SVERIGES GEOLOGISKA UNDERSÖKNING

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ALAN CRANE AND STEPHEN DALY

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CONTENTS

ABSTRACT

G. Park, K.-I. Åhäll, A. Crane and S. Daly: The structure and kinematic evolution of the Lysekil-Marstrand area, Östfold-Marstrand belt, southwestern Sweden. Sveriges geologiska undersökning, Ser C No. 816, pp. 1–12. Uppsala 1987.

The Lysekil-Marstrand area is a 2000 km^2 coastal sector of the southern Östfold-Marstrand belt. It is dominated by Proterozoic supracrustal gneisses of the Stora Le–Marstrand formation consisting of semipelitic to psammitic metasediments and contemporaneous volcanics. These are cut by several generations of igneous intrusions divided into four suites – A, B, C and D, separated by deformational episodes.

The emplacement of the A-group granitoid plutons was followed by the first deformation D1, and by regional metamorphism. The later B-group intrusions include major quartz-diorite to granite sheets, augen-granites and amphibolite emplaced between 1700 and 1510 Ma. These bodies become more prominent in the eastern part of the area. Their emplacement is followed by the D2 deformation which is accompanied by amphibolite-facies regional metamorphism and by extensive migmatisation, particularly evident in the west, where the metasediments are transformed into a granite vein complex. The intense D2 deformation has produced widespread transposition of all previous structures into a composite gneissose banding (S2) which is the dominant small-scale structure seen in the area; nearly all the mappable structures post-date S2.

The D2 structures are cut by the group C intrusions dated at 1510–1220 Ma. These include the Orust dyke suite (mainly mafic) and also widespread minor sheets of granodiorite, granite, and metagabbro, and by larger bodies of augen granite.

The first deformation (D3) to affect the C-group intrusions is accompanied by amphibolite-facies metamorphism dated at about 1090 Ma and is considered to be the first Sveconorwegian event in the area. The C-group intrusions may thus be used to separate Sveconorwegian from earlier events. The most important D3 structures are sets of shear zones of which the largest are NE–SW with a dextral strike-slip sense of movement. The D4 deformation formed widespread major and minor folds with gently to moderately inclined axial planes and a characteristic crenulation cleavage in micaceous layers. In the most intensely deformed belts, L4 elongation lineations trend NE–SW. The D5 structures include a variety of localised minor structures (crenulation cleavages, minor shear zones etc.) and large-scale open folds. The most intensely deformed belts imply NW–SE to N–S movements.

The kinematic evolution of the area is interpreted in terms of a major D2 E-dipping shear zone followed, in Sveconorwegian times, by movements on a major sub-horizontal shear zone with a N–S to NE–SW trending ramp in the east, along the Göta Älv, the earlier movements (D3–4) being northeastwards and the later (D5) southeastwards.

INTRODUCTION

In this paper, we present a structural analysis of part of the southern Östfold–Marstrand belt which makes up a coastal part of the Sveconorwegian Province in southwestern Sweden (Fig. 1). The belt is dominated by Proterozoic supracrustal gneisses (the Stora Le–Marstrand formation) which are cut by several generations of igneous intrusions. Its eastern boundary is arbitrary and occurs where intrusive orthogneisses become dominant over the supracrustal gneisses.

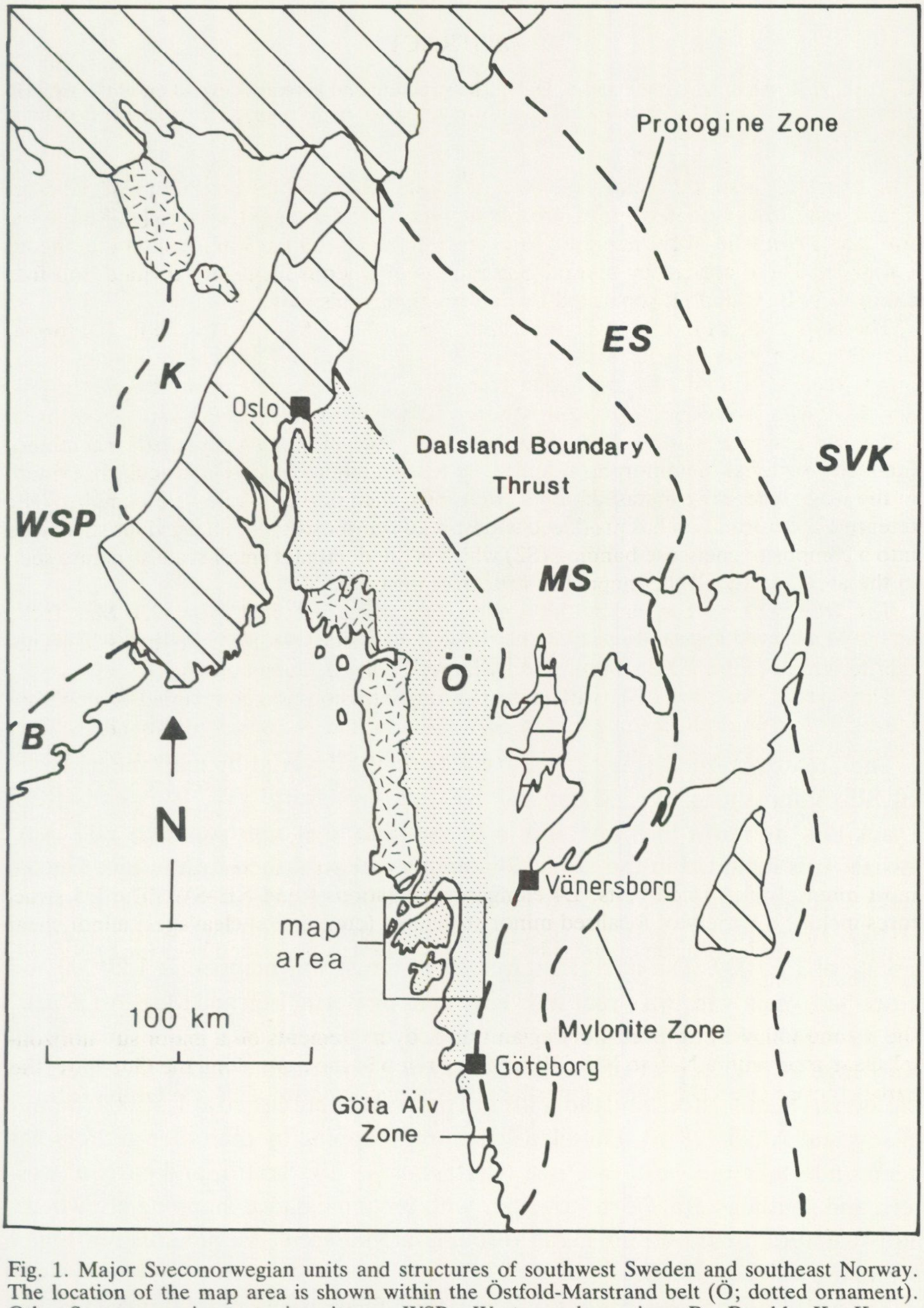


Fig. 1. Major Sveconorwegian units and structures of southwest Sweden and southeast Norway. The location of the map area is shown within the Östfold-Marstrand belt (Ö; dotted ornament). Other Sveconorwegian tectonic units are: WSP – Western sub-province, B – Bamble, K – Kongsberg, MS – Median segment, ES – Eastern segment, SVK – Sveco-Karelian; Dal formation – horizontal ruled ornament; late Sveconorwegian granites – hachured ornament ; post-Sveconorwegian rocks – ruled ornament. Units named mainly after Berthelsen (1980).

Fig. 3. Well banded migmatitic gneisses consisting of metasediments, dark sheets of amphibolite and subparallel granite dykes. West of Skärhamn, Tjörn.

The area concerned (Fig. 2, see back cover) is covered by map-sheets Lysekil SE, Vänersborg SW, Marstrand NE and Göteborg NW. It extends from Lysekil in the north to Marstrand in the south and is approximately 2000 km^2 in size. It is included in the Uddevalla map-sheet published by Sveriges Geologiska Undersökning (SGU) on a scale of 1:100 000 and described by Lindström (1902). Bergström (1963) has described the petrology of Tjörn with a map on a scale of 1:50 000. The northeastern part of Orust was mapped at 1:20 000 and described, mainly from a structural viewpoint, by Berthelsen and Murthy (1970).

The area has been completely re-mapped on a scale of 1:10 000, mainly by Karl Inge Åhäll, as part of the SGU mapping programme under the direction of Lennart Samuelsson, and the southern part is now published at 1:50 000 (Samuelsson and Åhäll 1985a). Detailed structural mapping by the other authors has been undertaken in western Orust (Park *et.al.* 1979), Skaftö, and parts of western and southeastern Tjörn, together with reconnaissance mapping elsewhere, and structural observations made throughout the area. All pictures but Fig. 7 are taken by K.I. Åhäll.

The rocks of the area consist of semipelitic to psammitic metasediments and contemporaneous mafic volcanics of the Stora Le–Marstrand formation (Lundqvist 1979) together with a large number of intrusive bodies of various ages and compositions (Fig. 3). The larger bodies are predominantly granitic to quartz

TABLE 1. Simplified chronology of the Lysekil-Marstrand area.

Rocks and Structures	Metamorphism	Age Ma
Deposition of Stora Le-Marstrand sediments and emplacement of contemporaneous volcanics		?1700
Emplacement of group A intrusions (mainly granitoid)		
D1 deformation	M1 amphibolite-facies with (weak?) migmatitic veining	
Emplacement of group B intrusions (mainly granitoid)		1650
D2 deformation	M2 amphibolite-facies with intense regional migmatitic veining	
Emplacement of group C intrusions (bimodal)		1510 -1220
SVECONORWEGIAN: D3 deformation	M3 amphibolite-facies	1090
SVECONORWEGIAN: D4 deformation	probably lower grade, and locally retrogressive	
SVECONORWEGIAN: D5 deformation		
Emplacement of group D intrusions Bohus granite		890

dioritic and the smaller include dykes of mafic to intermediate composition and sheets and veins of granite and pegmatite.

Most of the western part of the area (Fig. 2 in back cover; Fig. 4A) consists of metasedimentary gneisses and migmatites. A zone along the eastern side of the map consists largely of plutonic rocks, mainly granodiorites, which are interbanded with metasedimentary gneisses. The plutonic sheets become thinner and less numerous towards the west. A central plutonic belt consisting of three large augen granite sheets, together with many smaller intrusive bodies of various types, extends in a NE–SW direction across the central part of the map through Tjörn and eastern Orust.

The geological history of the area (Table 1) was recently summarised by Samuelsson and Åhäll (1985b). The Stora Le–Marstrand supracrustal rocks were laid

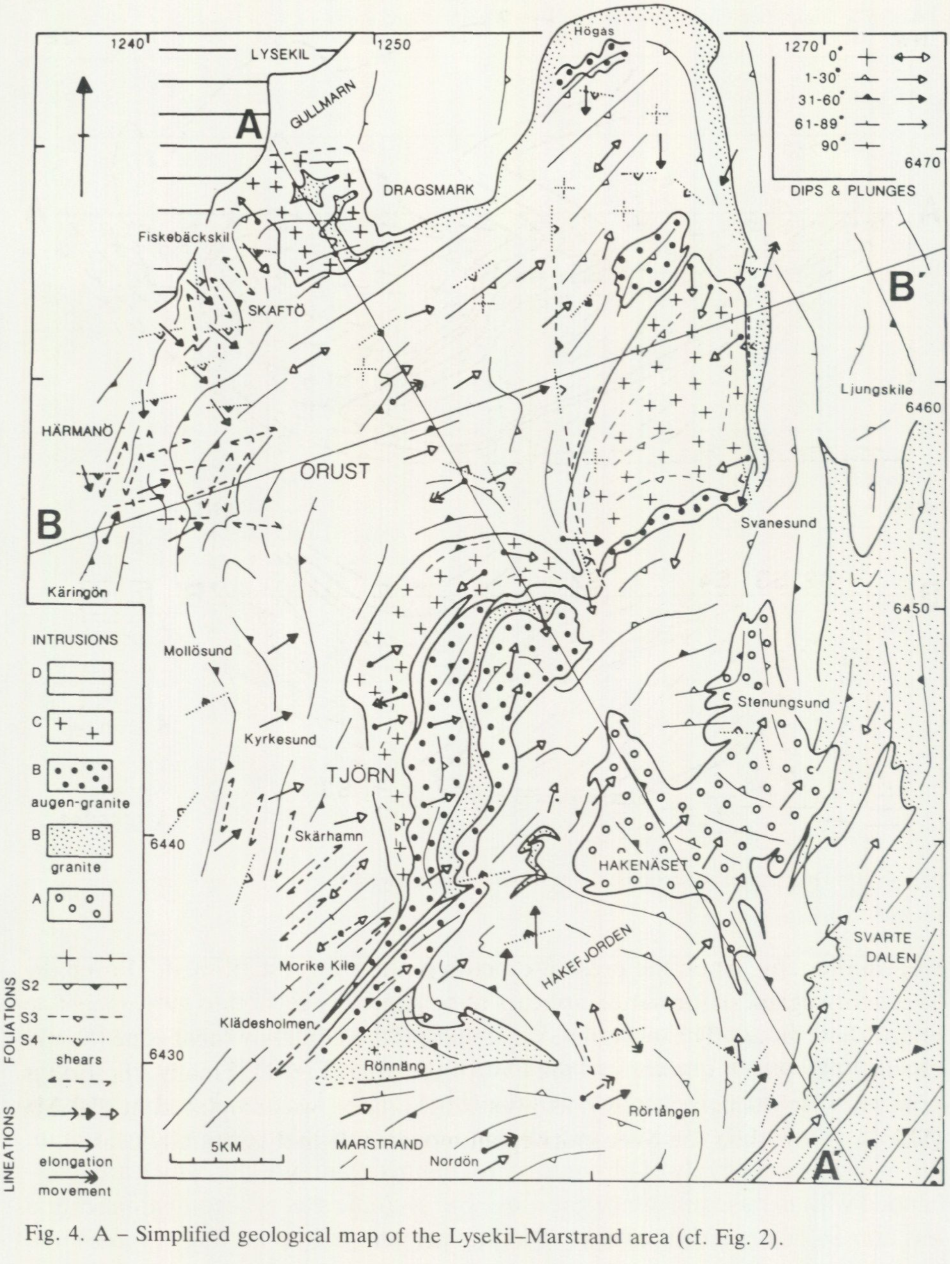


Fig. 4. A – Simplified geological map of the Lysekil–Marstrand area (cf. Fig. 2).

down before 1.7 Ga and the major regional gneiss-forming events were essentially completed by c. 1.5 Ga. Thereafter an important episode of bimodal magma emplacement (Åhäll and Daly 1985) occurred, possibly associated with cratonic rifting; it was followed by deformation and metamorphism during the Sveconor-

