Mineralium Deposita (1999) 34: 422–471

ARTICLE

T. Grenne · P. M. Ihlen · F. M. Vokes

Scandinavian Caledonide Metallogeny in a plate tectonic perspective

Received: 14 November 1998 / Accepted: 1 February 1999

Abstract Caledonian metallogeny has endowed Scandinavia with abundant metalliferous mineral resources of several genetical and compositional types, many of which have been exploited at various scales from the seventeenth century onwards. Because of this long history of exploration/exploitation, coupled with excellent exposures, the Caledonian orogen in Scandinavia can be taken as a model to illustrate the relationship between metallogenic evolution and plate tectonics. Its orogenic and metallogenic development can be related to a period of plate movements which started about 700–600 Ma ago with rifting and break-up of a Proterozoic megacontinent (*Rodinia*) followed by the opening-up of a wide ocean (*Iapetus*), and ending with collision between the Laurentian and Baltic continents (the climactic Scandian phase of orogeny) in Silurian times. Fragments of this sedimentary, magmatic and tectonic history are recorded in various autochthonous, and allochthonous units which were ultimately thrusted eastwards above the Baltic plate margin.

The present consensus is that sequences deposited on the margin of the Laurentian plate are represented in the Uppermost Allochthon (*UmA*) mostly in northern Norway. The Neoproterozoic and Cambrian history of this margin started with the rifting of Rodinia, followed by the development of an Atlantic-type margin which was characterised by an easterly thickening, continental, shelf-wedge of basal quartz sandstones and an overlying blanket of thick carbonate banks reflecting the drift of Laurentia towards equatorial paleo-latitudes. This setting is considered to have been host to two characteristic types of stratabound-stratiform ores: massive to disseminated Zn-Pb-Cu and Cu-Zn sulphides in sedimentary and mixed sedimentary-volcanic lithologies with original ore reserves up to 5–6 Mt (Bleikvassli, Mofjellet); and numerous, laterally extensive, magnetite-hematite deposits in marble-metapelite lithologies. The economically most important of the latter group are the deposits of the Dunderlandsdal area where resources of around 500 Mt were present.

Early rift basins preserved on the Baltic side of the rifted megacontinent, were filled with coarse clastites prior to establishment of a passive plate margin in Cambrian times. The passive margin was characterised by shallow marine sandstones and later bituminous Alum Shales deposited in a stable, epicontinental sea. Platform sedimentation was accompanied by local magmatic activity of rift-type tholeiitic through to carbonatitic compositions. This plate margin is presently represented in autochthonous and allochthonous sequences in the lower parts of the Caledonian nappe pile. Metalliferous mineral formation related to this time and setting was of limited importance and comprised previously worked Nb, P and Fe ores in carbonatites of the Fen Complex, vast but uneconomic resources of U, Mo, Ni and V in the Alum Shales, and minor stratabound base metal sulphides and orthomagmatic Cr and Ni-Cu-(PGE) occurrences.

Continental margin and oceanic successions, probably developed along the edge of a microcontinent within the Iapetus ocean, are represented in the Gula, Støren and equivalent, sequences in the Upper Allochthon (*UA*), tectonostratigraphically above and west of the Baltic platform lithologies. These host many Cu-Zn sulphide ores intimately related to tholeiitic basalt units in sedimentary sequences dominated by pelitic and psammitic material, as well as bituminous shales and quartzites of possible ribbon-chert origin. Original ore reserves around 20 Mt were known at the now abandoned Tverrfjell mine and the recently closed Joma deposit. Minor Cu-Ni ores occur in subvolcanic, mafic-ultramafic intrusions.

Editorial handling: DR

T. Grenne (✉) · P.M. Ihlen
Geological Survey of Norway,
N-7491 Trondheim, Norway
e-mail: tor.grenne@ngu.no

F.M. Vokes
Norwegian University of Science and Technology,
Dept. of Geology and Mineral Resources Engineering,
Høgskoleringen 6, N-7491 Trondheim, Norway

Major plate convergence is first recorded in the Middle to Late Cambrian (about 505 Ma), when subduction along the outer margin of Baltica affected rocks which are now found in or below the basal parts of the *UA*. The metallogenic significance of this subduction is uncertain; related magmatic and ore-forming processes have yet to be documented. The earliest subduction-related sequences of major ore-forming importance, however, are slightly younger (Early Ordovician) and are presently found in the *UA* and partly in the *UmA*.

One of these is the Stekenjokk-Fundsjø arc sequence (about 490 Ma) which forms a central unit in the mountain chain, comprising bimodal, immature arc-type volcanites and high-level felsic intrusions. The sequence formed in a primary oceanic setting outboard of the Baltica plate while this lay in an approximately east-west position opposite to, and at some distance from, the Siberian plate, and was amalgamated with the Gula Complex in Ordovician times. Abundant VMS deposits are associated with thick, often graphitic, tuffites and are of the Zn-Cu type with generally high Zn/Cu ratios. The biggest known deposit (Stekenjokk-Levi) contained 26 Mt of ore, four others had individual tonnages of about 3 Mt and have been important base metal producers.

Another series of arc sequences are found at higher levels in the nappe pile, in southwestern Norway, the western Trondheim Region, the western Grong District, Leka and Lyngen. Mafic or bimodal volcanic and plutonic lithologies comprise many types characteristic of immature arcs and often include ophiolitic successions. They all formed in oceanic arc-marginal basin systems on the Laurentian side of the Iapetus ocean between 500 and 480 Ma. VMS deposits of the Cu-Zn type are abundant and several of these were important base metal producers in the past. The biggest deposit is Løkken which contained 30 Mt of ore; six fall in the 1–10 Mt class and include the Skorovas and other deposits in the western Grong District and in southwest Norway. Orthomagmatic ores occur in the form of PGE mineralisation in ultramafic cumulates in the basal parts of ophiolite successions and Cu-Ni-PGE mineralisation related to high-level intrusions of boninitic affinity; none of these have hitherto been of economic significance.

The immature arc-marginal basin systems near Laurentia continued to evolve and in Early to Middle Ordovician times magmatism gradually changed to predominantly calc-alkaline igneous activity characteristic of an active continental margin. Major VMS ores seem to be scarce in these sequences which are most extensively developed in central and southwest Norway. Known metalliferous deposits are predominantly iron-formations ranging from magnetite- to pyrite-dominated types with varying base-metal contents; Zn-Pb-Cu mineralisation is subordinate. Major granodioritic plutons which intruded the mature-arc sequences at an advanced stage of development (c.460 Ma) occasionally contain vein- and stockwork-type Cu-Mo mineralisation, so far with no economic significance.

By the end of the Ordovician, convergence of the Laurentian and Baltic continents had resulted in considerable narrowing of the Iapetus ocean and obduction of the arc/arc-basin systems on to the edge of the Laurentian plate. Material derived from the uplifted sequences supplied detritus to the remaining, narrow, basin. At about the Ordovician/Silurian boundary these thick clastic, often calcareous, sequences and their crustal substrata were intruded by rift-type, mainly tholeiitic to alkaline magmas and minor subduction-related melts; local volcanism also accompanied this activity. This important magmatic event is interpreted to reflect a paleotectonic setting characterised by transcurrent movements and development of local transtensional regimes and fault-controlled sedimentary basins during the initial, oblique, interference of the Baltic and Laurentian plate margins. Its metallogenic manifestation is seen partly in occasional Ni-Cu deposits in mafic intrusions, including the Bruvann, Råna, deposit presently being exploited. More abundant, however, are stratabound sulphides which are associated with the volcanic rocks, or hosted in the sedimentary successions often closely related to mafic intrusions. The most important past-producers were found in the Røros and Sulitjelma districts, and included several individual deposits ranging from 1 up to nearly 9 Mt in size and dominated by Cu and Zn in highly variable proportions and grades.

Partly overlapping in time with the rift-related magmatism, an array of large, mafic to granitic batholiths was emplaced in rock sequences which are presently found in the Uppermost and Upper Allochthons. This activity continued through the Late Ordovician and Early Silurian, presumably along the Laurentian plate margin in response to westward subduction of the edge of Baltica. Its metallogenic significance is limited to small and uneconomic skarn-, pegmatite- and quartz-vein mineralisation of Zn-Pb-Cu, Mo, W and Be.

The ultimate collision between Laurentia and Baltica occurred during the Silurian, when the accretionary prism with granitic batholiths was obducted onto the Baltic margin. The obduction and subsequent uplift of the subducted edge of Baltica led to the formation of intramontane ORS basins in the Early and Middle Devonian. The Caledonian orogeny terminated with the deformation of the ORS basins in the Late Devonian.

The collisional stage is metallogenically represented by three types of deposits, i.e. lead sandstone deposits (Pb, Zn, Ba, F and Cu), carbonate-hosted base-metal deposits, and vein deposits with variable proportions of Au, Ag, Pb, Cu, Zn, Fe, As, Sb, W, Mo and/or U. The first type, which comprises deposits with up to 5.0 Mt lead metal (Laisvall) is by far the most important economically. The vein deposits have in the past been the site for small-scale mining of precious metals and molybdenite. Although the exact timing of the different ore-forming events is poorly constrained, all types seem related to a continuous process of tectonically induced fluid flow during episodes of crustal shortening and uplift. Brief comparisons with other parts of the now-rifted Caledonian-Appalachian orogen reveal both similarities and differences in the relative importance of the ore types generated during the time span covered in the present account.

Introduction

The Caledonian orogenic-metallogenic belt in Scandinavia constitutes the northernmost sector of the composite Caledonian-Appalachian belt (Fig. 1), which stretches from northern Norway to Alabama. If the effects of the comparatively recent Atlantic sea-floor spreading are ignored, this belt is some 7000 km long and could be said to constitute one of the major metallogenic features of the Earth's crust.

The Caledonian orogenic belt is the result of a plate-tectonic cycle spanning a time-period of some 300 Ma, beginning in Neoproterozoic times at around 700 Ma with rifting and continental break-up, and ending in the Devonian subsequent to a continent-to-continent collision. During this time a wide range of ore deposit types were generated, many of which it is possible to relate to different stages in the development of the orogenic belt.

The present contribution seeks to relate the metallogenic events in the Scandinavian Caledonides to the orogenic development and to the type of crust involved at each stage; however, a good deal of uncertainty attaches to the geological ages of many deposits in the present-day Caledonides. By no means all of them were initially formed during the period under review (Neoproterozoic to Devonian). Some of the deposits are undoubtedly of Mesoproterozoic, or earlier, depositional ages. For others, such an age is likely, though not proven. However, most of these proven or assumed older ores have been affected, to a greater or lesser extent, by the Caledonian metamorphism and deformation and are now present in Caledonian allochthons. It is not possible in many cases to distinguish between these older deposits and 'true' Caledonian deposits formed during the Caledonian tectonic cycle. Evidence of the ages of the deposits will be presented where available; some of these, which may ultimately prove to have pre-Caledonian ages of formation, will be included as they have historically been regarded as Caledonian in Scandinavia. Others, of definitely earlier or very doubtful ages, will not be considered. These latter include:

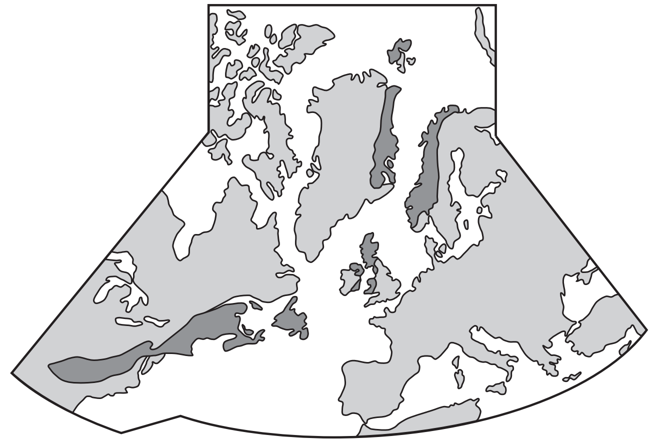


Fig. 1 The Caledonian-Appalachian orogen (*shaded*). Pre-Mesozoic refit map after Stephens et al. (1984)

1. Proterozoic orthomagmatic Fe-Ti-V ores in both Norway and Sweden, e.g. Rødsand and Selvåg (Korneliussen et al. 1985); Ruotevare (Grip and Frietsch 1973; Frietsch 1975)
2. Proterozoic orthomagmatic Fe-Ni-Cu deposits in Norway, e.g. Hosanger, Espedal and Senja (Boyd and Nixon 1985)
3. Stratabound/stratiform ores of Cu, Cu-Zn and Zn-Pb in Paleoproterozoic greenstone belts within tectonic windows and thrust sheets in the northern Caledonides
4. Stratabound Pb-Zn-Cu sulphide ores in thick sequences of interbedded psammites, feldspathic quartzites and schists of undetermined age (in part Mesoproterozoic) in the Middle Allochthon of northern Norway (Lindahl and Bjørlykke 1988; Grimm and Stendal 1991)

The Caledonian ores considered below number several hundred individual deposits (Foslie 1925; Poulsen 1964; Frietsch 1975; Grip 1978; Juve and Grenne 1993) and can be grouped into the following main types:

1. Stratabound, partly stratiform, massive to disseminated deposits of mainly Zn-Pb (±Cu) sulphides in metasedimentary successions (sedex deposits). Age of host rocks uncertain, possibly Mesoproterozoic to Cambrian
2. Stratabound magnetite-hematite deposits in metasedimentary carbonate-pelitic successions (metasedimentary iron ores). Host rocks of uncertain age; probably Neoproterozoic
3. Carbonatite-hosted Nb-Fe-P-REE etc. deposits in carbonatite-alkaline complexes of late Neoproterozoic-Cambrian age
4. Organic-rich black shale deposits with concentrations of U, V, Mo, Ni and other elements (alum shale deposits). Latest Cambrian-Tremadoc age
5. Stratabound, partly stratiform, massive pyritic deposits of Cu-Zn (±Pb) sulphides in Cambro-Silurian metavolcanic or mixed metavolcanic-metasedimentary successions (VMS or volcex deposits)
6. Stratabound magnetite- (pyrite-chalcopyrite) deposits in Early to Mid-Ordovician metavolcanic-sedimentary sequences (volcanite-hosted iron ores)
7. Orthomagmatic Ni-Cu-S and Cr deposits with local high PGE contents in mafic-ultramafic intrusive bodies showing a wide spread of ages; latest Proterozoic to early Silurian
8. Minor Cu-Mo stockwork mineralisation in felsic magmatic rocks of Middle Ordovician age
9. Stratabound, disseminated to semi-massive accumulations of Pb (±Zn) sulphides in latest Precambrian to Lower Cambrian quartz-arenites (sandstone lead deposits)
10. Various, small, vein- and replacement type deposits characterised by elements such as Au, Ag, Pb, Zn, Sb, As, W, Mo or U, in metamorphic and plutonic complexes. Late Ordovician to Devonian ages

Economic aspects: ore production

Large numbers of deposits have been exploited at various times and on varying scales since at least the seventeenth Century. This historical production has been mainly concerned with deposits of iron oxides, iron- and base-metal (Cu, Zn, Pb) sulphides (± Ag, Au); more recently, nickel sulphides (Table 1). Minor, often intermittent or short-lived, production of chromite, gold and silver, niobium and uranium has also taken place, while deposits of scheelite, molybdenite and precious metals (Au, Ag, PGE) have been investigated from time to time.

