr	W.r.	P-O Persson 1986

W.r = whole rock.

*The age is calculated on four out of six zircon fractions. Two of them fall just below the discordia. Therefore, the results should be regarded as preliminary (A. Lindh, pers. com. 1993). The analyze was performed by H. Schöberg.

**Recalculated ages by Welin 1980.

Recently, new geochronological data (Table 2) from intrusive rocks in the eastern segment have been presented. Some of the ages can be correlated with the 1510 Ma zircon-age, presented in this paper. The age data indicate that extensive magmatism occured throughout in the eastern segment during the middle Proterozoic (1400-1600 Ma). For more detailed information the reader is referred to the original publications.

The lower intercept age of 630 Ma is not easily explained since it does not correspond to any known tectonothermal event which could have caused episodic lead-loss. The apparent lack of geological significance of the lower intercept age, therefore makes a single episodic lead-loss event questionable. Models have been proposed i.e "the continuous loss of lead model" (Tilton 1960) and "the dilatency model" (Goldich et al. 1972), that explain lead-loss in zircons that is not caused by any geological event in particular. A continuous lead-loss during a long period of time can possibly explain the lower intercept age (Fig. 12).

In previous geochronological work north of Lake Vänern and in the western segment of the SGC (Fig. 1, page 2), lower intercept ages also seem to lack any geological significance (e.g. Åhäll et al. 1989, Persson 1986 and Hansen et al. 1989).

Both Sm-Nd and Ar-Ar dating have given late Sveconorwegian ages for the granulite and amphibolite facies metamorphism. There is therefore reason to expect that this high-temperature event could have caused loss of radiogenic lead in the zircons around 900 Ma instead of the 630 Ma, as indicated by this study. If this is the case, models with multi-stage lead-loss can explain the 630 Ma lower intercept age.

Complementary isotopic analyses, applying the "Kober-technique" (Kober 1986) will be carried out during 1993, in order to further evaluate the significance of the upper intercept age .

7.2 *Interpretations of the timing of the tectonothermal events*

The interpretation of structures in high-grade metamorphic terranes may be problematic. Some of the hypotheses put forward here needs further investigations in the field and laboratory analyses to be corroborated.

7.2.1 *The D1 event of unknown origin*

The oldest planar structure recognised in the mafic rocks, is the compositional S1-banding, representing either a sedimentary or a tectonic origin (Fig. 7). The S1 foliation is mainly seen in the internal parts of the amphibolites. A corresponding early planar structure probably existed in the grey gneisses as well, but have been eradicated during later deformation (D2). The S1 fabric predates the emplacement of 1a and 1b pegmatitic dykes, since it is truncated by these intrusions.

7.2.2 *Type 1a and 1b dykes*

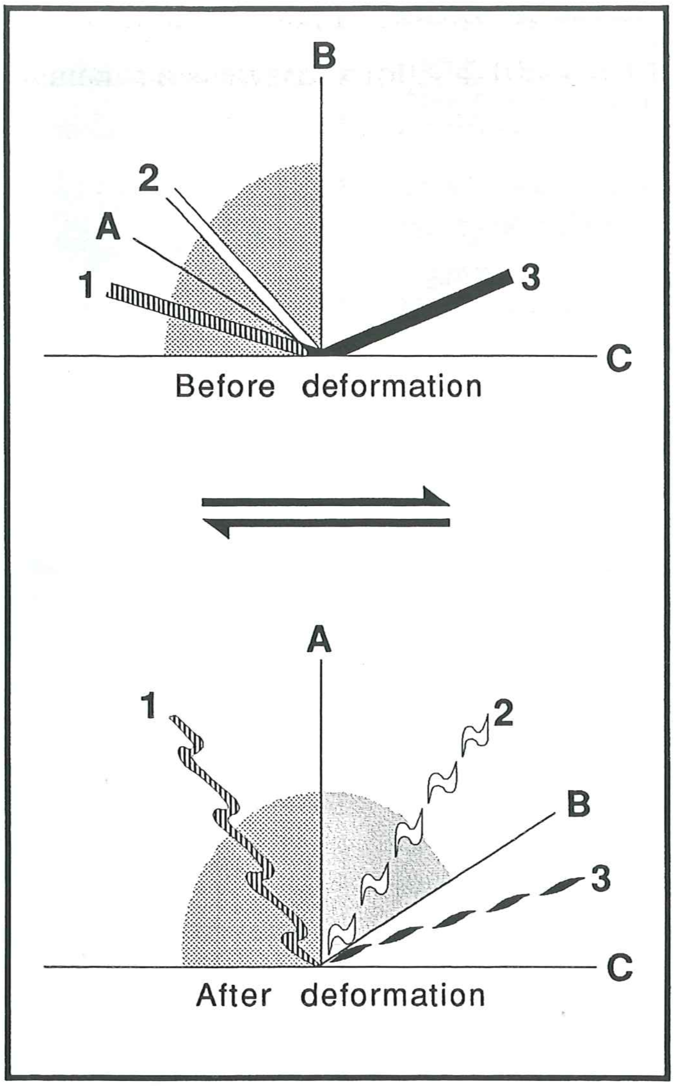
Around 1510 Ma, the type 1a and 1b felsic dykes intruded. They most likely belong to the same generation and the morphological differences between them are due to post-intrusive reworking.