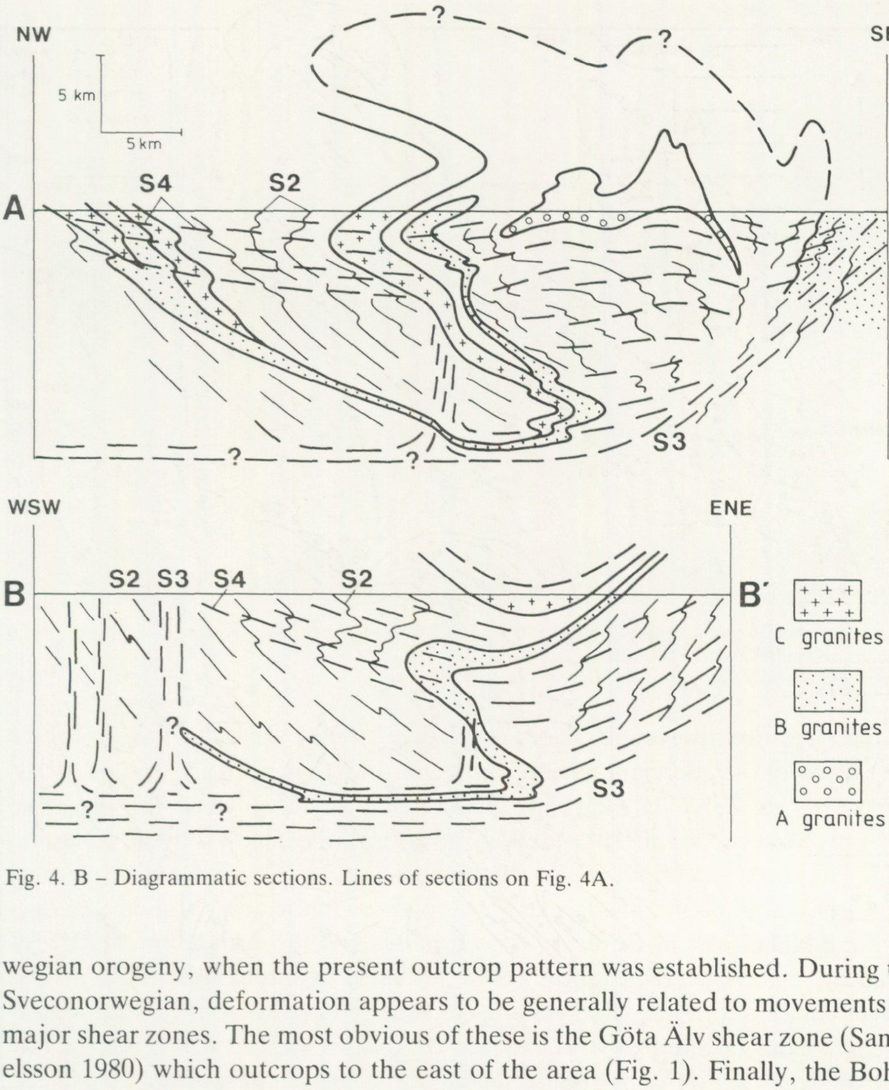


Fig. 4. B – Diagrammatic sections. Lines of sections on Fig. 4A.

wegian orogeny, when the present outcrop pattern was established. During the Sveconorwegian, deformation appears to be generally related to movements on major shear zones. The most obvious of these is the Göta Älv shear zone (Samuelsson 1980) which outcrops to the east of the area (Fig. 1). Finally, the Bohus granite, which occurs in the northwest of the area, was emplaced at 890 Ma (Skiöld 1976) when the Sveconorwegian movements had essentially ceased.

STRUCTURAL CHRONOLOGY

The structure of the area is extremely complex, produced by several superimposed deformations of a heterogeneous and variable nature. The outcrop pattern and form-line geometry (Fig. 4A–B) indicate interference patterns which cannot be simply interpreted from the map alone but can only be understood by unravelling the sequence of minor structures at outcrop scale and determin-

Fig. 5. Isoclinal F1 fold refolded by upright F2 folds in metagreywacke. Knife (in F2 plane) is 20 cm long. Härmanö, western Orust.

ing their relationship to the major structures. A key factor in this process is the division of the abundant igneous intrusions into four main age groups (A, B, C and D – see Table 1) each separated by deformations which can therefore be dated relative to them. The oldest (A-group) granites share with the metasediments the first recognisable deformation, D1 (Fig. 5). Only two (possibly connected) large bodies of this age are recognised in the area, around Stenungsund and Hakefjorden. Both the early granites and the metasediments are affected by regional metamorphism (M1), probably in amphibolite facies and an associated quartzo-feldspathic veining (or weakly developed migmatisation).

S1 and the M1 veining are cut by the B-group intrusions which incorporate the major quartz-diorite to granite sheets of the eastern part of the map-sheet, including the important Rönnäng body (dated at c. 1670 Ma – Welin *et al.* 1982), and the older augen granites of the central Tjörn plutonic belt. Similar but smaller augen granite bodies occur in Dragsmark and probably in eastern Orust. A thin granitic to granodioritic sheet which occurs between the two augen granites in Tjörn can be followed almost continuously to Dragsmark and traces out a major fold structure (Fig. 4A). The emplacement of the B-group intrusions is followed by (or is possibly partly co-eval with) amphibolite-facies metamorphism (M2) and an extensive regional migmatisation. This migmatisation is particularly evident in the western part of the area where the metasediments are transformed into a granitic vein complex.

The second recognised deformation, D2, is the most important regionally. It produces the first foliation found in the widespread B-group intrusions. In the older gneisses, tight F2 minor folds are widespread, and previous structures – bedding, S1 foliation, and two generations of migmatitic veining (pre- and post-D1) are generally transposed into parallelism with F2 axial planes on a outcrop scale (Fig. 6A–B). S2 is thus a composite foliation consisting mainly of the transposed F2 fold limbs. Almost all the mappable structures postdate S2, and the S2 form-lines therefore trace out interference structures of essentially post-D2 age (Fig. 4A–B).

In the western gneisses, late D2 steep shears (Fig. 7) are found sub-parallel to the F2 axial planes. Late M2 migmatitic neosome is often emplaced along these shears. Displacements of the order of several metres have been measured along these structures but the sense of movement does not appear to be consistent.

The D2 structures are cut by the intrusions of group C, which include the chronologically important Orust dyke suite (Park *et al.* 1979, Daly *et al.* 1983, Åhäll & Daly 1985). Early C-group intrusions have been dated at 1510 and 1420 Ma (Åhäll *et al.* 1986, Åhäll & Daly 1985) and the first deformation (D3) affecting the intrusions has been dated at c. 1090 Ma (Daly *et al.* 1983). Thus the intrusions of group C can be used as a chronological marker to separate Sveconorwegian from earlier events.

The first structures to affect the C-group intrusions are a set of shear zones of varying orientation and sense of movement but indicating overall WNW–ESE shortening. These shear zones are particularly well developed in western Härmanö (Fig. 4A and see Park *et al.* 1979) where the resulting foliation is associated with amphibolite-facies recrystallisation of the Orust dykes during the M3 metamorphism.

The larger shear zones form two conjugate sets in the western part of the area. One of these has a sinistral sub-horizontal sense of movement and varies between NW–SE and NNE–SSW in trend; the other set has a dextral sense of movement and NE–SW to NNE–SSW trend. Some of the variation in trend is attributable to rotation during subsequent deformation. Major NE-trending shear zones of this age occur in western Orust and in southern Tjörn. In both cases the zones are very heterogeneous, consisting of many sub-parallel small shear zones with variably-developed new S3 foliation and tight to isoclinal F3 folds, separated by blocks of gneiss with older structures showing varying degrees of rotation into the new shear direction (Fig. 8). The mean shear direction in both western Orust and southern Tjörn is c. 050° and sub-horizontal. The complementary sinistral set appears to have suffered considerable rotation as a result of later (D4 and D5) deformation and the original orientation is difficult to determine.

A radical change takes place after this D3 deformation causing the wide-

Fig. 6. (A and B). F2-folded metasediments, western Tjörn.
A – Asymmetric F2 folds in migmatitic gneisses. The hammer is 55 cm long and marks a discordant granite dyke of the C-group. Bågareholmen, west of Kyrkesund.

spread development of folds with sub-horizontal to moderately-dipping axial planes which generally dip northwards in the south and south or southeastwards in the north. These folds are attributed to the D4 deformation (Fig. 9) which is most intense in a NE–SW belt across northwestern Orust, and in the southeast from Marstrand along Hakefjorden to Stenungsund. Minor F4 folds exhibit a distinctive crenulation cleavage in suitable lithologies. In western Orust, no regrowth of biotite is seen and the metamorphic conditions appear to have changed from D3, probably to low greenschist facies. Elsewhere, for example in the eastern part of the area, amphibolite-facies conditions seem to have continued, with axial-planar crystallization of biotite, and the development of local granitic leucosomes, sometimes with amphibole. A conspicuous feature of highly deformed zones of both D3 and D4 age, is the widespread development of muscovite, and less commonly hornblende, which is probably mainly post-tectonic in relation to these deformations.

Major F4 folds occur in the granitoid sheets of the central plutonic belt, and in the east, where S2 is rotated into a WNW–ESE or E–W trend with northward dips over a large area. There is a wide variation in the attitude of both F4 axial planes and fold axes but in the areas of most intense D4 deformation,

B – F2 folded veined gneisses. Hammer is placed between two slightly discordant dm-wide granites of the C-group. Note that thin pegmatitic neosome is emplaced along the limbs subparallel to the F2 axial plane. Mollön, south of Kyrkesund.

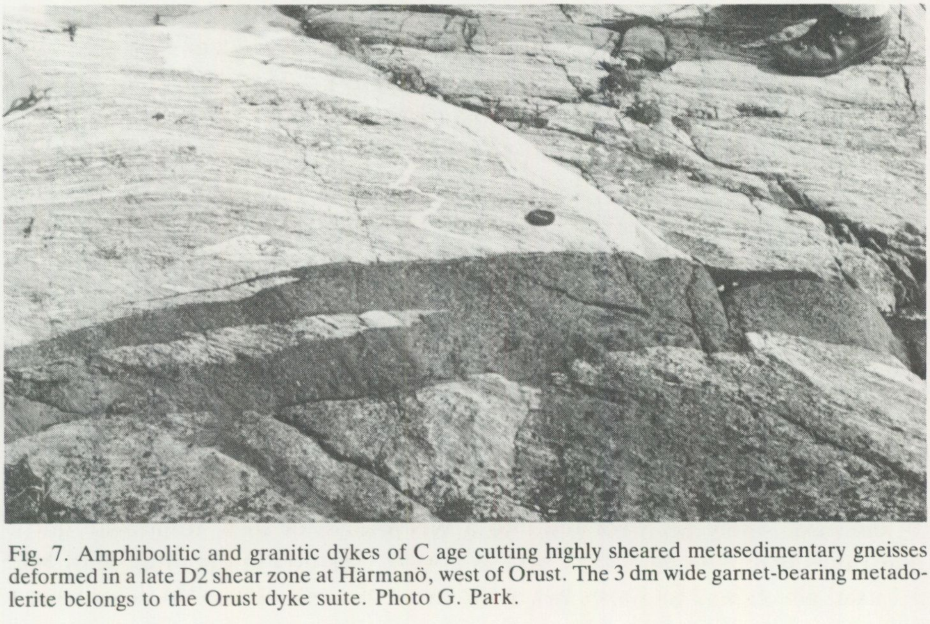


Fig. 7. Amphibolitic and granitic dykes of C age cutting highly sheared metasedimentary gneisses deformed in a late D2 shear zone at Härmanö, west of Orust. The 3 dm wide garnet-bearing metadolerite belongs to the Orust dyke suite. Photo G. Park.

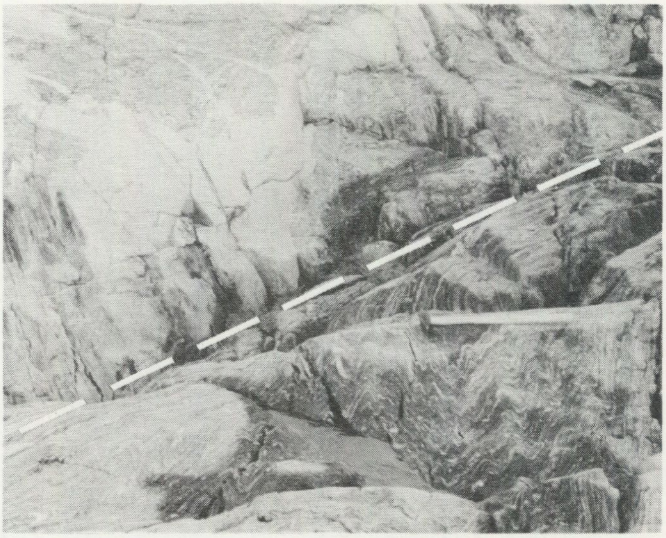


Fig. 8. (A and B). Minor D3 shear zone in the Kyrkesund area, Tjörn. Dashes mark the positions of the zone.
A – To the left of the shear zone the cross-cutting granodiorites of C age (light) are undeformed.

the L4 lineations are orientated NE–SW. The relative age of D3 and D4 structures can be demonstrated in a number of areas (e.g. along the west coast of Tjörn around Skärhamn) where narrow S3 shears are crenulated by F4.

In several areas (e.g. northeastern Orust, Råholmen) the gently inclined F4 fold limbs and the S4 crenulation cleavage are affected by upright folds, steeply dipping crenulation cleavages and shears. These later structures are grouped together in the D5 phase of deformation (Fig. 10). Narrow zones of NW–SE F5 crenulations with steep axial planes occur locally throughout the western half of the area; in the east, similar structures are N–S in orientation, whereas in the south–east, they are oriented NE–SW. Complementary N–S sinistral and E–W dextral shears in the western Orust-Skaftö area are also attributed to this deformation. A wide NE–SW zone of intense deformation, crossing western Orust from southern Härmanö through the Stocken peninsula and the small islands, was ascribed to D5 by Park *et al.* (1979). The relationship between this deformation and D4 was then regarded as ambiguous but it now seems clear that much of this intense deformation predates D4 and is related to a NE–SW D3 shear zone which is locally re-orientated by an E–W dextral D5 shear zone (see later chapter).

The variation in dip of S4 from SE in the north to N in the southern part of the area may also be due to D5 deformation, but there is considerable variability in S4, which may be partly original.

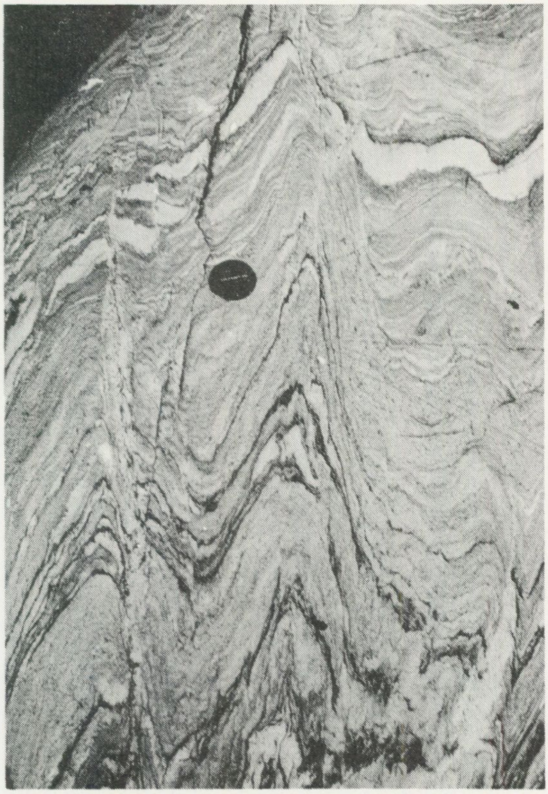
B – To the right of the main shear the C-dyke is folded, while further away it is undeformed (at upper right corner).

