SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 769 AVHANDLINGR OCH UPPSATSER ÅRSBOK 73 NR 10

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ABSTRACT

The Caledonides occupy the northwestern part of Sweden, occurring in a northeast trending belt some 50–150 km wide along the international border with Norway. This mountainous area, composing the eastern regions of the Scandes, forms a subordinate part of the Caledonian orogen in Scandinavia. Caledonian structures in Sweden are dominated by a variety of thrust nappes, displaced eastwards onto the Baltoscandian Platform with its thin autochthonous veneer of Cambrian and, locally, latest Precambrian and Ordovician sediments. Nappe movement is considerable; the highest allochthon is thought to have been transported at least 500 km. Late Precambrian and Lower Palaeozoic sequences of the Caledonian geosyncline occur in the nappes. The lower units (Lower Allochthon) contain platformal to miogeoclinal sedimentary successions (with occasional bentonites) deposited on the Baltoscandian Platform and along its margin. Overlying nappes (Middle Allochthon) incorporate substantial Precambrian crystalline basement along with Late Precambrian sandstones. Only in the higher nappes (Upper Allochthon) is there extensive evidence of Caledonian igneous activity, with the occurrence of intrusive and extrusive rocks in the allochthonous eugeoclinal successions. In the lower part (Särv Nappe) there is evidence for the existence in the Late Precambrian of a tensional regime, with the intrusion of an extensive tholeiitic dyke swarm, thought to be related to the opening of a Caledonian (Iapetus) ocean basin. Higher units (Seve-Köli Nappe Complex) provide evidence of the development of an Ordovician volcanic island arc along the Baltoscandian margin. Successions reach into the Early (?Mid) Silurian prior to orogenesis that culminated in the Mid-Late Silurian and probably continued into the Early Devonian, with deformation and metamorphism of the geosynclinal rocks and their emplacement onto the Baltoscandian Platform. The latter resulted in the inversion of metamorphic isograds and the spectacular development of mylonites. Folding of the entire tectono-stratigraphic sequence on axes parallel to the length of the orogen occurred after nappe emplacement. The dense allochthon occurs now in thin, westward thinning, thrust sheets that apparently achieved their final geometry during late-stage collapse and spreading of the nappe pile.

The Caledonides in Sweden are of considerable economic importance; a variety of natural resources are being exploited today. Stratabound sulphides provide the basis for the three producing mines – Pb-Zn deposits in autochthonous sandstones at Laisvall and Idre (Vassbo–Guttusjö) and polymetallic Cu-Zn-Pb deposits at Stekenjokk in the volcano-sedimentary allochthon. A large number of related sulphide mineralizations have been identified. Cambrian black shales with high contents of trace elements (particularly Mo, U and V) and organic matter are under investigation as are uranium mineralizations in the Precambrian basement of the Olden Window. Köli ultramafites and detrital serpentinites are potential sources of Ni. Schistose flagstones of the Middle Allochthon and Ordovician limestones of the Autochthon are used as building and paving stones.

INTRODUCTION

Caledonian structure dominates the western part of Scandinavia occurring within a mountain belt, the Scandes, that extends for c. 1 800 km along the northwestern margin of the Baltic Shield. These west Scandinavian mountains were established after rifting and separation of the Greenland and Eurasian continents, during development of the North Atlantic Ocean by Tertiary sea-floor spreading. The latter split the North Atlantic Caledonides into two parts, dividing an orogen which previously had a width of c. 1 000 km and submerging a substantial part beneath the continental shelves of the Greenland and Eurasian Plates.

The North Atlantic Caledonides developed in the Late Precambrian and Early Palaeozoic with accumulation of geosynclinal volcano-sedimentary sequences. Miogeoclinal successions were deposited along the continental margins of the Baltoscandian and Laurentian Plates, separated by an eugeoclinal prism that is thought to contain both Caledonian (Iapetus) ocean crust and volcanic island arc assemblages. An interplay of processes involving plate separation and convergence are thus thought to control Caledonian development. Deformation and metamorphism accompanied the building up of the island arcs and the obduction of the ophiolites. Tectogenesis reached a climax in the Late Silurian with accompanying uplift and erosion leading to deposition of fluvial sandstones and conglomerates in intra- and extra-montain basins, this sedimentation continuing into the Devonian. Thereafter followed extensive Late Palaeozoic and Mesozoic erosion, preceeding the Cenozoic fragmentation of the Orogen. In East Greenland, Caledonian structure is characterized by the westerly displacement of extensive thrust nappes; in Scandinavia, the tectonic style is in many respects similar, the structure being dominated by a composite allochthon, but the direction of displacement was towards the east on to the Baltoscandian Platform.

A substantial part of the Scandes (Fig. 1) is Norwegian territory; in Sweden the mountains extend from c. 61–69°N, occupying a north-trending belt some 100–150 km wide in the western part of the country and extending from Kopparberg County in the south via the counties of Jämtland and Västerbotten to Norrbotten in the north.* The terrain rises gently westwards towards the mountains, dissected by the numerous east-flowing rivers. The mountain front is in part coincident with the scarp of the Caledonian thrust front which is generally a well-marked feature. In the south, the foothills of Kopparberg and southern Jämtland County are capped by the quartzite-dominated lower nappes. The scarp of the thrust front can be followed northwards into central Jämtland where the lower tectonic units are largely composed of shales,

*Footnote.
The counties should not be confused with the provinces (landskap, in Swedish) some of which have the same name.

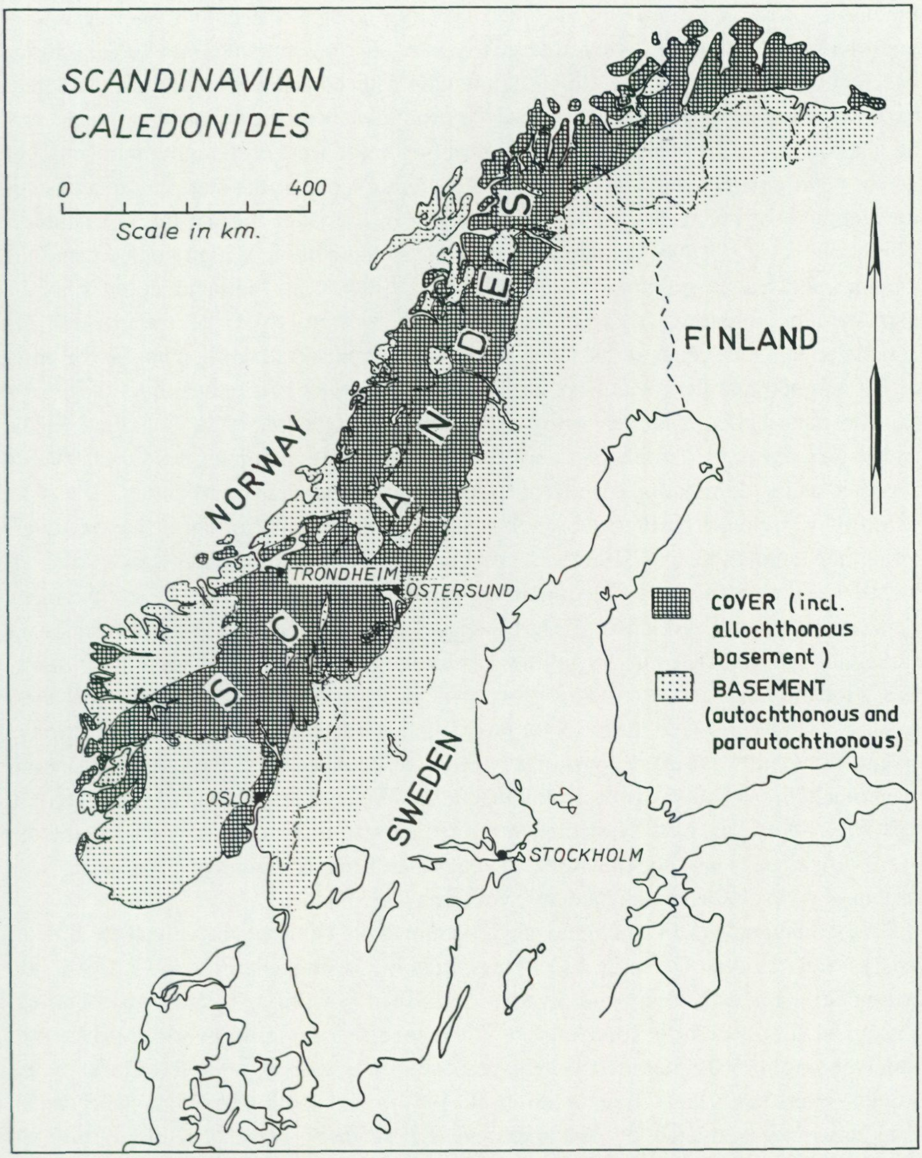

Fig. 1. Relationships between Precambrian crystalline basement (autochthonous and parautochthonous) and cover (autochthonous and allochthonous) in the Scandinavian Caledonides.

limestones and greywackes forming a gently undulating terrain around and north of Storsjön, the county's largest lake. Here the mountain front has retreated westwards to coincide more closely with higher allochthonous units. In northern Jämtland, quartzites again dominate the lower nappes and a well-marked thrust front can be followed far northwards. The quartzites are overriden by higher thrust units in northern Västerbotten and Norrbotten, where the gently west-dipping autochthonous Precambrian basement with its overlying, thin sedimentary veneer and composite allochthon is exposed in the deep river valleys. Here the prominent, east-facing scarp of the frontal allochthon in part coincides with and in part lies to the west of the mountain front.

The central part of the Scandinavian Caledonides is one of the classical areas for the development of the theory of nappe tectonics. In the latter part of the last century, Törnebohm (1888, 1896) demonstrated that the superposition of high grade crystalline metamorphic rocks on top of fossiliferous sediments in Jämtland could only be explained by thrusting from the more central, westerly parts of the orogen. He concluded that the transport distance of the metamorphosed allochthon was in the order of 100 km and that the rocks were derived from Norway. This radical hypothesis of a far-transported allochthon met with much opposition (Quensel 1922, Backlund 1925), and it was not until the nineteen-thirties that large-scale nappe tectonics was finally accepted as the dominating feature of Caledonian structure in Scandinavia.

Study of mylonitized Precambrian basement complexes in northern Sweden, overriding the autochthonous sediments, persuaded Kulling (1930) that large-scale allochthoneity characterized Caledonian tectonics. Similar conclusions were drawn by Zenzén (1932) and Asklund (1933) based on work in southern Jämtland. In 1936, Holtedahl inferred that the crystalline complex of Jotunheimen in southern Norway was allochthonous and derived from west of the Norwegian coast. Two years later, Asklund (1938) provided the basis for inferring that Törnebohm's classic allochthon in central Jämtland was also derived from west of the same coast. Subsequently there has been much discussion of displacement distances. However, the essential structure of at least the eastern part of the Caledonian orogen in Scandinavia, namely its domination by a variety of relatively thin thrust nappes has been unanimously accepted. This structural style characterizes the entire Swedish Caledonides.

Caledonian geology in Scandinavia was summarized comprehensively at the time of the 21st International Geological Congress, held in Copenhagen in 1960. 1:1 000 000 geological maps of Norway and Sweden, published previously by the two countries' geological surveys (Norges Geologiske Undersøkelse 1953, and Sveriges geologiska undersökning 1958), provided a general basis for a variety of descriptions of the orogen (Holtedahl 1960, Magnusson et al. 1960). The southern part of the Swedish Caledonides was treated by Asklund and the northern part by Kulling, both in Magnusson et al. (1960). Subsequently, syntheses of the entire orogen have been provided by Strand (1961) and Nicholson (1974). The Swedish Caledonides have been described by Kulling (in Strand and Kulling 1972), by Lindström (in Lundegårdh et al. 1974) and by Gee (in Tozer and Schenk 1978) and the reader is referred to the first of these for a more detailed treatment than is possible here. The four counties in Sweden containing Caledonian rocks in their western parts, Kopparberg, Jämtland, Västerbotten and Norrbotten have been or are being described; these descriptions are accompanied by geological maps at a scale of 1:200 000 or 1:400 000: Kopparberg by

Hjelmqvist (1966), Jämtland by Högbom (1920) and Strömberg (in Lundegårdh et al. in prep.), Västerbotten by Kulling (in Gavelin and Kulling 1955), southern Norrbotten by Kulling (in press) and northern Norrbotten by Kulling (1964). Strömberg (1971) summarized aspects of the previous twenty-five years of Caledonian research in Sweden.

The Scandinavian Caledonides are more deeply eroded than most other Phanerozoic orogenic belts. Relationships between the Precambrian (pre-Caledonian) crystalline basement, the overlying sedimentary veneer and the various superimposed nappes are exposed from the Caledonian front autochthon, via the windows to the Norwegian coast (Fig. 1). This level of exposure is particularly favourable for study of nappe geometry and estimation of the distances of nappe transport; taken along with the stratigraphic and radiometric evidence for the timing of deformation, this control of geometry and transport distance provides an essential basis for interpretation of the mechanism of displacement of the allochthon.

The tectono-stratigraphy of the Swedish Caledonides can be conveniently treated in four major categories: the Autochthon (and Parautochthon), Lower Allochthon, Middle Allochthon and Upper Allochthon. We have preferred this subdivision (cf. Kulling in Strand and Kulling 1972) to other alternatives involving application of local nappe nomenclature to the entire orogen in Sweden, local correlation of nappe units being problematical in some areas. The informal subdivision of the tectonic units presented here is also more convenient for subsequent correlation with the tectonic units in Norway.

The various Caledonian thrust nappes in Scandinavia are characterized geometrically by a marked tendency to thin westwards. Nicholson and Rutland (1969) drew attention to this phenomenon in the southern Norrbotten area, Zachrisson (1969) in central and southern Västerbotten and more regionally (1973), and Gee (1975a and 1975b) summarized the evidence from further south in Jämtland. Nevertheless, the westerly thinning and excision of the tectonic units is far from regular; accompanying this regional pattern is an extensive pinching-and-swelling of the allochthon both parallel and perpendicular to the axis of the orogen (Gee 1976, 1978 a). Individual allochthonous units or composite units (Gee 1977a) compose vast lenses, the result, at least in part of a stretching process. This geometry provides evidence for both build-up of the tectonic pile and its subsequent collapse. It is of interest, in this context, to note that the allochthon, derived as it is from a wide variety of environments and including elements of the Precambrian basement, Late Precambrian sediments, Lower Palaeozoic volcano-sedimentary units and intrusive suites, is generally denser than the underlying autochthon of granites and rhyolites (Elming in prep.).