The number and output of Caledonian metal mines in Scandinavia has shrunk markedly during the last 10–20 y. In the late-1970s, nine Norwegian and three Swedish base-metal sulphide mines produced a total of some 4.0 Mt per year of ore yielding approximately 90 000 tonnes of Cu concentrates, about 51 000 tonnes of Zn concentrates, some 75 000 tonnes of Pb concentrates and in excess of 0.5 Mt of pyrite (S) concentrates and lump sulphide ore. Individual mine outputs ranged from 130 000 to over 1 Mt per year. In addition, during this period, three iron mines treated 4.5 Mt of ore per year to yield just under 1.7 Mt of concentrates. By 1994 the number of mines of all types working strictly Caledonian ores had shrunk to six, all but one of these in Norway. Sulphide ore production was down to just over 3 Mt and iron ore production to about 1.9 Mt. At the time of writing (late 1998), two sulphide mines (Laisvall and Bruvann, Råna) and one iron ore mine (Rana) are still maintaining some production.

Geological framework

The Scandinavian Caledonides comprise a number of nappes which include rocks of very varying lithology and metamorphic grade, ranging in age from Precambrian to Devonian. The present-day tectono-stratigraphic build-up of the Caledonides (Roberts and Gee 1985) is a result of the combined effects of early Caledonian deformation, including the Finnmarkian phase, and of the climactic Silurian (Scandian) phase of generally west to east thrusting and nappe translation. The nappes generally thin out westwards, while there are large variations in the thicknesses of the allochthons along the length of the orogen. Subsequent uplift of the central parts of the orogen led to large-scale extension of the thrust-pile and the deposition of Early and Middle Devonian molasse in fault-controlled basins.

The nappes overlie a crystalline basement of autochthonous to parautochthonous rocks, ranging from Archaean to latest Mesoproterozoic in age, constituting the Fennoscandian or Baltic Shield. This basement is covered thinly by an autochthonous to parautochthonous cover of Latest Precambrian (Vendian or latest Neoproterozoic) and Lower Paleozoic sedimentary rocks. On the easternmost foreland it is only mildly affected by the Caledonian events (but see, e.g. Romer and Bax 1992). Westwards, it becomes increasingly ‘caledonised’ especially in its upper parts and along thrust planes (Bryhni and Andreasson 1985). Basement rocks outcrop frequently in the central parts of the Caledonides in tectonic windows, of domal or anticlinal nature, due to erosion of the overlying nappes. These ‘basement’ windows are not truly autochthonous, but parts of the lowermost nappe complexes (Hurich et al. 1989). In most cases they are overlain by their own ‘cover sequences’ which correspond to the Vendian-Lower Paleozoic cover sequences along the eastern margin of the Caledonides (the ‘Caledonian Front’).

The individual nappe units have been grouped into four allochthonous complexes (Roberts and Gee 1985): the Lower Allochthon (*LA*), the Middle Allochthon (*MA*), the Upper Allochthon (*UA*) and the Uppermost Allochthon (*UmA*). In recent years attempts have been made to interpret the tectonostratigraphical se-

Table 1 Scandinavian Caledonian ore deposits. Main historical producers. Data from Bjørlykke et al. (1980) and the mineral resource data base at the Geological Survey of Norway

Deposit	Original resource (Mt)	Grades					Ore produced	
		Cu %	Zn %	Pb %	S %	Other	Mt	Period
VMS								
Løkken	30	2.3	1.8	0.02	41	19 g/t Ag; 0.2 g/t Au	24.0	1654–1987
Stekenjokk-Levi	25.7	1.43	2.55	0.23	19	50 g/t Ag; 0.3 g/t Au	7.1	1975–1988
Tverrfjellet	19.0	1.0	1.2	0.2	32		15.0	1963–1993
Joma, Grong	17.0	1.3	1.7	tr.	35		9.7	1972–1998
Skorovas, Grong	10.0	0.8	1.6	tr.	40			1952–1985
Giken, Sulitjelma	9.5	2.25	0.70	tr.	19		5.8	1892–1991
Litlabø, Stord	9.0	<0.1	<0.1	<0.1	23			1865–1968
Bjørkåsen	4.7	0.45	1		30		6.0	1917–1964
Jakobsbakken, Sulitjelma	4.5	1.55	2.42		31		4.5	1896–1968
Charlotta, Sulitjelma	3.5	2.0	0.58	tr.	17		3	1894–1991
Hankabakken, Sulitjelma	3.2	1.4	0.4	tr.	14		2.0	1901–1987
Hersjø, Røros	3.2	1.4	1.4	0.01	35			1685–1833
Folldal, Old mine	3.0?	1.5	3.0	0.2	35			1748–1940
Storwartz-Olav, Røros	3	2.4	1.5		20			1645–1972
Killingdal	3	1.7	5.5	0.4	45		2.5	1677–1986
Vigsnes, Karmøy	2.5	1.7	1.4		35		1.4	1865–1894
N. Gjetryggen, Folldal	2.5	1.3	3.2	0.2	34		2?	1920–1970
Ny-Sulitjelma	2.3	1.99	0.55		20		2.6	1893–1965
Sagmo, Sulitjelma	2.1	1.6	0.23		19		1.9	1906–1986
Båsmo, Rana	2.0	0.13	0.14	tr.	20		1.85	1894–1937
Sedex(?)								
Bleikvassli	6	0.2	4.2	2.5	25	25 g/t Ag	4.9	1957–1998
Mofjell, Rana	4	0.3	4	0.8	35		4.35	1926–1987
Orthomagmatic								
Bruvann, Råna	7	0.1	–	–		0.53% Ni	5.7	1989-
Iron ores								
Dunderland, Rana	500?					33.0–37.4% Fe	77.1	1904-
Fosdalen	40?	0.06	–	–	2.2	34.4% Fe	36	1906–1997
Lead sandstone								
Laisvall	60	<0.1	0.5	3.9	?	8 g/t Ag	60	1942-
Vassbo	5	?	0.3	4.6	?	14 g/t Ag	5	1960–1982

quences in the Scandinavian Caledonian nappes in terms of the terrane concept (see, e.g. Stephens and Gee 1985, 1989; Roberts 1988a). At present there is no apparent general consensus, either on the number of individual terranes recognised or on their ultimate derivation and, consequently, on their relation to the previously defined tectonostratigraphic units or allochthons. The latter will therefore be used as the main tectonostratigraphical divisions referred to in the subsequent text.

Plate tectonic development

The orogenic and metallogenic development of the Scandinavian Caledonides can be related to a period of plate movements which started with rifting and break-up of the Proterozoic megacontinent beginning at about 700 Ma ago, followed by ocean-floor spreading and later plate convergence, and ending with continent-continent (Laurentia-Baltica) collision (the climactic Scandian phase of orogeny) in Silurian times. A simplified, cartoon-type illustration of this development as presented in this study is shown in Fig. 2.

One of the present writers (Vokes 1988) attempted to describe this development in terms of an idealised *Wilson Cycle* involving the Laurentian and Baltic fragments of the megacontinent and the formation and subsequent destruction of an intervening ocean, Iapetus (Roberts and Gale 1978). Recent advances in our knowledge of the timing and nature of both the orogenic and metallogenic history of the Scandinavian Caledonides now require a revision of the details of this cycle. Among the many questions that remain to be solved are the paleogeographic position and polarity of subduction systems within the Iapetus Ocean, where models which deviate significantly from that presented here have been advocated by, e.g., Sturt and Roberts (1991; see also later in this present work).

The picture of a generally simple, east-west opening and closing of Iapetus presented previously has recently been considerably modified by paleomagnetic and other investigations (e.g., Torsvik et al. 1992, 1996; Dalziel 1997; Smethurst et al. 1998). An exhaustive review of this literature will not be attempted here, though a brief account of a possible sequence follows. Prior to the break-up in early Neoproterozoic time of the supercontinent Rodinia, the Scandinavian margin of the future continental plate Baltica was situated immediately south of the equator, close to the Greenland margin of the future Laurentian plate. Baltica began to separate from Laurentia and the rest of the supercontinent by rotating clockwise to high southerly latitudes towards the end of the Neoproterozoic. Subsequently, Baltica, rotating anticlockwise, began to move to the north and west leading to an equatorial position in the Early Silurian when an approximately pre-rifting orientation with respect to the northeastern margin of Laurentia was resumed. The climactic, Scandian, continent-continent collision of the two plates occurred in the Silurian, fragments of the two plates being incorporated into the various allochthonous and autochthonous units which make up the present-day Caledonides in Scandinavia. Interference of the Baltic plate with the Amazonian and/or the Siberian plates may have occurred during the Neoproterozoic to Cambrian rotation of Baltica, but the possible effects of this are currently uncertain, e.g. in respect to the Early Caledonian or Finnmarkian orogenic phase.

In spite of this newer, more refined, picture of the movements of the Laurentian and Baltic plates during Late Precambrian to Devonian times, the main metallogenic features of the Caledonian orogen can still be, in the main, referred to stages in the opening and closing of the Iapetus Ocean. In particular it is possible to refer many of the syngenetic ore-forming events to the type(s) of crust (continental, oceanic, etc.) formed during the various stages of orogen development. Since the nappe-piles, or allochthons, have been defined as, in general, containing dominantly terranes which developed during well-defined stages of the life of the orogen, the mineral-deposit, or metallogenic, belts coincide roughly with the trend of the allochthons. This is approximately NNE in clear contrast to the generally westerly or north-westerly trends of the metallogenic belts in the Baltic Shield to the east.

It is generally accepted that the sedimentary and volcanic successions of the different terranes represented in the lower to the upper allochthons were originally formed at an increasing distance from the Baltic margin. The terranes reveal a continuous process of rifting, oceanic crust development, basin-sedimentation and -volcanism, and island arc magmatism, punctuated by episodes of obduction, collision, uplift and/or erosion. Deciphering of the geological evolution of the individual terranes has made it possible to develop a composite model of the evolving Caledonian Orogen and its metallogeny. The present account subdivides this complex model into three main sequential stages, comprising (1) continental rifting and ocean floor spreading, (2) plate convergence and ocean closure, and (3) continent collision. The metallogenic significance of these stages is summarised in Fig. 3.

Stage 1: continental rifting and ocean floor spreading

During a period of anorogeny following the Sveconorwegian (Grenvillian) tectonothermal event (900–1000 Ma) the Proterozoic megacontinent underwent crustal attenuation and rifting prior to the initial break-up in the Neoproterozoic to Early Cambrian (Vokes and Gale 1976; Kumpulainen and Nystuen 1985) (Fig. 2). The Neoproterozoic aulacogens, rift basins and fault-controlled crustal depressions were filled with coarse clastic fluvial sandstones and conglomerates locally grading into turbidites, prior to the development of passive, Atlantic type margins along the rifted continent edges. The Baltic margin was dominated by quartz-rich clastic deposits, minor dolomitic carbonates and tillites (Bergström and Gee 1985) whereas the Laurentian margin comprised an easterly thickening, continental shelf wedge of basal quartz sandstone with an overlying, thick carbonate bank blanket (Schwab et al. 1988).

Paleomagnetic data (e.g. Torsvik et al. 1992, 1996) and traditional interpretation of faunal provincialism (see, e.g. Spjeldnaes 1985), indicates that the initial continental rifting was followed by a long period of oceanic crust formation extending at least into the Late Cambrian. During this period, the two plate margins experienced completely different paleogeographic positions, the Baltic plate margin essentially drifting to high southerly paleolatitudes and back while the Laurentian plate margin maintained a relatively stable, equatorial position.

Remnants of this major ocean (Iapetus) are scarce or absent in the preserved parts of the Caledonides, probably due to subduction of the oceanic crust during the later stages of plate convergence and ocean closure. However, a fairly complete record of contemporaneous sedimentary and magmatic processes occurring in the *interior* and along the *margins* of Laurentia and Baltica is preserved in various allochthonous units of the present-day Caledonides (Fig. 3).

The Laurentian margin

The present consensus is (see, e.g. Stephens et al. 1985b; Stephens and Gee 1985 and references therein) that sequences deposited on the margin of the Laurentian plate in the latest Precambrian and Lower Paleozoic are rep-

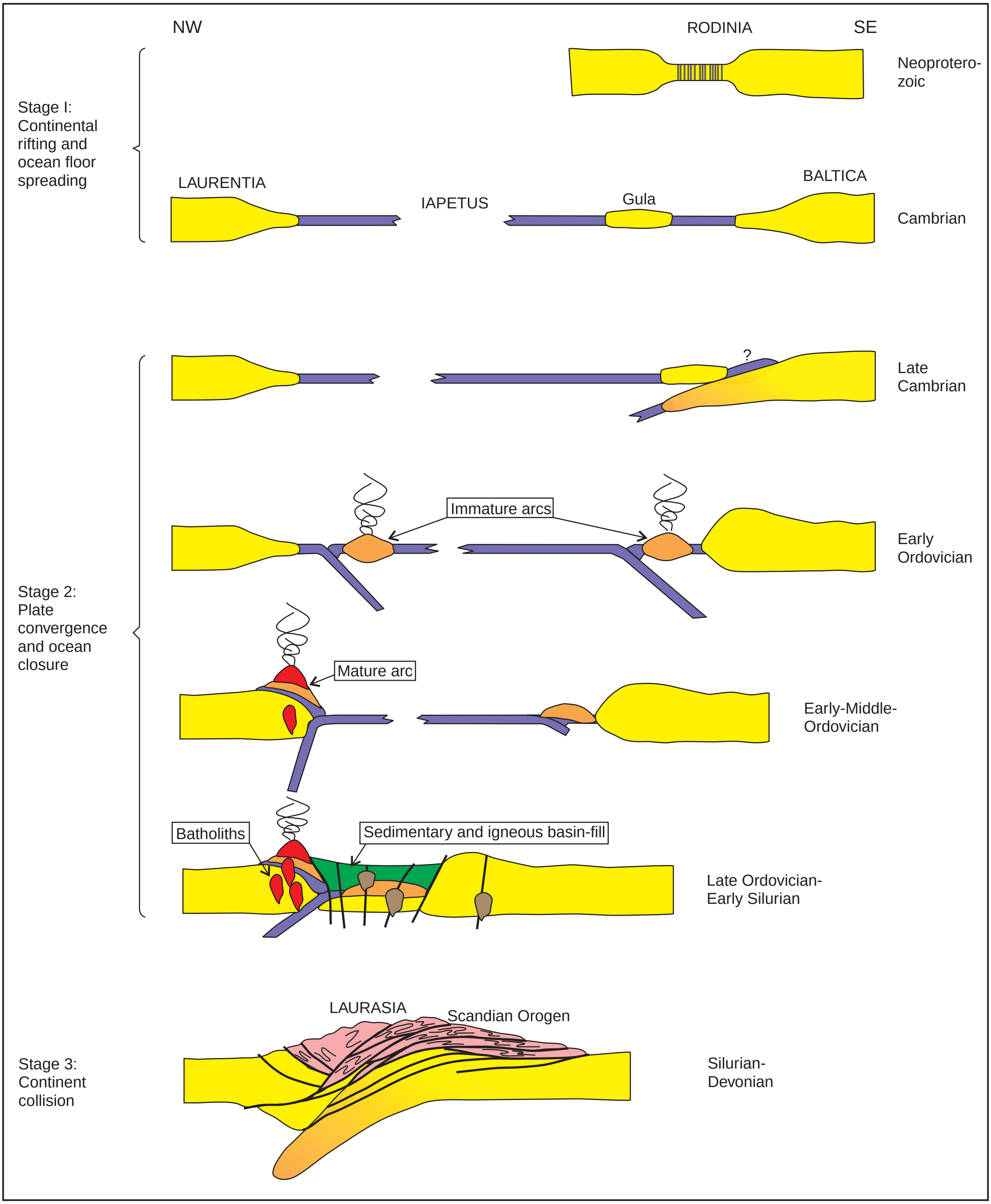
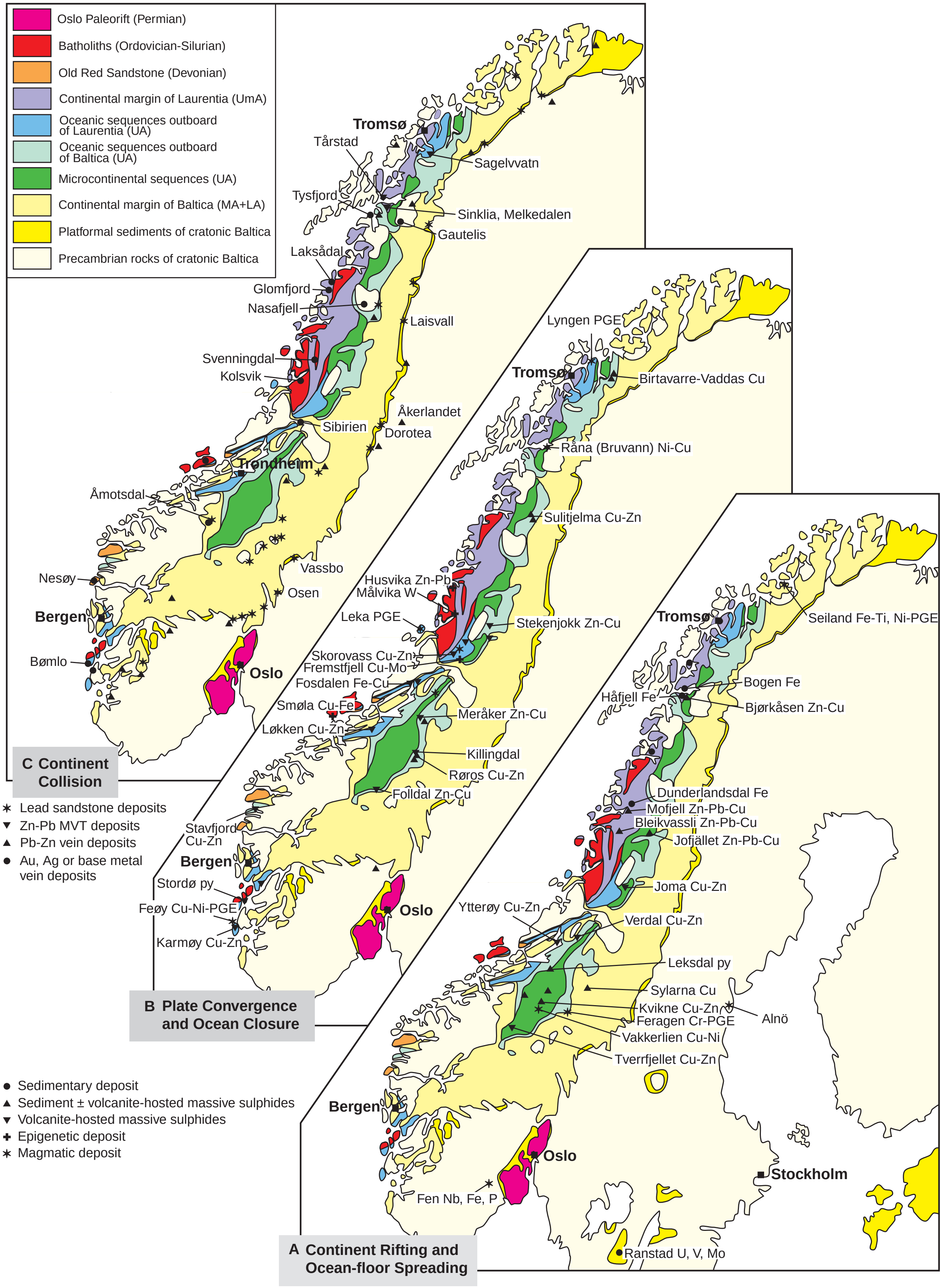


