SVERIGES GEOLOGISKA UNDERSÖKNING

SER. Ca AVHANDLINGAR OCH UPPSATSER NR 75

H. PALM, D.G. GEE, D. DYRELIUS
AND L. BJÖRKLUND

A REFLECTION SEISMIC IMAGE OF CALEDONIAN STRUCTURE IN CENTRAL SWEDEN

UPPSALA 1991

SVERIGES GEOLOGISKA UNDERSÖKNING

SER Ca AVHANDLINGAR OCH UPPSATSER NR 75

H. PALM, D.G. GEE, D. DYRELIUS
AND L. BJÖRKLUND

A REFLECTION SEISMIC IMAGE OF CALEDONIAN STRUCTURE IN CENTRAL SWEDEN

UPPSALA 1991

ISBN 91-7158-489-7
ISSN 0348-1352

Addresses:

Hans Palm and Dan Dyrelius
Department of Solid Earth Physics
University of Uppsala
Box 556,
S-751 22 Uppsala, Sweden

David Gee and Lennart Björklund
Department of Geology
University of Lund
Sölvegatan 13,
S-223 62 Lund, Sweden

Redigering och layout : SGU, Uppsala
Tryck: Offsetcenter AB, Uppsala 1991

CONTENTS

ABSTRACT

Palm, H., Gee, D.G., Dyrelius, D. & Björklund, L., 1991: A Reflection Seismic Image of Caledonian Structure in Central Sweden. Sveriges geologiska undersökning. Ser. Ca 75. 36 pp. Uppsala 1991.

Reflection seismic profiling in the Scandinavian Caledonides is being carried out in the central part of the orogen between Trondheim and Östersund. About one hundred and fifty kilometres of the three hundred kilometres long transect have been investigated so far. About eighty kilometres have been located in western Jämtland, Sweden, reaching from the Norwegian border to the vicinity of Järpen. These measurements are presented and interpreted here.

Very clear reflections have been observed in the Jämtland profile down to about 6 s TWT (c 18 km depth); the deeper crust is apparently transparent and the Moho has not been detected. Reflections in the uppermost second TWT are readily correlated with the surface geology, both the characteristic lithologies in the Caledonian nappes and the major open upright folds (the Skardöra Antiform, the Tännfors Synform, the Mullfjället Antiform and the Åre Synform) that deform the thrust sheets. Below the folded reflections, there is a nearly continuous distinct planar reflection that dips westwards from c 1.1 s TWT at the eastern end of the profile to c 2.5 s TWT at the Swedish-Norwegian border. This reflection is interpreted as a sole thrust along which significant Caledonian transport has occurred. It separates the folded Caledonian allochthon in the hanging wall from a passive, largely undisturbed pre-Caledonian structure in the footwall. Below this reflection, a variety of strong distinct reflections occur down to a depth of nearly 20 kilometres; many of these are foreland (east) dipping. They are not influenced by the Caledonian folds in the allochthon above the sole thrust and are thought to represent rock units and structures in the passive Proterozoic basement. This interpretation is favoured by the regional magnetic anomaly data which clearly indicate that the highly magnetic, c. 1700 Ma Dala-type granites in the autochthon of Dalarna can be followed northwards beneath the Swedish Caledonides. In the Dalarna autochthon, these granites intrude acid volcanites and are overlain by Jotnian Dala sandstones; the latter contain basalt flows and, along with the granites and volcanites, are extensively intruded by dolerites. The sub-thrust reflections are, therefore, argued to be mainly related to mafic sills in granites, volcanites and subordinate Mid Proterozoic sandstones. These lithologies are known from previous reflection seismic experiments to provide a reflective upper crust similar in many respects to that seen in the Jämtland profile.

These first reflection seismic experiments in the Swedish Caledonides have demonstrated that the basement in the cores of the major late antiforms in the central part of the orogen is allochthonous. Considerable basement shortening occurred during Scandian collisional orogeny.

Hans Palm and Dan Dyrelius, Department of Solid Earth Physics, University of Uppsala, Box 556, S-751 22 Uppsala, Sweden.
David Gee and Lennart Björklund, Department of Geology, University of Lund, Sölvegatan 13, S-223 62 Lund, Sweden.

Introduction

Reflection seismic profiling through mountain belts has provided some excellent control of structural geometry and has strongly influenced tectonic interpretations (e.g. Bally et al. 1966). This technique, originally developed by the oil industry for investigation of sedimentary terrains, has been applied increasingly in recent years to the study of the deep structure of older orogens. It has met with remarkable success in many parts of the world (Clark et al. 1978, Cook et al. 1979, Barazangi & Brown 1986a and b, Matthews & Smith 1987, Choukroune et al. 1989, Spencer et al. 1989), and is now being used increasingly in Fennoscandia to investigate the crystalline bedrock. Extensive Caledonian thrust sheets with contrasting lithologies and thick mylonites provided a suitable incentive for this first experiment in the Scandes.

The Scandes expose a deeply eroded section through part of a collisional orogen (Gee & Sturt 1985, Stephens 1988). Surface mapping provides evidence for the Caledonian emplacement of a variety of eugeoclinal terranes many hundreds of kilometres onto the Baltoscandian platform of continent Baltica (Fig. 1). From analysis of the rocks at or near the surface, a long and complex history of terrane development and accretion to Baltica can be deciphered. The latter involved early Caledonian (Finnmarkian c. 520–480 Ma) assembly of various oceanic and continent-ocean transitional units along Baltica's outer margin and subsequent thrusting of this nappe pile onto the platform; tectonothermal activity culminated in Scandian collisional orogeny (c.430–390 Ma). This collision, occurring after closure of the Iapetus Ocean, involved underthrusting of Laurentia by Baltica and substantial shortening and thickening of the Proterozoic and, in northern Scandinavia, Archean crystalline crust.

Analysis of Caledonian high pressure parageneses in eclogites in the Baltica basement of the Scandian hinterland has shown that the underthrusting of Laurentia by Baltica involved subduction of crustal units to depths of 70–80 km, perhaps more; depths comparable with those known for the lower crust beneath the hinterland of some of the world's highest mountain belts. Isotopic age-determination studies indicate that this deep depression, during Scandian continent collision, was followed by very rapid uplift, erosion and deposition of intramontane and extramontane molasse (Old Red Sandstones). Crustal extension accompanied this uplift of the mountain belt.

Understanding of these processes of collision, with crustal shortening and thickening, extension and thinning, requires control of structural geometry in depth. This paper presents new reflection seismic data for interpretation of deep structure in the central part of the mountain belt (Fig. 2). It assesses these data in relation to the previously acquired geophysical (refraction seismic, gravity and magnetic) and geological data, and discusses alternative interpretations of both the geometry and the tectonic evolution. Interpretation of this geometry is much dependent on the analysis of surface structure, particularly the kinematic analysis of the various faults, some of which have complex compressional and extensional histories.

The central part of the mountain belt was chosen by the International Lithosphere Programme (ILP) committees in Norway and Sweden for this first reflection seismic profile in the Scandinavian Caledonides. The choice was dictated first and foremost by the existing data base, both geological and geophysical, and the knowledge that reflection data would greatly help constrain previous interpretations of deep structure, based primarily on other geophysical techniques. The central Scandes are classical ground for the early development of the nappe hypothesis (Törnebohm 1888) and have been the focus of many subsequent studies, more recently during the International Commission on Geodynamics. Together with adjacent off-shore areas of the Vöring Plateau, it has been selected for transect interpretation in the context of the new ILP project Global Geoscience Transects (Monger 1986).

Mapping of the Caledonian mountain belt towards the end of the last century established the distribution of the major allochthons (Högbom 1894, Törnebohm 1896) and a number of windows were identified, exposing basement rocks in their cores. The distribution of the basement rocks in the windows and in major culminations (e.g. the Grong-Olden Culmination), persuaded Högbom (1909) and Asklund (1938) that the overlying allochthons were probably derived from west of the basement now exposed along the Norwegian coast; this interpretation found support in a variety of other lines of independent evidence (Gee 1975a).

The extent to which the basement in the windows was involved in the Caledonian thrusting has long been a subject of debate. Some of the windows are clearly composite, containing thrust repetitions of basement and Caledonian cover; others contain only basement rocks, but their geometry and internal deformation indicate some lateral displacement. Nevertheless the ambiguity of many of these relationships led Gee et al. (1985a), when compiling the Tectonostratigraphic Map of the Scandinavian Caledonides, to refer to all these basement units in the deepest levels of the windows as "parautochthonous". The term parautochthon was defined (Gee & Zachrisson 1979, p. 13) to allow significant lateral displacement, the extent of which was unspecified, but inferred to be less than that of the overlying allochthon. In the hinterland, towards the Norwegian coast a greater confidence in the allochthonous character of the base-

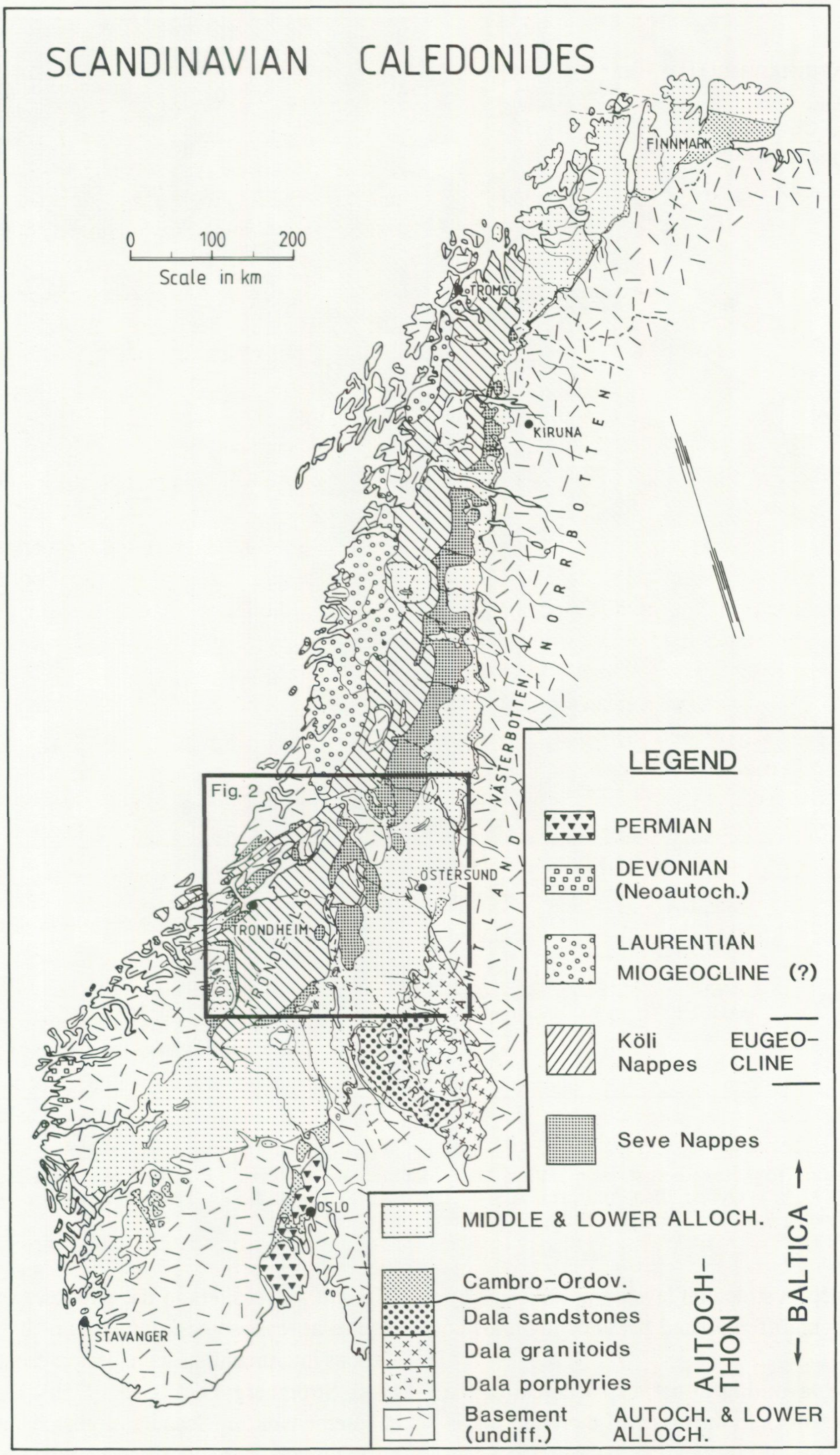


Fig 1. Simplified terrane map of the Scandinavian Caledonides. Note the distribution of the Dala sandstones and igneous rocks in the autochthon.

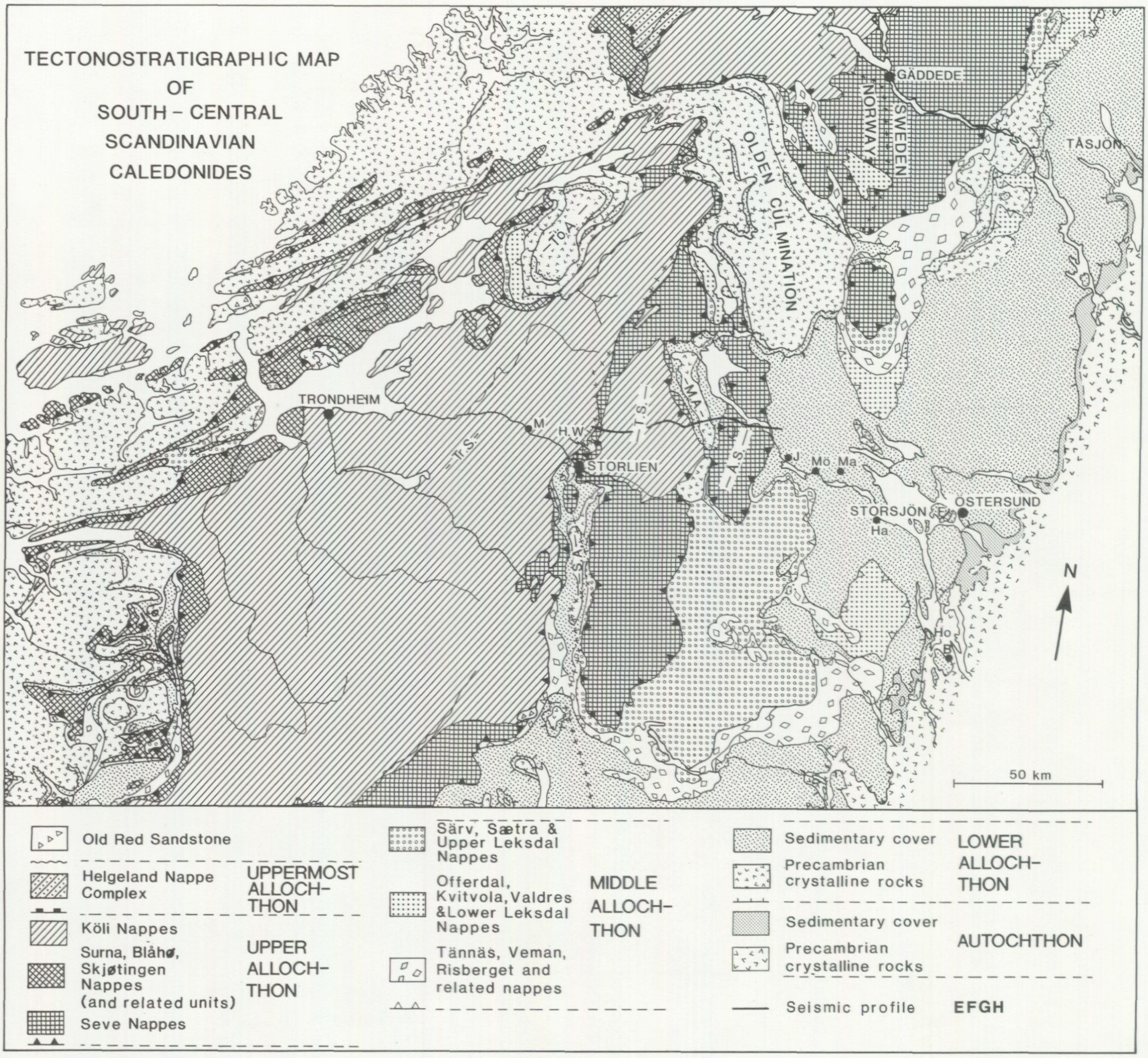


Fig 2. General tectonostratigraphic map of the central Scandes, redrawn from Fig 1 in Gee et al. (1985b). *Localities:* B = Bingsta, D= Djupsjön, F = Frösön, Ho = Hoverberget, Ha = Hallen, Ma = Mattmar, Mö = Mörsil, J = Järpen, M = Meråker. *Structures:* M.A. = Mullfjället Antiform, Ov.A. = Oviksfjällen Antiform, Å.S. = Åreskutan Synform, T.S. = Tännfors Synform, H.W. = Hästryggarna Window, Tr.S. = Tröndelag Synform, Tö.A. = Tömmerås Antiform.

ment rocks in the deepest structural levels was indicated by referring to them as undifferentiated parautochthon/lower allochthon.

Indirect evidence favouring thrust displacement of the basement crystalline rocks in the cores of the windows is provided by comparison of the Vendian to Ordovician successions deposited on the older crystalline rocks in the autochthon, in the "parautochthon" of the windows and in the lowermost thrust sheets of the Caledonian foreland. Inferred thrust displacements of the Cambro-Silurian cover of a few kilometres to tens of kilometres (Thorslund 1940) in the thrust front and comparison with related, but significantly different successions in the windows (eg Gee et al 1978) require at least some kilometres of basement shortening. Various interpretations have been presented (Asklund 1938, 1960, Strömberg 1974, Gee 1975b). However, shortening of basement during Scandian collision has not been accepted by all authors, particularly those who favoured diapirism as the driving force for the nappe displacements (Ramberg 1966, 1980, Stephansson 1976). Thus, several multi-author contributions resulting from the work in the 1970s (e.g. Dyrelius et al. 1980, Gee et al. 1983) chose to avoid this controversial issue, portraying a passive, gently folded basement in the windows. Subsequently, during the 1980s, interpretations have favoured considerable basement shortening (eg Hossack & Cooper, 1986).

Geophysical surveys provide the most compelling evidence for extensive basement-shortening in the mountain belt. High level flight magnetic measurements (Eleman et al. 1969) identified a large (c. 400 nT) positive anomaly, related in the autochthon to Proterozoic (c. 1750–1650 Ma) magnetite-rich granitoids (Riddihough 1972, Dyrelius 1980); this, the Jämtland Anomaly, can be traced for nearly 200 kilometres westwards beneath the Caledonian nappes. Although the crystalline rocks, coring the Caledonian windows, are petrographically similar to those in the autochthon, they prove to have much lower magnetic susceptibilities (Elming 1980), possibly the result of Caledonian deformation and low greenschist facies metamorphism. A passive basement, little influenced by Caledonian deformation and metamorphism, was therefore inferred to underlie these deformed rocks in the windows.

Supporting evidence for basement shortening was found in a variety of shallow, seismic refraction experiments (Palm and Lund 1980, Palm 1984) in the Caledonian front, where the upper surface of the basement (the Cambrian unconformity) was traced beneath the nappes, from the thrust front towards the west. A gentle (1–2°) westerly dip of the basal unconformity and the sole thrust of the frontal décollement was shown to increase slightly westwards and, farther west, to be interrupted by faulting and basement uplift; gross geometry suggested basement imbrication. Likewise, interpretation of magnetic data (Dyrelius 1980, 1985, 1986) favoured an irregularity of the basement surface that could be interpreted as related to Caledonian thrusting.

