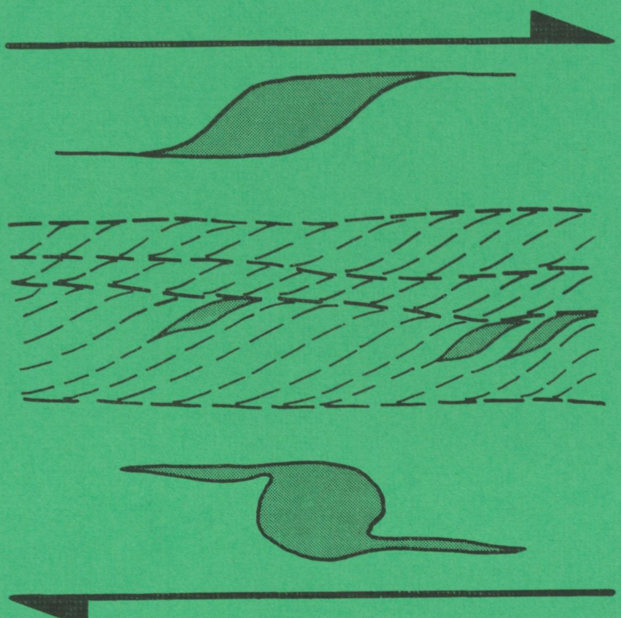
SVERIGES GEOLOGISKA UNDERSÖKNING
Rapporter och meddelanden nr 76

WORKSHOP

Ductile shear zones in the Swedish segment of the Baltic Shield

ABSTRACTS AND EXCURSION GUIDE



Conveners
Michael B. Stephens and Carl-Henric Wahlgren

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INTRODUCTION

M.B. Stephens and C.-H. Wahlgren

Considerable attention has been placed over the last few years on younger, brittle deformation zones in the Swedish segment of the Baltic Shield, especially in the context of nuclear waste disposal problems. Older ductile shear zones have attracted considerably less interest and these zones are poorly understood, particularly in the Svecokarelian orogen in the eastern part of the shield. It is apparent, however, that ductile shear zones are of utmost importance in dictating the basic geometric assembly of the bedrock in both the Svecokarelian and the Sveconorwegian orogens in this segment of the shield. Furthermore, their relationships to the younger, brittle deformation zones are more complex than generally assumed.

The present workshop aims to document the state of the art where it concerns the geometry, kinematics and timing of deformation of ductile shear zones in the Swedish segment of the shield. Sessions dealing with the geometry and kinematics of such zones in the Svecokarelian and Sveconorwegian orogens as well as the timing of deformation along them were planned. This volume presents the abstracts of 28 short talks and posters submitted to the workshop. It also includes a guide to a two-day excursion which follows the workshop. The excursion focuses attention on the deformation zones in the Karlskoga–Kristinehamn area, in the eastern part of the Sveconorwegian orogen.

The workshop has been organized under the auspices of the Geological Survey of Sweden's programme for Research and Development.

ABSTRACTS

Edited by M.B. Stephens and C.-H. Wahlgren

Structures and sense of displacement in the Protogine Zone type area (poster)

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Before the name Protogine Zone became established, the zone was referred to as "Förskiffringszonen" ("Schistosity Zone") by Scandinavian geologists. Magnusson (in 1, p. 47) referred to an area between Lake Vättern and Lake Rusken for the typical development of the zone, describing the Barnarp granite as "a Gothian granite originally of the same type as the granites east of the (Schistosity) zone but deformed to a rock rich in schistosity planes". This poster describes the progressive development of the PZ schistosity when the zone is approached from the east in excellently exposed massive granites (SE Barnarp), and when it is approached from the west in gneisses and massive 1200 Ma old Vaggeryd syenite (Skillingaryd).

In the east, spaced, narrow shear zones in massive granite display two sets of unequally developed cleavage zones with opposite senses of dip-slip. An early CS-fabric with top-to-the-east sense is cut by shear bands of steeper dip (e.g. N10°E/60°W), showing western block down. The characteristic strong feldspar and quartz lineation of the PZ belongs to the early C-fabric (e.g. N20–30°E/50°W). On horizontal outcrops, the conjugate sets result in sinistral or dextral sense of strike slip. In the west, the dominant dip-slip shows eastern block down. Fold structures include dragfolds and sheath folds of local development, and late chevron folds with subhorizontal axial planes developed in strongly sheared rocks. The latter folds are the only of regional significance. There is no difference in metamorphic grade between PZ fabrics in the east and west.

The poster discusses alternative interpretations of the bulk sense of displacement and their kinematic implications. Structures in the PZ type area do not support recent models (2, 3) describing the PZ foliation as related to folding during Early Sveconorwegian plate collision caused by rotation of Baltica.

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Age and tectonic significance of high-alumina deposits along the Protogine Zone, south Sweden. Constraints from 40Ar/39Ar mineral ages

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The Protogine Zone (PZ) is a composite geological feature and several aspects in addition to structural considerations deserve attention. Hydrothermal mineralizations indicate, by their mere existence, specific tectonic environments. Moreover, they bring heat and fluids into the bedrock and may strongly influence deformational processes.

Geijer (1) discussed the origin of four deposits of Al_2SiO_5, rutile and rare Al-phosphates occurring in metavolcanites and -sedimentary rocks along the PZ. He was intrigued by their spatial relations to the PZ and the mafic dyke swarm along the zone. However, not until recently has their potential bearing upon the development of the PZ again been considered (2, 3, 4). Identical deposits occur in intensely altered volcanic rocks along lineaments and shear zones worldwide. There is increasing evidence that at least some of these deposits formed by Al-silicate enrichment during hydrolysis, and subsequent crystallization of Al-phosphates was caused by acid phosphorous solutions acting upon the Al-silicates (5, 6). At Hökensås, high-alumina alteration occurred on PZ deformation zones cutting massive granite and a thin metavolcanite. Microstructures indicate that the development of the PZ schistosity and the crystallization of high-alumina assemblages represent different stages of one and the same process:

1. $1.5KAlSi_3O_8 + H^+ = 0.5\mathbf{KAl_3Si_3O_{10}\,(OH)_2} + 3SiO_2 + K^+$
2. $KAl_3Si_3O_{10}\,(OH)_2 + H^+ = 1.5\,Al_2SiO_5 + 1.5\,SiO_2 + 1.5\,H_2O + K^+$
3. $Al_2SiO_5 + H_3AlPO_4 = Al_2PO_4(OH)3 + SiO_2$

Muscovite separates interpreted to represent the muscovite formed in reaction 1 above (bold) yielded $^{40}Ar/^{39}Ar$ plateau ages of 964.2±2.7 Ma and 937.2±1.2 Ma, telling when the schistosity cooled below c. 350°C. The tectonic reason behind the occurrence (preservation?) of the mineralizations along the PZ and the implication of the ages for uplift and cooling patterns of south Sweden will be discussed.

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Structural and metamorphic contrasts across the Nömmen–Oskarshamn deformation zone (poster)

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Several steep deformation zones with approximate E-W trends transect the Proterozoic bedrock of southeast Sweden. As evident from geological and geophysical maps (1, 2, 3), the zones often define lithological boundaries. According to recent geophysical models, some of these zones penetrate the whole thickness of the crust. However, the vertical displacement along the zones appears to be difficult to assess from structural criteria alone (4). This report describes lithological, structural and metamorphic contrasts across the Nömmen-Oskarshamn lineament (NOL). At Lake Nömmen, the WNW–ESE trending Nömmen Fault (NF) separates mica schists in the south from volcanics in the north; both units were intruded by c. 1.8 Ga Svecofennian plutonics (5). South of the NF, outcrops display incipient melting, and metamorphic parageneses indicate reactions as: cordierite + muscovite + quartz = andalusite + biotite + H_2O; biotite + Al_2SiO_5 + quartz = K-feldspar + cordierite + melt. North of the NF, excellently preserved pillow lavas, lava breccias and other volcanics of greenschist facies grade and lacking any sign of pervasive regional foliation occur. The NF is defined by a zone of anastomosing, narrow, steep deformation zones with WNW-ESE trends. Conglomerate and sandstone of the < c. 1000 Ma old Almesåkra Group rest peacefully on top of strongly sheared volcanics raised to steep dips by the NF.

Our results suggest a significant crustal relief across the NOL. The poster describes the eastern extension of the fault (NOL) and discusses various criteria of age, bulk sense of displacement and orogenic significance. The NOL is a possible northern equivalent to the Nyatorp Shear Zone (4) which runs approximately along the southern boundary of the Vetlanda belt.

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Shear zones in the Proterozoic rocks of northern Västerbotten, Sweden

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Preliminary results from mapping south of the Skellefte district by the Geological Survey of Sweden as well as PIM (Research programme "Ore Geology Related to Prospecting")-funded research in the central Skellefte district show that ductile shear zones of at least two generations exist in the area.

In the Skellefte district, shearing has previously not been considered important during deformation. Recent mapping in the central part of the district has, however, shown that a number of shear zones cut through the area. These shear zones are readily observed on aeromagnetic maps, but are unfortunately poorly exposed. Shear zones have, so far, been observed at seven localities. Six of the observed shear zones strike WNW, subparallel to the main cleavage in the area. Zones are at least 1 m wide, are subvertical, and have a steep lineation. Movements on these shear zones have not yet been determined. The age of the shearing is also unclear. Penecontemporaneous slip along cleavage occurred during the first deformation which probably also caused shearing. Shear zones observed on magnetic maps cut through post-orogenic, c. 1800 Ma old Revsund granites, which may indicate reactivation of older shears. A possible earlier phase of shearing is recorded in an outcrop near Fäbodmyran. A massive quartz porphyritic rock has a strong cleavage which is deformed by the first deformation.

South of the Skellefte district, several up to 1 m wide mylonites cut through the post-orogenic Revsund granites. These mylonites strike generally N–S, are subvertical, and have steep lineations. The shear zones are not visible on aeromagnetic maps, and the regional implication of the shear zones is unknown.