The sharp intrusive contact as well as the planar shape of the dykes, indicate a brittle deformational behaviour in the country rock at the instant magma was triggered, which may further indicate a relative shallow crustal level for the country rocks at Glassvik, around 1510 Ma.

7.2.3 *The tectonothermal event - D2*

The complexity in deformational fabrics, *i.e* rootless folds and boudins of the type 1a and 1b is not necessarily the result of a polyphase deformation. It should be emphasised that folding must not always be associated with regional shortening and boudinage with regional extension. In fact, any flow type comprises extensional and constrictional domains. Boudins and folds can develop synchronously in layers and veins of different orientation and/or competence contrast (Passchier et. al. 1990) (Fig.13).

Figure 13. Deformation of veins by progressive simple shear. Fields are indicated of extension (white), shortening (open stippled) and shortening followed by extension (dense stippled). Depending on their original orientation, veins can be shortened (vein 1), extented (vein 3) or first shortened and then extended (vein 2). Lines (a), (b) and (c) are boundaries of domains with different extension and shortening histories. Illustration modified from Passchier et al. 1990.



During the D2 event, the 1a and 1b dykes were deformed in a process of non-coaxial flow (shear folding; e.g. Ragan 1973). The differences in deformational fabric of the dykes can be explained by at least two models. Both models involve rotation of the pegmatitic dykes into increasing parallelism with the direction of shearing. Consequently, the original discordance between the dykes and the shear planes continuously becomes more and more concordant (Fig. 14). The tectonothermal event during which the gneisses were formed postdates the intrusion of the 1510 Ma dyke. During this event the rocks were thoroughly reworked, and older foliations that may have been present became overprinted and more or less obliterated. In the first model (Fig. 15A) the thicker and more competent dykes, almost escaped internal deformation since they behaved as rather passive rigid bodies during shearing. This is why the original morphology of type 1a dykes has been better preserved, revealing their intrusive origin. The thinner dykes of type 1b, on the contrary, were less resistant to deformation and thus became deformed to a greater extent. This model thus proposes that all the dykes were intruded more or less parallel, and that their final morphology