Fig. 9. F4-folded contact with metasediments to the left and a granodioritic sill of B age to the right. Note the strong L4 lineation. Below the arrow a vein in the orthogneiss out-lines an F2 closure. Hakenäset, Tjörn.

Fig. 10 (A and B). Steep F5 folds in islands southwest of Klädesholmen, Tjörn.
A – The white band close to the hammer is a granite of C age.

Steep kink bands and asymmetric chevron folds affecting strongly foliated gneisses in Härmanö were attributed to D6 by Park *et al.* (1979) but there is no good evidence that these belong to a separate deformation and they are therefore grouped with D5 in this paper. Other late structures include open folds in a variety of orientations, which are not easy to relate to other structures, and faults.

The structure is analysed by examining first the geometry of the major structure and then the relationship between major and minor structure in three areas which were mapped in detail. An interpretation of the structural development of the area is given in the last chapter. A series of models illustrated in Figs. 23 and 25 (highly simplified and diagrammatic) give a possible interpretation of the kinematic evolution of the area. D1 and D2 are related to a major E-dipping shear zone with a NE–SW transport direction. D3 to D5 may be related to movements on a gently inclined shear zone with a N–S to NE–SW-trending ramp in the east along the line of the Göta Älv, the earlier movements (D3–4) being essentially northeastwards and the later (D5) southeastwards.



B – A new cleavage is developed along some limbs.

ROCK TYPES AND METAMORPHISM

THE STORA LE–MARSTRAND FORMATION

The metasediments of the Stora Le–Marstrand (SLM) formation consist of variably migmatised paragneisses which, from their composition, presumably originated as greywackes. The paragneisses are typically well banded and veined, and are predominantly semipelitic in composition, containing the assemblage quartz + plagioclase (c. An 30) + biotite ± muscovite ± microcline ± garnet ± chlorite, with accessory apatite, zircon and opaques. Light grey psammitic layers are rather homogeneous and vary from 5 to 30 cm in width. In some areas frequent calc-silicate horizons (or more often lenses) occur within the psammites. Pelitic layers are typically 1–20 cm wide but, due to deformation, are not as persistent as the psammites. Usually the boundaries of the pelitic layers are sharp, but transitional contacts also occur. Graded bedding is commonly seen in areas least affected by subsequent migmatisation or deformation. Bands of feldspathic quartzite occur, but no pure quartzites – although the latter have been reported from adjacent areas (Lundegårdh 1958). Some m-wide lenses of coarse psammite occur in the Djupvik area with grains up to 4 mm across. The migmatitic paragneisses in the western part of the area consist of sheets of veined gneisses intersected and surrounded by diktyonitic neosome of typically variable grain size, which mostly occurs subparallel to the gneissosity. Stictolytic structure is common, in which garnets overgrow the older structures. Bodies of granitic neosome also occur on the scale of 1–100 metres.

In the eastern part of the area, the migmatitic development is much more variable. In southern Hakefjorden, southeast of Tjörn, the metagreywacke is sparsely veined, and the veins are quartz rich. Well-preserved graded bedding and various pressure solution cleavages (Fig. 11) are common features. Immediately surrounding this area the metasediments show more abundant and more feldspathic veining, while further away they become migmatites, especially towards the orthogneisses in the east. There are no obvious differences of original lithology between the various parts of the area. In the area of well-preserved metasediments, pillow-lavas, minor sills, dykes and contemporaneous mafic volcanics with intermediate-to-acid intercalations have been distinguished (Åhäll 1984). These early amphibolites have the same structural imprints as the metasediments, and together with them make up the Stora Le–Marstrand formation.

GROUP A INTRUSIONS AND THE M1 EVENT

Amphibolites – Numerous early amphibolites occur within the metasediments many of which probably belong to the volcanic suite described above. Many show a well-developed primary compositional banding, but homogeneous amphibolites, and metagabbroic and ultramafic bodies also occur. In the migmatitic areas the amphibolites typically show both thin concordant veining and also discordant coarse pegmatoid neosome, which in the larger bodies is localised and often restricted to marginal parts.

Granitoids – heavily veined orthogneiss ranging from tonalite to granite in composition, occurs in the Stenungsund area. F2 folds in this body fold an early (S1) fabric and thin early veins. These M1 veins are overgrown by the second and dominant veins of M2 age, which in turn are cut by younger C-group rocks.

This early (M1) migmatitic veining is widespread in the paragneisses. It can be distinguished from the later, more intense, migmatisation by its relationship to the intervening group B intrusions.

The Rönnäng body (of B age) contains numerous SLM-xenoliths in which a few older veins of M1 age are seen. It is clear that the M1 in this area produced only minor veining. The veins are all thin and of the same type as those seen folded by F1 in other areas. What little evidence there is points to low amphibolite-facies conditions for M1 metamorphism and the associated veining.

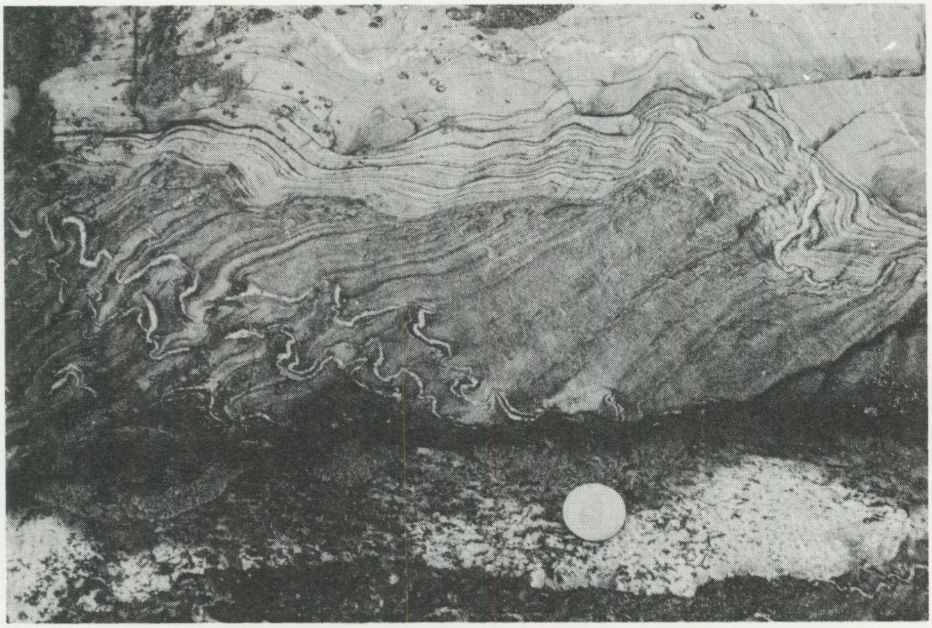


Fig. 11. Pressure solution cleavage in well-preserved metagreywacke. The bedding (So) is horizontal and shown by the contact between the psammite (above) and the semipelite. The S1 fabric is, as usual, subparallel to So and shown by the thin banding in the lower part of the psammite. In the semipelitic band the So/S1 fabric was crenulated during D2, when a pressure solution cleavage (diagonal) was developed. The subhorizontal fabric in the C-age granite dyke (at the coin) is Sveconorwegian (S3). Oxeviken, Tjörn.

Rb-Sr and U-Pb dating of the Stenungsund body gives ages of c. 1530 Ma by both methods (Samuelsson and Åhäll 1985b). These ages are significantly younger than the 1680–1590 Ma ages (Welin *et al.* 1982) obtained for the geologically younger group B calc-alkaline granitoids (e.g. the Rönnäng tonalite). Thus the age determinations appear to contradict the earlier (A) age of the Stenungsund body. However Åhäll (in prep.) argues that the structural evidence is more reliable and that the 1530 Ma age relates to the M2 event.

GROUP B INTRUSIONS

East of the Östfold–Marstrand belt, orthogneisses of B age are a major crustal constituent but in the present area these intrusions are more limited in outcrop. The majority of these rocks forms part of a calc-alkaline suite, with tonalites and granodiorites being the most common members. These intrusions are usually not veined and have a gneissic fabric. The abundant smaller sill-like bodies, however, and the margins of the larger bodies, are usually heavily veined. Outside the described area, many of these calc-alkaline granitoids are associated with basic rocks, ranging from ultramafic to dioritic in composition. One such body within the area is the Hälleviksstrand amphibolite (Daly *et al.* 1979). This body, mainly dioritic in composition, contains in parts, m-wide rounded lenses of ultramafic, dark metagabbro and metagabbro mixed within the metadiorite. It is first affected by the D2 event, and unlike the rocks of A age, no early fabric is found to be folded by F2.

Another type of intrusion is found in the central Tjörn zone forming two sheets of red gneissic augen granite. These are separated by a screen of SLM-gneisses (mostly amphibolite) and grey granite of B age. The eastern augen granite contains xenoliths of the grey granite and of the Rönnäng tonalite. The augen granites are affected by the D2 deformation, as are the other B-group rocks, but most parts of the granite sheets are affected by later (Sveconorwegian) blastesis which is responsible for abundant large euhedral K-feldspar megacrysts.

Several trondhjemitic sills are found in the metasediments around Vallhamn on eastern Tjörn. One of these sills is over 100 m thick but the remainder are only a few metres. Their unusually high Na_2O/K_2O ratio of about 6 suggests a different source from the calc-alkaline suite (Samuelsson and Åhäll 1985b).

THE M2 METAMORPHISM AND MIGMATISATION

All the rocks described above are affected by regional amphibolite-facies metamorphism accompanied by a widespread migmatisation which is particularly well developed in western Orust (Park *et al.* 1979) and western Tjörn.

In many places, thin cm to m-wide dykes occur, ranging from mafic to acid in composition. They cut the early M2 migmatitic veining but are themselves cut by later diktyonitic M2 neosome, which distinguishes them from the younger dykes of C age.

GROUP C INTRUSIONS

A large number of small intrusions, typically of sheet-like form, were emplaced during the period after the M2 metamorphic event and before the Sveconorwegian deformation and metamorphism. These intrusions have recently been described by Åhäll and Daly (1985) and will only be briefly summarized here.

An early set of intrusions comprises a suite of tonalitic to granitic sheets (Fig. 12; the "younger granites" of Park *et al.* 1979). The granitic sheets often have coarse pegmatitic borders. Another early set consists of bimodal metagabbro/metadolerite augen granite bodies in which the gabbroic parts grade into or are cut by the dolerite. For the gabbro, Åhäll *et al.* (1986) report a U-Pb emplacement age from zircons of 1510 Ma. Southwest of Tjörn the dolerite is net-veined by augen granite. The largest body in this suite is the Stigfjorden augen granite which extends for 30 km from Tjörn to Orust. A Rb-Sr emplacement age of 1420 Ma is given by Åhäll and Daly (1985) for this granite. The youngest ele-

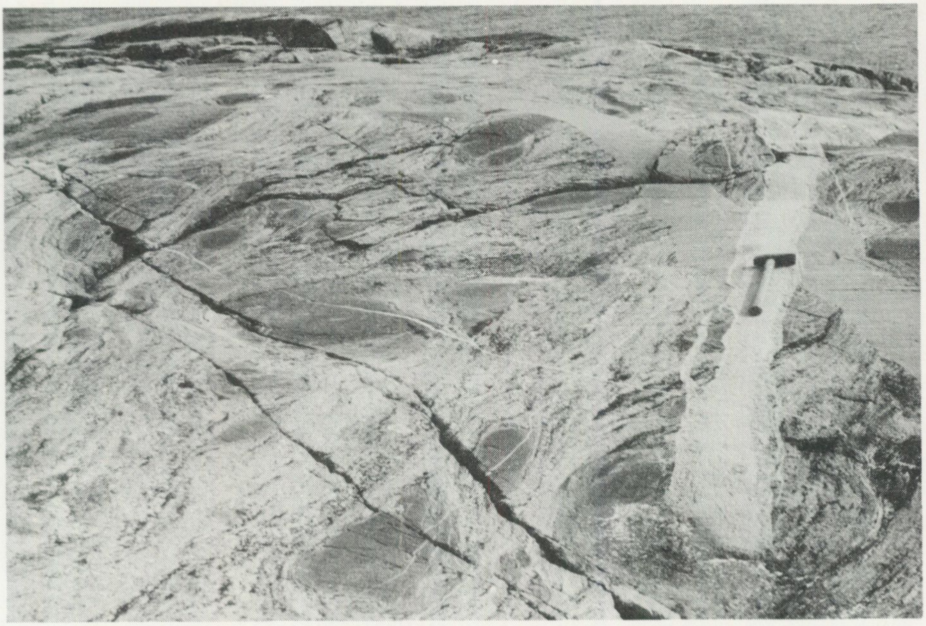


Fig. 12. Migmatite of M2 age intruded by dykes of the C-group, where intermediate members commonly are cut by more acid ones. Mollön, Orust.

ment in the C group is probably the Orust dyke suite (Park *et al.* 1979, Daly *et al.* 1983) which is predominantly composed of metadolerites, but includes minor intermediate and acid members.

GROUP D INTRUSIONS

This group comprises intrusions which are post-tectonic in relation to the Sveconorwegian deformation.

The Bohus granite is regarded as a late orogenic Sveconorwegian pluton (cf. Magnusson 1965, Gorbatschev 1971). Skiöld (1976) gives an Rb-Sr age of 890 Ma for this body, interpreted as the age of emplacement. This granite clearly post-dates the main Sveconorwegian deformations in this area (Daly *et al.* 1982). Numerous younger pegmatites are associated with this body (Welin & Blomqvist 1964).

Two post-tectonic igneous bodies of anorthosite-bearing norite occur on Älgön and Brattön, forming 500 m-wide E–W trending sheets with a combined length of 7 km. The anorthosite occurs as a large-scale breccia in which individual plagioclase crystals of dm size were apparently formed before the emplacement of the norite (Bergström 1963). The age of this body is unknown. Several small E–W trending dolerites occur in the south of the area and might correspond to a set of WNW dolerites found around Göteborg. One of these, the Tuve dyke, has probably been emplaced between 800 and 900 Ma, from its palaeomagnetic characteristics (Abrahamsen 1974).

The youngest intrusion is a N–S dolerite which can be traced across western Tjörn, through Orust to Skaftö and is considered to be Permian in age (Samuelsson 1971).

MAJOR STRUCTURE

A dominant tectonic feature of the area (Fig. 2 in back cover; Fig. 4A) is the large N–S open fold, the *Högås synform* described by the gneissose banding which closes in the north around Högås. This fold closure is also traced out by a continuous belt of thin granodiorite and augen-granite sheets which are well exposed around Dragsmark, Högås and eastern Orust and link up with the Tjörn plutonic belt. In the central part of the map there is a belt of complicated structure running NE–SW from southern Tjörn to southeastern Orust, corresponding in part to the outcrop of three augen-granite sheets.

Southeast of this belt, in the area of southern Hakefjorden, the gneissose banding describes a large open antiform with a northern limb dipping at 20–30° northwards and an eastern limb dipping east or southeast rather more steeply. A complementary synform lies between this fold and the South Tjörn shear zone (Figs. 4A, 24). This structure, the *Rörtången monoform* is terminated on its southeast side by a zone of regular NE–SW banding, dipping to the northwest at around 45°. The attitude of the banding here appears to be influenced by the major *Göta Älv shear zone* (Samuelsson 1980) which lies only 1 km east of the southeast corner of the map. When followed northwards, this shear zone bends into a N–S orientation around Västerlanda (about 8 km east of the eastern margin of the map). Thus the attitude of the foliation along the eastern margin of the map is determined in part by the orientation of this important W-dipping shear zone.