Orogenic deformation of the allochthonous units in the Swedish Caledonides occurred in the Late Silurian. It may have started in the Mid Silurian, the early deformation and depression of the volcano-sedimentary succession of the Upper Allochthon leading to metamorphism and subsequent thrusting towards the east. Nappe emplacement probably continued into the Early Devonian at least in the Caledonian Front. In both

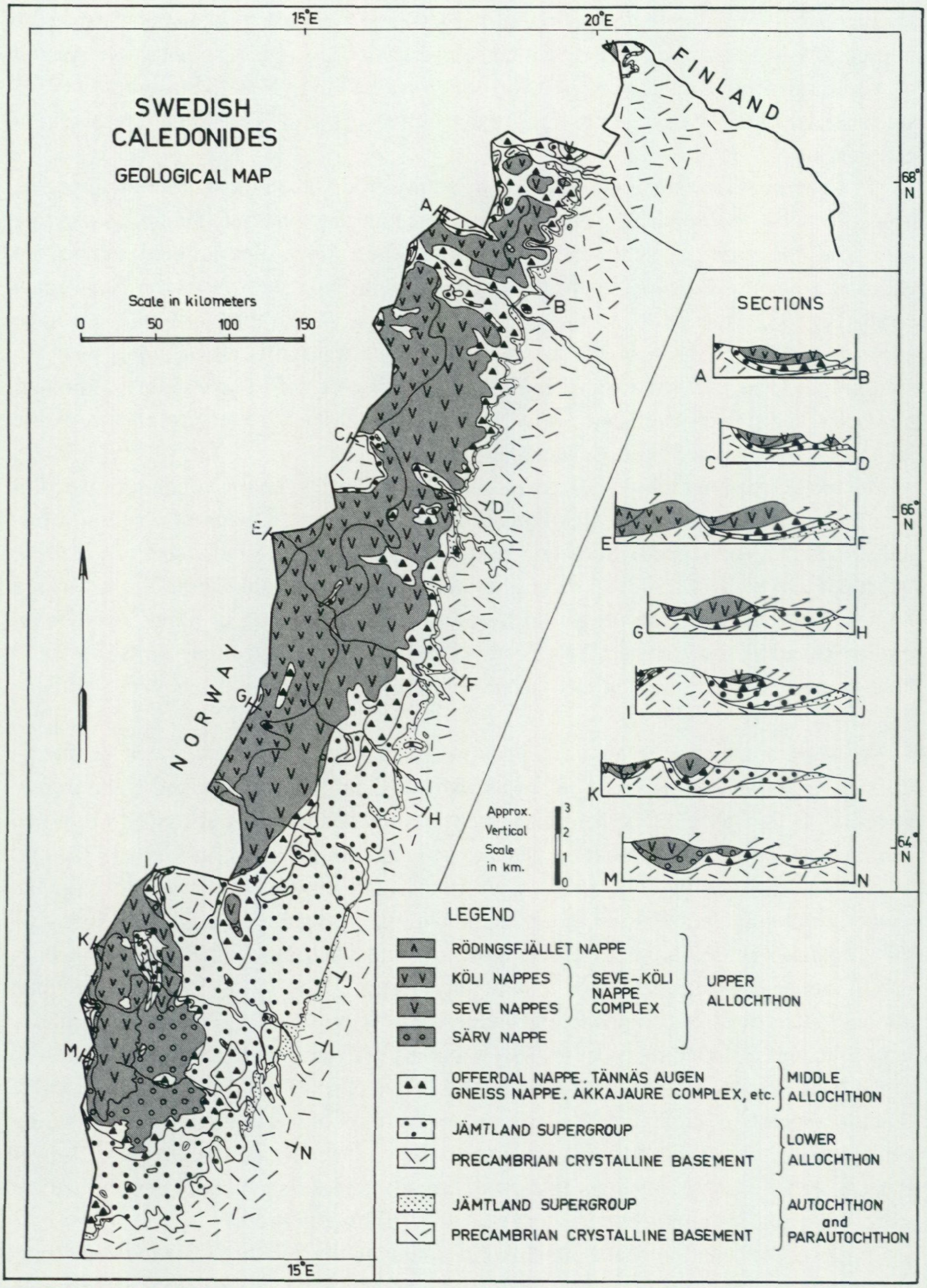

Fig. 2. Geological map of the Caledonides in Sweden.

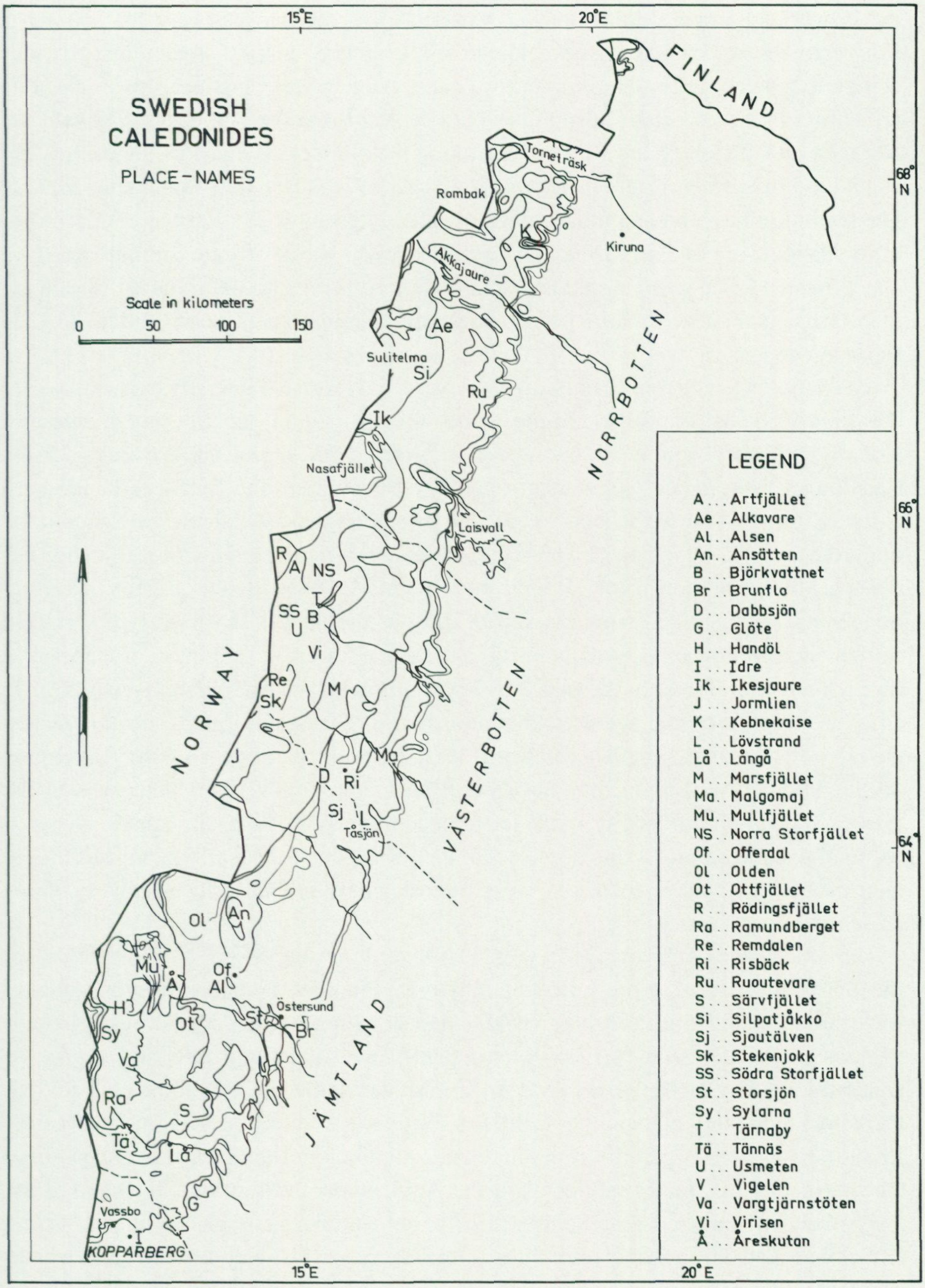

Fig. 3. Place-names referred to in the text.

the Lower and Upper Allochthon, Lower Palaeozoic sequences occur that extend at least into the upper Llandovery. The fossil evidence in these two units provides compelling evidence for the Silurian (or younger) age of deformation. Devonian strata are absent in the Swedish Caledonides but occur close to the border with Norway (at Røragen in Trøndelag) and further west along the Norwegian coast of the central and southwestern Scandes (Steel in Schenk and Tozer 1978). The oldest sediments in these late-tectonic, intramontane molasse basins, clearly established after the emplacement of the nappes, are of Early Devonian or possibly (on Hitra) of Late Silurian age (Gee and Wilson 1974), implying that the main phase of orogenic deformation (the Scandian Orogeny of Gee 1975b) and related nappe emplacement is of Middle to Late Silurian age.

The nappe pile apparently built up in the west and migrated laterally eastwards on to the Baltoscandian Platform. Emplacement that started in the Silurian in western Norway probably continued into the Early Devonian in the eastern parts of the Caledonian front at least in southern Norway (Oslo area) and Sweden. In northern Norway, Lower Silurian sequences are also present in the allochthon, testifying to the importance of the Scandian Orogeny there. However, age-determination evidence has persuaded some authors (Sturt, Pringle and Roberts 1975) to favour orogenic deformation, metamorphism and emplacement of most of the nappes in the early Ordovician (Finnmarkian Orogeny). Evidence for an early phase of Caledonian orogenesis in Sweden has been found in the uppermost part of the Upper Allochthon (see p. 36). In addition, recent isotopic age-determination studies (Claesson in prep.) have indicated the possibility that the emplacement of at least the lower part of the Upper Allochthon on the Middle Allochthon may have occurred in the Ordovician. Sequences in the Lower Allochthon, ranging from the late Precambrian to the Silurian, contain no major regional unconformities. This implies that the influence of this early phase of Caledonian orogenesis was restricted to westernmost areas, probably located west of the present Norwegian coast.

The main geometry of the regional structure in the Swedish Caledonides is illustrated in Fig. 2. The pre-Caledonian basement in the Caledonian front dips gently westwards beneath the allochthon and reappears further west in various windows towards the border with Norway. Major, gentle-open, late antiforms and synforms, generally trending NNE, axial to the orogen, influence the entire tectonic pile, folding the allochthon and autochthon together. Within the different tectonic units, the structural style varies greatly from the relative simplicity of the frontal décollement in the sub-greenschist facies sediments of the Autochthon and Lower Allochthon to the extensively mylonitized greenschist facies basement-cover complexes of the Middle Allochthon and the polymetamorphic, refolded greenschist-amphibolite (and locally higher) facies, volcano-sedimentary complexes of the Upper Allochthon.

General descriptions of the various tectonic units follow; most of the place-names referred to in the text are located on Fig. 3.

AUTOCHTHON (AND PARAUTOCHTHON)

The autochthonous tectonic units are exposed below and east of the Caledonian thrust front. Overlying the Precambrian crystalline basement there occurs a thin veneer of latest Precambrian, Cambrian and, locally, Ordovician sediments. The term parautochthon is reserved here for units closely comparable with those in the autochthon but subject to minor tectonic disturbance in the thrust front or as recognized in drill-holes further west. It is also applied to all the autochthonous-like relationships occurring in the windows where the crystalline basement with its sedimentary cover is exposed below the allochthon. The extent to which these units in the deepest parts of the windows have been laterally displaced is open to discussion; that they have been elevated in the late antiforms is uncontroversial and we prefer, therefore, to distinguish them from the autochthon, sensu stricto, of the Caledonian Front. The term parautochthon has been applied previously in a wider context in the Swedish Caledonides (e.g. Gee 1972, and in Tozer and Schenk 1978, Strömberg 1974) including units referred to here in the Lower Allochthon; this practice was motivated by stratigraphic similarities between the sediments in the autochthon and in the lower nappes and by uncertainty over nappe transport distances. Drilling through the frontal décollement (Gee et al. 1978) has provided new evidence on the displacement distances of the lower nappes; we now believe these to be too great (several tens of kilometres) to allow use of the term parautochthon in this context.

The concept of the Caledonian Front has also been the subject of some controversy in recent years (Strömberg 1974, Gee et al. 1978). We prefer to include in it the zone of folding and thrusting that can be followed throughout the eastern margin of the orogen, overlying (and including) the Autochthon. The zone is narrow (usually not more than a few kilometres wide) in northern and southernmost areas but broadens out in southern Västerbotten and northern-central Jämtland Counties to include the folded and thrust Jämtland Supergroup sequences underlying and east of the Middle Allochthon. We distinguish the Caledonian thrust front when referring to the topographic expression of the lowermost thrust.

BASEMENT

Svecofennian (c. 1 700–1 800 Ma) granites and gneisses compose the pre-Caledonide basement throughout much of the Autochthon. In the far north an older gneissic basement has been inferred on the basis of U/Pb age-determinations on zircon and sphene. Late or post-Svecofennian volcanic rocks (locally with associated fluvial sandstones) occur in the north in the vicinity of Kiruna and Doubblon and in the south in Kopparberg County and southern Jämtland County. Age-determination studies of these and related rocks have yielded ages of c. 1 550–1 700 Ma. Younger gabbros and dolerites intrude the basement; they range in age from c. 1 550 to c. 900 Ma. Details of this Precambrian evolution are presented by Lundqvist (1979).