Fig. 2 Cartoon illustrating the three stages of Caledonian plate tectonic development referred to in the text

resented in the nappes of the *UmA* of the Scandinavian Caledonides. Present-day lithology consists of amphibolite facies gneisses and migmatites, and marble-schist complexes, locally with conglomerates and sedimentary


Oslo Paleorift (Permian)
Batholiths (Ordovician-Silurian)
Old Red Sandstone (Devonian)
Continental margin of Laurentia (UmA)
Oceanic sequences outboard of Laurentia (UA)
Oceanic sequences outboard of Baltica (UA)
Microcontinental sequences (UA)
Continental margin of Baltica (MA+LA)
Platformal sediments of cratonic Baltica
Precambrian rocks of cratonic Baltica
Tromsø
Tårstad
Sagelvvatn
Tysfjord
Sinklia, Melkedalen
Gautelis
Laksådal
Glomfjord
Nasafjell
Laisvall
Svenningdal
Kolsvik
Åkerlandet
Sibirien
Dorotea
Trondheim
Åmotsdal
Vassbo
Nesøy
Osen
Bergen
Bømlo
Oslo
C Continent Collision
∗ Lead sandstone deposits
▼ Zn-Pb MVT deposits
▲ Pb-Zn vein deposits
● Au, Ag or base metal vein deposits
Lyngen PGE
Tromsø
Birtavarre-Vaddas Cu
Råna (Bruvann) Ni-Cu
Sulitjelma Cu-Zn
Husvika Zn-Pb
Målvika W
Leka PGE
Stekenjokk Zn-Cu
Skorovass Cu-Zn
Fremstfjell Cu-Mo
Fosdalen Fe-Cu
Smøla Cu-Fe
Løkken Cu-Zn
Meråker Zn-Cu
Killingdal
Røros Cu-Zn
Folldal Zn-Cu
Stavfjord Cu-Zn
Bergen
Stordø py
Feøy Cu-Ni-PGE
Karmøy Cu-Zn
Oslo
B Plate Convergence and Ocean Closure
Tromsø
Seiland Fe-Ti, Ni-PGE
Bogen Fe
Håfjell Fe
Bjørkåsen Zn-Cu
Dunderlandsdal Fe
Mofjell Zn-Pb-Cu
Bleikvassli Zn-Pb-Cu
Jofjället Zn-Pb-Cu
Joma Cu-Zn
Ytterøy Cu-Zn
Verdal Cu-Zn
Leksdal py
Sylarna Cu
Kvikne Cu-Zn
Feragen Cr-PGE
Alnö
Vakkerlien Cu-Ni
Tverrfjellet Cu-Zn
Bergen
Oslo
Stockholm
Fen Nb, Fe, P
Ranstad U, V, Mo
A Continent Rifting and Ocean-floor Spreading
● Sedimentary deposit
▲ Sediment ± volcanite-hosted massive sulphides
▼ Volcanite-hosted massive sulphides
✚ Epigenetic deposit
∗ Magmatic deposit

◄

Fig. 3 Simplified tectonostratigraphic map of the Scandinavian Caledonides depicting the distribution of different terranes and ore deposits related to the evolutionary stages. The terranes are modified from Roberts (1988a) and Stephens and Gee (1989)

iron ores. It is thought that at least some of the gneisses may represent a pre-Caledonian (?Grenvillian) basement complex, upon which the marble-schist sequences were deposited as a cover unit (see Stephens et al. 1985b).

Considerable uncertainty has been attached to the ages of the interpreted Laurentian successions hosting the main ore types present in the *UmA*, and thus to the ages of the ores themselves. It has not been possible to equate, for example, the marble-pelitic schist sequences hosting the important iron ores with the carbonate bank deposition mentioned above. Investigations of the Sr and C-isotopic composition of the marbles in some of the constituent nappes of the *UmA*, have yielded values consistent with the composition of Neoproterozoic seawater, and this is considered the most likely depositional age for the marbles (Trønnes 1994; Trønnes and Sundvoll 1996; Melezhik et al. 1997). Thus the marble-schist sequences could be interpreted as latest Proterozoic cover sequences deposited on a possibly Grenvillian basement. This supports the conclusions of Tørudbakken and Ramberg (1982) that significant parts of the *UmA* consist of Precambrian rocks and that important structural and metamorphic events affecting these were of the same age. Skauli et al. (1992) have also interpreted the slope of the Pb isotopic data from the wall-rocks of the Bleikvassli Zn-Pb-Cu deposit to indicate a maximum age of about 1 Ga.

Two main types of stratabound, often stratiform, ore deposits are characteristic of the rocks under consideration:

1. Stratabound, massive to disseminated, polymetallic sulphide ores in metasedimentary and metavolcanic lithologies
2. Stratiform iron oxide ores, in places manganiferous, in metasedimentary pelite-carbonate successions

Stratabound sulphides

In spite of their high degree of deformation and metamorphism, these massive to disseminated, variably pyritic/pyrrhotitic, sphalerite ± galena ± chalcopyrite ores have up to now been considered to be of syngenetic, exhalative (*sedex or volcex*) origin. Ores of this type are widespread in the *UmA*, but are most abundant in the Rana District of Norway and adjacent parts of Sweden (Fig. 4), and in the Ofoten district of Norway (Fig. 5). Marbles in the *UmA* of the southern part of Nordland, Norway (Helgeland) are hosts to minor stratabound sulphidic ores (Birkeland et al. 1993a).

From a compositional point of view, the stratabound sulphide ores in the interpreted Laurentian terranes of the *UmA* may be classed into two main types: (1) moderately pyritic (± pyrrhotite) Zn-Pb-(Cu) ores with base-metal contents (dominantly Zn + Pb) of the order of 3–7% and (2) heavily pyritic Zn-Cu ores with low total base metal (< 2%) contents. Historically, both ore types have contributed to production statistics, though the metal-richer Zn-Pb-(Cu) ores have been by far the economically most important. Of these, the larger *Bleikvassli* deposit, some 50 km south of Mo i Rana, was worked from 1957 to 1997, producing some 5 Mt of ore grading approximately 4% Zn, 2% Pb, 0.3% Cu and 25 ppm Ag. It is hosted by a sequence of kyanite-, staurolite-, garnet- and graphite-bearing mica-schists, quartzo-feldspathic gneisses, metacherts and amphibolites, with a distinctive microcline-mica gneiss in the immediate footwall (see, e.g. Vokes 1963, 1966; Skauli et al. 1992; Bjerkgård et al. 1997; Cook et al. 1998). The *Mofjell* deposit further north, hosted mainly by metapelitic quartz-mica-feldspar gneisses and amphibolites, yielded about 3 Mt of predominantly zinc ore during parts of the nineteenth and twentieth centuries (Saager 1967; Bugge 1978). The only significant producer of the second type of stratabound sulphides in the *UmA* was *Båsmo*, also in the vicinity of Mo, where in excess of 0.5 Mt of pyrite concentrates were produced from just over 1.5 Mt of ore in the period 1894–1921 (Foslie 1926).

Zn- and Pb-bearing deposits of a somewhat different character and of apparently little economic significance occur on both sides of the Ofotfjord, west of Narvik (Fig. 5). Their metasedimentary host rocks are dominantly pelitic schists, in places with prominent quartzite interlayers The metamorphic and deformational features of two of these deposits (*Skårnesdalen* and *Djupvik*) in the Håfjell synform, south of the fjord, have been described by Juve (1967). Similar deposits occur on the north side of the fjord at Skogøy (Torgersen 1935), Villdalsfjell and Niingen (Torgersen 1935; Moorbath and Vokes 1963), as well as at Gamvik, further north.

The lead isotope abundances of the stratabound sulphide ores of the *UmA* in Norway have been investigated on two occasions. The results serve to distinguish these ores from other sulphides in the Caledonides, but also to suggest possible correlations between ores in the two main districts where they occur. In an early investigation of Pb isotopes in galenas from the Djupvik, Villdalsfjell and Niingstoppen deposits, Moorbath and Vokes (1963) calculated model ages of the order of 700 to 800 Ma. A recent Pb-isotopic investigation of Caledonian ore leads by Bjørlykke et al. (1993) included samples from deposits in the Ofoten-Troms region (Skårnesdalen and Gamvik), in the area south of Bodø, as well as in the Rana District. The results showed that several of the ores, including Skårnesdalen and Gamvik, fall on an array with higher ^{207}Pb/^{204}Pb ratios (termed the Ofoten trend) than that of the main Caledonian trend. Bjørlykke et al. (1993) concluded from their results that the deposits falling on the Ofoten trend are older in age than both the *UA* deposits and the other Rana District deposits mentioned; they may all be approximately 1000 Ma old. Their hosting shallow-marine sedimentary rocks and associated iron formations were considered analogous to those hosting the Grenvillian lead-zinc deposits in Canada.

Other lead-bearing deposits in metasedimentary lithologies in the *UmA* (including Mofjell, Bleikvassli, Kongsfjell and Malmhaugen), as well as Gräskevardo and Ripudden in Sweden (see Fig. 4) show lead isotope compositions that are more similar to those of deposits in the *UA* (Sundblad and Stephens 1983). As already discussed, the age(s) of the host rocks to these sulphides is not known with certainty. They could be of Grenvillian age or they may be related to the initial opening of the Iapetus ocean as already suggested by previous workers. In the latter case they may have had source rocks similar to those of the deposits in the *UA*.

Metasedimentary oxide iron ores, in places manganiferous

Stratabound-stratiform iron oxide ore deposits are both widespread and numerous in the interpreted Laurentian metasedimentary lithologies of several of the nappe complexes of the *UmA* in northern Norway. The ore-hosting sediments belong to a characteristic sequence of mainly calcareous mica schists and marbles to which the name Dunderland Group has been applied (Søvegjarto 1977; Bugge 1978) after its most important area of development in the Dunderlandsdal, north of Mo i Rana.