Thus, prior to the planning of the reflection seismic studies reported here, it could be inferred that the Scandian thrusting involved not only cover detachment close to the basement-cover interface, but also substantial imbrication of the underlying crystalline rocks (Gee 1986). The character of this basement shortening at depth across the orogen, and its relationship to crustal thickening, development of the very high pressure metamorphism in the hinterland and subsequent extension were subjects that could be best investigated by reflection seismic measurements. Significant differences in seismic velocity (Palm 1986) and density (Elming 1980) between the dominating lithologies in the nappes, and the extensive development of mylonites along many of the thrusts provided promising preconditions for reflection profiling.

In 1986, an experimental two kilometre profile was recorded in the vicinity of Meråker (Fig. 2) in central Tröndelag, in collaboration with colleagues from Bergen University; it demonstrated the high reflectivity of the upper crust in this central part of the mountain belt. Systematic profiling, using explosives for the energy source, was therefore started in 1987 with the recording of 22 kilometres of section (Hurich et al. 1988, 1989) across the Skardöra Antiform from Storlien to Meråker (Fig. 3, Segments B–C); in addition, a 7 km long test profile was shot in the Tännfors area in the vicinity of Bodsjön (Fig. 3, segment F). During 1988, the measurements continued in Norway, westwards from Meråker, using a newly acquired vibroseis energy source. In Sweden, explosion seismic profiling was extended from the national border, eastwards across the Tännfors Synform, the Mullfjället Antiform and the Åre Synform, to the vicinity of Järpen. It is this eastern section (c. 67 km long) and its connection (c. 15 km) to the 1987 profile across the Skardöra Antiform that is reported here.

Outline of the geology

The general geology of the profile treated here and shown in Fig. 2 has been described in several papers, most recently in Gee et al (1985b). Following Kulling (in Strand & Kulling 1972) with minor modification (Gee and Zachrisson 1979, Gee et al. 1985a), the tectonic units in western Jämtland can be conveniently treated in four main complexes, the Autochthon, Lower, Middle and Upper Allochthons.

These are summarized below, along with a brief treatment of the regional structure.

AUTOCHTHON

Throughout the Caledonian front Cambrian shales and/or thin basal sandstones rest on a late Vendian to early Cambrian peneplain and are underlain by Precambrian rocks dominated by granites and gneisses. Generally, the shales and, particularly, the kerogen-rich varieties (Alum Shale Formation) provide the main detachment surface for the frontal décollement. The thermal maturity of these autochthonous shales (Snäll 1988), taken along with the evidence of conodont thermal alteration (Bergström 1980) indicate that the Caledonian tectonic overburden in the mountain front was in the order of ten kilometres, implying that the deformation front during thrusting must have reached many tens of kilometres east of the present thrust front. There is as yet little evidence that the autochthonous basement, east of the thrust front, was involved in the Caledonian thrusting, but this possibility cannot be excluded.

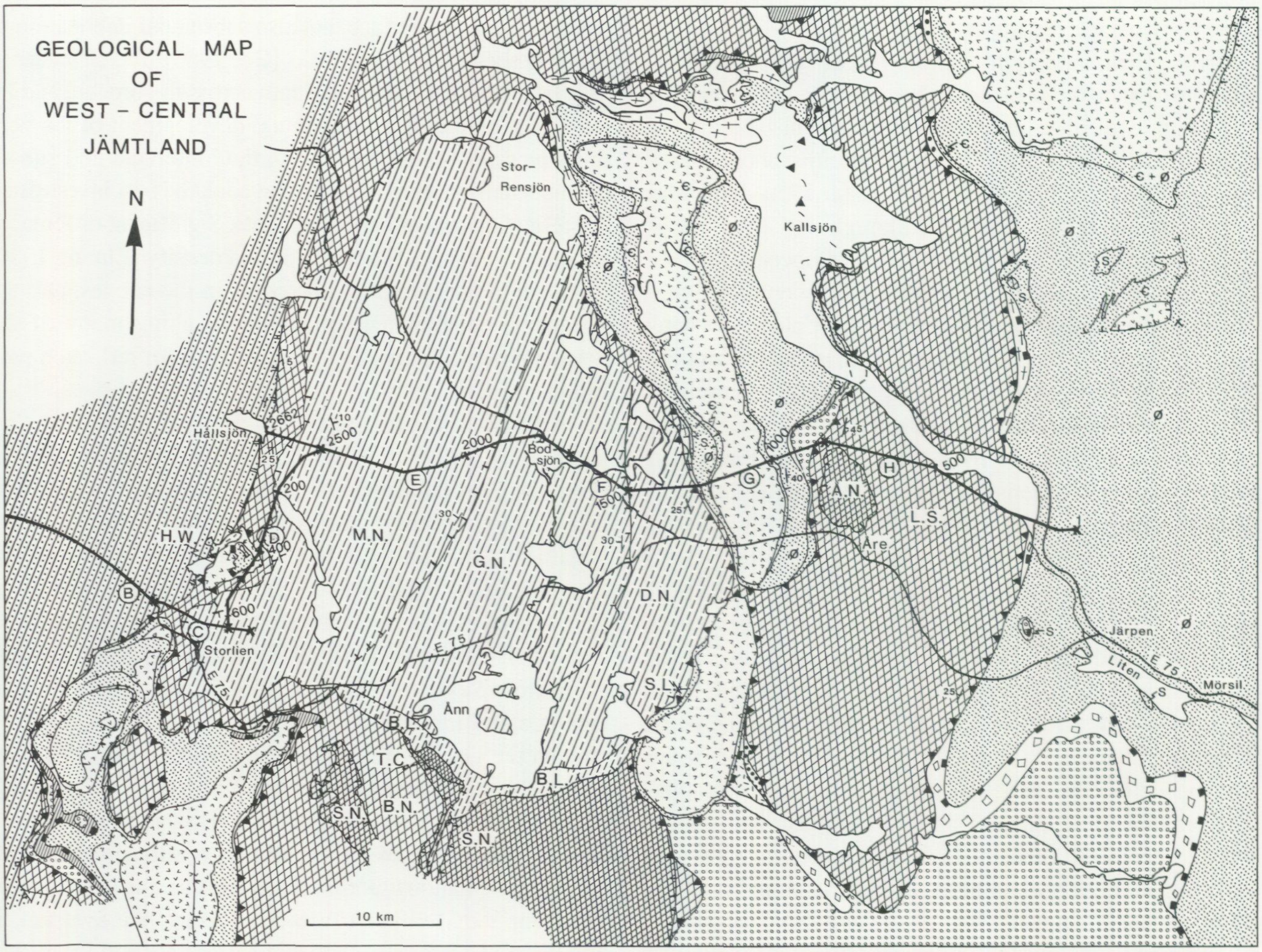


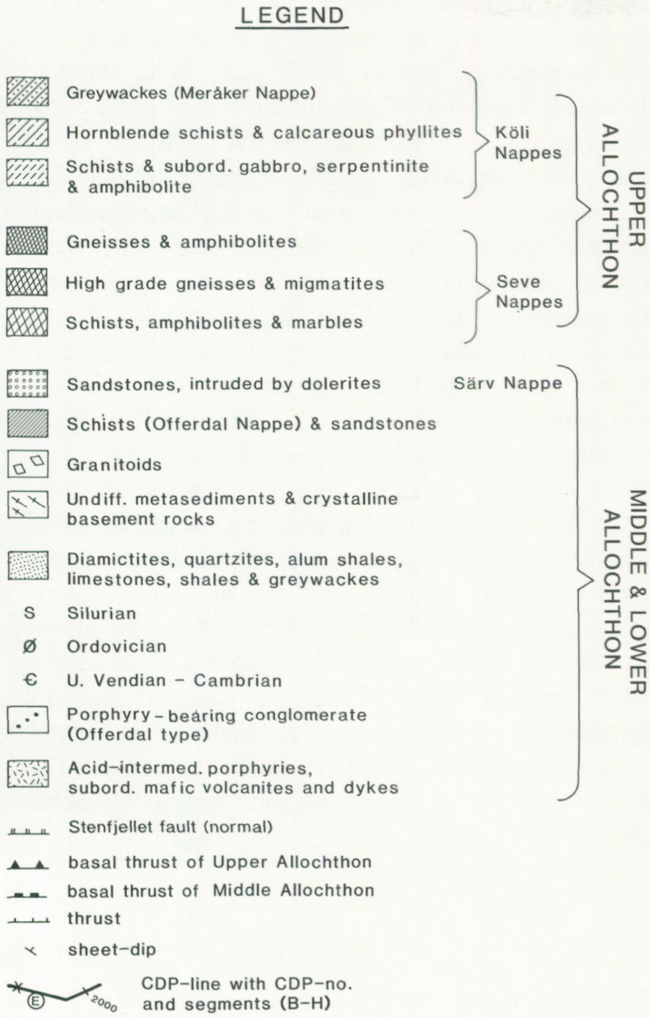
Fig 3. Geological map of west-central Jämtland, showing the line of the reflection seismic profile with segments and CDP (common depth point numbers). Abbreviations: L.S. = Lower Seve Nappe, Å.N. = Åreskutan Napppe, B.N. = Blåhammarfjället Nappe, S.N. = Snasahögarna Nappe, T.C. = Täljstensvalen Complex, S.L. = Svarttjärnen Lens, B.L. = Bunnerviken Lens, D.N. = Duved Nappe, G.N. = Gevsjön Nappe, M.N. = Middagsfjället Nappe. Compiled from Hardenby (1980), S. Tirén in Gee & Kumpulainen (1980), Beckholmen (1984), SGU (1984), Sjöström (1984), Gilotti & Kumpulainen (1986), Sjöström (1989 pers. comm.) and Björklund (unpublished data).

The autochthonous Precambrian basement is dominated by crystalline rocks. An important north-trending contact (Fig. 1) separates Dala-type granites (eg the Rätan granite, c. 1700 Ma) and rhyolitic porphyries, from an older terrain to the east, consisting of Svecofennian supracrustal rocks, migmatites and granites (e.g. the Revsund granite, c. 1800 Ma); this boundary reaches the Caledonian front in the vicinity of Hoverberget (Fig. 2). As mentioned above, a prominent magnetic anomaly related to the post-Svecokarelian, Dala-type granites, can be followed northwards beneath the mountain belt, indicating that this contact is preserved beneath the allochthon at least as far north as Gäddede (Dyrelius 1980 p. 423).

Overlying the Dala volcanites, in Härjedalen, are nearly a kilometre of non-marine, Dala sandstones containing some basalt intercalations c. 100 m thick (the Öje "diabase" of Hjelmquist 1966). The entire volcanosedimentary sequence and the granites are intruded by dolerite sills of Åsby and Särna type (c. 1220 Ma) and vertical Tuna dykes (c. 1370 Ma, Patchett 1978, Lundqvist 1979), generally a few tens of meters thick; however, Hjelmquist (1966) reports a local sill thickness of several hundred meters. These very low grade Mid Proterozoic sedimentary and igneous rocks (Nyström & Levi 1980, Nyström 1983) are preserved in a shallow open NW-trending syncline; they separate the crystalline rocks from the Caledonian cover in northern Härjedalen (Fig. 1) and have been followed northwards beneath the mountain front for c. 20 km in the vicinity of the Vassbo lead-zinc mine (Christofferson et al 1979).

LOWER ALLOCHTHON

Throughout the Caledonian front in the central Scandes a sole thrust, with alum shales in the footwall, dips 1–2° W



beneath a folded and thrust succession of Cambro-Silurian sedimentary rocks. Surface mapping of the thrust front demonstrates that ESE-transport on this basal detachment exceeds 30 km. A drilling project (Gee & Snäll 1981, Andersson et al 1985) in the area immediately south of Storsjön has shown that the sole thrust can be followed a further 20 km to the WNW, carrying Lower Cambrian (possibly Upper Vendian) quartzites, Middle and Upper Cambrian black shales and Ordovician limestones shales and greywackes in the hanging wall. In this allochthon, in the surroundings of Storsjön, the Middle Ordovician turbidites pass up into Upper Ordovician to lowermost Silurian shales and shallow marine sandstones. These are overlain by Lower Silurian limestones and then dark shales and greywackes, the latter reaching into the Middle Silurian (early Wenlock age) and being capped by non-marine sandstones (Bassett et al. 1982). An Ordovician facies transition, from limestones in the mountain front east of Storsjön to shales and greywackes in central and western Storsjön (Thorslund 1940, Karis in Gee & Kumpulainen 1980, p. 18), is telescoped by several thrusts splaying off the basal detachment (Andersson et al. 1985).

The Cambro-Silurian successions (included in the Jämtland Supergroup of Gee 1975a) of the Lower Allochthon are most extensively preserved in areas of west-central and northwest Jämtland, where limited exposure in the farming and forested areas has not allowed detailed analysis of structure; only in connection with extensive prospecting operations, as mentioned above for the area south of Storsjön, or in northern Jämtland in the vicinity of Tåsjön (Gee et al. 1978), has it been possible to reconstruct internal geometry in these lower thrust sheets in any detail. The sedimentary successions are thin in the eastern front, the entire Cambro-Silurian packet being in the order of 300 m. Further west, the Ordovician greywacke successions are much thicker than the corresponding limestone facies in the thrust front. However, we have no basis today for a confident estimate of their stratigraphic thickness, which must exceed a kilometre and may be several kilometres. Fossil finds are rare, and the parts of the fragmented succession that have been studied in detail locally, have proved difficult to relate to the development of the entire succession.

Early interpretations of the internal structure of these lower tectonic units, favoured the presence of two major thrust sheets, the Föllinge and Olden Nappes (Asklund 1938, 1960), transporting the Ordovician greywacke facies eastwards onto the underlying imbricated, more locally derived platform facies in the thrust front (Thorslund 1940). These interpretations do not find support in the recently published map of Jämtland county (SGU 1984, Strömberg in prep.), where the cover and basement shortening has been inferred to have occurred by folding and transport on minor thrusts that more uniformly telescope the entire succession (Strömberg 1986).

Within the windows of western Jämtland, basement rocks exposed in the Olden, Mullfjället and Skardöra Antiforms (Fig. 2) were incorporated by Asklund (1938) in the Olden Nappe. Subsequent recognition of extensive cover detachment (e.g. Tirén in Gee & Kumpulainen 1980, p. 46–50), and the preservation of only a thin Cambrian veneer of sediments deposited on these crystalline massifs, implied that the thick Ordovician clastic wedge, at least in part, was thrust over these Proterozoic units. Nevertheless, the latter were clearly involved in the crustal shortening; the extent of their displacement was undefined and they were therefore referred to as parautochthonous. The new reflection seismic data presented here favours their incorporation in the Lower Allochthon.

Supporting evidence for the existence of an important thrust carrying both the crystalline rocks of the windows and their overlying detached cover was obtained by refraction seismic profiling in the Caledonian front between southern

Storsjön and Järpen (Palm & Lund 1980). These experiments constrained the depths to the crystalline rocks beneath the Caledonian cover, from the east, where passive basement is defined by drilling (Andersson et al 1985), and westwards to the Mullfjället and Olden Windows, where involvement of the basement in the thrusting was anticipated. Studies of the Olden Window by Sjöström & Talbot (1987) have provided further evidence that this major structure is a thrust culmination.

MIDDLE ALLOCHTHON

A major thrust, with development of thick phyllonites and mylonites, truncates underlying structures in the Lower Allochthon, carrying a greenschist facies complex of miogeoclinal rocks and sheets of Proterozoic crystalline basement in the hanging wall. Several internal thrusts have been recognized and the complex is readily divisible into two parts. A lower packet of thrust sheets up to about two kilometres thick intercalates granites and augen gneisses with unfossiliferous metasandstones (including the Offerdal and Tännäs Augen Gneiss Nappes). The upper part (the Särv Nappes) is composed of thick late Proterozoic sediments (Kumpulainen 1980), extensively intruded by latest Proterozoic dolerites (Claesson & Roddick 1983).

The general structure of the Särv thrust sheets has been described by Strömberg (1961) and Kumpulainen (1980). In the main area of development in southern Jämtland, Gilotti and Kumpulainen (1986) have shown that the characteristic lenticular geometry is controlled by hanging wall flats and ramps. Thus, the Särv thrust sheet, presently c. 2 km thick in southern Jämtland and northern Härjedalen, cuts out on a lateral ramp north of Ottfjället (Fig. 3). Further north, these thrust sheets occur as a series of horses in west-central and northwest Jämtland.

UPPER ALLOCHTHON

Two major tectonic complexes, the Seve and overlying Köli Nappes, compose the Upper Allochthon. In western Jämtland, the Köli units are restricted to the Tännfors area which is crossed by the seismic profile. The Seve (Zachrisson 1973) is a more extensive allochthon in this part of the mountain belt; its basal thrust transgresses a variety of tectonic units of the Middle and Lower Allochthons.

Amphibolite facies and higher grade units characterize the Seve thrust sheets (Hellfrisch 1966, Arnbom 1980). In contrast to the underlying Särv units, highly penetrative strains are distributed throughout and there is approximate concordance between the different lithologies and tectonic units. The Seve rocks are characterized in the lower parts by interbanded amphibolites and schists, the latter mainly of psammitic and calcareous composition; marbles are locally important components. An overlying tectonic unit in west-central Jämtland is dominated by granulite facies gneisses and migmatites; further north (e.g. in northernmost Jämtland), another high grade unit is composed of eclogite facies gneisses (van Roermund & Bakker 1984). These in turn are overlain in most areas by schists and amphibolites.

These Seve units vary greatly in thickness, reaching a few kilometres in northern Jämtland; locally they are cut out completely and the overlying Köli units rest directly on the underlying Lower and Middle Allochthons. Lenses of Seve occur further towards the hinterland in eastern Tröndelag on Öyfjellet and further west in the Tömmerås Antiform.

Köli thrust sheets in west-central Jämtland are dominated by monotonous calcareous phyllites and schists (Frödin 1922, Beckholmen 1984), but contain a heterogeneous basal unit thrust onto the higher grade Seve. A fragmented ophiolite with igneous bodies up to c. 200 m thick is preserved in a lenticular sheet at the base of the Köli in the southern part of the Tännfors area (Gee & Sjöström 1984, Bergman 1987), overlain by the calcareous phyllites. Higher in the synform two important thrusts place higher grade metasedimentary units above these phyllites, the highest unit being dominated by garnet, hornblende, mica schists (Beckholmen 1984).

STRUCTURE

The major thrust complexes of the Lower, Middle and Upper Allochthons are folded together on approximately N-trending axes. The Sweden-Norway border runs close to the axis of the Skardöra Antiform, flanked to the east by the Tännfors Synform, the Mullfjället Antiform, the Åre Synform and the Olden Antiform (Fig. 2). These major late Caledonian folds influence all rock units, folding the thrusts separating the different nappes and the wide variety of earlier major and minor structures in the various allochthons.

The structure of the Lower Allochthon, east of the Åre Synform, is dominated by E-vergent cylindrical folds and related thrusts. The latter are inferred to be listric and curve back into a basal décollement, drillhole data locally providing unambiguous evidence for this geometry. An axial surface cleavage related to these folds increases in intensity westwards and is particularly well developed west of Storsjön. In the contact zone to the overlying Middle Allochthon, this cleavage is overprinted by a thrust-related penetrative foliation. Major folds within the Lower Allochthon in the Offerdal-Alsen area are discordantly overridden by the Offerdal Nappe (Middle Allochthon), implying significant, late, out-of-sequence movement on the basal Offerdal thrust. In more westerly areas, where the Lower Allochthon is exposed in the Mullfjället and Skardöra Antiforms, the sedimentary rocks are more penetratively deformed and early cleavages are arched by the antiforms.