It is likely that much of the deformation in the Skellefte district and surroundings was caused by several episodes of shearing. The fact that many ores are situated on or near shear zones makes these structures important for future studies.

A basement-inherited discontinuity in the central Scandinavian Caledonides (poster)

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A variety of "anomalous" features within a broad zone in the central Scandinavian Caledonides appear to manifest the influence of a major shear zone in the underlying Proterozoic basement on the early Palaeozoic Caledonian evolution. These include:

1. Facies variations over short distances in Vendian–Ordovician sedimentary rocks and the characteristics of possible syntectonic sedimentation.
2. Age patterns of both late Ordovician – early Silurian,rifting-related magmatic rocks and high-grade metamorphism that may be controlled by the shear zone.
3. The location and orientation of lateral ramps in the Seve and lower tectonic units during Scandian collision and thrusting that were apparently controlled by basement heterogeneities.
4. The rotation of planar structures from northeast (orogen-parallel) to northwest (shear zone parallel) in the Lower Allochthon west of Östersund indicating an underlying lateral ramp (in this area illite-crystallinity patterns are also influenced).

5. Regional patterns of 430-400 Ma hornblende cooling ages indicating different uplift histories on either side of the Grong-Olden Culmination, the anomalous orientation of which coincides with the supposed extension of the shear zone.

Passive as well as variably reactivated pre-Caledonian basement structures may explain most of the observed features.

Radiometric dating of shear zones – a review

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The determination of ages of tectonic movement in shear zones is not a trivial task. Only rarely can such ages be satisfactorily constrained by discordant relations to older and younger rocks of known ages. In most cases, it is necessary to identify and investigate isotopic clocks which started or were totally reset as a direct response to mineralogical, geochemical or temperature changes related to the shearing, and thereafter have remained closed systems. The development of shear zones may be complex and include repeated reactivation. Furthermore, isotopic ages can also be related, in some cases, to younger geochemical alterations caused by penetrating fluids, rather than to the deformation.

Rb-Sr whole-rock systems can be totally reset by extreme deformation and Rb-Sr whole-rock dating can be successfully applied for dense ultramylonites. More commonly, Rb-Sr systems are only partly reset and there are several examples in the literature where the interpretation of such data is wrong. Recrystallization does in many cases reset isotopic clocks, and Rb-Sr and $^{40}Ar/^{39}Ar$ data on recrystallized minerals are commonly useful. However, it is important to remember that obtained ages date the time when minerals cooled below their blocking temperatures (c. 500°C and 350°C for Ar in hornblende and muscovite, respectively), rather than the time when they crystallized. For vertical movement, it is sometimes possible to date the passage of the uplifted crustal segment through various blocking temperatures, and thus to indirectly date the related shearing.

The U-Pb clock in sphene is particularly useful. Sphene commonly yields concordant U-Pb ages and, during amphibolite facies or higher metamorphic grade, secondary sphene can crystallize. Normally, this is optically distinguishable from primary magmatic sphene. Isotopic analysis of metamorphic sphene has proven to be a powerful dating tool for shear zones, when it is combined with careful structural and petrographic examination of the rock in which it occurs.

Ductile horizontal shears and strike-slip zones associated with the Svecofennian migmatites in SW Finland

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The migmatite granites of southern Finland form a 500 km long and 100 km wide belt of sheet-like intrusions. The age of these deformed granites is 1840-1830 Ma which is an age bracket unique for this zone and some 50 Ma younger than the granitoids outside of the zone. This zone has a history of deformation, metamorphism and intrusive activity different from the Svecofennian domains both to the north and to the south.

The southwestern border of the migmatite zone is exposed as a ductile dextral strike-slip shear zone than can be traced more than 100 kilometres eastwards. Its U-Pb age is roughly between 1890 and 1840 Ma.

The migmatite zone is characterized by a long history of early overturned primary lithologies followed by strong and repeated horizontal ductile shearing producing a transposed horizontal lithology visible all over the migmatite zone of SW Finland. The latest ductile thrust-movements are synchronous with the emplacement of the 1840–1830 Ma old granite sheets and are shown by systematic rotations of feldspar megacrysts in sheared granite sheets. A selected area in the SW archipelago of SW Finland (the Torsholma area) has been studied in more detail. It contains thin interthrusted horizontal slabs of rocks with strong stretching lineations and parallel axes of small folds, separated by sheets of granitoids of different ages. Some new U-Pb ages enable us to roughly date some of the deformational episodes.

The Storsjön-Bothnian Sea Zone - a major crustal boundary in the central Baltic Shield complicated by subsequent faulting

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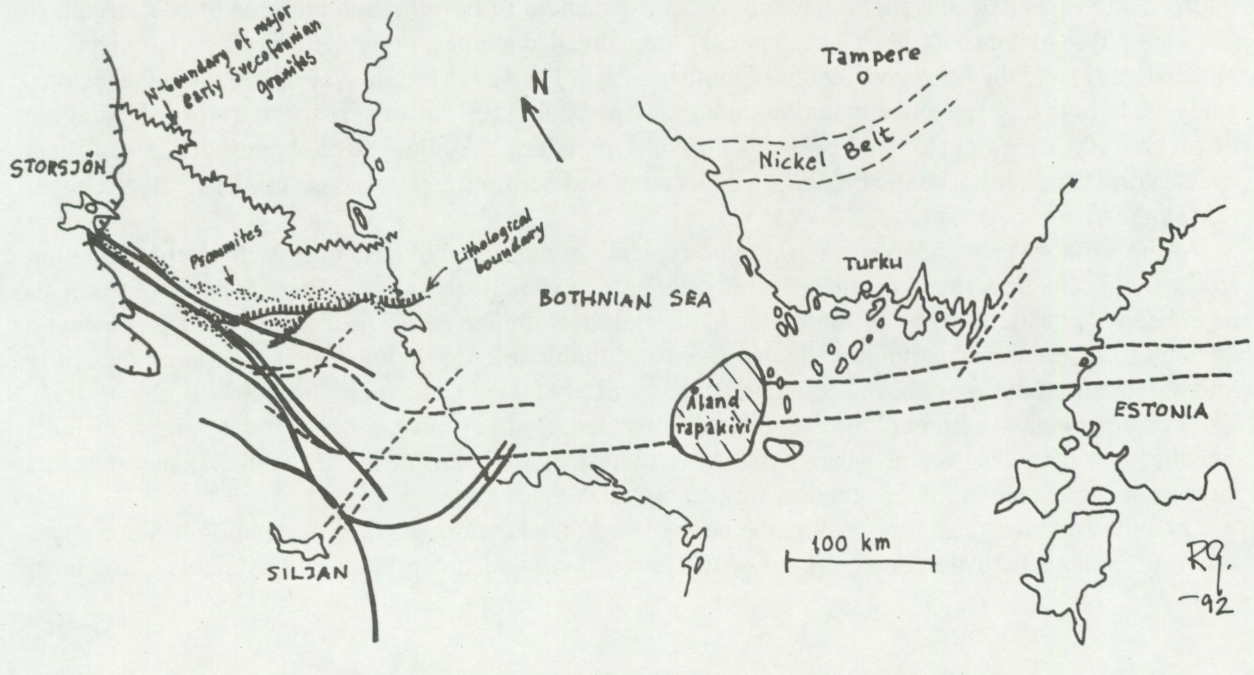
A belt of lithological contrast, major faults, and zones of strong foliation extends from the Caledonian Front at Lake Storsjön in Jämtland southeastwards to the Bothnian Sea.

The principal lithological boundary in the area is that between the South Svecofennian ("Bergslagen") volcanic province and the Central Svecofennian ("Bothnian") Province of dominant greywackoid sedimentary rocks and subordinate, mostly mafic volcanic rocks. The belt of lithological transition is c. 30 km wide, but magnetics indicate a much sharper change of dominant lithologies in a narrow belt marked by mafic igneous and immature psammitic metasedimentary rocks.

This boundary also controlled lithological development after its original formation. Thus, it trends parallel to the northern boundary of major occurrences of early Svecofennian granitoids, and is the northeastern limit of the c. 1.7 Ga old Rätan-Dala granites and the southwestern boundary of the occurrence areas both of the c. 1.78 Ga Revsund granite and the Jämtland-Nordingrå sheet intrusions of c. 1.25 Ga old dolerites. Although the main and trace element patterns of Transscandinavian-Belt granites are similar on both sides of this boundary, there is marked contrast in the Nd-isotopic characteristics.

In the northwest, the course of the Storsjön-Bothnian Sea Zone coincides closely with that of several NNW-trending major faults but, further southeast, these faults splay to form a fan-shaped pattern. The apparently older of these faults, among them the Ljusnan Zone, are marked by semi-ductile deformation and seem to continue into similar faults in the Åland area and in the basement of Estonia. Other major faults are distinctly later than the Rätan and Dala granites, and may even have been active as late as during the Sveconorwegian-Grenvillian orogeny.



Aspects of the Protogine Zone – a long-lived belt of tectonic unrest

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The Protogine Zone (PZ) offers a wide variety of deformational environments of variable age ranging from brittle faulting to granitic intrusion tectonics. The recently much intensified study of this geodynamically important feature has even led to mutually, seemingly incompatible results regarding the nature and timing of deformation as well as the very definition of the PZ. Thus, the PZ may be a lithological divide in one place, while similar rocks occur on both sides of the PZ elsewhere. The type and age of the predominant deformation are described much differently in the north and in the south.

A way out of this quandary appears to be the recognition that the PZ developed during a very long time, that the ages of the locally dominant deformation vary along its course, and that the structures most dominant in the field may not be the geodynamically most important ones. While there is hardly any doubt that the PZ is not the boundary either of the Transscandinavian Belt or of the Svecofennian and Sveconorwegian orogens, penetrative foliation is much more dominant in the west and there are numerous aligned igneous rocks that indicate uniform patterns and causes of development. Apart from this, however, features like the Vättern rifting and the 1.18 Ga dolerites follow only part of the PZ, then to leave its course and splay into the forelands.