Within the windows, the parautochthonous basement is generally comparable with that in the Autochthon. In the southern part of the Swedish Caledonides, porphyritic rhyolites and related granites, locally intruded by gabbros and dolerites, compare petrographically with the basement lithologies of the southeastern front. These rocks occur in the Vigelen, Sylarna, Mullfjället and Olden Windows. A Rb/Sr whole rock age-determination study of the Olden granites has yielded an age c. 1 500–1 550 Ma (Klingspor pers. comm.). Further north, the granites, gneisses and subordinate greenstones of the northern Jämtland windows are petrographically comparable with the Svecofennian units further east. In the Börgefjället Window (County of Västerbotten), the granitic gneisses have provided evidence of a Svecofennian age (Priem et al. 1967). In central Västerbotten County, the mylonitized syenites of the Bångfjället Window (near Tärnaby) have yielded a Rb/Sr whole rock isochron age of 1 490+140 Ma (Wilson pers. comm.) comparable with that of the Sorsele granites and syenites of the Caledonian Autochthon further east. The granitic gneisses of the Nasafjället Window (Wilson and Nicholson 1973) of southern Norrbotten County have been dated by the Rb/Sr isochron method to c. 1 740 Ma, whilst the similar lithologies in the Rombak Window (Kulling 1964) west of northern Norrbotten yielded c. 1 670 Ma (Heier and Compston 1969). All Rb/Sr ages given in this paper are based on $^{87}\text{Rb}\lambda = 1.42 \times 10^{-11} a^{-1}$.

The radiometric age-determination evidence from the pre-Caledonian basement of the Autochthon and windows indicates the lapse of a long interval (c. 1 000 m. y.) from the youngest orogenic deformation of this part of the western margin of the Baltic Shield to the deposition of the Caledonian sedimentary sequences. Only the intrusion of anorogenic basic rocks disturbed this period. Further south in Sweden and Norway, the Sveconorwegian orogeny (c. 1 000 m. y.) reworked the older basement and was accompanied by intrusion of granites. The eastern Sveconorwegian front strikes northwards, obliquely to the Caledonian front; its continuation below the central Scandinavian Caledonides is unknown but it is possible that mineral ages of c. 1 000 Ma from some windows reflect a thermal event related to this orogeny. Recent dating (Reymer et al. in press) of the allochthonous Seve units (p. 29) also indicates that Sveconorwegian deformation and metamorphism probably influenced rocks located (prior to the Caledonian thrusting) along the present Norwegian continental shelf.

COVER

Extensive erosion and peneplanation established the Baltoscandian Platform in the late Precambrian, preceding deposition of the Caledonian Front sediments during the latest Precambrian and Lower Palaeozoic. Whereas in the Caledonian Front and further east the peneplained platform remained relatively stable into the Lower Palaeozoic, further west, in and west of Norway (as now recorded in the allochthon), extensive deposition of fluvial and shallow marine sandstones and conglomerates during the late Precambrian testify to a less stable environment, thought to be related to the initiation of the latest Precambrian to early Palaeozoic (Iapetus) ocean basin (Harland and Gayer 1972, Gee 1975a, Roberts and Gale 1978).

The sedimentary sequence (Bergström 1979) deposited on the autochthonous basement in the Caledonian Front and now preserved beneath the sole thrust of the frontal décollement is generally thin, in the order of a few tens of metres, thickening only locally to over a hundred metres. It is largely composed of Lower Cambrian sandstones and Middle and Upper Cambrian shales: only in northernmost areas have Vendian sandstones and shales been identified and only in the south does the succession continue up into Lower Ordovician limestones and shales. Throughout the Caledonian Front, the Middle and Upper Cambrian shales and particularly the black (alum) shales, provide the main detachment surface for the Lower Allochthon; in parts of Jämtland this sole thrust ramps up into the Ordovician, thus preserving a thicker autochthonous–parautochthonous succession.

In southernmost areas of the front (Vassbo area of Kopparberg County) Cambrian shallow marine sandstones (Tegengren 1962) underlie Middle and Upper Cambrian black shales. Karis (pers. comm.) reports the occurrence of thin, probably parautochthonous Middle Ordovician *(Ogygiocaris)* shales at the Vassbo mine, overlying the Cambrian shales. Further north, in southern Jämtland, the sole thrust rides very close to the basement-cover contact and the autochthonous sediments are less than a metre thick. Locally (near Glöte), Ordovician limestones and Cambrian black shales are preserved below the thrust. In central Jämtland, the autochthonous stratigraphy is more complete (Thorslund 1940, 1969): a few decimetres of uppermost Lower Cambrian sandstones and siltstones were deposited directly on the crystalline basement overlain by Middle Cambrian grey-green and dark shales with subordinate limestones (c. 25 m) and Upper Cambrian black shales and bituminous limestones (c. 3–5 m). Uppermost zones of the Upper Cambrian and lowermost Ordovician (Tremadoc) are absent in the Autochthon. A thin glauconitic, phosphatic calcarenite at the base of the Ordovician succession passes upwards into micritic and shelly limestones, nodular at some levels and with subordinate calcarenites (Thorslund 1940, Jaanusson 1973, Larsson 1973). In the vicinity of Lockne, southeast of Östersund, Thorslund (1940) identified a basement high with Middle Ordovician limestones, sandy and conglomeratic at the base, resting directly on the Precambrian granites or breccias derived from the granites. The conglomerates and sandstones (''Loftarstone'' of Thorslund 1940) can be traced laterally into the neighbouring limestone succession where they contain clasts of the Lower Ordovician limestones, with occasional fragments of Cambrian shales and stinkstones and basement granites and dolerites. The geometry of this basement high, rising to c. 70 m above the surrounding peneplain, is not yet fully established. Thorslund (1940) demonstrated that this local irregularity of the basement surface existed at least from the Middle Cambrian into the Middle Ordovician, the Cambrian shales filling the deeper pockets in the basement surface and the various

Ordovician limestones and conglomerates capping the highs. Nevertheless, some Ordovician tectonic instability is implicit in the uplift and erosion of the older sediments and their incorporation in the Ordovician conglomerates.

Ordovician limestones, a few tens of metres thick, are preserved below the sole thrust of the Lower Allochthon throughout much of central and northern Jämtland. In the vicinity of Tåsjön, the décollement surface again is located in the alum shales (Gee et al. 1978). Asklund and Thorslund (1935) demonstrated an important tectonic repetition in these Cambrian shales below the quartzite allochthon on Tåsjöberget, the repeated sequence containing a thicker Upper Cambrian black shale unit and including a Tremadocian fauna in the uppermost part.

Only locally, north of Jämtland, have Ordovician strata been recorded in the Autochthon (Kulling 1942). Near Malgomaj (southern Västerbotten), Lidén (1911) has described c. 15 m of Lower Ordovician limestones resting on the black shales and overlain tectonically by the quartzites of the Lower Allochthon. Here, the Upper Cambrian black shale facies (c. 40 m) passes down into grey and green shales and siltstones (c. 40 m). These are glauconitic, phosphatic and sandy in the basal part and rest directly on the basement.

Northwards from Malgomaj, the sole thrust of the Lower Allochthon rests in or below the Upper Cambrian black shales. A quartz sandstone reappears below the Cambrian shales, reaching a thickness in the Laisvall area of c. 50–60 m. Lilljequist (1973) described this sandstone-dominated unit (the Laisvall Formation) to be composed of six members; a basal arkose and breccia (7–17 m) overlain by green and red shales and siltstones (10–17 m), a lower white quartz sandstone (15–30 m), a middle dark quartz sandstone (2–12 m), an upper light coarse quartz sandstone (4–11 m) and finally an overlying shale fragment conglomerate up to 2 m thick. This succession is overlain by a formation (c. 40 m) of grey-green shales and siltstones containing Lower Cambrian fossils in the upper part (F. Kautsky 1945). It is, in its turn, overlain by black shales, irregularly preserved below the Lower Allochthon.

These sandstone, siltstone and black shale formations can be followed northwards (though cut out locally below the sole thrust of the Lower Allochthon) throughout the length of the Caledonian thrust front to the Torneträsk area where the succession has been described in some detail by Kulling (1964 and in Strand and Kulling 1972) and referred to as the Hyolithus Series (or group) and, more recently (Kulling in press), as the Torneträsk Group.

On the mountain Luopakte, Kulling described the black shale formation (c. 30 m) to be underlain by a grey shale formation (c. 15–20 m) containing a Lower Cambrian fauna. Below this unit he identified three sandstone formations separated by shale formations, in all c. 80 m thick, resting on the Precambrian basement. Within the upper part of the middle sandstone unit he found Ediacaran body fossils (referred to as *Spriggia annulata*) and abundant trace fossils. The identification of the *Spriggia* has been reassessed recently by Glaessner (in Føyn and Glaessner 1979) and the medusoid has been renamed *Kullingia concentrica*. G. Vidal (pers. comm.) has identified latest

Vendian algae and acritarchs in the same unit and in the underlying ''lower shale''. The overlying, ''middle shales'' contain *Platysolenites*, indicating an Early Cambrian age and the ''upper sandstone'' has yielded *Holmia* Beds age diagnostic acritarchs (G. Vidal pers. comm.).

Locally in the Torneträsk area (in the vicinity of a stream section, Vakkejokk), a spectacular breccia (the Vakkejokk breccia) containing boulders of Precambrian basement rocks and the underlying sandstones and shales occurs between the Vendian sandstones and the Cambrian shales. This breccia, described in some detail by Kulling (in Strand and Kulling 1972), though tillite-like in general aspect, is clearly younger (see Vidal, above) than the Varanger glacials developed extensively elsewhere in the Scandinavian Caledonides and is probably not of glacial origin.

West of the Caledonian thrust front, the sedimentary successions deposited on the basement are known from the windows and locally in Jämtland from deep drill-holes. The latter in the Tåsjön area (Gee et al. 1978) have provided evidence that the stratigraphy in the Autochthon, up to 30 km west of the thrust front, is closely similar to that in the front. Further west in the windows some important differences have been recorded. In these parautochthonous successions a few metres to tens of metres of white and bluish-grey quartzites overlie the basement, locally overlain by grey and black shales (phyllites in the border zone to Norway). Fossils have not been found in these successions in the windows but the abnormally high radioactivity of the black shales provides a secure basis for correlation with the uraniferous Upper (and Middle) Cambrian black shales of the Caledonian Front and further southeast in the south and central Sweden (Andersson et al. in prep.). In northern Jämtland and southernmost Västerbotten, tillites (c. 10 m) separate the quartzites from the basement in some western areas (Kulling 1942, Thelander in press). They also occur locally in the Vigelen Window (Gee and Norén, unpublished data) and possibly in central Jämtland (Hotagen) as reported by Schenk (1975).

Within the windows, it is often difficult, due to poor exposure, to establish whether the thin veneer of sediments overlying the basement was deposited on this (parautochthonous) basement or is allochthonous (and part of the Lower Allochthon). Substantial thicknesses of quartzites overlain by black shales and thin greywackes have usually been treated as part of the sequence deposited directly on the basement. Detailed investigations, at least in some areas such as the Mullfjället Window (S. Tirén pers. comm.), have identified radioactive black shales close to the basement surface underlying the Vendian–Lower Cambrian quartzites and implying the probable allochthoneity of the overlying sedimentary succession.

LOWER ALLOCHTHON

In the numerous river valleys cutting through the Caledonian Front, the autochthonous sediments can be observed to dip gently (1–2°) westwards beneath the allochthon. Décollement clearly dominates the structural style and the passive basement may continue, at least in northern areas as far as the NNE-trending axis of windows along the border to Norway. Minimum transport distances of the Lower Allochthon are generally in the order of several tens of kilometres.

The Lower Allochthon is a complex of thrust nappes composed of sediments of Late Precambrian and Early Palaeozoic age. With the exception of a few Lower Silurian and, recently discovered (L. Karis pers. comm.), Middle Ordovician bentonites, volcanic rocks are completely absent, as are intrusions. Thin slices of Precambrian crystalline rocks are locally preserved at the base of the thrust sheets, apparently derived from basement irregularities existing prior to the thrusting.

Throughout much of the Caledonian Front in the north (Norrbotten and northern Västerbotten Counties) and extreme south (southern Jämtland and Kopparberg Counties), the rock sequences in the Lower Allochthon are highly disturbed and have not yielded fossils; detailed stratigraphic relationships are difficult to decipher. Lithologies are dominated by quartzites, with subordinate siltstones and black shales, the latter often radioactive. Correlation with the better-preserved successions in Jämtland allows the conclusion that the quartzites are of Vendian or Early Cambrian age and that the shales reach into the Middle and probably, on the basis of the high uranium contents, into the Late Cambrian.

Within the thrust front of Norrbotten County, the Lower Allochthon is thin (too thin to be represented on Fig. 2) and partly cut out by the higher tectonic units which rest directly on the Autochthon. Further south in the areas of more extensive preservation of this tectonic unit, drilling to basement (Gee et al. 1978) has provided new evidence of the regional extent of the décollement. In the central parts of the Caledonides in Sweden, detachment and associated folding characterize the deformation within the Lower Allochthon. Below this complex of thrust, folded and cleaved sub-greenschist facies (Kisch in press) sediments, the basement with its thin autochthonous (or parautochthonous) veneer remains largely undisturbed.