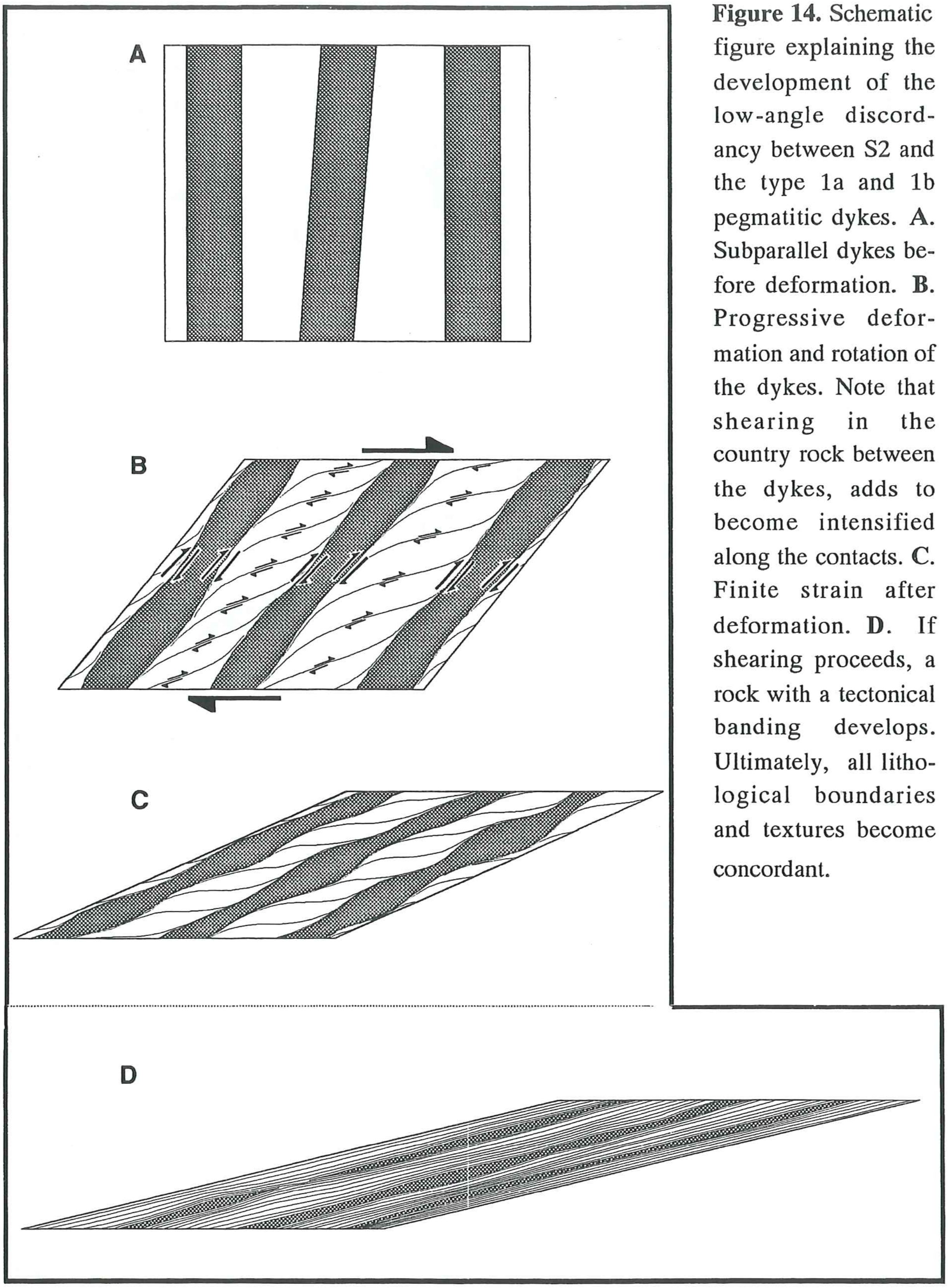


Figure 14. Schematic figure explaining the development of the low-angle discordancy between S2 and the type 1a and 1b pegmatitic dykes. **A.** Subparallel dykes before deformation. **B.** Progressive deformation and rotation of the dykes. Note that shearing in the country rock between the dykes, adds to become intensified along the contacts. **C.** Finite strain after deformation. **D.** If shearing proceeds, a rock with a tectonical banding develops. Ultimately, all lithological boundaries and textures become concordant.

