DEFORMATION ZONES IN EASTERN BERGSLAGEN
(UPPLAND-SÖRMLAND)

Research report of a project entitled:
Deformationszoner i östra Bergslagen (Uppland-Sörmland):
Karaktär och signifikans under svekokarelsk och efterföljande
tektonometamorf utveckling

financed by:
Geological Survey of Sweden

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Uppsala 2001
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ACKNOWLEDGEMENTS

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DEFORMATION ZONES IN EASTERN BERGSLAGEN
(UPPLAND-SÖRMLAND)

ABSTRACT

In this report we present results from a structural investigation of deformation zones in Eastern Bergslagen. Key areas for investigation have been the NNE-SSW Österbybruk/Skyttorp Zone (ÖSZ), the N-S Gimo Zone (GZ) and the Banded Series in the southeastern Stockholm archipelago.

Both the ÖSZ and the GZ is here interpreted to be splays from the Singö Shear Zone (SSZ) system where they originally enveloped tectonic lenses oriented approximately parallel to the SSZ. Solidification of a c. 1.8 Ga granite within the SSZ possibly caused a strain distribution southwards from the SSZ leading to the large scale clock-wise rotation and development of E-verging footwall folds to the SSZ. The E-verging fold have steep axes and rotate both the regional foliation as well as the stretching lineation.

The ÖSZ and the GZ show E-up kinematics (with a sinistral horizontal component) related to the E-vergent folding. An earlier (?) W-up pattern along the western margin of ÖSZ is here interpreted to be related to a dextral/NE-down shear along the SSZ prior to the folding.

The GZ located closer to the SSZ shows generally a higher metamorphic grade than the ÖSZ. Microstructures and chlorite-bearing shearbands of the ÖSZ indicate upper greenschist facies conditions during deformation, while striped gneisses and a C-S fabric with stable hornblende and biotite along both planes indicate amphibolite facies conditions along the GZ.

The Banded Series (BS) is a high-T deformation zone exposed on several islands in the Stockholm archipelago (Utö-Ornö-Mörtö-Runmarö-Skarprunmarn). The shear zone evolved from folds and has in turn been folded by regional-scale S-folds. The kinematic pattern is complex due to the existence of tectonic lenses, recrystallisation and annealing, and partly due to the later folding of the BS. The tectonic lenses contains hinges of rootless folds with generally NE plunging axes parallel to a very pronounced stretching lineation indicating intense stretching during shearing. Red Kf-augens common within the BS is here interpreted to be derived from dismembered early pegmatites, while white, less common augens were derived form neosomes. These conditions indicate that the BS was temporally related to c. 1816-1821 Ma pegmatites and peak metamorphism.

Additional studies of the intensely folded Värmdölandet-Ingarö-Södertörn area has revealed that an important sinistral/W-up shear occurred coeval with an eastward to southeastward hinge escape of the E-W mainland folds. A regional approximately N-S shortening has probably caused both the hinge escape as well as a conjugate, co-existing shear system with a dextral/NE-down (SSZ) and sinistral/NW-up (BS) shear system.
**INTRODUCTION**

**Aim and methods**

The aim of the study of deformation zones in eastern Bergslagen (Uppland-Sörmland) is to contribute to the understanding of the tectonic evolution of the area. The project has focused mainly on shear zones in Uppland and in the Stockholm archipelago and their relation to regional folding (Fig. 1). One important aspect is the relationships between the high grade metamorphic domain in the Mälar-region and the lower grade Uppland domain. In the project description a few points were addressed motivating studies of the area:

1. Interpretations of BABEL-data indicate large-scale listric deformation zones that possibly reach the surface in eastern Bergslagen (Korja and Heikkinen, 1995; Law and Snyder, 1997). The zones reaches the mid-crust alternatively MOHO and have been interpreted as main extensional features of the late Svecokarelian evolution (collapse) and postdating anorogenic (Rapakivi-) magmatism. One of the zones has been correlated with the Singö deformation zone (Law and Snyder, 1997).

2. A system of NNO- to N-S striking deformation zones truncating the older E-W fabric of northeastern Uppland have recently been inferred (Bergman et al., 1996; Antal et al., 1998).

3. A major NO-striking zone of banded rocks on Omo-Uto extending at least 80 km (Stålhos, 1982a & 1982b) coincide with the boundary between the lower metamorphic units in the archipelago and the migmatites on the mainland (Stålhos, 1982a & 1982b). Possibly this zone is conjugate to the Singö zone. The zone is known as “Bandserien” (Sundius, 1939) or the bedded series as presented to the participants at the Interscandinavian Congress field trip in 1938. Thermo-barometric results show that this zone developed during, or have been overprinted by the, 1.80-1.85 Ga, low-pressure metamorphic event of central Sweden (Bergman and Sjöström, 1996). The kinematic character of the deformation zone is unknown.

4. There are geophysical and geological indications of steep deformation zones (E-W, NO and NW) within the Mälar region. Only a few are shown on maps and their eventual relations to the Svecokarelian folding have not been considered previously although the kinematics of the deformation zones can be crucial in order to determine the fold mechanisms, especially concerning the direction of compression (E-W vs. N-S) (Stålhos, 1991; Sjöström and Bergman, 1998). Their relation to “Bandserien” need also be considered.

5. There are numerous locally generated “younger” granites, in spite of the relatively low metamorphic grade (Stephens et al., 1994; Lundqvist, 1994).

The methods include fieldwork combined with interpretations of aeromagnetic- and bedrock maps. Kinematic results, in meso- and micro scale, and new structural information are integrated with previously published data to evaluate the importance of primary (magmatic) structures and structural overprint, and the nature and significance of major shear zones and their subsequent reactivation.

GEOLOGY OF THE FENNOSCANDIAN SHIELD

The Fennoscandian shield (Fig. 2) has traditionally been divided into three major tectonostratigraphic units (Gaál & Gorbatschev, 1987); the Archaean domain, the Svecokarelian domain, and the Southwest Scandinavian Domain. The Svecokarelian domain (2.0-1.75 Ga), is bordered in the north by the Archaean domain (3.2-2.5 Ga). The latter is covered by Karelian metasedimentary and volcanic rocks (2.5-1.9 Ga) in the northeast. In the southwest the Svecokarelian domain is bordered by the Southwest Scandinavian Domain (1.76-0.9 Ga), in the northwest by Caledonian nappes, and to the south by Phanerozoic sedimentary formations (Gaál and Gorbatschev, 1987; Korja and Heikkinen, 1995). The Svecokarelain Domain (SD) consists of several generations of granitoid batholiths surrounded by medium to high-grade polydeformed supracrustal belts (Korja and Heikkinen, 1995). SD has been intruded by Subjotnian rapakivi batholiths and associated mafic intrusions (1.67-1.52 Ga). The crust is locally overlain by Riphean, Jotnian, and Vendian sedimentary basins (1.70-0.57 Ga). The last extensive period of magmatism resulted in the Postjotnian diabase dykes of the Central Scandinavian Dolerite Group (1.20-1.25 Ga), which possibly reflect the onset of the Sveconorwegian orogeny to the west (Gorbatschev et al., 1987).

The Svecofennian rocks formed during the Svecokarelian orogeny is a result of the collision between a juvenile Island arc complex or a collage of several island arcs (Nironen, 1989; Park,
1991) and the cratonic Archaean Karelian domain (Gaål and Gorbatschev, 1987). Within the SD several conductive and reflective structures penetrate the upper and middle crust. These structures have been interpreted as internal terrane boundaries and imply that several local collisions occurred during the principal collision of the Svecofennian island arc complex and the Archaean craton (Korja et al., 1993). Based on formline patterns and major deformation zones as well as taking into consideration the plate tectonic setting, major rock types and metamorphic and internal tectonic features, the Swedish part of the Baltic Shield can been divided into several structural domains (Sjöström and Bergman, 1998). By combining structural data (Bergman & Sjöström, 1994; Sjöström & Bergman, 1998) with formline patterns (Stephens et al., 1994), the Svecokarelian part of Sweden has been divided into six domains (Sjöström & Bergman, 1998; Fig. 3).

Figure 2: The Fennoscandian shield (After Gaål & Gorbatschev, 1987; Europrobe, 1996).

Domain D corresponds to a major part of the Bergslagen district, historically the most prosperous area in Sweden (Stephens et al., 1997) and has been a well-known mining area for more than 1000 years. The region is interpreted as an extensional, probably back-arc, active continental margin magmatic region (Allen et al., 1996) in accordance with earlier interpretations suggesting a continental margin environment (Lundström 1987; Gaål & Gorbatschev 1987).

As a consequence of the ore deposits the primary conditions and processes related to the formation of the ores have been the main targets for studies. Apart from the present Bergslagen project, less attention has been paid to the structural and metamorphic conditions within the main part of the Bergslagen region, this with exception of studies of the Mälar-region - an area considered a type-region of the Svecokarelian deformation in the eastern part of the central Sweden (Stålhös, 1969, 1981, 1991; Wikström, 1975, 1979). However, the high-grade and
comparatively few large bodies of granites in the Mälar region are features that deviate from the main part of the lower grade Bergslagen region. In addition, it is not known with certainty that the areas are structurally similar. If early Svecofennian metamorphism exists in central Sweden, it is evident that the lower grade parts of Bergslagen has been less affected by the late regional (1.85-1.80 Ga) low pressure metamorphism than the domains to the north and south (C and E in Fig. 3). Early Svecokarelian structures and metamorphic patterns (not known to be preserved in the middle part of Sweden, but recorded in Finland) may therefore be preserved and possibly be the reason for its unique signature. It is likely that Bergslagen represent a shallower part of the Svecokarelian crust than the domains to the north and south (Fig. 3) (Stephens and Wahlgren, 1996; Beunk et al., 1996; Bergman and Sjöström, 1996; Sjöström and Bergman, 1996, 1998; Andersson, 1997; Sjöström et al., 1998).

**Structural domains defined by formlines and major deformation zones**

Deformation zones in east central Sweden

1. Storjöde-Esbys S
2. Hassela S
3. Ljune S
   a. Töredöger S
   b. Hapia S
   c. Lislå S
4. Singo S
5. Omå S
6. Lekhammar-Lindöping S

**Figure 3: Structural domains of Sweden**

(Bergman & Sjöström, 1994; Sjöström & Bergman, 1998). SFDZ; Sveconorwegian Frontal Deformation Zone.

Based on Stephens et al. 1994
GEOLOGY OF EASTERN BERGSLAGEN (UPPLAND AND SÖRMLAND)

The Bergslagen region is composed of metavolcanic and metasedimentary successions, enveloping large syn- to posttectonic intrusions. The early, pre-tectonic intrusions comprise foliated synvolcanic and postvolcanic plutons that were emplaced prior to metamorphism (Allen et al., 1996). These are mainly granites, granodiorites, and tonalites, although they range in composition from granite to gabbro with a trend of more intermediate compositions toward the east (Lundström, 1987). The basement to the Svecofennian rocks is unexposed but various studies imply an older Proterozoic, possibly in part Archean, felsic basement in the western part of the region (Vivallo and Rickard, 1984; Baker, 1985; Beunk et al., 1985; Johansson and Richard, 1985; Patchett et al., 1987; Welin, 1987 and Valbracht et al., 1994). In the western part of the region a 8 km thick metavolcanic succession is interbedded with metalimestones and conformably overlain by thinner argillite-arenite units in the cores of some synclines (Allen et al., 1996). Near the base of the succession an ignimbrite at Ekebergshöjden (east of Hälsöfors) has a zircon U-Pb age of 1891±4 Ma (Lundstrom et al., 1998). A few zircon U-Pb ages of the metavolcanics in the west, southwest, and central parts of the region give approximately the same age of 1891 ± 10 Ma (Welin, 1987; Kumpulainen et al., 1996).

The metavolcanic rocks, metasediments, early plutons, and most ore bodies were subject to strong deformation and metamorphism after 1854 Ma (Lundström, 1988). An age of 1.85-1.80 Ga of medium to high grade (low pressure) metamorphism of south central Sweden has been inferred by Stephens et al. (1997) where most of the regional metamorphism and formation of migmatitic gneisses observed in the Svecofennian was produced during or shortly before the late orogenic event (1.83-1.77 Ga) (Andersson, 1997). The rock distribution and early folding has been described as strongly influenced by “granite tectonics”, that is syn-magmatic and related mainly to the earliest magmatic intrusions (Stålhöss, 1991; Berthelsen, 1987). However, the bedrock maps of Östhammar region (Stålhöss, 1986; 1987; 1988; 1989) show a penetrative foliation and lineation in these early granitoids that together with results from Bergman et al. (1996) show that post-solidification Svecokarelian deformation of the magmatic intrusions have been pronounced. Stålhöss (1991 and earlier) also suggested that an “essential part” of the foliation and lineation in the rocks of central Sweden were developed during closely related F1 + F2 cross folding and that the competent bodies of early Svecofennian granitoids greatly influenced the stress distribution.