There is little evidence of contemporary volcanic activity in these rocks, which are present intermittently over a distance of more than 500 km from the Mosjøen area of Nordland to the

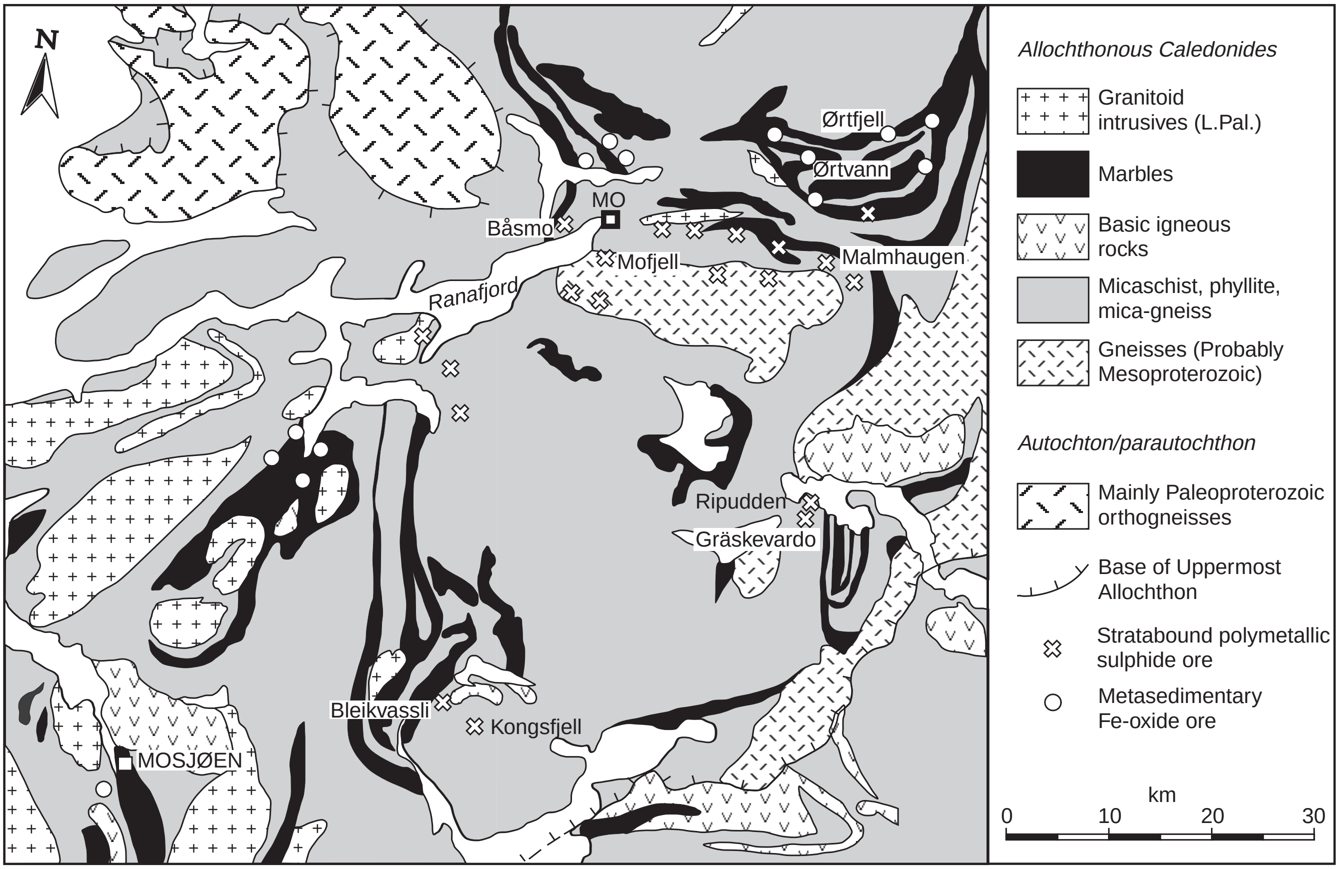


Fig. 4 Geological map of the Rana district, north-central Caledonides, showing distribution of stratabound/stratiform sulphide and iron oxide deposits. Geology simplified from Sigmond et al. (1984)

vicinity of Tromsø (Fig. 5). According to Bugge (1978) the Dunderland Group shows a 'nearly identical stratigraphy' over the whole region. Its age has been discussed for some time; both late Precambrian and Cambro-Silurian ages have been proposed. The recent dating of metacarbonate lithologies in the *UmA* reported at the beginning of this section makes the older age more probable. A schematic diagram by Søvegjarto (1977) suggests that the Dunderland Group was deposited as a distinctive facies development within the more persistent pelitic-psammitic sedimentation of the Ørtfjell Group which overlies a basement composed of the Mofjell gneisses (Fig. 4).

The deposits of the *Dunderlandsdal* area (Fig. 4) have been by far the most important of the Laurentian metasedimentary iron deposits (see Vogt 1894, 1910; Bugge 1948, 1978), yielding some 80 Mt of ore with 33 to 37% Fe since the first years of this century (see Table 1). The ore-bearing layers vary from a few to perhaps 30 m in thickness; the individual ore bodies and groups of bodies show marked structural control, with greatest thicknesses located in the hinges of folds.

Both Søvegjarto (1977) and Bugge (1978) point to the presence of two distinct horizons of iron ores within the Dunderland Group; an upper horizon of magnetite-hematite ores with from 0.15–0.30% P and a lower one of apatite-magnetite ores with from 0.8–1.0% P. Søvegjarto (1977) indicates that the two horizons show significant differences in gangue mineralogy; the P-poor horizon being characterised by quartz, while the P-rich horizon has more carbonate and amphibole. Manganese contents are fairly low in the ores as a whole (0.15–0.40%) but along certain horizons in the Bogen (Salangen) Group in the Ofoten area, Mn contents can be as high as 15%, present mainly as spessartine garnet, less importantly as mangano-calcite (Foslie 1949).

Bugge (1948) was of the opinion that the Dunderlandsdal ores were originally of sedimentary origin; most of the iron was derived by normal weathering of nearby coastal areas and was deposited initially as ferric hydroxide under relatively shallow marine conditions. The hydroxide was converted to hematite during consolidation of the rocks, while the magnetite-rich parts of the ore bodies were, in Bugge's opinion, formed by reduction of hematite during the Caledonian metamorphism. In view of the two distinct types of ores present (see earlier), one may question whether a single mode of formation is applicable to the iron ores of the *UmA*. The lower horizon of high-P, magnetite-rich ores is often characterised by amphibole-rich, at times amphibolitic, host-rocks. It is tempting to suggest that this horizon indicates that volcanic processes may have been operative.

The Baltic plate and margin

The sediments deposited on the Baltic plate are now preserved as thin autochthonous units along and east of the present Caledonian Front, and as westward-thickening parautochthonous and allochthonous equivalents (Gee et al. 1985; Kumpulainen and Nystuen 1985; Stephens and Gee 1989).

The coarse clastic sediments of the intracratonic basins that developed during the initial continental rifting graded upwards into shallow-marine quartz-rich clastic deposits and dolomitic carbonates which were overlain by tillites deposited during the Varangian glaciation at about 590–610 Ma (Pringle 1973; Willdén 1980; Knoll and Walter 1992).

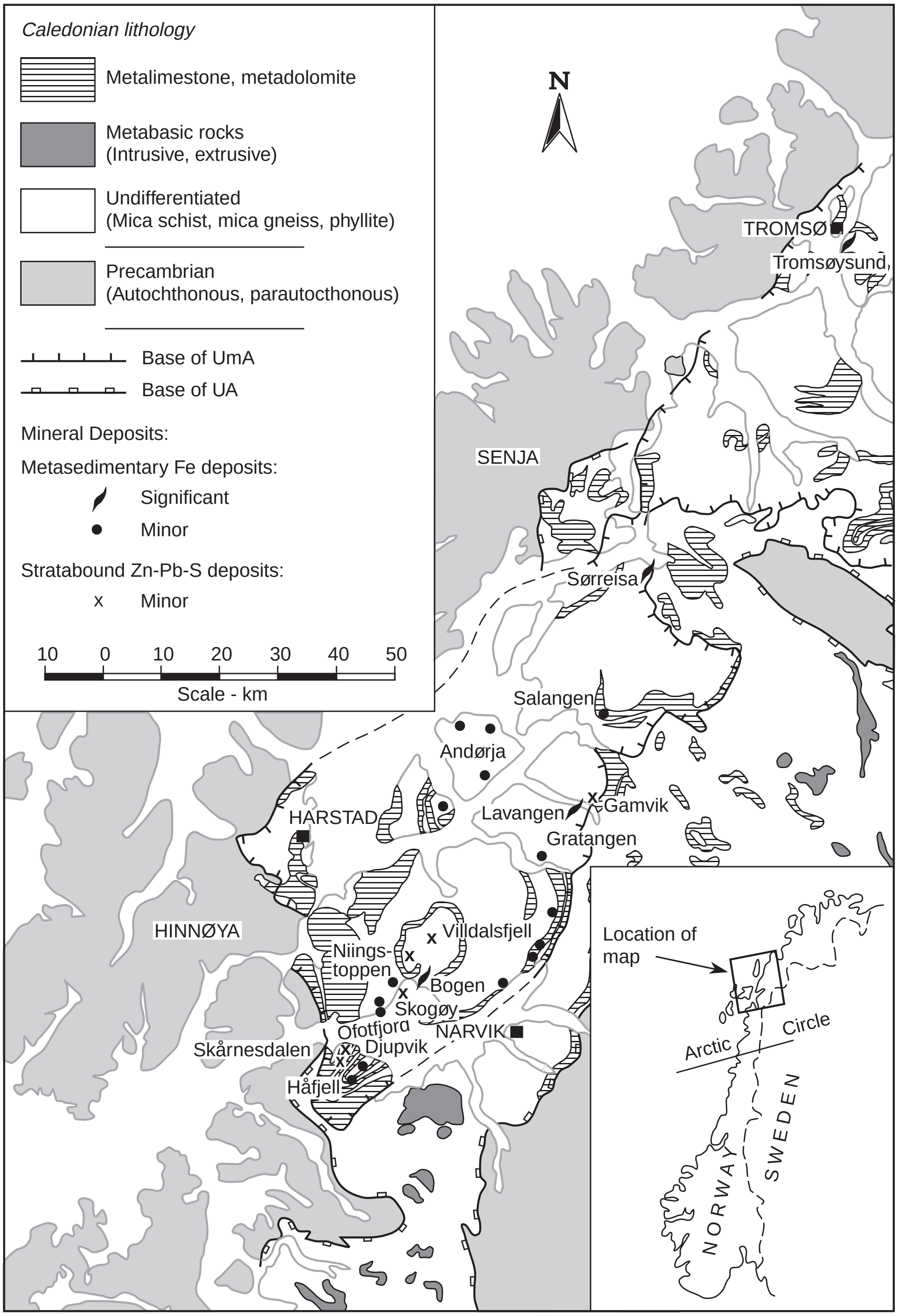


Fig. 5 Geological map of the Ofoten-Troms district, northern Caledonides, showing distribution of stratabound/stratiform polymetallic sulphide and iron (manganese) oxide deposits. Geology simplified from Sigmond et al. (1984)

Dolerite dyke swarms intruded various Neoproterozoic sedimentary sequences which are now found in the *MA* (Stephens and Gee 1989), as well as Proterozoic crystalline rocks assumed to represent their basement. Fissure eruptions occurred locally and are represented by tholeiitic basalt flows of continental affinity immediately below the Varangian tillite (Sæther and Nystuen 1981; Furnes et al. 1983). The magmatic activity ranged in composition from tholeiitic to alkali-olivine-basaltic, with trace element composition similar to within-plate and ocean floor basalts (see, e.g. Andreasson et al. 1992 and references therein).

These high-level manifestations of magmatism related to crustal thinning and rifting may have their deep-seated counterparts in the tholeiitic and alkaline intrusions of the Seiland Igneous Province (SIP) which has been proposed as representing deeper parts of a rift situated in the extending passive margin of Baltica (Robins and Gardener 1974, 1975; Krill and Zwaan 1987; Krill 1989; Stephens and Gee 1989). The mafic intrusives, which were emplaced into deformed and metamorphosed psammites of the Klubben Group (Ramsay 1971), yield isotope ages between 700 ± 33 Ma and 523 ± 2 Ma (Stephens et al. 1985a; Pedersen et al. 1988; Daly et al. 1991; Krogh and Elvevold 1990; Mørk and Stabel 1990). The igneous activity started with the intrusion of subalkaline gabbronorites and later subalkaline gabbros which were followed by emplacement of gabbros with syenitic differentiates, nepheline normative olivine gabbros, ultramafites and late carbonatites and nepheline syenites. Most of the mafic intrusives are in the form of layered gabbros (Robins 1985; Stephens et al. 1985a). Early to Middle Cambrian carbonatite magmatism encountered in the SIP (Cadow 1993) is time–correlated with the Fen (539 ± 14 Ma; Andersen and Taylor 1988) and Alnö (610 Ma to 530 Ma; Brueckner and Rex 1980) alkaline complexes (Fig. 3).

By the Early Cambrian, a passive Atlantic-type margin was established along the edge of the platform (Bergström and Gee 1985). The outermost margin of this platform is thought to be represented by the lithologies of the *Seve Nappes* which constitute the base of the *UA* (Stephens and Gee 1985). These units are characterised by quartzofeldspathic metapsammites, metapelites and quartzites, doleritic dyke complexes and amphibolites of extrusive origin; marbles, calc-silicate gneisses, graphitic schists and ultramafites are subordinate (Andreasson 1994 and references therein). Local sheeted-dyke complexes have been interpreted to represent ophiolites, derived possibly from the transition between continental and oceanic crust, and together with the extrusive rocks show a geochemical signature varying from that of MOR tholeiites to within-plate alkaline basalts. Included in this group is the Handöl ophiolite in central Sweden (Bergman 1993) and the Vågåmo ophiolite (Sturt et al. 1991) and supposedly correlatable ultramafic bodies at Feragen (Nilsson et al. 1997; Sturt et al. 1997) in south-central Norway. Some of the Seve metabasalts are intimately related to overlying thin marbles which have yielded Sr and C isotope compositions indicating a depositional age of 550–570 Ma (Trønnes 1994). This is in accordance with recent Sm-Nd dating of Seve dolerites which yields a crystallisation age of 573 ± 74 Ma (Andreasson 1994).

The Seve Nappes, together with parts of the *MA*, are generally more strongly deformed and metamorphosed (up to eclogite facies in northern areas) than tectonostratigraphically lower and higher units. Recent dating (see later) denotes that this is largely relatable to an early Caledonian (*Finnmarkian*) tectonothermal event.

The platform and its margin gradually became more stable during the Cambrian, with cycles of regional transgression and regression leading to gradual submergence. The latest Neoproterozoic (Vendian) quartz sandstones overlying the peneplaned crystalline basement were overlain by shallow marine quartz sandstones of Early Cambrian age. On parts of the shield, as in central Sweden, these Cambrian sediments are a few tens of metres thick, but they thicken southwards and eastwards, as well as westwards into the Caledonides, where they are intercalated with a variety of siltstone and shale members. The sandstones are usually glauconitic and phosphatic in their upper parts and are overlain in some areas by grey-green siltstone of Middle Cambrian age.

Submergence of the Baltic platform reached its culmination in the Middle Cambrian and earliest Ordovician with the regional development of highly bituminous shales, the Alum Shale Formation, deposited in a very stable, wide, shallow-marine epicontinental sea (Bergström and Gee 1985; Andersson et al. 1985). The youngest members of this formation, of Tremadoc age, extend eastwards into the Baltic states and southwards into Poland. The formation can be traced in allochthonous or parautochthonous units as far west as the present Norwegian Coast (Gee 1980).

Orthomagmatic Fe-Ti, Ni-Cu and PGE occurrences

The association of disseminated Fe-Ti oxides with mafic intrusive rocks of the Seiland Igneous Province (Fig. 3) has been recognised for a long time (e.g. Vogt 1902, 1910). Despite a large number of recorded claims (Poulsen 1964) and the existence of extensive impregnations with around 10% ilmenomagnetite (with up to 0.59% V) and 9% ilmenite (Geis 1971), the deposits have neither been exploited, nor subjected to detailed investigations. Work by Robins (1985) shows that the Fe-Ti oxides occur mainly as intercumulus and cumulus crystals in the middle and upper parts of subalkaline layered gabbros, where modal contents are up to 13% with 4–5% TiO_2. Apatite-rich ores are locally found in association with pegmatitic gabbros, nepheline-normative gabbros and carbonatites (V. Aggerholm personal communication 1982; Mørk and Stabel 1990; Robins 1985; Cadow 1993). Local, high contents of ilmenite + ilmenomagnetite (up to 20%) are found in the core of apatite-rich hornblende-clinopyroxenite dykes (50–100 cm wide) occurring along the margin of the Lillebukt carbonatite complex. The dykes which are surrounded by mafic fenites are thought to represent injections from an olivine melanephelinite magma undergoing fractional crystallisation (Robins 1985; Cadow 1993).

Pyrrhotite has been encountered as weak disseminations in mafic fenites, massive gabbros and in the lower cumulate sequences of layered gabbros and ultramafic intrusives with Alaskan-type affinities (Boyd and Nixon 1985). None of these has proved to contain economically significant concentrations of Ni, Cu or PGE, though grab samples from subalkaline gabbros and fenites locally contain up to 1 ppm PGE.

Carbonatite mineralisation of Nb, P, Th and Fe

Intrusive carbonatite-alkaline rock complexes dating from the period under consideration (latest Precambrian-Early Cambrian) are present both within the Caledonides and on the Baltic Shield to the east of the mountain chain. Such intrusions, forming the latest stages of magmatic activity in the SIP, have already been briefly referred to. Two other complexes of comparable age were emplaced in Precambrian rocks, at distances up to 150 km from the present Caledonian front, at about the same time.