In other cases, later events, like the post-Sveconorwegian uplift in the south, may have obliterated or removed from the presently exposed crustal level features such as the early, east-dipping faulting and foliation that are still seen north of Lake Vänern.

Against this backcloth, it appears little surprising that the looks of the PZ vary along its course as do the dominant senses of movement and even the apparent geodynamic significance. However, the PZ is a good example of a once-formed crustal boundary that controls the location of subsequent deformation.

Regional steep shear zones in northern Fennoscandia

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In the Nordkalott project, a compilation of large databases and efforts to produce a uniform aeromagnetic interpretation resulted in a first approach for an assessment of deformation patterns over a large area from geophysical data sets. Two, subsequently more detailed studies, in the Lansjärv area (southeastern Norrbotten, 1) and the Masi area (central Finnmark, 2), utilized even terrain elevation data in the tectonic analysis. In both cases, a close spatial relationship was established between suspected steep shear zones of several 100 km extension and post-glacial faulting patterns. A network of shield-wide, steep shear zones along which lithospheric blocks are dislocating and deforming in response to plate tectonic forces was suggested.

At the surface, these steep shear zones are typically represented by sets of low-magnetic oxidation zones slicing the uppermost brittle crust into elongate tectonic lenses. Large, strike-slip displacements have been suggested for one of these zones, the Baltic–Bothnian megashear zone (3). It is, however, difficult to assess the accumulated displacement as suitable reference structures are generally lacking. Slices of similar lithologies have been found approximately 50 km apart along the Baltic–Bothnian zone. Their original location cannot, however, be reconstructed. Distinct and extensive gravity gradients indicate that very large displacements are possible. Geophysical modelling of individual fault zone segments indicate widths of about 200 m and dips from about 50 degrees to vertical.

On a lithospheric scale, the spacing, the large extension and width, and the orientation of steep shear zones all indicate their function as zones of weakness along which continuous adjustments of the local plate shape can be accomplished. When seen in conjunction with current earthquake activity, the steep shear zones are the edges of lithospheric blocks responding to compression or extension. Adding the information from elevation data, it is noted that the variation of the free surface reflects the accumulated relatively recent deformation. The earthquakes seem to be located within upper crustal volumes under extension rather than along the steep shear zones (or in volumes under compression).

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U-Pb titanite ages from ductile deformation zones in the eastern part of the Sveconorwegian orogen, Karlskoga-Kristinehamn area, south-central Sweden

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The Transscandinavian Igneous Belt (TIB) in the area between Karlskoga and Kristinehamn, south-central Sweden, has been affected by spaced (eastern part) to more or less penetrative (western part) ductile shear deformation. Titanites from five deformed rocks (including one gneissic meta-TIB variety in the west) and from one undeformed granitoid in the TIB complex have been separated and analysed using the U-Pb age-dating technique. Zircons from the undeformed granitoid were also analysed. This study was carried out in the same area as the $^{40}Ar/^{39}Ar$ geochronological investigation of Page, Stephens and Wahlgren, also reported in this volume. These two studies complement each other.

The zircon analysis gave an upper intercept age of 1665±5 Ma which is inferred to be the crystallization age. This rock belongs to a generation of granitoids not previously recognized in this area and is equivalent to the TIB 3 suite of Larson and Berglund (1).

The titanites can be divided into three types with distinctly different optical appearances.

Type I: reddish brown with few crystal surfaces. They are also more magnetic than the two other types.

Type II: pale yellowish brown with several crystal surfaces, sometimes euhedral crystals. They are usually transparent.

Type III: white, milky grains without any crystal surfaces.

In some of the deformation zones both types I and II were present.

Type III titanites occur in two low-grade deformation zones in the eastern part of the area. They are almost devoid of U and Pb and, therefore, useless for dating purposes. These zones are not discussed further.

Type I titanites occur in the undeformed granitoid as well as in three of the deformed samples. The titanite from the undeformed granitoid plot on the concordia at 1655±5 Ma. The type I titanites from two of the deformed samples plot concordantly at 1675 Ma and somewhat off the concordia line at around 1600 Ma. Analysis of the type II titanites is not yet complete but preliminary results indicate distinctly younger ages. These titanites are poor in U as well as Pb which, combined with a high common lead content, give a somewhat uncertain age determination.

It is concluded that the type I titanites are magmatic and are only mildly affected by the younger ductile deformation. Type II titanites, by contrast, are interpreted to have crystallized during a younger (Sveconorwegian) tectonometamorphic event.

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U-Pb dating of titanites from Southwest Sweden

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Whereas the U-Pb system in zircons often yields information on the age of crystallization of magmatic rocks, titanite is more susceptible to recrystallization during metamorphism and deformation but insensitive to lead loss during low-temperature leaching, thus often giving concordant U-Pb ages that date deformational events (cf. 1). From the Southwest Swedish Gneiss Province, only a limited number of U-Pb titanite datings are available so far, and these will be reviewed below. Although few, they may illustrate the potential of titanite in dating deformation, metamorphism and/or uplift of the different bedrock segments in Southwest Sweden.

The Gumlösa–Glimåkra gneissic granite in the Protogine Zone in northern Skåne, which has a zircon age of c. 1200–1230 Ma, yields a concordant U-Pb titanite age of c. 940 Ma, interpreted to date deformation and/or uplift along the Protogine Zone (2). Further north along the Protogine Zone at Alvesta, a gneissic granite with a zircon age of c. 1710 Ma contains discordant titanite with a $^{207}Pb/^{206}Pb$ age of 1580 Ma, suggesting only partial resetting of the U-Pb system in this titanite (2).

Titanite in garnet pseudomorphs in a mafic lens at Grässkär, in the Mylonite Zone north of Varberg, shows a slightly reverse discordance with model ages ranging from 917 to 933 Ma (3). This age is close to the Sm-Nd mineral ages obtained on mafic granulites in the Varberg region (4), and suggests that the Mylonite Zone was undergoing deformation, uplift and cooling while the rocks within the Eastern gneiss segment at Varberg were still at considerably higher temperatures. Titanite from an acid metavolcanite at Skårsjön close to Kungsbacka in the Western gneiss segment, having a zircon age of c. 1360 Ma, yields a concordant U-Pb age of c. 1040 Ma (Johansson, Ahlin and Welin, unpub. data). This age agrees with K-Ar cooling ages (5), suggesting earlier uplift and cooling of the Western relative to the Eastern gneiss segment.

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Imaging of fracture zones in the Finnsjön area using the seismic reflection method (poster)

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In 1987, the Swedish Nuclear Fuel and Waste Management Co. (SKB) funded the shooting of a 1.7 km long high resolution seismic profile over the Finnsjön study site. The site is located about 70 km north of Uppsala and the host rocks are mainly granodioritic. One of the objectives of the profile was to image a known fracture zone dipping gently to the west at depths of 100 to 400 m with high hydraulic conductivity. The initial processing of the data failed to image this fracture zone. However, a steeply-dipping reflector was imaged indicating that the field data were of adequate quality and the problem lay in the processing. These data have now been reprocessed and a clear image of the gently-dipping zone has been obtained. In addition, several other reflectors were imaged in the reprocessed section, both gently-dipping and steeply-dipping ones. It is likely that the origin of these reflections are also fracture zones. The main reason for failure of the initial processing was that geophone static corrections were not applied. Seismic wavelengths of the signal correspond to about 10 ms cycles (50 m) on the same order as the corrections applied using refraction statics in the reprocessed data.

Imaging of Proterozoic shear using pre-critical wide-angle data from the BABEL survey

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The BABEL survey of 1989 was an integrated deep-seismic study of the Baltic Shield, consisting of several deep-seismic reflection profiles and over 50 land stations recording wide-angle arrivals from the airgun shots. Four of these land stations were occupied by linear geophone arrays, with a potential for multi-fold coverage. These arrays recorded the shots over a variety of geometries, but always at offsets less than the critical distance for P-wave reflections from the Moho.

One such land station (station 702) was situated at an offset from the western end of line 7. This line imaged dipping reflectors within the mid-crust towards this western end which have been linked to on-shore outcrop of major Proterozoic ductile shear zones. Should the effects of strain on the petrology or petrofabric of the shear zone have caused it to become seismically reflective, then the station 702 should be in an ideal position to image this strain-induced reflectivity, and thus project the reflectors seen on line 7 further towards the surface. To this effect, I am using the data collected by station 702 to produce a structural model to test this hypothesis.

To constrain the model as much as possible, a field excursion to eastern Sweden was necessary to study the shear zone in situ. As well as geometrical and petrological data, many velocity measurements were made in the field, providing a large velocity database. These have been extrapolated to depth using high-pressure velocity measurements of key samples, and linked to previous strain analyses and existing geological and geophysical data to provide the best starting point for the construction of the model.

$^{40}Ar/^{39}Ar$ geochronology across the Mylonite Zone in western Halland and Bohuslän, southern Sweden (poster)

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The large crustal segment betwen the Mylonite Zone and the Protogine Zone in southern Sweden (the Southwestern Granulite Province, SGP) is characterized by numerous occurrences of granulite and upper amphibolite facies rocks including migmatitic gneisses, mafic granulites, garnet amphibolites and charnockites. PT-estimates of mafic granulites from the SGP range from 705°C and 8 kb at Hallandsås in the south to 770°C and 10.5 kb at Ullared in the north (1), corresponding to high-pressure granulite facies conditions. Four Sm-Nd mineral isochron dates from mafic granulites and one charnockite in this region have given Late Sveconorwegian ages of 880–920 Ma (1, 2). These ages have been interpreted to date the metamorphic conditions at or close to the metamorphic peak.