Part of the deformation has resulted in development of mylonites and even breccias. The breccias are related to NNO- or N-S striking faults that cut through the sub-Cambrian peneplane (Stålhöss, 1991; Lidmar-Bergström, 1994; Bergman et al., 1996). These faults have a western block down movement (Stålhöss, 1991; Bergman et al., 1996). The area has been described as comprising probably two generations of mylonites, where the older? (E-W) follows the regional foliation and the younger? (N-S) truncate that pattern. The N-S mylonites have been interpreted to be related to deformation zones that are indicated by integrated geological-geophysical-topographical studies (Bergman et al., 1996; Antal et al., 1998). These zones have partly been reactivated resulting in the tectonic breccias. The two generations of mylonite zones resembles the conditions in Hälsingland area where older thick, often flat-lying deformation zones make up a part of the regional form line pattern which is cut by younger steep shear zones in the limbs of regional fold-structures (Sjöström and Bergman, 1996 & 1998).
Two fold phases have been recognized; tight to isoclinal $F_1$ folds deformed by a later $F_2$ folding (Stålhöns, 1984; Carlon and Bleeker, 1988; Stephens and Wahlgren, 1993). The axial surfaces of the $F_1$ and $F_2$ folds are both steep (Allen et al., 1996). The axial surfaces of the $F_1$ folds trend mainly north to northeast, whereas the $F_2$ axial surfaces trend east-west in the southeastern part of the region and mainly northeast to northwest in the western part (Allen et al., 1996). The irregular pattern and intensity of folding have been attributed to the competence contrasts and the variable distribution of the intrusions, massive volcanic rocks, and layered volcanic-sedimentary rocks (Allen et al., 1996). A strong, generally steep dipping foliation ($S_1$) parallel to the axial surface of $F_1$ folds and sub-parallel to the bedding ($S_0$), as well as a generally strong, east plunging (Allen et al., 1996), partly steep (Stålhöns, 1991) stretching lineation ($L_2$) have been recognized. The orientation of $D_1$ fold structures is not known with certainty but inferred to be approximately N-S. The $L_2$ lineation is generally steeper in domain D than in the higher-grade structural domains to the north and south. According to Stålhöns (1981) the high-grade region in the southern Bergslagen (Sörmland; Fig. 1) has been subject to cross folding. An east-west regional directed stress (alt. subduction from the west) caused the $F_1$ isoclinal folding whereas simultaneously a secondary stress of variable strength, in a perpendicular direction, caused the $F_2$ folding. This cross folding is said to be due to the variable competence contrast (non-plastic vs. plastic). The "non-plastic" and "plastic" in this case refer to the relatively competent large granitoid massifs and the less competent surrounding meta-argillites. This competence contrast is also the control of the intensity of the secondary stress (Stålhöns, 1981). The model is also dependent on the timing of intrusion of the competent bodies. The sequence of events implies intrusion and solidification of the granitoids prior to deformation.

The regional controls of the deformation history are poorly understood. In particular the relative importance of deformation related to the intrusion of the earliest granitoids and subsequent folding. In addition to Berthelsen (1987) and (partly) Stålhöns (1991), there are several early studies emphasizing important deformation during the emplacement of the earliest granitoids. A map of Högbo (1910) shows a cross-like structure of felsic metavolcanic rocks north of Uppsala (Fig. 4). Högbo (1910) noticed that in some areas the granites were foliated only at the boundaries and he interpreted these structures to be magmatic (see later). The same feature was interpreted by Geijer (1916) as Daly type stipping and by Stephanson (1975) as due to polydiapirism affecting the entire Bergslagen. Also Kuipers (1987) and de Groot et al. (1988) favored a model where a system of major synclines developed, as narrow volcano-sedimentary basins between rising granite diapirs, by synvolcanic gravity tectonics. However, Allen et al.'s paper discard the above theory as the stratigraphy and facies patterns indicate that the synclines and granite-cored dome or diapiric structures post-date the entire stratigraphy and are superimposed on much more extensive primary depositional basins.

The region comprises lower to upper amphibolite facies metamorphic rocks. A small area of greenschist facies occurs in the west (Hällefors) and has been extensively studied (e.g., Sundius, 1923; Oen et al., 1982 & Lundström, 1995). Peak metamorphism outlasted the main deformation and consequently the depositional structures and deformation fabrics are overprinted by strong granoblastic recrystallization in amphibolite facies areas. Migmatites, gneisses, and pegmatites are also common in the high-grade areas. The metavolcanic rocks in the region has traditionally been
divided into "hälleflintas" with finely recrystallized matrix (corresponding to greenschist facies rocks) and "leptites" with coarsely recrystallized matrix (closer to amphibolite facies rocks).

Figure 4: The cross-like structure of felsic volcanics north of Uppsala, Uppland (Högbo, 1910).

Interpretation of BABEL-data (Baltic and Bothnian Echoes from the Lithosphere; BABEL Working Group, 1990 & 1993) indicate large-scale listric deformation zones that might reach the surface in eastern Bergslagen (Korja and Heikkinen, 1995; Law and Snyder, 1997). The seismic sections image two generations of listric shear zones dipping toward SE and flattening at major detachment zones 35-40 km and 48 km in depth (Korja & Heikkinen, 1995). The first generation of shear zones, with a detachment zone between the middle and lower crust, may record the extensional collapse of the overthickened Svecofennian crust (Korja and Heikkinen, 1995). The second generation of shear zones with Moho as detachment zone, then records either the continuation of the post-collision collapse or a separate anorogenic extensional period (Korja and Heikkinen, 1995). The shear zones are up to 5 km wide, and the piecewise continuous seismic reflectors have apparent strike directions of 035°-040° and 040°-045° (Korja and Heikkinen, 1995). A conjugate direction (305°) is interpreted as a transfer fault system linking shear strain between listric faults (Korja and Heikkinen, 1995).

A case study in the Paleoproterozoic Singhó deformation zone based on a 3D-strain model indicated that the early plastic deformation was transpressional with a dextral horizontal
component (Talbot & Sokoutis, 1995). A west up dip-slip component for the Singö shear zone has also been reported from other field based data (Bergman et al, 1996; Sjöström and Bergman, 1998). The zone has later been reactivated and overprinted with development of pseudotachylite (Talbot and Sokoutis, 1995). The first ductile shear probably began to localise in the Singö shear zone while a swarm of mafic dykes was being emplaced (Talbot and Sokoutis, 1995) at ~1.859 Ga (based on U-Pb data on a deformed pegmatite Welin and Stålhös, 1986).

Law and Snyder (1997) combined velocity studies with the results of Talbot and Sokoutis’ (1995) strain model. Their velocity study focused on the same unique field area of the Singö shear zone to examine any link between velocity and the ductile component of strain. By updip projection they linked eastward dipping deep seismic reflections from the BABEL 7 profile to strain induced acoustic impedance contrasts within the regional brittle-ductile shear zone of Singö (Law and Snyder, 1997).

The origin of the banded rocks on Ornö-Utö, in the southern Stockholm archipelago, have mainly been described as primary structures such as volcanic sedimentary layering (Dietrich, 1963), magmatic differentiation (Högbom, 1910) or chemical differentiation (Sundius, 1938). Also Stålhös (1982) interpreted the banded sequence in primary terms as "well" layered tuffs with porphyritic lenses representing layered intrusions, but also noted a high degree of deformation. In summary, several early interpretations implicit have a component of deformation that was supposed to be related to the intrusion of magma.
RESULTS

Structures and metamorphism in Uppland

Fold interference, fold phases and shearing

The maximum number of fold phases indicated by the distribution of metavolcanic rocks is \( F_1 \), \( F_2 \) and \( F_3 \) (Fig. 5). The best established fold structures are \( F_1 \) and \( F_3 \), while \( F_2 \) probably represents trailing edges of tectonic lenses or splays of shear zones. Also the plutonic rocks (gabbros and augen gneisses) outline tight or isoclinal folds, e.g. east of Fornbo and southeast of Masugnen (Fig. 5). Applying \( F_1 \), \( F_2 \) and \( F_3 \), the latest ductile deformation in the Singö shear zone is of \( D_3 \) age. If only two fold phases exist, that deformation is \( D_2 \). In meso-scale a possible first generation of folds is detected close to Ramhäll (Happsta) in the E-W trending felsic volcanic rocks of the Vattholma cross structure. The axial plane structure of these folds is the regional foliation and there is no sign of an earlier foliation (Fig. 6A). However, these folds may be apparent reflecting sheared irregular primary boundaries between the volcanic rocks and the granitoid, but arrow-type interference folding in the mafic volcanic rocks at Fombo (Fig. 5), west of lake Strömare, imply the existence of two fold-phases (Fig. 6B) predating the inferred \( F_3 \) in figure 5.
The foliations in northeastern Uppland are steep and rotate around steep axes (Fig. 7). Some augen gneisses are L-tectonites, especially in the vicinity of areas with dominantly N-S trending foliation e.g. along lake Vallen (Fig. 8). An important feature condensed from published data (Stålhös, 1987; 1988; 1991) is that the stretching lineation in the c. 1.8 Ga serorogenic granite coincide with the rotation axis indicated by poles to foliations plotting on a great circle, i.e. conditions of cylindrical folding with stretching along the fold axis. There are only two significant bodies of such granite on the maps 12I Östhammar (Stålhös, 1986; 1987; 1988; 1989). One is located along the southern margin of the Singö shear zone (SSZ), and the other 1.5-9 km N of Fornbo also to the south of the SSZ. It is therefore likely that they have been affected by or generated due to deformation related to the SSZ. The simplicity of the stereograms for the younger granites probably reflect both that the structures were recorded in homogeneous domains and that these rocks only show a single structural imprint. Even if the structures are inherited from older protoliths, the simple structural patterns indicate synmagmatic or post-crystallization ductile deformation at c. 1800 Ma, which is in accordance with results from the Happsta Gneiss Zone 100 km to the NW (1809 ± 6 Ma, Högdahl et al., 1996). In the older granitoids, the stereograms are more complex. Foliations show a large variation in strike and tend to be steeper (Fig. 7), and consequently rotate around steep axes not entirely coinciding with the stretching lineation. This indicates that the granitoids had a steep foliation prior to the rotating event, i.e. this pattern supports the existence of isoclinal folds as shown in Fig 5. Also lineations rotate in the older granitoids, but not on well defined small circles as is typical for cylindrical buckling folds. Partly they tend to rotate irregularly on great circles indicating shear folds. The volcanics have a more irregular foliation pattern reflecting a primary subhorizontal deposition. A common feature is that most rock types show SE plunging stretching lineations (Fig. 7). A subdivision into smaller, more homogeneous structural domains shows how the foliation rotates clockwise from the WNW Singö shear zone trend into the NNE trend of rock units in the Vällen area (cf. subareas C and D in Fig. 8B). Also the lineation rotates correspondingly (cf. subareas F, C and D, in Fig. 8C). The inferences are that northeastern Uppland is affected by large-scale SE-vergent (shear) folding on steep axes and that the folding postdates the development of a regional foliation and a
stretching lineation. With respect to the indicated age of the structural imprint in the younger granites discussed above, the maximum age of this folding is c. 1.8 Ga.

The cross structure of the Österbybruk/Skyttorp Zone (ÖSZ) (Fig. 9) and the N-S Gimo Zone (GZ) along lake Vällen (Fig. 8 & 9), both show an apparent dextral horizontal displacement on aeromagnetic maps (Fig. 10). If the ÖSZ cross structure is due to shearing a dextral apparent horizontal displacement of at least 12 km is required. However, the moderate to steep down-dip stretching lineations recorded in the field indicate that the proportions of horizontal components (sinistral or dextral) are subordinate even if they are locally obvious on the outcrops and indicated by aeromagnetic maps. In addition, a 12 km displacement would result in a much larger vertical displacement, which is obviously not the case as there is no metamorphic break across the ÖSZ. The alternative explanation that disturbed isotherms may have been restored, i.e. that metamorphism outlasted deformation, can be excluded as the mylonitic fabric is well preserved (eg. Figs.13A and D). Microstructural data verify steep stretching lineations, and a dominantly east side up component in the north-south ÖSZ (see later).

Figure 7: Lineations and poles to foliations of northern Uppland. Compiled by Härdmark (1999) from maps SGU Ser. A nr 169 & 166, 121 Östhammar NO & NV (Stálhös, 1987; 1988).
Serorogenic granitoids

- Granite

Primorogenic intrusions

- Granite, red or whitish grey, fine- to medium-grained, slightly gneissic
- Granit-granodiorite, medium-grained, slightly gneissic
- Do porphyritic, slightly gneissic
- Granodiorite-tonalite, reddish grey to grey, medium grained, slightly gneissic
- Gabbro-diorite

Svecokarelian supracrustal rocks

- Metaandesite-metabasalt
- Metahyodacite, andecite
- Metahyolite
- Metahyolite, mostly quartzporphyritic

Figure 8A: Bed-rock map of Lake Vällen area (GZ)
Figure 8B: Foliations from subareas in the Vä llen area, 121 Ö sthammar SO. Data compiled after collected data within this project as well as after Stålhös (1989).
Figure 8C: Lineations from subareas in the Vällen area, 121 Östhammar SO.
Figure 9: The Österbybruk/Skyttorp Zone and Gimo Zone with key localities. Kinematics from thin-sections are indicated.

Figure 10: Aeromagnetic map of northern Uppland (Produced by Gological Survey of Sweden).
In the Koltorp-Strömhagen area (Fig. 9) many shear zones have sinistral and E-up kinematics (Fig. 11A & B), although the apparent sense of shear indicated by formlines and N-S offset of the E-W occurrence of the supracrustal rocks including the Ramhäll ore is dextral. These shear zones occur in the granitoids to the east of the folded, narrow syncline (?) dominated by felsic volcanic rocks northeast of Vattholma (Fig. 9). The shear zones are 2 cm to 3 dm wide and typically show exsolution of quartz and some K-feldspar from the parent rock during deformation and deposition in the central parts of the zones (Fig. 11C). As a consequence the shear zones are enriched in biotite. Kinematic indicators (mainly C-S fabrics) are generally very distinct and typical for upper greenschist/lowest amphibolite facies conditions. Aplitic veins are truncated and rotated indicating that these shear zones are late-metamorphic in timing. The stretching lineations in the shear zones plunge SE and partly overlap with the intersection between sinistral and dextral shear zones. This probably indicate transpressive conditions. Also several small similar ductile, shear zones in a diorite body within the leptite in the southern part of the Vattholma cross-structure (Fig. 12A), indicate a prominent pure shear component. Dextral and sinistral shear zones are symmetrically oriented around the foliation and indicate NE-SW shortening and NW-SE extension (Fig. 12B & 12C). The foliation also outline the F₂ folds on figure 5 where the NE-SW shortening is perpendicular to the long limbs of the fold (Fig. 12).