Along the western margin of the regularly foliated zone in the southeast, numerous E–W to WNW–ESE trending F4 folds may be seen to refold S2 and also the margins of the granite sheets.

In northeastern Tjörn, adjacent parts of Orust and the mainland around Stenungsund, is a region of complicated interference involving several deformations but most obviously between N–S open upright folds and E–W trending, tighter, F4 overfolds dipping to N or NW. This interference structure is shown most clearly in the region of southern Hakenäset (Figs. 4A, 13). Here a N–S-trending antiform and adjoining synform to the east give way southwards to E–W-trending, northerly dipping banding. East of these folds, the N–S margin of the granite, and the concordant S2 foliation, are folded by E–W F4 folds.

The most complex part of the area is the central belt running across Tjörn to eastern Orust. The southwestern part of this belt is marked by a prominent

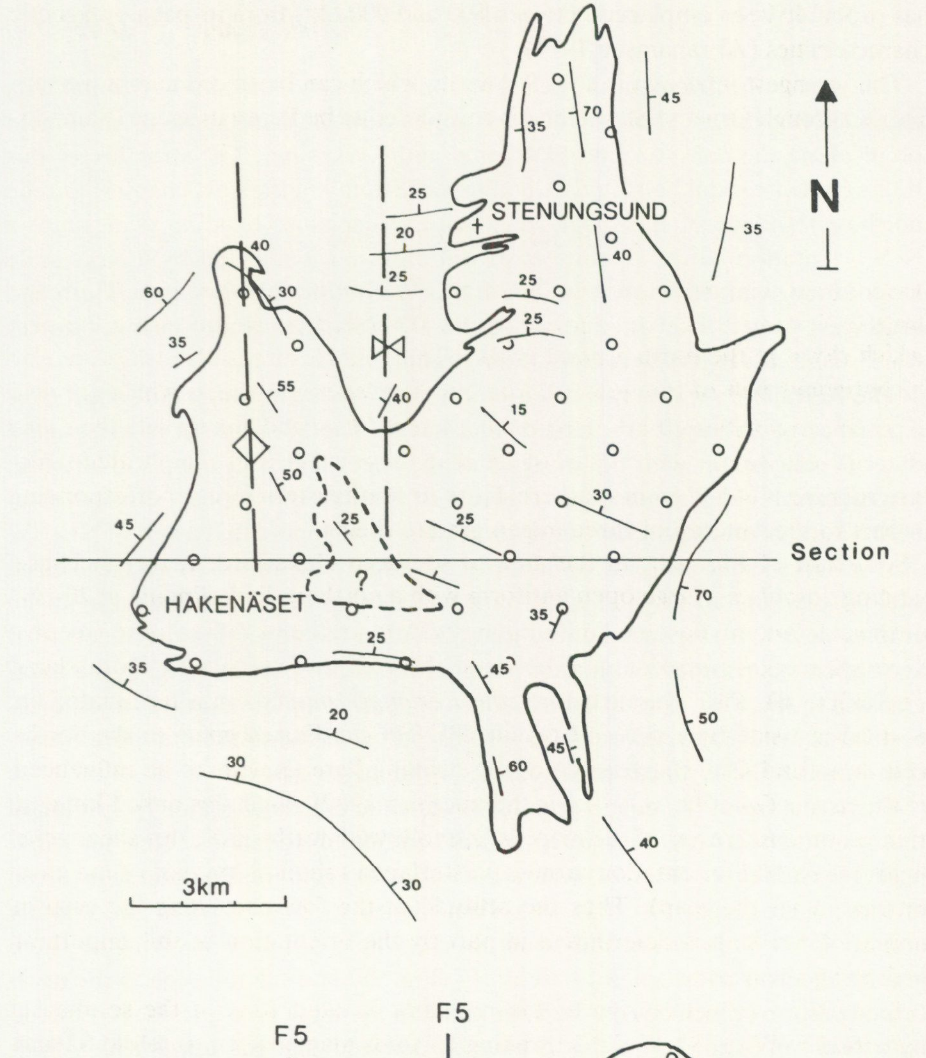


Fig. 13. *Structure of the Stenungsund intrusion.* The outcrop of the granite (ornamented) indicates interference between gently inclined E–W F4 folds and upright N–S F5 folds.

steep NE–SW shear zone of D3 age (the *South Tjörn shear zone*) through Morike Kile (Fig. 4A).

The sense of movement in the shear zone is dextral and sub-horizontal with a gentle NE plunge. Many small shear zones with the same sense of movement occur along the coast around Skärhamn and Kyrkesund. The structure of this well exposed coastal belt is described in more detail in the next chapter. On the northwestern side of the shear zone belt the gneissose banding swings into a N–S orientation with moderate eastward dips and is affected by a large-scale monoformal kink structure trending ENE–WSW through northwest Tjörn and southwest Orust. The orientation of the D3 shear zones also changes northwards from a NE–SW to a NNE–SSW trend.

The S2 foliation within this belt is cut by the C-group augen granite sheet over a distance of about 10 km, east of Skärhamn. The S3 foliation in the granite sheet is concordant with the margins of the sheet and with the S2 foliation in the adjoining older augen granite sheets to the east but appears discordant to both S2 and S3 in the gneisses to the west. It would appear that a belt of NE–SW dextral D3 shear zones has rotated already highly sheared S2 into parallelism while preserving an original discordant relationship between S2 and the augen granite sheets. It should be noted that S2 within the augen granite sheets of B age appears concordant with their margins and is not parallel to S2 in the paragneisses to the west. The D3 shear zones appear to die out upwards and northeastwards, where the deformation is replaced by a less intense but more evenly distributed NE–SW linear or LS fabric in the augen granites.

The structure of the augen granites reveals the effects of major F4 folding of the granite sheets together with their S2 and/or S3 foliations. One such fold occurs at Stenkyrka (Fig. 14) where the eastern augen granite sheet is involved in three linked tight F4 folds with axial planes striking NE–SW and dipping around 45° NW. North of this structure the whole complex involving all three granite sheets is overturned to the north (Fig. 15) and the foliation in the overturned section (which lies on the upper limb of the large F4 overfold) is refolded by a N–S antiform. From this it may be deduced that the upright N–S folds (F5) post-date the F4 folds, with their NW-dipping axial planes.

The latter structure is bounded to the northeast by a further tight synformal overfold with axial trace running NW–SE through Varekil. The eastern limb of this synform is marked by a mylonitised shear zone which bends into a N–S orientation and runs northwards for about 10 km. Northeast of this structure, S3 reverts to a southeastward dip and must therefore lie on the uppermost limb of a large F4 double overfold (Fig. 16). Here again S3 is refolded by a later N–S upright synform. Fig. 17 illustrates diagrammatically, in three dimensions, how these F4 structures may be related to the major Högås synform (F5) and to a postulated large-scale fold with its hinge north of Svanesund. The present outcrop shape results partly from F4 and partly from F5 deformation (see Figs.

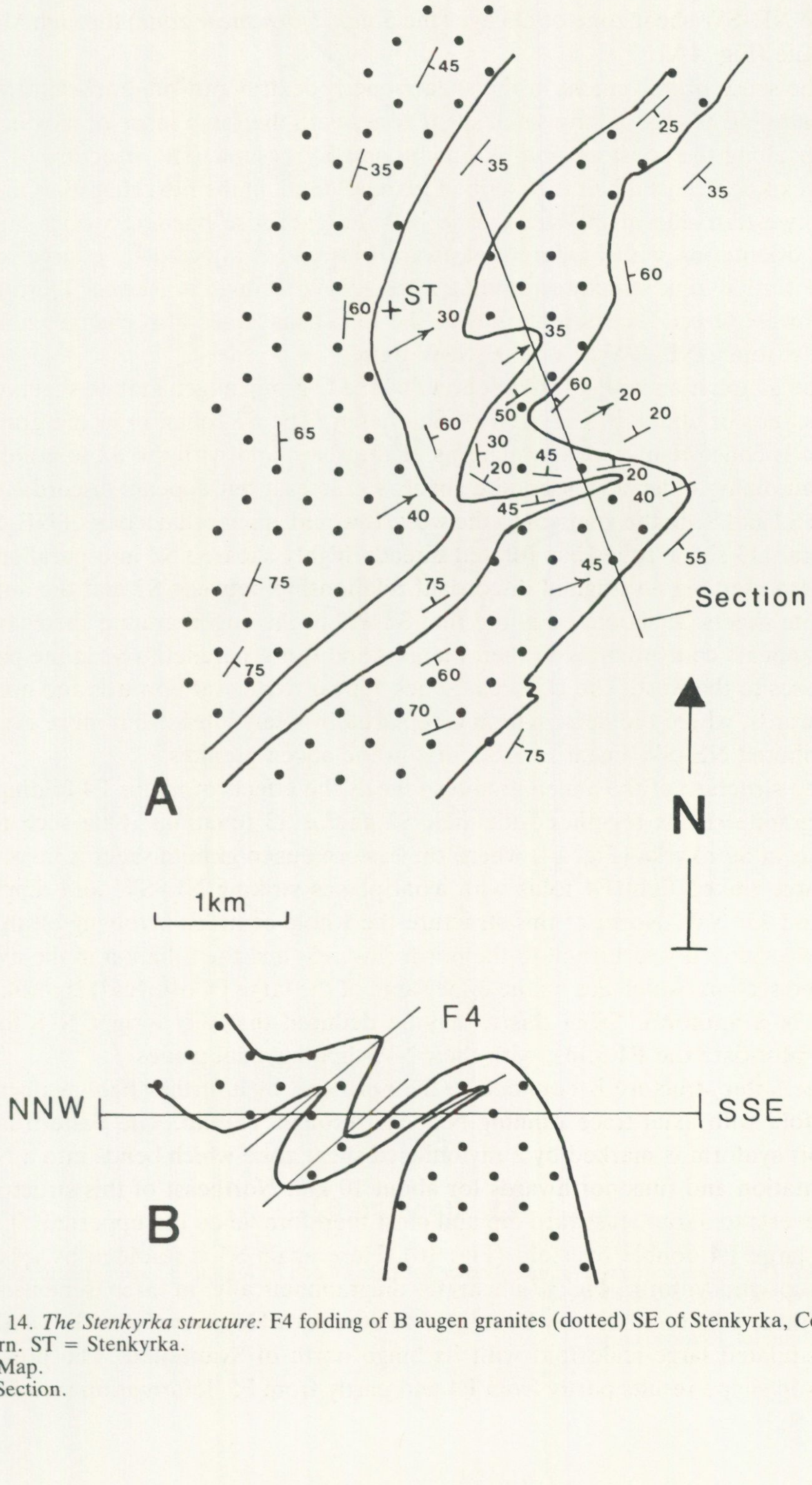


Fig. 14. *The Stenkyrka structure:* F4 folding of B augen granites (dotted) SE of Stenkyrka, Central Tjörn. ST = Stenkyrka.
A: Map.
B: Section.

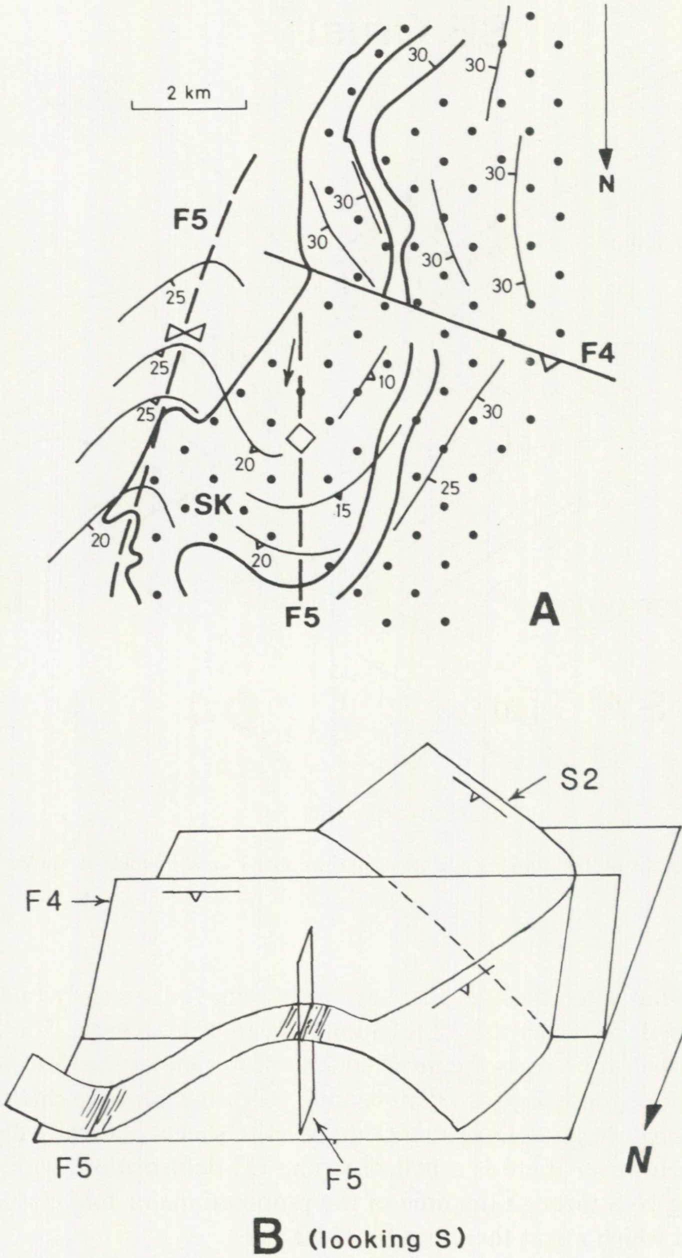


Fig. 15. *The Skåpesund structure:* interference between F4 and F5 folds in B augen granite (dotted) in northern Tjörn. SK = Skåpesund.
A: Map.
B: 3D-model, looking south.

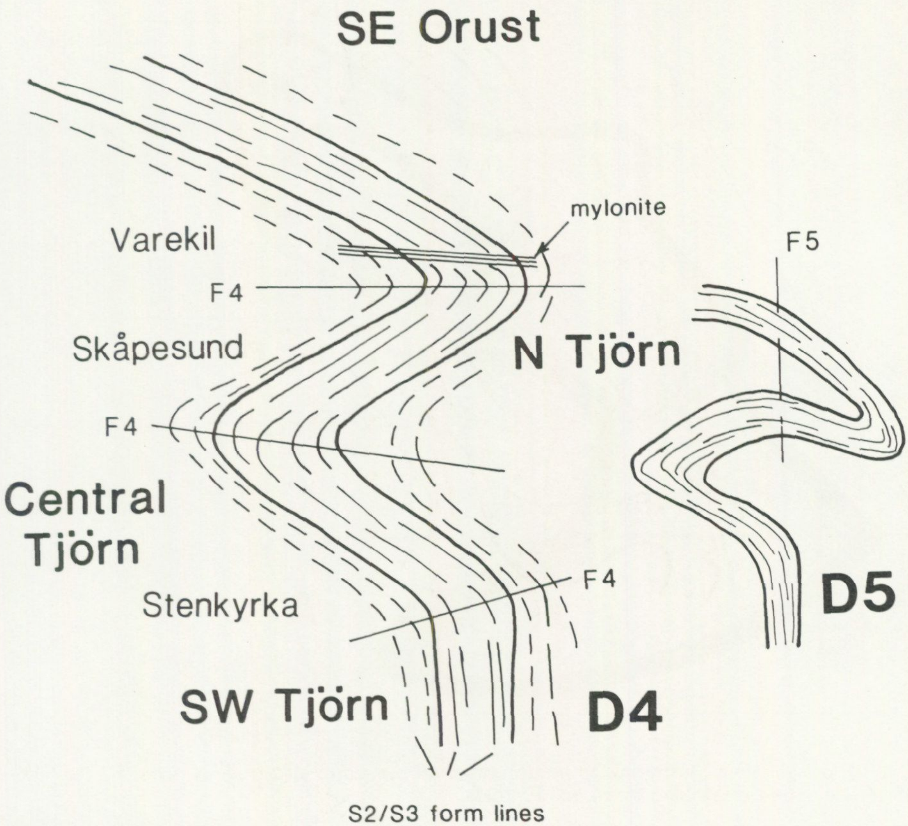


Fig. 16. Diagrammatic profile, looking northeast, of the major F4 and F5 folds of Tjörn and southern Orust.