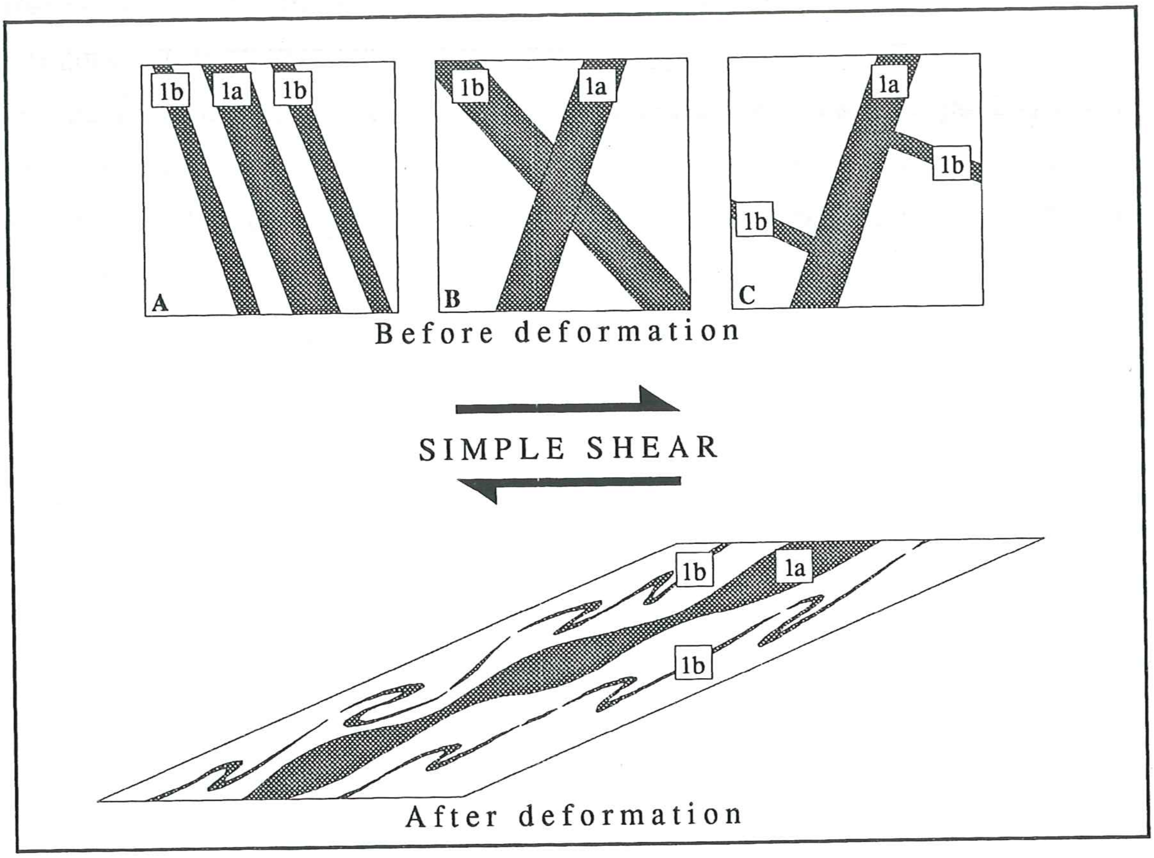


Figure 15 A-C. The remarkable differences in shape and thickness between the type 1a and 1b pegmatitic dykes can be explained by the following models. **A.** Primary parallel dykes of different thickness and thus also in competence. The thicker dykes resist internal foliation more successfully by behaving as passive rigid bodies during shearing. **B.** The type 1b dykes originally had a higher intrusive angle to shearing, resulting in a tectonical related thinning and lowering in competency. **C.** A combination of the A and the B models is also possible during which the type 1b dykes are regarded as apophyses to the type 1a dykes.

largely are explained by differences in thickness (competence).

The second model (Fig. 15B) is based on originally different intrusive angles of the dykes. The higher the intrusive angle is to the shear plane, the higher degree of intense deformational textures will develop, e.g. isoclinal and rootless folds. The type 1b folded veins may primary have been thinner apophyses to the thicker dykes of type 1a. However, thinning of the dykes may also have been caused or enhanced by a more intense shear folding, due to an original higher angle (Fig. 15C). Due to the extent of ductile shearing no truncating contacts between the dykes are exposed, indicating if any of the models described above can be rejected. This is why it has not been possible, by structural studies in the field, to confirm whether or not the type 1a and 1b dykes belong to more than one generation of pegmatitic intrusions.

All the models presented, explain why the thinner dykes (type 1b) are more often isoclinally folded, rootless and form Z-folds. These dykes are more abundant in the grey gneisses, which is to be expected, when considering the different intensity of shearing during high-thermal conditions in mafic and felsic rocks. Where shearing was particularly intense, the dykes were torn apart evolving into rotless folds and boudins.