![Stereonets of shear zones from Koltorp-Strömhagen (A) showing poles to shear-planes, and (B) shear-planes. Equal area and lower hemisphere projection. (C) Shear zone with exsolution of quartz and some K-feldspar.](image-url)
Shear sense indications from thin-sections of the N-S Österbybruk/Skyttorp Zone

The N-S zone of metavolcanic rocks in the Vattholma cross-structure is mylonitized in the eastern part while the western contact to the granitoids appears to be a primary contact. At Slätten, north of Skyttorp, the deformed metavolcanic rocks dip c. 65° towards SW (Fig. 9). A prominent stretching lineation indicates a predominant dip-slip component. Thin-section of the mylonitic metaryolite shows quartz-ribbons partly recrystallized to larger grains by dynamic recrystallization (Fig. 13A). The feldspar porphyroclasts show extensive sericitization. The same outcrop a bit further west is severely mylonitized. Shearbands defined by chlorite show a sinistral sense of shear. Taking into account the orientation of the stretching lineation, the sense of shear is E-up with a dextral horizontal component. The microstructures and the chlorite bearing shearbands indicate upper greenschist facies conditions during deformation.
(A) Thin-section of mylonitic metaryolite, Slätten. Quartz-ribbons are partly recrystallized to larger grains by dynamic recrystallization (16x, XP).

(B) Thin-section of quartz grain subdivided by the development of a deformation band due to dynamic recrystallization. Dextral shear sense and E-up vertical component (31.5x, XP).

(C) Thin-section from Dammen, Vattholma. Feldspar grain with tails indicating E-up vertical component (16x, XP).

(D) Thin-section from Dammen, Vattholma, with quartz porphyroclast showing undulose extinction with deformation bands and tails reflecting sinistral shear resulting in E-up (16x, XP).

(E) Thin-section from Rensbo. Dextral C-S fabric of chlorite indicating SW-up. The resulting horizontal component is sinistral. (16x, PP)

(F) Thin-section from Knivsta showing dextral shape fabric in quartz aggregate (16x, XP).
1.7 km to the north at Andersby, the vertical component is again E-up as indicated by σ-
porphroclasts of quartz (deformed phenocrysts). The stretching lineation plunges steeply to the 
north and combined with the foliation attitude the horizontal component is dextral.

South of Slätten (c. 1.5 km) at Dammen (Fig. 9), both quartz grains and feldspar grains with 
tails show a dextral shear sense in thin-section (Fig. 13B&C). The foliation dips 82° towards 
the west and as the stretching lineation plunges 65° to the south, the dextral sense of shear recorded 
in thin-sections indicates an E-up component and sinistral horizontal displacement. Samples from 
the same locality a bit further west show highly strained quartz porphyroclasts with undulose 
extinction and incipient development of optically oriented sub-grains as well as recrystallized tails 
both showing sinistral and an E-up sense of shear (Fig. 13D).

At the northern end of the felsic volcanic cross-structure, at Rensbro 11 km northwest of 
Österbybruk (Fig. 9), the foliation strikes NW-SE and dips towards the NE. The stretching 
lineation is fairly shallow plunging compared to the previously described localities (38° towards 
the east). A C-S fabric of chlorite in thin-sections indicate a SW-up vertical component (Fig. 13E), 
resulting in a dextral horizontal component. The feldspar grains are extensively sericitised and 
the quartz grains show both undulose extinction and development of sub-grains. The C-S fabric of 
chlorite and the quartz microstructures indicate greenschist facies conditions during deformation.

**Ramhall supracrustals**

Thin-sections from Knivsta, in the westernmost part of the east-west trending Ramhall 
supracrustals (Fig. 9), show quartz with shape fabric (Fig. 13F). The optically oriented sub-grains 
within the quartz aggregate show a distinct dextral shear sense (Fig. 13F). The foliation dips 79° 
to the NNE and the stretching lineation dips 56° to the NW (Fig. 9). The shear sense indicates a 
S-up vertical component and a sinistral horizontal component.

A north-south profile over the Ramhall supracrustal rocks (from Kungsvedjan to Transättra 
gruva) shows that the mylonites are mainly restricted to the southern boundary and even there 
difficult to trace (also due to lack of outcrops). The mylonitization seems to be heterogeneous and 
may be indicative of shear lenses. The most prominent mylonite zone recorded is located SE of 
Ramhall (Happsta, Fig. 14). It is at least 60 m wide and has been traced 2.5 km. Platy quartz is 
typical in fine-grained recrystallized mylonite and 2-3 cm thick straight pegmatites have 
protomylonitic internal fabrics. The ductile deformatonal pattern shows strong stretching in 
vertical sections. Vertical sections show (a few) S-up asymmetric boudinage structures and 
shearbands along the southern boundary between the metavolcanic rocks and the granite. Vague 
dextral shear bands on horizontal surface in granite exist and there are also dextral foliation 
boudinages on horizontal surfaces. However, kinematic data are not consistent. Dextral and 
sinistral indicators may coexist in one single outcrop. This may reflect high proportion of pure 
shear which is in accordance with the large variation of the plunge of the stretching lineation (Fig. 
15). Altogether between Knivsta and Happsta, there is a dominance of oblique dextral/south up 
shear that is distributed partly along the boundary between the granitoids to the south and the 
metavolcanic rocks to the north, and partly within the supracrustal rocks. This ductile pattern is 
truncated by steep epidote-bearing, semibrittle faults striking in a sector between N and NW.
Figure 14. Mylonitic fabric, Happsta.

Figure 15: Structural data from the E-W occurrence of metavolcanic rocks including the Ramhäll iron ore.

Shear sense indications from thin-sections of the Gimo Zone

Compared to the ÖSZ, the GZ indicates higher temperatures (amphibolite facies). Well developed striped gneisses, and a C-S fabric defined by hornblende and biotite along both planes (Fig. 16A) have been recorded at Fredriksberg in the southern part of the GZ. Metamorphic titanite exists along both S and C, i.e. the absolute age of the deformation could be constrained by dating the mineral (outcrop now unfortunately covered after road-construction). Also thin-sections from a mafic volcanic rock at Masugnen in the northern part of the GZ (Fig. 9) indicate a higher metamorphic grade than that in the ÖSZ. Kinematic indicators including hornblende crystals with tails indicate a SSW-down component.
(A) Thin-section from Fredriksberg. C-S fabric defined by biotite and hornblende along both planes (14x, PP).

(B) Thin-section from Kolsvedjan (GZ). Metamorphic hornblende have overgrown the oldest biotite foliation (28x, PP).

(C) Thin-section from Kolsvedjan of a metamorphic poikiloblastic hornblende with quartz inclusions. The inclusions are of smaller grain-size than the matrix indicating metamorphic grain growth (28x, XP).

(D) Thin-section from Kolsvedjan showing biotite defining two foliations. A dextral C/S fabric indicate an E-up vertical component (14x, PP).

(E) Thin-section from Björkmyra. Dextral C/S fabric of biotite verify an E-up vertical component. Quartz show tendency to form a striped gneiss fabric (14x, XP).

(F) Thin-section from Björkmyra. Same as (E) but with one nicol (14x, PP).

(G) Thin section from Masugnen. Hornblende with dextral tails indicating a S-down vertical component (14x, PP).

(H) Thin section from Masugnen. Twinned hornblende with dextral tails indicating a S-down vertical component (14x, XP).
Thin-sections of a metavolcanic rock from Kolsvedjan, east of Lake Vällen (Figs. 9 & 16B-D) give somewhat contradictory kinematic implications (both E- and W-up). Biotite has grown along two planes and hornblende overgrew the oldest biotite foliation, i.e. prograde metamorphism is indicated (Fig. 16B). A poikiloblastic hornblende has inclusions of quartz of smaller size than that of the matrix, indicating metamorphic grain growth of an originally fine-grained rock (Fig. 16C). The quartz fabric within the hornblende possibly records dextral shear resulting in a W-up component (Fig. 16C). In another thin-section from the same locality, (Kolsvedjan) a hundred meters further to the east, biotite defines two foliations in a distinct C-S fabric indicating E-up (Fig. 16D). The blue-green color of the hornblendes indicates medium grade metamorphism and/or the presence of Na in the lattice. At Björkmyra, east of Kolsvedjan, porphyroclasts in the outcrop show a dominant E-up vertical component. In thin-section, perthitic K-feldspars with core-and mantles are common. Deformation twinning in K-feldspar is also rather common and quartz shows a tendency to the development of a striped gneiss fabric (Fig. 16 E&F). A dextral C-S fabric of biotite verifies an E-up vertical component (Fig. 16 E&F). The overall fabric within the thin-section indicates higher temperature and is also more recrystallized than the samples from the ÖSZ.

The eastward increase in metamorphic grade from ÖSZ to GZ is consistent with thermobarometry data from the Östhammar area, showing a trend toward higher temperature and pressure from SW to NE (Sjöström & Bergman, 1998). This may be part of the regional metamorphic pattern in the Bergslagen region showing the lowest grade rocks in the west.

Brittle and ductile faults
Several faults are outlined on the map Östhammar 12 I SV (Stålhöls, 1986). They are part of a fault and fracture system that on a larger scale define large blocks bounded by approximately E-W and N-S structures in the south (Skyttorp-Hallstavik) and WNW-ESE structures in the Singö Shear Zone (Bergman et al., 1996).

One of the N-S faults having west side down kinematics coincides with the ÖSZ (Bergman et al. 1996) The fault is associated with a topographic expression, i.e. offsets the Subcambrian peneplain showing that late movements have occurred. It is part of a regional fault/fracture system that can be traced southwards to Lake Mälaren (Lidmar-Bergström, 1994).

Both mylonites and cohesive breccias are common along the fault (Stålhöls, 1986; 1987) indicating a complex evolution, which has been verified by a recent study within this project (Engström, 2001). Locally, fairly large areas of brecciated rocks are shown on the tectonic maps (Stålhöls, 1986; 1987). In some thin sections the breccia fragments consist of ductile mylonites showing that ductile Svecokarelian deformation preceeded the brecciation. Both the breccias and other metavolcanic rock along the fault have a conspicuous reddish brown or violet color and are exposed in many outcrops along road 290. An important finding is that the rocks affected by faulting are more or less pervasively affected by alteration (Engström, 2001).

Locally brecciated felsic volcanic rocks are cemented by fine-grained, white quartz having a cryptocrystalline (possibly chalcedony) appearance (Fig. 17). Rock crystals and tabular quartz have formed in cavities of the quartz cement showing that the brecciation took place at shallow crustal depth.
Calcite is also common in the brecciated rocks. Locally the calcite is fibrous down-dip the fault surface reflecting both syntectonic growth and dip-slip kinematics. Other minerals recorded in the fault rocks are chlorite, laumontite, prehnite and epidote (Engström, 2001).

Although Engström (2001) has defined relative ages of growth of the various minerals based on cross-cutting relationships of veins, the mineral association and their partly pervasive occurrences indicate substantial hydrothermal alteration along the fault, conditions that seem unlikely along a late structure affecting the Subcambrian peneplain. Laumontite and prehnite form at 100-300°C and 200-400°C, respectively (Liou, 1971), which are unexpectedly high if the fault formed when the sedimentary cover was in the order of hundreds of metres rather than kilometers. Another unexpected condition is that the hydrothermally altered metavolcanic rocks have been folded by brittle-ductile boxfolds that also affect the quartz cemented breccias, i.e. brittle-ductile deformation post-date brittle brecciation. A likely explanation for the change from brittle towards
ductile conditions is softening caused by invading hydrothermal fluids along the faults. Such a process would also explain the anomalous temperatures indicated by the mineral association recorded along the fault and has been demonstrated in several recent publications (Guermami and Pennacchioni, 1998).

**Finnsjön-Valö**

A formline compilation indicates a possible southern branch of the SSZ extending from Finnsjön in the west to Valö and further to the ESE (Bergman et al., 1996). Our reconnaissance study in a N-S profile from Valö to Gimo shows that the strain varies considerably along the profile. This is expressed by a strong or weak steep dipping gneissosity; locally L-tectonites dominate. Both the S- and L-fabrics include a stretching lineation plunging moderately to the E or ESE. This pattern is truncated by semi-brittle shear zones.
The Banded Series (BS) in the southern Stockholm archipelago

Skarprunmarn

The BS exists as a SSW-NNE belt on the northern part of the island. It is dominated by metavolcanic rocks bounded to the south by fine-grained red "salic" granites and orthogneiss (Fig. 18). Our results show that the "salic" granites at least partly are intensely deformed, red augengneisses containing red pegmatites and locally some cm thick bands of mafic or intermediate rocks (deformed dykes?). In some cases the mafic enclaves are irregularly shaped as a result of shearing (see later, e.g. Fig. 23). Apparently the deformation transforming the coarse augengneiss into fine-grained salic granites is as strong as within the part outlined as BS and should be included if it is defined as a zone of high strain.