The overlying units in the lower part of the Middle Allochthon are characterized by much higher penetrative strains than in the Lower Allochthon, with most Precambrian crystalline rocks mylonitic and associated metasediments isoclinally folded. Lenticular bodies of better preserved granitoids occur locally within the mylonites. The strong planar fabrics of these thrust sheets are folded gently by the major late folds, referred to above. Likewise the overlying Särv Nappes (Strömberg 1961), dominated by sandstones and dolerites, are generally strongly penetratively deformed, with the contrasted lithologies concordantly interbanded; only in eastern areas, particularly in the type area for the Särv Nappes (Gilotti & Kumpulainen 1986) and locally further west in subordinate lenses are high angle discordant primary relationships between dykes and bedding well preserved.

Both the overlying Seve and Köli units are characterized by strong penetrative deformation with regionally developed isoclinal folding and related schistosities, concordant with the main thrusts. The extensive shearing and folding, together with the great lithological heterogeneity and differences in competence of the Seve units, has resulted in a characteristic internal lenticularity; lithologies interdigitate, and can seldom be followed over distances of more than a few kilometers. By contrast, the isoclinally folded and refolded Köli metasediments in western Jämtland are singularly monotonous, their internal structure being dominated by regionally developed penetrative flat-lying schistosities.

Choice of profile

The 1987 measurements from Storlien to Meråker across the Norwegian-Swedish border were primarily aimed at imaging the internal structure of the Skardöra Antiform and the general geometry of the overlying allochthon (the Meråker Nappe) to the west. The 1988 measurements, reaching seventy kilometres east from the national border towards the mountain front, cross most of the tectonic units described above.

The 1987 seismic profile followed the main highway (E 75) on the Norwegian side of the border (Segment B on Fig. 3) and extended cross-country eastwards in Sweden from the border to pass north of Storlien (Segment C). This line of section was the most appropriate for future extension westwards through Tröndelag. However, in Sweden a direct continuation eastwards, approximately following the path of road E 75, would have implied crossing considerable thicknesses of glacial overburden in southern parts of the Tännfors area and in the Indalsälven valley to Åre. Thicknesses of as much as 100 m of glaciofluvial sediments occur in some of the valleys and beneath parts of the main roads. Sands dominate and these are the most troublesome, absorbing the seismic signals and generating high amplitude surface waves that obstruct recording of reflected energy and may be dangerous for buildings.

In anticipation of these problems, a seven kilometres long profile was acquired in 1987 in the central part of the Tännfors area (Segment F, Bodsjön) to test shot and geophone intervals, charge size, borehole depth and spread configuration. This successful experiment provided the basis for the choice of the seismic line and the field parameters for 1988.

It was decided to traverse the Tännfors Synform centrally, by extending the 1987 Bodsjön profile (Segment F) both westwards to the Norwegian border (Segment E) and eastwards over Mullfjället (Segments G and H). A N–S profile (Segment D) from Storlien to near Hållsjön (Fig. 3) was shot to link these new measurements to Segment C. Thus the main part of the seismic line is located far from the roads; it avoids the steeper mountain ridges, but keeps as much as possible above tree-line and to areas of good bedrock exposure.

The exact line of the profile was chosen on the basis of the existing bedrock maps and knowledge of the thickness and character of the Quaternary overburden. The line was kept as straight as possible, following the gentler ridges above the tree line and minor roads and paths in the wooded areas.

Lithologies and structures along the line of the reflection seismic profile

The easternmost part of the seismic line is located a few kilometres north of Järpen (Fig. 3), where it crosses a gently W-dipping sequence of Ordovician turbidites in the Lower Allochthon. These are well-bedded greywackes, with individual beds generally showing grading from grits and sands to very fine grain sizes. Bed thicknesses are generally 1–3 dm, but vary greatly from a few centimetres up to a metre. The bedding is folded into foreland verging, open to tight folds, with generally N-S trending axes and an associated high angle W-dipping cleavage. Bedding is mainly upright, dipping 20–30° W; however, locally, it dips steeply eastwards or is overturned, with steep westward dips. Towards the overlying nappe units in the Åre Synform, this fold-pattern is commonly modified and refolded by open to tight, gently NW-plunging folds and an associated crenulation cleavage.

In the line of profile at the southern end of Kallsjön the basal thrust to the overlying nappes rests on the Ordovician greywackes. However, both north and south of the line, a sequence of Silurian sediments overlying the Ordovician greywackes and shales is locally preserved in the footwall of this thrust. The Silurian sequence, the Änge Group of Strömberg (1974), reaches a maximum thickness of a few hundred metres and includes, from base upwards, a few metres of quartzites and limestones, overlain by shales and greywackes.

At the southern end of Kallsjön, the seismic profile crosses the major thrust at the base of the Seve Nappes (Upper Allochthon). A minor lens of the Middle Allochthon, consisting of mylonitized porphyry, a few tens of metres thick occurs in the footwall of this thrust.

Two main thrust sheets are distinguished here within the Seve Nappe Complex of the Åre Synform; a lower unit of amphibolite facies lithologies (Lower Seve Nappe) and a higher unit (Åreskutan Nappe) of upper amphibolite to granulite facies gneisses, migmatites and metabasites (Arnbom 1980, Arnbom & Troëng 1982, Gee & Kumpulainen 1980). The seismic profile is located entirely within the Lower Seve Nappe, following close to the southern shore of Kallsjön and then continuing westwards, to pass just north of and below the basal thrust of the Åreskutan Nappe. In the eastern limb of the Åre Synform, the basal units of the Lower Seve Nappe are dominated by calcareous schists and gneisses, micaceous marbles and amphibolites, all dipping c. 10° SW. Overlying these rocks in the hinge of the synform, the seismic line crosses quartzitic and quartzo-feldspathic schists, interlayered with concordant sheets of amphibolite a few tens of metres thick and subordinate larger more irregular basic bodies. A few lensoid peridotites occur, usually together with the thicker sheets of amphibolites. In the western limb of the synform, the seismic profile passes through the base of the Lower Seve Nappe, there dominated by mica schists, quartzo-feldspathic schists and amphibolites sheet-dipping c. 35–40° E.

In the western limb of the Åre Synform a lens of the Särv Nappes, consisting of highly schistose and folded psammites and metadolerites (the latter locally discordant, but generally concordant and penetratively deformed), occurs beneath the basal thrust of the Seve Nappes. This lens is estimated to be a maximum of 200 m thick, where crossed by the seismic line. Its eastward extension beneath the Seve Nappes is not constrained from the surface geology.

West of the Åre Synform, the seismic profile crosses the NNW-trending Mullfjället Antiform, the latter cored by Precambrian volcanic rocks and overlain by low grade metasediments of the Jämtland Supergroup. Mainly acid and minor intermediate, porphyric metavolcanites occur along the line of profile; the porphyries are generally homogeneous, lacking conspicuous primary layering and other structures. Immediately south of the profile, however, such structures are common, including compositional and ignimbritic banding, calcite- quartz- and fluorspar-filled amygdules, agglomerates and fragment-rich beds, and crystal and lapilli tuffs (Beckholmen 1980, Gee & Kumpulainen 1980). A minor outcrop of very coarse quartz-syenite with irregular intrusive contacts to the surrounding porphyries occurs just south of the profile. This indicates the possible presence of more significant volumes of granitoids at deeper levels in the antiform. A penetrative foliation commonly cuts the primary layering, dipping generally 40–60° NW. At a few localities, this foliation occurs as an axial-plane schistosity to open asymmetric N60W-plunging folds, verging towards the NE.

A few sub-vertical NNE-striking dolerites, up to 75 m thick, cut the primary layering in the porphyries at high angles. The dolerites are ophitic, medium-grained and massive, but little of the primary mineralogy is preserved (cf. Beckholmen 1980). Chilled margins are common.

The low grade metasediments of the Jämtland Supergroup, overlying the porphyries and dolerites in the eastern limb of the Mullfjället Antiform, though much attenuated, include the entire Vendian to Silurian succession. A few metres of diamictites occur, deposited locally on the porphyries and overlain by thin (up to 20 m) quartzites and a few metres of quartz phyllites. These are followed by black graphitic phyllites correlated with the Mid- to Upper Cambrian Alum Shale Formation and then by Ordovician turbiditic greywackes, and Silurian quartzites, limestones, shales and greywackes. Diagnostic fossils have only been found in the Silurian limestones. Along the seismic profile, this sequence is about 400 m thick and the right way up; however, evidence (see below) from further north suggests that it is probably interrupted by an important thrust above the Alum Shale Formation. These metasediments separate the lens of Särv Nappe in the footwall of the Lower Seve Nappe from the porphyries in the core of the Mullfjället Antiform.

Mapping of the northern (Tirén in Gee & Kumpulainen 1980, p. 46–50) and western (Beckholmen 1980) parts of the Mullfjället Antiform identified an important décollement surface close above the basement, separating the Precambrian volcanic rocks with a thin veneer (a few metres to tens of metres) of quartzites and alum shales from an overlying thrust sheet, the Kallsjön Nappe, of Cambro-Silurian strata. Along the seismic profile, the Kallsjön thrust is apparently located at the top of the alum shales where the latter are highly sheared in the contact zone to the overlying Ordovician greywackes. In the seismic profile, the latter are c. 350 m thick in both limbs of the Mullfjället Antiform and the overlying Silurian quarzites, limestone shales and greywackes are less than 30 m. Within the eastern limb of the antiform, the E-dipping strata are folded by tight S-vergent, neutral folds plunging ESE, and with an associated NE-dipping cleavage.

A similar, but thinner (Vendian?) Cambrian to Silurian stratigraphic sequence, occurs in the western limb of the Mullfjället Antiform (Beckholmen 1980). Basal diamictites have not been recognized and the quartzites are extensively sheared, suggesting detachment of the sedimentary sequence along the contact with the underlying Precambrian porphyries. These rocks have, therefore, all been considered to lie above the Kallsjön thrust referred to above (Tirén in Gee & Kumpulainen 1980, p. 46–50).

In the western limb of the Mullfjället Antiform, lenses of mylonitic crystalline rocks and quartzites, of the Middle Allochthon, overlie the sedimentary rocks of the Lower Allochthon (Beckholmen 1980). Their thicknesses vary from several hundred metres to only a few metres, where they are crossed by the seismic profile. Minor lenses, less than 50 m thick, of Seve amphibolites overlie the Middle Allochthon, a few kilometres north of the line, but are cut out in the vicinity of the latter.

The seismic profile continues westwards across the Köli Nappes of the Tännfors Synform. The lowermost units along the profile are metasediments of the Duved Nappe, all in low greenschist facies, isoclinally folded and refolded and sheet-dipping at c. 30° W. Subordinate conglomerates and quartzites occur near the base, but this thrust sheet is dominated by calcareous phyllites. Locally, more coarse grained units provide evidence of grading, suggesting that the sequence is of turbiditic origin. As mentioned earlier, a variety of other lithologies occur locally in the hanging wall of the basal Köli thrust elsewhere in the Tännfors Synform. The Duved Nappe phyllites are overthrust by the Gevsjön Nappe. The contact zone is well exposed close to the line of the seismic profile at Tännforsen where the thrust is marked by a 30 m thick zone of mylonites and phyllonites (Beckholmen 1982), dipping c. 30° W. Metamorphic grade is somewhat higher in the Gevsjön Nappe with biotite conspicuous and hornblende occurring locally, particularly in the upper part. The lithologies are dominated by calcareous turbidites, with metasandstones more frequent than in the underlying unit. Isoclinal folding is associated with a schistosity that parallels compositional banding and sheet-dips c. 20° W. Another important thrust occurs higher in the Köli units further west, bringing the hornblende schists of the Middagsfjället Nappe onto the Gevsjön Nappe. The strata in these two thrust sheets are similar, but metamorphic grade is clearly higher in the former where schists dip very gently east and west in the hinge of the Tännfors Synform. A concordant basic body, up to 500 m thick, occurs in the Middagsfjället Nappe (Beckholmen 1983) c. 15 km north of the line of profile. This is the only record of igneous rocks in the Köli Nappes of the Tännfors area, with the exception of the fragmented ophiolite and subordinate concordant sheets of greenschists, amphibolites and keratophyres preserved locally at the base of the complex. The westernmost part of the seismic profile, west of the axis of the Tännfors Synform, crosses from low angle E-dipping Köli schists to underlying Seve schists and amphibolites, the latter extensively retrogressed. The Seve units occur in the eastern limb and hinge of the Skardöra Antiform along the line of the profile; foliations are gently arched by this fold.

The seismic line (Segment D), designed to connect the main 1988 profile, described above, to the 1987 profile, is located in the gently E-dipping limb of the Skardöra Antiform (Fig. 3). It crosses southwards from the Middagsfjället Nappe, through Seve units, into a minor window (referred to here as the Hästryggarna Window, Fig 2) and then back through the Seve into the Middagsfjället Nappe again to intersect the 1987 profile (Segment C), a few kilometres northeast of Storlien. The shallow (c. 20–30°) easterly dips within the segment D profile, suggest that the Seve and Köli units together here, do not exceed a thickness of c. 1000 m. The underlying rocks, as they are exposed in the Hästryggarna Window are composed of a c. 200 m thick sheet of mylonitic granitoids and porphyries (?) of the Middle Allochthon. Below follow mylonitic arkoses, quartzites and porphyries of the Lower Allochthon, these lithologies are repeated by at least three thrusts, all arched by the Skardöra Antiform (H. Sjöström, pers. comm. 1989). A few kilometers further south, where Segment C crosses the Skardöra Antiform, similar rock units, some 2–3 km thick, occur beneath the retrograde Seve schists and amphibolites. The low grade metasedimentary units, thrust together with porphyries in this Lower Allochthon, though dominated by quartzites, also include both quartz and graphitic phyllites, the latter radioactive and probably related to the Alum Shale

Formation. Further south, up-plunge, into the core of the Skardöra Antiform, granites, porphyries and occasional dolerites are much less strained (Schaar 1961) and more close ly comparable with the Precambrian crystalline core of the Mullfjället Antiform.

Seismic data

ACQUISITION

The seismic data acquisition and processing has followed normal procedures, described in most standard text books (e.g. McQuillin et al. 1984). For the Jämtland profile the only available source for deep seismic surveying off the roads was explosives detonated in drillholes. The shot holes were drilled in advance during the winter when the heavy equipment could be transported on sleighs behind a large weasel (groomer). All shot holes were drilled with a 110 mm diameter down to 15 m depth, except in the trial 1987 segment at Bodsjön (Fig. 3, Segment F) where the depth was varied between 12 and 20 m. Only 8 of the 111 holes did not reach bedrock. The charges were tamped with water and, sometimes, with sand or drilling mud. The main seismic recording campaign was carried out in August 1988, the equipment being transported by four weasels capable of crossing the rough terrain.

Subdivision of the seismic line into 8 segments (A to H) was made to facilitate description of the varying acquisition parameters and processing. The field parameters used along the different segments (Fig. 3) varied somewhat (see Table 1). Segments E, F and G had nominal folds ranging from 6 to 12. Segment D, shot to connect the 1987 and 1988 profiles, and Segment H were both only single fold sections. This reduction in fold was necessary in order to both keep within a tight budget and to lengthen the profiles as much as possible. It resulted in poorer near-surface data and loss of signal enhancement by stacking reflected energy. Correlation of the reflections within the Skardöra Antiform in the Storlien area (segments B and C) with those across the Tännfors Synform (segment E) was regarded as essential, as was the desire to extend the profile as far east as possible (segment H). In as many cases as possible (70%) the shotholes were reoccupied. This is shown in Table 1 under "Spread configuration", where 96 (in parentheses), indicates

Profile segment	D and H		E and G		F
Length (km)	15	25	25	18	6
Shot interval (m)	≈ 4800		400		200
Charge size (kg)	10				1 and 15
Station interval (m)	50				25
Spread configuration No. of channels with respect to shotpoint (SP)	96 – SP – (96)				32 – SP – 64 (+96)
Nominal stacking fold	1		6–12		6–12
Geophones	single 28 Hz				
Record length (s)	20				
Sampling length (ms)	2				

that the geophone spread was used on both sides of the reoccupied shot point in the line of profile. Single geophones were used throughout the campaign for two main reasons. Firstly, signal to noise ratios are generally high, most of the profile being located in unpopulated areas with little background noise. Secondly, along the parts of the profile with a high frequency of bedrock outcrops, the thickness and composition of the superficial deposits varies considerably, the former on a scale of tens of metres. If geophone arrays had been used, such variations would have provided great differences in the intra-array static delays, the latter sometimes resulting in out-of-phase recording of reflected signals. Only 28 Hz geophones were available for the recording. These geophones have proven to be sufficient to record frequencies down to 10 Hz when used together with an instrument with 15 bits floating point dynamic range (Dahl-Jensen et al, in press).

Seismic recording away from the roads implies a slower rate of profiling, largely because of the extra time necessary for moving equipment along the line. However, there are some advantages, particularly above the tree-line where surveying is faster, shot patrolling is easier and human noise can be completely controlled. A negative factor can be wind noise which becomes a more serious problem above the tree-line. Winds in open areas may be too strong for seismic recording, the noise varying greatly from geophone to geophone and requiring extensive trace editing during the processing. Nevertheless, high winds prevented recording on only two days of the campaign; weather conditions were generally unusually favourable and allowed the acquisition of high quality data.

PROCESSING

Data from the 195 shots and 96 channels, recorded along segments D–H, have been put through a normal sequence of processing steps by use of programs developed at the Department of Geohysics, Uppsala. Field data were sorted and read onto 288 Mb disks, providing easy access to the data, but limited storage capacity. Processing of these field data therefore required that they be split into three parts: one, with data from 0–10 seconds two way travel time (TWT) from the eastern half of the profile (segments F, G and H), another with 0–10 s TWT from the western half (segments D and E) and a third with the data from the whole profile resampled to 8 ms from 0 to 20 s TWT.

A brief description of the processing steps follows, including the methods and parameters that have been employed.

Plotting of shot gathers. All recordings were plotted from 0 to 10 s TWT after applying a wide bandpass filter (10–110 Hz) to enable analysis of data quality from each recording station. The first second of recording from all shots also was plotted with the same filter setting (60–100 Hz) as used for the upper seconds in the final stacked sections. These plots were used to define the time-windows for top muting.

Editing. The field data showed an unusually great variation in signal/noise ratio with respect to geophone location and time. Poor traces, with relatively low signal/noise ratios or otherwise aberrant recordings, were removed, totally or in part, before further processing. Typical reasons for high noise, requiring exclusion of traces, or parts of traces, were short gusts of wind, falling stones and casings near to shot points, and shot generated air pulses that sometimes only disturb a few channels on shot gathers.

Top muting. All first arrivals were removed before stacking to avoid constructive stacking and consequent obscuring of shallow reflectors. Since the pulse length of the first arrival varies with recording distance and from shot to shot, the top mute times have been defined individually for each shot and trace. To simplify this process, the times have been defined for 2–8 channels in each shot gather and calculated by interpolation for the rest of the channels. For the nearest channels, usually within 300 m of the shot points, strong S- and surface waves were also muted, since their amplitudes and pulse lengths prohibit detection of reflected waves.

Sector muting. This pie-slice mute was only used to remove air pulses when they affected most of the traces in a shot gather. The apparent velocity of the air pulse varied from shot to shot, depending on wind strength and direction as well as air pressure and temperature. The onset with regard to shot moments and length of the air pulses also varied from shot to shot relative to the line of profile; therefore the sectors for muting were defined for each shot. The upper and lower boundaries, defining the sector where the amplitudes are set to zero, were specified by intercept times and velocities.

CDP(common depth point)-line definition. Midpoints between each pair of shotpoints and recording positions were displayed in a single plot. From the distribution of midpoints, a CDP-line was chosen with as few segments as possible, but still with as many midpoints as possible within 500 m from the line. The chosen line (segments E–H on Fig. 3), has 12 bends and a length of 67 km. Along segment D, the CDPs were simply defined as the midpoints between shot and geophone positions.