The southwest part of the Mylonite Zone (north of Varberg) marks a tectonic upper boundary of the SGP. The deformation along this zone clearly retrogrades granulite facies rocks into garnet-free, titanite-bearing, amphibolite-facies parageneses and therefore post-dates the Late Sveconorwegian granulite facies event. The migmatitic gneisses and amphibolites of the upper plate, above the Mylonite Zone, lack granulite facies parageneses and are dominated by garnet-free, epidote-titanite-bearing assemblages, with local garnet-bearing amphibolites. These assemblages correspond to epidote-amphibolite to middle amphibolite facies conditions. The MZ thus appears to represent an abrupt metamorphic boundary of Late Sveconorwegian age (3; C. Möller, in progress).

An $^{40}Ar/^{39}Ar$ study was initiated across the Mylonite Zone along a profile from Halmstad to Tjolöholm in order to constrain and compare the ages obtained from within the SGR with those obtained north of and within the Mylonite Zone. To date, 12 hornblendes have been analysed with the ages being interpreted as cooling ages through the 500°C closure temperature for hornblende. Four $^{40}Ar/^{39}Ar$ hornblende analyses from the upper plate (from Bua in the south to Tjolöholm in the north) yield good plateau ages of between 911±3 and 917±4 Ma,while two good plateau ages of 915±3 and 917±4 were obtained from within the Mylonite Zone (Grässkär north of Varberg). These ages confirm a Late Sveconorwegian cooling age for the Mylonite Zone. Three samples from the area between Steninge and Falkenberg within the west-central part of the SGP yield plateau ages of 931±3, 968±3 and 1007±3. Any interpretation of these ages is somewhat speculative until more data are obtained; however, the data obtained to date suggest that parts of the SGP may preserve records of an earlier Sveconorwegian history. Future work will include examination of the regional distribution and PTt-evolution of a possible older history within the SGP. These results are the first $^{40}Ar/^{39}Ar$ results from the MZ and clearly demonstrate the efficacy of this technique within the Proterozoic shear zones of Scandinavia.

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$^{40}Ar/^{39}Ar$ geochronology across the eastern part of the Sveconorwegian orogen from Karlskoga to Kristinehamn, south-central Sweden (poster)

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The presence of major ductile shear zones in the Proterozoic of south-central Sweden, related to crustal movements during the Sveconorwegian orogeny (c. 1200-900 Ma), has been known for a considerable time. Recent detailed structural studies have provided some constraints on the movement sense along these zones. This structural work has naturally inspired an urgent need for tighter constraints on the timing of deformation along these zones and, thereby, the uplift history in the neighbouring crustal segments. A pilot $^{40}Ar/^{39}Ar$ study to constrain timing of deformation and uplift history has been initiated across the eastern part of the Sveconorwegian orogen in the Karlskoga-Kristinehamn area. This segment of the orogen includes a deformation zone traditionally referred to as the "Protogine Zone". It has been demonstrated that the foliation related to the ductile shear deformation (< c. 1570 Ma) in this area dips moderately to steeply to the west in the eastern part, and fans through the vertical to dip moderately eastwards further to the west. The sense of movement remains more or less constant c. 40 km across the area with a predominantly dip-slip, top-to-the-east motion.

Four muscovites and three hornblendes were analyzed from the Karlskoga-Kristinehamn area. The muscovites and two of the hornblendes are oriented along the foliation which is related to the ductile shear deformation. The third hornblende is pargasitic in composition and has crystallized in a pegmatitic segregation which is concordant with the foliation. Hornblende and muscovite closure temperatures are interpreted to be ca 500° and 350°C, respectively. Three muscovites yielded plateau ages of 904±3, 918±3, and 930±3. The fourth (the easternmost sample) yielded a diffusive loss profile indicative of loss at less than 950 Ma. This age is significant since it demonstrates that Sveconorwegian deformation continues c. 40 km east of the so-called "Protogine Zone". One good hornblende plateau age was obtained yielding an age of c. 965 Ma (segregation sample). A second sample did not produce a plateau but yielded a disturbed spectra with ages between 960–985 Ma. The third hornblende yielded a saddle-shape spectra with a minima c. 1160 Ma. These results demonstrate the value of the $^{40}Ar/^{39}Ar$ technique within Proterozoic shear zones and within this area may indicate a late-Sveconorwegian overprint of an earlier Sveconorwegian story.

Sveconorwegian shear zones and mid-Proterozoic plate tectonics

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The movement history recorded by the ductile shear zones of the Swedish part of the Baltic Shield may be used to test plate-kinematic reconstruction of Baltica in relation to neighbouring continents during the Middle to Late Proterozoic. Evidence from the western shear zones in SW Sweden suggests that the 'main' Sveconorwegian collision at around 1050–1000 Ma involved at least two separate deformational events, each caused by oblique sinistral movements. It is suggested that Baltica may have collided initially with part of South America, then with N. Britain/E. Greenland, and subsequently moved in a sinistral strike-slip manner along the Laurentian continental margin between about 950 and 750 Ma. This model requires that SW Baltica rifted away from South America at c. 950–900 Ma and thereafter became a passive margin, whereupon tectonic activity moved to the western margin of Baltica (Western Norway) and eastern Laurentia (NW British Isles and east Greenland). Evidence for extensional movements of the Swedish shear-zone network associated with late Sveconorwegian thermal activity would lend support to the later part of this scenario.

Preliminary data from the Loftahammar Shear Zone, southeastern Sweden

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This study concerns a 10 km wide NW-SE dextral strike-slip shear zone along the southern boundary of the Svecokarelian Province, near Loftahammar. Zones of high ductile shear strain recur up to Valdemarsvik, composing a shear belt >25 km wide. Along strike the zone probably extends to the Protogine Zone (M.B. Stephens and C.-H. Wahlgren, pers.comm., 1992). The BABEL profile, W of Gotland island, appears to witness its southeastward continuation in the subsurface of the Baltic Sea.

The shear zone affected plutonic and supracrustal rocks. Variation of shear strain is best illustrated by the K-spar megacrystic Loftahammar augen gneisses and supracrustal xenoliths, mafic dikes and Na-metasomatized zones therein. Younger granite dikes, possibly related to the Transscandinavian Igneous Belt, are sheared as well. The Grundemar Gabbro Massif (GGM), intrusive into the Loftahammar granite, is only foliated along its margin. The rheological contrast between gabbro and surrounding felsic rocks created a megascale pressure fringe SE of the GGM. Shear foliations steeply dip NE (-80°). Mineral lineations (quartz ribbons, amphibole c-axes and extension direction of K-spar) plunge either NW (-25°), or (mostly) SE (-30°), indicating dominant 'southwest block up' sense of movement. Initial shear fold axes steeply plunge NW, but rotate on increasing shear strain. Initial ductile conditions evolved to brittle deformation of K-spar. Low-strain zones progressively grade from S–C into ECC-fabrics, shear folds and mylonitic fabrics on scales ranging from centimeters to hectometers. Another ductile (pure shear?) fabric is preserved in the Loftahammar granite in the pressure fringe of the GGM. Time relations between both fabrics will be discussed.

Metamorphic grade reaches up to amphibolite facies, e.g. local, syntectonic anatexis of intermediate metavolcanic rocks and growth of Ti-rich biotite along C-planes in augen gneiss. Under greenschist-facies conditions, a late, narrow zone (1 km) of brittle deformation affected the area. A zone of Na-U-metasomatism roughly coincides with ductile simple shear deformation, suggesting a genetic link.

Future work will include thermobarometry and precise age dating of the ductile deformation, inferred to be <1.84 Ga.

Mafic intrusions in the Småland Taberg area: evidence against significant strike-slip and folding along the Protogine Zone after 1.2 Ga (poster)

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Mafic, syenitic and granitic intrusions occur along the Protogine Zone (PZ), from the Baltic coast in the south to Lake Vättern in the north. At the southern end of Lake Vättern, a swarm of some 270 mafic bodies straddles the Skillingaryd–Taberg–Jönköping fault zone, with a concentration of larger bodies

(c. 160) around Småland Taberg. Mineralogical and microchemical criteria have been used to identify petrological properties in common for some of the larger bodies. Four bodies of the swarm have been dated by Sm-Nd and Rb-Sr methods; three bodies (Taberg, Bondstorp, Röshult) yielded ages around 1.18 Ga (1).

Several bodies have low-angle or subhorizontal chilled contacts towards the underlying granitoids and gneisses. At two localities, it is clear that the intrusions are remnants of sills; one remnant was possibly 300–400 m thick and at least 2 km wide. Rafts of anorthosite and igneous layering support structural indications that the numerous mafic bodies in the Småland Taberg area belonged to a former large sill-like intrusion, in which the Småland Taberg ore body is an olivine-titanomagnetite cumulate. Another potential evidence in support of a low-angle intrusion is the abundance of associated pegmatitic mobilizates of which some occur as net-veining or as flat sheets close to the granitoid footwall.

Several models for the evolution of the PZ assume large-scale strike-slip displacement along the zone, and relate the schistosity to regional-scale folding. Since the inferred Småland Taberg sill straddles several major PZ deformation zones, significant strike-slip displacement or folding along these zones after c. 1.2 Ga is unlikely.

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The tectonometamorphic history of a major shear zone in central Sweden – integrated geological-geophysical study

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This study focusses on a major shear zone (15–30 km wide, <200 km long) apparently separating two Proterozoic provinces in central Sweden. The aim is to define the extent, the kinematic evolution, the PT-conditions during periods of activity, the stress- and strain-history and the timing of the various phenomena along this zone. Integration of geological and geophysical data is the basis for the large-scale interpretation of the zone.

Four episodes of dominantly dextral strike slip movements are recognized in mylonites ranging from plastic, previously unknown *high*-magnetic varieties to cataclasites. Relative ages of the different episodes have been established with respect to known, regional events. Parameters of bulk strain and displacement for plastic mylonites (>10–20 km) have been determined. A significant metamorphic break, indicated by preliminary P–T data, may record the transpressive deformation indicated by estimates of stress orientations during brittle-plastic deformation. The shear zone and a previously unknown splay appear to control the geometry of the major, Svecofennian Ljusdal Batholith. A direct or indirect influence of the Caledonian evolution is strongly suggested by a compilation of published data.