Figure 18: Bedrock map of Runmarö and Skarprunmarn (after Sundius, 1939). The Banded Series exists as an NE-SW belt on northern Skarprunmarn and as a large scale S-fold on northern and eastern Runmarö.
Within the metavolcanic rocks at least two phases of folds exist (Fig. 19). By contrast from most other areas in the region showing fold interference, associated linear structures can be separated. The earliest folds ($F_1$; Fig. 20) have extremely long limbs and narrow hinge areas and are accompanied by an intersecting lineation affected by intense stretching. These lineations and the fold axes plunge NE (e.g. 35/65; see Fig. 19). The axial surface cleavage defined by biotite and a grain-shape fabric is the regional cleavage. In the hinges of the folds, a bedding-parallel cleavage of biotite appear to be folded. This implies pre-$F_1$ deformation that also may have caused pinching out of pelitic, biotite-rich layers. However, these observations are not convincing enough to exclude the possibility that the first foliation is a bedding cleavage.

![Figure 19: Stereogram of recorded data, northwestern Skarpurnarn. Equal area and lower hemisphere projection.](image)

Figure 19: Stereogram of recorded data, northwestern Skarpurnarn. Equal area and lower hemisphere projection.

Figure 20: Hinge area of $F_1$ fold. The axial surface cleavage is the regional cleavage.

The second generation of folds ($F_2$) have axes plunging SW (e.g. 227/56; see Fig. 19). The grain-shape and biotite foliation of $D_1$ is folded. Along the axial surfaces and also partly truncating the folds, white pegmatites have intruded (Fig. 21). These pegmatites cut across the $F_1$ folds, but are also boudinaged showing that they either were intruded early during $F_2$ or that the $F_2$ folds have been flattened subsequently (by $D_3$?) (Fig. 21B).
Figure 21: (A) Sketch of pegmatite showing complex realtionships to a F2-fold. The large pegmatite appears to invade (i.e. postdate) the fold. Thin older pegmatites have been pytgmatically folded (F1?) and later refolded by F2. (B) Thin, gray pegmatites have intruded along the axial plane of F2 and have also been affected by sinistral shear. Northern Skarprunmarn.

Pegmatites in the BS have responded differently to deformation depending on dyke thickness, i.e. competence vs. matrix. Dykes thinner than c. 2 cm are folded, whereas dykes up to ca 10 cm are arranged as en echelon along axial surfaces and also "thrusted" (dextrally) while 1/2 to 1m thick dykes only show pinch-and swell structures (Figs 22A-C). A crude lineation along the boundaries of some pegmatites plunges SW (247/25) i.e. approximately as the F2 fold-axes/lineations. An important inference is that large pegmatites appear to postdate deformation due to their competent behavior although the deformation of thin dykes show that the pegmatites intruded pre- or coeval with (D2-) deformation. The (minimum) structural features recorded are thus S0, S1 bedding cleavage (?), F1 folds (first folds) and F2 pegmatite-associated folds.

In the "salic" red granites, thin red pegmatites are deformed by west-verging, asymmetric folds or have sinistral flames along boundaries. Such pegmatites also exist in the cores of isoclinal, flattened folds. In these rocks there are also mafic enclaves with an internal foliation, and foliation boudinage that both indicate sinistral shear on horizontal surfaces (Fig. 23). The difference in kinematics indicated by these pegmatites and the mafic enclaves and the "dextrally" deformed pegmatites in the BS may reflect that there are two generations of pegmatites.
Alternatively, two kinematic episodes are recorded. The first (sinistral) due to the development of the large S-fold with its short limb located on northern Runmarö (Fig. 18) and the second (dextral) episode during the hinge escape of the Värmdölandet fold described in following sections, if analogous to the relationship between pegmatites and the BS on Ornö (see below). Both these episodes probably post-date the formation of the BS.

Figure 22: Deformed pegmatites within the BS that have responded differently depending on dyke thickness. (A) Dykes thinner than c. 2 cm are folded, whereas (B) dykes up to ca 10 cm are arranged as en echelon along axial surfaces and also “thrusted” (dextrally) while (C) 1/2 to 1 m thick dykes show pinch-and swell structures. Foliation strikes W (left)-E. Horizontal surfaces.

Figure 23: Sinistral mafic enclaves in salic red granite, Skarprunmarn. Left is to the west. Horizontal surface.

Runmarö

The BS defines a large scale S-fold on the northern and eastern side of Runmarö (Fig. 18). Fold interference patterns indicate three phases of folding. To the west, in the long limb, the BS locally “underlies” metavolcanic rocks. The foliation is generally intermediate to steep (Fig. 24 A) with the long limb striking NE-SW and the short limb striking WNW-ESE (Fig. 18) All measured foliations on Runmarö give a calculated F₃ fold axis of 095/64 but the foliation pattern is complex in that the poles indicate two crossing girdles, i.e. fold interference (Fig. 24 A). The stretching lineations generally have a moderate plunge (30°-65°) and a large variation in trend (Fig. 24 B). The fold-related crenulation lineations plunge mainly between E and S and partly tend to define a NNE-SSW girdle indicating that they were formed on an already folded surface (Fig. 24 B).
stretching lineations show a larger variation plunging both in the same direction as the crenulation lineation as well as toward NW (Fig. 24 B). The large scatter is probably a result of complex (re) folding. The $F_3$-fold axes plunge E to NNE and locally steep towards the S (Fig. 24 C). $F_3$ folds with the latter orientation could explain the E-W crossing girdle defined by poles to the foliation in Fig. 24 A. The $F_2$ fold axes with a few exceptions scatter in plunge around E (Fig. 24 C). The $F_1$ fold axes tend to be steeper or equally as steep as the $F_2$ fold axes (Fig. 24 C). The only $F_1$ fold axis that has been possible to measure have a shallow plunge towards SSE (157/13; Fig. 24 C). A beautiful locality of fold interference patterns ($F_1$ and $F_2$) is found on the eastern coast north of Byholmen (Figs. 25 and 26).

Figure 24: Stereonets (Schmidt Equal Area Projection, lower hemisphere) of (A) poles to foliations with a calculated fold axis (dashed line indicates a crossing girdle, i.e. fold interference), (B) lineations, (C) fold axes and axial planar surfaces, and (D) foliation around local fold and the calculated fold axis, northern Runmarø.
There is a rather large scatter of fold axial planes (Fig. 24 C). Poles to the F₂ axial surfaces plot on a great circle indicating F₂-refolding on an east-plunging axis (Fig. 24 C). The F₁ axial surfaces strikes approximately NE (or NNE) with the exception of few E-W oriented surfaces. The rotation of the foliation west of Byholmen where the BS starts to swing from NW-SE to NE-SW strike indicates a F₂-fold axis of 090/60 (Fig. 24 D). The rather steep plunge of some F₃-axes as well as the "unusual" orientation of the axial surface compared to the steep E-W trending axial surface and the shallow plunging fold axes on the mainland, is possibly a late local modification due to E-W or WNW-ESE shortening during hinge escape of the mainland folds also resulting in overturning of the long NE-SW limb. Such an evolution would explain the complexity shown in the stereograms (Fig. 24 A-C).

Figure 25: Geological map with structural data and a NW-SE profile over northern Runmarø. Both map and profile modified after Sundius (1939).
At several localities of the short limb of the $F_3$-fold, sheath folds are observed (Fig. 27) indicating high shear strain prior to the $F_3$ folding, i.e. that BS-deformation predates the folding. Minor conjugate shear zones on the long limb on the northern side indicate a NNE-SSW z-axis (maximum contraction) (Fig. 28 A). Further south along the limb where the BS starts to rotate towards E-W, the z-axis rotates clockwise to a more NE-SW direction. Conjugate shear zones from the central part of the short limb give a similar maximum contraction direction of NE-SW (Fig. 28 B). However the entire population of the shear zones measured along the BS on northern Runmarö, shows a large variation in orientation indicating that they have been rotated around a steep axis, i.e. that they pre-date the large scale S-fold. Neosomes occur along some of the shear zones indicating a synmetamorphic age.

Figure 26: Fold interference patterns of $F_1$ and $F_2$ north of Byholmen.

North of Långviken (Fig. 25) sinistral shear sense indicators of the BS along the northern long limb gives a W-down vertical component, if the stretching lineation is the movement direction. The sinistral patterns seem to be disturbed by smaller cross cutting dextral shear zones (related to the folding?). Sinistral shear folds have been recorded at several localities along the short limb as well as indications of a S-up component. The sinistral shear folds on the short limb have a vergence opposite to that expected with respect to their location in the large scale S-fold indicating that they are shear folds predating that structure. At several localities along the short limb porphyroclasts with dextral (horizontal) shear sense are seen as well as in thin-sections, where feldspar have dextral tails. Feldspars with core and mantle structures are also common.
(Fig. 29). In the eastern long limb at Tallkobben (Fig. 25), intensely sheared orthogneisses indicate an east down movement of probably BS age (Fig. 30A). A very strong stretching lineation plunges 55° close to down dip the c. N-S shear zone showing that the horizontal (dextral?) component is subordinate (Fig. 30B). Neosome material has formed along the NNE-SSW crenulation cleavage planes (microlithon) as well as along steep E-down shear bands (C').

The existence of a major E-down shear zone (= the BS) is indicated also by the pinching out of the middle leptite unit on northeastern Runmarø (Fig. 25) and in particular by a NW-SE cross-section (Fig. 25).

Figure 27: Sheath folds in the short limb of the \( F_3 \) fold indicating high strain prior to the \( F_3 \) folding.

Figure 28: (A) Conjugate shear zones measured on the long limb of the \( F_3 \)-folded BS; (B) Dextral and sinistral conjugate shear zones at locality along the short limb of the \( F_3 \) fold; (C) All sinistral and dextral shear zones measured along the northern long limb and the E-W short limb.
Figure 29: (A) Dynamically recrystallized feldspar grains around a core of the same mineral composition. Thin section from the short limb of the BS of northern Runmarö. (16x, XP). (B) Boudinaged and shortened pegmatites in the BS. The shortening is due to F₃ folding. N is to the left. Located in N-S short limb of F₃-fold. Båthamsviken, N. Runmarö. (C) Anti clockwise D₃ rotation of neosome pockets formed in a dextral C-S fabric in the BS. North is to the left. Located in the N-S limb of F₃-fold Båthamsviken, N. Runmarö.

Pegmatites on Runmarö both cut and are deformed along the mylonitic foliation, i.e. appear to be post- as well as pre/syn-tectonic. Thick pegmatites truncate both early folds and the mylonitic foliation, but thin veins (c. 1 cm) from a meter-size pegmatite are sometimes mylonitized when they are oriented parallel to the mylonitic foliation. They are also disrupted into bands with K-feldspar porphyroclasts. Other veins rooted in the larger body truncate relatively older mylonitized veins at a high angle but are folded and distinctly lineated. Possibly more than one generation of pegmatites exists but a stretching lineation developed along the boundaries of the “younger”, truncating pegmatite shows that also this generation has been affected by deformation. More likely, the pegmatites intruded during progressive deformation and the foliation parallel veins promoted localized shear.

Folding of the BS during the F₃ flexural-slip folding has locally caused stretching of competent layers with development of boudinage with sinistral E-up sense of shear, as well as foliation boudinage with neosomes where no competence contrast is visible. In the eastern part of the short limb a slip related lineation plunge S (SSE). Another slip lineation (16/38) intersect a fold-related lineation (161/38) and indicate flexural-slip related to the F₃ folding with steep axes. Such fold-related flexural slip is verified by shortened, boudinaged pegmatites showing both sinistral stacking and sinistral asymmetric folds and anticlockwise rotation of neosome pockets in a dextral C-S fabric (Fig. 29C). These pegmatites are parallel to a mylonitic foliation oriented c. 10/58. In somewhat less deformed pods enveloped by the mylonitic foliation two phases of folds exists showing that the maximum age of the mylonitisation is D₂. Another important observation is that dextral (and E-down) χ-porphyroclasts are common and that some of these with long tails are overprinted by the north-vergent “sinistral” folds, i.e. that dextral (east down) shear pre-date the large scale S-folding. The kinematics here is thus in accordance with that described in the long eastern fold limb above (Tallkobben). In summary, porphyroclasts seem to indicate a dextral horizontal component in both the long limb and short limb of the S-fold on northern Runmarö,
and E- and N-down respectively. The picture is however complicated by the recognition and indications of complex refolding which makes it difficult to ascribe the kinematic results to a particular event in the history of the BS.

South of the BS north of Vidtrasket two distinct lineations exist in metavolcanic rocks. Here the stretching lineation plunges SW (207/31) and the crenulation lineation plunges NNE (13/38). Axial planes to the crenulation strike 307/38 ($S_3$).

![Figure 30: (A) Shear indicating an E-down vertical component and a dextral and/or shortening horizontal component. Right is approximately east. (B) Strong stretching lineation (117/55) at the same locality. Left is approximately east. Tallkobben, eastern Runmarö.](image)

**Mörtö**

Although not mapped as part of the BS (Sundius, 1939), deformation is strong and locally mylonitic (Figs. 31 and 32). The main part of southwestern Mortö consists of interbedded marbles and volcanic rocks (Fig. 33), which have suffered intense folding. The folds ($F_3$) are indicated on Sundius map (1939) with the long NE-SW limb along the western coast and the short E-W limb along the southern part of the island (cf. Fig. 33). The same is also indicated on stereonet of plotted foliation measurements (Fig. 34A). The indicated fold axis of 90/31, and as
well as those measured in the field, have a shallower plunge than corresponding folds on Runmarö (cf. Figs. 24C & 34B-C).

Figure 31: The bedrock north of Norrängsdals brygga, Mörtö.