CDP gathering. The CDPs were chosen at 25 m intervals along the CDP-line and their coordinates were calculated. The line along segments E–H has 2665 CDPs. Each recording was then sorted to the CDP on the line nearest the midpoint between shot and recording position. Thus, for each CDP, a set of recordings was established for later stacking. Along segment F, the same CDP spacing was chosen, even though the distance between stations was half (25 m) that used along E, G and H. For this reason, the fold is twice as high along segment F.

Calculation of residual statics. Data were corrected for individual time shifts caused by varying near surface delays. The latter are dependent on the character and thickness of superficial deposits and local variations in altitude in relation to the general trend in the topography (see elevation correction, below). The very strong and distinct reflections along the whole profile favoured calculation of the time shifts by adjusting the traces in time to get the maximum power on stacked traces. A condition for these calculated time shifts is that they should be constant for a certain recording position, i.e. surface consistent.

Residual statics have been calculated iteratively by random starts and by using a modified Monte Carlo technique (Dahl-Jensen 1989). An input condition for calculation was a maximum change of 10 ms between two consecutive recording positions.

Velocity analysis. This analysis was made to find the velocity distribution in the upper crust to be used for normal move-out corrections, ie corrections for the increased two-way travel time to a reflecting point when source-receiver distance is increased. Along the CDP-line, with c. 10 km spacing (closer in the western part) and where the fold was 3 or higher, a set of 20 consecutive CDP bins was chosen. These were stacked with a normal move-out correction, calculated from constant crust velocities, and then plotted. The velocities were then varied in the interval 4.5–7.5 km/s, plotted and visually analyzed with regard to maximum stacked energy within different time intervals. This analysis showed great lateral variations along the profile, particularly in the western areas. The chosen time-velocity distribution, shown on the stacked sections (Plates 1–4), is a mean of many analyses along the whole profile.

Stacking. In the stacking procedure, the recorded signals were summed into a single trace, after correction for normal move-outs. If all corrections are made properly, the stacked traces will have an increased ratio of reflected energy/noise since only reflected energy is stacked constructively. For this data set, all recordings were bandpass filtered (10–110 Hz) before stacking to remove non-seismic noise. No limitations on the minimum and maximum source-receiver distances were used in the final stack, but to avoid time shifts due to lateral crustal changes perpendicular to the profile, a maximum distance between CDP and midpoint was set to 500 m.

Elevation correction. The displayed data in the stacked section are adjusted to a common height of 400 m a.s.l. for time zero. This correction is made using a reduction velocity of 6.0 km/s. The altitude of each CDP was calculated as a mean along a distance of one spread (4.8 km) from the CDP. The reason for this smoothing is that time delays due to minor elevation variations from the general topographic trend are already compensated when calculating residual statics.

Bandpass filter analysis. The stacked sections have been plotted with different filter intervals to find optimal signal/noise ratio for different time interval. The final sections along segments E-H are filtered using the following parameters: 0–2 s, 40–100 Hz; 2–5 s, 30–80 Hz; 5–10 s, 10–60 Hz.

Migration. The sections were migrated using both frequency-domain (FK) and finite difference methods. The former was preferred (Plate 2) because the distinctive reflections from below 2 s TWT on the unmigrated sections were best preserved by this method.

Plotting sections. The final stacked sections have been plotted with each trace being normalized with respect to its mean amplitude, and then scaled by time in seconds raised to the power of 1.3. A Calcomp electrostatic plotter has been used for the plotting.

Seismic sections

The stacked seismic sections of the main profile (Segments E to H) down to 10 s TWT are presented both as unmigrated and migrated sections (Plates 1 and 2, respectively). The main reflections, referred to below, are marked on Fig 4 to facilitate their description and discussion of alternative interpretations. In addition, an unmigrated section from 3–20 s TWT is included (Fig. 5) to show the non-reflective character of the lower crust in the area. A section of the single-fold connecting profile (segment D), running south-north between Storlien and Middagsfjället, is shown on Fig. 6. Common data points (CDP) along segments H, G, F and E are numbered from east to west and along segment D from north to south, as shown on Fig 3 and Plates 1 to 3.

The seismic data are of generally high quality and contain

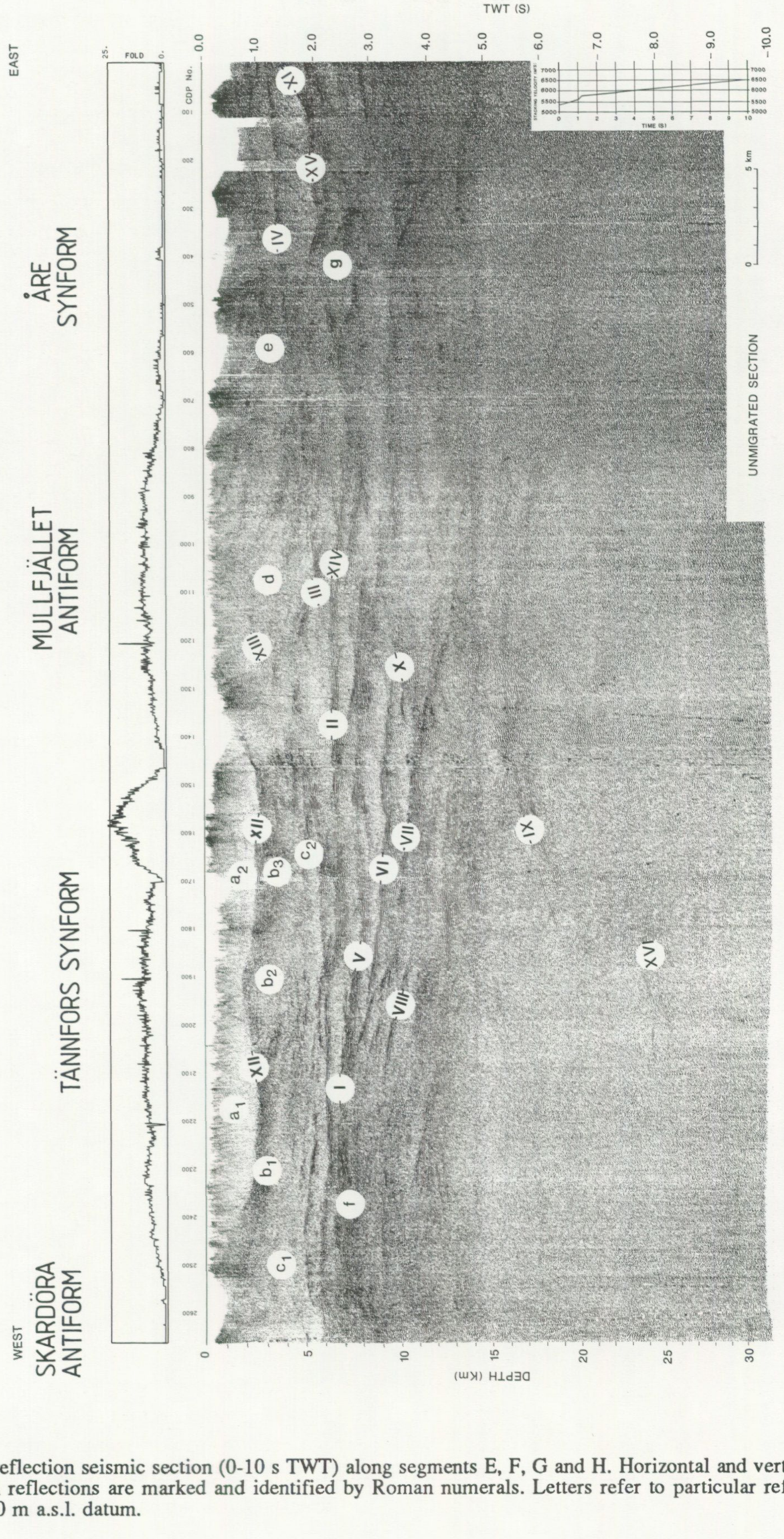


Fig 4. Unmigrated reflection seismic section (0-10 s TWT) along segments E, F, G and H. Horizontal and vertical scales are equal at 6.0 km/s. The main reflections are marked and identified by Roman numerals. Letters refer to particular reflection intervals. Zero time relates to a 400 m a.s.l. datum.

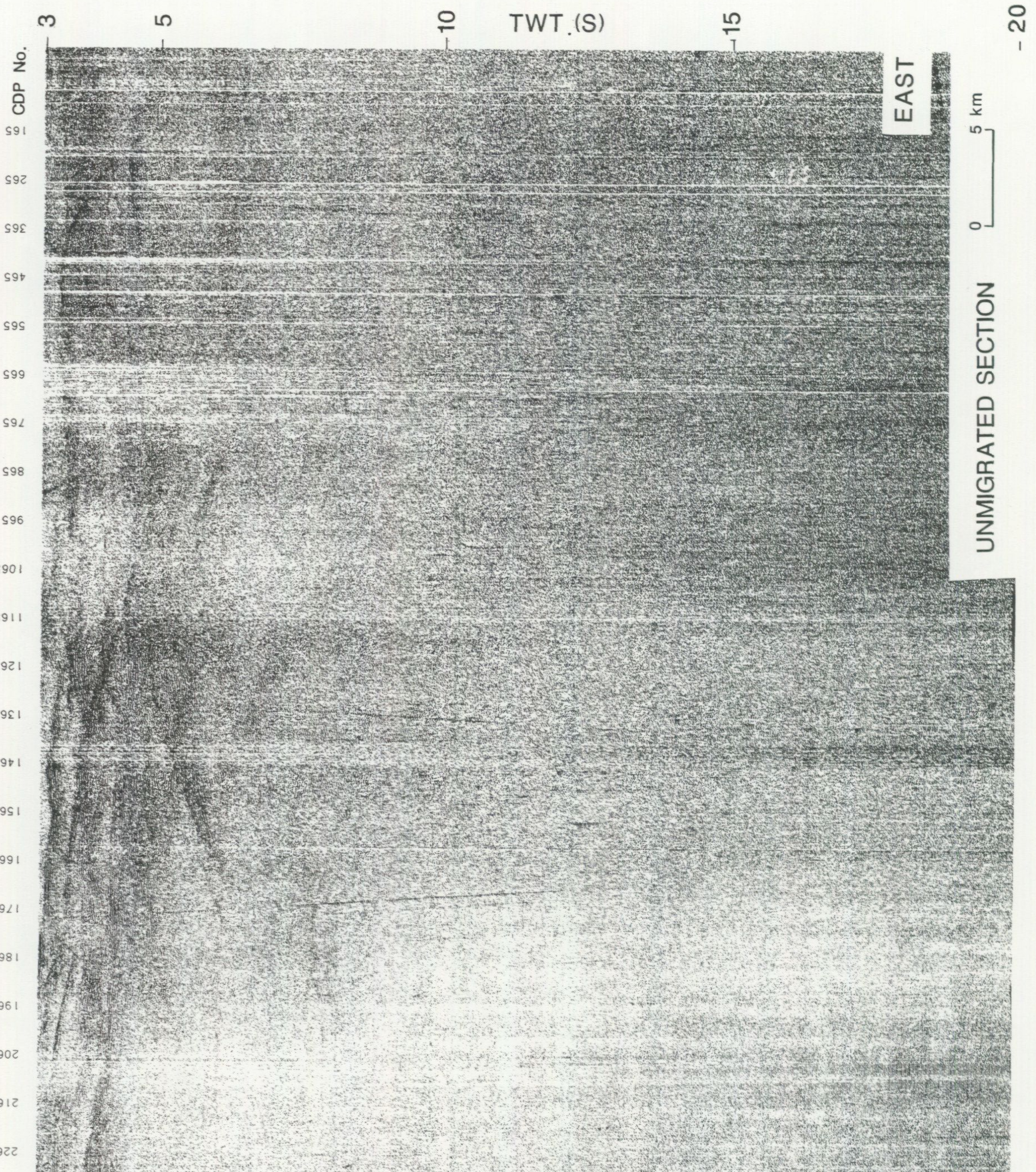


Fig 5. Unmigrated reflection seismic section (3-20 s TWT) along segments E, F, G and H. Zero time relates to a 400 m a.s.l. datum.

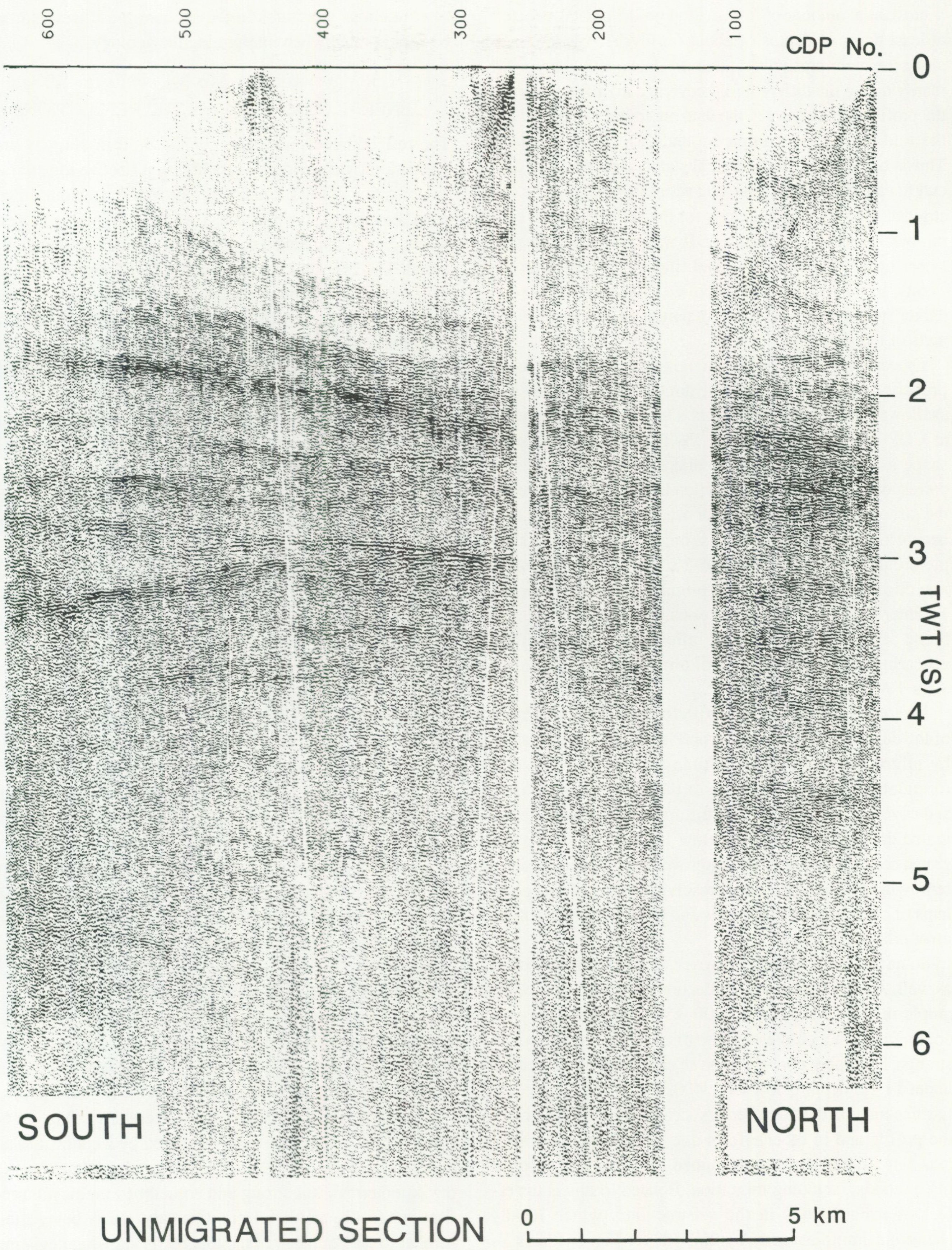


Fig 6. Unmigrated reflection seismic section (0-7 s TWT) along segment D (see Fig 3 for location). Horizontal and vertical scales are equal at 6.0 km/s. Zero time relates to a 400 m a.s.l. datum.

a substantial amount of information on the crustal structure, at least down to depths of about 6 s TWT. This is true all along the main profile, although the data quality varies, primarily due to the different fold coverage in different parts of the profile. Some flaws in the data are found in places where the fold drops, for example around CDP 1700 and 1450. This is because accurate residual static corrections are difficult to calculate at low fold, and result in small, poorly constrained time shift calculations for the seismic traces, causing black spots in the sections. It was not always possible to perform adequate muting and filtering of refraction first events, surface waves and air pulses. This has caused some darker streaks on the sections, in particular along single-fold parts of the profiles.

Especially at deeper levels, some of the weaker events are probably multiple reflections, duplicating the shapes of shallower and stronger reflectors. One example is the event at CDP 1500-1600 and 6.5 s TWT, which has the same shape as reflection IX one second earlier. This time shift corresponds to a multiple reflection between the surface and the strong reflection XII. Other weak multiples may have been generated in this zone of strong reflections, for example around CDP 1500 and 2 to 5 s TWT, where apparent repetitions of the shape of the primary reflection at around 1 s interfere with other reflections. Further examples are found at CDP 800–1000, with reflections at 5.5–6 s TWT appearing as surface multiples of primary reflections at 2.5–3.5 s TWT.

No software was available to perform pre-stack migration of the data. The section shown on Plate 2 has been obtained by migration of the original time section, using an FK-formulation (Stolt 1978). Due to the variable data quality and coverage along the profile the uppermost part of the migrated data is degraded, but below 1/2 to 1 s TWT the migrated section shows several improvements, in particular by removing diffraction events, resolving some of the problems of cross-cutting reflections and lining up several of the most prominent reflections.

Some problems remain, however, in the migrated section as well. A few cross-cutting reflections are still seen, for example in the CDP interval 1400–1500. Multiples may account for some of the weaker discordant reflections. A strange, E-dipping concentration of energy has developed at about 11 km depth below CDP 400. These and other peculiarities may be due to reflectors located out of the plane of the profile and to other effects due to deviations from the two-dimensional geometry assumed for all applied processing methods, including migration. Related to this is the effect of irregularities in the seismic line, which locally changes azimuth abruptly by 20°–40° (cf Fig. 3, Plates 1–3). This may well give rise to apparent cross-cutting of reflections and also to some distortion such as a change in dip of continuous structures in the section; these factors must be kept in mind when interpreting the geology.

GENERAL COMMENTS ON THE REFLECTIONS

The reflection seismic experiments, both in Norway and Sweden, provide evidence of a highly reflective upper crust down to 6–7 s TWT and a more or less transparent lower crust. Processing down to 20 s TWT (Fig. 5) yielded no coherent energy and hence nothing that could be related to the Moho. The latter has not been defined with any confidence by previous refraction profiling in this part of the mountain belt (Vogel & Lund 1971, Dyrelius 1985), but has been interpreted further north (Blue Road profile, Lund 1979) to be at c. 45 km depth beneath the mountain belt. Moho depth compilations (e.g. Luosto 1989) indicate that the crust thins from east to west across the mountain belt, from c. 45 km in the mountain front to c. 35 km along the coast; immediately off-shore, the thickness decreases more rapidly. Thus, the relief in the Scandinavian mountains appears not be compensated by thickening of the crust; compensation was suggested by Meissner (1979) to occur deeper in the lithosphere or in the asthenosphere (see also Avedik et al. 1984).