7.2.4 *Type 2 segregates*

The formation of the leucosome segregates 2a and 2b are interpreted to be contemporaneous with D2. It should be emphasised, that in the author's opinion, no substantial partial melting occurred during D2, neither in the amphibolites, nor in the grey gneisses. If a high degree of partial melting occured, the character of the granitic rocks and the structures formed prior to, as well as synchronous to D2, ought to be much more difficult to distinguish. Instead, solid- to subsolid state processes (dynamic recrystallisation, precipitation of material and infiltration of fluids) are inferred for the formation of these segregates. Similarily, a non-anatectic formation of migmatites in southwestern Sweden, has been proposed by Karlsson & Wahlgren 1982 and Wahlgren 1984. Studies on the origin of leucosomes suggest that these usually can be regarded as products of solid state diffusion, i.e. metamorphic differentiation.

7.2.4.1 *Type 2a segregates*

The emplacement of the type 2a segregates is interpreted to be intimately associated with the dynamic rotation of the thick, more competent dykes. During rotation, domains in neighbouring rocks probably experienced deviating litostatic pressures. Because of the relatively high competency of the mafic rocks, the local change in lithostatic pressure was not counterbalanced instantly. A process involving migration of fluids into low-pressure domains, precipitating material and/or facilitating metamorphic differentiation, is the most attractive theory explaining the origin of the 2a segregates.

Even though considering a local decrease in lithostatic pressure in combination with the presence of fluids, the temperature was presumably not high enough to generate anatectic formation of leucosomes.

7.2.4.2 *Type 2b segregates*

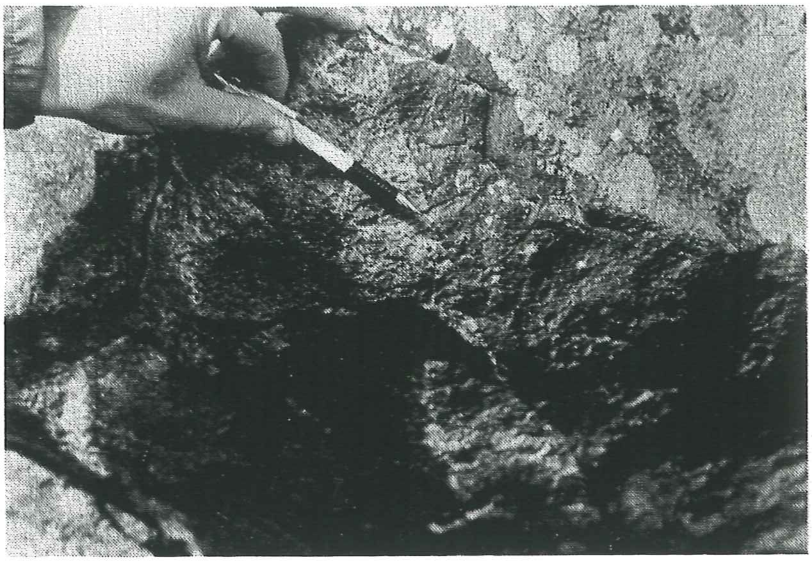
The melanosome-bearing 2b leucosomes are interpreted to represent late-stage equivalents to the 2a segregate. These were formed by similar processes in a high-thermal condition, but escaped more or less later affection of deformation. No obvious corresponding granitic mobilisate are present in the grey gneisses at the Glassvik locality. Most likely, the ductile shearing ceased earlier in the mafic rocks than in the felsic rocks, explaining the absence of undeformed segregates in the grey gneisses. Thus, the segregates generated in the felsic rocks synchronously with formation of the 2b segregates, were probably instantly deformed during the ongoing shearing in the felsic rocks. At the end of D2 the temperature was probably not high enough to continue formation of segregates in the felsic rocks.

7.2.5 *The high-grade metamorphic event*

The high-grade metamorphism dated to c. 920 Ma (Johansson et al. 1991), is problematic to relate in age to D2. In other words, was the dated 920 Ma event include a static metamorphism, that can be separated in age from D2, or are these events closely related to each other?