4, 16 and 17) but when these effects have been removed, an early fold closure may be inferred, to which the S2 foliation appears axial planar. The NE–SW central Tjörn belt represents the inverted limb of this major overfold where S2 is generally more gently inclined than bedding/S1 or the intrusive sheets. In the northern outcrop (e.g. at Dragsmark) the granite sheets generally dip gently southwards. However there is a belt of strong D3 deformation, with tight F3 folds, running N–S through the area of the proposed major fold closure north of Svanesund which might therefore be of F3 age.

The whole of this complex central area is bounded to the east by the regular N–S trending belt described earlier.

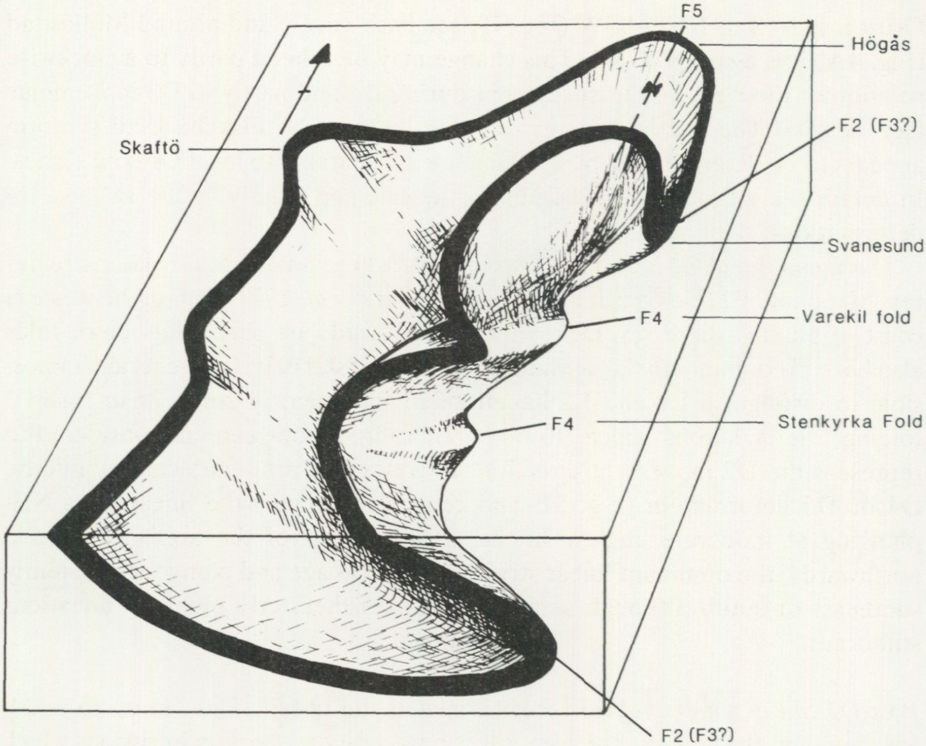


Fig. 17. Block diagram illustrating an interpretation of the major structure. A major F2 (or F3?) synformal overfold is refolded by F4 and F5 folds.

RELATIONSHIPS BETWEEN MAJOR AND MINOR STRUCTURE

WESTERN ORUST AND SKAFTÖ

The extremely well exposed coastal sections in western Orust are fully described by Park *et al.* (1979) and it was in this area that the detailed structural chronology used in the present study was established. Skaftö forms the northern extension of the Orust area. It includes the closure of one of the major folds of the Lysekil-Marstrand area, at Fiskebäckskil, and the margin of the Dragsmark augen granite complex (Fig. 4; Gambles 1984). The major belt of D4 deformation crosses the western Orust-Skaftö area and continues in a NE–SW direction across northern Orust.

The map (Figs. 18, 19, see back cover) shows the gneissose banding with a general N–S trend in western Orust bending into a NW–SE trend in Skaftö, then assuming an E–W to WNW–ESE trend on the northern limb of the Fiskebäckskil synform. In the southern part of the area the banding again bends into a NW–SE orientation. These changes in trend are probably due to several effects. The dominant shear zone trend in Skaftö is NW–SE whereas in western

Orust it is N–S to NNE–SSW (Fig. 19, see back cover) and around Mollösund (Fig. 4A) it is again NW–SE. This change may be related partly to a clockwise rotation of the western Orust segment during D4 and partly to D5 movements (see below). The northern gently-dipping limb of the Fiskebäckskil synform appears to be determinated by F4 since it is sub-parallel to local F4 axial planes. In detail, the attitude of the banding is determined mainly by the D2 and D4 deformations.

The mean dip of S2 is about 45° to the east where unaffected by later structures. Mappable F2 folds occur at Björni (see Park *et al.* 1979) and on the western coast of Skaftö where several asymmetric 'Z' folds are seen. The minor folds also have predominantly 'Z' asymmetry in this coastal belt. It is generally impossible to distinguish L1 and L2 lineations in this area; in zones of intense F2 folding, the lineations appear to be parallel throughout and are considered to represent the D2 movement direction. In zones that are unaffected by intense D4 or D5 deformation (e.g. SE and central Härmanö) the lineation is NE-plunging at moderate angles. In the northern part of the area, from Lavö northwards, the dominant linear structure is of D4 age and plunges consistently southeast or south although some north or northeasterly plunging lineations still occur.

Post-D2 Shear zones – Minor shear zones of the order of cm. to m. in width are abundant throughout the area. Most post-date the C-group intrusions which are represented in the area by the mafic Orust dyke swarm and by abundant granite and pegmatite sheets. Some steep N–S to NE–SW shear zones pre-date C-group sheets and are referred to late D2 deformation (the D2A of Park *et al.* 1979: Fig, 6A). However most of the shear zones are either demonstrably later or their relative age was not determinable. The later shears are extremely variable both in orientation and displacement direction.

The deformation is expressed in two main ways: firstly as shears along the margins and within dykes, where the shear direction is partly controlled by the orientation of the dykes, and secondly as discordant shears or shear zones, up to several metres in width, which cut through C-group intrusions without regard to their orientation. An analysis of the sense of movement on dykes with a wide range of orientations yielded a σ_1 direction of WNW–ESE in Härmanö (Park *et al.* 1979).

The great majority of the discrete discordant shears fall into four groups: (1) steep sinistral shears trending N–S to NNE–SSW in western Orust and NW–SE in Skaftö (Fig. 19, see back cover); (2) steep dextral shears trending NE–SW concentrated mainly in a single broad shear zone running northeastwards from Härmanö to Björni (Fig. 18, see back cover); (3) steep dextral shears trending E–W concentrated mainly in a belt extending through the small islands west and south of the Stocken peninsula towards Hälleviksstrand (Fig. 18, see back cover). These shears cut members of groups (1) and (2); (4) gently to moderately inclined shears mainly E, NE or SE-dipping and found in Skaftö, and in many cases obviously associated with F4 folding.

Very few shears do not fit into these groups: some N–S dextral and NE–SW or E–W sinistral shears indicate movement senses opposite to those of the majority of shears of these orientations, but their significance is difficult to assess.

Taking all the steep shears together (i.e. groups 1–3) (Fig. 20), it would appear that the critical trend line dividing sinistral and dextral orientations is at 010° and that another important line at 130° divides a wholly sinistral field from a field containing both sinistral and dextral shears. If the shear sets were generated by a regional stress field, this would suggest two sets of principal stress planes trending: (1) 010° and 100° and (2) 130° and 040°. For the first set, σ_1 = 100° and for the second, σ_1= 130°. The first corresponds to D3, producing NNW–SSE sinistral and NE–SW dextral shears and the second, which is later, producing N–S sinistral and E–W dextral shears (which cut the earlier NE–SW shears south of Stocken). The later set of steep shears is attributed to D5. The mean orientations which can be deduced for the two sets are: D3 – dextral 040°, sinistral 135° and D5 – dextral 085° and sinistral 005°. The real situation would be more complicated since the kinematic behaviour of the area would in practice determine the orientations of many of the shears, but the data at least suggest a change in regional compression from a roughly E–W to a more NW–SE direction between D3 and D5, and this change is borne out by the kinematic indicators discussed later.

D4 folding – F4 folds are immediately recognisable by their gently dipping axial planes. They are found throughout the area north of a line between Härmanö and the middle of the Lavö peninsula (Fig. 18, see back cover). There is a belt of intense D4 deformation about 3 km in width from northern Lavö to Islandsberg and extending in a NE–SW direction along the northern coast of Orust (Fig. 4). Within this belt the S2 banding is widely re-orientated by rather tight F4 folds with gently to moderately S- or SE-dipping axial planes, in such a way that the regional trend is dominated by the moderately SE-dipping long limbs of the F4 folds (Fig. 18, see back cover). North of this belt, minor folds are abundant but there has not been such marked re-orientation in the outcrop pattern. The F4 fold axes are rather variable and depend on the attitude of S2. The L4 lineations as a whole are rather more consistent and plunge predominantly to the south or southeast.

The Fiskebäckskil synform is an open fold with a NW–SE axial surface dipping steeply to the SW. This fold clearly post-dates both S2 and the emplacement of the C group intrusions; the Orust dyke on Blåbergsholmen on the northern limb of the synform has a NE–SW trend, in contrast with those on the western limb which are NW–SE. The general E–W trend and gentle southwards dip of

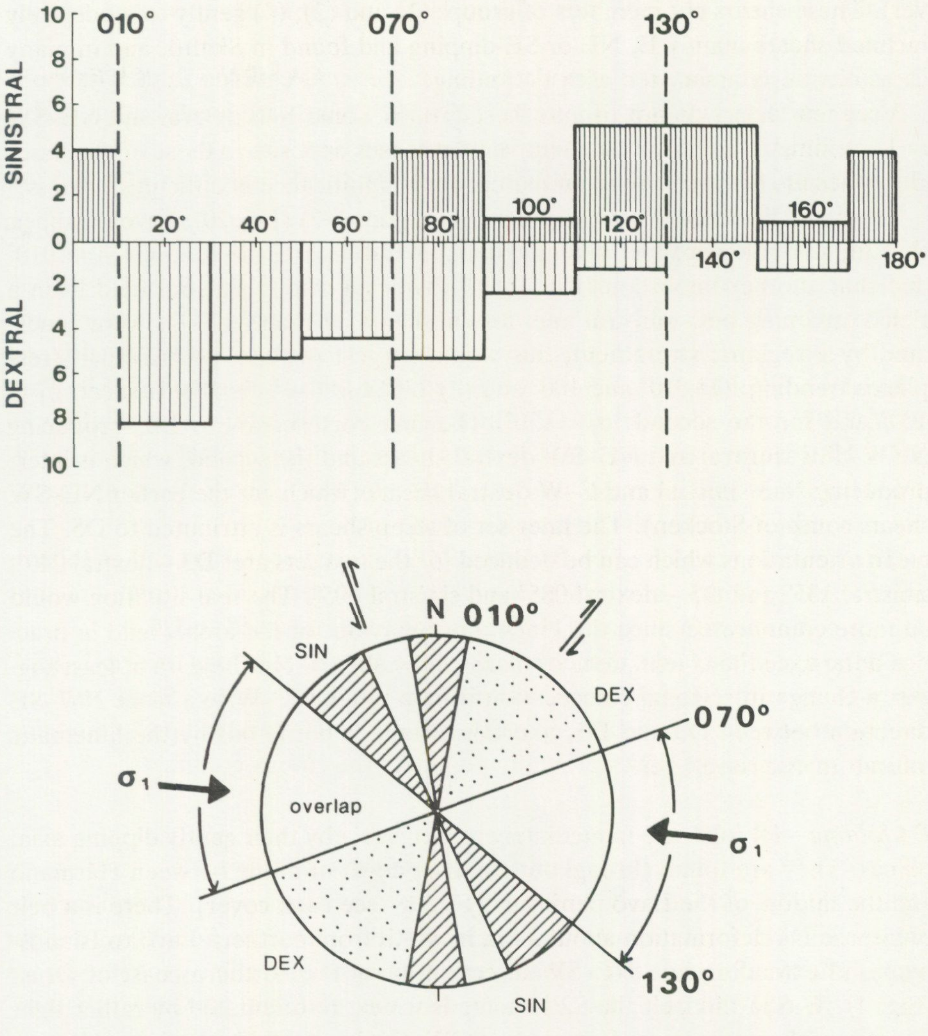


Fig. 20. Orientation pattern of steep shears on western Orust and western Tjörn. Histogram shows frequency of shears in 20° sectors; Rose-diagram shows sectors of sinistral and dextral shears and of overlap.

the gneisses on the northern limb is attributed to D4.

F4 folds are seen to affect NE–SW D3 shears in Lavö and on Silleskär, north of Härmanö, thus confirming their relative age.

Post-D4 deformation – Structures post-dating the F4 folding form several distinct groups with different characteristics whose relative age is difficult to establish.

1. Steep shears with E–W dextral and N–S sinistral sense of movement (described below).
2. Zones of crenulations, crenulation cleavages and chevron folds with steep axial surfaces and NW–SE trend (120°–140°) which are localised but widely distributed and very consistent in orientation.
3. Zones of chevron folding and kink bands tentatively assigned to D6 by Park *et al.* (1979).
4. Large-scale open warps with ENE–WSW trend.
5. Faults.

The steep shears and NW–SW crenulations are assigned to D5. In Lavö and on Tvistärten, the crenulations are seen to affect gently-dipping S4 surfaces. The NW–SW folding with associated penetrative fabric (assigned to D5 by Park *et al.* 1979) is re-allocated to D3, since in places this fabric is affected by F4 folds. However these structures frequently merge indistinguishably with the E–W D5 shear zones and are presumably re-aligned by them. The E–W shearing may also be responsible for the large-scale open warps.

The F6 folds recognised by Park *et al.* (1979) are uncommon and as there is insufficient evidence on which to assign them to a separate deformation, they are, in common with all post-D4 folds in the area, assigned to D5.

Of the many late faults in the area, the most important belong to a NNE–SSW to N–S set with NE–SW branches (Fig. 18, see back cover). Some of these faults can be seen to have a steep eastwards dip (c. 60°) and a dip-slip direction of movement. These faults probably post-date the Bohus granite.

HÄRÖN TO SKÄRHAMN (WESTERN TJÖRN)

This area (Fig. 21, see back cover) is another very well exposed coastal section, which links the structure of western Orust with that of the South Tjörn shear zone. The area extends from Härön, which consists of regularly foliated gneiss with NNE–SSW trend and steep to moderate easterly dip (typical of the western part of the map), to Skärhamn, where the gneisses are strongly deformed in the steep NE–SW shear zone.