The Fen complex (Fig. 3), on the margin of the Permian Oslo Paleorift, southwest of Oslo, consists of a composite central intrusion and numerous satellite intrusions (Bergstøl and Svinndal

1960) emplaced in Precambrian amphibolite facies gneisses and amphibolites. Carbonatites are the most abundant of the magmatic rocks exposed in the complex, making up 60% of the total outcrop area. Intrusive silicate rocks amount to less than 20% while metasomatised ('fenitised') country rocks make up the rest. Gravimetric surveys (Ramberg 1973) indicate that the presently exposed rocks are underlain at depth by a pipe-shaped body of dense mafic silicate rock of the type known as damtjernite (phlogopite-bearing alkaline lamprophyre) at least 15 km deep (see, i.e. Barth and Ramberg 1966). Both iron and niobium ores have been produced at various periods (Bjørlykke and Svinndal 1960; Bugge 1978). The *Fen* iron mines were worked from 1652 to 1957, yielding about 1 Mt of ore with 50% Fe, 0.45% P, 1–2 % Mn and 0.3% S. The ore, a fine-grained hematite, occurred in veins in an iron-rich variety of carbonatite known as rødberg (Andersen 1983). Niobium production from the *Søve* Mine took place between 1953 and 1965, and was based on a pyrochlore-bearing (0.5%) apatite-magnetite-calcite rock with minor amounts of pyrite.

The *Alnö* complex (Kresten 1986) on the east coast of Sweden has been of less economic interest, although carbonatites with up to 13% apatite have been reported (Grip 1978).

Orthomagmatic Cr ± PGE mineralisation

Chromite occurrences are found in several of the interpreted ophiolite fragments of the Seve Nappes. The *Feragen* area southwest of Røros contains the majority of previously exploited occurrences, situated in variably serpentinised dunite and harzburgite. The host rocks have been interpreted as representing cumulates (Moore and Hultin 1980); however recent investigations suggest that the Feragen complex is composed largely of mantle tectonites intruded by numerous dunitic dykes and veins (Nilsson et al. 1997). Chromite mineralisation is exclusively confined to the dunitic members, which can be followed along strike for more than 300 m. Within the dunite, chromite occurs as massive, or as 'leopard' (nodular), ore. The 235 occurrences which were exploited in the Feragen ultramafite body yielded a total production of 32 500 metric tonnes of ore. This represents about 90% of Norway's total chromite ore production (Poulsen 1960). The Feragen deposits have high Cr and low Fe values, but they are too small to be of economic interest today.

The majority of chromite occurrences at this general tectonostratigraphic level are smaller than those of the Feragen ultramafite bodies, and are mostly interpreted as having originated as podiform chromitites formed in magmatic feeders in mantle harzburgite (Vokes et al. 1991; Nilsson et al. 1997). PGE enrichments have been detected in several of the chromite occurrences. One podiform type mineralisation (Osthammeren), containing chromite with a very high Cr/Al ratio (8.6) which is strongly indicative of a mantle origin, also shows anomalous levels of Pt + Os + Ir + Ru(+ Rh) with total PGE contents ranging from 1 to 11 ppm in massive ore. The complex PGE mineralogy of the Osthammeren occurrences includes Os-laurite, irarsite and 15 other minor phases (Nilsson 1990).

Stratabound sulphides

The Seve Nappes contain a number of small, pyritic or pyrrhotitic Cu deposits with or without Zn. Many copper-rich deposits have been worked intermittently in the past but none of them is of any economic interest today. They are usually of the disseminated type, the subordinate massive varieties comprising very thin layers of sulphide and sometimes magnetite (Zachrisson 1980; Hill 1980; Stephens et al. 1984). In most cases mineralisation is clearly concordant to the layering or schistosity. The sulphides are associated with a variety of lithologies including metabasalts, mica-schists, calcareous meta-arkoses and phyllites, quartzites and graphitic phyllites. Thin carbonate lenses occur locally near the ores (Hill 1980; Sundblad and Stephens 1983). Copper/zinc ratios are variable but often high, and lead contents are very low with a few small exceptions. The largest deposits are found in the south-central Swedish part of the Caledonides (Zachrisson 1980, 1986a); the only one exceeding 1 Mt is the *Sylarna* occurrence, hosted by mica schists, comprising > 4 Mt of disseminated pyrite and pyrrhotite with about 0.4% Cu and 3% S over a thickness of 20 m.

Pb-isotope compositions of two deposits in Seve lithologies have been interpreted to reflect source rocks with relatively low Th/U ratios. Lower μ values in a volcanite-associated deposit than in a purely sediment-hosted one were ascribed to the lower U/Pb ratio of the source rock in the former (Sundblad and Stephens 1983).

Alum shales

The alum shales which were deposited on the Baltic platform have been long known to contain several heavy metals. The main lithology of the formation (Andersson et al. 1985) is a black shale with organic carbon contents of up to 20%, containing local interlayers of grey shale, siltstone and sandstone. Lenses and discontinuous beds of bituminous limestone as well as lenticular nodules and thin seams of organic matter ('kolm') are characteristic but generally subordinate members. Iron sulphides are present throughout the formation as nodules, thin bands and disseminations.

In general, the Alum Shale Formation has a thickness of about 20 m. Greater thicknesses (approaching 100 m) occur in the southernmost parts of Scandinavia and in parts of the Caledonides. In the latter areas, tectonic repetition undoubtedly plays an important role locally. The formation is remarkable for its chemical and mineralogical similarity over the whole region, though minor variations in facies allow subdivision into stratigraphic subunits. Its most diagnostic feature is an extreme enrichment of uranium, vanadium and molybdenum (Fig. 6).

Nordenskiöld (1893) reported the local occurrence of kolm lenses carrying up to 5000 ppm U. Later the abnormally high concentrations of metals such as V, Mo, Ni and some rare earths became obvious, revealing the shales as one of the greatest potential resources of these elements in Europe (see, e.g. Armands 1972; Gee 1972; Andersson et al. 1985). However, the elements of economic interest are seldom enriched together in the same stratigraphic unit or in the same area, a feature which has had a negative effect on the possibilities for economic exploitation.

The alum shales which have been of greatest economic interest in the past are found in the *Billingen-Fallbygden* area of southern Sweden. Relatively persistent beds of bituminous limestone or *stinkstone* have been used to divide the formation into three members (Fig. 6), of which the upper member has been worked in an open pit. This member is rich in organic carbon (14%) and pyrite (12%) and contains an average of 306 ppm U over 3.6 m including the kolm lenses and beds. Uranium is mainly associated with the organic matter but no discrete U mineral has been identified.

Continental margin – oceanic sequences of uncertain paleogeographic position

The Gula Nappe Complex (Gee et al. 1985) and the adjoining Støren Group, located in the Köli part of the *UA* in the Trondheim Region (Fig. 7), are both units of considerable areal extent and metallogenetic significance. A continental margin or shelf affinity, with continental crustal material present locally, has been suggested for the larger part of the Gula Complex *sensu stricto* and its equivalents further north (Guézou 1978; Stephens and Gee 1985; Billett 1987; Stephens and Gee 1989). On the other hand, parts of the Gula Complex contain clear oceanic lithologies, similar to those which are characteristic of the Støren Group. The paleotec-

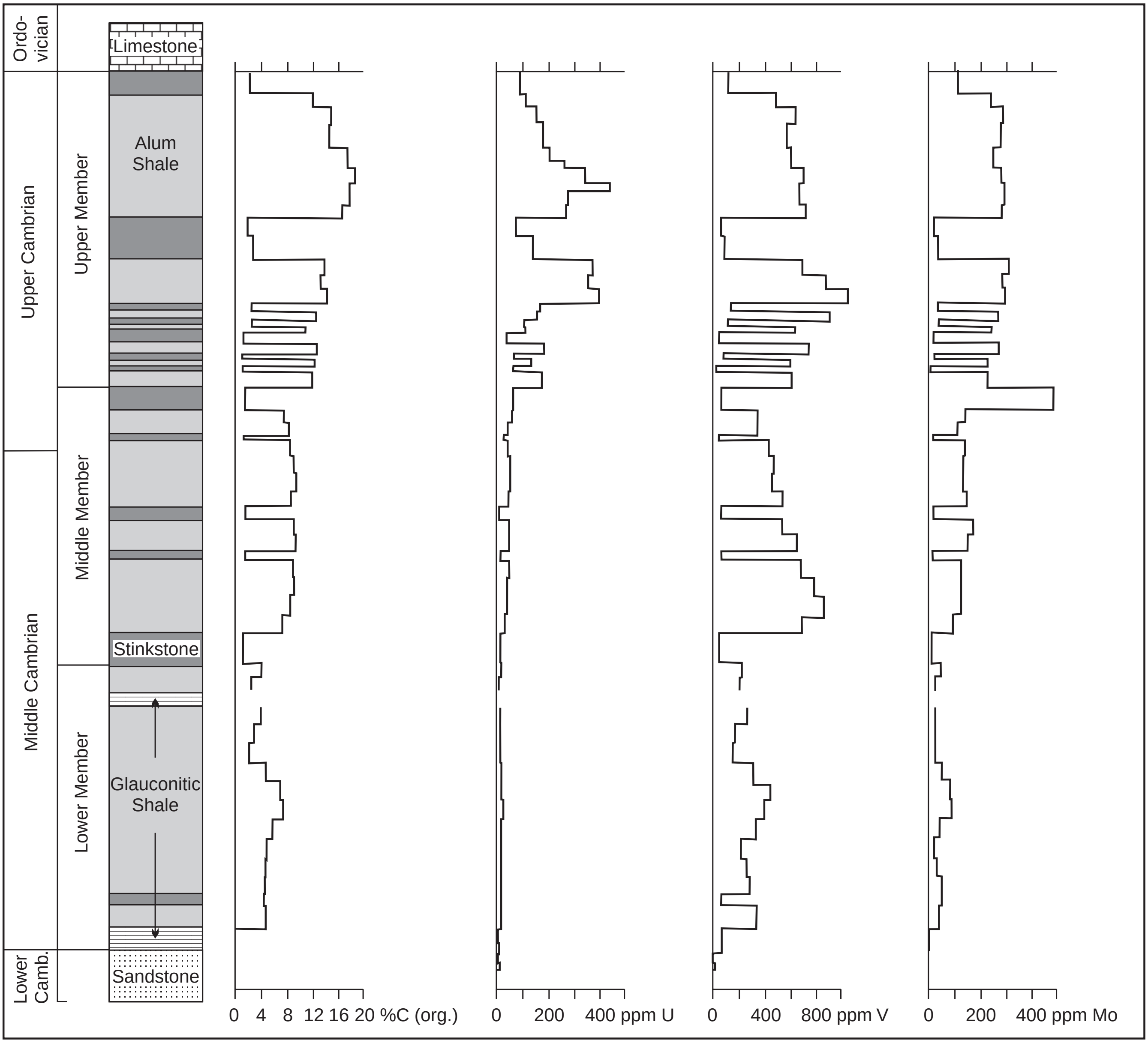


Fig. 6 Stratigraphic column through the alum shale formation in the Ranstad area, Sweden, showing variations in Mo, U, V and organic carbon contents. Modified after Andersson et al. (1985)

tonic and paleogeographic position of both these units is poorly constrained, but two settings have been advocated: either they represent fragments of the outermost parts of the Baltic plate margin and adjacent oceanic crust, implying correlation with the Seve Nappes as suggested by Bjerkgård and Bjørlykke (1994) and implied by Sturt et al. (1997) or, as suggested by Ihlen et al. (1997), they were related to a microcontinent situated close to the margin of Baltica. In our view, a direct link between Gula and Seve requires unrealistic, short-distance correlations between units that are lithologically contrasting. The schematic model in Fig. 2 is therefore based on the interpretation of Gula as representing a separate, microcontinental setting.

Present-day lithology of the Gula Complex (Fig. 8) includes quartzo-feldspathic to calcareous psammites and metapelites, as well as associated graphitic schists, banded quartzites (ribbon-cherts) and komatiitic to tholeiitic lava units together with minor, subvolcanic intrusive bodies. Alumina-rich metapelites and quartzite conglomerates are characteristic in parts of the complex (Guézou 1978; Nilsen 1978). Radiometric dating of an intrusive trondhjemite body (Stephens et al. 1985a) indicates a Middle Cambrian or older age of deposition for at least the central parts of the Gula Complex. The metamorphic grade varies from greenschist to upper amphibolite facies, with migmatites being common in the higher-grade parts.

The Støren Group *sensu stricto*, situated immediately west of the Gula Complex in the Trondheim Region, is a several km thick, submarine metabasalt-dominated, sequence with interlayered ribbon cherts, black shales and

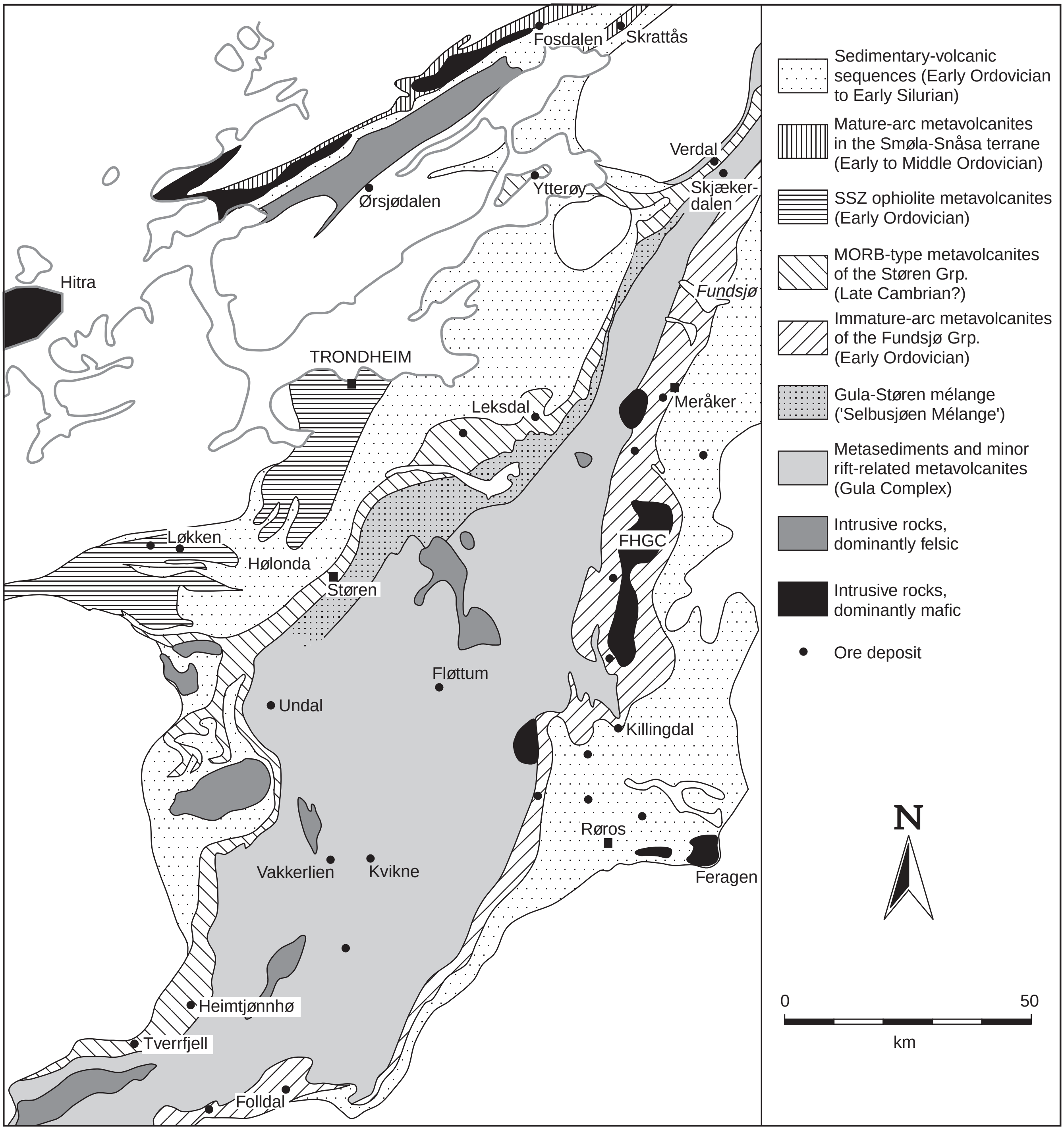


Fig. 7 Geological map and ore deposits/districts of the Trondheim Region, central Norway. *FHGC* = Fongen-Hyllingen Gabbro Complex. Geology from Sigmond et al. (1984)

mixed tuffaceous-cherty metasediments. Volcanite compositions range from MORB to WPB (Gale and Roberts 1974; Nilsen 1974; Grenne and Lagerblad 1985). In the northern parts of the Trondheim Region, rhyolitic volcanic rocks are locally abundant in lateral equivalents to the Støren Group. In one of these areas, on the island of Ytterøy (Fig. 3), a possible subvolcanic felsic intrusion has yielded a U-Pb zircon age of 495 ± 3 Ma (Roberts and Tucker 1998). The Støren Group is separated from the Gula Complex by a thrust contact (Gale and Roberts 1974); however lenses of Støren rocks occur also within a tectonic mélange, the *Selbusjøen mélange* of Horne (1979), in the western part of the Gula Complex.