Figure 32: Intensely mylonitized paragneiss (western Mörtö).
The marbles show complicated fold interference patterns reflecting their incompetent behavior during deformation. Here, as well as at localities with similar rocks further south (for example Persholmen & Utö) dome and basin (Fig. 35A) and refolded folds exist. At several places along the long limb a spaced NNW-SSE cleavage intersect the foliation and the earlier folds (Fig. 34B & 35B). As the cleavage cuts the limbs of the F₂ folds it is clearly later than the F₂ folding. Three sets of axial surfaces/or cleavage planes were found along the western limb (Fig. 34B). The youngest set is the spaced cleavage already mentioned. An earlier set is related to the F₃ folding and these axial surfaces strike NE-SW (Fig. 34B). The oldest set is related to the F₃ folding and plots (the poles) on a great circle together with the corresponding set (S₂ cleavage) on southern Mörtö (Fig. 34B-D) indicating refolding by F₃, as is also the case on Runmarö. The pole to the great circle is 095/25 – a value close to the expected F₃ fold axis (Fig. 34D). It is not clear if the spaced cleavages (the youngest set) seen on western Mörtö are related to the F₃-folding. They differ in orientation from the other measured cleavages along western Mörtö as well as further to the south (Fig. 34 B&C) and they seem to intersect the F₃-folds. They can also indicate a later event or local overprint as appears to be the case on northern Runmarö.

Only a few lineations have been recorded. Both a pronounced fold-related crenulation lineation and stretching lineations exist. The distinct crenulation lineation (Fig. 35C) strikes c. 089/24 close to the calculated fold axes value of F₃ (cf. Fig. 34A) indicating that it is closely related to the F₃-folding. In addition it has an orientation subparallel to the constructed F₃ fold axis.
Figure 34: Stereonets (Schmidt Equal Area Projection & Lower Hemisphere) showing (A) all measured foliations, (B) lineations, fold axes and axial surfaces along western Mörtö, (C) lineations, fold axes and axial surfaces along southern Mörtö, and (D) calculated fold axis using F2 axial surfaces.
Figure 35: (A) Dome-and-basin structure, western Mörtö. (B) Spaced cleavage intersecting both foliation and folds. The pencil shows the direction of the intersection. The cleavage plane strikes NNW-SSE. Western Mörtö. (C) Strong crenulation lineation in metavolcanic rocks, southern Mörtö.

Ornö

The BS on Ornö follows the west coast on Sundius map (1939)(Fig. 36). However, most parts of the island locally shows intense deformation. The island has been divided into separate study areas and is reported here as Klappen, Varnöbergen-Långträsk-Varnöladen, Sundby-Västanvik, Mörbyfjärd, Näsudden-Koviksudd, Lettinge-Torsnäsudd, Fiversättra-Hemträsket, Skinnardal-Hemträsket, and Ornö huvud-Svinäker.

Kläppen

On south-eastern Ornö large fold structures having a core of early-orogenic granite enveloped by supracrustal rocks (mainly metavolcanic rocks but also some marble) are outlined on existing maps (cf. Figs. 36 & Fig. 37 after Sundius 1939, Stålhos 1982). The foliation in augen gneisses is truncated by aplite dykes. The latter occur also along the margin of coarse grained pegmatites, showing that the two kinds of dykes are related and coeval. According to the mapping by Stålhos (1982) pegmatites and aplites are of (late) serorogenic (synmetamorphic) age.

At Kläppen, in the eastern limb of the fold, shear zones are common. These shear zones generally truncate and rotate the aplite dykes. Obviously this shearing is younger than the BS deformation. It is also of “lower metamorphic grade” showing pencil lineation and lack the annealed texture of the former. However, locally a few dykes of aplite can be traced continuously across the deformation zones and show structures indicating both shortening and shear. These patterns probably reflect both volume loss and a high proportion of pure shear during deformation (Fig. 38).

Shear zones with sinistral and dextral horizontal components are equally common (Fig. 37A). Intersection and stretching lineations overlap although the latter show large variation in the shear planes (Fig. 37B). Stretching lineations show a variation in plunge from north to south from northeast to southwest (Fig. 37B). The few fold axes recorded (in marble) plunge SW. The symmetrical arrangement and the large variations in plunge of the lineations indicate pure shear or a large proportion of pure shear during this late stage deformation.
ml = mineral lineation
cr = crenulation lineation
str = stretching lineation

foliation
axial plane
shear zone
lineation
fold axis
pegmatite

Figure 36: Bedrock map of Ornö with structural data

(Bedrock compiled after Sundius 1939 and Stålhös 1982)
Figure 37: Structural data from the Klappen area.

Figure 38: Aplitic vein affected by a low grade NE (left)-SW (right) shear zone at Klappen, SE Ömör. The vein is affected by both sinistral shear and shortening across the zone.
Varnöbergen-Långträsk-Varnöfladen

This area on SW Örnsö (Fig. 39) is outlined as a W- or NW-verging asymmetric fold refolding earlier folds (F₉?) or thin sheets of early Svecofennian granitoid intruding supracrustal rocks (Stålhöls 1982).

In the Stunnträsk-Långträsk area lineations plunge moderately (35-50°) to the N or NNE and the contact between metavolcanic rocks (below) and granitoid (above) is locally highly strained. In the metavolcanic rocks there are NW-plunging folds with intense stretching along the fold axis. Similar folds also exist in the granitoid showing that it is folded together with the supracrustal rocks.

(A)

(B)

Figure 39: In the Varnöbergen-Långträsk-Varnöfladen area the structural pattern is more complex than in most other subareas due to the rotation of structures in the short limb of the open S-fold affecting southern Örnsö and Utö. (A) Map with structural data of the Varnöbergen-Långträsk-Varnöfladen subarea. (B) Stereonets of the Varnöbergen-Långträsk-Varnöfladen subarea.

Close to the southern part of Långträsk, the supracrustal rocks are intensely sheared and the shear zone is the site for sulfide mineralization. Both the orientation of dextral and sinistral minor
shear zones, and symmetrical boudinage indicate flattening across the zone, i.e. a large proportion of pure shear. The shear zone dips 60-70° NE and coincides with the long, linear magnetic anomaly shown in Fig. 43 (see page 48). To the west (Varnöbergen) foliations are generally rather shallow dipping apart from close to steep (dip 70-80°) shear zones.

Pegmatites and aplites are more or less conformable to the foliation in the gneissose granitoids. This is also the case for the long NNW-SSE “dyke” of pegmatite shown on Stålhös map (1982) along the western shore.

Northwest of Långträsk asymmetric folds (NW-verging) refold earlier, isoclinal folds. The structures also rotate clockwise due to the open, large-scale S-fold affecting southern Ornö. Consequently the structural data show a large range of orientations reflecting the complex fold interference pattern, possibly due to three phases of folds (Fig. 39).

Figure 40: Structural data from the Sundby-Västanvik area. There is a dominance of oblique dextral/E-up shear zones. Dextral and sinistral shear zones partly overlap in orientation. Lervassa träsk is situated in the center of the subarea.
Sundby – Västanvik (Lervassa)

The Sundby – Västanvik area is situated in the central part of Ornő (Fig. 40). The foliation generally strikes N-S (Fig. 40B) and the rocks are at many localities (especially in the metavolcanic rocks) intensely folded with intrafolial tight to isoclinal folds. Southeast of Lervassa träsk also the granitoids (?) are M-folded. A tight fold in meta-porphyrite north of Lervassa träsk (Fig. 41), show both asymmetric boudinage as well as hornblende bearing conjugate dextral (ecc1) and sinistral (ecc2) shearbands. The shearbands overprint the fold and are asymmetric with respect to the foliation in that the dextral shearbands have a smaller angle to the foliation than the sinistral shearbands. Such monoclinic symmetry is typical in extending shear zones where both sets of shearbands (extensional crenulation cleavage 1; ecc1 + extensional crenulation cleavage 2; ecc2) have formed (Fig. 40A right + 40B). On a large scale within this sub-area, dextral kinematics dominates. It is also obvious that dextral shear zones and shearbands vary more in strike than the sinistral sets.

The axial planes have the same orientation as the general foliation indicating F₂ fold. The F₂ fold axes have the same orientation as the strong stretching lineation measured in the area (Fig. 40B), i.e. conditions typical of intense shearing. The existence of hornblende in a recrystallized fabric indicate that metamorphism (or a second metamorphic episode) outlasted deformation.

Figure 41: Tight fold defined by felsic band in meta-porphyrite. Note the dextral asymmetric boudinage in the core of the fold.
**Mörbyfjärd**

The biotite gneisses around Mörbyfjärden (Figs 36 & 42) are included in the BS by Sundius (1939). Asymmetric folds within the area locally have flat-lying to moderately dipping axial planes (similar to that of Varnöbergen and differing from those much steeper axial surfaces at Lervassa) and strikes E-W. These folds have spaced cleavages and the limbs are cut by white pegmatites. They refold earlier isoclinal folds.

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**Figure 42:** Structural data from Mörbyfjärd. Stereogram from Näsudden-Koviksudd shows typical cylindrical folding. Note that fold axes and stretching lineations are parallel indicating stretching along the fold axes. Stereonet from Brevik show data from a F2 hinge zone overprinted by D3 shear. Also shown is structural data from Lättinge-Torsnäsudd, south of Mörbyfjärd.
To the east of Mörbyfjärden, asymmetric foliation boudinage with neosome material in pressure shadows, and frequent \( \sigma \)-porphyroclasts indicate dextral sense of shear in augen gneisses. The dextral shears strike E-W to ESE-WNW. A relatively large, coarse grained, pegmatite closer to the coast, not marked on map Sundius (1939), cuts the BS foliation. Unfortunately Sundius map does not outline serorogenic granites and pegmatites by contrast from Stálhös map covering the southern part of Ornö. The lack of that information on the older map is an important drawback with respect to our attempt to unravel the relationship between BS and the pegmatites.

**Näsudden-Koviksvudd**

The SW part of Näsudden (Fig. 42) consists of intensely folded, locally garnet-bearing metagreywacke. It is bounded to the north by plagioclase-porphyritic diorite. The plagioclase is up to 1 cm (commonly 3-4 mm) in a fine-grained matrix with medium-grained hornblende. Thin beds of felsic, partly calcareous, metavolcanic rocks coexist with the diorite.

In the greywacke, bedding is often still visible in spite of the folding. The most obvious structures are 5-10 metres (limbs) folds. The axial surface cleavage of these folds is a spaced cleavage showing refraction across pelitic-psammitic boundaries. The folds are accompanied by a very pronounced rodding or a strong mineral stretching lineation. This lineation is also overprinted on older folds, i.e. there is only lineation visible.

Poles to the foliation indicate cylindrical folding on a moderately plunging axis (90/52) which plot among the lineations and recorded fold axes, i.e. intense stretching along the fold axis is indicated (Fig. 42, top right).

The greywacke contains two generations of pegmatites that are both folded. The first generation is medium- to coarse-grained and quartz-rich, but also contains red K-feldspar. It is very intensely folded and often disrupted into bands or individual augens. These pegmatites are obviously the source of at least parts of the conspicuous augens in the BS. The second generation of pegmatites is more coarse-grained. It is also red and contains some tourmaline and muscovite. Thick dykes (in metres) locally show a graphic texture. Also these pegmatites are folded and have been affected by the E-plunging stretching lineation. One dyke is sheared by a late, 1m thick, sinistral shear zone (110/80).

The structures recorded indicate that pegmatite generation one was affected by intense folding and shearing by the first folds, then the second generation of pegmatites intruded and were subsequently folded and sheared. Similar conditions exist c. 1.5 km to the east (Brevik), where dykes of pegmatites are intensely folded.

The conditions described above are not typical for the relationship between the BS and larger pegmatites in the interior of the island. The pegmatites often truncate a strong BS foliation abrupt and "smoothly" without later deformation. The characteristics of the Mörbyfjärd area and the anticlockwise rotation of structures shown in the stereograms indicate a late (D3?) sinistral shear in that area (Fig. 42). Kinematic indicators at Näsudden (\( \sigma \)-porphyroclasts and C-S fabric) indicate oblique sinistral N-up during earlier BS-deformation.
The fold structure at Koviksudd shown on Sundius' map (1939), and indicated by magnetic formlines (Fig. 43) is typically cylindrical (Fig. 42). It also affects a larger area than indicated on the map. Fold axes are parallel to the pronounced stretching lineation indicating strong stretching along the fold axes, i.e. conditions typical in shear zones. Most axial surfaces strike E-W to NE-SW and the fold closure at Koviksudd is the synformal part of a N-to NW-verging fold. An important finding for the structural interpretation is that mylonites can be traced around the synform i.e. that the BS is folded by the cylindrical fold.

![Diagram](https://example.com/diagram.png)

**Figure 43:** Magnetic formelines added to the geological map compiled from Sundius (1939) and Stålhös (1982).

**Lettinge-Torsnäsudd**

To the south of Mörbyfjärd (Fig. 42) there is a similar but larger point of land as that at Koviksudd. A possible fold is indicated on Sundius' map and by magnetic formlines (Figs. 42 and 43). However, structural data differs from those of Koviksudd (Fig. 42). Mylonitic foliations
are fairly consistent in orientation striking NNE with a steep to moderate dip to the ESE; stretching lineations plunge approximately NE. Foliations in non-mylonitized rocks fall in two groups: one striking c. ESE/dipping NNE and one among the mylonitic foliations (NNE/ESE). Apparently there is an anticlockwise rotation of the structural pattern compared to Koviksudd. In addition the mylonitic foliation (with one exception) appears not to be folded.