D2 deformation – In the section as a whole, the S2 banding/foliation is variably sheared, and in many places only weakly deformed. Although much of the shearing is post-D2, some of the sheared zones are cut by undeformed or weakly deformed younger granites or dykes indicating a D2 age for the shearing. Throughout the section, there occur numerous relatively narrow belts of D3 shearing which locally align S2 into parallelism. Away from such belts, S2 trends N–S to NNW–SSE in Härön with dips 50–70° to the east.

The F2 folds and lineations have a rather variable plunge, mostly northeastwards. The sense of asymmetry is also variable. "Z" folds predominate and there is a tendency for the "S" folds to concentrate in the narrow more S3-deformed belts. It is possible that some "S" folds may be F3 rather than F2, in conformity with the dextral pattern of the S3 shears. 'M' folds are common in a narrow belt north of Skärhamn where L2 has a sub-horizontal plunge. There is no clear link between sense of asymmetry, plunge direction and orientation of S2 foliation, and no major F2 fold closures can be identified. It is likely that this area, western Orust and Skaftö lie in a major D2 shear zone (see Fig. 23).

D3 deformation – The orientation of the D3 shear zones changes systematically from northwest to southeast. They trend 020° and dip 50–90° E in the northwest, changing to 030° dipping 60°–80° SE south of Kyrkesund and to 060° vertical at Skärhamn. The lineation in these shear zones is typically at moderate angles to the NE in the northwestern part of the section and sub-horizontal in the southeastern part. In the southeast, the shear zones are parallel to the major sub-vertical South Tjörn shear zone (Fig. 24), which has a dextral sense of shear. The shallow-plunging lineations in this zone indicate a dominantly strike-slip sense.

Much of the intense deformation south of Skärhamn in the South Tjörn shear zone is of D2 age but has probably been rotated into parallelism with the major D3 zone through Morike Kile.

Small dextral shear zones, not associated with Orust dykes or younger granites, fall into two categories. Many are parallel to nearby S3 shears and are probably of the same age. Some however, around Skärhamn, are E–W or WNW–ESE in orientation and are attributed to D5. Few sinistral shears are found.

Post-D3 deformation – There are very few F4 folds, and none south of the Kyrkesund peninsula. Axial planes trend NE–SW with low to moderate dips to the southeast except on the west coast of Härön where F4 folds trend NNW–SSE with moderate easterly dips. L4 plunges northeastwards at low angles.

The D5 shears are described above. Other D5 structures are uncommon, but similar to those of western Orust.

DJUPVIK TO RÖSSELVIKSSTRAND (SOUTHEASTERN TJÖRN)

The importance of this well exposed coastal section (Fig. 22, see back cover) is twofold: (1) it lies in the synform linking the northern limb of the major Rörtången antiform with the South Tjörn shear zone (see Fig. 4A); and (2) it is one of the few parts of the map where almost unmigmatised metasediments can be found, and from which the nature of the early structures can be worked out.

The metasediments consist mainly of psammites and semipelites in roughly equal proportions. The psammites range from massive m-thick units to alternating thin units interbedded with laminated semipelitic metagreywackes. The thinner units are often graded, yielding good way-up criteria. More pelitic units and occasional calc-silicate lenses also occur.

F2 folding and S2 foliation can be recognised over most of the section except in zones of very strong D4 deformation. In favourable outcrop and lithologies, S2 occurs as a well-developed spaced cleavage with pressure-solution stripes, and F2 clearly folds an earlier fabric (S1) and a set of quartzo-feldspathic veins which may be either parallel or oblique to bedding. Occasionally S1 may be seen also as a spaced cleavage with thin veins parallel to the cleavage planes. These structures are most clearly developed in thin semipsammitic units.

The nature of the early (M1) regional veining can be clearly seen in this area – only very thin locally derived veins being present. The later regional migmatisation is weakly represented by rather sparsely distributed, quartzo-feldspathic veins with biotitic selvedges.

F1 minor folds are uncommon but the presence of larger-scale isoclinal F1 folds of the order of tens to hundreds of metres in wavelength can be demonstrated using both younging direction, which appears to be reasonably consistent, and the orientation of S1 in relation to bedding (see Fig. 22, see back cover). Younging is consistently westwards in the northern half of the outcrop but reverses at least twice in the southern section from Bräcke to Rösselviksstrand. Several major F2 fold closures can be demonstrated in addition by reversals of minor F2 symmetry across mappable folds of bedding.

Relationship between D2 and D4 – Definite identifiable F4 and S4 structures are fairly consistent in orientation with a mean strike of 065° and dip of 35° NW, and a mean F4 plunge of 30° N. The bedding has a rather complex geometry, describing a series of asymmetric folds with NE–SW limbs dipping NW and NW–SE limbs dipping NE. The enveloping surface is steep and trends approximately NNE–SSW. The stereogram of bedding shows considerable scatter but with a girdle concentration with a pole near to the mean F4 plunge. The S2/F2 stereogram shows a very wide scatter which can be partly explained by rotation around F4 axes. Comparison with the bedding plot shows that S2 generally dips more steeply than bedding for E–W to NW–SE trends but shows a wide variation in dip for NE–SW trends. In the southwest, S4 consistently trends NE–SW at a high angle to S2. In the section between Bräcke and Olnäs, S2 has been rotated in many cases into near-parallelism with S4 and is difficult to distinguish from it. In the zone of strong S4, most of the minor folds have Z asymmetry both on NE–SW and NW–SE fold limbs (see Fig. 23). The major folds in this zone are not necessarily F4 in age. The structure can be partly explained by the rotation and tightening of F2 folds by F4 and the oblique intersection of S2 and bedding by S4. In their present orientation in the north and south of the section, where D4 is less intense, S2 strikes E–W to NW–SE and dips steeply N to NE. If the effects of F4 folding are removed, S1 or bedding strike NE–SW and dip steeply SE, whereas S2 dips SE less steeply, suggesting that the area is situated on the inverted limb of a major F2 overfold (see Fig. 17).

It is clear from a comparison of Fig. 22 with the main map (Fig. 4A) that the major Rörtången fold is an F4 fold which has re-orientated S2 into a WNW–ESE trend on the southeast side of the pre-existing (D3) South Tjörn shear zone.

A steep NE–SW belt of monoclinal folds running parallel to the coast is post-D5 and may be related to late sinistral NE–SW faults.

STRUCTURAL SYNTHESIS

Lineations, strain markers and movement directions. – In the more intensely deformed parts of major shear zones with shear strains commonly in the range $\gamma = 6$–10, the orientation of elongation lineations (i.e. of X in the finite strain ellipsoid) will be close to the movement direction (cf. Ramsay 1980, Coward 1984). Deformed pegmatitic material, which is abundant in the area, yields augen with frequently a strong elongation lineation. In intrusions of C age, this lineation is used to deduce the Sveconorwegian movement direction.

D1–2. Because of the pervasive effects of D2 and later deformations, it is not possible to reconstruct the geometry of the D1 structure. However the S1 foliation seems to be widespread, and F1 minor folds where recognisable are often tight to isoclinal, as are the only mapped F1 folds, in the Djupvik-Rösselviksstrand coast section. The concentration of granitoid sheets of B age in the Central Tjörn belt suggests that this may be a high-strain zone in D1 which facilitated their emplacement (Fig. 23).

The L2 lineations in areas little disturbed by later deformations (e.g. southern Härmanö) generally plunge northeastwards at varying angles. The widespread and intense development of F2 minor folds, and their general Z asymmetry, unrelated to the large-scale F2 fold, suggests that the D2 phase of deformation may represent a shear zone (possibly continuing from D1) with the F2 minor folds representing shear folds. The sense of asymmetry and the orientation of the lineations therefore suggest a southwesterly transport direction (of an upper block) on an easterly-dipping shear zone (Fig. 23). The geometry of the F2 major fold traced out by the B-group granites (Figs. 23, 24) is difficult to reconstruct because of the effects of subsequent D4 and D5 refolding. The central Tjörn belt appears to represent the inverted limb of an asymmetric overfold with the same Z sense of asymmetry as the minor folds which, however, do not appear to change their asymmetry across it. The major fold may thus have formed at an early stage in D2.

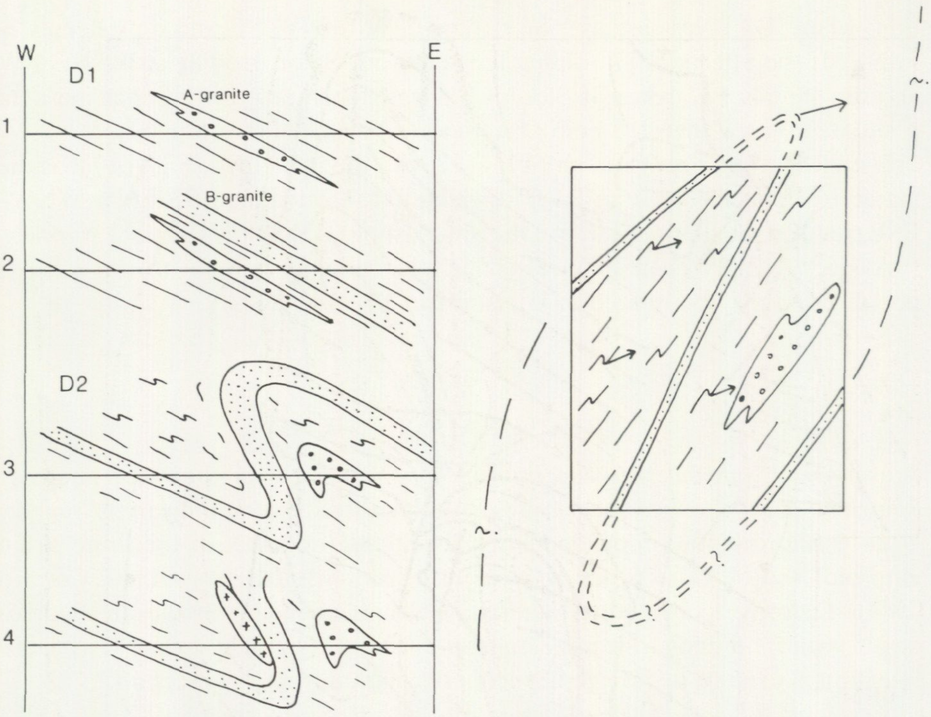


Fig. 23. Diagrammatic representation of the structural evolution of the area in D1 and D2. 1: D1 affecting paragneisses and A-granite. 2: Concordant intrusion of B-granite sheets. 3: F2 major overfold and minor folds with W. vergence. 4: Intrusion of C granite discordant with S2 but sub-parallel to B-granite sheet. Map shows likely geometry of area post-D2 and pre-D3 (assuming major fold is F2 rather than F3). Sections are approximately parallel to the inferred movement direction.

The metamorphic conditions during the D1–2 deformations are difficult to determine, since diagnostic mineral assemblages have generally not been preserved owing to pervasive Sveconorwegian recrystallization and the lack of suitable lithologies. However the presence of widespread granitic migmatite suggests high amphibolite-facies conditions during M2, possibly extending to the period of post-D2 shearing. The weaker M1 veining suggests lower temperatures for that event. The complex would appear to have cooled before the incoming of the C-group intrusions. Many of the dykes are emplaced along brittle fractures and there is no evidence in this area of high temperatures in the country rocks during emplacement.

At a number of localities along the western coastal belt, C-group dykes cut or are emplaced along steep shears which post-date the S2 foliation. However the majority of the very numerous shear zones found throughout the area affect intrusions of C age and are therefore ascribed to the D3–5 (Svecornorwegian) deformation.

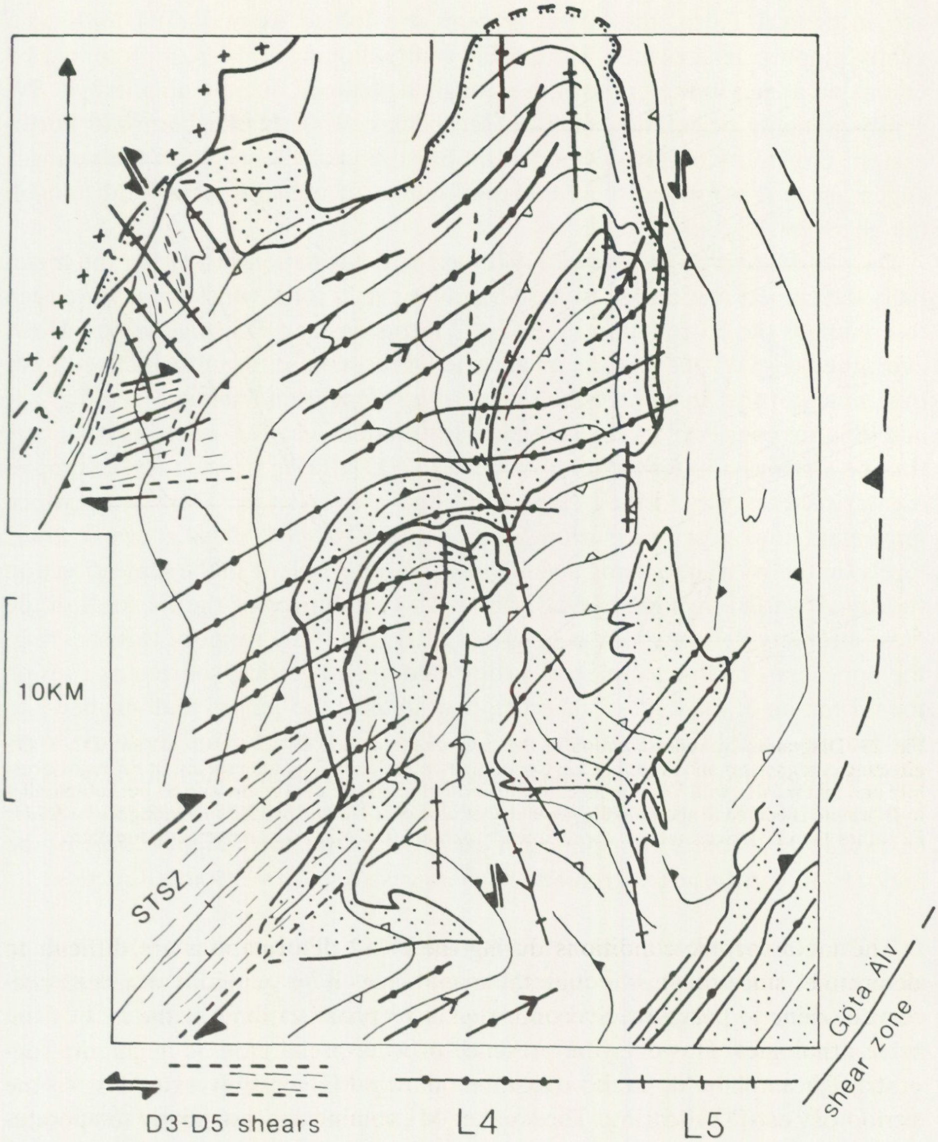


Fig. 24. Interpretative sketch map showing main structural elements of the Sveconorwegian deformation (D3–D5). A, B and C granites – dots; D granite – crosses; STSZ – South Tjörn shear zone. Form lines represent S2.