Stratabound sulphides

In the Trondheim Region, the predominant ore type of the Gula Complex is massive, stratabound and often stratiform sulphides,

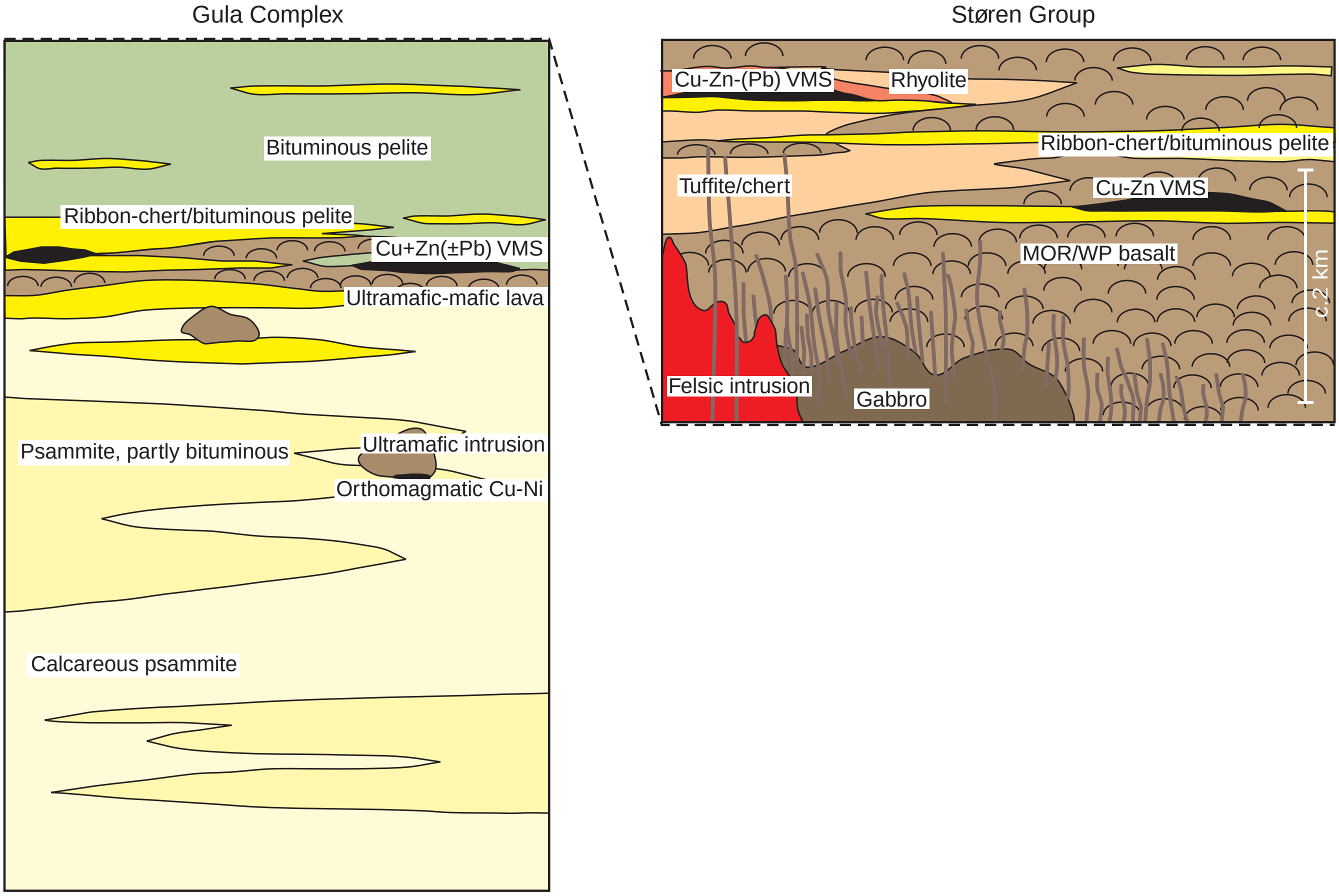


Fig. 8 Schematic, interpreted sections of the Gula Complex and Støren Group in the Trondheim Region, central Norway

generally confined to the level of komatiitic to tholeiitic lavas with associated graphite schists and ribbon-cherts (Nilsen 1978). They are hosted by metasediments at or close to the contact with the metavolcanic units or situated within the metavolcanites, forming lenticular and ruler-shaped bodies of massive or semimassive, coarse-grained pyrrhotite or pyrite. Known ores are relatively small (<0.4 Mt) and are often separated into several minor bodies arranged in an en echelon pattern. Cu/Zn ratios are variable but Cu-dominated ores seem to be most abundant (Nilsen 1978; Bjørlykke et al. 1980). The lead content is usually negligible, but may be significant locally, as in the *Fløttum* deposit. Gold and silver values of individual samples from eight selected deposits (Karlstrøm 1990) are mostly less than 0.2 ppm and 20 ppm, respectively.

None of the orebodies is of economic significance today; extensive exploitation of Cu-rich ores took place in the seventeenth to the nineteenth centuries and some deposits were worked for pyrite around the end of the nineteenth century. The most important deposits were those of the *Kvikne* area (Nilsen and Mukherjee 1972; Rui 1974) (Fig. 7). Iron-formations are abundant and are sometimes intimately related to the massive Cu-Zn deposits, occurring as 1–5 m thick, laterally extensive oxide/sulphide/silicate horizons characterised by enrichment of manganese (Nilsen 1978).

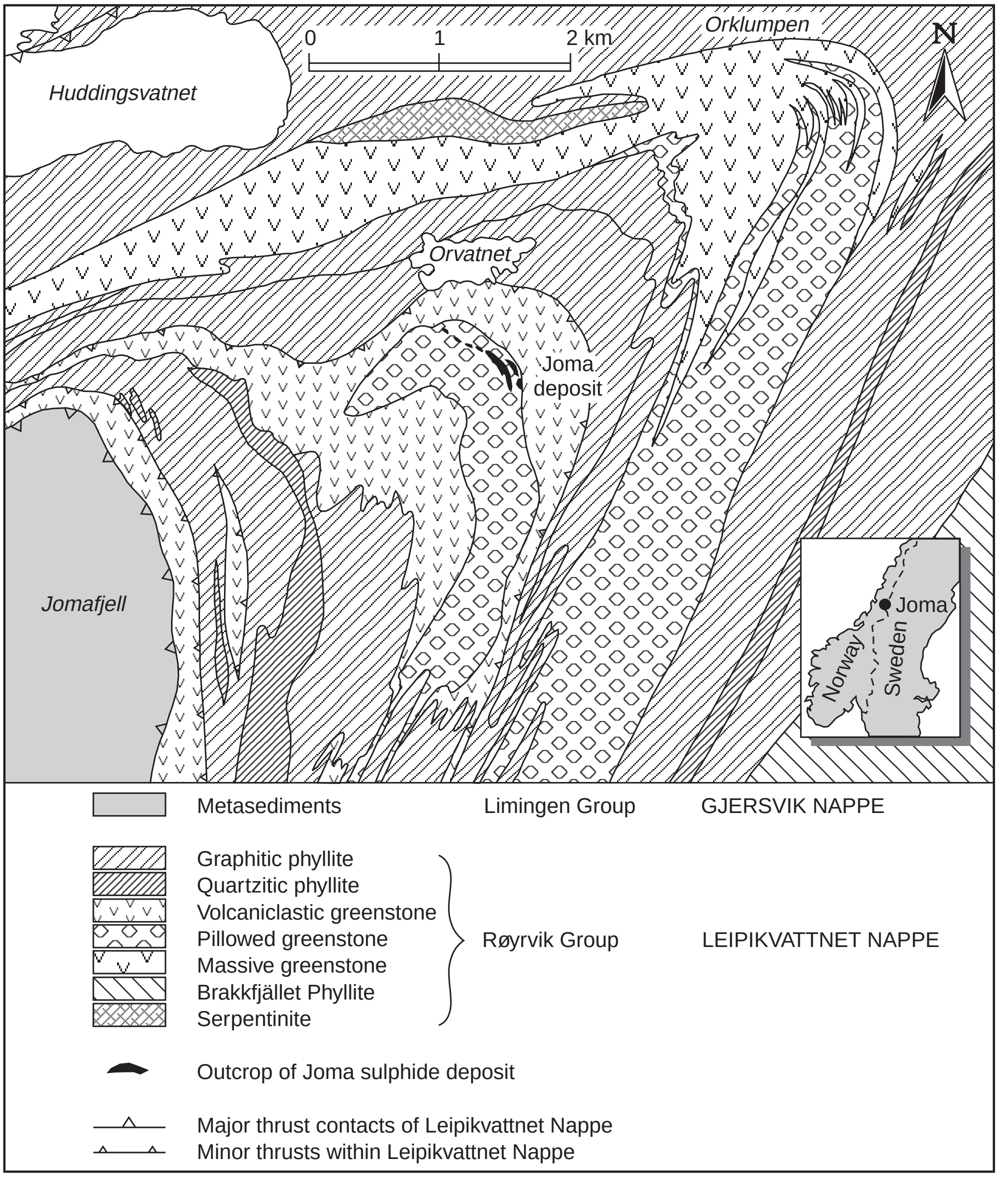
Stratiform mineralisation of greater economic interest is found in the basalt-dominated lithologies of the Støren Group and its equivalents. These Cu-Zn deposits have varying, but mostly low, Pb contents and often consist of a fine- to medium-grained, pyrite-dominated, sphalerite-chalcopyrite-bearing massive ore, stratigraphically underlain by a pyrrhotite-chalcopyrite feeder-zone ore. Carbonate is abundant in the matrix and also forms separate thin layers in the massive ore. In at least two of the major deposits (Tverrfjell and Joma), pyrite-sphalerite ore is underlain by Cu-rich massive ore with magnetite- and quartz-rich interlayers.

The *Tverrfjell* deposit in the southwestern part of the Trondheim Region (Fig. 7) was mined between 1963 and 1993, producing some 15 Mt of pyritic ore from an original reserve of about 19 Mt grading 1.0% Cu and 1.2% Zn and very little lead (Bjørlykke et al. 1980; Krupp and Krupp 1985). The deposit is situated in highly deformed mafic metavolcanites, closely associated with quartzites and green phyllites. A compositionally similar, but much smaller massive ore was worked at *Undal*, in a metabasaltic lens in the mélange zone between the Gula and Støren units (see earlier). Further north in the Trondheim Region, the *Mokk-Malså* (*Verdal*) and *Ytterøy* ore districts contain similar ore types, however with considerably higher Pb (and Ag) contents in some of the massive sulphide bodies. A distinguishing feature of this part of the Støren Group is a significant proportion of rhyolitic volcanites and felsic subvolcanic intrusions, a feature which may have contributed to the relatively lead-rich nature of these ores.

North of the Trondheim Region, massive sulphides comparable to those of the Støren Group are found at *Joma* (Fig. 9), in the eastern part of the Grong District. The approximately 22 Mt deposit contained 1.3% Cu, 1.7% Zn and minor amounts of Pb. The mine was closed in 1998 after 26 years of operation in which over 11.5 Mt at 1.49% Cu and 1.45% Zn, were processed out of the total geological resource (Arve Haugen, personal communication 1998). The deposit is hosted entirely by metabasalts (Reinsbakken 1986), which are thought to overlie, stratigraphically, banded partly graphitic, quartzites of possible pelagic origin (Reinsbakken and Stephens 1986) which pass further downwards into a sequence of graphitic phyllites and quartz-rich phyllites (Kollung 1979).

Further north, massive sulphide deposits at *Jofjället*, are found in a part of the Storfjället Nappe Complex which has been correlated with the Støren Group (Sandwall 1981a). The ores are situated in a sequence of pelitic, quartz-rich, graphitic and calcareous

Fig. 9 Geological map of the Joma area after Odling (1988)



phyllites or locally within metabasalts. They comprise subcircular, thin, pyrite-rich stratiform plates in the highly deformed sequence, enveloped by hydrothermally altered pelites. Sphalerite, galena and chalcopyrite are common constituents and lead contents are comparatively high (2–3%). The tonnage of individual orebodies is up to 0.5 Mt (Sandwall 1981b).

Similar ore types and settings are found in the Narvik Group in northern Norway, where minor Pb-rich massive sulphides occur in metapelites, and pyrite-dominated ores with subordinate Cu and Zn are associated with mafic metavolcanites. *Bjørkåsen*, belonging to the latter type, is the only deposit which has been of significant economic interest in this area (Foslie 1926). The deposit contained nearly 5 Mt of massive pyrite with low base metal contents.

Deposits of pyrite and/or magnetite are characteristic of the Støren Group, forming extensive and often well-laminated, layers with a thickness of up to a few metres. In the Norwegian mining terminology these units are known under the colloquial term *vasskis* (possibly derived from a German term introduced by the old Saxon mining officials, 'weiss-kies' or white sulphide, in contrast to the valuable, yellow, chalcopyrite-rich ore). The best-known and least-deformed are those at *Leksdal*, east-southeast of Trondheim, which include the type example of Carstens' (1923) 'Leksdal-type' mineralisation. Similar deposits were subject to trial production near Tverrfjell (Heimtjønnhø) and on Ytterøy. These deposits have very low base metal contents, typical Cu and Zn values being of the order of 100–300 ppm and 300–700 ppm, respectively (Sand 1986). Minor amounts of carbonaceous material are present with the sulphides. Sulphur isotope values are around –20‰ and indicate bacterial reduction of seawater sulphate. Primary soft-sediment deformation structures denote that sulphide deposition was in the form of a water-rich mud or gel on the sea floor.

The *vasskis* horizons are associated with graphite schists or banded quartzite within the basaltic sequence (Torske 1965). The quartzites locally pass into reddish jaspers probably representing recrystallised cherts. *Vasskis* horizons occurring in the stratigraphic upper parts of the metabasaltic sequence are characterised by abundant interlayers of magnetite-rich varieties which formed the basis for limited iron production in the seventeenth to the nineteenth centuries. Of the sulphidic types, only the Leksdal deposit itself has been worked for pyrite during a short period in the beginning of this century.