Interpreted together with the Koviksudd data, a sinistral rotation of structures along the western part of Örnö is implied and a progressive development of folds and shears during the BS deformation. This kinematic implication is thus opposite to those of the foliation boudinage and the frequent, dextral ρ-porphyroclasts recorded E of Mörfyjärð (see above). Possibly the conflicting data it is due to different locations with respect to the large-scale fold indicated by the aeromagnetic signature (Fig. 43), but it is also a general feature on the island, which makes the over all kinematic interpretation of the BS shear zone difficult based on local observations.

Fiversättra – Hemträsket

Several, steep, NNE-SSW shear zones were recorded along a SE-NW profile (Fig. 44A) showing that the entire island is affected by BS shearing. In the augen gneisses along the eastern shore, some K-feldspar augens are completely recrystallized into fine-grained aggregates deformed to bands that often are folded. Other augens still remain as single crystals showing Carlsbad twinning. Kinematic indicators are not consistent. Recrystallized dextral shearbands coexist with recrystallized δ-porphyroclasts and folds showing anticlockwise rotation (sinistral). An Rf/ϕ analysis of K-feldspar augens indicates rather low strain on horizontal surfaces (4:1). The orientation of the resulting ellipse indicates sinistral shear.

Aplitic and mafic dikes are conformable to the shear foliation (like on Skarprunmarn) while pegmatites truncate the shear structures. There is also evidence of retrogressive shearing affecting the pegmatites (cf. Klappen) and finally brittle faulting.

The shear zones recorded to the NW (towards Hemträsket) often exists along the boundaries of lens shaped topographic highs. Within these tectonic lenses (?) folding is locally intense. In the western part of the profile (SE part of Hemträsket), a clockwise rotation of the foliation accompanied by intense deformation indicate the presence of a dextral zone.

The structural data varify the existence of fold hinges not shown on Sundius map (1938) (Fig. 44 B&C). The accumulation of poles to the foliation on the primitive circle in the NW and SW quadrants probably reflects both flattening of the folds and shear along their limbs. As in most parts of the island, the indicated fold axis plot among the stretching lineation which is locally recorded in mylonite.
Figure 44: (A) Structural map and (B) structural data collected along a NW-SE profile on NE Örnö. (C) The calculated pole to the best fit great circle coincide with the stretching/intersection lineations in "B" indicating cylindrical folding with stretch along the axes.

**Skinnardal-Hemträsket**

On the western side of Nybysjön (Fig. 45) the rocks are intensely foliated and mapped as part of the BS by Sundius (1939). The major rock types are porphyritic diorite and metavolcanic rocks (± quartzitic sediments). The foliation generally strikes NE-SW (Fig. 45B) and the rocks are at many localities intensely folded by tight, intrafolial folds. The lengths of the fold limbs are sometimes 5-10 meters while the width is around 1 meter or less. The fold axes (F2?) plunge 25°-50° towards NE (Fig. 45B). The axial traces are parallel to the foliation.

In the granodioritic rock closer to Nybysjön the folds are less tight and not as flattened as in the diorite. A prominent stretching lineation strikes in the same direction as the fold axis plunging around 45° to the NE (Fig. 45B).
Ornö Huvud-Svinåker

The Ornö Huvud is a c. 3.5x2.5 km lens-shaped body dominated by intrusive rocks (Sundius 1939 and Figs. 36 and 46). It consists of a core of Ornöit enveloped by grey gneissose granite and a large proportion of diorite, gabbro and amphibolite. The name Ornöit refers to an inhomogeneous diorite with low contents of quartz and microcline, while brownish green hornblende is common (Sundius 1939). To the west and south of the plutonic rocks there is a thin band of BS rocks and below that metavolcanic rocks.
On Sundius map the lens is located in the synform of a large-scale Z-fold, which is one of several such folds on the island, existing from Ornö Huvud to Varnöbergen-Långträsk-Varnöfladen in the south where they have been rotated by an open S-fold (Figs 36 and 43). In the Svinåker area, several NNE-SSW shear zones truncate the short limb of the Z-fold. e.g. at the northwestern and southeastern parts of Hemträsket.

In mesoscale, the Z-folds deform a pre-existing foliation and locally isoclinal folds. This suggests that the Z-folds are F₂-folds. Hence the frequent S-folds in the archipelago, that fit into the system of large-scale folds e.g. on Värmölandet and Södertörn (Fig. 52) would be F₂-folds. Although this is comparable to Stålhös model comprising F₀, F₁ and F₂-folds, it is not supported by the recent investigations in the Bergslagen District, which shows that only two major fold phases have affected the area (M.B. Stephens, pers. comm 2001).

The kinematic picture of shear zones west of Ornö Huvud is complex. It is dominantly dextral along the northwestern margin and sinistral to the southwest (Fig. 46A). This pattern indicates a pure shear component across the lens during BS-deformation.

The fold closure on Sundius map (1939) in the metavolcanic rocks west of Ornö Huvud (Norrviksudden) is supported by our results. NE-plunging, tight folds are very common and a pronounced BS-foliation is parallel to their axial surfaces, in some cases accompanied by pegmatites. Subsequent refolding also exists.

A fault zone containing pseudotachylite, i.e. a result of later, low-grade, rapid deformation, truncates the BS southwest of Ornö Huvud. Slightly to the north, there are also well-preserved lenses of diorite in migmatite, which represent some of the protoliths to the BS.

The most typical development of the BS exists along the shore west and southwest of Ornö Huvud (Sundius 1939 and Fig. 36). Kinematic data are not consistent although there is a dominance of sinistral indicators on horizontal surfaces. Pegmatites truncating the BS are rather frequent and at Timmerudd they have been affected by late, dextral shear (see below).

Often there are two lineations on the pronounced BS-foliation: a stretching lineation plunging NE and a crenulation lineation plunging SW to SE (Fig. 46 B). The latter is probably the intersection between S and C or extensional crenulation cleavage and C. Also in this area, the poles to the foliations defines part of a girdle with a π-axis plotting among the stretching lineations. To the southwest, where the strain is locally extreme, there is less evidence of such a girdle indicating that eventual folds have been completely sheared out (cf. Fig. 47B). Also here, there is a slight dominance of sinistral kinematic indicators.
The BS of western Ornö

Evidence for a structural origin of the BS

The banded rocks of western Ornö has been described (as previously mentioned) mainly as of a primary origin. However, unequivocal evidence for a structural origin exists e.g. by the ferry bridge at Hässelmar (Fig. 47). As a part of the conspicuous banding, there are macroscopically extreme mylonites locally (Fig. 48). Augens within the BS have tails up to 20 cm long with maximum extension parallel to the stretching lineation (Fig. 48A). Such tails are typical for an
origin from core-and-mantle structures, i.e. sub-grain rotation recrystallization at sub-solidus conditions. An important feature is that the lengths of the tails show that many of the porphyroclasts originally were larger than the 1-3 cm maximum size recorded today. That is, the coarse rounded augens were derived from an even coarser-grained rock.

The BS contains rootless, isoclinal fold hinges within lenses enveloped by shear zones. Locally these folds refold earlier folds (or fold like primary contacts between orthogneiss and supracrustal rocks?) indicating that the BS was related to F2 or even subsequent folding. Although progressive refolding is typical in intensely sheared rocks (e.g. mylonites), i.e. the subdivision into several fold phases is less reliable than in surrounding, less deformed rocks, the BS folds deform an older foliation (S1 bedding cleavage or axial surface cleavage). Consequently the maximum age is syn F2.

![Figure 47: Structural data from Hasselmara in the south to Lekarviken in the north, western Ornö. In this area the BS is best developed on Ornö.](image)
Evidence for a high temperature solid-state origin and development of the BS

Microstructurally the mylonites are striped gneisses and the rounded porphyroclasts have myrmekitic intergrowths at their margins. Both features are typical for high-temperature deformation. Although myrmekitic textures also may form when a phenocryst interacts with magma, such reaction rims have here generally been removed and recrystallized in locally very long tails. Stair-stepping of tails is rather uncommon. Instead the most extreme mylonites (Hässelmara ferry-bridge) often expose objects with an orthorhombic symmetry (\( \phi \)-objects) in sections parallel to the stretching lineation. Such microstructures may indicate pure shear conditions but have also been discussed as a high-T phenomenon in strongly sheared rocks if mantles originally were exceptionally wide.

Thermobarometry data (garnet-biotite-plagioclase) verify that high temperature (and low pressure) metamorphism has affected the BS (Fig. 49). However the absolute timing of deformation and P-T paths are not determined as the deformational fabric is annealed, i.e. recrystallization (metamorphism) outlasted deformation. Also shear zones as ”magma pockets” on northern Runmarö (1999) indicate a synmetamorphic, high-T development as well as K-feldspar showing rodding parallel to the stretching lineation of the BS.

Locally in the metasedimentary rocks there is evidence that the shearing along BS resulted in the development of white K-feldspar augens associated with small neosomes, as these neosomes exist only in rocks affected by BS deformation but not in the adjacent rocks having a partly magmatic texture but also porphyroblasts of e.g. hornblende. Thus the BS appears as a synmetamorphic, locally vein-forming event. Pegmatites and aplitic veins that generally are interpreted as a result of the serorogenic metamorphism truncate this high-T fabric. In conclusion
the BS formed relatively early during the regional serorogenic metamorphism (the general model by Stålhöös) or BS was related to a separate earlier phase of metamorphism.

Figure 49: Garnet-biotite-plagioclase therobarometry from the BS west of Brevik. The sample is a strongly sheared paragneiss (meta-greywacke?). The P/T conditions indicated are typical (c. 400 MPa at >550-750°C) or slightly higher than those for low pressure - high-temperature metamorphism. They also correspond to conditions of incipient melting of pelitic rocks (e.g. Yardly, 1989). Thermobarometer according to Hodges & Spear (1982), Hoisch (1989).

Relative timing of pegmatite intrusion and the BS
Pegmatite dykes that truncate the very pronounced shear fabric of the BS are very common (Fig. 50A). Locally the pegmatites truncate two generations of BS intrafolial folds (Fig. 50B). The same type of pegmatites have also been folded. This could result from a sequential evolution comprising folding + shearing during BS development, later truncation by pegmatite dykes and refolding of both pegmatites and the BS itself. Such an evolution would explain why m- thick pegmatite dykes on Timmerudd truncate the pronounced, mylonitic BS-fabric but are also affected by boudinage and pinch-and swell development (Fig. 50A). However, the boundaries of the dykes show asymmetric flames with axes plunging SW and a stretching lineation plunging NE, i.e. structures recorded also in the more intensely deformed surrounding (Fig. 51). A similar situation exists north of Hässelmarka where an “augen-aplilitic” dyke both truncate the BS and is
folded and extended along an axis parallel to the strong, NE-plunging stretching lineation within the surrounding BS (Fig. 48B). Obviously both the pegmatites and the "augen-aplite" have structures common with the BS although the accumulated strain is much lower in the dykes. That is, rather than a sequential evolution the dykes are late components in a progressive evolution where the main BS-deformation is early- and/or syn-metamorphic and the pegmatites formed during the final stages of the metamorphic peak. Such an evolution suggests that the large porphyroclasts in felsic mylonitic layers in the BS are derived from pegmatites intruded syn-tectonically at an earlier stage. Accepting the BS as a synmetamorphic feature fits excellently with the previous interpretation by Stålhöss (e.g. 1982) where the relative synorogenic evolution is veining of quartz and feldspar - strong migmatization - even-grained red or reddish grey granite - pegmatite (large massifs?) - dykes and small massifs of granite, aplite and pegmatite.

It is also important that the folding affecting the BS and the distinct pegmatite dykes clearly postdates the intrafolial folding, a conclusion which is not in accordance with Stålhöss interpretation (e.g. 1991 and earlier) that the main folding episodes (his F₁ and F₂) where coeval.

Low peak vaning
-------------------------------------- metamorphism

F1 + F2

- - - - - - - - - - - - - - BS

---------- Mylonitized π

-------- Truncating π-dykes

-------- Regional F3

Red pegmatite dykes up to 1-1,5 m thick exist also in the BS on northern Runmarö. They are localized to intensely deformed BS and biotite-rich layers, while less deformed metavolcanic rocks are barren of pegmatites. Possibly this indicates a preference for intrusion in the well-foliated, biotite-rich, intensely deformed lithologies. Thin dykes are folded, including flames of m-thick dykes. Locally the latter have internal deformational fabrics and/or have been deformed to lenses. Structurally this locality is located in the long limb of a regional S-fold (F3) affecting the BS.
Figure 50: (A) Evidence for late dextral shear by pegmatite dykes truncating the BS foliation. The pegmatite parallel to the BS foliation (left) shows symmetric pinch and swell, the pegmatite truncating the BS foliation (right) shows asymmetric boudinage in accordance with a dextral horizontal shear component. Timmerudd, northwestern Ornö. 
(B) Intensely folded $(F_1 + F_2)$ metavolcanic rocks truncated by a dyke of pegmatite that in turn is folded. Södra Sand, southeastern Ornö.

Figure 51: Pegmatite truncating high strain fabric of the BS. Asymmetric flames along the boundary of the pegmatite indicate a dextral horizontal component. Combined with a crenulation lineation approximately perpendicular to the stretching lineation, oblique dextral and SE-up kinematics is indicated at a late stage of the BS deformation.

Fold-interference pattern on southwestern Ornö
The bend in the axial trace is due to the large E-W S-fold which is part of the regional fold structures apparent also on Muskö 12 km to the west and Södertörn, Värmdölandet and Norrtälje to the north. In Stålhös regional interpretations, the almost ubiquitous stretching lineation is related to this regional $F_2$ folding. However the lineations plunging NE on southern Ornö are folded together with the axial trace of the Utö-Ornö folds and the BS. Therefore these lineations
and associated folds/shears appear to be related to the earlier deformation resulting in the BS rather than the subsequent regional, E-W upright folding dominating the regional picture.