Among the major mineral phases, hornblende is the only suitable candidate for exposing a dimensional preferred orientation. Assuming that this phase was stable during D2, the hornblende must have been strongly recrystallised since it is randomly orientated in the rocks. The high-temperature conditions that probably prevailed at the end of D2, may have been sufficient to cause static recrystallisation (annealing) and thus reorientation of the amphiboles. A later high-grade event can as well caused recrystallisation.

Figure. 16. Undeformed dolerite dyke with granulite facies minerals truncating the S2-foliation, indicating a minimum age for D2 of around 900 Ma .



At Stensjö harbor (Fig. 2) mafic granulites, which do not display any post-intrusive deformational textures, truncate S2 at a high angle (Fig. 16). Similar granulites yield late Sveconorwegian ages for the high-grade metamorphism. These relations indicate a pre-Late Sveconorwegian origin for D2, suggesting high-temperature static conditions of the high-grade metamorphism around 900 Ma.

In amphibolites just north of Glassvik, huge garnet megacrysts, some more than 6 cm across occur in amphibolitic rocks. A similar metamorphic growth of pyroxene has occurred. As mentioned above, remnants of porphyroblastic pyroxene are sometimes found within the earlier mobilisates. At this locality in particular, the porphyroblastic growth of garnet and pyroxene seems to have occurred during a high-grade metamorphic event after D2.

At Steninge c. 1-5 km south of Glassvik, megacrystic remnants of pyroxene are found in strongly deformed gneisses (Johansson, pers. com. 1993). Garnet and amphibole, the latter formed from pyroxene form an association that have been affected by deformation, which may correspond to the D2 event. If this is the case, it is thus possible to find growth of granulite facies assemblages that pre-, syn- and post-dates D2-structures.

7.2.6 *The D3 event*

At the localities Grötvik and Tylösand, (Fig. 1) nearby Glassvik, pressures of around 9 kbars have been estimated (Johansson et. al. 1991), which corresponds to a crustal depth of 30-35 km.

The N-S oriented eastern segment between the MZ and the PZ constitutes a 30 to 120 km wide crustal block (Fig. 1, page 2). When considering at least 30 km of uplift of a crustal block of this size, internal tectonism should be expected. The S3-foliation may thus represent deformation, associated with uplift during late-Sveconorwegian time. In some outcrops, a pronounced and usually very steep, hornblende lineation (L3) can be found. Deformation in the zones syn- to post-dates the retrogression event of the granulite facies assemblages. The SL3-fabric is thus interpreted to represent the youngest exposed deformational fabric at the Glassvik locality.

The amphibolitic zones, characterised by a S3-cleavage, are similar in some aspects to mafic lenses, occuring in the southern part of the MZ. In both cases the granulite-facies assemblages have been almost completely retrograded. Titanite of a possible retrograde origin have been found in the S3 foliations at Glassvik.

7.2.7 *Type 3 veins*

The type 3 veins post-date all known tectonothermal events at the Glassvik locality. All structures are cut at a high angle by these veins. Internal deformation textures, as well as signs of any post-intrusive metamorphism, are absent (Fig. 3, page 5).

Summary and conclusions

U-Pb dating of zircons yield an upper intercept age of 1510 Ma for a pegmatite dyke of type 1a. This age is interpreted as the intrusion age of a generation of felsic dykes.

The planar shape of the thicker 1510 Ma old dykes, probably indicates a brittle deformation behaviour of the host rock at the instant fluid-rich melts were generated. This suggests a relatively shallow crustal level of the SGP around 1510 Ma.

A major tectonothermal event, referred to as D2, is bracketed between c. 900 Ma and 1510 Ma. During this high-grade event the gneisses were formed as a result of migmatitisation and ductile shearing. All the planar and intrusive structures (type 1a and 1b) were deformed by shear folding.

The 1a and 1b dykes are interpreted to belong to one and the same generation. The differences in shape, can be explained by contrasts in thickness (competence) and/or in intrusive angles, prior to D2.