The reflectors in the uppermost crust are clearly relatable to surface structure, and can be correlated with the rock units within, and the geometry of the Skardöra Antiform, the Tännfors Synform, the Mullfjället Antiform and the Åre Synform. These reflections image lithologic boundaries, structures and particularly fault zones. They appear to terminate along a single, or a combination of gently W-dipping surface(s), extending from a depth of 1.1 s TWT (i.e. c. 3 1/2 km) in the east near Järpen, to c. 2.3 s TWT (7 km) near the Norwegian border. The gently folded and thrust uppermost structure does not continue to depth, but terminates against this underlying flat discontinuity. Deeper in the upper crust there are a variety of gently dipping reflections (up to c. 30°), inclined to east and west, the former dominating. These deeper reflections are not traced into the uppermost crust.

In the western part of the main profile there are very significant changes of the reflective character with depth (Plates 1, 2 and Fig. 4). The uppermost part (a_1 and a_2 on Fig. 4) down to a maximum depth of 1 s TWT, between CDP 1300 and 2500, is rather homogeneously transparent, except for a few weak, W-dipping reflections in the eastern part (a_2). The bottom of this region is sharply outlined by a contrast to an underlying, complex pattern of commonly rather short (a few kilometres), but strong and sometimes multicyclic reflections (b_1, b_2 and b_3). Here dips vary, partly being subparallel to the boundary at the top, partly showing deviating attitudes of 10–20°. Cross-cutting dip orientations are rather common and may be artifacts of the processing as mentioned above. Several diffraction patterns are also seen (usually eliminated by migration, cf Plate 2). The thickness of this reflective interval varies between 0.3 and 1.1 s TWT, and its lower boundary is diffuse. In the eastern limb of the Skardöra Antiform (b_1) it becomes more diffuse towards the surface. In the central part of the Tännfors Synform, this generally highly reflective packet thickens and is arched; it contains an internal interval within b_2, that is less reflective. Further east (b_3) the most reflective packet first thickens and then wedges out in the western limb of the Mullfjället Antiform.

The section below this packet of strong reflections in the western limb of the Tännfors Synform down to about 2 s TWT, shows a few subhorizontal reflections, separated by much less reflective intervals (c_1). About five kilometres east of the axis of the Skardöra Antiform, these reflections are very gently arched. Below the eastern limb of the Tännfors Synform, intervals with similar reflection characteristics (c_2) appear to continue east into the Mullfjället Antiform *(d)* where the antiformal pattern is readily recognizable.

The base of this upper crustal interval beneath the Tännfors Synform is defined by gently dipping reflections (e.g. at 2.2 s TWT below CDP 2000) underlain by a complex of subhorizontal reflections (I). Although not completely continuous, the latter appears to be connected eastwards with similar features beneath the Mullfjället Antiform (II and III) and the Åre Synform (IV). This sequence of reflections starts at the western edge of the profile in Norway at a depth of 2.5 s TWT and ends in the east near Järpen at a depth of 1.1 s TWT.

Above reflections III and IV, to the east of the axis of the Mullfjället Antiform, some reflection patterns are observable *(e)*, for example the increased reflectivity in the eastern limb of the antiform (around CDP 800) and the synformally folded reflections with an axis below CDP 550. However, it should be noted that the section in this region has a lower fold (single) than in the western part of the profile.

Below 2.2 s TWT in the westernmost part of the section, a complex zone of high reflectivity *(f)* occurs which appears to continue eastwards, forming a prominent pattern of low angle E-dipping, diverging reflections V, VI, VII and VIII. These are separated at c. 0.2 s TWT intervals by much less reflective zones. Some less continuous, W-dipping events can also be seen at depth beneath the eastern limb of the Mullfjället Antiform. Further to the east, more complex patterns of distinct, but cross-cutting reflections are developed in the vicinity of *g*.

Below c. 6 s TWT, the reflectivity of the crust decreases. A package of rather strong, W-dipping reflections (IX) is found at about 6 s TWT beneath CDP 1500–1600. Subjacent to the west of this, between 7 and 8 s TWT, a few weak, subhorizontal reflections are seen. Above, and east of IX, several other W-dipping (c. 20–40°) reflections occur, e.g. X and XI.

At depths below 7–8 s TWT there is a remarkable lack of reflections, as is shown in the unmigrated section from 3 to 20 s TWT (Fig. 4). Using different processing techniques and filtering methods, several attempts have been made to search for deeper reflections, in particular from the expected Moho-depths at c. 11–14 s TWT, but without success. To test the possibility that this lack of reflectivity at greater depths, a phenomenon already apparent in the 1987 experiments, was related to the size of the energy source, a larger charge (50 kg) was detonated in the western part of the profile; however, no new reflections were observed from the lower crust.

It remains unclear whether or not the lower crust is transparent all the way down to the Moho. However, in most previous vertical reflection seismic surveys in Sweden it has been notoriously difficult to find any clear indications of the Moho transition. In Värmland, west of the Protogine Zone, a few short and weak reflections were observed at the expected Moho depth (Dahl-Jensen et al 1989). In the Siljan area, a band of weak reflections at 12 to 14 s TWT were interpreted to indicate the Moho (Lund et al. 1988). The present area shows a remarkable transparency of the lower crust, comparable only to that of the easternmost part of the Värmland profile (Dahl-Jensen et al. 1989). In this connection it is worth noting that all the above mentioned seismic profiles to some extent are located within the Transscandinavian Granite-Porphyry Belt (Gorbatschev 1985). It is possible that the low seismic reflectivity indicates characteristic properties of the lower crust and the Moho transition in these particular parts of the Baltic Shield. However, in the Jämtland profile, scattering of seismic energy in the highly reflective upper crust may also be an explanation for the lack of signals from the lower crust. In contrast, larger offset reflection experiments do appear to depict the Moho rather clearly (e.g. in the Värmlandsnäs experiment, Juhlin et al. 1989).

The connecting profile (Segment D, Fig. 6) is of poorer quality than the main profile (E to G): its single fold character severely limits the amount of processing that can be applied to the data. For example, much noise from surface waves remains around the shot points and no noise reduction by stacking has been possible. Despite these drawbacks, the section shows several reflections that are continuous across most of the profile. As in the main profile, these coherent reflections occur down to depths of about 6 s TWT. The general pattern and individual reflections can be correlated in the south with the results (cf Fig. 7) of the Storlien-Meråker profile (Hurich et al. 1988, 1989) and in the north with the main profile presented here.

Alternative interpretations

A variety of interpretations of the reflections are possible, particularly for those that are foreland-dipping in the deeper parts of the upper crust. The latter may be related to Precambrian or even Lower Palaeozoic rocks and structures, practically uninfluenced by Caledonian deformation, isolated below a major detachment zone; alternatively, they may provide the first evidence of a much more complex Caledonian structure with foreland-dipping thrusts contributing to basement-shortening of the orogen. These and other alternatives are discussed below.

The near-surface images are considered first, starting in the west where the correlation is most secure. These uppermost reflections can be readily correlated with geological phenomena (rocks and/or structures) mapped at the surface and inferred to provide reflectors at depth. It is convenient to treat the reflections in the uppermost crust in subareas, in relation to the Tännfors Synform, the Mullfjället Antiform and the Åre Synform. Interpretation of the easternmost areas is naturally influenced by extrapolation further east towards the mountain front, where only surface mapping, shallow drilling and refraction seismic and magnetic interpretations constrain the models. Likewise interpretation of the westernmost areas is strongly influenced by the north-south profile (segment D, Storlien-Middagsfjället) allowing connection westwards with the 1987 Storlien-Meråker measurements (Hurich et al. 1988, 1989). The deeper reflections are discussed after this treatment of the uppermost structure.

UPPERMOST STRUCTURE

Tännfors Synform

Lithologies exposed in the broad, open synform in the Tännfors area, are dominated by calcareous phyllites and schists, composing a rather monotonous packet a few kilometres thick. The new reflection data (Plate 1) with the upper c. 0.6–1.0 s TWT nearly transparent, indicate that these Köli metasediments have a maximum thickness of c. 3 km; they are underlain throughout the synform by a sharp contact (XII on Fig. 4) to the more reflective zones b_1, b_2 and b_3, described above. A central arch within the synform corresponds with analysis of the regional structure (Beckholmen 1984). The reflective zone below XII has a complex internal structure that can be readily related to the rock units in the Seve Nappes.

Within the nearly transparent upper second (TWT), the weak, gently W-dipping reflections in the eastern parts of the synform are listric, curving back west into the inferred Seve-Köli contact; they partly coincide with the base of the Gevsjön Nappe and possibly also the Middagsfjället Nappe (Beckholmen 1984).

Seve lithologies in the northern and southern parts of the Tännfors Synform provide the basis for interpreting the interval of high reflectivity beneath the Köli. North of Storrensjön, on Skäckerfjällen, flat-lying banded garnet mica schists, gneisses and amphibolites dominate these intercalated units together being up to 2 km thick. In southern areas, south of Ånnsjön, a much thicker and more varied Seve tectonostratigraphy is preserved. In the upper levels, Sjöström (1984) has identified an amphibolite-dominated unit, overlying granulite facies gneisses, the latter thrust over a lower unit of amphibolites and schists (Fig. 3). The proportions of amphibolites to metasediments vary greatly. Further south, up-plunge in the synform, upper greenschist facies greenstones and psammitic schists dominate the lower Seve. Thus, the lithologies responsible for the high reflectivity beneath the Köli in the Tännfors Synform are probably dominated by concordantly interbanded basic igneous rocks and metasediments, rock units that can be expected to be characterized by high contrasts in acoustic impedance. However, the presence of thin (a few tens to a couple of hundred metres), heterogeneous units (fragmented ophiolite, etc) at the base of the Köli further south, within the Bunnerviken lens, and further east in the Duved Nappe, suggests that lowermost Köli units also contribute to this highly reflective zone.

The probability that a substantial component of Seve rocks are preserved within the Tännfors Synform along the line of the seismic profile is supported by an analysis of gravity data. Elming (1988) demonstrated the presence of a local positive Bouguer anomaly over the Tännfors synform, superimposed on the regional negative field. Based on density measurements and estimates of the proportions of the various Seve lithologies elsewhere in the synform, he modelled this anomaly as a slab of higher density Seve a little over a kilometre thick, underlying about three kilometres of Köli metasediments.

Within the eastern limb of the Tännfors Synform, the rapid easterly thinning of the highly reflective unit b_3 coincides well with the preservation of only thin lenticular bodies of Seve amphibolites at the surface. In western areas, along the border to Norway and the axis of the Skardöra Antiform (Figs. 3 and 8), retrograde amphibolites and schists cut out in the western limb of the antiform, the excision apparently being related to normal movement on the Steinfjellet fault (Norton 1987, Sjöström & Bergman 1989). From this border zone, the Seve reflections brighten and thicken eastwards towards the hinge of the Tännfors Synform. The lenticular zone of less reflective units (b_2 on Fig. 4) in the central part of the synform may be related to a major body of granulite facies gneisses similar to those on Sna-

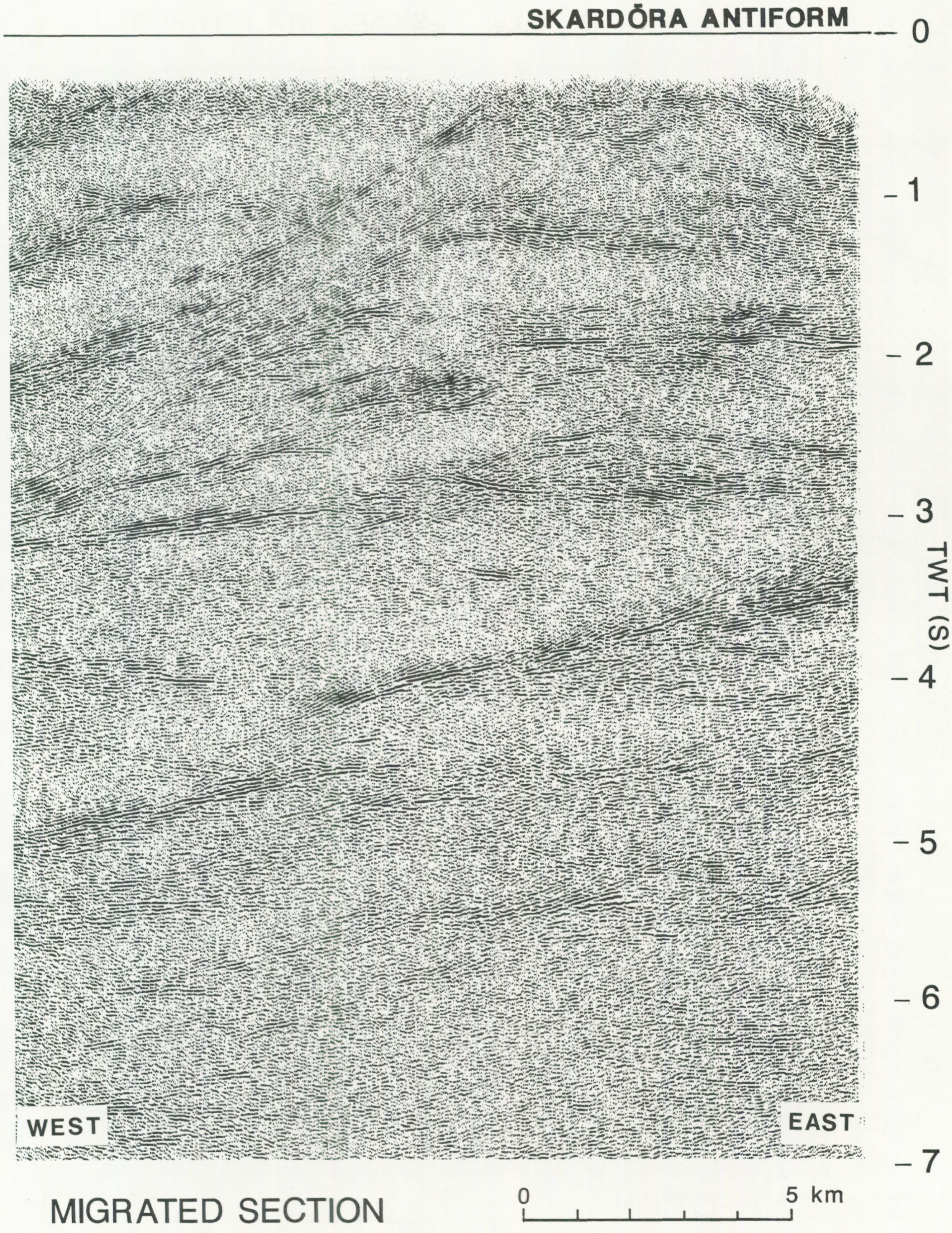


Fig 7. Migrated seismic reflection profile (Segment BC) across the Skardöra Antiform (from Hurich et al 1989). Horizontal and vertical scales are equal at 6.0 km/s. Zero time relates to a 400 m a.s.l. datum.

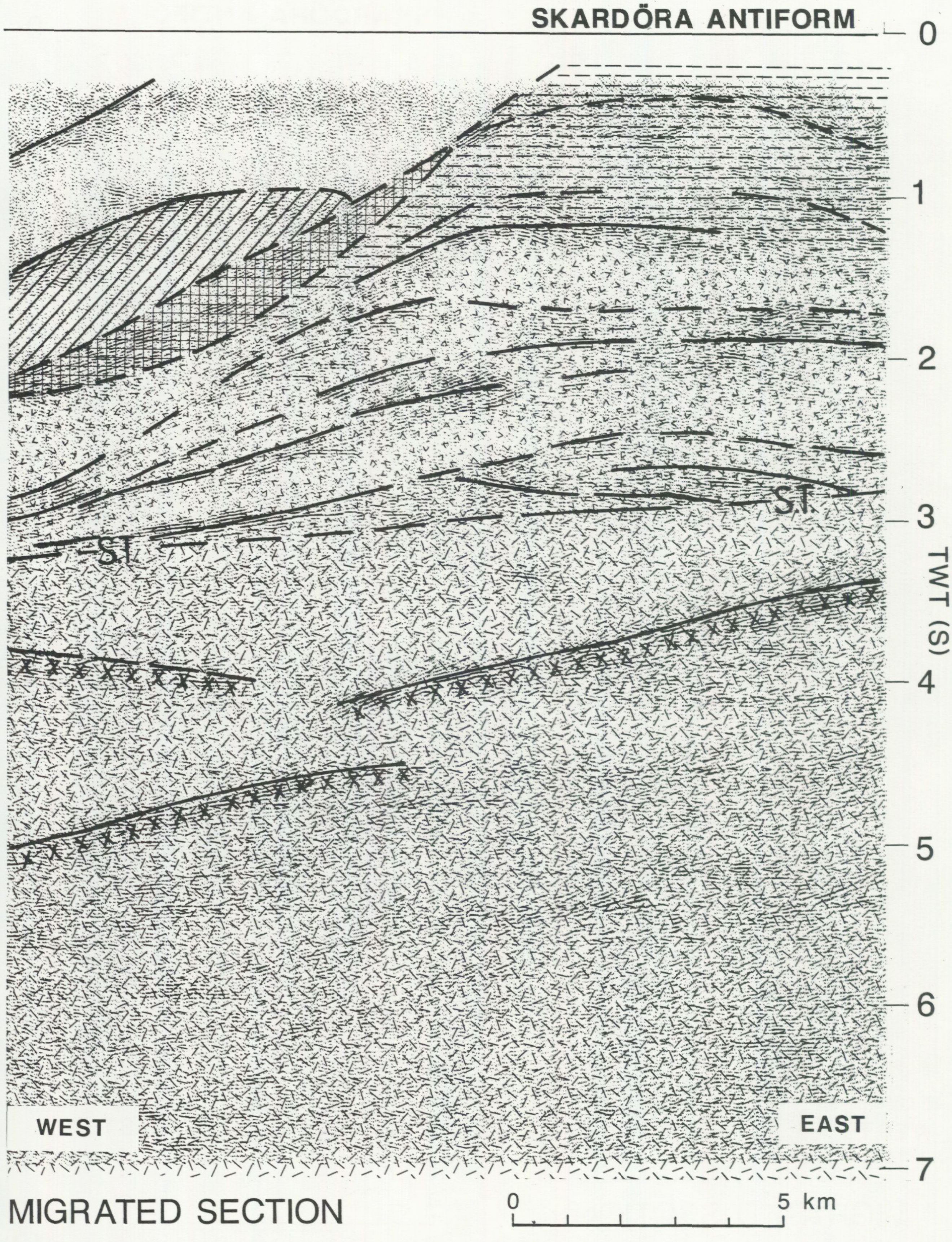


Fig 8. Geological interpretation of segment BC superimposed on a migrated seismic reflection profile (cf. Fig 7). See Plate 3 for legend. Zero time relates to a 400 m a.s.l. datum.