In central and northern Jämtland the extensive development of the Lower Allochthon contains fossiliferous sequences (Thorslund 1940, 1960) extending from the Lower Cambrian at least into the Lower Silurian. Underlying quartzites are of Vendian or Early Cambrian age. In the highest tectonic units of the Lower Allochthon (and also within the Middle Allochthon) these unfossiliferous sediments overlie tillites correlated with the Varanger glaciation which in turn overlie feldspathic sandstones. The entire succession has been referred to as the Jämtland Supergroup (Gee 1975b). Regional interrelationships, as far as they can be inferred to have existed prior to the Silurian (to Early Devonian) thrusting, are shown on Fig. 4. The successions, now observed in Sweden, were deposited in a basin that extended far westwards into Norway. The oldest units appear in these western parts, where the greatest sedimentary thicknesses were developed. Cambrian deposition was relatively uniform with some westwards thickening culminating in the Upper Cambrian with extensive deposition of uraniferous black shales over the entire area. Ordovician deposition was dominated by a facies transition from platform limestones in the east to shales and greywackes in the

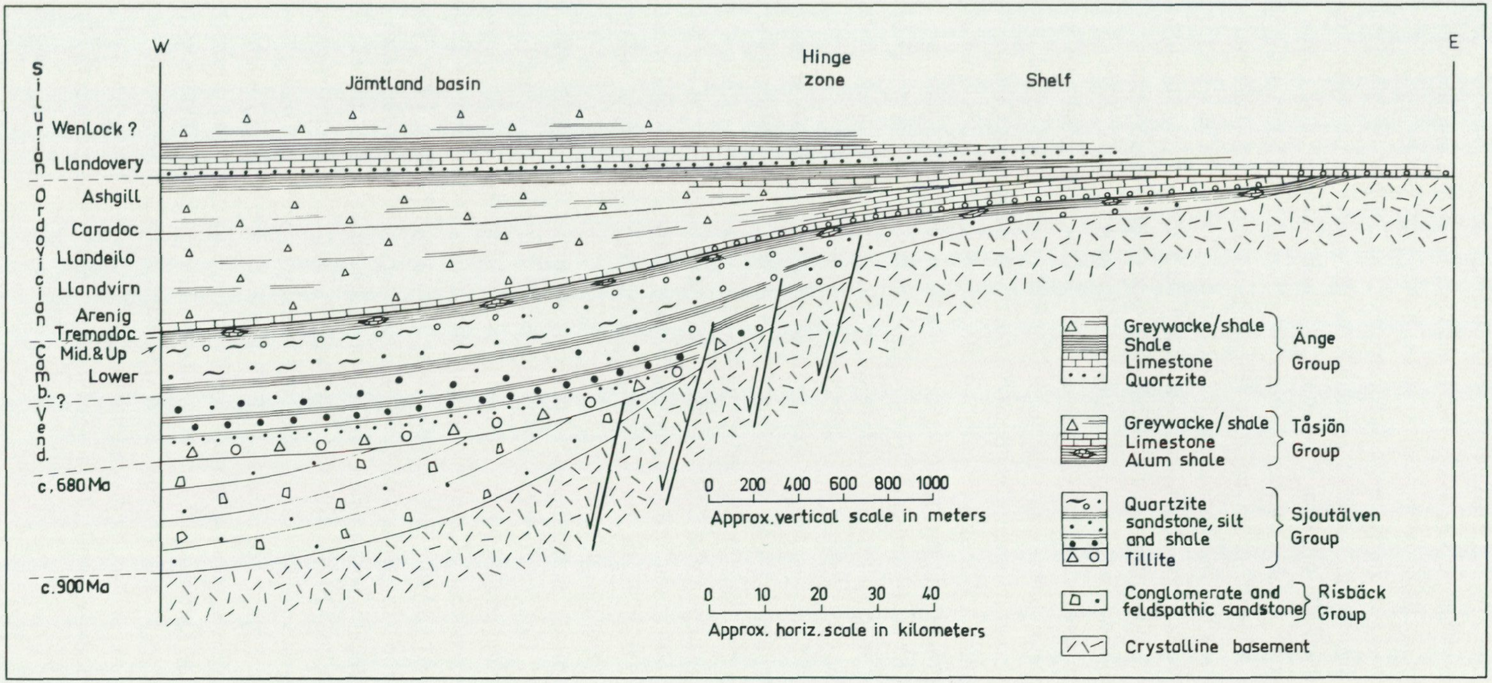

Fig. 4. Lateral variation in Jämtland Supergroup stratigraphy.

west. Regression towards the end of the Ordovician was followed by deposition of Silurian shallow marine sandstone and limestones prior to basin deepening and accumulation first of Llandovery black shales and then greywackes.

The oldest rocks in the Jämtland Supergroup of the Lower Allochthon occur in two main areas, the one in southern Jämtland and Kopparberg Counties, the other in northern Jämtland and southern Västerbotten Counties. In central Jämtland, pre-Vendian sediments are notable for their absence in the Lower Allochthon but they do occur in the Middle Allochthon. Stratigraphy (Fig. 5.) in the northern Jämtland – southern Västerbotten area has been described by Gee et al. (1974). Tillites occur, deposited both on the Precambrian crystalline basement of the windows (parautochthon) and on allochthonous Late Precambrian fluvial sandstones and conglomerates. The latter, composing the Risbäck Group (Kulling in Strand and Kulling 1972), were thought to be more or less autochthonous, deposited in Late Precambrian graben (Asklund 1938, 1960). This interpretation was contested by Du Rietz (1960) who regarded most of the Upper Precambrian sediments as allochthonous. In Västerbotten County, Kulling (in Strand and Kulling 1972) also favoured an allochthonous hypothesis. Recognition of a décollement structure in the Tåsjön area of northern Jämtland (Gee et al. 1978) and remapping of the areas dominated by the Late Precambrian successions (Kumpulainen and Thelander in prep.) have established the general allochthoneity of the Risbäck Group and overlying Vendian to Ordovician successions.

The Risbäck Group occurs in several isolated areas and in two or three different thrust sheets within the upper part of the Lower Allochthon in northern Jämtland and southern Västerbotten. Stratigraphic correlation between the different areas and tectonic units is in progress. Successions of these dominantly fluvial sediments are in the order of 1 500 m thick (R. Kumpulainen, pers. comm.) and locally pass up into a dolomite (c. 100 m thick), the Kalvberget Formation, overlain by tillites probably related to the Varanger glaciation.

In southernmost Jämtland and Kopparberg Counties, unfossiliferous sediments (Stålhös 1956, 1958, Strömberg 1961) similar to the Risbäck Group occur in the Lower Allochthon and have been referred to as the Långå Group (Strömberg 1974).

A few metres to tens of metres of glacial diamictites and laminated siltstones with outsized clasts, composing the Långmarkberg Formation (Kulling 1938, Thelander in press) rest on the various units of the Risbäck Group in northern Jämtland – southern Västerbotten, locally with marked angular unconformity. These sediments have been correlated (Kulling 1942) with the Varanger glacials of northern Norway (Reusch 1891, Reading and Walker 1966). They are overlain by white and blue-grey quartzites with subordinate grey-green shales and siltstones (c. 300 m thick) referred to as the Gärdsjön Formation, containing trace fossils in the upper part and a probable Lower Cambrian fauna (Larsson 1976) in limestones in the uppermost siltstone member. The Långmarkberg and Gärdsjön Formations together comprise the Sjoutälven Group of northern Jämtland and southern Västerbotten. In the lowest thrust sheets of the Lower Allochthon, quartzites similar to those of the Gärdsjön Formation occur in the Caledo-

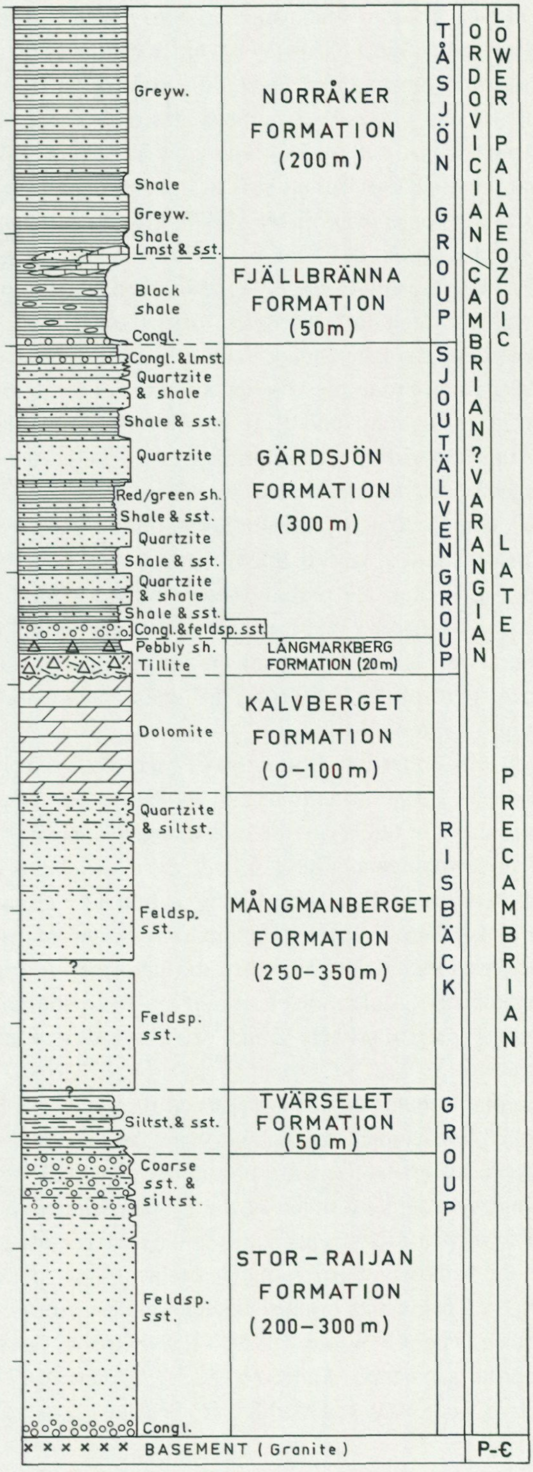

Fig. 5. Stratigraphy of the Jämtland Supergroup in northern Jämtland – southern Västerbotten (Gee et al. 1974, 1978).

nian thrust front. Risbäck Group and Långmarkberg Formation sediments are absent. The quartzites (Ström Quartzites, Grip 1941, Du Rietz 1960), locally resting on a thin (a few metres) slice of Precambrian crystalline basement, ride on the sole thrust. Imbrication is intense and internal stratigraphy has only locally been deciphered. In southernmost Västerbotten County, drill-hole data (Du Rietz 1943, 1960, Gee et al. 1978) suggest that the quartzite formation is in the order of 60 m thick and passes up into a few metres of siltstones overlain by Middle Cambrian black shales. In southern Jämtland and Kopparberg Counties, similar quartzites occur at the same tectonic level and in northernmost Kopparberg County they also overlie the Långå Group. They have been referred to as the Vemdal Quartzites (Törnebohm 1872, Asklund 1933) or Vemdal quartzite group, the latter being employed by Strand and Kulling (1972) to refer to all the Caledonian Front quartzite units in the Lower Allochthon. The lack of definition of internal stratigraphy (and the major problems involved in attempting such definition) makes this application inappropriate and we prefer to continue the informal local use of the terms Vemdal and Ström quartzites (of formation status), accepting their probable correlation with the Gärdsjön Formation of the Sjoutälven Group.

The Lower Cambrian and, at least in the Torneträsk area, Vendian sandstones of the Caledonian Front Autochthon are probably correlatives of the Gärdsjön Formation. These shallow marine sandstones thin eastwards, overlapping on to the Baltoscandian Platform. Together with the overlying black shales, their presence in the Lower Allochthon indicates that, in the Cambrian, this stable area extended far west of the Caledonian Front into western Norway.

The black shales with subordinate bituminous limestones overlying the Sjoutälven Group and referred to in northern Jämtland and southern Västerbotten as the Fjällbränna Formation (up to c. 50 m thick) are the most conspicuous and regionally extensive stratigraphic unit in Scandinavia. These so-called ''alum shales'' of the Upper and usually also Middle Cambrian, locally extending up into the Tremadoc, occur from the province of Skåne in southern Sweden to Finnmark in northernmost Norway (Martinsson 1974). In the Caledonides they are often too deformed to yield a fauna but the characteristic geochemistry (Andersson et al. in prep.) with unusually high contents of various trace elements (particularly U, V and Mo) provides a secure basis for correlation.

The Fjällbränna black shales compose the basal formation of the Tåsjön Group, a unit that occupies large areas of central and northern Jämtland and southern Västerbotten Counties. Ordovician limestones with subordinate grey shales generally overlie the Cambrian black shales throughout much of the Lower Allochthon. Thicknesses vary from a few metres in the west to tens of metres in the easternmost parts where they can be correlated with the Kalkberget Formation and related limestones of the Autochthon (Löfgren 1978). In the Tåsjön area of northern Jämtland and southern Västerbotten the limestones are replaced laterally westwards by a few metres of calcareous, glauconitic, phosphatic, uraniferous sandstone (Andersson 1971, Armands 1972, Gee 1972) which in turn pass up into grey shales and then greywackes. This sequence above the

Fjällbränna black shales has been referred to as the Norråker Formation. West of Tåsjön, the Norråker shales and greywackes directly overlie the Fjällbränna black shales.

The thickness of the Tåsjön Group is estimated at about 500 m; it may be substantially thicker but poor exposure has not allowed sufficient control of the internal stratigraphy of the group. The shales and greywackes of the Norråker Formation (that in the early literature have been referred to as greywackes of Föllinge–Holmsjö facies) in central Jämtland are overlain (Thorslund 1943, 1948) by a few metres of cross-bedded sandstones (Ede Formation) passing up into c. 70 m of limestones (Berge Formation) and then 50 m of black shales with bentonites (Bångåsen Formation) which give way upwards into greywackes (Ekeberg Formation) of unknown thickness. These formations are all of Silurian age and compose the Änge Group (Strömberg 1974). They directly underlie the basal thrust of the Middle Allochthon (Offerdal Nappe).

The palaeontological evidence from the Tåsjön and Änge Groups indicates that deepening of the Jämtland Basin with turbidite deposition started at least in westernmost areas in the Early Ordovician and continued through to the Late Ordovician. A black shale interval (c. 20 m) occurs in the late Middle Ordovician (Thorslund 1960). The facies change from limestones in the east via shales to greywackes in the west, documented in the Lower Allochthon of the Storsjön area by Thorslund (in Thorslund and Jaanusson 1960), suggests active faulting of the eastern margin of the basin during the Early and Middle Ordovician. Basement hinging was also inferred futher north in the Tåsjön area (Gee 1972); new evidence on the extent of the Tåsjön décollement requires that this hinge-zone was located substantially further west than was previously suggested, towards the border with Norway. Regional regression during Ashgill times was followed in the Early Silurian by deposition of shallow marine sandstones and limestones. Not until the late Llandovery did the basin deepen again, possibly in response to the onset of Scandian deformation further west. Reassessment of fossil evidence (Thorslund 1948) from the Ekeberg greywackes (E. Klaaman written comm. 1977) suggests that deposition of the latter may have continued into Ludlow time.