Due to more intense ductile shearing in the grey gneisses, the 1a and 1b dykes are exposed as similar folds more frequently in the grey gneisses, than in the amphibolites .

The type 2 segregates are interpreted to have formed contemporaneous with the formation of the migmatitic gneisses (D2). A non-anatectic origin is not only possible, but also probable. The absence of corresponding in-situ mobilisates in the grey gneisses, may be due to more intense ductile shearing in these rocks, that ceased later than within the amphibolites.

The high-grade granulite metamorphism is interpreted to be closely associated in time with D2.

The SL3-fabric may be associated with uplift along the MZ of the eastern segment during the late Sveconorwegian age.

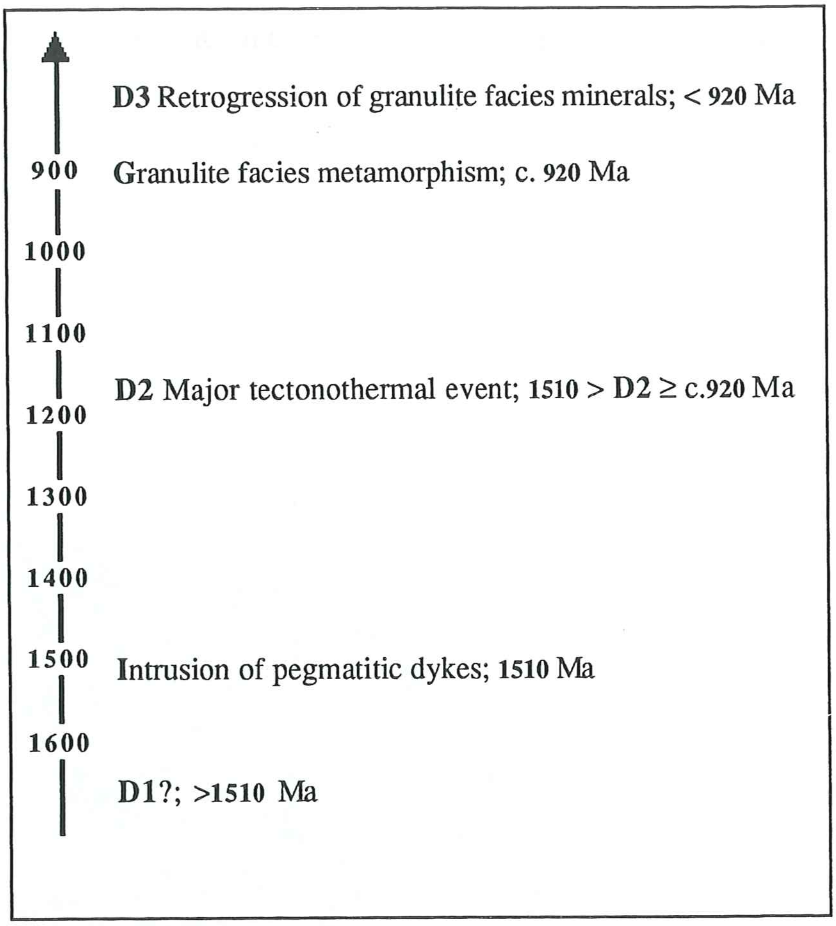


Figure 18. Suggested tectonothermal history of the rocks at the Glassvik locality and nearby.

This study has demonstrated the importance of understanding deformational processes and their influence on pre-deformational intrusive rocks. Further geochronological studies coupled with pressure and temperature data and structural analyses are required to constrain the detailed timing of tectonothermal events in order to model the PTt-evolution of the SGP.

Future work

To confirm the interpretation of the development of the S3 fabric, the amphibolites should be sampled across the diffuse contact between S2 and S3 foliations. An increase in plagioclase and in biotite, replacing hornblende in the S3 foliation, could indicate post-D2 displacements at retrograde conditions that probably are related to late Sveconorwegian uplift of the southern part of the eastern segment.

An age estimate of the shearing in the S3 deformation zones can possibly be obtained by U-Pb dating of titanite that was formed during deformation and retrogression.