**Foliation- and fold-patterns on Ornö**

Foliations and rock distribution on the map by Sundius (1939) outline linear rock units folded by a train of large-scale S-folds in the archipelago that fit into the pattern of regional E-W folds on the mainland (Figs. 36 and 52). Deviations from this fold train exist on northern, western and southeastern Ornö where Z-folds are indicated.

The areomagnetic map shows, elongated areas of strong, positive magnetic anomalies partly on western Ornö and mainly west thereof (Fig. 43). A pronounced, straight anomaly indicates intense shearing between Ornö and the mainland to the west. This anomaly outlines folds in both ends: a Z-fold in the northeast approximately joining the structure on Ornö Huvud and a disrupted S-fold in the southwest. In addition, the anomaly diverge from an isoclinal fold hinge (?) in the southwestern part into an eastern branch (fold limb?) indicating two Z-folds and one S-fold. These anomalies partly coincide with the mapped BS and they outline the folding of the BS at Tornäsudd and Koviksudd indicated by Sundius (1939) which are verified by our structural data above. They also define the spectacular points of land at these localities as parts of Z-folds, which is not possible to decipher in the field or from published maps (Sundius, 1939; Stålhös, 1968). Integrated with our data, the Z-folds appear to be related to the development of the mylonites in the BS. At least at Koviksudd, the folding is typically cylindrical (see above). By contrast, e.g. along the axial surface of the S-fold at Stora Brevik, the folding is more irregular in style, pegmatites are folded and the axial surface structures are retrogressive in character.

In the southern part of the island the long S-shaped linear magmatic anomaly coincides with intense mylonitization to the south and north of Långtråsk. This c. 20m wide zone is locally pyrite-rich accompanied by typical alteration of the country rock (metavolcanic rocks and marble).
Mainland folds and shears

Värmdölandet-, Ingarö- and Södertörn (Haninge) fold structures
(Based on localities at Strömma-Ingarö-Klacknäset-Björkö-Stavsnäs-Djurö-Skarpo-Ramsdalen-Boda-Värmdö kyrka)

Värmdölandet makes up a regional E-W fold closing to the east (Sundius 1939; Stålhöös 1981, 1991; Persson et al., 2001). It is obvious on aeromagnetic maps which also show another east-closing fold to the south, the Södertörn structure (Figs. 52 A and B).

The Värmdölandet fold is isoclinal and its aeromagnetic signature indicates E-W-stretching and even pinching close to Gustafsberg (Fig. 52B). These structures demonstrate profound N-S shortening during folding opposing an earlier model, in which this generation of folds (F2 in the model) and a slightly older phase (F1) were the result of E-W shortening (Stålhöös, 1991).

According to Stålhöös (1991 and previously) the axial surfaces of the earlier folds (F1) can be traced around the Värmdölandet fold structure. It is also indicated that the F1 structures represents a second, structurally lower equivalent to the Ornö BS. Another inference by Stålhöös is that the F1-folds exist as a linear belt that extends both to the south and north of the Värmdö fold.

Northwards, as a continuous structure along the coast around the Norrtälje synform to the Singö Shear Zone, the Hamränge and Söderhamn synforms and as a NW-SE structure north of Hudiksvall outlining the long limb of a regional F2 fold. That limb approximately coincides with the recently discovered shear zone along the northern margin of the Ljusdal Batholith (the Hassela Shear Zone, Sjöström & Bergman, 1998) (Fig. 53).

Shearing is intense in both limbs of the Värmdölandet fold and have been studied at Boda (northern limb) and at Ingarö church (southern limb) (Fig. 52C). The kinematics of the shear varies depending on location with respect to the large scale fold. Symmetric distribution with respect to foliations of sinistral and dextral ductile shear zones/shearbands with steep intersections (Y-axis) and shallow plunging stretching/slip-lineations indicate pre-dominantly pure shear conditions during final stages of fold development (F3) both at Boda and Ingarö church (Figs. 54 A and B). Due to intense fold-related deformation in the limbs, any eventual earlier BS kinematics can not be deciphered.

Within the fold hinge (south of Boda) localized shear occurred on widely spaced crenulation cleavage (Fig. 55). Here the shear sense along the cleavage planes is dextral and a prominent pure shear component is indicated by folding of back-rotated gneissosity between the shears, i.e. shortening of the foliation when orientated in the compressional flattening field (Harris, in prep; Harris and Persson, in prep). Further east, in the upper hinge area at Ramsdalen, a truncating cleavage (indicating Z-symmetry of folds) and sense of shear on minor shear zones (dextral horizontal component) is consistent with the large scale fold geometry and a mechanism of buckling. A crude crenulation lineation related to the (F1) folding plunges to the east (Fig. 54A). The axial surface structures are steep and consists of a spaced crenulation cleavage that appears
Figure 52: The folds of Värmdölandet (and Södertörn) as indicated on (A) aeromagnetic map, (B) magnetic formline patterns, and (C) sketch map with kinematic data.
Figure 53: Bedrock map of east central Sweden (Lundqvist et al., 1994) modified to outline regional folds and major deformation zones. Note the folding of the Ornö BS and its possible continuation northwards to the Hassela SZ as one of several deformation zones along the coastal region. Full lines outline early ("D1") shears and broken lines subsequent ("D2") shears. Deformation zone data compiled and modified after Stålhöös (1991), Bergman and Sjöström (1994), Stephens et al. (1994), Sjöström and Bergman (1998) and Antal et al. (1998).
to postdate garnet growth in paragneiss, although K-feldspar crystals in neosome material show a preferred orientation along the axial surface, demonstrating that metamorphic conditions prevailed during folding.

At the Skarpö peninsula reverse oblique top-to SW shear is indicated. This would be a possible location to show BS kinematics but apparently the metamorphic grade in the shear zones is lower grade than that typical of the BS. Consequently the shear is also here most likely related to the folding and not the BS-deformation. The reverse component indicate eastwards escape of the fold hinge.

Figure 54: (A) Poles to foliations define a girdle indicating a fold axis with a shallow plunge to the ENE. Most stretching lineations and crenulation lineations plunge E to NE. (B) Dextral and sinistral shear zones spread considerably but are consistent with approximately NS or NNW-SSE shortening. Axial surfaces are steep.

At Stavsnäs in the hinge of the Södertörn fold, sinistral and dextral shear zones overlap in orientation and are contractional, i.e. axial surface structures. Similar-type folds with extremely sheared limbs are probably earlier folds (F₂) that are truncated by pegmatites. The pegmatites are in turn mylonitized by D₃-deformation. A stretching lineation (L₂) plunges NE and can be distinguished from a coarse, east-plunging L₃ crenulation lineation. The structures described so far
thus consistently show that the large scale F₁ folds developed a crenulation lineation, and that the
fold formed by buckling.

An excellent and illustrative profile across several shear zones exists along the N-S road cuts at
the road junction 2 km north of the Ingarö church (Figs. 56). Degree and timing of deformation
vary along the profile, which consists of neosome-rich paragneisses, orthogneiss and various
pegmatites and medium grained granitic dykes.

The earliest folds are intrafolial, isoclinal folds (F₂) with a completely recrystallised fabric. The
few fold axes recorded are steep and the axial surface cleavage is the regional gneissosity. These
folds are refolded by at least locally S-verging folds (F₃) with steep axial surfaces and E or NNE-
plunging axes accompanied by a crude crenulation lineation. Like on e.g. Örnö the folds affect
pegmatite dykes, i.e. post-date the dykes. Also west of Ingarö church a shear zone spectra
truncates pegmatites, i.e. shearing postdates pegmatites.

With one exception all existing rock types are truncated/affected by two generations of shear
zones. The first generation resulted in the development of ductile mylonites with an apparent
semi-brittle protomylonitic stage in coarse grained, feldspar-rich rocks. Mylonitic lineations
plunge west and indicated kinematics is dextral and N-up (Fig. 52C). Coarse, quartz-rich dykes
carrying white feldspar formed as tension gashes during the shearing. Combined with kinematic
data from similar mylonites in other parts (limbs) of the large-scale fold structure (e.g. Boda),
hinge escape is indicated at a late stage of the F₃-folding. The truncation of neosomes and
pegmatitic dykes as well as the character of associated mylonites show that this deformation took
place after the metamorphic peak, but still at metamorphic conditions.

Subsequent to the D₃ shear, brittle-ductile deformation zones formed. These zones abruptly
truncate the rocks and are typically accompanied by pseudotachylite(?) and epidote. A slight
rotation of adjacent rocks including quartz veins demonstrates a partly ductile behavior. Our data
are to few and scattered but a couple of conjugate pairs of shear zones indicate approximately N-
S extension and vertical compression, i.e. conditions of normal faulting. This brittle overprinting
has obviously occurred along the southern shear zone (along the southern fold limb) from
Strömma to Nacka and further west into southern Stockholm (Årstaviken) (Fig. 52C). The
frequency of mylonites and a clockwise rotation of foliations and rock units in the western part
(Stålholm 1981) indicate that this fault had a ductile precursor with a dextral horizontal component
which further support hinge escape of the Värmdölandet fold. Also along the northern limb there
is a lower grade overprint characterized by epidote bearing narrow shear zones on the ductile
fabric (Boda). The topography and shapes of small islands outline a NE-SW fault zone here.
Figure 55: Localized shear on widely spaced crenulation cleavages. A prominent pure shear component is indicated by folding of back-rotated gneissosity between the shears.

Figure 56: Profile with varying degree (and timing) of deformation along a N-S road cut, 2km north of Ingårö church.
DISCUSSION

The Vattholma leptite cross structure

Several previous contributions have favored interpretations where the rock distribution and the structures were related to the emplacement of magma. Högbom (1893) explained the parallel structures in the leptite cross-structure as a result of both primary and secondary magmatic processes. He considered that a primary preferred orientation of the crystals formed in the magma during consolidation, the so called "primary fluidal or protoclastic structures". He also described the rocks as sometimes showing a lineated ("rodding") fabric that could not be seen in cross-section of the long-axis of the crystals (i.e. L-rectonites). The secondary structures, called "secondary pressure foliations" (sekundär tryckförskiffring) were believed to be a result of the pressure inside a magma during the end-phase of consolidation.

Geijer (1916) explained the parallelism existing in the granite and intruded host-rock as a combination of two processes. The first was Daly-type stoping, i.e. the roof of a magma chamber was fissured by tension caused by unequal heating whereafter the detached, relatively more dense fragments sunk in the magma. The second process was intrusions of Turner-Tigerstedt type, so called roof doming, where the surrounding bedrock has been forced aside by the intrusion.

Stephanson (1975) described the same area as a result of polydiaprism, where younger granite diapirs have forced their way up through older diapirically formed granitoid rocks and supracrustal septa. The process is driven by the density contrasts between the diapir and the surrounding rocks. Stålhos (1991 and earlier) interpreted that some folds (F₂) were related to the intrusion of the early Svecofennian granitoids but described the "leptite cross" as a result of fold interference. Recent studies indicate that splays from the Singö shear zone are located along both the ÖSZ and the GZ (Bergman et al., 1996; Antal et al., 1998).

Our data indicate that Uppland has been considerably affected by folding and shearing obscuring much of the magmatic pattern. No typical magmatic shear indications are found, e.g. tiling of K-feldspar, and the characteristic stretching lineation in the early Svecofennian rocks (both plutonic and supracrustal), were formed under metamorphic, solid-state conditions. The recognition of stretching lineations also in the late-orogenic granites (Stålhos, 1987) is in accordance with such an evolution.

There are several reasons to why shear folding is necessary to explain the structures of central and northern Uppland. Firstly, the steep stretching lineations contradict and cannot explain a N-S dextral displacement by shear of the E-W Ramhäll supracrustals, and the dominant sinistral shearing in the southern part of the cross-structure (Koltorp-Strömshagen) further contradicts a continuos dextral shear zone. The apparent horizontal shear of 12 km seen on the aeromagnetic maps and bedrock maps would demand a vertical movement of approximately 35 km if the stretching lineations (of c. 70° plunge) mapped in the field correspond to the shear direction. Secondly, the lineations (and foliations) rotate into the N-S shear zone by the latest fold phase.
(F3) for example at Gustafsberg west of Finnsjön. If the folds (F3) mature to shear zones (like Singö) that in turn are progressively folded, the lineation can be affected by both folding and shearing. And thirdly, the dextral and sinistral shear zones at Koltorp (in one of the hinges) when plotted on a stereonet intersects at a point approximately coinciding with the stretching lineation in the shear zone (Fig. 11). These shear zones are therefore likely to be caused by the folding event.

If a transport lineation is oriented close to down dip a steep foliation, a small change of its orientation (e.g. the movement direction) can cause the horizontal shear component to change from dextral to sinistral along strike of a continuous shear zone. This is very common in Uppland and there is no consistency of the horizontal shear component. Such variations in horizontal displacement and consistency in vertical displacement show that the vertical components are dominant. The vertical shear component mapped by us in the field and studied in thin-sections indicates a dominant E-up component. However, a recent study of the ÖSZ based on extensive sampling of thin-sections along the N-S striking felsic volcanic rocks indicates almost equally common E- and W-up shears (Engström, 2001). This study also shows that most stretching lineations plunge SW. A W-up shear resulting in a small dextral horizontal component would explain the clockwise rotation of foliation immediately W of the ÖSZ on the maps Östhammar NV and SV. This would also be expected if the zone consists of several shear lenses or flower structures where the sense of shear would differ on each end of the lens. At Vällen (GZ) both E-up and W-up components are indicated at Kolsvedjan. However, also there our mapped data as well as thin-sections are dominantly indicating an E-up shear component.