D3–4. D3 was defined as the first deformation to affect the group C intrusions. In the western part of the area (Fig. 19 in back cover; Fig. 24) this deformation produced steep shears forming complementary sets indicating WNW–ESE to W–E compression. Large shear zones occur in southern Tjörn and western Orust with a NE–SW trend and horizontal dextral displacement. Further northeast, in central Tjörn, the augen granites are folded by major F4 folds with gently dipping axial planes. Here S3 is gently-dipping and L3, represented by elongated augen in the granites, is strongly developed, maintaining its NE–SW gently-plunging orientation (Fig. 2, see back cover). In northern and northeastern Orust, a strongly developed L4 lineation parallel to L3 in the younger augen granite, is formed by crenulation hinges of tight F4 recumbent folds in the gneisses.

D4 was defined by Park *et al.* (1979) as the deformation producing the regionally developed recumbent to moderately inclined folds which locally are seen to crenulate the S3 foliation in group C intrusions and D3 shear zones. However, the NE–SW steep S3 shears and the F4 recumbent to gently-inclined folds over much of the area share the same strong elongation lineation (see Fig. 24) and thus are considered to be kinematically related. The D3–4 deformation may thus be visualised in terms of an early stage (D3) during which a set of complementary shears was formed (Fig. 25A) and a later stage (D4) during which movement took place both along certain steep NE–SW shear zones at lower levels (in the west) and along a gently-inclined shear plane in the same direction (northeastwards) at higher levels, parallel to the hinges of the F4 folds in the most intensely deformed areas (Figs. 24, 25B, 26). As a result of this shearing, the upper part of the complex was subjected to sub-vertical shortening causing the formation of the large-scale recumbent folds of the central plutonic belt and the Rörtången fold in the south (see Fig. 4B). Evidence for the sense of movement obtained from extensional cleavages, shear bands and shear folds in group C pegmatites and augen granites is inconclusive. Most indicators suggest a northeastwards direction of transport. An exception is the north-dipping limb of the major F4 fold in the augen granites which suggests a southwestwards direction.

D5. The D5 deformation has been re-defined (cf. Park *et al.* 1979) to include all post-D4 structures. Although these may not all be related, there is insufficient evidence to suggest a wholly later (D6) phase of deformation. Only the faults are regarded as definitely later than D5.

Structures attributed to this deformation include steep shears (mainly in western Orust and Skaftö); localised zones of crenulations, crenulation cleavages and chevron folding; and large-scale warping of S2 and open folding of S4. These structures can be kinematically related if the area is divided into a "basement" containing mainly steeply-dipping gneisses (southwestern Tjörn to Skaftö) and a "cover" with well-developed gently-inclined S4 structures. The key to interpreting the D5 structure is the variation in trend of the Sveconorwegian lineations. In the southeast, these lineations change in trend from NE–SW in Nordön and Rörtången through N–S to NW–SE between Råholmen and Stenungsund (Fig. 2 in back cover; Fig. 24). The same effect can be seen in the northwest from Lavö to Skaftö. By observing the augen shapes in deformed

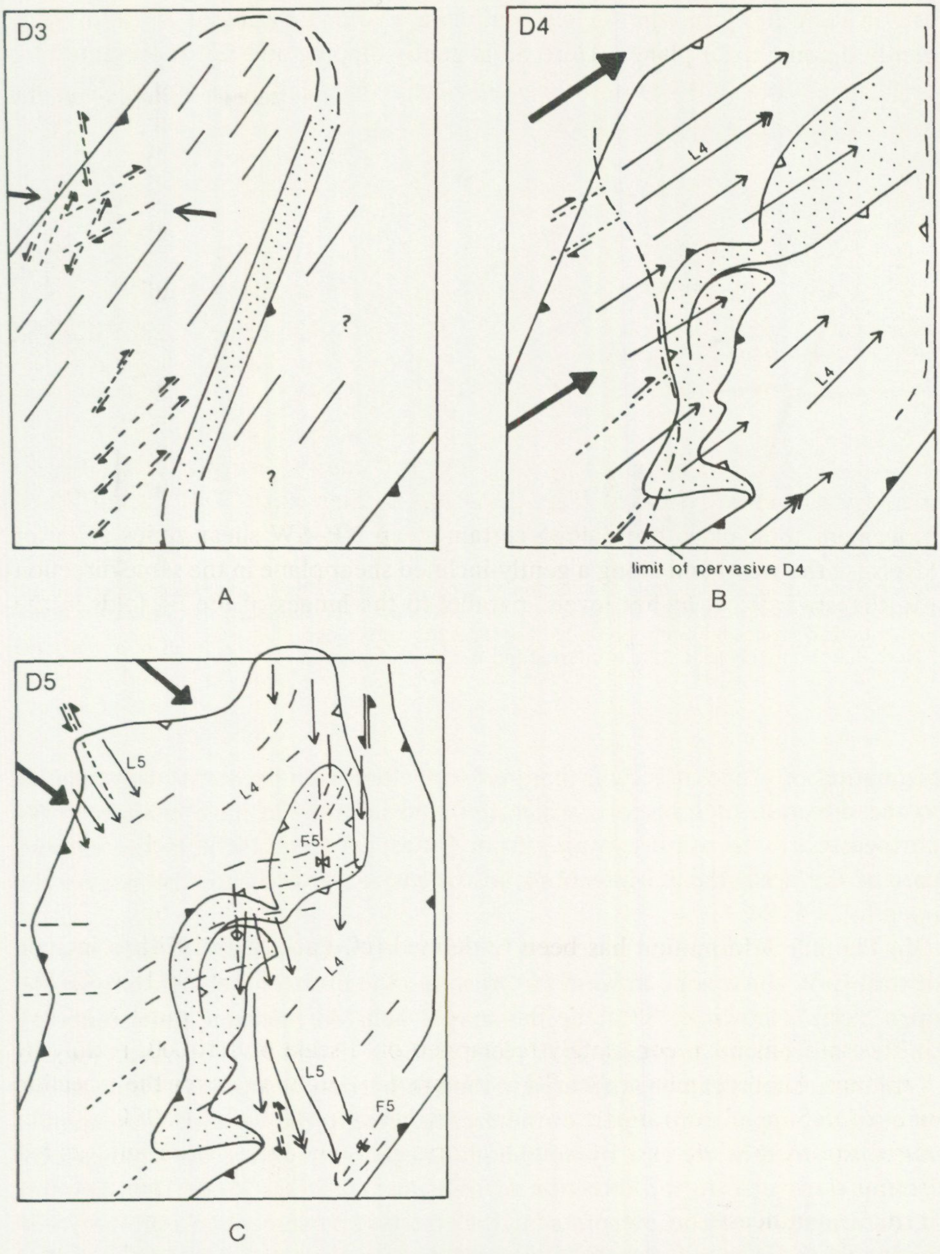


Fig. 25. Kinematic evolution of the area during the Sveconorwegian deformation (D3–D5).
A – Complementary D3 shear zones implying WNW–ESE compression
B – (D4) northeastwards movement on gently-inclined shear zone and continuation of movement on steep NE–SW dextral shears.
C – (D5) SE-wards to S-wards movement on gently-inclined shear zone. Note that L5 lineations are N–S in the east, parallel to the main shear-zone ramp, and that L4 lineations are refolded by F5. The F5 folds are parallel to the N–S ramp in the centre and to the NE–SW ramp in the SE.

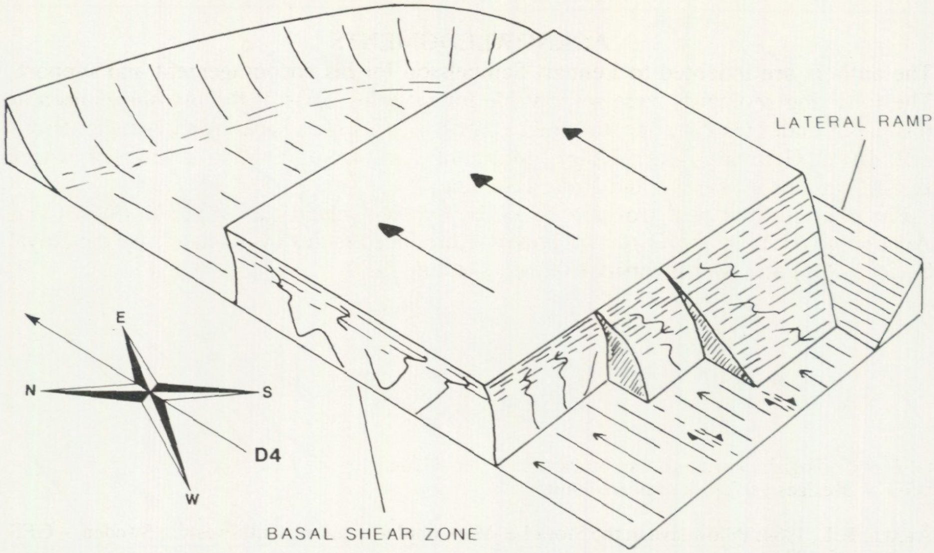


Fig. 26. Block model to illustrate the combination of steep and subhorizontal shear zones and an inclined lateral ramp during northeastwards D4 movement. The displacements would be distributed in ductile zones but are represented as planes for convenience.
Note that the basal shear zone is inferred but not seen at outcrop.

pegmatites of C age, it is clear that these are elongation lineations, sub-parallel to the direction of transport, which must be inferred to have changed from northeastwards to southeastwards from D4 to D5 (Fig. 25C). In the eastern part of the area, the L5 lineations are orientated N–S as are the large-scale open folds of S4.

In the steeply-dipping "basement", the most prominent D5 effects are the dextral E–W shear zone in western Orust and the probably related, large-scale open "kink" shown by S2 along the coastal belt. At the same time, renewed sinistral movements probably took place along N–S and NW–SE steep shears.

All these effects can be attributed to the sub-horizontal southeastwards movement of the upper central part of the area relative to the western "basement", but constrained in the east by an oblique lateral ramp and in the southeast by a ramp transverse to the direction of transport (see Fig. 25C). Thus D4 and D5 deformation may be interpreted as the effects of movement on a sub-horizontal ductile shear zone with a N–S trending W-dipping ramp in the east, bending into a NE–SW, NW-dipping, ramp in the south, with the movement direction changing from northeast to southeast (Figs. 25, 26).

The important N–S to NNE–SSW normal faults described in western Orust-Skaftö indicate an E–W extensional phase which is probably post-Bohus granite in age (i.e. late Sveconorwegian at earliest).

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SGU = Sveriges geologiska undersökning

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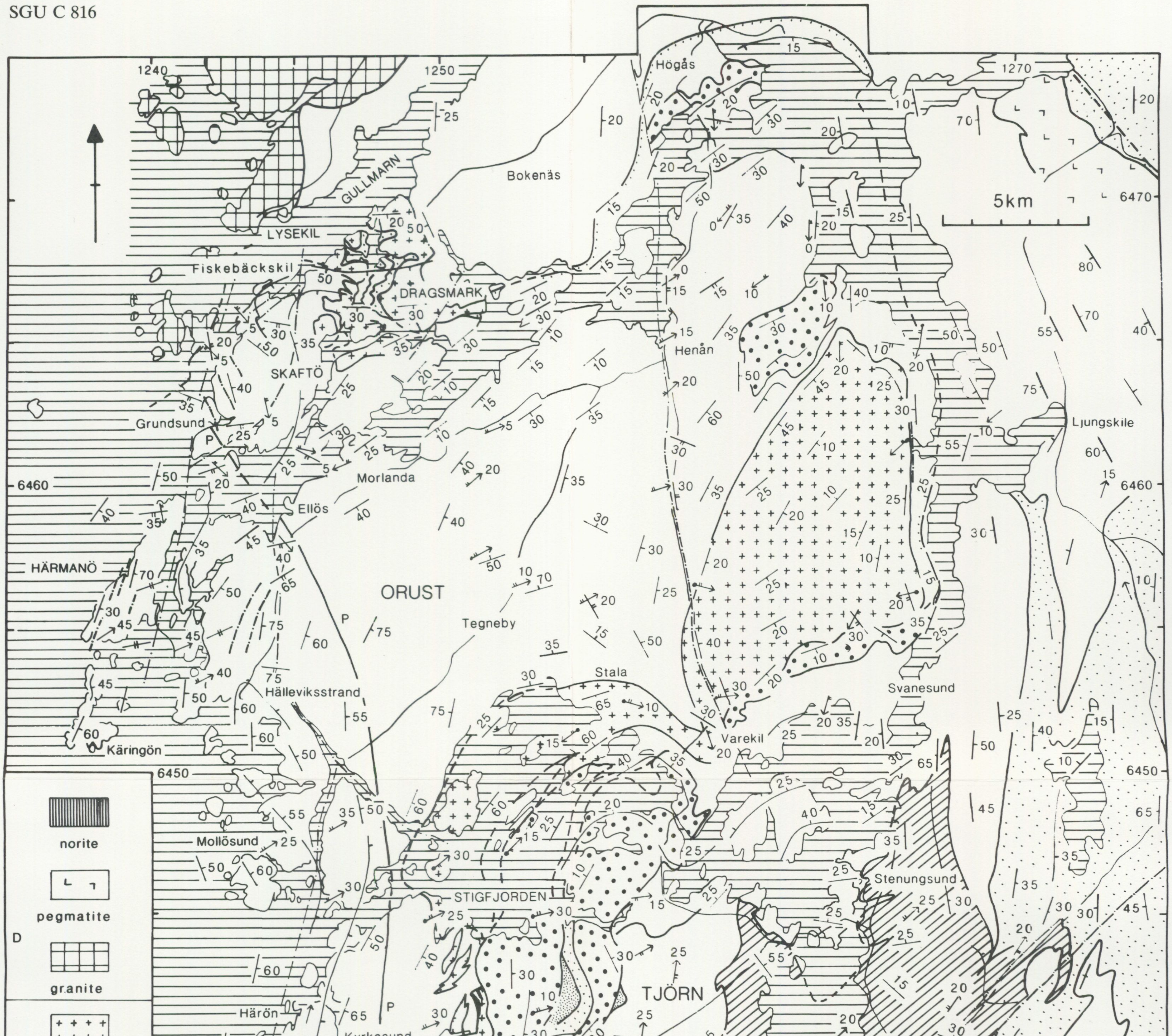

Fig. 2. Geological map of the Lysekil–Marstrand area.