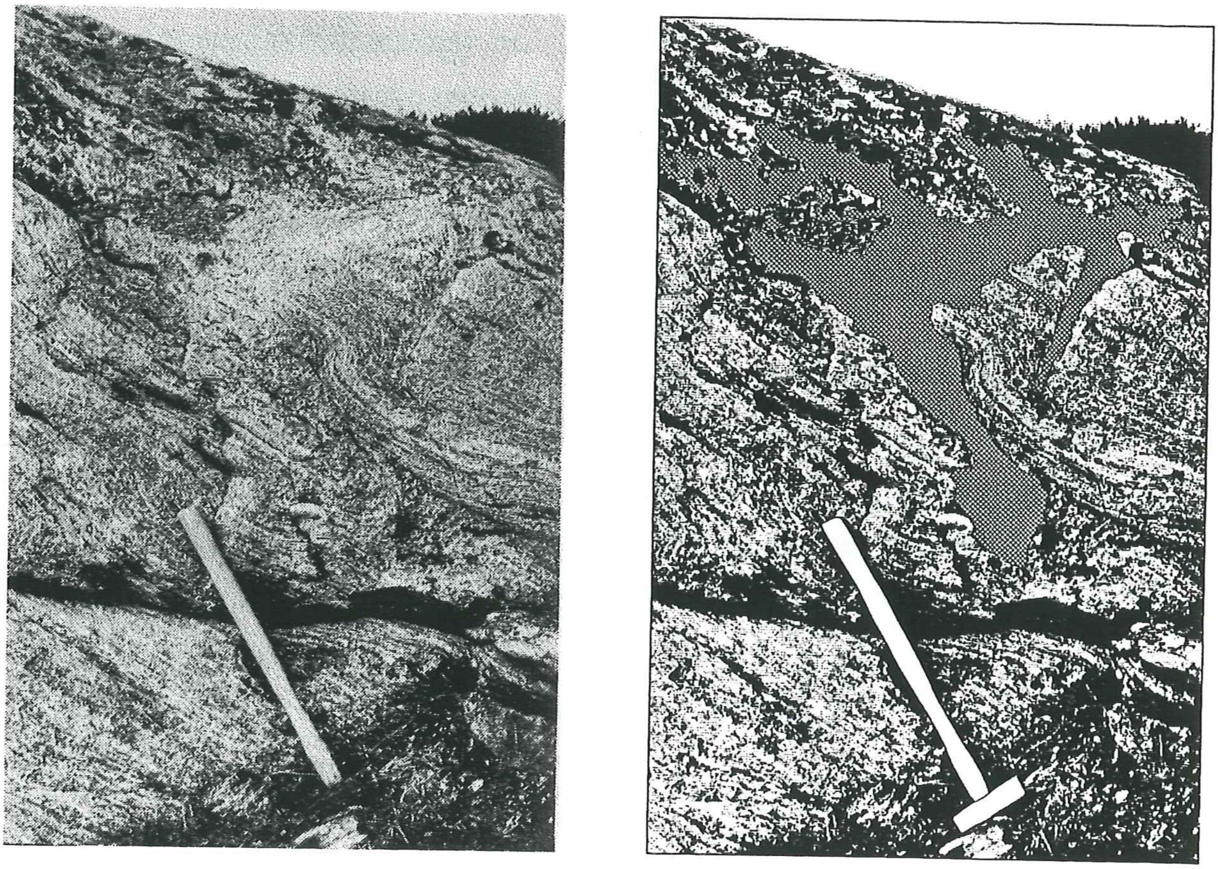


Figure 18. In-situ granitisation in a felsic gneiss c. 2 km north of Glassvik. A future candidate for radiometric analyzes, in order to post-date the D2 event. Observe the possible magmatic flow-textures within the mobilisate in the center of the picture.

The age of the D2 is bracketed between c. 1510 and c. .900 Ma (Fig. 18). Geochronological studies of zircons in the granitic mobilisates exposed in gneisses nearby the Glassvik locality (Fig.18), may give a maximum age of D2. To confirm the geological significance of the upper intercept age of 1510 Ma, the Kober-technique on single-grains will be carried out during 1993. By applying this technique a one or two generation origin of the prismatic and the rounded zircons can be evaluated as well (Kober 1986).

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