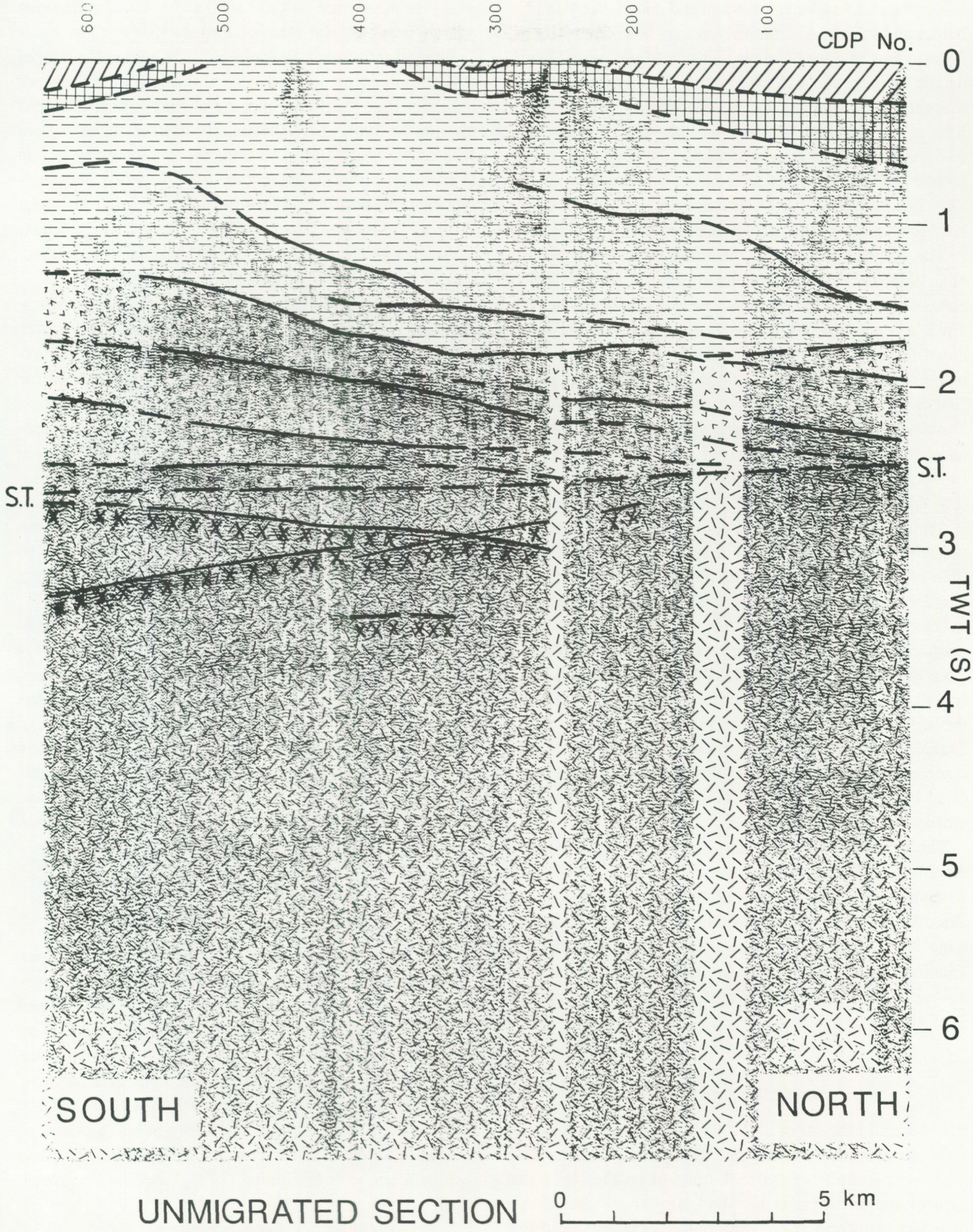


Fig 9. Geological interpretation of segment D superimposed on an unmigrated seismic reflection profile (cf. Fig. 6). See Plate 3 for legend. Zero time relates to a 400 m a.s.l. datum.

sahögarna and Åreskutan, overlain and underlain by amphibolites and schists. Alternatively, it may be composed of an isolated lens of Särv dolerites and sandstones, possibly underlain by reflective mylonites of the Middle Allochthon.

Beneath the highly reflective zone (Seve) in the western limb of the Tännfors Synform, an interval of lower reflectivity occurs, containing a weaker, flat-lying and gently arched reflection fabric. It thickens westwards into the Skardöra Antiform (Fig. 7), where it can be shown to be related to rock units dominated by the Lower Allochthon.

The seismic profile across the Skardöra Antiform (Hurich et al 1988, 1989) shows that the crust contains several thin zones of high reflectivity, the upper four within the first 3 s TWT being arched by the antiform and the lower ones, down to c. 7 s TWT, dipping gently westwards. Surface mapping (Sjöström 1984) suggests that the units in the first 3 km below the Seve in the western limb of the Tännfors Synform are composed of metasediments (mainly quartzites) and basement-derived crystalline rocks of the Lower Allochthon, repeated in an antiformal thrust stack (Fig. 8).

Segment D (Fig. 6) provides some control of these relationships, being oriented c. N–S and located in the eastern limb of the Skardöra Antiform, about 3–4 km east of and parallel with the fold axis. Prominent reflections imaging structures and/or rock units below the Seve dip consistently northwards (c. 20°) in the interval from the surface down to 2.0 s TWT. Below this, to c. 4 s TWT, reflections are gently S-dipping. The N-dipping reflections coincide well with the surface evidence for the general northerly plunge of the Skardöra Antiform. However, these reflections provide no evidence in the subsurface for the plunge culmination defined by the Hästryggarna Window. An interpretation of profile D is presented in Fig. 9.

The prominent flat reflection I at c. 2.3 s TWT beneath the Tännfors Synform, dips at less than 1° W and persists westwards into the flat reflections at deeper levels in the Skardöra Antiform (referred to above). These and the underlying foreland-dipping reflections are uninfluenced by the Tännfors Synform; they are therefore considered further below after treatment of the Mullfjället Antiform and Åre Synform.

Mullfjället Antiform

Reflections in the upper c. 2 s TWT dip gently westwards and eastwards off the axis of the Mullfjället Antiform. The internal reflectivity of the rock units (d on Fig. 4) in the core of the antiform is low and similar to that in the Skardöra Antiform (c_1). The contact between Jämtland Supergroup sedimentary rocks and basement porphyritic rhyolites in both limbs of the antiform coincides with projection to the surface (at CDP 1000 and 1160) of reflections dipping gently into adjacent synforms.

Internal reflections, for example XIII, within the core of the antiform are arched to a depth of nearly 2 s TWT; deeper reflections are flat-lying, dipping at very low angles both towards the foreland and the hinterland. Beneath the western limb of the Mullfjället Antiform, the W-dipping reflection II continues uninterrupted into a very gently foreland-dipping reflection, XIV. It is overlain immediately above (at 2.1 s TWT) by the gently W-dipping reflection III which appears to persist eastwards into the prominent flat reflection IV, beneath the Åre Synform.

The porphyritic rhyolites, minor andesites, basic volcanites and locally preserved granites and discordant dolerites that compose the Proterozoic crystalline rocks in the exposed core of the Mullfjället Antiform provide a basis for interpreting the internal arched reflections (e.g. XIII) referred to above. These thin reflective horizons within the basement rocks could represent concordant basalts or dolerites in the Precambrian acid igneous rocks, the concordance being of primary origin or resulting from Caledonian shearing. However, comparison with the surface geology of the Skardöra Antiform suggests the alternative that they may be folded thrusts, with Vendian to Cambrian sedimentary units in the footwall.

In both limbs of the Mullfjället Antiform the characteristic homogeneous low reflectivity of the Precambrian crystalline rocks, interrupted by only a few arched reflectors, passes laterally and transitionally away from the core of the fold into somewhat more reflective intervals (e and c_2). These may suggest a change in lithology. However, in view of the lack of independent evidence for such a change, this increase in reflectivity, is related here to greater penetrative deformation of the crystalline rocks and greater concordance between lithologies with different acoustic impedance.

Åre Synform

The line of the seismic profile crosses the northern slopes of Åreskutan, where the lithologies are dominated by amphibolites, psammitic and calcareous schists, gneisses and subordinate marbles. Reflectivity is relatively high where the reflections in the uppermost 1 s TWT dip gently into the axis of the open synform. Projection of these dipping reflections to the surface and comparison with the surface mapping suggests that the Seve rocks reach a thickness of c. 3 km in the hinge of the synform, a figure that compares well with estimates by Elming (1988) based on the gravity data.

In the eastern limb of the Åre Synform, the conspicuous bright reflection IV dips gently (c. 3°) westwards from the easternmost limit of the seismic line (Fig. 4) at a depth of

1.1 s TWT. It persists westwards beneath the axis of the Åre Synform and, though less well defined beneath the eastern limb of the Mullfjället Antiform, appears to continue into the slightly steeper W-dipping reflection III at 2.1 sec TWT beneath Mullfjället. In the eastern parts of the profile (though not at the easternmost edge), reflection IV is directly overlain by an interval of low reflectivity about a kilometre thick. It is underlain by a transparent interval down to about 1.9 s TWT, at which level another persistent parallel W-dipping reflective horizon (XV) is located; however, the latter forms part of a more complex pattern of cross-cutting foreland- and hinterland-dipping reflections. None of these lower reflections are influenced by the geometry of the overlying Åre Synform.

Projection eastwards of the gently west-dipping (3°) bright reflection IV, from the eastern limb of the Åre Synform near Järpen towards the Caledonian thrust front, suggests that it should reach the surface in the vicinity of Storsjön coinciding approximately with the sole thrust in the Caledonian front. The interval (c. 0.4 s TWT) of low reflectivity above reflection IV, extends westwards to the eastern limb of the Mullfjället Antiform, suggesting that it is imaging Precambrian crystalline rocks. Therefore reflection IV is interpreted to be a major thrust, the reflectivity being enhanced by the presence of Cambrian (and perhaps younger) sediments, mainly shales and limestones, in the footwall, overlain by Precambrian crystalline rocks of low reflectivity. This interpretation finds support in the shallow refraction measurements (Palm & Lund 1980) that indicate the presence of a basement high at a depth of c. 300 m in the vicinity of Liten, a few kilometres east of Järpen.

Gently hinterland-dipping reflections

The evidence, discussed above, for the planar, gently W-dipping reflection IV in the eastern part of the profile, being related to a sole thrust with considerable shortening in the hanging wall, implies a similar origin for the flat-lying discontinuities further west below the Mullfjället Antiform (III and II), Tännfors Synform (I) and Skardöra Antiform (cf. Hurich et al. 1988, 1989). It favours the interpretation that a planar sole thrust also exists beneath the western Jämtland Caledonides, separating a more or less passive basement from a vastly shortened allochthon. The various related flat reflections are not completely continuous across the entire profile. However, a number of factors, such as similarity in acoustic impedance of lithologies in the hanging- and footwall of the thrust, local minor ramping or late normal faults, could explain the local lack of complete continuity. The absence of any obvious geometrical relationship between the structures above and below this discontinuity surface is strong evidence for its interpretation as a major zone of movement, a sole thrust beneath the Caledonian allochthon.

DEEPER STRUCTURE OF THE UPPER CRUST

Below the planar discontinuity discussed above and down to a depth of c. 6 s TWT, the crust is highly reflective. Beneath the Tännfors Synform and the Mullfjället Antiform foreland-dipping reflections dominate; beneath the Åre Synform the pattern is less regular.

The foreland dipping reflections below the main discontinuity (I–II), between the axes of the Tännfors Synform and the Mullfjället Antiform, are strong and continuous over distances of several tens of kilometers. These are particularly conspicuous, being separated by zones of variable lower reflectivity. They converge westwards and are underlain by a few shorter reflective zones, some dipping the same way and others flat-lying to W-dipping. These underlying reflections give way downwards (between 4–6 sec TWT) into an interval of diffuse reflectivity overlying a nearly transparent middle crust; the latter contains a few, but prominent, shorter W-dipping reflections (e.g. IX and XVI). Both these reflections IX and XV resemble, in terms of depth, dip and character, reflections found in the Eastern Gneiss Region in central Värmland (Dahl-Jensen et al 1989) where they were suggested to be related to Sveconorwegian structure.

The strong, foreland dipping, easterly diverging reflections XIV, V, and VI appear to be cut by and terminate along a weaker reflection zone, X which dips at a low angle westwards. VII is stronger than X, apparently cuts the latter, and continues eastwards, becoming broader and more diffuse with depth below the Mullfjället Antiform.

Further east, below the Åre Synform, flat to shallow dipping reflections are also present below the main discontinuity (IV); they are shorter and less regular than further to the west.

Two categories of interpretation for the reflections beneath a sole thrust are discussed below, those favouring a source within a passive autochthon of basement and cover and those requiring Caledonian faulting at deeper structural levels.

Passive successions on crystalline basement beneath a sole thrust

Svecofennian supracrustal rocks, granites and migmatites

Within the extensive terrains of Svecofennian metamorphosed supracrustal rocks east of the Caledonian front, there are few known occurrences of gently regularly dipping strata extending over hundreds of square kilometres. Thus it is very unlikely that the sub-discontinuity reflections west of

Mullfjället are Svecofennian in origin. However, below the Åre Synform in the areas of lesser regularity where reflections are shorter and vary in dip, partial migmatization and granite intrusion of a supracrustal succession cannot be ruled out.

Mid-Late Proterozoic granites intruded by dolerite sills

In the autochthonous granites of the Siljan area of central Sweden, reflection seismic profiling (Juhlin & Pedersen 1987) identified several strong flat-lying, laterally persistent reflections, separated by non-reflective intervals. The reflections occur in the upper crust and are underlain by largely transparent middle and lower crust down to mantle depths. Drilling to nearly 7 km depth allowed identification of these reflectors, which proved to be thick (c. 40 m) dolerite sills or clusters of thinner sills. Thus a pattern similar to that beneath the Tännfors Synform and the Mullfjället Antiform (V, VI, VII and VIII) might be produced by basic intrusions into acid igneous rocks. Likewise some of the cross-cutting relationships between reflections, for example in the vicinity of XV in the easternmost parts of the profile could be imaging discordant intrusions.

Middle Proterozoic, post-Svecofennian sandstones, lavas, dolerites and granites

Extension of the Jämtland magnetic anomaly beneath the Caledonides of western Jämtland (Dyrelius 1980) strongly favours the existence of granites of Dala type of considerable thickness (>10 km) beneath the allochthon. In Dalarna, in the autochthon, some of these intrude acid to basic lavas and pyroclastic rocks (Hjelmqvist 1966, Lundqvist 1968) and are unconformably overlain by sandstones (Fig. 1). The latter, the Dala sandstones, contain basalt flows, together up to c. 100 m thick (the Öje diabase), and are intruded by basic sills and dykes of which the Åsby sill extends over a distance of 80 km (Hjelmqvist 1966). The original thickness of the sandstones is unknown; only c. 800 m are preserved in Dalarna. However, studies of Proterozoic post-Svecofennian metamorphism of the Dala sandstones (Nyström & Levi 1980) indicate that the succession may have been several kilometres thick. The under-lying volcanites are a few kilometres thick. These mid Proterozoic volcanic rocks and sandstones occur in a major NNW-trending open syncline, plunging very gently beneath the Caledonian front. Sveconorwegian thrusting and folding influences the western limb, where the strata are locally vertical to overturned.

A local reflection seismic experiment (Lindgren et al., unpublished report 1988) over Dala sandstones in the gentle eastern limb of the syncline acquired data down to 2 s TWT. Several well defined flat reflectors were identified in the crust below the sandstones. These were interpreted as probably related to dolerite sills intruded into acid volcanites. Marked compositional variations in the volcanic sequence (Hjelmquist 1966) might also provide an explanation for the reflectivity.

The sub-discontinuity, foreland-dipping reflectors V, VI and VII, below the Tännfors Synform and the western part of the Mullfjället Antiform are composed of laterally persistent intervals of higher reflectivity, separated by intervals of much lower concordant reflectivity. Their sub-parallel geometry and tendency to converge westwards suggests that they might represent a volcano-sedimentary succession deposited in a half graben, the eastern margin being controlled by W-dipping growth faults (e.g. reflectors IX and X). The succession could well be dominated by volcanites. The passage downwards into lower reflectivity is likely to be due to the presence of underlying granites. Likewise, the less regular reflection pattern at deeper levels (>1.5 s TWT) beneath the Åre Synform could result from Dala volcanites and/or sandstones being variously intruded by associated post-Svecofennian granites.

An Andino-type evolution, with rifting and graben formation, was proposed by Nyström (1982) for the Transscandinavian Granite-Porphyry Belt in general and the above described Dala granites, volcanites and sandstones in particular. The diffuse reflectivity pattern beneath reflections X, VII and VIII may image the intrusive relationship between a granite and its overlying volcanic pile, resulting from cauldron subsidence.

Upper Proterozoic graben

The evidence cited above, interpreting some of the reflectors as related to a supracrustal succession in a half-graben, suggests an alternative hypothesis – that strata are preserved in a late Proterozoic, Iapetus-related extensional basin. Similar sub-thrust structures in other orogens are thought to originate in this way, eg in the Appalachians (Lillie 1984). In the Scandes, graben with similar geometries are thought to have existed further towards the hinterland and to have provided the source for various of the thrust sheets in the Middle Allochthon and the uppermost parts of the Lower Allochthon (Kumpulainen & Nystuen 1985). However, with the exception of the highest sheets in the Middle Allochthon (Särv Nappes) these do not contain igneous rocks except very locally in southern Norway. It is unlikely that a succession typical of the late Proterozoic sandstones and conglomerates in the Scandes would provide a so varied reflection image, without the presence of lithologies with markedly different accoustic impedance, i.e. intercalations of basic lavas or sills.

Lower Palaeozoic strata

An Iapetus rift-related basin, considered above, might be expected to be active into the early Cambrian and be overlain by the mid to late Cambrian alum shales. Early tectonic loading of the outer margin of Baltica in the late Cambrian to early Ordovician (Finnmarkian) led to development of a foreland basin filled with Middle Ordovician turbidites. These are now preserved in the Jämtland Supergroup and incorporated in the thrust sheets of the Lower Allochthon. A possibility exists that a subordinate foreland basin may have developed further from the Balto-scandian margin; subsequent thrusting could have left it in the footwall beneath a master décollement. Such a basin would be expected to be dominated by intercalated fine and coarse clastic sediments. However, the considerable (c. 6 km) thickness of this reflective interval and the need for very strong variations in acoustic impedance, as well as the lack of any associated potential field, particularly magnetic anomalies (see discussion below p. 30) argue against this alternative.

Caledonian shortening beneath a sole thrust

Although the Caledonian structure appears to be separated from the deepest structure by a low angle W-dipping discontinuity imaged by reflections I, II, III and IV, the possibility remains that the underlying reflections provide evidence of Caledonian deformation. Two alternatives are considered below.

Back thrusting

Some of the major thrusts in the Scandes provide evidence of late-stage hangingwall west movement. Thus in southern Norway, Milnes & Koestler (1985) described late hinterland-directed transport on the Jotun thrust and more recently Milnes et al (1988) have postulated back-thrusting on gently foreland-dipping shear zones within the basement below the Jotun Nappe.

Likewise, in the Himalayas, foreland-dipping back-thrusts beneath the sole thrust have been postulated (Burg & Chen 1984) to account for some of the basement-shortening in the orogen. These authors based their interpretation on Hirn et al's (1984) evidence of foreland-dipping deep crustal reflectors below the high Himalayas and mountain front. Although the reflectors reported here in the upper crust of the Scandes from directly below the main discontinuity bear little direct resemblance to these deep Himalayan reflectors they might both imply tectonic shortening of the basement.

Foreland-directed thrusts

Another alternative for the foreland-dipping reflections is that they might originate from shear zones related to the emplacement of the main Caledonian allochthon towards the foreland. Such foreland-directed thrusts would need to have sufficient displacements to produce lithological concordance within mylonite zones. Some are cut by reflection X. This interpretation requires that reflection X is imaging a late Caledonian normal fault that was active after the initial thrusting, but before the final overriding of the Caledonian allochthon on the sole thrust (I–IV). Such a complex possibility appears unlikely, yet is made more plausible by Cashman's (1988) evidence for normal faults interrupting the early thrust geometries of the Rombak Window, further north in the mountain belt.

Some of the deeper W-dipping reflections, e.g. IX and XI, could be late Caledonian thrusts (perhaps reactivated normal faults of early Caledonian or Proterozoic origin). Such an interpretation would imply some basement shortening after emplacement of the main Caledonian allochthon on the sole thrust (I–IV). Reflection XI converges towards reflection IV at the eastern end of the profile and both these reflections project towards the surface further east. Continuation of the reflection seismic profile towards the east will be necessary for further analysis of this alternative.