Orthomagmatic deposits

Minor ultramafic to mafic intrusive bodies in the Gula Complex often carry weak sulphide disseminations of pyrrhotite, chalcopyrite and pentlandite. The ultramafites are found either adjacent to the komatiitic to tholeiitic lava units, or as isolated bodies in the psammitic wall-rocks. A genetic link to the volcanites has been suggested by Nilsen (1974, 1978), the Ni-Cu-bearing bodies probably representing parts of a subvolcanic feeder system. Heavy sulphide disseminations have been exploited for copper in the past and more recently have been investigated for their nickel potential. The only deposit of possible economic significance so far investigated is the *Vakkerlien* prospect (Boyd and Nixon 1985) in the Kvikne area, some 100 km south of Trondheim (Fig. 7), which contains 0.4 Mt grading 1% Ni and 0.4% Cu.

Stage 2: plate convergence and ocean closure

Following the more than 100 Ma period of continent break-up and crustal extension, with development of passive continental margin sequences and a wide Iapetus ocean, the first record of major plate convergence is seen in an early Caledonian tectonothermal event in the Seve Nappes of the *UA* and in the *MA* in northern Scandinavia. Sm-Nd and Ar-Ar dating of eclogites in the Seve Nappes indicates a high-pressure metamorphism in the Late Cambrian (500–505 Ma). This has been interpreted to be due to subduction of the outer margin of Baltica under oceanic crust, and was followed by imbrication, uplift and eastward nappe translation above the platform margin (Andreasson 1994, and references therein). The term *Finnmarkian* (Sturt et al. 1978) is widely accepted for this early Caledonian orogenic event. An island arc is inferred to have existed above the subducting plate margin, but no remnants of this arc have so far been documented in the Scandinavian Caledonides.

The earliest *preserved* magmatic sequences of clear subduction affinity appeared in the earliest Odovician. The precise paleogeographic position of these has been a long-lasting matter of controversy in Scandinavian geology. An origin outboard of the Baltic margin is advocated by some authors for *all* the arc complexes (e.g. Roberts et al. 1985; Sturt and Roberts 1991). In contrast to this, arguments have been forwarded for subduction taking place only near the opposite, supposedly Laurentian, plate margin (e.g. Pedersen et al. 1992).

The present authors, on the basis of the combined evidence cited, prefer a model which is more in accordance with that of Stephens and Gee (1989), that immature, oceanic arc systems emerged outboard of both the Laurentian and the Baltic plate margins in the Early Ordovician (Fig 2). In our model, these arcs are represented, respectively, by the Stekenjokk-Fundsjø sequences in the middle part of the *UA*, and by various volcanic/plutonic complexes, including ophiolites, belonging to the upper parts of the *UA* in southwestern to central Norway, or to the *UmA* and possibly *UA* in northern Norway. While the Baltica-related arc apparently had a short lifetime in the Early Ordovician, the subduction system near Laurentia continued to evolve, with a changeover from oceanic to continent-margin type magmatism, throughout the Ordovician period. The lithologic and ore-genetic characteristics of these arc complexes are schematically shown in Fig. 10.

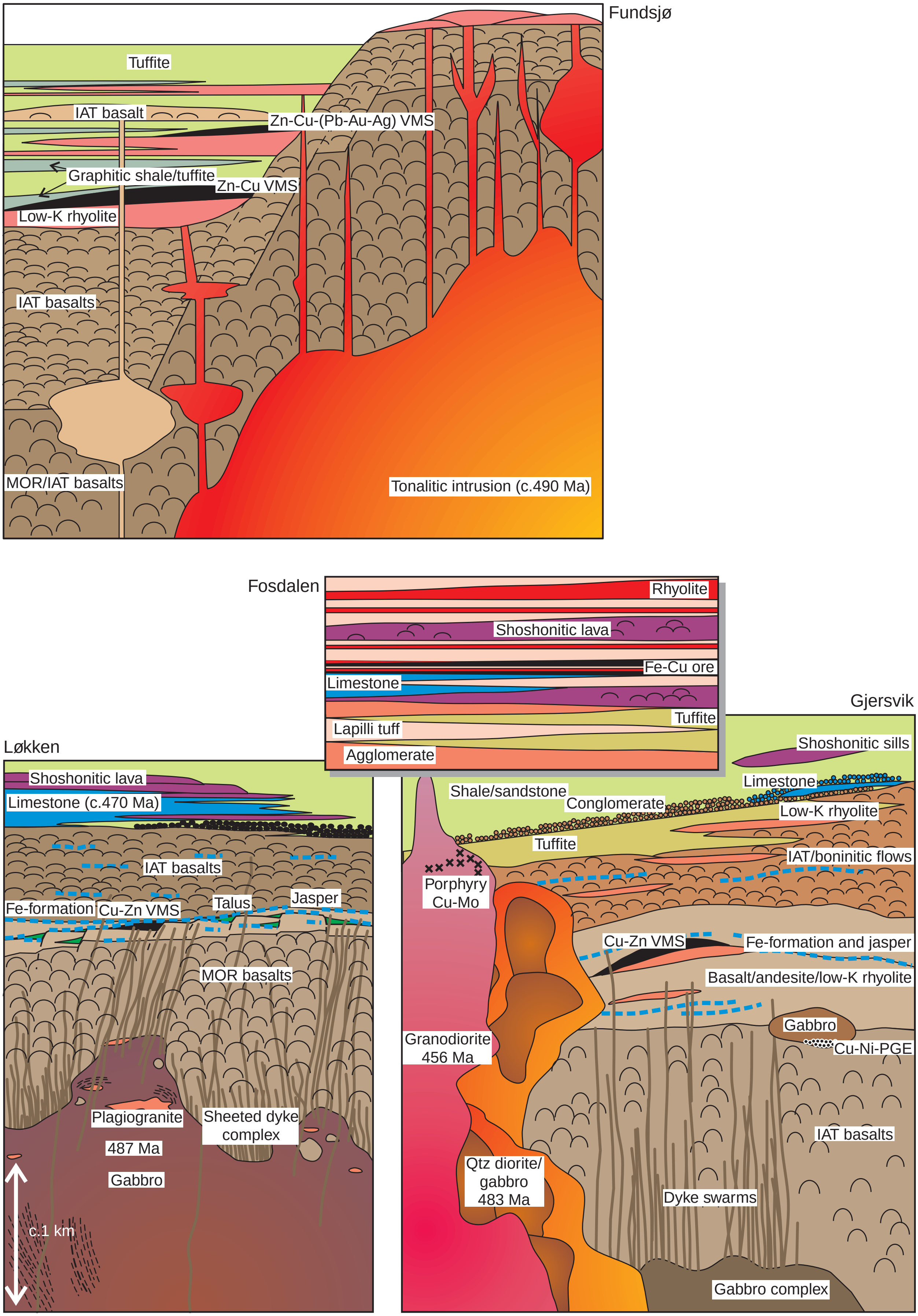
►

Fig. 10 Schematic, interpreted sections of arc-related sequences in the Scadinavian Caledonides. Immature arc of Baltic affinity in the Fundsjø Group, eastern Trondheim Region, Norway; SSZ ophiolite-immature arc of Laurentian affinity in the Løkken and Grong districts and mature arc in the Fosdalen district, central Norway

Several lines of evidence (see Stephens and Gee 1985; Torsvik et al. 1992, 1996; Pedersen et al. 1992) indicate that, by the end of the Ordovician, the Iapetus ocean had narrowed considerably and that Baltica had approached the Laurentian continent in an oblique manner. The first signs of collision-type interaction between Baltica and Laurentia is the Terråk orogenic phase as defined by Sturt and Ramsay (1994), when a number of different nappes containing Early to Middle Ordovician island arc and ophiolite sequences, was accreted and then intruded by granitic batholiths of Late Ordovician-Early Silurian age.

This initial collision between the Laurentian and Baltic continents was diachronous along the orogen through the Late Ordovician to Early Silurian. In the remaining, narrow ocean basin, the period was characterised by the deposition of thick, clastic sequences in fault-controlled basins with accompanying rift-related intrusive and volcanic activity. Contemporaneously, tectonomagmatic activity continued above the west-dipping, obliquely subducting, Benioff zone below the Laurentian plate margin with the formation of rift basins, ensialic arcs and granitic batholiths. In the following, this complex history of plate convergence and ocean closure, prior to the ultimate continent collision with the climactic phase of the Scandian Orogeny, is thus divided into five settings (Fig. 2):

1. Early Ordovician, immature arc/marginal basins outboard of Baltica (Stekenjokk and Fundsjø sequences)
2. Early Ordovician, immature arc/marginal basins outboard of Laurentia, with,
3. Overlying, Middle to Late Ordovician, volcano-sedimentary sequences and plutonic complexes of mature arc/marginal basin affinity
4. Late Ordovician to Early Silurian, magmatic and sedimentary development in the narrow, remaining ocean basin, related to initial collision of the Baltic and Laurentian plates, and,
5. Contemporaneous batholith development related to continued subduction beneath the Laurentian plate margin


Fundsjø
Tuffite
IAT basalt
Zn-Cu-(Pb-Au-Ag) VMS
Graphitic shale/tuffite
Zn-Cu VMS
Low-K rhyolite
IAT basalts
MOR/IAT basalts
Tonalitic intrusion (c.490 Ma)
Fosdalen
Rhyolite
Shoshonitic lava
Fe-Cu ore
Limestone
Tuffite
Lapilli tuff
Agglomerate
Løkken
Shoshonitic lava
Limestone (c.470 Ma)
IAT basalts
Fe-formation
Cu-Zn VMS
Talus
Jasper
MOR basalts
Plagiogranite
487 Ma
Sheeted dyke complex
Gabbro
c.1 km
Gjersvik
Shoshonitic sills
Limestone
Shale/sandstone
Conglomerate
Low-K rhyolite
Tuffite
IAT/boninitic flows
Porphyry Cu-Mo
Cu-Zn VMS
Fe-formation and jasper
Basalt/andesite/low-K rhyolite
Gabbro
Cu-Ni-PGE
Granodiorite 456 Ma
IAT basalts
Qtz diorite/ gabbro 483 Ma
Dyke swarms
Gabbro complex

Immature arc development near the Baltic margin

Various paleogeographic models have been suggested for the Stekenjokk and the correlatable (Grenne et al. 1995) Fundsjø sequences; the latest models, based partly on Pb isotope interpretations, favour an oceanic setting near the Baltic margin (Bjørlykke et al. 1993; Ihlen et al. 1997). A paleogeographic setting near the Baltic margin is also supported by the composition of graphitic phyllites associated with the Stekenjokk volcanites, which are geochemically similar to the Alum Shales found on the Baltic platform (Sundblad and Gee 1985).

The contact between the Fundsjø and Stekenjokk metavolcanites and the structurally overlying Gula Unit is controversial: a primary stratigraphic contact, with the upper part of Gula constituting a sedimentary substratum to the magmatic sequence (Sturt et al. 1997), as well as a major thrust contact (e.g., Gee et al. 1985) have been inferred. The present authors would strongly advocate a thrust contact. Several arguments are in favour of this: detailed studies in the Meråker area (Grenne et al. 1995) have shown the existence of a significant mylonite zone at the contact; it is unreasonable to assume that the several-kilometre-thick volcanic-plutonic Fundsjø Group was deposited stratigraphically above the sedimentary Gula sequence without leaving traces of relatable feeder intrusions in the latter; and the petrochemical characteristics of the Fundsjø Group imply a purely oceanic setting which is in strong contrast to the model forwarded by Sturt et al. (1997).

The bimodal volcanic sequence informally termed the Stekenjokk Quartz-keratophyre Formation (Zachrisson 1969) has been interpreted to represent the back-arc side of an island arc (Stephens 1982); a felsic, probably co-magmatic, intrusion dates the volcanic sequence to 492 ± 1 Ma (U-Pb in zircon, Claesson et al. 1988). The sequence is regionally overturned, the stratigraphic base of the magmatic rock pile being marked by an abrupt lithological change into underlying phyllites (partly graphitic), quartzites, limestone, metabasalt (MORB to WPB type) and quartzite conglomerate of the Remdalen Group (Stephens 1986) which is, in the present account, considered to be an equivalent of the Gula Unit (see above).

The lithology of the strongly deformed, about 650 m thick, Stekenjokk Quartz-keratophyre Formation (Zachrisson 1986b) is dominated, in the lower part, by co-magmatic extrusive and intrusive felsic rocks with subordinate mafic intrusions. This grades upwards into a sequence of interlayered quartz-keratophyres and mafic metavolcanites, interpreted as representing vitric-crystal felsic tuffs deposited mainly as submarine ash flows, and extrusions and subvolcanic intrusions, respectively (Stephens 1982). A graphitic phyllite unit and an overlying sequence of well-banded felsic-mafic rocks constitutes the upper part of the volcanic formation.

A generally similar stratigraphy (Fig. 10) has been established further south, in the Fundsjø Group of the Meråker-Folldal area (Grenne and Lagerblad 1985; Grenne 1988; Bjerkgård and Bjørlykke 1994). Recent studies in the Meråker area where deformation is in places less intense, has led to the following, simplified, evolutionary model for the up to 8 km thick, volcanic-plutonic, sequence (Grenne et al. 1995):

1. Accumulation of a thick pile of submarine basalts of primitive IAT geochemical signature
2. Intrusion of large volumes of felsic magma of immature arc signature, and extrusion of cogenetic tuffs and submarine flows of low-K rhyolitic composition. Contemporaneous development of intra-arc basins
3. Deposition of reworked volcanic material as felsic to mixed felsic-mafic, partly graphitic, tuffites in euxinic basins, with continued, local, volcanism producing primitive IAT basalts and low-K rhyolitic tuffs

Stratabound sulphides

Massive sulphides are very frequent along the more than 300 km-long Fundsjø, and the 150 km-long Stekenjokk, volcanic units (Fig. 3). However, a tendency to clustering is evident in certain areas, such as (from north to south) the Stekenjokk, Meråker, Ålen and Folldal districts. The biggest deposit is the *Stekenjokk* orebody (worked from 1975 to 1988) containing originally about 26 Mt of ore averaging about 1.3% Cu, 2.9% Zn, 0.3% Pb, 50 ppm Ag and 0.3 ppm Au (see, e.g. Zachrisson 1971, 1984, 1986b; Juve 1977). Five ore-bodies in the Fundsjø Group contained individual tonnages of about 3 Mt (Bjørlykke et al. 1980), the most important ones being those of the Folldal district (Foslie 1926; Page 1963; Pedersen 1979; Bjerkgård and Bjørlykke 1996) and the *Killingdal* deposit (Rui 1973).

Zn-dominated, partly very Zn-rich, ores are a general feature of the Stekenjokk-Fundsjø zone. Lead contents are low, but average values between 0.2 and 0.4% are found in a number of deposits. Gold and silver are quite variable: average values of the order of 1–2 ppm Au and 50–100 ppm Ag have been found in a few deposits in the *Meråker* area (Grenne et al. 1995); the Stekenjokk and some of the Folldal ores are also relatively enriched in the precious metals (Zachrisson 1986b; Karlstrøm 1990).

The massive sulphides occur as highly deformed sheets or rulers conformable to layering in the host rocks. Much of the present morphology is obviously controlled by tectonic deformation, although for the Stekenjokk deposit a primary length of more than 10 km and a width ranging from 100 to 700 m has been suggested on the basis of pre-deformation reconstruction (Zachrisson 1984). Sulphide disseminations associated with chlorite-quartz and quartz-sericite alteration of stratigraphic foot-wall volcanites are common and the majority of investigated deposits can be regarded as being proximal relative to their hydrothermal feeder conduits. Studies in the Meråker area (Grenne et al. 1995) indicate that the most important ore-forming event was the intrusion of large bodies of felsic magma into the pre-existing basaltic lava pile. The ores are intimately associated with felsic effusives related to this event, locally occurring also within the overlying tuffites; an intense hydrothermal activity induced and driven by the large volumes of cooling felsic magma is inferred. The geology of the major Stekenjokk deposit is in accordance with this general model, being located at the contact between predominantly felsic volcanic rocks and an overlying graphitic phyllite unit which passes further into a tuffitic sequence.