MIDDLE ALLOCHTHON

Throughout the Swedish Caledonides, a complex variety of highly deformed Precambrian crystalline basement rocks and unfossiliferous, feldspathic sandstones separate the Upper Allochthon from the underlying tectonic units. Cataclasis and mylonitization characterize the basement lithologies; the sediments are isoclinally folded and penetratively deformed, with development of a fine-grained schistosity and greenschist facies mineralogy. A conspicuous zone of mylonites and phyllonites, often several metres to tens of metres thick, usually separates this Middle Allochthon from the underlying lower grade tectonic units. These mylonites are clearly discordant to the folds, cleavages and thrusts in the underlying allochthon implying that the latter structures developed in front of the advancing Middle Allochthon prior to its final emplacement. The thick development of mylonites at the base of the Middle Allochthon led to its being traditionally accepted as the base of the major far-travelled nappes in the Swedish Caledonides. It is apparent now that, at least in areas where the uppermost units of the Lower Allochthon are composed of Late Precambrian sandstones (e.g. northern Jämtland), the Middle and Lower Allochthon are notably similar and the distinction between them is controversial. Likewise in Norrbotten County, some of the feldspathic sandstone units included in the Middle Allochthon may in fact be at a lower tectonic level; relevant data are lacking.

In southern Jämtland and northern Kopparberg Counties, the Middle Allochthon is composed of coarse, potash feldspar augen gneisses varying in thickness up to c. 1 000 m and usually in the order of a few hundred metres thick. They are referred to as the Frönberget Gneiss (in the extreme south) and the Tännäs Augen Gneiss. A Rb/Sr whole rock age-determination study (S. Claesson pers. comm.) has recently shown that the gneisses are derived from the Precambrian (c. 1 600–1 700 Ma) crystalline basement, an origin proposed originally by Törnebohm (1896) and supported by Asklund (1938) and Strömberg (1955). Claesson's detailed investigation of the gneisses and the mylonites separating the former from the overlying allochthon has shown that only the throughly mylonitized units yield an unambiguous Caledonian (probably Ordovician) age.

The Tännäs Augen Gneiss Nappe in southern Jämtland County (east of Särvfjället) overrides eastwards on to a granitic–granodioritic unit interpreted by most previous authors as a ''horst'' (Asklund 1938). Recent investigations (Röshoff 1978) have shown this basement unit to be allochthonous, wedging out westwards beneath the augen gneisses and northwards beneath schistose sandstones (in the Fuda Klippe). This unit has been distinguished as the Veman Nappe (Röshoff op. cit.), forming the lowest unit in the Middle Allochthon of southern Jämtland.

In central Jämtland, the Middle Allochthon is dominated by fine-banded schistose quartzo-feldspathic rocks that have been variously interpreted as derived from sediments and/or from basement granites and syenites by mylonitization. They occur in the Fuda, Alsen and Ansätten Klippes and are also represented (though only a few metres to tens of metres thick) in the Sylarna, Mullfjället and Olden Windows. Sedimentary structures such as cross-bedding have been recognized locally; although the Middle Allochthon in central Jämtland appears to be dominated by sediments there is an important component of mylonitizied granites, rhyolites and locally, augen gneisses (Walser 1979). This composite basement-cover complex is referred to as the Offerdal Nappe (Högbom 1920, Asklund 1938). In some areas of development a subordinate unit of better-preserved conglomerates with subordinate feldspathic sandstones occurs at the base of the allochthon (e.g. the Offerdal conglomerate, Törnebohm 1896, Asklund 1938) and at one locality (Bottenviken, Strömberg 1975) this unit passes up via quartzites into uraniferous black shales, favouring correlation with the Cambrian of the lower tectonic units and supporting the Late Precambrian age of the underlying clastic rocks.

The Offerdal Nappe can be followed into northern Jämtland and southern Västerbotten where it overrides units of the Lower Allochthon, dominated by Late Precambrian sandstones and conglomerates: distinction here between the two major tectonic units is ambiguous. Further north in Västerbotten County, the sandstones and conglomerates of the Stalon Nappe (Kulling 1942) apparently represent the same tectonic level as the Offerdal Nappe, as do the Fjällfjäll arkoses of the Fjällfjället Window (Zachrisson 1969). In Norrbotten County, both feldspathic sandstones and deformed basement rocks occur in the Middle Allochthon, the most notable units being the Akkajaure Complex (G. Kautsky 1953) which is dominated by mylonitized granites, and the Abisko Complex (Kulling in Strand and Kulling 1972) which is composed of cataclastically deformed basement overlain by quartz schists (the so-called ''hårdskiffer'') with subordinate dolomites.

Identification of the units of the Middle Allochthon overlying the Parautochthon and Lower Allochthon of the windows, occurring along the border between Sweden and Norway, requires derivation of these nappes from Norway or areas west of Norway. In the central Scandes, Gee (1978) inferred deposition of the sandstones of the Offerdal Nappe in the area now occupied by coastal Norway.

UPPER ALLOCHTHON

The Upper Allochthon is composed of a variety of nappe units, generally polydeformed and in greenschist or higher metamorphic facies and characterized by one unifying factor – the presence of Caledonian (sensu lato) igneous rocks. The latter are variously developed as dykes, volcanic rocks and major plutons. Lithologies in the Upper Allochthon range in age from the Precambrian (including Pre-Caledonian basement slices) to the Silurian. The rocks are derived from continental margin environments including island-arc and back arc assemblages and possibly oceanic crust existing in the Early Phanerozoic in areas now occupied by the Norwegian continental shelf.

Within the Upper Allochthon three main tectonic units are identified here. The lowest is composed essentially of a sandstone sequence intruded by a tholeiitic dyke swarm and is called the Särv Nappe. The middle unit is a complex of amphibolite facies and higher metamorphic grade schists, gneisses and amphibolites (the Seve) overlain by a greenschist facies volcano-sedimentary sequence (the Köli) composing the Seve-Köli Nappe Complex. The upper unit is dominated by migmatites, schists and amphibolites and is referred to as the Rödingsfjället Nappe.

Kulling (in Strand and Kulling 1972) included the Särv Nappe in his Middle Thrust Rocks, possibly due to the similarity between the sandstones of the Offerdal and Särv Nappes. Strömberg (1969) stressed the affinities of the Särv and overlying lower Seve units, despite the higher metamorphic grade of the latter. We prefer to include the Särv Nappe in the Upper Allochthon, accepting that the dolerite dyke swarm represents the earliest phase of Caledonian magmatism (probably latest Precambrian, p. 27) in this part of the North Atlantic Caledonides.

SÄRV NAPPE

Mapping of Jämtland during the last century demonstrated the presence in the lower part of Törnebohm's (1896) major allochthon of a suite of basic dykes – the Ottfjället dolerites (Holmquist 1878) – intruding an apparently monotonous sandstone sequence. Strömberg (1955, 1961) identified this remarkable association as a separate tectonic unit, introducing the name Särv Nappe. In 1969, Strömberg drew attention to a general similarity in tholeiitic composition between the basic dykes in the Särv Nappe and the major amphibolite units in the overlying Seve and suggested that the former provided the feeder channels for the Seve volcanism. These relationships have been further explored by Solyom et al. (1979).

The development of the Särv Nappe in central-southern Jämtland is characterized by the occurrence of a thick sandstone-dominated sequence, exhibiting well-preserved sedimentary structures, intruded at a high angle by the dolerites. The sediments generally dip at low to moderate angles eastwards and the basic sheets are orientated at moderate to high angles westwards. Strikes vary considerably (cf. Strömberg 1969, Fig. 1) apparently due to internal rotation within the nappe during transport.

In the zones of high strain at the base and top of the nappe and locally within it, the dyke-sediment intersection angle is reduced to zero and the sediments and basic rocks are exceedingly attenuated. A penetrative schistosity is developed along with a greenschist facies mineralogy, and isoclinal folding of the transposed banding, on transverse WNW axes, is characteristic. However, away from these zones of high ductile strain, the Särv Nappe is remarkable for the excellent preservation of dyke-sediment relationships; the general tectonic condition of the dyke-intruded Särv is in marked contrast to that of the overlying and underlying (Middle Allochthon) units.

Recent study of the sedimentology and stratigraphy of the Särv Nappe sequences (Kumpulainen in press) has demonstrated the presence of a thick (c. 4.5–6 km), largely fluvial sandstone sequence including subordinate formations of dolomitic limestone (c. 100 m) overlain by glacial and lacustrine-marine deposits (up to 120 m thick) near the top (the Lillfjället Formation). The identification of diamictites of probable glacial origin (Röshoff 1976) and their regional development and relationship within the stratigraphy, strongly favour a late Precambrian (including Vendian) age for the extensive sedimentary sequence of the Särv Nappe. The dyke swarm, at least locally, occupies a greater volume than the country rock; it was estimated by Strömberg to imply crustal extension within the existing outcrop area alone of c. 30 km.

Textures in the dolerites vary from aphanitic to coarsely ophitic; feldspar porphyritic varieties are common and olivine and/or pyroxene phenocrystic types occur occasionally. These variations in mineralogy and texture are accompanied by only minor changes in composition; analyses of major, minor and trace elements indicate that the Ottfjället suite is completely dominated by tholeiites of ocean floor affinities (Solyom et al. 1978). The same authors identified a small group of alkaline dykes.

Isotopic age-determination studies of the Ottfjället dolerites have been carried out employing the K/Ar and Rb/Sr methods. The former yielded ages from c. 2 500–600 Ma (Point et al. 1976, Claesson 1976). Claesson (op. cit.) obtained a Rb/Sr isochron of 735±260 Ma, thus supporting the stratigraphic evidence favouring a late Precambrian age of intrusion and implying the presence of large volumes of excess argon in most samples dated by the K/Ar method. This conclusion was disputed by Point et al. (1977) and discussed by Claesson (1977).

Rb/Sr dating of the mylonites separating the Särv from the underlying Tännäs Augen Gneiss Nappe has suggested that this tectonic relationship may have been established in the Early Ordovician (S. Claesson pers. comm.).

In the lowermost part of the Särv Nappe at a variety of localities in southern Jämtland, basement units occur, intruded by dolerites. Basement lithologies are dominated by foliated basic plutonic rocks but also include some garnetiferous hornblendic gneisses. These lithologies occur as lenticular sheets at the base of the main Särv Nappe and clearly represent a separate but related tectonic unit; they provide information on the character of the Precambrian crystalline basement on which the easternmost parts of the Särv Nappe sedimentary sequence were deposited.

The Särv Nappe occurs outside the main area of development in central and southern parts of Jämtland County at a variety of localities (Asklund 1961), separating the Middle Allochthon from the Seve-Köli Nappe Complex. It has been reported from the Alsen and Ansätten Klippes, the Mullfjället Window and the western flank of the Olden Window. Further north it has been located in northernmost Jämtland in the area of Dabbsjön. In the southern part of Norrbotten County (near Jäkkvik), Kulling (in press) records dolerites in the eastern part of the Seve. These basic rocks intrude feldspathic sandstones and are an obvious candidate for the Särv Nappe. The unit may well be present elsewhere; in areas where it is thin it is often difficult to recognize, due to concordance of basic rocks and sediments and post-attenuation refolding.

SEVE-KÖLI NAPPE COMPLEX

A complex allochthon of granulite to greenschist facies rocks overlies the Särv Nappe and/or Middle Allochthon throughout the Swedish Caledonides. The higher grade units generally occur in the lower part and are referred to as the Seve Nappes. They are overlain by the largely greenschist facies Köli Nappes and together these two units compose the Seve-Köli Nappe Complex (Zachrisson 1969). In westernmost Sweden and locally e.g. in the west limb of the Mullfjället Antiform, the Seve units wedge out completely leaving the greenschist facies Köli rocks in direct contact with the underlying tectonic units. Both Seve and Köli are complex, heterogeneous, polymetamorphic units composed of several subordinate nappes. That much of this deformation and metamorphism is of Caledonian (Scandian) age is demonstrated by the presence of Ordovician and Silurian fossiliferous sequences in the Köli. Nevertheless, isotopic age-determination evidence (Reymer 1978, Reymer et al. in press) indicates that at least parts of the highest grade Seve represent pre-Caledonian crystalline basement units incorporated into the Caledonian cover at an early stage of the orogenic process, metamorphosed, and subsequently thrust eastwards onto the Baltoscandian Platform along with the cover.

SEVE NAPPES

The concept of the Seve has changed considerably during the years since its original introduction (Törnebohm 1872). Seve development in Sweden has been treated by Zachrisson (1973), who drew attention to the regional geometry of the nappe complex, dominated as it is by gentle westerly sheet-dips, along with westwards thinning and excision. The Seve is subject to extensive pinch-and-swell deformation; subsequent studies (Gee 1978 a) have shown that the unit reappears further west (largely in Norway) as major tectonic lenses or parts of lenses. The amphibolite and higher grade metamorphism of the Seve rocks was clearly achieved prior to nappe emplacement, the pinch-and-swell geometry being established under lower grade conditions during the later stages of displacement.

Åreskutan in central Jämtland is the classical mountain locality where relationships between the major Seve crystalline allochthon and underlying fossiliferous sediments were first established by Törnebohm (1872, 1888) in the latter part of the last century. Here, pyroxene granulites on the top of the mountain overlie amphibolite facies schists, gneisses and amphibolites which in their turn rest on greenschist facies Särv units and underlying sub-greenschist facies Cambro-Silurian sediments. This complex allochthon, occurring in an open synform, has been studied more recently by Helfrich (1967) and Yngström (unpublished thesis 1971). Rb/Sr age-determination studies (S. Claesson pers. comm.) of the highest grade units on Åreskutan have yielded Caledonian isochrons but have indicated the presence of pre-Caledonian crustal material. Fission track studies of sphenes from the amphibolite facies units provided evidence of Precambrian metamorphism (c. 1 700 Ma; H. Koark pers. comm. in Gee 1978 b).

West of Åreskutan, the Seve rocks thin dramatically westwards over the Mullfjället Antiform but appear again further south and north as composite nappes at least 2 km in thickness. In the southernmost area, the Seve of the Helags Synform is composed of a greenschist-amphibolite facies volcano-sedimentary sequence, several kilometres thick, in the lower part (Sjöstrand and Zachrisson pers. comm.), overlain by a granulite facies upper unit (Sjöström pers. comm.) similar to that on Åreskutan. In northern Jämtland and Västerbotten Counties, the Seve has been shown (Trouw 1973, Zwart 1974) to be composed of at least three tectonic units the lower two being separated by a conspicuous blastomylonite zone. Granulite facies gneisses usually compose the central unit over- and underlain by schists and amphibolites. Eclogites, with jadeitic pyroxene alteration to an albite-diopside symplectite, have been recorded locally in the kyanite, potash feldspar-bearing gneisses. These gneisses have yielded Rb/Sr age-determination evidence of a Precambrian (c. 1 000–1 200 Ma) origin (Reymer et al. in press).