Summary of other geophysical evidence

Reference has been made in this text to various other lines of geophysical evidence relevant to the interpretation of the reflections. Particular attention has been drawn to refraction seismic (Palm & Lund 1980, Palm 1984), gravity (Dyrelius 1985, 1986, Elming 1988) and magnetic (Dyrelius 1980) studies that have helped constrain the geometry of the rock units in the upper crust. Density and magnetic susceptibility data (Elming 1980) have provided an essential basis for many of the interpretations. A closer integration of the various lines of geophysical data with the reflection seismic profiling is in progress.

Seismic refraction experiments further north in the orogen (Blue Road in Västerbotten County) have provided evidence for two low velocity layers, one within the allochthon and the other in the basement (Lund 1979). The high velocities in the upper crust in that area correlate well with Seve amphibolite schists and gneisses and are underlain by lower velocities relatable to underlying allochthonous units and basement. Velocity data from Jämtland (Palm 1984, 1986) support these interpretations and are in general agreement with the results of the reflection profiling, the denser Seve lithologies being characterized by high reflectivity, implying strong contrasts in acoustic impedance.

The lower velocity layer identified deeper in the crust in the hinterland in the Blue Road profile at 10–14 km depth (Lund 1979) may be comparable with that in the Kristiansand-Dombås profile at 14–18 km depth (Mykkeltveit 1980, Mykkeltveit et al 1980). Reflection seismic data are not yet available from these areas; it is possible that the gently W-dipping reflection(s) in Jämtland extend westwards into this low velocity interval.

Extension of the vast, total field Jämtland magnetic anomaly beneath the Caledonides has not only favoured the interpretation that relatively undeformed, passive basement extends far west beneath the allochthon; it has also allowed closer analysis of the depths to the magnetic source beneath the nappes (Dyrelius 1980). Only very few of the rocks in the Caledonian cover have high enough magnetic susceptibilities (Elming 1980) to significantly contribute to the magnetic anomalies. Even such units as the Seve amphibolites generally have susceptibilities that are one or two orders of magnitude less than those of the Rätan granite. The dolerites of the Särv Nappes have susceptibilities only slightly lower than those of the Rätan granite and may, when present in large proportions, make a significant contribution to the magnetic anomaly. The allochthonous Proterozoic crystalline units, such as the rhyolitic porphyries in the Mullfjället Antiform, are essentially non-magnetic; they do not influence the anomaly pattern. Thus, analysis of the depth to the magnetic source has been inferred to provide information on the depth to the magnetic crystalline basement beneath the Caledonian cover.

In the Caledonian front in Jämtland, where both magnetic and refraction seismic measurements exist, the depths to basement determined from magnetic data are generally in close agreement with those obtained from the seismic surveys; only a few local discrepancies have been observed (Palm 1984). This suggests that, in that area, the basement directly beneath the Caledonian cover to a large extent consists of granites of Rätan type. The present seismic reflection profiling, on the other hand, suggests that the rock units below the Caledonian allochthon may vary greatly in composition and therefore magnetic properties. If the dominant source for the Jämtland anomaly is a vast, at least 10 km thick, granite of Rätan type (Dyrelius 1980), then the reflection seismic data suggest that the upper surface of this batholith is probably irregular, only partly coinciding with the sub-Cambrian peneplain. However, the magnetic anomaly data place substantial constraints on the alternative interpretations of the seismic reflections. Thus, it has been suggested above that a half-graben, up to 6 km deep, might exist below the eastern part of the Tännfors Synform and the Mullfjället Antiform, filled with Dala sandstones and volcanites and containing subordinate concordant mafic bodies. Assuming the graben to be filled with sandstones and low susceptibility volcanites, similar to those in the Dalarna autochthon, would require that it should be marked by a prominent negative magnetic anomaly. This is not seen (e.g. in profiles L 3–5 and H 5 of Dyrelius 1980); the magnetic source appears homogeneous with only minor undulation of the upper surface. Thinner (up to a few hundreds of metres), low susceptibility volcanites and/or sandstones may be present, but the magnetic data do not favour a major graben, unless it is filled by volcanites of moderate to high susceptibility. To establish more precisely the relationship between the features of the magnetic anomalies and the seismic reflections, a three dimensional interpretation of the Jämtland anomaly in Dalarna is needed.

Preferred interpretation

The discussion above of alternative interpretations of the reflections in the Swedish sector of the central Scandes, has attempted to take into account all the main geological and geophysical constraints. Other interpretations or variations of those treated here will surely arise by closer analysis of the reflection data and acquisition of more profiles. Particularly relevant would be an extension of the reflection profiling to the east, from Järpen to Östersund. This should provide control for the relationships between the W-dipping reflections (e.g. IV) and the surface structures and also the geometry and distribution of the underlying reflections. The latter may continue eastwards beneath the areas where the autochthon has been controlled by drilling, where they can more easily be related to the Proterozoic geology.

Complete unanimity over the interpretation of these kinds of deep crustal data will probably never be achieved. Deep drilling will eventually be needed to test alternative hypotheses. The interpretation preferred here (Plate 3) accepts that a major structural break, represented by reflections I–IV, separates a folded Caledonian allochthon from an underlying largely undisturbed autochthon. This gently W-dipping (c. 4° from Järpen to the Norway-Sweden border) discontinuity is interpreted as a sole thrust, implying considerable eastwards transport not only of the folded Caledonian thrust sheets, but also of the Proterozoic crystalline rocks in the cores of the Mullfjället and Skardöra Antiforms.

Surface geological mapping, drilling, shallow refraction experiments and interpretation of magnetic data in the Caledonian front of central Jämtland have provided evidence for an extensive décollement, separating autochthonous basement, covered by a thin skin of Cambrian sediments, from an allochthon composed almost entirely of Vendian to Silurian, subgreenschist facies (epizone) sedimentary rocks. Only very locally, e.g. on Hoverberget and Frösön, are Precambrian crystalline rocks (Proterozoic acid volcanites) incorporated in this allochthon.

The refraction experiments (Palm 1984) traced a fairly regular shallow basement surface westwards to c. 10 km west of Hallen, implying that basement is probably passive from the thrust front (e.g. in Bingsta) at least fifty kilometres towards the WNW, the direction from where the allochthon was derived. Interpretation of the seismic refraction data, indicating that the surface of the basement dips more steeply (c. 5°) to the west in areas of western Storsjön (west of Hallen), suggests greater involvement of basement in these areas. Further west, refraction and magnetic data support this interpretation, providing evidence for the presence of a basement high within a few hundred metres of the surface near the east end of Liten. This area of basement uplift lies along the N–S axis of the Oviksfjällen Antiform (Fig. 2), running from Olden in the north, via Djupsjön to Oviksfjällen in the south. It coincides with the projection eastwards from Järpen of the interval of low reflectivity immediately above reflection IV, thus favouring the interpretation that Proterozoic crystalline rocks are present near the surface and that they occur in the hangingwall of the sole thrust. Comparison with the structure in Oviksfjällen suggests that a hangingwall ramp anticline cored by crystalline rocks is present below Liten. Imbrication along the forward edge of this crystalline sheet might be expected, with development of a thickened stack of quarzitic sandstones and porphyritic rhyolites (cf. Oviksfjällen).

The extent to which movement on the sole thrust is taken up on the frontal décollement remains to be assessed. The geological map of Jämtland (SGU 1984) shows no major thrusts disrupting the Lower Allochthon. This map provides no support for Asklund's (1960) interpretation that two major thrust sheets dominate the Lower Allochthon of west-central Jämtland, the Olden and Föllinge Nappes. However, the trace of the Olden Nappe in the vicinity of Mattmar coincides with the basement irregularity referred to above; thus, a closer analysis of the field relationships will be needed to distinguish between the different possibilities. Facies changes from greywackes to shales and limestones in the Middle Ordovician successions around Storsjön may be obscuring the character and extent of the cover-shortening in this critical segment of the mountain front.

If it is accepted that the Caledonian front décollement passes westwards into the sole thrust, identified here by reflections I–IV, then it follows that the reflectivity of this prominent gently W-dipping zone is probably related to the presence of Caledonian sedimentary rocks and/or mylonitized basement units. The bright reflection IV beneath the Åre Synform has been interpreted to imply the presence of at least a few tens of metres of shales (probably Cambrian), resting on the Proterozoic basement and overthrust by acid volcanites of similar composition to those in the core of the Mullfjället Antiform. How far west these footwall sedimentary rocks persist is clearly conjectural and influences estimates of displacement distance on the sole thrust. In view of the apparent lack of evidence (SGU 1984) of cover-shortening by extensive thrusts in the Lower Allochthon around Storsjön, we have adopted a conservative interpretation that involves a minimum of thrust displacement. Hence the reflections from the sole thrust (I, II and III) west of the Åre Synform are inferred to be related to mylonitic pre-Caledonian rocks, e.g. sheared mafic and felsic rocks, and not to the presence of Caledonian sedimentary rocks.

Likewise, within the Mullfjället Antiform, the arched reflectors above the sole thrust may be caused either by the presence of Caledonian sedimentary rocks within the basement acid volcanites or by concordant basement rocks of contrasted acoustic impedance. The latter interpretation is shown in Plate 3, thus favouring a minimum of thrust displacement. The evidence at the surface of very subordinate concordant mafic volcanic rocks (S. Tirén, pers. comm. 1989) and dykes in the Mullfjället rhyolites has favoured the interpretation that the arched reflections probably are related to mafic igneous rocks, reoriented concordantly within the Caledonian shear zones.

Further west, the inferred sole thrust (reflections II and I) converges with flat to slightly foreland dipping sub-thrust reflections. Differences in the reflectivity of the former are interpreted to be related to the variable presence and thickness of mafic igneous rocks in this basal shear zone. Within the Skardöra Antiform the upper, arched reflections of Hurich et al. (1989) can be shown by down plunge projection of surface structure (Sjöström 1984), to very probably be related to Caledonian sedimentary intercalations imbricated together with the Proterozoic acid igneous rocks. However, the reflections deeper than c. 1 s TWT are less well constrained and are interpreted to be related to Caledonian-deformed Mid Proterozoic basic intrusions. As in the case of Mullfjället, Caledonian sedimentary rocks might be present.

The close correspondence of surface structures and lithologies within the Caledonian nappes and the geometry and character of the reflections in the upper c. 1–2 s TWT has made interpretation of the structure in the uppermost crust, above the sole thrust, less controversial. Nevertheless, much uncertainty remains, eg as to the nature and thickness of the various units of the Middle Allochthon below the Seve Nappes in the Tännfors and Åre Synforms. In view of the characteristic lenticularity of these thrust sheets, down plunge projection of the surface geology into the line of section can only be regarded as a first attempt to interpret the reflectors.

Thinning and excision of some units of the Köli, the Seve and the Middle Allochthon in the western limb of the Skardöra Antiform can be related to late normal faulting (Devonian extension) cutting the Scandian thrusts at the surface and curving back into them at depth (Norton 1987, Gee 1988). A similar interpretation has been applied to the cut-out of these units in the western limb of the Mullfjället Antiform, although we have as yet no independent evidence (e.g. kinematic indicators) for this sense of movement.

Interpretation of the sub-thrust reflections has been dictated by the occurrence of Early to Mid Proterozoic rocks of Dala "association" as minor isolated slices in the Lower Allochthon (e.g. at Hoverberget), and by the various lines of geophysical evidence (magnetic and reflection seismic) that favour continuity of the rock units in the Härjedalen autochthon northwestwards beneath the Caledonian allochthon of western Jämtland. The general lack of distinct reflectivity of the middle and lower crust is comparable to that obtained from profiling over the Värmland and Siljan granites and favours the presence of a considerable (at least 20 km) thickness of homogeneous Early to Mid Proterozoic granites beneath this part of the mountain belt. The strong, sub-thrust reflections in the upper crust, several of which are persistent over distances of more than ten kilometers, are comparable to those obtained from profiles over the Dala volcanites and sandstones (Lindgren et al 1988) and the Siljan granites of the autochthon.

The interpretation presented in Plate 3 is obviously speculative in that the rock associations known from surface mapping of the autochthon in Härjedalen may be present in quite varying thicknesses beneath the mountain belt. Granites of Rätan type at depth, intruded by a few flat-lying dolerites, are inferred on Plate 3 to be overlain in the central part of the profile by a succession of volcanites and subordinate sandstones, also intruded by dolerites. The contact between the granites and the supracrustal rocks may be either intrusive or unconformable. The rock volumes distinguished as granites are characterized by a general lack of reflectivity interrupted by a few bright reflections; the supracrustal rocks are inferred where the persistent strong reflections are interlayered with units of lower, but apparently concordant reflectivity.

A more detailed analysis of the reflection data is in progress along with a reassessment of the potential field data in relation to the interpretations presented here. Reflection seismic profiling is clearly an important technique for investigation of Caledonian structure and will surely provide many new insights into the character of the bedrock in Sweden in the years to come.

ACKNOWLEDGEMENTS

Both during the planning of the seismic profiling and the interpretation of the results we have benefited from discussion with several of our colleagues, particularly M. Beckholmen, J. Gilotti, L. Karis, R. Kumpulainen, H. Sjöström and S. Tirén. Our earlier profiling across the Skardöra Antiform was carried out in collaboration with C. Hurich and his council at various stages of the Jämtland work has been greatly appreciated. During the planning and execution of the field campaign, L. Dynesius and R. Nocke were invaluable assistants. T. Dahl-Jensen is thanked for helping with the processing of the data.

The seismic profile and interpretation illustrated here was presented in poster form at the 28th International Geological Conference in Washington USA in July 1989. We benefited from the comments of many colleagues and were particularly interested to learn that E. Hauser (Cornell USA) had also concluded from the Skardöra and Bodsjön profiles (Hurich et al. 1989) that gently dipping mid-Proterozoic dolerites probably contributed to the upper crustal reflectivity (Hauser 1990, Hurich et al. 1990).

We thank E. Hauser, C. Juhlin, R.J. Lillie, H. Sjöström, A. Strömberg and E. Zachrisson for constructive criticism of an earlier edition of this manuscript and the Swedish Natural Science Research Council for financial support.

REFERENCES

ANDERSSON, A., DAHLMAN, B., GEE, D.G. & SNÄLL, S., 1985: The Scandinavian Alum Shales. – Sveriges Geologiska Undersökning Ca 56, 1–50.

ARNBOM, J.-O., 1980: Metamorphism of the Seve Nappes at Åreskutan, Swedish Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 102, 359–371.

ARNBOM, J.-O. & TROENG, B., 1982: Fe-Mg partitioning between biotite and garnet from the Seve Nappe Complex Åreskutan, Swedish Caledonides. – Neues Jahrbuch für Mineralogie, Abhandlungen 145, 34–49.

ASKLUND, B., 1938: Hauptzüge der Tektonik und Stratigraphie der mittleren Kaledoniden in Schweden. – Sveriges Geologiska Undersökning C417, 99 pp.

ASKLUND, B., 1960: The geology of the Caledonian mountain chain and of adjacent areas in Sweden. – Sveriges Geologiska Undersökning Ba16, 126–149.

AVEDIK, F., BERENDSEN, D., FUCKE, H., GOLDFLAM, S., HIRSCHLEBER, H., MEISSNER, R., SELLEVOLL, M.A. and WEINREBE, W., 1984: Seismic investigations along the Scandinavian "Blue Norma" profile. – Annales Geophysicae 2, 571–578.

BALLY, A., GORDY, P. & STEWART, G.,1966: Structure, seismic data, and orogenic evolution of the southern Canadian Rockies. – Bulletin of Canadian Petroleum Geology 14, 337–381.

BARAZANGI, M. & BROWN, L. (eds.), 1986a: Reflection Seismology: A Global Perspective. – Geodynamics series 13, American Geophysical Union, Washington, DC. 311 pp.

BARAZANGI, M. & BROWN, L. (eds.), 1986b: Reflection Seismology: The Continental Crust. – Geodynamics series 14, American Geophysical Union, Washington, DC. 339 pp.

BASSET, S.M., CHERNS, L. & KARIS, L., 1982: The Röde Formation: an Old Red Sandstone facies in the Silurian Jämtland, Sweden. – Sveriges Geologiska Undersökning C793, 24 pp.

BECKHOLMEN, M., 1980: Geology of the Nordhallen-Duved-Greningen area in Jämtland, central Swedish Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 100, 335–347.

BECKHOLMEN, M., 1982: Mylonites and pseudotachylytes associated with thrusting of the Köli Nappes, Tännforsfältet, central Swedish Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 104, 23–32.

BECKHOLMEN, M., 1983: Petrography, petrochemistry and regional significance of the Saxvallklumpen metabasite, Köli Nappe Complex, Tännforsfältet, central Swedish Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 104, 293–303.

BECKHOLMEN, M., 1984: The Köli Nappe Complex in the Tännforsfältet, western Jämtland, Swedish Caledonides. – Meddelanden från Stockholms Universitets Geologiska Institution 259, (unpubl. Ph.D-thesis), 16 pp.

BERGMAN, S. 1987: A possible ophiolite at Handöl, Swedish Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 109, 340–343.

BERGSTRÖM, J., 1980: The Caledonian margin of the Fennoscandian shield during the Cambrian. *In:* Wones, D.R. (edit.), – The Caledonides in the USA. Virginia Polytechnic Inst., and State University. Dept. Sci. Mem. 2. 9–13.

BURG, J.P. & CHEN, G.M., 1984: Tectonics and structural zonation of southern Tibet, China. – Nature 311, 219–223.

CASHMAN, P.H., 1989: Geometry and kinematics of extensional deformation along the northern edge of the Rombak Window, Nordland, North Norway. – Norges Geologiske Undersökelse Bulletin 415, 71–85.

CHOUKROUNE, P. & ECORS TEAM, 1989: The Ecors Pyrenean deep seismic profile reflection data and the overall structure of an orogenic belt. – Tectonics 8:1, 23–39.

CHRISTOFFERSON, H.C., WALLIN, B., SELKMAN, S. & RICKARD, D.T., 1979: Mineralization controls in the sandstone lead-zinc deposits at Vassbo, Sweden. – Economic Geology 74, 1239–1249.

CLAESSON, S. & RODDICK, J., 1983: 40Ar/39Ar data on the age and metamorphism of the Ottfjället dolerites, Särv Nappe, Swedish Caledonides. – Lithos 16, 61–73.

CLARK, H.B., COSTAIN, J.K. & GLOVER, L., 1978: Structural and seismic reflection studies of the Brevard ductile deformation zone, near Rosman, North Carolina. – American Journal of Science 278, 419–441.

COOK, F.A., ALBAUGH, D.S., BROWN, L.D., KAUFMAN, S., OLIVER, J.E. & HATCHER, JR., R.D. ,1979: Thin-skinned tectonics in the crystalline southern Appalachians; COCORP seismic-reflection profiling of the Blue Ridge and Piedmont. – Geology 7, 563–567.

DAHL-JENSEN, T., 1989: Static corrections on crystalline rock. – Geophysical Prospecting 37, 467–478.

DAHL-JENSEN, T., DYRELIUS, D. & PALM, H., 1989: Deep crustal reflection seismics across two major tectonic zones in southern Sweden. *In* Dahl-Jensen, T., 1989: *Reflection seismic studies in the Baltic Shield: Special processing techniques and results.* – Acta Universitatis Upsaliensis, 188 pp. (Ph.D.-diss., Uppsala University).

DYRELIUS, D., 1980: Aeromagnetic interpretation in a geotraverse area across the central Scandinavian Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 102, 421–438.

DYRELIUS, D., 1985: A geophysical perspective of the Scandinavian Caledonides. *In:* Gee, D.G. & Sturt, B.A. (eds.). *The Caledonide Orogen – Scandinavia and related areas.* – John Wiley & Sons Ltd. Chichester, 185–194.