Deformation zones in the Svecokarelian Province of Sweden as seen in 3-dimensions on deep seismic reflection profiles

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In the autumn of 1989, a cooperative experiment involving 12 research institutions in northwestern Europe collected 2268 km of deep seismic reflection profiles in the Gulf of Bothnia and the Baltic Sea to provide coincident refraction surveys, fan-spreads, and 3-D seismic reflection coverage of much of the Gulf of Bothnia. Nearby onshore outcrops allow us to make convincing correlations of prominent reflections on the seismic profiles with both dolerite intrusions and mylonitic shear zones. The common depth point (CDP) technique enhances subhorizontal reflectors and usually fails to image subvertical reflectors. Therefore, sills and subhorizontal shear zones are most often seen as prominent reflections on reflection profile sections.

The BABEL sections, particularly those near the Åland archipelago, also show moderately-dipping reflection bands that project to the surface onshore near shear zones 10–25 km wide. These reflections form an anastomosing pattern in 3-dimensions throughout the crust and locally into the uppermost mantle. Reflective zones are generally 1–2 km thick and spaced from 10–15 km apart. The reflective shear zones form non-reflective boudins or 'megalithons' approximately 10 x 30 to 15 x 60 km in cross section.

It is not yet possible to completely separate reflectivity observed on the BABEL sections that is caused by petrologic variations (mafic intrusions) from that attributable to deformation (mylonitization). These processes may be interlinked. Precise geobarometry and dating of intrusion and deformation, extrapolated from the surface to Moho depths, is critical if we are to gain further insights from the new information provided by the seismic reflection data. It appears that many regional ductile shear zones in Sweden are listric and cut the entire crust. Shear strain may be nearly equally partitioned between horizontal shortening and strike-slip deformation, and may include superimposed extensional deformation.

Oblique-slip, right-lateral ductile deformation zones in the Svecokarelian orogen, south-central Sweden

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A belt of WNW–ENE trending ductile deformation zones has been recognized in the Svecokarelian orogen of south-central Sweden. Key zones extend from Loftahammar to Linköping (see also Rieffe et al. this volume), from Norrköping to Åsbro, along Bråviken, and from Nyköping to Vingåker. This belt has a strike length of >100 km, from the Baltic Sea in the east to the frontal segment of the Sveconorwegian orogen in the west, and is at least 100 km in width. Individual deformation zones are several hundred metres up to at least 10 km wide. They formed under low- and medium-grade metamorphic conditions and are younger than a complex group of structures (D_1) which formed under higher-grade conditions. The latter are preserved in relic megalithons between the younger deformation zones (D_2) and are spectacularly rotated into these zones. This is evident on previously published geological and aeromagnetic maps. The D_2 zones strike at a relatively high angle with respect to the D_1 structures. Sparse time constraints limit the D_2 deformation to the period c. 1.84 to c. 1.53 Ga.

The D_2 protomylonitic to mylonitic foliation in the individual deformation zones is subvertical and the stretching lineation varies from more or less horizontal in the south (Loftahammar area) to an often moderate plunge to the southeast further north. Shear-sense indicators (composite planar fabrics, winged porphyroclasts, rotation of older D_1 structures) indicate an important right-lateral, horizontal component of shear. This is consistent with the regional-scale rotation of larger-scale D_1 structures. A variation in the sense of shear from predominantly right-lateral, horizontal motion in the south to oblique, right-lateral and reverse motion further north is apparent. These results establish a radically new interpretation for the regional structural framework of the Palaeoproterozoic rocks in this segment of the Svecokarelian orogen. They provoke a rejection of previous models involving either folding under pure-shear strain conditions or a major meteorite impact structure.

Counterflow boundary shears in power-law fluids (poster)

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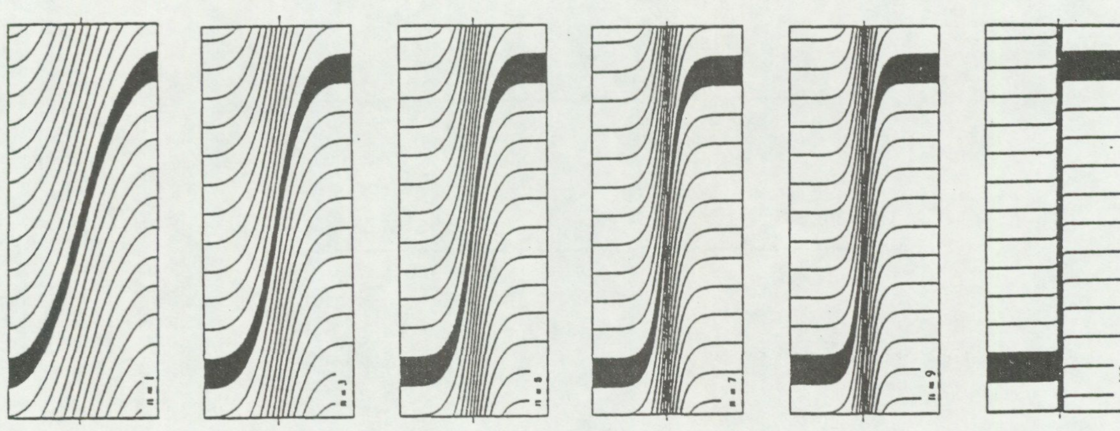
Individual faults and coupled flow folds are end members of a continuous spectrum of shears between bodies of power-law fluids that have flowed past each other. By fixing the kinematic reference frame in the single no-slip boundary between two counterflowing fluid masses, the displacements, δ, increase outwards as the shear strain, γ, and contemporaneous distortion, ε, decrease outwards in two back-to-back boundary shears. Profiles of the related variables δ, γ and ε depend solely on time (via velocity and displacement), the vector of relative displacement, and a material property, **n**, the power-law exponent of the shear stresses in each of the two counterflowing fluid masses. By assuming constant-volume heterogeneous biaxial shears in profile, the distortion of pre-existing passive planar markers depends solely on **n** of the two shearing masses.

Realistic geological shears can be forward modelled by assuming mutual retardation between adjoining masses of power-law fluids (1>**n**< c. 100) flowing in opposite directions. Similarly, backward modelling by simple graphical techniques allows constraint of **n** from profiles of geological examples of counterflow boundary shears. This is possible because profiles of δ are unique for each value of **n** whatever the width, maximum displacement and orientation of pre-existing passive markers.



Forward models of shear spectrum in rocks with constant **n**.

Mylonitisation and volume loss in the Singö gneiss zone, eastern Sweden

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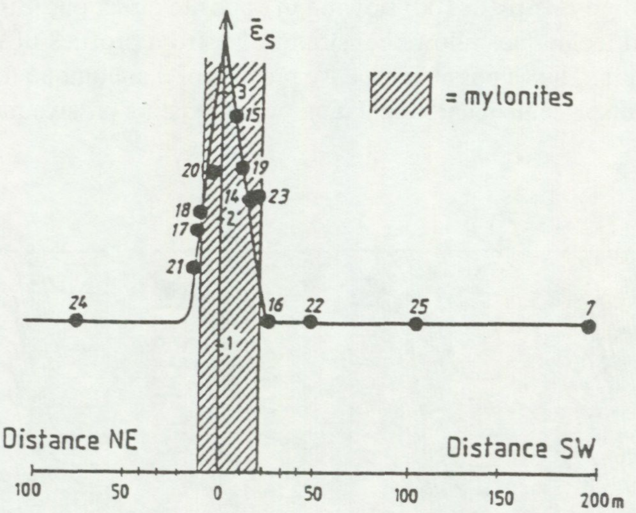
Mafic sheets are useful strain markers, not only when they have folded or necked as competent single layers, but also when they have mullioned or extended as incompetent layers. The orientation and degree of homogeneous bulk strain can be measured by constraining poles to the surface of no finite longitudinal strain. This is done by distinguishing attitudes in which contacts of mafic dykes are planar from those that are mullioned.

Structures on scales of a few decimetres in incompetent mafic enclaves, competent xenoliths, a swarm of incompetent mafic dykes, and competent veins within some of the dykes, are integrated to identify minimum strain ellipsoids (X>Y>Z) on scales of a few metres at 30 localities in a 3 x 3 km area near Östhammar in eastern Sweden. Homogeneous strains on locality scale are then used to analyse the inhomogeneous mylonitisation of Svecofennian granitoid and supracrustal gneisses in the WNW trending Singö shear zone. As far as we know, this is the first study to demonstrate that a particular deformation zone involved simple shear with uniaxial volume loss, and the first to quantify mylonitising strains.

The deformation of the enclaves and the Östhammar dyke swarm record two separable shears. Both imposed steep WNW trending XY foliations. The first foliation was gneissose and developed in a zone over 5 km wide. The second was confined to 30 m wide mylonites that anastomose in an on-land zone c. 300 m wide. Mylonitisation involved bulk plane strains in excess of natural logarithmic strains e_s=2.1. Deformation in both the gneisses and the mylonites involved syn-shearing uniaxial volumetric loss along Z of quartz and feldspar at c. 3% per 10% total shortening.



Early structural evolution of central Sweden as revealed on detailed relief maps

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A remote structural study of central Sweden (Hjo–Norrköping–Eskilstuna–Ludvika, an area of 32 500 km^2) based on 1:250 000 analogue relief maps (processed elevation data, grid 50*50 m) indicates a complex structural history in the transition zone between the southwest Swedish gneiss region (1.8–1.55 Ga) to the west, the Transscandinavian Igneous Belt (1.78–1.6 Ga) in the western and southwestern parts of the map area, and the Svecofennian rocks (2.0–1.78 Ga) in its eastern and northern parts. In the central and southern part of the area, the ground surface coincides with the sub-Cambrian peneplain, although distorted by faulting along the regional E–W trending Sörmland horst with local down-faulted remnants of Cambro-Silurian sedimentary rocks in its marginal areas. North of Vättern and Kilsbergen (the Hjo–Kilsbergen–Lindesberg shear zone), the ground surface is elevated and eroded, forming a hilly landscape and the detectibility of detailed information is obscured.