Flat-lying Seve Nappe amphibolites and schists occupy large areas of the Scandes in northern Västerbotten and Norrbotten Counties, forming the country's highest mountains (Kebnekaise 2 117 m a.s.l.). From thicknesses of the order of five kilometres in the east they thin out in the vicinity of the border of Norway. Amphibolitized eclogites have been reported locally (northeast of Nasafjäll, A. Wikström, pers. comm.). In the lowermost parts of the Seve, a meta-igneous association of anorthosites with subordinate gabbros and ultramafites, occurs in two major lenses in Norrbotten. One of these (at Ruoutevare) contains a titaniferous magnetite ore-body. This igneous suite is in many respects similar to Precambrian basement rocks (Romey 1971) occurring in the Lofoten Window (Norway) some 200 km to the west of Ruoutevare. Though subject to Caledonian metamorphism with crystallization of garnet and well-lineated hornblende, these Ruoutevare igneous rocks are probably of Precambrian origin. Derivation from or west of the Lofoten area is compatible with the evidence from the underlying Middle Allochthon of transport from west of the windows spanning the border between Norway and Sweden.

Plutonic rocks are unusual in the Seve, with the notable exception of ultramafites. As is apparent from the 1:1 000 000 Geological Map of Sweden (Sveriges geologiska undersökning 1958), the upper part of the Seve (and lower part of the overlying Köli), particularly in northern Jämtland and Västerbotten Counties, contains a large number of lenticular ultramafites. Compositions are dominated by peridotites (Stigh 1979 a). An anhydrous mineralogy is usually preserved in these higher grade environments in contrast to the extensive serpentinization of the ultramafites in the overlying greenschist facies Köli environment (Stigh and Ronge in press).

KÖLI NAPPES

The schists and amphibolites of the Seve are overlain by a greenschist facies volcano-sedimentary sequence referred to as the Köli. Like the Seve, the Köli is best treated as a nappe complex composed of at least three separate tectonic units. The contact between the Seve and the Köli is usually concordant and transitional but characterized by a rapid decrease upwards in metamorphic grade. At least in Jämtland and southern Västerbotten Counties, low angle regional discordance has been recognized (Zachrisson 1969, Trouw 1973, Sjöstrand 1978) and a tectonic discontinuity inferred. Further north, in Västerbotten County, lithologies and metamorphic grade pass transitionally from the Seve up into the Köli and no discontinuity has been identified (Stephens 1977).

A complex deformational history has been recognized (Zachrisson 1969, Gee 1971, Trouw 1973, Stephens 1977, Sjöstrand 1978) for the Köli, involving early isoclinal folding prior to a main phase of regional porphyroblastesis, followed by refolding and development of an intense penetrative schistosity. The isoclinal folding related to the latter is often, but not always, developed on transverse (NW) axes; in zones of high ductile strain these can be shown (Williams and Zwart 1978) to result from rotation of earlier fold axes (Lindström 1961) into the direction of displacement of the nappes. Extreme flattening characterizes both the Köli and the Seve with ubiquitous evidence of boudinage and development of stretching lineations. All these structures are folded along with the underlying and overlying nappes by the late-stage open antiforms and synforms with axes parallel to the length of the orogen.

Tectono-stratigraphy (Fig. 6.) within the Köli has been investigated in detail in several areas of Jämtland and Västerbotten Counties during the last two decades (Nilsson 1964, Zachrisson 1964, Stephens 1977, Sjöstrand 1978). Only locally, such as in the classical Björkvattnet-Virisen area of central Västerbotten County (Kulling 1933), have the lithologies largely escaped the intense penetrative deformation. Here the presence of abundant sedimentary structures and the discovery of fossils in two formations have allowed the establishment of a coherent Lower Palaeozoic stratigraphy of Late Ordovician and Early Silurian age.

A few other localities with Middle and Upper Ordovician fossils have been located in Västerbotten and Norrbotten (Kulling in Strand and Kulling 1972) but in general, the extensive penetrative deformation of the Köli has obliterated most of the evidence, only the occasional preservation of crinoids stems testifying to the Ordovician or Silurian age of the strata. General concordance within the regional schistosity characterizes the Köli sequences. The tectonic history prior to the development of this pervasive penetrative structure is only fragmentarily preserved (e.g. in the Björkvattnet-Virisen area) and difficult to decipher. Suffice it to say that the complex premetamorphic history that can be inferred from this fragmentary evidence and its comparison with structures in other orogens requires caution in the interpretation of general Köli tectono-stratigraphy in terms of Early Palaeozoic history.

The classical Köli stratigraphy described by Kulling (1933, in Gavelin and Kulling 1955, and in Strand and Kulling 1972) has been substantiated by unpublished SGU mapping and recent investigations in the Björkvattnet area by Stephens (1977). It is preserved in two major late synforms, the so-called Eastern and Western Synforms of Zachrisson (1969), separated by the Fjällfjäll Antiform (Fig. 7). The Seve amphibolite facies sediments and basic volcanic rocks pass transitionally upwards in the eastern limb of the Eastern Synform via hornblende porphyroblastic greenschists and garnetiferous phyllites into more massive actinolite-bearing greenstones of the upper part of the Seima Formation. These volcanic rocks are overlain by phyllites, greywackes and matrix-supported conglomerates of the Gilliks Formation, indicative of relatively deep water deposition and tectonic instability. Serpentinites and detrital serpentinites occur in this unit and in association with the underlying volcanic rocks (Stigh 1979b). Regression towards the top of the Gilliks Formation was followed by deposition of quartzite conglomerates and cross-bedded quartz sandstones (Vojtja Formation) passing transitionally upwards via calcareous sandstones into the Slätdal Formation limestones. The latter have yielded a fauna dominated by corals and

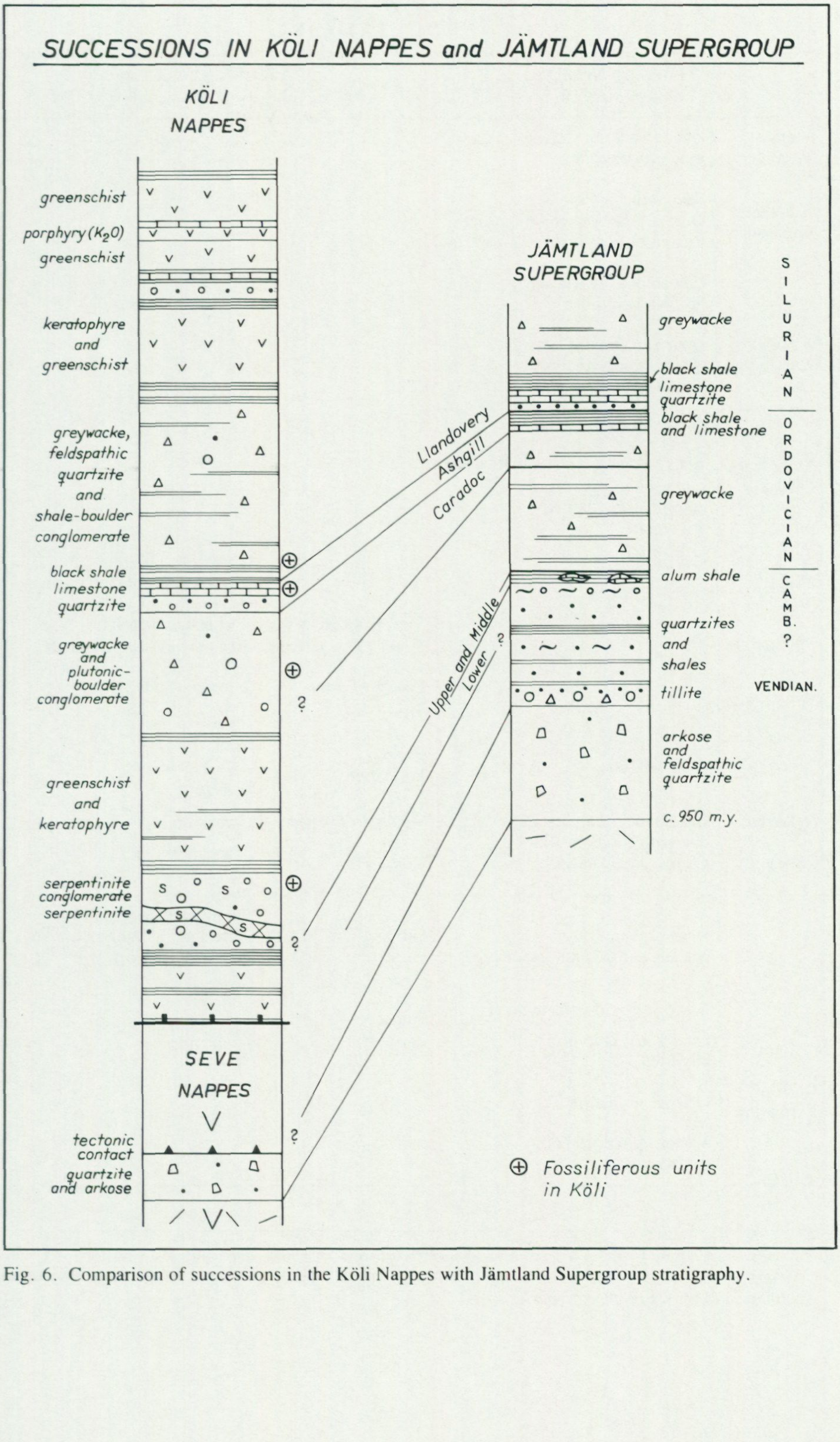

Fig. 6. Comparison of successions in the Köli Nappes with Jämtland Supergroup stratigraphy.

KÖLI SUCCESSIONS				
WESTERN SYNFORM (Zachrisson 1969, 1971)			EASTERN SYNFORM (Kulling 1933, Strand and Kulling 1972)	
REMDALEN GROUP	Frems Phyllite	Quartz and graphitic phyllites.		
	Remdalen Greenschist	Basic volcanic rocks. Quartz-porphyry and limestone. Basic volcanic rocks.		
		Calcareous, quartz and graphitic phyllites.		
	Remdalen Conglomerate	Quartzite conglomerate, Quartzite and quartz phyllite.		
LASTERFJÄLL GROUP		Graphitic phyllites.		
	Stekenjokk Quartz-Keratophyre	Acid and basic volcanic rocks with tuffites and graphitic phyllites in lower part.		
	Blåsjö Phyllite	Calcareous phyllites (with gabbros).		Calcareous phyllites, greywackes, conglomerates.
			Viris Formation	Feldspathic quartzites.
			Vesken Formation	Greywackes, conglomerates.
			Lövfjäll Formation	Calcareous phyllites.
		Dark phyllites.	Broken Formation	Black shale (×) (incl. greenstone locally).
	Bellovare Formation	Limestone, quartzite and quartzite conglom. (incl. greenschist locally).	Slätdal Formation	Limestone. (×)
			Vojtja Formation	Quartzite and quartzite conglomerate.
TJOPASI GROUP		Dark phyllites, greywackes and conglomerates.	Gilliks Formation	Greywackes, phyllites and conglomerate (incl. detrital serpentinites).
		Basic and acid volcanic rocks.	Seima Formation	Basic volcanic rocks.
		Quartz and graphitic phyllites.		
	Rotiken Formation	Detrital serpentinities. (×)		
		Various phyllites and tuffites.		
SEVE NAPPES				

Fig. 7. Köli successions in the Western and Eastern Synforms of south and central Västerbotten. Units marked with a cross are fossiliferous (cf. Fig. 6). (The formations in the Eastern Synform were referred to by Kulling as groups.)

brachiopods (Kulling 1933, Kulling in Strand and Kulling 1972) of Ashgill age. Transgression followed the deposition of the fossiliferous limestones and there is a rapid passage upwards into black phyllites (Broken Formation) in which graptolites of middle Llandovery and possibly upper Llandovery (C 1) age have been recorded (Skoglund in Strand and Kulling 1972, p. 221). A few metres of greenschists occur in the Broken Formation locally, on Virisfjället, with the preservation of pillow structures. The black phyllites pass transitionally upwards into graded calcareous sandstones and phyllites of the Lövfjäll Formation. The facies development in the sediments above the Broken Formation varies considerably even within Björkvattnet-Virisen area. In the vicinity of Virisen, the Lövfjäll shales and sandstones first coarsen upwards into greywackes and matrix-supported conglomerates (Vesken Formation) and then, with decrease in grainsize and increase in content of quartz sand, pass up into the Viris Formation, a unit of generally parallel bedded but locally cross-bedded quartzites. An unnamed formation of calcareous phyllites, conglomerates and greywackes overlies the Viris Formation, composing the highest stratigraphic unit in this part of the Eastern Synform. Elsewhere distinction between these formations has not proved possible and it can be concluded that rapid facies changes occur.

Thickness variations are so great within the Köli and the intensity of deformation so variable that estimates of pre-tectonic thickness have proved difficult. The better preserved sections allow local estimates to be made but in neighbouring localities the units may be very thin or absent, the result of primary variation, and/or Caledonian deformation. Total thicknesses for the Köli of a few kilometres have been suggested. The presence of over 1 000 m of sediments above the middle Llandovery black shales implies that deposition probably continued higher into the Silurian. Sedimentation in the Köli is assumed to have ceased prior to the deposition of the Hitra sandstones within the late-orogenic intra-montain basins of western Tröndelag (Norway).

The formations referred to above can be traced westwards over the Fjällfjäll Antiform and into the Western Synform (Zachrisson 1969) where they are attenuated and subject to a more penetrative deformation (Kulling's 1933 ''tectonized'' sequence). Crinoids and highly deformed and recrystallized corals have been found in the limestones correlated with the Slätdal Formation. At a lower stratigraphic level there occur numerous detrital serpentinites and one locality has yielded gastropods (A. Holmqvist pers. comm.) of probable Middle Ordovician age (Yochelson written comm. 1978). Thus it seems probable that the classical Köli succession ranges in age from at least the Early-Mid Ordovician into the Mid Silurian.