Three possible models can describe the structures seen on the maps (Fig. 57).

(1) F1-F3 fold phase model
(2) F2-F3 model
(3) “F3" folded lenses

We suggest model 3 to resemble the structures of Uppland with the following progressive development: During progressive shear of the Singö SZ the strain aside the main shear zone was localized in narrow zones with development of several shear lenses. These splays are folded/rotated, possibly due to “stitching” by a c. 1.8 Ga granite in the Singö SZ. This granite has the same structural imprint (stretching lineation) as the surrounding Singö SZ (Fig. 7). It is unknown whether the granitoid was deformed as a melt or post-solidification (or both). As the Singö zone is partly pinned by the granitoid, subsequent strain is distributed southwards leading to rotation and folding of the lenses. This is consistent with the fact that both Österbybruk-Skyttorp Zone and the Gimo Zone splays from Singö Shear Zone, i.e. they do not cut the Singö SZ and can therefore not be a separate later event. An important consequence of our model is that the folding/rotation of the ÖSZ and GZ is a comparatively late feature as the maximum age is constrained by the c. 1.8 Ga granitoid.
As the lenses are folded, the lineation as well as the foliations rotate around a steep axes. The generally steep lineations seen in all rocks and the development of lenses may indicate transpression probably with large pure shear component. The dioritic body (lens) within the fold \((F_2)\) southeast of Vattholma (Fig. 12) with symmetric sinistral and dextral shear indicate this pure shear component, while further north at Koltorp the sinistral and dextral shears in the granitoid are related to the folding with intersections in the direction of the fold axes.

(1) \(F_1\)-\(F_3\) model (if folded folds)  (2) \(F_2+F_3\) model  (3) "\(F_3\)" folded lenses

Figure 57: The three possible models that can describe the bedrock patterns seen on the maps 12 I Östhammar.

Some results from detailed study of the ÖSZ (Engström, 2001)
The horizontal shear components are generally relatively small and vary in sense when the stretching lineation vary on each side on the dip direction of the mylonitic foliation. The normal and reverse components are thus the most important. We have recorded mainly E-up sense of shear. However, a recent detailed study of the ÖSZ show a more complex kinematic picture (Engström, 2001). Her results support our finding that the “blocks” of granitoids east of the ÖSZ and south of the E-W Ramhall synform has been displaced relatively upwards. This fits with the kinematics along the Ramhäll synform, i.e. dextral and S-up. An unexpected result by Engström (2001) is that many observations indicate W-up of the area west of the ÖSZ. There are also areas with mixed E-up and W-up kinematics and even a meter-scale lens with internal W-up porphyroclast overprinted by E-up kinematics in shear zones enveloping the lens.

The kinematic picture with granitoids moving relatively upwards relatively the intervening metavolcanic rocks along the ÖSZ seems to support the early interpretations that the granitic magmas move upwards through the supracrustal rocks (Högbon, Geijer, Stephanson, Stålhö). However, the reverse or normal shear zones related to the dip slip movements are typical greenschist facies structures in both the metavolcanic rocks and the granitoids, i.e. they formed
during regional metamorphism. Moreover the shear zones define elongate symmetric lenses in vertical sections of the volcanic rocks. These conditions do not only exclude the magma tectonic model but also suggests that the variation in kinematics is due to the development of shear lenses. The symmetric shape of the lenses indicates a high proportion of pure shear in sections parallel to the stretching lineation. The early W-up kinematics to the west of the ÖSZ recorded by Engström (2001) would also explain the dextral rotation of foliation into the ÖSZ as most stretching lineation plunge steeply SW and consequently the horizontal component would be dextral. As mentioned previously, this dextral component cannot explain the apparent large displacement of the Ramhäll supracrustal rocks. Such a horizontal displacement would require a substantial vertical movement with respect to the steep stretching lineation. Consequently there would have been a profound break in metamorphic grade across ÖSZ which is not the case. We suggest the possibility that the early west-up/dextral kinematic pattern formed before the folding of the ÖSZ into its present NNE-SSW orientation. That is when the ÖSZ enveloped a tectonic lens with an orientation along the NW-SE striking Singö shear zone.

**The Banded Series**

Our results show that the BS is a result of deformation of a composite lithology at high-T, essentially solid- state conditions. There is also a close relationship between folds and shearing. In addition it is obvious that the BS is only the spectacular part of a much wider and more extended deformation zone (or several deformation zones), as was indicated by Stålhös (1991). The original restriction of the BS to banded rocks combined with the interpretation of a primary origin (Sundius 1939) is most likely the reason why it abruptly terminates (e.g. east of Runmarö). Our finding that also more homogeneous rocks (like augen gneisses) are strongly deformed, indicates that the BS, when considered as a deformational feature, is much more consistent than originally considered. The most likely rocks to have been affected by intense deformation are the fine-grained salic granites and red and greyish, aplitic gneisses on Sundius (1939) map, as we have recorded transitions from red, coarse augen gneisses to recrystallised fine-grained mylonites on e.g. Skarprunmarn.

The kinematic indicators within the BS are obscured by recrystallisation and often affected/disturbed by subsequent folding. But also in more homogeneous domains, like on western Örnö, kinematic indicators are often contradictory although there is a dominance of sinistral/W-up shear during early deformation. However, tectonic lenses on various scales are common within, and particularly aside, the BS. On a larger scale, mylonites are often recorded along the boundaries of “topographic” lenses. Some of these are made up by internally folded, composite units although the lenses are not outlined on Sundius (1939) map or visible on available aeromagnetic maps. A shear zone system made up by lenses – and at oblique
movements – would result in a very complex kinematic pattern. To decide the overall kinematic character of the system, it would be necessary to carefully define the lenses and to establish the kinematics around several of these, which has not been possible in this kind of regional study.

A simpler way to find out the overall kinematics would be to define the rotation of mainland structures into the shear zone. Accepting the structural model of Stålhos (1991), that the regional lineation is related to E-W F2-folds, there is an obvious anticlockwise rotation into the BS demonstrating sinistral W-up shear, with at least locally a dextral overprint. However, the folds related to the shear zone are often NW-verging and asymmetric suggesting that they are equivalent to Stålhos F1-folds. As these are supposed to have approximately N-S fold axes without a pronounced lineation, the correlation of folds related to the BS (with a pronounced stretching lineation) is problematic.

The timing of the BS-deformation may be defined by the relationships to sheared, folded and truncating pegmatites. Age determinations of pegmatites from Utó and Norrò close to Ornó yield ages in the interval 1816-1821 Ma (Romer & Smeds, 1997). These results imply that the BS was active during that time span, and in turn that the BS at least in part was coeval with the Singö Shear Zone (SSZ). The BS and the SSZ deviate in that the latter is not folded (but related to folds; see the preceding section) and is characterised by a SSE-plunging stretching lineation, while the BS is characterised by a NNE-plunging lineation. This difference in plunge of lineations would be expected if the SSZ and the BS were conjugate shear zones with opposite senses of shear i.e. the SSZ dextral/SW-up and the BS sinistral/NW-up.

Our data from Skarpunmarö-Runmarö indicate that the BS was affected by the hinge escape of the mainland folds on Värmdölandet-Ingarö-Södertörn. Apart from rotation/overprinting of folds, a significant feature is that the linear, aeromagnetic anomalies of Ingarö indicate folds due to WNW-ESE shortening across the BS (Fig. 52B). There is also a sinistral rotation of structures and linear magnetic anomalies on Värmdölandet-Fågelbrolandet. We therefore suggest that the BS was a structure that accommodated part of the N-S shortening resulting in the folding and hinge escape on the mainland. However, it is possible and likely that the BS also had an earlier history, if related folds are the F1-folds of Stålhos (1991) and in particular if it is a continuous structure along a large part of the eastern coast of central Sweden (cf. Fig. 53).

**Fold episodes in eastern Bergslagen**

In this report we refer to three fold phases in the description of the mainland folds and the subareas in the archipelago. This is a consequence of the recognition of refolding including deformation of a cleavage by the first folds. The nature of this cleavage is however unknown and it may therefore represent a bedding cleavage, i.e. a structure not related to folding.

The deformation history recorded is very similar to that described from southern Finland (Ehlers et al. 1993, Selonen and Ehlers 1998), where the two most important folding episodes are referred to as F2 and F3 (Table 1). This evolution appears also to be in accordance with the results

Compared to Stålhös (1991) model, also comprising three fold phases ($F_0$, $F_1$, $F_2$), the major difference of our results is that our $F_2$- and $F_3$-folds (corresponding to Stålhös $F_1$ and $F_2$) are not coeval and that the later episode records regional rather than local approximately N-S shortening.

Table 1: Table summarizing the tectonic history of Uppland and Sörmland by Stålhös (1991) and Southern Finland by Ehlers et al. (1993) and Selonen & Ehlers (1998).

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<td>unknown basement</td>
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<tr>
<td>Syngenetic, small-scale, interfolial folding + block-movements</td>
<td>Sedimentary rocks (volcanic rocks, limestones, conglomerates...) Ore-deposits, Mafic dykes and intrusions (gen. 1)</td>
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<td>Magmatetonic diapirism? $F_0$ (stronger in Uppland than Sörmland)</td>
<td>Greenstones Synorogenic mantle derived granitoids</td>
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<td>Block movements + fracturing</td>
<td>Mafic dykes (gen. 2) Development of penetrative foliation + lineation Migmatites and pegmatites Granitoids?</td>
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<tr>
<td>Crossfolding ($F_1$ &amp; $F_2$) (weaker in Uppland than Sörmland)</td>
<td>Development of penetrative foliation + lineation Migmatites and pegmatites</td>
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<td>Block movements + fracturing</td>
<td>Metadiabase (gen. 3) (Sörmland-Bergslagen)</td>
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<td>Block movements + fracturing</td>
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<tr>
<td>Local artritic migmatitisation + plastic folding</td>
<td>Serorogenic granites + pegmatites</td>
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<td>Block movements + fracturing</td>
<td>Diabases (rare in Uppland)</td>
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CONCLUSIONS

Uppland

The NNE-SSW Österbybruk/Skyttorp Zone (ÖSZ) and the N-S Gimo Zone (GZ) are splays from the Singö Shear Zone (SSZ) system. Originally the ÖSZ and the GZ enveloped tectonic lenses oriented approximately parallel to the SSZ. Subsequently they were rotated clockwise by large-scale, E-verging footwall folds to the SSZ. Possibly the distribution of strain southwards from the SSZ was due to the solidification of c. 1.8 Ga granite in that zone. The E-verging folds have steep axes and rotate the regional foliation and the stretching lineation. As the latter also exist in the c.1.8 Ga granite, this implies that the folds are c.1.8 Ga or younger.

The ÖSZ and the GZ share E-up kinematics; along the former also an older (?) W-up pattern is common along its western margin. We conclude that the E-up movements, often with a sinistral component, were related to the E-vergent folding and that the earlier (?) W-up pattern was developed during dextral/NE-down shearing along the SSZ prior to the folding of the ÖSZ and the GZ.

Rectivation of the ÖSZ resulted in W-down offset of the Precambrian peneplain and brecciation, locally accompanied by pervasive hydrothermal alteration. The invading hot fluids resulted the development of local new mineral associations (quartz, calcite, chlorite, laumontite and prehnite) and also changed the rock properties from brittle to brittle-ductile.

The Banded Series and mainland folds

The Banded Series (BS) is a component of a much wider and more extensive high-T shear zone than that defined by the spectacular banded rocks existing on Utö, Ornö, Rumnarö and Skarpnumnarm. The shear zone evolved from folds and has in turn been folded by regional-scale S-folds.

Tectonic lenses containing hinges of rootless folds are typical features. These cylindrical folds generally have axes plunging NE parallel to a pronounced stretching lineation demonstrating intense stretching during shearing.

The characteristic, red Kf-augens in various rocks of the BS were derived from dismembered early pegmatites, while white, less common augens were derived from neosomes. This indicates that the BS was temporally related to c. 1816-1821 Ma pegmatites and peak metamorphism.

The kinematic pattern is composite and very complex. Partly this is due to folding of the BS, but more important is the existence of tectonic lenses that moved obliquely relatively up and down during shearing.

Important sinistral/W-up shear occurred coeval with E-wards to SE-wards hinge escape of the E-W Värmdölandet-Ingarö-Södertörn folds. The inferred timing of that deformation indicates that the BS was part of a conjugate dextral/NE-down (Singö Shear Zone) and sinistral/NW-up (BS) shear zone system. That is, the strain related to approximately N-S shortening was partitioned into the E-W folds and the conjugate shear zone system.
ACKNOWLEDGEMENTS

This project has been jointly supported by the Geological Survey of Sweden (SGU) and the Uppsala University. We acknowledge the funding from both sources.

This study has benefited of the work by Nils Sundius and in particular from the regional compilations and interpretations by Göran Stålholms. Their work is greatly acknowledged. Prof. Stefan Claesson, Swedish Museum of Natural History, suggested the Örnö BS as a suitable object to a study of shear. Prof. Thomas Lundqvist kindly informed us about his work in the BS and suggested several key localities and references important for the study. Dr Anders Wikström and Prof. C.J Talbot contributed with important comments also in the field. Dr M.B. Stephens informed us about the results of the Bergslagen Project and took part in discussions that were very important for the interpretation of our results. We acknowledge the contributions from all of them. Lena Persson and Niklas Juhojuntti (SGU) kindly provided the aeromagnetic maps and Stefan Bergman Fig. 49. Our work on Örnö became particular pleasant due to the kind hospitality of Mrs Ulla Ehnkvist.
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