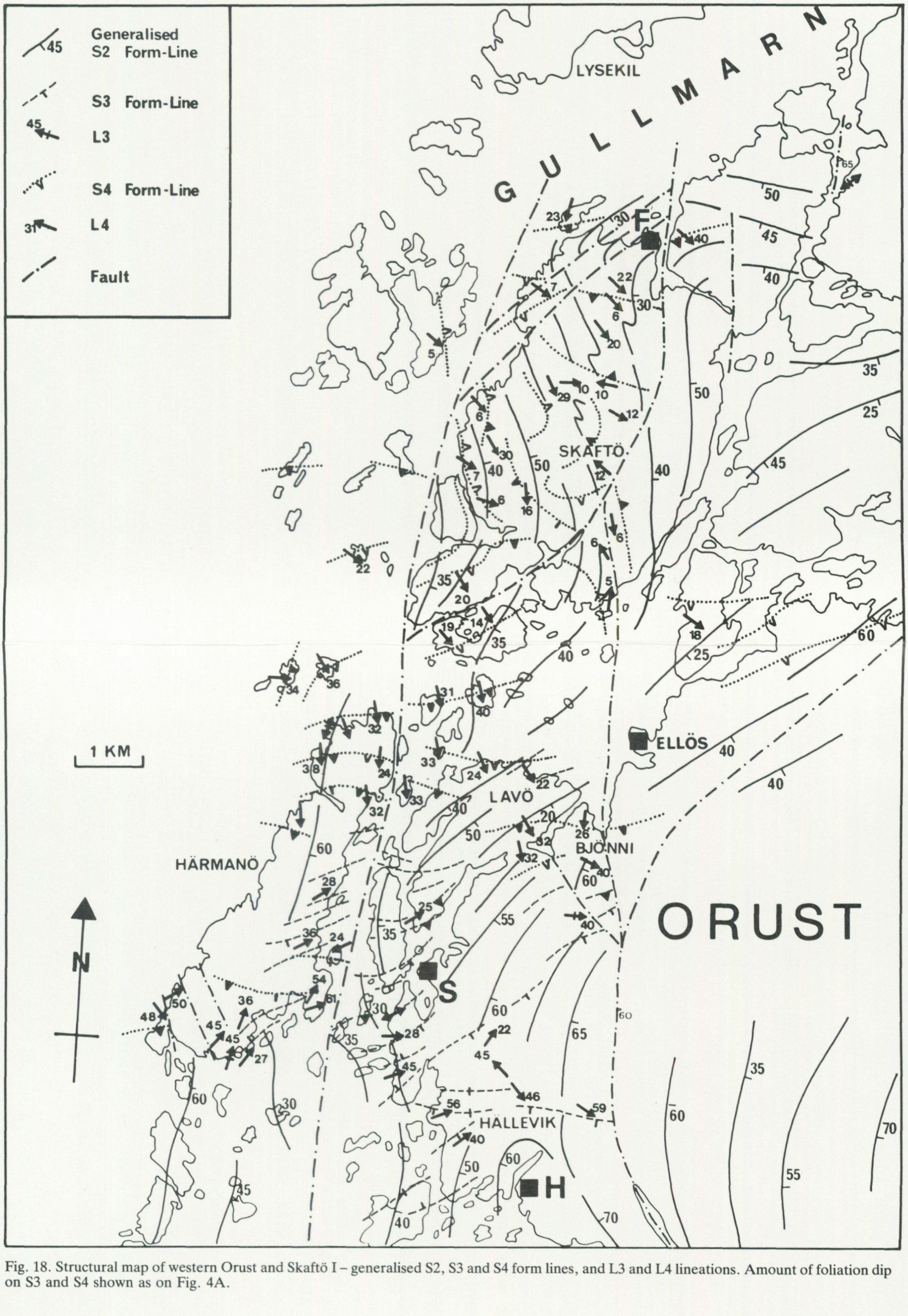

Fig. 18. Structural map of western Orust and Skaftö I – generalised S2, S3 and S4 form lines, and L3 and L4 lineations. Amount of foliation dip on S3 and S4 shown as on Fig. 4A.

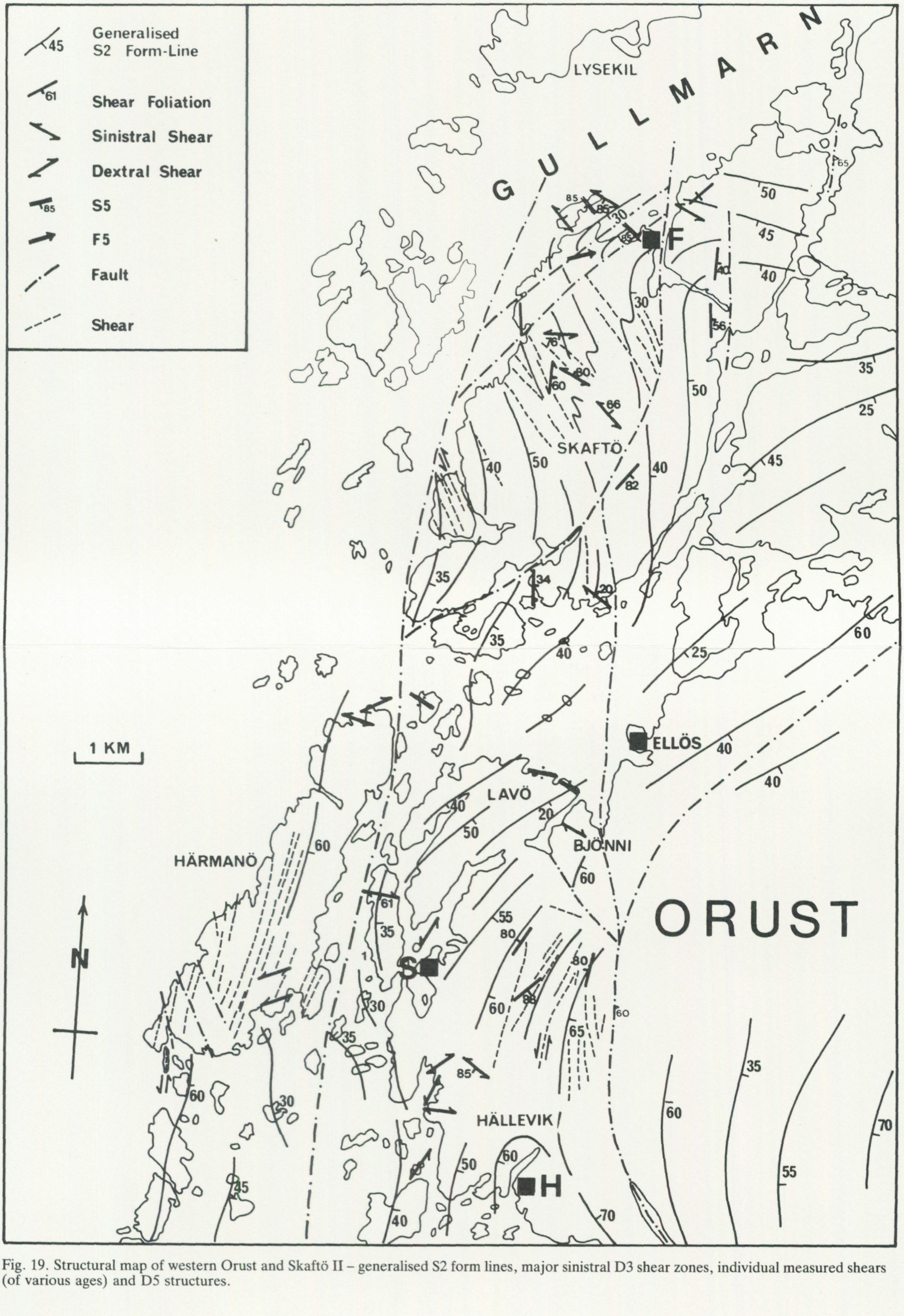

Fig. 19. Structural map of western Orust and Skaftö II – generalised S2 form lines, major sinistral D3 shear zones, individual measured shears (of various ages) and D5 structures.

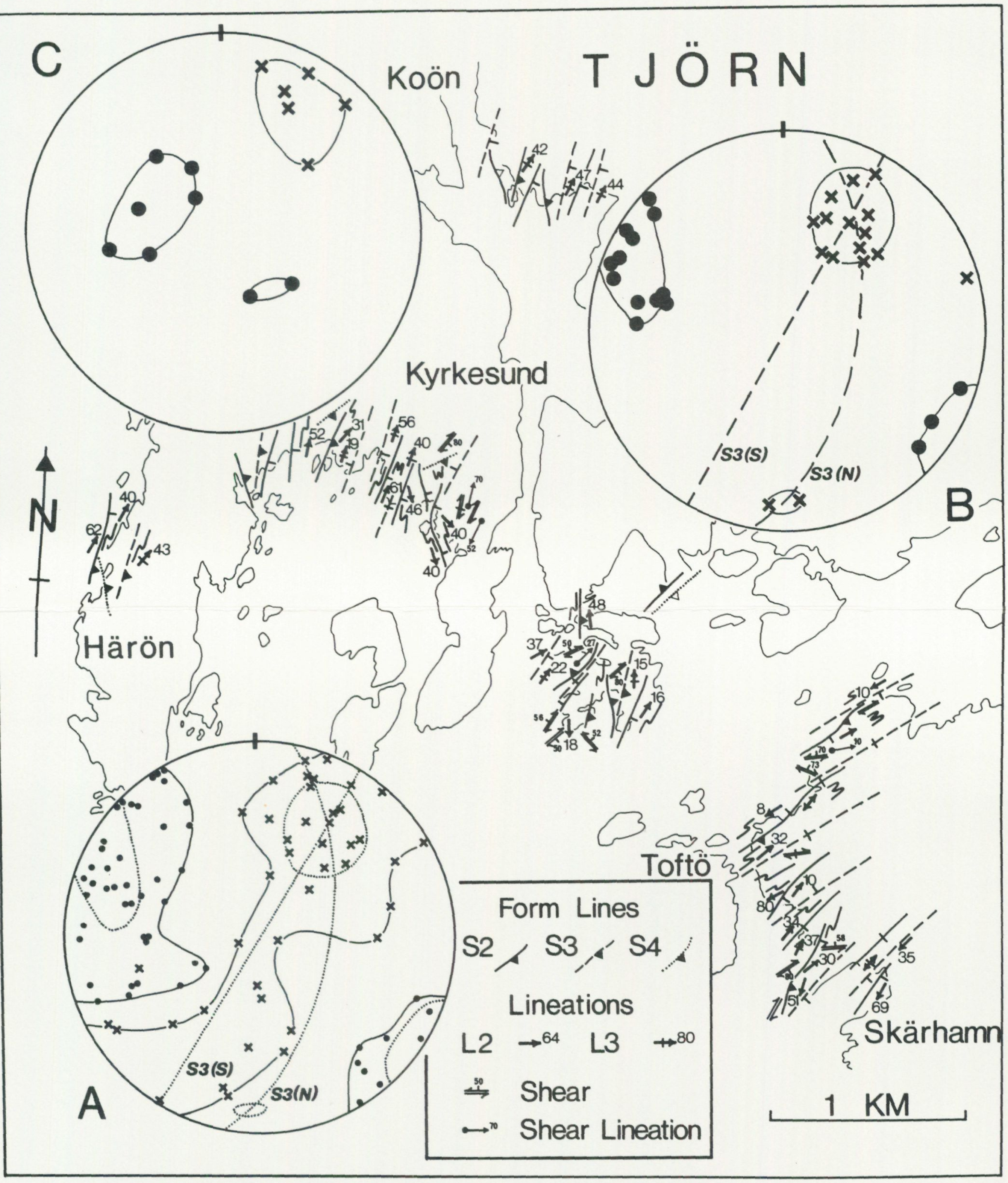

Fig. 21. Structure of the coast of western Tjörn from Härön to Skärhamn.
Inset: A – Poles to S2 foliation (dots) and L2 lineations (crosses), (S3 given for comparison).
B – Poles to S3 foliation (dots) and L3 lineations (crosses) with mean S3 for northern and southern outcrop.
C – Poles to S4 foliation (dots) and L4 lineations (crosses).
Foliation dip amount on form lines shown as on Fig. 2A.

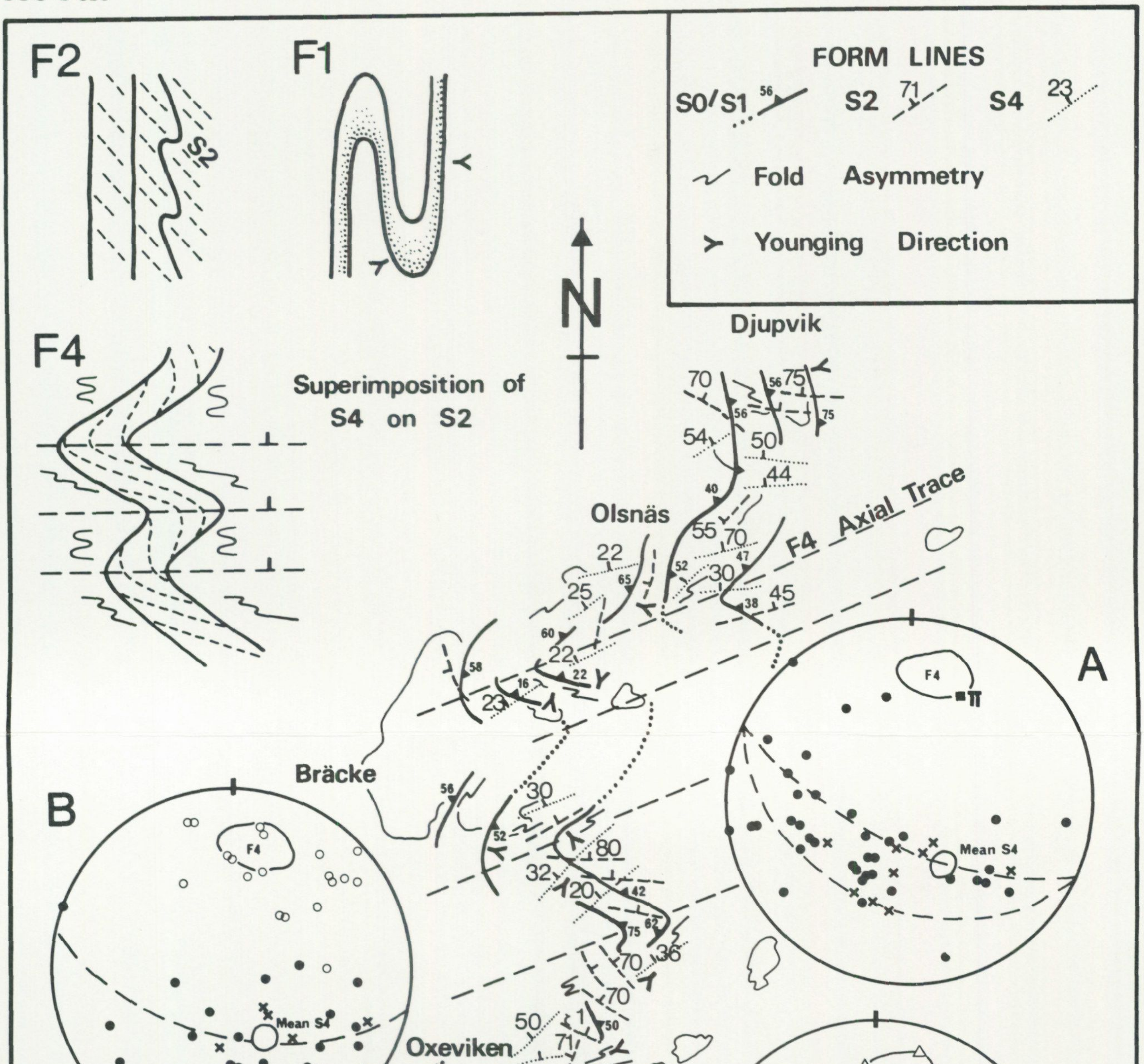

Fig. 22. Structural map of the southeastern Tjörn coast from Djupvik to Rösselviksstrand.
Inset: A – Poles to bedding (dots) and transposed bedding (crosses); F4 area shown for comparison.
B – Poles to S2 (dots), S2 transposed by F4 (crosses) and L2 (open circles); F4, and mean S4 shown for comparison.
C – Poles to S4 (dots), transposed S2 (crosses) and L4 (triangles).

Profiles show diagrammatic view northwards along F4 plunge of F1, F2 and F4 structure. Note that on the NW–SE, NE-dipping fold limbs, S2 now dips more steeply than bedding/S1. Its original attitude, obtained by unfolding F4, is less steep, since this area is situated on the inverted limb of a major F2 overfold (see Fig. 17).

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