The tectonic signature regarding early structures differs remarkably from the eastern to the western part of the mapped area and the divide is the NNE-trending Hjo–Kilsbergen–Lindesberg shear zone, a regional structure transecting the NNW-trending boundary between the Svecofennian and Transscandinavian Igneous Belt. The eastern area expresses in its Svecofennian rocks early ductile deformation as refolding and formation of WNW-trending left-lateral shear zones associated with asymmetric folds (fold hinges may contain "post-kinematic" granites, e.g. the Graversfors granite, and the WNW-trending shear zones are often intruded by 1 530 Ma dolerite dykes, undeformed). The Hjo–Kilsbergen–Lindesberg shear zone is a more than 25 km wide zone of duplex shears ("piggy-back" riding) along the NNE prolongation of "the schistosity zone" and it is transected by N-S trending 900 Ma dolerites. The earliest type of structures detected in the western part of the area is a NNW-trending, winding foliation/banding, which is overprinted by strongly elongate NNW-trending shear lenses parallel to the Svecofennian boundary. Reactivation or partial reactivation of the early structures in a brittle mode is common.

The Mylonite Zone north of lake Vänern – a left-lateral transpressive deformation zone in the Sveconorwegian orogen, southwestern Sweden

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The Mylonite Zone (MZ) is a major, N-S trending, ductile deformation zone in the Sveconorwegian orogen, southwestern Sweden. It can be followed for over 400 km from the west coast of Sweden into Norway. The width often exceeds 5 km and, near the Norwegian border, it swells out into a combined duplex and imbricate structure approximately 25 km in width. Aeromagnetic maps indicate that the MZ possibly widens into several duplex and/or imbricate structures along its continuation into Norway before it disappears beneath the Caledonides.

The deformation in the MZ north of lake Vänern occurred under retrogressive, low- to medium-grade conditions at a minimum age of 904±13 Ma. The present study was concentrated along E–W profiles in three subareas from the Värmlandsnäs peninsula in the south, to the Norwegian border in the north. The planar and linear structures vary systematically across the MZ. The stretching lineation plunges subhorizontally to gently to the north on the subvertical to steeply dipping western boundary zone, and swings around consistently to plunge more down the dip of the shear foliation on the more shallowly- and westerly-dipping internal parts of the MZ. A similar structural variation is found across the duplex and imbricate structures, i. e. a subhorizontal to gently plunging lineation along the subvertical boundaries and a more down-dip lineation in the internal horses. Smaller duplex structures are responsible for the structural variations even southwards along the MZ.

Abundant shear-sense indicators (composite planar fabrics, tectonic lenses, winged porphyroclasts, asymmetrical folds, mica fish) consistently indicate a left-lateral strike slip motion along the subvertical boundaries and a top-to-the-east, reverse sense of movement on the west-dipping internal parts. Duplex-like structures along the eastern shore of Värmlandsnäs suggest the existence of an eastern, subvertical, strike-slip boundary. This is, however, overprinted by a younger brittle fault which defines the eastern shore-line of Värmlandsnäs.

The MZ is an orogen-parallel deformation zone, dominated by left-lateral, strike-slip motion with associated compressive duplex and imbricate structures, i. e. the MZ is formed in a transpressive tectonic régime. It may be the result of oblique-collisional (cf. the Caledonides of northeastern Greenland) or late-stage, lateral-escape tectonics (cf. the Himalayas).

The Hammarö (de-)formation

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In southern Värmland, on the northern shore of lake Vänern, the bedrock is involved in a large, steep, east-west-trending shear zone.

There have been suggestions that the bedrock in this region consists of metasupracrustal rocks (The Hammarö formation), involving both metavolcanic and metasedimentary rocks. Many of the outcrops are dominated by fine- to medium-grained, intensely banded rocks. The scale of the banding varies from mm upwards. The rocks outside the Hammarö shear zone are orthogneisses, dominantly reddish, medium-grained, and sometimes with migmatitic veins.

There are very instructive cross-sections to be found in the area, where a progressive increase in strain can be demonstrated. It is possible to walk from a characteristically foliated/lineated orthogneiss of the country rock, into intensely deformed central parts of the deformation zone, with intense lithological banding (metamorphic segregation?), three fold phases, dynamic recrystallisation and grain-size reduction. There is, thus, much evidence for extensive tectonic overprinting of any primary or pre-tectonic structures.

The shear zone actually consists of several individual shear zones, striking approximately east-west. The kinematic interpretation is not straightforward, but different relative movements between the crustal blocks south and north of the zone appear to have taken place. There was apparently a major component of strike slip involved. Approaching the zone from the north, older structures swing in to parallelism with the shear zone, preferentially indicating dextral movements.

The early deformation in the zone was in the upper amphibolite facies judging from the mineral parageneses, the abundant migmatitic leucosome, and the occurrence of parallel aplitic dykes. The strain was successively concentrated, and mylonitic shear zones developed. These latter zones are usually less than 100 m wide and commonly exhibit a lower grade of metamorphism. The entire zone is approximately 10 km wide.

The southernmost part of the Mylonite Zone, southern Sweden

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The eastern portion of the Sveconorwegian Province in SW Sweden and SE Norway is made up of crustal segments which are separated by major, N-S trending tectonic zones, e.g. the Mylonite Zone (MZ). The shear deformation that created these zones overprints older lithological and tectonic structures. The present boundaries of the tectonic segments are therefore not necessarily identical with original terrane boundaries.

Immediately south of Lake Vänern, the MZ is a steep, kilometre-wide zone of mylonite (J. Berglund, pers. comm., 1991). Further southward, it grades into a gently west-dipping zone of strongly lineated rocks, where only thin layers of mylonite have been developed. East of Göteborg, the MZ dips west and is about 3 km wide. Further south, the MZ breaks up into several branches forming a gently northwest-dipping system of shear zones extending to the coast in the Varberg region. Much of the strain appears here to have been taken up by the adjoining gneiss complex rather than by major high-strain zones. Minor shear zones, up to 80 m thick, are, however, present.

Along its c. 200 km long course south of Lake Vänern, the west-dipping MZ is characterised by a west- or WNW-dipping lineation, a dip-slip structure. In the extreme south, however, where the southernmost branches of the MZ system turn westward, the shear zones are instead characterised by mainly strike-slip deformation.

Studies of the MZ kinematics have suggested eastward or southeastward thrusting (1, 2). Since the 1.38 Ga old Torpa granite (3) has been affected by the deformation that characterises the MZ, i.e. the west-dipping lineation, this deformation must be younger than the granite and most probably is Sveconorwegian in age.

East of Göteborg, the MZ is well-defined and coincides with the boundary betwen the comparatively weakly migmatised lithologies of the c. 1.6 Ga Åmål–Horred Belt and the more intensely migmatised gneisses in the Eastern Segment. In the Varberg region, no such distinct metamorphic discontinuity occurs, but the basement gneisses are gradually more migmatised toward the southeast. This southeastern increase occurs in a stepwise fashion and some of these steps coincide with branches of the MZ. It is still, however, unclear whether this stepwise increase in the migmatisation reflects a Sveconorwegian feature associated with deformation along the MZ, or is mainly pre-Sveconorwegian in origin.

The field relationships between the 1.38 Ga Torpa granite intrusion, the basement gneisses and the MZ clarify that the most marked deformation in the region is not due to the MZ deformation, but related to the penetrative gneissose banding in the Eastern Segment gneisses, and that this deformation must have occurred before 1.38 Ga.

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EXCURSION GUIDE

Style, geometry and kinematics of Sveconorwegian ductile deformation zones in the Karlskoga–Kristinehamn area, south-central Sweden

M.B. Stephens and C.-H. Wahlgren

INTRODUCTION

The Karlskoga–Kristinehamn area is situated in the eastern, frontal part of the Sveconorwegian orogen. Between the Kilsbergen Fault Zone in the easternmost part of the area and the town of Karlskoga (Fig. 1), the bedrock is variable in character. Svecofennian metasupracrustal rocks and a variety of gabbroic to granitic intrusions comprise the oldest suite of rocks, c. 1890 to 1850 Ma in age (Welin 1992). All these rocks have been affected by Svecokarelian deformation and two petrographically distinctive suites of younger intrusions are conspicuous (Fig. 1). These include equigranular to porphyritic granites and pegmatites which are often spatially associated with migmatitic rocks, and porphyritic quartz monzonites to granites belonging to the Transscandinavian Igneous Belt (TIB). These intrusions as well as younger dolerite dykes are affected by discrete ductile shear zones, inferred to be Sveconorwegian in age, which are variable in strike and dip. Regionally, there are two principle sets striking NNW–SSE and NE–SW. The latter display an oblique sense of shear with both a reverse and an often right-lateral, horizontal component of movement.

North and west of Karlskoga, the bedrock is much more homogeneous and is dominated by various types of intrusions belonging to the TIB which ranges in age from c. 1810–1650 Ma (Larson and Berglund 1992). The eastern part of the TIB, in the area around Karlskoga, is affected by several, spaced ductile deformation zones which show a predominantly dip-slip, top-to-the-east sense of shear. Movement along such zones occurred under low-grade metamorphic conditions and is associated with the development of a conspicuous planar grain-shape fabric and a stretching lineation. Younger deformation zones with a right-lateral horizontal component of shear are also present and account for the marked change in strike of the tectonic foliation from NNW–SSE to NNE–SSW in this area. The majority of ductile deformation zones dip to the west and the dominant dip-slip component is, thus, reverse in character (Fig. 2).