Conformably overlying this sequence in the Western Synform is a thick volcano-sedimentary sequence in which tectonic discontinuities have been recognized at at least two levels (Zachrisson 1969) and the Leipik and Gelvenåkko (Gellvernokko) Nappes identified. Within the Remdalen Synform (the local name for the Western Synform in southern Västerbotten County), Zachrisson (1964, 1969) recognized three major lithological units, the Tjopasi, Lasterfjäll(et) and Remdalen Groups. The Tjopasi Group is comparable in most respects with the phyllites and volcanic rocks of

Kulling's type area beneath the Vojtja Formation. The Lasterfjället Group commences with quartzites and limestones, passing up via black phyllites into calcareous phyllites, a sequence strongly reminiscent of the Vojtja, Slätdal, Broken and Lövfjäll Formations of the Björkvattnet-Virisen area. Throughout the Western Synform over a distance of c. 200 km, these calcareous phyllites are intruded, usually in the upper part, by concordant meta-gabbros ranging in thickness up to c. 50 m but usually being in the order of a few metres thick. Their intrusion apparently occurred prior to all the recognizable deformation in the host-rocks. These gabbro-intruded calcareous phyllites are overlain by greenschists and black phyllites and then by a prominent, dominantly acid volcanic unit, the Stekenjokk Quartz-Keratophyre Formation, which hosts an important polymetallic sulphide ore body (p. 38) and a variety of smaller mineralizations. The overlying Remdalen Group contains a prominent quartzite-pebble conglomerate in its lower part, is dominated by phyllites, greenschists and tuffites and contains one of the rare, non-spilitic volcanic units in the Köli – the microcline-bearing Remdalen porphyry.

The extent to which the upper successions (above the Lövfjäll equivalents of the Lasterfjället Group) in the Western Synform represent a younger stratigraphy is controversial. Regional concordance has suggested the possibility that younger (post-Llandovery) Silurian sequences are represented. Against this interpretation are two lines of evidence favouring tectonic repetition. The first is the time factor; the established fossiliferous stratigraphy reaches at least into the middle Llandovery and is overlain in the Eastern Synform by a substantial sedimentary succession. Late-orogenic (post-nappe emplacement) sediments in western Norway require that the allochthonous tectono-stratigraphy was established prior to deposition of the Hitra sandstones of probable Downton age. The time available for the accumulation of the substantial volcano-sedimentary sequences in the upper part of the Lasterfjället Group and the Remdalen Group is apparently very short. Secondly, studies of the geochemistry of the volcanic rocks (Stephens in press) suggests a complex history of island-arc volcanism, behind arc spreading and/or arc splitting, a history that is not known from elsewhere in the Scandinavian Caledonides for the Mid-Silurian.

Recent work in northern Västerbotten in the Tärna area (Stephens 1977) and on Södra Storfjället (Häggbom in press) has provided evidence for a tectonic contact between the Lasterfjäll gabbro-intruded calcareous phyllites and the underlying succession. It is possible that this discontinuity continues southwards through central Västerbotten into southern Västerbotten and northern Jämtland.

Above the calcareous phyllites and gabbros of northern Västerbotten there occurs a major allochthon, the Storfjället Nappe Complex (Storfjäll Nappe Complex of Kulling, in Strand and Kulling 1972). On Södra Storfjället, Beskow (1929) described this volcano-sedimentary succession to be of higher metamorphic grade than the underlying Köli formations. He identified, at the base of the succession, the so-called ''Ropen granite'', a complex of quartz-keratophyres, albite granites and intrusive greenstones (Stephens pers. comm.), and recognized the lower contact to be a thrust. Similar intrusive rocks are absent from the underlying and overlying units and both contacts are therefore very probably of tectonic origin. The higher grade metamorphic rocks occur above the ''Ropen granite'' and the contact between these units has therefore been distinguished (Häggbom in press) as the base of the Storfjället Nappe Complex. Similar relationships have been described from the base of the Nappe Complex on Laxfjället, near Tärnaby (Stephens 1977). Häggbom (op. cit.) has shown that the Storfjället Nappe Complex is composed of a lower part in amphibolite facies and an upper part in greenschist facies. Locally on Södra Storfjället and extensively on Norra Storfjället, the amphibolite facies kyanite and staurolite-bearing schists pass laterally into migmatites. Häggbom's important contribution identified the vast lenticularity of the higher grade parts of the Storfjället Complex referring to them as the Krutfjället Nappe, overlain by the lower grade Jofjället Nappe. The more competent high grade units compose vast lenses (or parts of lenses) that pinch-and-swell between the overlying and underlying phyllites and greenschists.

The Krutfjället Nappe, composed of schists, marbles, conglomerates and volcanic rocks is at least in part of Early Palaeozoic age, a crinoid having been found in a limestone pebble in one of the conglomerates. In the overlying lower grade Jofjället Nappe calcareous phyllites and gabbros occur along with various other phyllites and greenschist facies volcanic rocks. Intruded into the higher-grade volcano-sedimentary rocks of the Storfjället Nappe Complex in northern Västerbotten is a major gabbro massif, the Artfjället gabbro and a closely associated granite, the Vilasund granite. The latter intruded the host rocks after they had been isoclinally folded, but are themselves, extensively deformed. Gee and Wilson (1974) provided a Rb/Sr isochron of 438 ±6 Ma ($^{87}\mathrm{Rb}\lambda = 1.42\times10^{-11}\ \mathrm{a}^{-1}$) for the Vilasund granite. Recently, Reymer (1978) has obtained a similar age (442±30 Ma) on the migmatites of Norra Storfjället. Based on recent data on the Lower Palaeozoic time-scale these ages would be pre-Silurian and indicate an important phase of Ordovician deformation, metamorphism and intrusion influencing the Storfjället Nappe Complex prior to Scandian thrust emplacement onto the underlying Köli.

The contrast in metamorphic grade and tectonic history between the Storfjället Nappe Complex and the underlying Köli implies that the tectonic contact separating the units is of major importance. It can be argued that the Storfjället Nappe Complex should be treated as a separate tectonic unit and not as part of the Köli. This view is supported by similarity in tectonic history between the Storfjället Nappe Complex and the overlying Rödingsfjället Nappe. Nevertheless, we prefer to retain the Storfjället Nappe Complex within the traditional concept of the Köli. South of Södra Storfjället, the amphibolite facies schists and underlying ''Ropen granite'' are greatly attenuated and retrogressed; greenschist facies Jofjället Nappe units are nearly in contact with underlying greenschist facies Köli. Where these relationships exist the separation of the Storfjället Nappe Complex from underlying units is highly problematical; existing data do not allow this separation and it is convenient to include the entire succession between the Rödingsfjället Nappe and the Seve in the Köli.

In central Jämtland an extensive area of flat-lying Köli phyllites overlies the Seve in the Tännforsen Synform. Calcareous phyllites dominate the succession which includes limestone, quartzite and a variety of conglomerates in the lowermost parts (Beckholmen in press). Locally the Seve pinches out completely and the Tännforsfältet Köli directly overlies the Jämtland Supergroup lithologies. A mylonite zone is usually well-developed in this contact-zone testifying to the post-metamorphic character of the nappe emplacement.

North of Västerbotten County, the Köli has been described by Kulling (1964, in Strand and Kulling 1972, and in press). Fossiliferous successions north of Ikesjaure and near Sulitelma testify to rock sequences correlatable with the classical successions of central Västerbotten. A variety of Köli Nappes have been recognized in central Norrbotten County being referred to as the (from base upwards) Pieske, Vasten, Salo and Gasak Nappes (G. Kautsky 1953). The tectonic contacts between these units have been questioned (Kulling 1964, Henley 1970) and it is apparent that detailed mapping will be required to test the different hypotheses. Kulling correlated his ''Uppermost thrust rocks'' (including most of Kautsky's Gasak Nappe) with the Rödingsfjället Nappe: we believe the lithologies of the Gasak Nappe to resemble more closely those of the Storfjället Nappe Complex and this interpretation is shown on Fig. 2.

RÖDINGSFJÄLLET NAPPE

Above the greenschist facies units of the upper part of the Storfjället Nappe Complex in northern Västerbotten, there occurs an allochthon composed of migmatites in the lower part, giving way upwards into schists, marbles and subordinate amphibolites. These higher grade units, composing the highest tectonic unit in the Swedish Caledonides, occupy only a small area in the border-zone to Norway. They were identified by Kulling (in Gavelin and Kulling 1955) as a major tectonic unit and named the Rödingsfjäll Nappe.

Spanning the border to Norway in the uppermost part of the Rödingsfjället Nappe (as it occurs in Sweden), there occurs a vast lens of gabbro (the Umbukta Gabbro). Flodberg (in prep.) has demonstrated that this intrusive complex is characterized by several generations of basic rocks including various gabbros and subsequent dolerite injection. Late-stage granites and pegmatites occur as subordinate components and also in the country rocks cutting the prominent regional schistosity. These granitic dykes have been dated by the Rb/Sr whole-rock isochron method to 447±7 Ma (Claesson in press), an age comparing closely with that of the Vilasund Granite and the migmatites of the Storfjället Nappe Complex. It is clear that both these, the two highest units of the Swedish Caledonian allochthon, have been subject to important pre-Silurian deformation prior to being thrust from the continental margin onto the Baltoscandian Platform during the Scandian Orogeny. Reymer (pers. comm.) has obtained age-determination evidence that Sveconorwegian deformation and metamorphism influenced at least some of the rock units in the Rödingsfjället Nappe.

ECONOMIC GEOLOGY

Within the Swedish Caledonides a variety of natural resources are being exploited today and a number of others are potentially exploitable in the future. Base metals are mined in three places and several related stratabound, sub-economic sulphide mineralizations are known. Uranium occurs in the Precambrian basement of the windows, in Cambrian black (alum) shales and, locally, in overlying phosphatic sandstones. Titaniferous magnetite and ilmenite ores have been investigated in the Ruoutevare anorthosite (Norrbotten). Nickel and chrome are potential economic metals in ultramafites of the Seve-Köli Nappe Complex. At present soapstone is quarried at Handöl as are Offerdal flagstone and Brunflo limestone, all in Jämtland County. A brief account of these industrial resources is given below (cf. Tegengren 1924, Grip and Frietsch 1973, Frietsch 1975, Zachrisson in press), treated in three categories: sulphides, uranium mineralizations and other economic objects.

SULPHIDES

The more important sulphide mineralizations in the Scandes are stratabound; in addition a variety of vein deposits are also present. The stratabound deposits occur in two main and separate associations. In the Autochthon, Parautochthon and Lower Allochthon lead-zinc deposits occur, hosted in Vendian-Cambrian sandstones. In the Upper Allochthon of the Seve-Köli Nappe Complex and Rödingsfjället Nappe, complex polymetallic ores completely dominate, with copper and zinc as the main base metals.

STRATABOUND SULPHIDES

Stratabound sulphides form the basis for the three producing mines in the Scandinavian Caledonides. Two of these occur in the quartz sandstones of the Autochthon, at Laisvall in southern Norrbotten County and near Idre in northern Kopparberg County. In addition, an important similar mineralization occurs in the Lower Allochthon of northernmost Jämtland and southernmost Västerbotten Counties at Bellviksberg and Lövstrand (Du Rietz 1960). Of the two mines in production, the one in the south near Idre has been described by Tegengren (1962). The main ore-body (Vassbo, 4.3 million tonnes) and associated deposit (Guttusjö, 2.7 million tonnes) are being mined at a rate of c. 300 000 tonnes a year. At Laisvall (Grip 1960, 1967, Grip and Frietsch 1973), several large ore bodies occur, together amounting to c. 60 million tonnes with an average of 3.9 % Pb and 0.5 % Zn. The annual output of ore is c. 1.4 million tonnes. The lead and subordinate amounts of zinc occur in the more pure sandstone members of the Laisvall Formation (Lilljequist 1973), the distribution of the probably epigenetic mineralization apparently being controlled by sedimentary facies variations related to the local palaeogeography. Galena and sphalerite are the main ore minerals; fluorite and barite are also important constituents though at present subeconomic. Higher concentrations of fluorite occur elsewhere in these sandstones and investigations of possibly economic stratabound fluorite deposits have been carried out in an area c. 100 km south of Laisvall.

Within the Upper Allochthon, stratabound base metal sulphide deposits occur at many levels in the volcano-sedimentary sequences. The schists and amphibolites of the Seve Nappe contain several mineralizations, especially in the south (Tegengren 1924, Grip and Frietsch 1973). In the Helags area, a few of these (Ramundberget, Snasahögarna) have been worked in the 18th–20th centuries both for copper and, intermittently, for iron (magnetite). A recently discovered copper prospect at Sylarna has some potential, as indicated by geophysics, geochemistry and a few diamond drill-holes. In the Åreskutan area, the two largest deposits occur at Fröå and Bjelkes (Helfrich 1967). Mineralogically the Seve occurrences are dominated by either pyrite or pyrrhotite, with chalcopyrite, sometimes bornite, and sphalerite as base-metal carriers. They are generally copper mineralizations with some zinc and with very low lead contents.

In the Köli the classical fossiliferous sequences have yielded only minor mineralizations. However, the overlying successions host an important ore province especially where they are developed in the Western Synform (see. p. 33) of northern Jämtland and Västerbotten Counties (Zachrisson 1977 and in press, Grip and Frietsch 1973). Most occurrences are small and plate-shaped, while some have a pronounced ruler-shaped geometry (Stekenjokk-Levi, Usmeten). Stekenjokk (Zachrisson 1971, Juve 1974, 1977) is the only deposit which at present is being mined, at a rate of 600 000 tonnes a year. The Stekenjokk-Levi ore bodies have a total tonnage of more than 23 million tonnes with an average grade of 1.4 % Cu, 2.5 % Zn and 0.2 % Pb. These Köli deposits are thus copper/zinc-dominated. They are massive or disseminated pyrite and/or pyrrhotite ores with base metals contained in chalcopyrite, sphalerite and galena and with some silver and gold. They occur intercalated in both purely sedimentary greywacke sequences (Jormlien, Ankarvattnet, Unna Gaisartjåkko, Usmeten) and in connection with acid (quartz-keratophyre) and basic volcanites of the Tjopasi, Lasterfjället (Stekenjokk-Levi) and Remdalen Groups (Remdalen).