DYRELIUS, D., 1986: Gravity and magnetics in the central Scandes. – Geologiska Föreningens i Stockholm Förhandlingar 108, 278–280.

DYRELIUS, D., GEE, D.G., GORBATSCHEV, R. & RAMBERG, H. & ZACHRISSON, E., 1980: A profile through the central Scandinavian Caledonides. – Tectonophysics 69, 247–284.

ELEMAN, F., BORG, K. & ÖQUIST, U. (eds.), 1969: The aeromagnetic survey of Denmark, Finland, Norway, Sweden 1965. 59 pp. – Geomagnetic Section, Swedish Board of Shipping and Navigation. (Svenska Reproduktions AB, Stockholm).

ELMING, S.-Å., 1980: Density and magnetic properties of rocks in the Caledonides of Jämtland, Sweden. – Geologiska Föreningens i Stockholm Förhandlingar 102, 439–453.

ELMING, S.-Å., 1988: Geological modelling based on gravity data from the central part of the Swedish Caledonides. – Geologiska Föreningens i Stockholm förhandlingar 110, 317–327.

FRÖDIN, G., 1922: Über die Geologie der zentralschwedischen Hochgebirge. – Bulletin of the Geological Institution of the University of Uppsala 18, 57–197.

GEE, D.G., 1975a: A geotraverse through the Scandinavian Caledonides-Östersund to Trondheim. – Sveriges Geologiska Undersökning C417, 66 pp.

GEE, D.G., 1975b: A tectonic model for the central part of the Scandinavian Caledonides. – American Journal of Science 275A, 468–515.

GEE, D.G., 1986: Middle and upper crustal structure in the central Scandinavian Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 108, 280–283.

GEE, D.G., 1988: Thrust tectonics in the Scandes - upper crustal extension during Scandinavian compression. – Geologiska Föreningens i Stockholm Förhandlingar 110, 390–392.

GEE, D.G., KUMPULAINEN, R. & THELANDER, T., 1978: The Tåsjö décollement, central Swedish Caledonides. – Sveriges Geologiska Undersökning C742, 35 pp.

GEE, D.G. & ZACHRISSON, E., 1979: The Caledonides in Sweden. – Sveriges Geologiska Undersökning C769, 48 pp.

GEE, D.G. & KUMPULAINEN, R., 1980: An excursion through the Caledonian mountain chain in central Sweden from Östersund to Storlien. – Sveriges Geologiska Undersökning C774, 65 pp.

GEE, D.G. & SJÖSTRÖM, H., 1984: Early Caledonian obduction of the Handöl ophiolite. – Meddelanden från Stockholms Universitets Geologiska Institution 255, 72.

GEE, D.G. & SNÄLL, S., 1981: Alunskifferprojektet-Fjällen. Analyser, metodik och resultat. – Sveriges Geologiska Undersökning, Rapport till NSG. BRAP 81512. Unpublished report. 35 pp.

GEE, D.G. & STURT, B.A. (eds.), 1985. *The Caledonide Orogen – Scandinavia and related areas.* – John Wiley & Sons Ltd. Chichester, 1266 pp.

GEE, D.G., GORBATSCHEV, R. & RAMBERG, H., 1983: The Scandinavian Caledonides. *In:* Rast, N. & Delany, F.M. (eds.), Profiles of Orogenic Belts, *Geodynamic Series 10.* – American Geophysical Union. 45–51.

GEE, D.G., KUMPULAINEN, R., ROBERTS, D., STEPHENS, M.B., THON, A. & ZACHRISSON, E., 1985a: Scandinavian Caledonides, Tectonostratigraphic map. – Sveriges Geologiska Undersökning, Ba 35.

GEE, D.G., GUEZOU, J.-C., ROBERTS, D. & WOLFF, F.C., 1985b: The central-southern part of the Scandinavian Caledonides. *In:* Gee, D.G. & Sturt, B.A. (eds.), *The Caledonide Orogen - Scandinavia and related areas.* – John Wiley & Sons Ltd. 109–133.

GILOTTI, J. & KUMPULAINEN, R., 1986: Strain softening induced ductile flow in the Särv thrust sheet, Scandinavian Caledonides. – Journal of Structural Geology 8:3/4, 441–455.

GORBATSCHEV, R., 1985: Precambrian basement of the Scandinavian Caledonides. *In:* Gee, D.G. & Sturt, B.A. (eds.), *The Caledonide Orogen - Scandinavia and related areas.* – John Wiley & Sons Ltd. 197–212.

HARDENBY, C., 1980: Geology of the Kjølhaugan area, eastern Trøndelag, central Scandinavian Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 102, 475–492.

HAUSER, E.C., 1990: Comment and reply on "Deformation of the Baltic continental crust during Caledonide intracontinental subduction: Views from seismic reflection data". – Geology 18(6), 578–580.

HELLFRISCH, H.K., 1966: Ein Beitrag zur Geologie des Åregebietes, aus dem zentralen teil der Schwedischen Kaledoniden. – Sveriges Geologiska Undersökning C612, 35 pp.

HIRN, A., LEPINE, J.-C., JOBERT, G., SAPIN, M., WITTLINGER, G., XU, Z.X., GAO, E.Y., WANG, X.J., TENG, J.W., XIONG, S.B., PANDEY, M.R. & TATER, J.M., 1984: Crustal structure and variability of the Himalayan border of Tibet. – Nature 307, 23–25.

HJELMQVIST, S., 1966: Beskrivning till berggrundskarta över Kopparbergs län. (Summary description to map of the Pre-Quaternary rocks of the Kopparberg County, Central Sweden). – Sveriges Geologiska Undersökning Ca 40, 217 pp.

HOSSACK, J.R. & Cooper, M.A., 1986: Collision tectonics in the Scandinavian Caledonides. *In* M.D. Coward & A.C. Ries (eds.), Collision Tectonics, 287–304. – Geological Society of London Special Publication 19.

HURICH, C.A., PALM, H., DYRELIUS, D., KRISTOFFERSEN, Y., WOLFF, F.C. & ROBERTS, D., 1988: Activation of the Precambrian basement in the Scandinavian Caledonides: views from seismic reflection data. – Norges Geologiske Undersökelse, Special Publication 3, 66–69.

HURICH, C.A., PALM, H., DYRELIUS, D. & KRISTOFFERSEN, Y. 1989: Deformation of the Baltic continental crust during Caledonide intracontinental subduction: views from seismic reflection data.– Geology 17, 423–425.

HURICH, C.A., PALM, H., DYRELIUS, D. & KRISTOFFERSEN, Y., 1990: Comments and reply on "Deformation of the Baltic continental crust during Caledonide intracontinental subduction: Views from seismic reflection data". – Geology 18(6), 578–580.

HÖGBOM, A.G., 1894: Geologisk beskrivning öfver Jämt-lands län. – Sveriges Geologiska Undersökning C 140, 107 pp.

HÖGBOM, A.G., 1909: Studies in the post-Silurian thrust region of Jämtland. – Geologiska Föreningens i Stockholm Förhandlingar 31, 289–346.

JUHLIN, C. & PEDERSEN, L.B., 1987: Reflection seismic investigations in the Siljan impact structure.– Journal of Geophysical Research 92, B13, 14113–14122.

JUHLIN, C., DYRELIUS, D., LUND, C-E. & PALM, H., 1989: Crustal Reflections underneath Lake Vänern, Sweden. – Geophysical Journal International 99, 567–578.

KULLING, O., 1972: The Swedish Caledonides. *In:* Strand, T. & Kulling, O., *Scandinavian Caledonides.* – John Wiley & Sons Ltd. Part 2, 147–285.

KUMPULAINEN, R., 1980: Upper Proterozoic stratigraphy and depositional environments of the Tossåsfjället Group, Särv Nappe, southern Swedish Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 102, 531–550.

KUMPULAINEN, R. & NYSTUEN, J.P., 1985: Late Proterozoic basin evolution and sedimentation in the westernmost part of Baltoscandia. *In:* Gee, D.G. & Sturt, B.A. (eds.), *The Caledonide Orogen - Scandinavia and related areas.* – John Wiley & Sons Ltd. 213–232.

LILLIE, R.J., 1984: Tectonic implications of subthrust structures revealed by seismic profiling of Appalachian-Ouachita orogenic belt. – Tectonics 3:6, 619–646.

LINDGREN, J., DAHL-JENSEN, T., PALM, H. & PEDERSEN, L.B., 1988: Reflection seismic investigations of the Dala Sandstone Area, central Sweden. 1: Method evaluation. – Unpublished Report to Nämnden för Statens Gruvegendom, November 1988.

LUNDQVIST, Th., 1968: Precambrian geology of the Los-Hamra region, central Sweden. – Sveriges Geologiska Undersökning Ba23, 255 pp.

LUNDQVIST, Th., 1979: The Precambrian of Sweden. – Sveriges Geologiska Undersökning C768, 87 pp.

LUND, C.-E., 1979: Crustal structure along the Blue Road Profile in northern Scandinavia. – Geologiska Föreningens i Stockholm Förhandlingar 101:3, 191–204.

LUND, C. E., ROBERTS, R., DAHL-JENSEN, T. & LINDGREN, J., 1988: Deep crustal structure in the vicinity of the Siljan Ring. *In* Bodén, A. and Eriksson, K. G. (eds.), *Deep drilling in crystalline bedrock, vol. 1: The deep gas drilling in the Siljan Impact Structure, Sweden and Astroblemes,* – Springer-Verlag, Berlin Heidelberg, 1988, 355–364.

LUOSTO, U., 1989: Seismic data from the northern segment of the EGT and from the nearby profiles. – Sixth EGT workshop: data compilations and synoptic interpretation. Einselden, 29 november – 5 december 1989. European Science Foundation. 53–63.

MATTEWS, D. & SMITH, C. (eds.), 1987: Deep seismic reflection profiling of the continental lithosphere. – Geophysical Journal of the Royal Astronomical Society (Special issue) 89, 1–448.

MCQUILLIN, R., BACON, M. & BARCLAY, W., 1984: An introduction to seismic interpretation. 2nd ed. – Graham & Trotman Ltd, 287 pp.

MEISSNER, R., 1979: Fennoscandia – a short outline of its geodynamical development. – GeoJournal 3.3, 227–233.

MILNES, A.G. & KOESTLER, A.G., 1985: Geological structure of Jotunheimen, southern Norway. (Sognefjell-Valdres Crosssection). *In:* Gee, D.G. & Sturt, B.A. (eds.), *The Caledonide Orogen - Scandinavia and related areas.* – John Wiley & Sons. 457–474.

MILNES, A,G., DIETLER, T.N. & KOESTLER, A.G., 1988: The Sognefjord north shore log – a 25 km depth section through Caledonized basement in western Norway. – Norges Geologiska Undersökelse, Special Publication 3, 114–121.

MONGER, J.W.H., 1986: The Global Geoscience Transects Project. – Episodes 9:4, 217–222.

MYKKELTVEIT, S., 1980: A seismic profile in southern Norway. – Pure and Applied Geophysics 118, 1310–1325.

MYKKELTVEIT, S., HUSEBYE, E.S. & OFTEDAHL, C. , 1980: Subduction of the Iapetus Ocean crust beneath the Möre Gneiss Region, southern Norway. – Nature 288, 473–475.

NORTON, M.G., 1987: The Nordfjord-Sogn Detachment, W. Norway. – Norsk Geologisk Tidsskrift 67, 93–106.

NYSTRÖM, J.O. ,1982: Post-Svecokarelian Andinotype evolution in central Sweden. – Geologische Rundschau 71:1, 141–157.

NYSTRÖM, J.O., 1983: Pumpellyite-bearing rocks in central Sweden and extent of host rock alteration as a control of pumpellyite composition. – Contributions to Mineralogy and Petrology 83, 159–168.

NYSTRÖM, J.O. & LEVI, B., 1980: Pumpellyite-bearing Precambrian rocks and post-SvecoKarelian regional metamorphism in central Sweden. – Geologiska Föreningens i Stockholm Förhandlingar 102, 37–39.

PALM, H., 1984: Time-delay interpretation of seismic refraction data in the Caledonian front, Jämtland, central Scandinavian Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 106, 1–14.

PALM, H., 1986: Conclusions from seismic refraction profiles in the central Scandinavian Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 108, 298–300.

PALM, H. & LUND, C.-E., 1980: A seismic refraction study in the Caledonian front of Jämtland, Sweden. – Geologiska Före-ningens i Stockholm Förhandlingar 102:4, 561–568.

PATCHETT, P.J., 1978: Rb/Sr ages of Precambrian dolerites and syenites in southern and central Sweden. – Sveriges geologiska Undersökning C747, 1–63.

RAMBERG, H., 1966: The Scandinavian Caledonides as studied by centrifuged dynamic models. – Bulletin of the Geological Institutions of the University of Uppsala 43, 72 pp.

RAMBERG, H., 1980: Diapirism and gravity collapse in the Scandinavian Caledonides. – Journal of the Geological Society of London 137, 261–270.

RIDDIHOUGH, R.P., 1972: Regional magnetic anomalies and geology in Fennoscandia: a discussion. – Canadian Journal of Earth Sciences 9, 219–232.

ROERMUND, VAN, H.L.M. & BAKKER, E., 1984: Structure and metamorphism of the Tången-Inviken area, Seve Nappe, central Scandinavian Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 105, 301–319.

SCHAAR, G., 1961: Petrological and geological investigations in the Sylene-Skardørsfjell region (Sør-Trøndelag, Norway). – Geologisch Instituut, Universiteit van Amsterdam, Medeling 273, 1–74.

SGU, 1984: Karta över berggrunden i Jämtlands län utom förutvarande Fjällsjö k;n (Bedrock geology of Jämtland County). Map to the scale 1:200.000. – Sveriges Geologiska Undersökning Ca 53.

SJÖSTRÖM, H., 1984: The Seve-Köli Nappe Complex of the Handöl-Storlien-Essandsjøen area, Scandinavian Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 105, 93–118.

SJÖSTRÖM, H. & TALBOT, C.J., 1987: Caledonian and post-Caledonian structure of the Olden Window, Scandinavian Caledonides. – Geologiska Föreningens i Stockholm Förhandlingar 109, 359–361.

SJÖSTRÖM, H. & BERGMAN, S., 1989: Asymmetric extension and Devonian (?) normal faulting; examples from the Caledonides of eastern Tröndelag and western Jämtland. – Geologiska Föreningen i Stockholm Förhandlingar 111, 407–410.

SNÄLL, S.1988: Mineralogy and maturity of the alum shales of south-central Jämtland, Sweden. – Sveriges Geologiska Undersökning C118, 46 pp.

SPENCER, C., GREEN, A., MOREL-a-l'HUISSIER, P., MILKEREIT, B., LUETGERT, J., STEWART, D., UNGER, J. & PHILIPPS, J., 1989: The extension of Grenville basement beneath the northern Appalachians: results from the Quebec-Maine seismic reflection and refraction surveys. – Tectonics 8:4, 677–696.

STEPHANSSON, O., 1976: A tectonic model of the Offerdal-Olden area, Jämtland. – Geologiska Föreningens i Stockholm Förhandlingar 98, 112–119.

STEPHENS, M.B., 1988: The Scandinavian Caledonides: a complexity of collisions. – Geology Today 4, 20–26.

STOLT, R.H., 1978: Migration by Fourier Transform. – Geophysics 43, 23–48.

STRÖMBERG, A., 1961: On the tectonics of the Caledonides in the southwestern part of the county of Jämtland, Sweden. – Bulletin of the Geological Institution of Uppsala 39, 92 pp.

STRÖMBERG, A., 1974: Kaledonisk tektonik i Jämtland. – Geologiska Föreningens i Stockholm Förhandlingar 96, 125–129.

STRÖMBERG, A., 1986: The Caledonides in Jämtland. – Geologiska Föreningens i Stockholm Förhandlingar 108, 305–308.

THORSLUND, P., 1940: On the Chasmops Series of Jämtland and Södermanland (Tvären). – Sveriges Geologiska Undersökning C436, 191 pp.

TÖRNEBOHM, A.E., 1888: Om fjällproblemet. – Geologiska Föreningens i Stockholm Förhandlingar 10, 328–336.

TÖRNEBOHM, A.E., 1896: Grunddragen af det centrala Skandinaviens bergbyggnad. – Kongliga Svenska Vetenskaps Akademins Handlingar 28:5, 212 pp.

VOGEL, A. & LUND, C.-E., 1971: The trans-Scandinavian profile of 1969: Profile section 2–3. *In:* Vogel, A. (ed.), *Deep seismic Sounding in Northern Europe.* – Swedish Natural Science Research Council, Stockholm. 62–75.

ZACHRISSON, E., 1973: The westerly extension of Seve rocks within the Seve-Köli Nappe Complex in the Scandinavian Caledonides. Geologiska Föreningens i Stockholm Förhandlingar 95, 243–251.

List of Plates

Plate 1. Unmigrated reflection seismic section (0–10 s TWT) along segments E, F, G, and H. Horizontal and vertical (at 6.0 km/s) scales c. 1:100,000. Zero time relates to a 400 m a.s.l. datum.

Plate 2. Migrated reflection seismic section (0–10 s TWT) along segments E, F, G and H. Horizontal and vertical (at 6.0 km/s) scales c. 1:100,000. Zero time relates to a 400 m a.s.l. datum.

Plate 3. Preferred geological interpretation of the reflection seismic profile EFGH. In this interpretation, information has been used from the unmigrated section (Plate 1), the migrated section (Plate 2) and from Fig 6.


WEST
EAST
SKARDÖRA ANTIFORM
TÄNNFORS SYNFORM
MULLFJÄLLET ANTIFORM
ÅRE SYNFORM
25.
FOLD
0.
2600
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
CDP No.
DEPTH (Km)
0
5
10
15
20
25
30
TWT (S)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
STACKING VELOCITY (M/S)
5000
5500
6000
6500
7000
TIME (S)
UNMIGRATED SECTION
0
5 km
Plate 1


WEST
EAST
SKARDÖRA ANTIFORM
TÄNNFORS SYNFORM
MULLFJÄLLET ANTIFORM
ÅRE SYNFORM
CDP No.
DEPTH (Km)
TWT (S)
STACKING VELOCITY (M/S)
TIME (S)
MIGRATED SECTION
0
5 km

Plate 2

WEST
EAST
SKARDÖRA ANTIFORM
TÄNNFORS SYNFORM
MULLFJÄLLET ANTIFORM
ÅRE SYNFORM
Connection-point with segment D
CDP No.
Azimuth of CDP-line
2600
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
106°
079°
058°
084°
124°
094°
088°
066°
100°
124°
114°
084°
B.N.
M.N.
G.N.
D.N.
S.N.
T.C.
L.S.
S.T.
DEPTH (Km)
0
5
10
15
20
TWT (S)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
LEGEND
Köli Nappe Complex (M.N., G.N., D.N. cf Fig.3)
Seve Nappe Complex (B.N., S.N., T.C., L.S. cf Fig.3)
Middle Allochthon (incl. Särv Nappe)
Undiff. Lower & Middle Allochthon (subord)
Vendian-Silurian sedimentary rocks
Proterozoic acid volcanic rocks
Lower Allochthon
SOLE THRUST (S.T.)
Cambrian(?) sedimentary rocks
Mafic igneous rocks
Acid volcanic rocks (Dala type) & subord. Dala sandstones
Granitoids (Rätan type)
Tectonic and/or lithologic boundary, based on strong reflectors
Extrapolated tectonic and/or lithologic boundary
0
5km
MIGRATED SECTION
STACKING VELOCITY (M/S)
TIME (S)

Plate 3

Distribution
SGU
Box 670, S-751 28 UPPSALA
Tel. 018-17 90 00

Tryck: Offsetcenter AB, Uppsala 1991

ISBN 91-7158-489-7
ISSN 0348-1352