Further west towards Kristinehamn, progressively deeper crustal levels are exposed. In connection with the traverse to deeper crustal segments, the deformation zones become thicker, the grade of syn-deformational metamorphism increases and the deformation zones form a fan-like structure in which steep, westerly dips pass westwards through the vertical into steep to moderate easterly dips (Fig. 2). There remains, however, a consistent, predominantly dip-slip, top-to-the-east sense of shear along the deformation zones across the fan-like structure. These zones thus change in character from reverse to normal from east to west. $^{40}Ar/^{39}Ar$ plateau ages for syn-deformational white mica in rocks around and west of Karlskoga are c. 920 Ma (Page et al. this volume).

The deepest crustal levels in the excursion area are encountered in western areas, around Kristinehamn (Fig. 2). Here, the TIB rocks are affected by a more or less penetrative deformation, medium-grade metamorphism, and conspicuous post-foliation folding the asymmetry of which is again consistent with a top-to-the-east sense of shear. An $^{40}Ar/^{39}Ar$ hornblende plateau age of c. 965 Ma has been obtained in a syn-deformational pegmatite segregation. These meta-TIB rocks are marked as red orthogneisses on virtually all previous regional compilations and the eastern boundary of these gneisses is traditionally considered to be the eastern limit of Sveconorwegian deformation. In the present interpretation, this boundary, referred to as the "Protogine Zone" in several regional compilations, merely marks the changeover from a spaced to a more penetrative crustal reworking during the Sveconorwegian orogeny. This new interpretation has far-reaching implications for the regional structure in the eastern part of the Sveconorwegian orogen north of the lake Vättern.

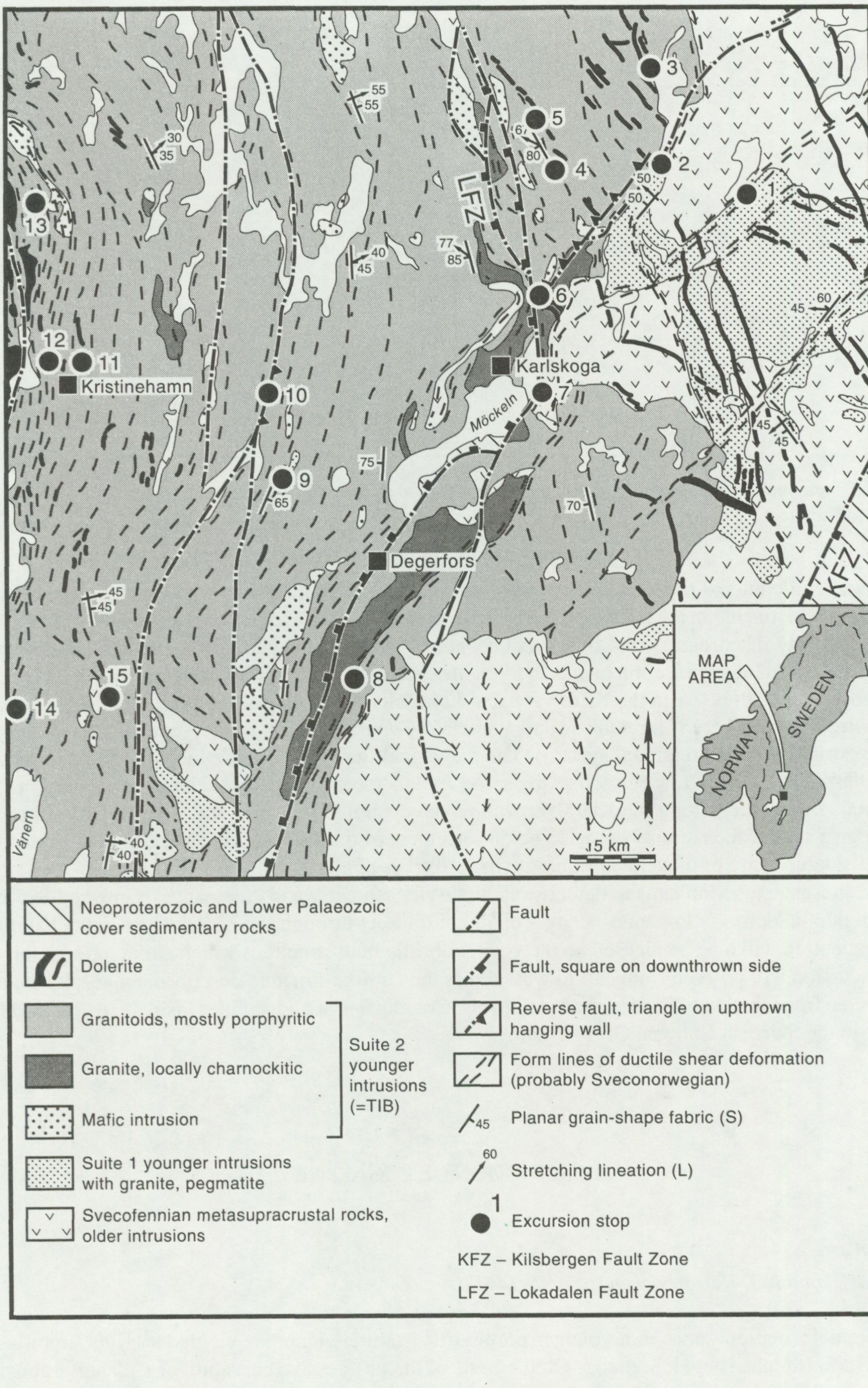

Fig. 1. Geological map of the Karlskoga–Kristinehamn area with excursion stops.

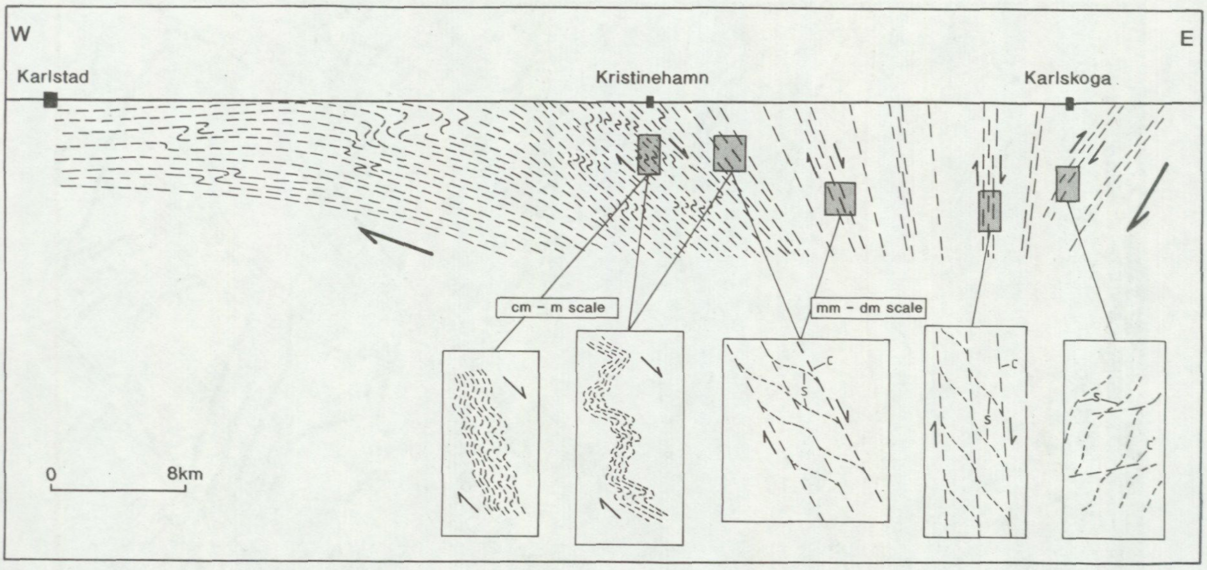

Fig. 2. Schematic structural section across the eastern frontal segment of the Sveconorwegian orogen, from Karlskoga to Karlstad.

Phanerozoic and/or possibly even Neoproterozoic brittle faults are the youngest structures in the Karlskoga-Kristinehamn area. These usually strike parallel to the older ductile deformation zones. However, markedly discordant strike relations between older and younger structures and distinctive dips along the brittle and ductile components in the same deformation zone have been documented in the area. The crustal segment between the Kilsbergen and Lokadalen Fault Zones (Fig. 1) forms the core of a major uplifted block. There still remains some uncertainty whether this is a horst (extensional system) or a pop-up structure (compressional system). The major fault just west of Kristinehamn (Fig. 1), which is also referred to as the "Protogine Zone" by some authors (see, for example, Henkel and Erikson 1987), continues northwards along the Klarälven valley and eventually disturbs the Caledonian Front on the Norwegian side of the national border. The displacement of this Caledonian structure is consistent with an east-side-up sense of movement similar to the Lokadalen Fault Zone.

The present excursion aims to demonstrate the style, geometry and kinematics of inferred Sveconorwegian ductile deformation zones along a c. 40 km transect through the Karlskoga-Kristinehamn area. Some attention will also be focused on the younger brittle fault structures which strike through this area. The excursion will proceed from east to west across the fan-like structure described above, and essentially traverse from shallower to deeper crustal levels. Coordinates at all localities visited are given with reference to the Swedish National Grid System.

DESCRIPTION OF LOCALITIES

Locality 1

10E Karlskoga NO, Kejsarbacken (658879/144210)

Discrete deformation zones in a younger porphyritic granite which has yielded a U-Pb zircon age of 1807±5 Ma (Stephens et al. in prep.). On the basis of the progressive curvature of a planar grain-shape fabric into the mylonitic shear surface, a top-to-the-west, reverse dip-slip component of movement has been inferred on shear surfaces which strike NE–SW and dip to the southeast.

The style of deformation at this locality is representative of the discrete ductile deformation zones which transect the Svecofennian metasupracrustal rocks and younger intrusions in the area between the Kilsbergen Fault Zone and Karlskoga (Fig. 1). Since these zones also deform dolerite dykes inferred to be c. 1.56–1.51 (WNW-ENE strike) and 1.00–0.91 (NNW–SSE strike) Ga in age, it is concluded that they are late Sveconorwegian. A complex array of shear zones anastomosing around km-scale, tectonic lenses summarizes the style of inferred Sveconorwegian deformation in this easternmost, frontal part of the orogen.