Higher in the Köli, in the Storfjället Nappe Complex, several small stratabound sulphide deposits occur (Grip and Frietsch 1973), such as Tjåter, Rikarbäcken and Västra Storbäcksdalen in the Jofjället area. In the highest tectonic unit in Sweden, the Rödingsfjället Nappe, a similar small mineralization occurs at Gräskevardo, south of Överuman. All these sulphide occurrences are similar to those in the underlying Köli but they contain substantially more galena.

VEIN DEPOSITS

Sulphide vein deposits form a geologically distinct group (Wickman et al. 1963, Grip and Frietsch 1973). Generally associated with quartz and often calcite, they occur both in the nappe sequences and in the basement near the Caledonian thrust front and in the windows. The veins are generally discordant to the regional foliation, except close to tectonic zones where they tend to be concordant. Geochemically and mineralogically, the vein deposits are comparable with the Caledonian Front lead-zinc mineralizations but they also contain some pyrrhotite, arsenopyrite, chalcopyrite and boulangerite, especially in western occurrences. They have a distinctly higher content of silver. Several of these deposits, e.g. Olden, Nasafjäll, Silpatjåkko and Alkavare (Tegengren 1924), have been mined for their silver content during the 17th–19th centuries. None of them are economic today.

URANIUM MINERALIZATIONS

Upper Cambrian black shales, locally reaching down into the upper stage of the Middle Cambrian or up into the Tremadoc, are notable for their moderately high uranium contents. In some areas within the Lower Allochthon, e.g. along the southern side of Storsjön in Jämtland County, where tectonic repetition thickens the sequence, sections from several tens of metres to 150 m contain an average of 150–200 ppm U and contain subordinate units with as much as 250 ppm U. The anthracitic shales (c. 10–13 % $C_{org.}$) usually contain high contents of vanadium (reaching up to 0.34 % V) and molybdenum (0.04–0.05 % Mo). Although marginally poorer than the highly uraniferous Ranstad black shales (c. 300 ppm U over 3.6 m) of central Sweden (Dahlman and Gee 1978), the greater thicknesses and higher contents of other trace elements make these shales attractive for future exploitation.

In northern Jämtland and southern Västerbotten, in the vicinity of the lake Tåsjön, the sediments overlying the Cambrian black shales are calcareous sandstones and siltstones containing large amounts of glauconite and phosphorite. The phosphorite contains unusually high concentrations of uranium (Armands 1970, Andersson 1971), and beds a few decimetres thick can contain up to c. 1 000 ppm U. Maximum stratigraphic thicknesses reach c. 7 m (locally nearly doubled by fold and/or fault repetition) with a uranium content ranging from c. 200–270 ppm and with P_2O_5 contents of c. 2.5–3.5 %.

In addition to these two sedimentary uranium associations, minor uranium mineralizations also occur in Norrbotten County in the basal sandstones and conglomerates of the Autochthon. Fracture-related pitchblende mineralizations have recently been located in the Precambrian granites of the Olden and Nasafjället Windows.

OTHER ECONOMIC OBJECTS

Ultramafic (dunite, olivinite, peridotite and serpentinite) bodies (Du Rietz 1935, Stigh 1979 a) occur in the Upper Allochthon, especially in the upper Seve and lower Köli sequences. In the Köli, solitary bodies of olivinite and peridotite are often associated with detrital serpentinites, usually conglomerates. The latter are especially high in nickel (mainly as heazlewoodite) and may in the future be exploited, also for cobolt, platinum, chronium and magnesite. Altered serpentinite occurrences (soapstone) are at present being quarried at Handöl (talc) and peridotite was used for a short period in the iron industry (added as a scorification product). Dunite at Kittelfjäll has sporadically been taken out for the production of cast sand.

At Ruoutevare in Norrbotten County, titaniferous iron ore is associated with an anorthosite-gabbro complex of probable Precambrian age, incorporated as a lower thrust unit at the base of the Seve. The 50 million tonne ore-body contains c. 40 % Fe, 10 % TiO_2 and 0.18 % V (Frietsch 1975).

Further west in the Kvikkjokk area, several small magnesite occurrences within the Seve amphibolites have been investigated, but the restricted size and geographic position make them uneconomic today.

Schistose meta-arkoses of the Offerdal Nappe (Middle Allochthon) are being quarried at Rönnöfors and Ordovician limestones at Brunflo both in Jämtland County, being used for paving stones and building purposes.

CORRELATION OF TECTONO-STRATIGRAPHY AND TIMING OF DEFORMATION

Throughout most of the Caledonides in Sweden the identification of the different tectonic units is easily achieved; the main characteristics of the different major tectono-stratigraphic units, as outlined above, are unambiguous. Nevertheless, uncertainty does exist locally, for example with regard to whether the feldspathic sandstones and arkoses in the lower part of the allochthon in Norrbotten County should be included within the Lower or Middle Allochthon (as shown on Fig. 2.). And within the major allochthonous units, considerable work remains to be done identifying the sedimentary, igneous, tectonic and metamorphic histories and correlating these laterally and vertically within the tectono-stratigraphy. This is particularly the case within the Upper Allochthon where the complex structural and metamorphic sequences have made the earlier history exceptionally difficult to decipher.

Displacement distances within the movement zones separating the main nappes are large; the individual tectonic units are clearly derived from separate environments of accumulation and have been subject to differing structural and metamorphic histories prior to nappe emplacement onto the Baltoscandian Platform. Thus, similarities between the feldspathic sandstones in the Offerdal, Särv and (at least locally, in Jämtland) lower Seve suggest lateral affinities. However, the presence of an extensive tholeiitic dyke swarm in the Särv and the higher metamorphic grade of the Seve require that these units existed substantial distances from each other prior to superposition by thrusting. Likewise in the Köli, the complicated tectonic and metamorphic history of the Storfjället Nappe Complex, with evidence of Ordovician deformation and metamorphism, is in contrast to the record in the underlying Köli Nappes, where tectonic instability in the Ordovician is apparant (e.g. in the occurrence of monomict detrital serpentinites in a variety of continentally derived clastic sediments) but no important pre-Ashgill deformational and metamorphic events have been detected.

The character and intensity of the deformation within the individual nappes varies immensely particularly in the Upper Allochthon. Within mega-lenses, pre-tectonic relationships are locally very perfectly preserved (for example in the Särv Nappe of the Dabbsjön area, northwest Jämtland County), only to be completely obscured in adjacent zones of extreme attenuation. This heterogeneity of deformation is at the same time both the frustration and the satisfaction of those seeking to analyse the orogen; even within the most attenuated zones, better preserved relationships occur locally, allowing analysis of the earlier history. The local preservation of fossils in the limestone and phyllites of the Köli illustrates the same heterogeneity, providing hope for new discoveries in the zones of lower strain within units that generally are too penetratively deformed to stimulate and engage the interest of the palaeontologist.

Reconstruction of the orogenic history of the Caledonides in Sweden involves analysis of pre-orogenic history. A prerequisite for this analysis is the replacement of the nappes to their correct relative positions prior to thrusting. This replacement inevitably involves areas further west, most of the Swedish allochthon being derived from areas now occupied by Norway or the Norwegian continental shelf. Thus no analysis would be complete without consideration of the Norwegian Caledonides and particularly the deepest levels of the orogen as exposed along the Norwegian west coast. Such a treatment is outside the scope of the present paper but has been attempted elsewhere (Gee 1975b, 1978a) for the central part of the mountain belt. However, some comparison of the Swedish allochthon with that in Norway is useful as a basis for consideration of the general tectonic evolution.

Caledonian Front structure is characterized by décollement. The thrust front that can be identified throughout the Swedish part of the orogen, with a sole thrust dipping 1–2° W above a passive basement, can be followed southwards into the Mjøsa area and via Valdres to Hardangervidda. Folding of the Cambro-Silurian (including Downton) sequences in the Oslo graben are a response to the same décollement tectonics. In the so-called Mjøsa basins and the southernmost parts of the Swedish Caledonides, the sole thrust can often be followed several tens of kilometres northwestwards into the orogen, beneath the late Precambrian sedimentary sequences. Evidence that these Precambrian successions are also allochthonous on the windows further northwest (e.g. Sylarna and Vigelen Windows and those marking the southeastern margin of the Trøndelag-Jotunheimen Synform) strongly suggests that all these successions are derived from substantially further west and northwest (Oftedahl 1943, Gee et al. 1978, Hossack 1978).

Movement on the lowermost décollement surface occurred in the latest Silurian or Early Devonian in these southern areas as witnessed by the stratigraphic evidence in the Oslo graben. Likewise in Jämtland County, the stratigraphic evidence requires a latest Silurian or younger age for the movement of the Lower Allochthon. Further north the fossil control is too limited to provide constraints on the time of movement.

In southern Norrbotten, northwest of Laisvall (Lilljequist 1973) and in the Merkenes (Mierkenis) Group of the Nasafjället Window (Kulling in press), grey sandstones and phyllites suggest correlation with the Ordovician greywackes and shales of the Jämtland Supergroup but no fossils have as yet been found. The décollement surface at the base of the Lower Allochthon can be followed from northwest Sweden into the Finnmark Area of northernmost Norway where movement on the sole thrust is claimed (Sturt and Roberts 1978) to be of Finnmarkian (Early Ordovician) age (p. 12). Again adequate geological constraints are lacking and the interpretation of the age of movement is based on two Rb/Sr whole-rock isochron ages on cleaved shales occurring in the Caledonian Front. This evidence is hardly an adequate basis for requiring diachroneity of 80–100 million years for the movement on the décollement sole thrust. We favour Scandian emplacement (Late Silurian–Early Devonian) of this entire composite Caledonian Allochthon in Scandinavia, only parts of the Upper Allochthon being subject to Finnmarkian deformation prior to superposition on to the Middle Allochthon and Lower Allochthon and emplacement onto the Baltoscandian Platform.

Evidence of pre-Silurian deformation in the Swedish part of the Caledonides in Scandinavia has only appeared in recent years based on Rb/Sr isotopic age-determination studies particularly of the Upper Allochthon (Reymer 1978, Claesson in press, Gee and Wilson 1974). Recognition of a sub-Ashgill unconformity in southwestern Norway (Kvale 1960, Naterstad 1977, Sturt and Thon 1977) and age-determination studies in northernmost Norway (Pringle and Sturt 1969, Sturt et al. 1975) have emphasized the importance of this polyphase deformation and metamorphism occurring prior to deposition of the Late Ordovician successions. This orogenic activity is thought to have occurred on an active continental margin, significantly earlier than the initiation of thrust emplacement of the Scandian allochthon.

CALEDONIAN EVOLUTION AS RECORDED IN SWEDEN

Analysis of the stratigraphic, structural and metamorphic histories of the different tectonic units in the Swedish Caledonides allows at least partial reconstruction of the Caledonian evolution. The existence of particular lithologies and combinations of lithologies in the Autochthon, Parautochthon, Lower and Middle Allochthon, although lacking fossils in western areas, permits reconstruction of the Baltoscandian Platform margin westwards to areas at least three hundred kilometres from the eastern front. The uraniferous, black (alum) shales of Cambrian and earliest Ordovician age play a critical role in this reconstruction. They have been identified in the Parautochthon as far west as Tømmerås (Gee 1974, 1977a) in the central part of the Norwegian Caledonides and existed even further west as documented by their occurrence in the basal part of the Middle Allochthon e.g. in the western limb of the Mullfjället Antiform (see. p. 24 above). In these western areas (now occupied by coastal

Norway), thick late Precambrian to Early Cambrian sandstones and conglomerates underlay the black shales and the latter probably were overlain by Early Ordovician limestone and perhaps greywackes (Tåsjön Group). The western extent of the latter remains uncertain.

Further west (off-shore of the present Norwegian coast) the development of a thick Late Precambrian fluvial sequence extending upwards via dolomites and tillites (probably Vendian), possibly into the Lower Cambrian, has been documented by Kumpulainen (in press), as recorded in the Särv Nappe. The overlying tectonic units of the Upper Allochthon, derived from west of the Särv Nappe, record in the Seve a complex interrelationship of basement (largely Sveconorwegian) and cover of unknown age in the lower part. The overlying Köli provides evidence of development of an Ordovician island-arc (Stephens in press), presumably related to an east-dipping subduction zone. The upper Köli (Storfjället Nappe Complex) evidence of Ordovician deformation of a volcano-sedimentary sequence is indicative of a more complex history affecting westernmost areas. Thus, the Baltoscandian continental margin extended several hundred kilometres west of the present platform as it now appears in the Caledonian Front, existing as a passive Atlantic-type margin (the southeastern flank of the Iapetus Ocean) into the latest Cambrian. Early Ordovician subduction led to the development of a volcanic arc, built up at least partly on continental Sveconorwegian basement.

The status of the Rödingsfjället Nappe remains too uncertain (p. 36) to contribute to this model of Caledonian evolution. The schists, gneisses and amphibolites may represent a new basement slice superimposed on the Köli arc.

The Ordovician instability recorded in the Jämtlandian turbidites and the Köli volcanic and plutonic rocks and turbidites terminated in the Late Ordovician. Latest Ordovician to earliest Silurian shallow water sedimentation was followed by deposition in late and/or post Llandovery time of turbidites probably reflecting the onset of Scandian deformation further west. Deformation, metamorphism and emplacement of the nappes occurred in the Mid–Late Silurian. It needs emphasis that this emplacement involved the transport of a relatively dense allochthon vast distances and upwards onto the Baltoscandian Platform from a variety of deep environments along and west of the continental margin. Just as plate movement has been appealed to for development of the Iapetus Ocean and the Ordovician island-arc, so it is natural to conclude that plate collision and the accompanying lateral compression provided the necessary forces for emplacement of the nappes. As one of us (Gee 1978) has argued elsewhere, this superposition of a denser allochthon on the lighter Baltoscandian Platform may well have provided the inverse density relationships necessary for the subsequent rise of the lighter basement domes in the western Scandes (Ramberg 1966); the latter may have accounted for continued eastward movement of the allochthon in response to an essentially gravitational regime.

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GFF=Geologiska Föreningens i Stockholm Förhandlingar
NGT=Norsk Geologisk Tidsskrift
NGU=Norges geologiske undersøkelse
SGU=Sveriges geologiska undersökning

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