The following localities (2–8) aim to demonstrate the deformation in the eastern part of the fan-like structure in the Karlskoga-Kristinehamn area (Fig. 2).

Locality 2
10E Karlskoga NO, Älvsnabben (658980/143748)

Ductile deformation zone in a coarsely porphyritic granite with relics of metasupracrustal material. This zone strikes NE–SW, more or less parallel to that observed at locality 1, and dips moderately to the northwest. The mylonitic foliation contains a stretching lineation which plunges more or less down the dip of the foliation. The mylonitic foliation is folded and a new axial surface crenulation cleavage, more or less parallel with the shear zone boundaries, is developed. These folds plunge down the dip of the mylonitic foliation parallel to the stretching lineation. $^{40}Ar/^{39}Ar$ analysis of white micas from this deformation zone yielded a disturbed spectrum with loss of Ar at less than 950 Ma (Page et al. this volume). On a regional scale, the planar grain-shape fabric associated with deformation zones in the TIB rocks to the northwest is rotated into the younger shear zone at this locality suggesting a right-lateral, horizontal component of movement.

Locality 3
10E Karlskoga NO, Tväråhlund (659624/143714 to 659612/143680)

(a) Coarsely porphyritic granitoid with mantled feldspar phenocrysts belonging to the younger suite of intrusions referred to as TIB. The outcrops along the road here show evidence for magma mingling relations with mafic rocks. This granitoid is petrographically identical to the so-called "Filipstad granite" dated by the U-Pb zircon technique to 1783±10 Ma (Jarl and Johansson 1988).

(b) Same granitoid affected by ductile deformation zone which strikes NNW–SSE and dips steeply westwards. This is the fabric which is rotated into the younger deformation zone at locality 2.

(c) Younger, cross-cutting brittle deformation zone along topographic lineament (NNE–SSW to N–S). Partly shows a random structure with porphyroclasts of K-feldspar enclosed in an epidote-rich matrix; grain-shape fabric lacking. Partly shows a thin zone with extreme grain-size reduction (ultramylonite) and foliation/lineation development (XY surface visible). The lineation plunges steeply northwards. On the basis of the lineation orientation and the weak composite planar fabric here, there appears to be a predominantly dip-slip, top-to-the-west, reverse sense of motion.

Locality 4
10E Karlskoga NO, Lersjötorp (658996/143184)

Intense deformation (CS composite planar fabric, stretching lineation plunging steeply westwards) in coarsely porphyritic TIB granitoid. View of steep XZ section shows CS fabric which allows us to determine sense of movement (top-to-the east and reverse).

This is a relatively common structure observed in the porphyritic granitoid north of Karlskoga and virtually 100% of the kinematic determinations indicate a predominantly dip-slip, top-to-the-east, reverse sense of movement.

Locality 5
10E Karlskoga NO, Lomtjärnen (659310/143082)

Discrete, ductile deformation zones in coarsely porphyritic TIB granitoid striking N–S to NNW–SSE with mylonite to ultramylonite development up to 20 cm thick. The stretching lineation plunges steeply to the NW and the sense of movement, based on deflection of a planar grain-shape fabric established during the shearing, is top-to-the-west.

Discrete, ductile deformation zones either similar to the ones observed here or demonstrably younger than the planar grain-shape fabric (i.e. comparable to the deformation zone at locality 2) are more or less restricted to the eastern part of the fan-like structure recognized in the Karlskoga-Kristinehamn area. They display a variable sense of movement but are nevertheless considered to be broadly related to the deformational event which produced the grain-shape fabric in the TIB granitoids.

Locality 6
10E Karlskoga NO, Karåsforsen (658384/143110)

Medium-grained and predominantly equigranular TIB granite is here reduced to a protomylonite to mylonite and then subsequently deformed by a brittle deformation zone striking NE–SW and dipping to the northwest along the northwestern side of the Svartälven river. This granite is locally charnockitic in composition and has been dated to 1796±7 Ma using the U-Pb zircon technique (Stephens et al. in prep.). The mylonitic foliation trends NNE–SSW to NE–SW and dips steeply to the west. It contains a strong down-dip stretching lineation. Fragments of mylonite are enclosed in a crush breccia related to the younger brittle deformation. Slickensides associated with the brittle faulting plunge relatively steeply and the sense of movement is top-to-the-east and reverse.

The Svartälven Fault Zone forms the eastern boundary of a subordinate uplift structure, the western limit of which is the important Lokadalen Fault Zone (Fig. 1). The latter downfaults Neoproterozoic Visingsö sandstone on its western side, south of Karlskoga. This uplift structure is suggested to be the core of a regionally more important zone of uplifted crust bounded to the east and to the west by the Kilsbergen and Lokadalen Fault Zones, respectively (see Fig. 1). The age and tectonic setting (extensional or compressional) of this relatively young uplift is uncertain.

Locality 7
10E Karlskoga NO, Immetorp (657826/143108)

A massive garnet-cordierite fels is retrograded to a phyllonite some 200 m thick. A more or less perfect down-dip stretching lineation can locally be seen. The well-exposed XZ sections display a C'S composite planar fabric indicating a top-to-the-east and reverse sense of motion. The phyllonite lies in the same NE–SW-trending complex zone of deformation as localities 1, 2, 6 and 8. White micas from the phyllonite foliation provide an $^{40}Ar/^{39}Ar$ plateau age of 918±3 Ma (Page et al. this volume).

Locality 8
10E Karlskoga SV, Korpkärret (656140/142050)

Subvertical to vertical ductile deformation zone along the contact zone between a porphyritic and an equigranular, locally charnockitic TIB granitoid (same lithology as at locality 6). C´CS and CS fabric indicate "west-side-up" motion. Note the pronounced strain increase towards the contact, which is well illustrated by the increasing elongation of mafic enclaves in the porphyritic granitoid. This shear zone can be followed along the contact between these two TIB lithologies for c. 20 km.

Locality 9
10E Karlskoga SV, Lilla Vismen (657240/141600)

Steeply east-dipping ductile deformation zone in a porphyritic TIB granitoid in the spaced to semi-penetratively deformed western central part of the fan-like structure. The mineral stretching lineation plunges steeply to the northeast and neocrystallized white mica in the c planes indicates relatively low-grade conditions. Kinematic indicators display a top-to-the-east, normal sense of shear. $^{40}Ar/^{39}Ar$ dating of white mica from this deformation zone yielded a 930±3 Ma plateau age (Page et al. this volume).

Locality 10
10E Karlskoga NV, Bodalen (657785/141555)

Roadcut on the E18 highway showing relations between older ductile and younger brittle deformation. The latter forms part of a major N–S to NNE–SSW trending regional fault system (c.f. Lokadalen Fault Zone). Deflection of the older ductile shear foliation into the steeply east-dipping fault surfaces indicates top-to-the-west, i. e. reverse sense of movement along the brittle fault.

Locality 11
10E Karlskoga NV, Kristinehamn (658015/1404550)

Small outcrop of strongly deformed quartz-monzonitic TIB granitoid in the western part of the fan-like structure. A well-developed CS fabric indicates top-to-the-east, normal sense of movement along the east-dipping shear planes. The stretching lineation plunges steeply to the northeast.

Locality 12
10E Karlskoga NV, Kristineham (658005/140295)

Roadcut on the E18 highway in the transition zone between semi-penetrative and penetrative, east-dipping ductile shear deformation in the western part of the fan-like structure. The outcrop shows a strongly deformed quartz-monzonitic TIB granitoid. Note the pronounced strain increase from east to west in the outcrop. In the more highly deformed western part, strong z-asymmetric folding of the shear foliation can be seen. The vergence of the folds is consistent with a top-to-the-east, normal sense of movement, which is in agreement with other kinematic indicators elsewhere in the area. This vergence is very consistent throughout the western part of the fan-like structure.

The outcrop is delimited in the west by a younger brittle fault, along which the boundary between the so-called "Sveconorwegian Province" and the TIB rocks is traditionally drawn on regional compilations. Thus, the outcrop is situated exactly on the classical "Protogine Zone". The latter merely separates semi-penetratively, low- to medium grade and penetratively medium-grade deformed rocks in the western part of the fan-like structure.

Locality 13
10E Karlskoga NV, Juntern (658925/140220)

The outcrops are composed of a porphyritic granitoid and a subordinate equigranular, leucocratic granite and a larger sheet-like body of diorite to quartz diorite. These rocks occur in the penetratively deformed, medium-grade, western part of the fan-like structure. These rocks are traditionally classified as unspecified orthogneisses in the Sveconorwegian orogen. However, field relationships strongly suggest that they constitute strongly reworked TIB rocks.

The foliation is strongly crenulated with a tendency for the development of an almost horizontal spaced axial surface cleavage in an inferred hinge zone of a larger-scale, asymmetric fold.

Locality 14
10E Karlskoga SV, Lilla Edsvattnet (655945/140035)

Roadcut in strongly deformed quartz-monzonitic TIB granitoid in the semi-penetratively deformed, east-dipping, western part of the fan-like structure. The upper part of the outcrop displays a well-developed CS fabric which indicates a top-to-the-east, normal movement along relatively gently-dipping shear surfaces. Note the pronounced strain increase from the top to the bottom of the roadcut.

Locality 15
10E Karlskoga SV, Fågelsången (656075/140605)

Dolerite which belongs to the numerous c. 1500 Ma old, so-called "hyperites"" further to the west in the Sveconorwegian orogen. It is deformed in the contact zone to the surrounding TIB granitoid where small garnets can be observed. The dolerites usually exhibit a very inhomogeneous alteration pattern and all stages between completely fresh dolerite and garnet amphibolite can be found. An increasing idiomorphy of the garnets with increasing deformation is commonly observed, suggesting a strain-induced growth.

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