The deposits of the Stekenjokk-Fundsjø successions yield an array of Pb isotope compositions, ranging from the mantle curve to the orogen curve of Zartman and Doe (1981) and showing a considerable spread of μ values (Sundblad and Stephens 1983; Bjørlykke et al. 1993; Bjerkgård and Bjørlykke 1996). The data have been interpreted as indicating hydrothermal leaching of mixed mantle lead and lead from sediments derived from a Baltic crustal source.

Immature arc sequences-SSZ ophiolites of Laurentian affinity

The immature arc-SSZ ophiolite sequences represent, together with the immature arc sequences of the Stekenjokk-Fundsjø terranes, one of the most fertile of the paleoenvironments hosting massive sulphides in the Scandinavian Caledonides. In addition the sequences also host a number of mineralisation types of magmatic origin such as PGE associated with chromite or Ni-Cu sulphides.

Sequences which can be included in this group are extensively developed in the Karmøy-Bømlo-Bergen area in southwest Norway, in the Løkken-Hølonda area, in the western Grong District, on the island of Leka in central Norway, and the Lyngen peninsula in northern Norway (Fig. 3). Comprehensive data on the evolution of these sequences have been gathered since the early recognition of dismembered ophiolites in the Caledonides in the late seventies (e.g. Furnes et al. 1980; Grenne et al. 1980; Prestvik 1980). It is commonly accepted now that most of the ophiolites considered here were formed at spreading axes positioned above subduction zones, as the results of back-arc spreading or arc rifting, and thus fall within the category of supra-subduction zone (SSZ) ophiolites (Furnes et al. 1988; Grenne 1989a; Pedersen and Hertogen 1990). In the Løkken-Hølonda area, one of these terranes contains a fossil fauna of Laurentian affinity. Coupled with an overall correspondence with processes and timing of events in ophiolite-arc successions of the Newfoundland Appalachians (Dunning and Pedersen 1988), this has been taken to suggest an origin close to the Laurentian margin in Early Ordovician times (e.g. Stephens and Gee 1985; Pedersen et al. 1992).

The lithology of these sequences is variable. The ophiolites are partly represented by lower units, such as on Leka where mantle harzburgite and dunite are overlain by ultramafic cumulates, layered and variably-textured gabbro and higher sheeted dykes and pillow lavas (Prestvik 1980; Furnes et al. 1988). In other ophiolite fragments, like those in the western Trondheim Region (Grenne et al. 1980; Roberts et al. 1984; Heim et al. 1987; Grenne 1989a) only their upper parts are preserved, comprising gabbros which pass upwards into a 1 km-thick sheeted dyke complex and an overlying, more than 1 km thick volcanic sequence of submarine basalts.

The metallogenetically most important of the SSZ ophiolites is found at Løkken (Fig. 11). Grenne (1989a) divided the 1–2 km thick, regionally inverted, but generally little deformed, volcanic stratigraphy into the following units (Fig. 10):

1. An approximately 1 km thick Lower Volcanic Member (LVM) comprising a monotonous pile of basaltic pillow lavas and hyaloclastites of N-type MORB compositions, deposited in a fairly deep marine setting. The basalts pass downwards into a sheeted dyke complex.
2. A Middle Volcanic Member (MVM) composed of massive and subordinate pillow basalts thought to represent voluminous eruptions at high flow rates, fault-scarp-related talus and thick jasper beds. Intermediate lavas were erupted locally and can be related to the N-MORB-type parent magmas of the MVM basalts. A co-magmatic plagiogranite has given a U-Pb zircon age of 487 ± 5 Ma (Dunning and Grenne, unpublished data).
3. A variably thick Upper Volcanic Member (UVM) of essentially basaltic pillow lavas and massive flows with local rhyolitic effusives interpreted as submarine flows. The basalts are of transitional MORB-IAT type and are interlayered with pillow breccias, local jasper beds and mixed sulphide/oxide/silicate iron-formations (*vasskis*).

The upper lavas of the UVM interdigitate with coarse conglomerates and sediments derived essentially from the volcanic complex, probably reflecting a rapid uplift of the oceanic crust. In the Hølonda area, this is followed upwards by limestones, shales and highly evolved, arc-related volcanic rocks (see later).

In contrast to the SSZ ophiolites, the associated arc sequences are characterised by abundant felsic volcanites together with subordinate intermediate types, forming lavas, pyroclastic-flow deposits, crystal tuffs and various volcaniclastic deposits such as at Bømlo in southwest Norway (Nordås et al. 1985). The relative proportions of these and of mafic members are highly variable although mafic volcanites are in general volumetrically predominant. The metallogenetically most important of these is the immature arc sequence of the Gjersvik Group (Fig. 10) in the western Grong District (Fig. 12). This is composed of volcanic and intrusive rocks, unconformably overlain by conglomerates and calcareous psammites of the Limingen Group. A minimum age of the metavolcanites is given by a tonalitic intrusion dated at 483 ± 4 Ma (Stephens et al. 1993).

The supposed stratigraphic base of the regionally inverted sequence comprises strongly tectonised metabasites (Lutro 1979) of uncertain origin. These are found near the major thrust contact to the structurally overlying *UmA*, and pass stratigraphically upwards in the regionally inverted sequence into moderately deformed, lower greenschist facies rocks typical of the Gjersvik Group. The low-grade part of the Gjersvik sequence can be subdivided into three major stratigraphic units (Reinsbakken 1992):

1. A lower unit comprising massive and pillowed lavas of basalt to basaltic andesite composition.
2. A very heterogeneous middle unit composed of feldspar-phyric rhyodacite flows and pyroclastites at the base, followed by ferrobasalts and basaltic andesites forming massive and pillowed flows and hyaloclastites. Extensive exhalite beds are abundant (Halls et al. 1977) and include laminated chert-magnetite-carbonate-rich sediments and banded pyrite + magnetite + Fe-silicate + chert horizons (*vasskis*). The

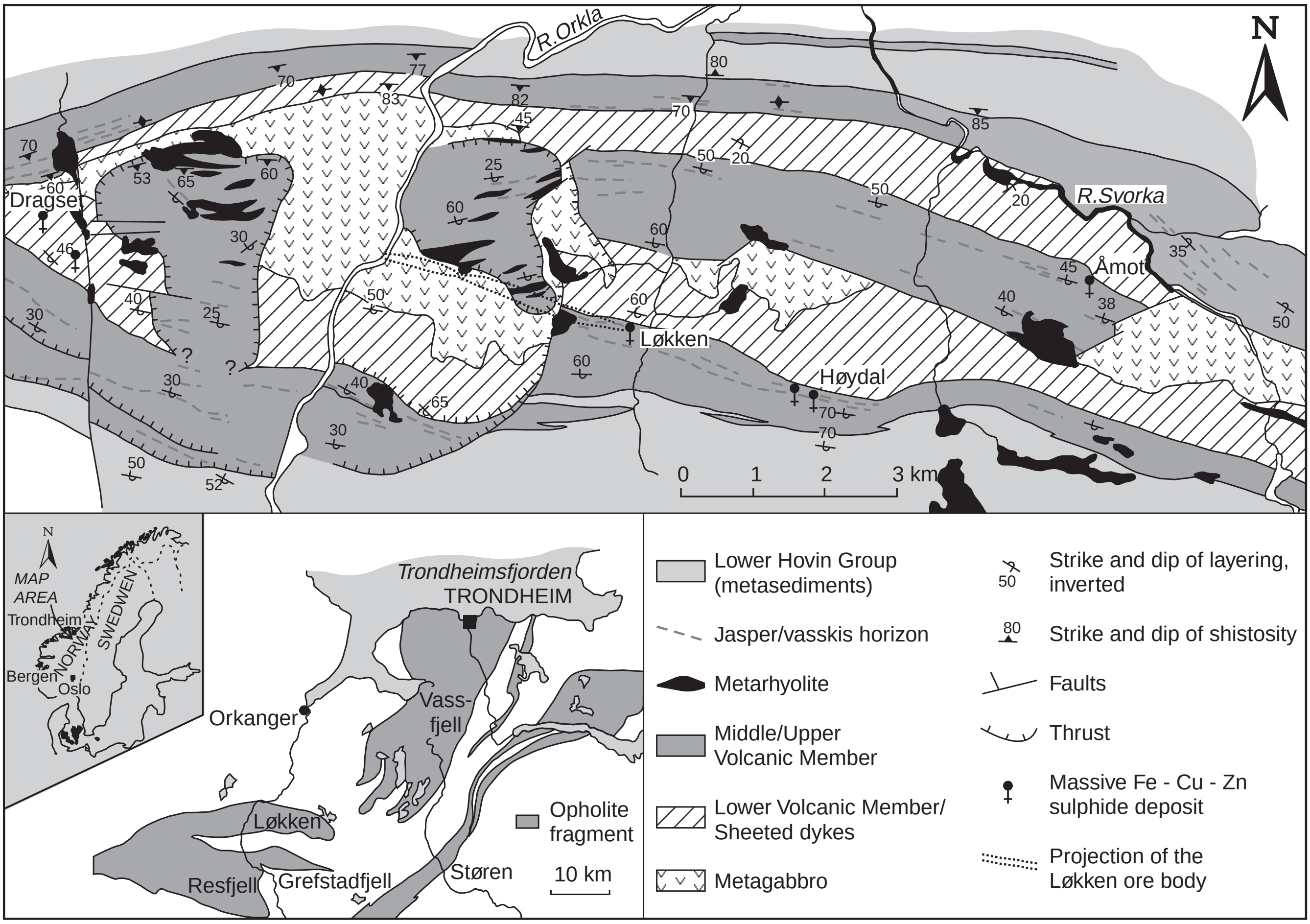


Fig. 11 Geological map of the Løkken Ophiolite, western Trondheim Region, showing main VMS ores. After Grenne (1989a)

middle volcanic unit was apparently related to underlying dyke swarms or local sheeted dyke complexes which pass further downwards into gabbros.

3. An upper unit comprising primitive, pillowed and massive tholeiitic basalts and local boninites, with interlayers of quartz-phyric rhyodacite or rhyolite flows and tuffites.

Gabbroic to tonalitic bodies are abundant and are interpreted as subvolcanic intrusives related mainly to the middle volcanic unit. The entire volcanic-plutonic complex was later intruded by numerous, and often large, mafic to felsic magmas of mature arc affinity (see later). Available geochemical data indicate an affinity to a subduction setting for the whole metavolcanic sequence (Reinsbakken 1992). The lower unit is thought to be related to the early stages of ensimatic arc construction, whereas the middle and upper units formed in response to rifting processes within the arc complex.

Stratabound sulphides

By far the biggest of the immature arc-SSZ ophiolite-related massive sulphides is the pyritic Cu-Zn deposit at *Løkken* (Vokes 1960; Grenne et al. 1980; Grenne 1986), which contained an original tonnage in the order of 30 Mt grading 2.3% Cu, 1.8% Zn, 0.02% Pb, 16 ppm Ag and 0.2 ppm Au. The orebody was the biggest ophiolite-hosted VMS deposit known in the world and perhaps the most important of all deposits in the Scandinavian Caledonides, and was mined over a period of 333 y between 1654 and 1987, cumulative production exceeding 24 Mt (Vokes 1996). Comparable but smaller deposits are known at Vigsnes (Foslie 1926; Bjørlykke et al. 1980) in the Karmøy ophiolite in southwest Norway. Altogether, six known deposits fall in the 1–10 Mt class, but most of the known deposits are less than 1 Mt. Several of these have been subject to exploitation in the past.

The ophiolite-hosted massive sulphide ores show many compositional features and primary structures similar to those of recent sulphides deposited on the modern ocean floor, such as colloform textures and sedimentary talus breccias. Stockwork feeder-zone mineralisation, with associated chloritic alteration, always occurs directly below the massive ore. At Løkken, the main sulphide mass had the form of an elongate body with a total length of about 4 km, an average width of between 150 and 200 m and an average thickness of about 50 m, a morphology which can be ascribed to primary features such as subparallel sea-floor faults and an extensive, fissure-related, hydrothermal vent system (Grenne 1989b; Grenne and Vokes 1990). Lead-isotope analyses (Bjørlykke et al. 1993) are consistent with the geochemistry of the igneous host rocks, denoting derivation from a mantle source.

Abundant jaspers, consisting essentially of silica with up to 20% microcrystalline hematite, are intimately associated with the Cu-Zn bearing pyritic ores and may be of more distal and/or lower-temperature hydrothermal origin. They can be followed along strike for several kilometres, forming lenses or discontinuous layers with thicknesses locally exceeding 10 m. In the upper part of the MVM there are also iron-formations of the *vasskis* type (see earlier),

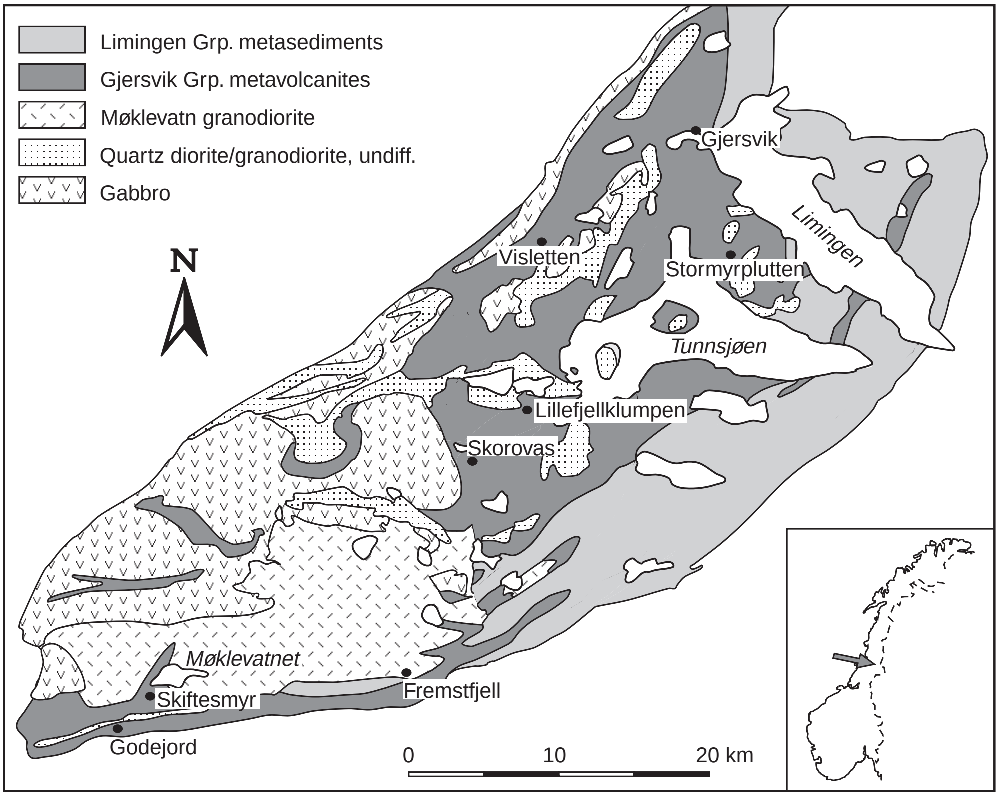


Fig. 12 Geological map and ore deposits of the Gjersvik Nappe in the Grong District, north-central Norway

forming extensive horizons with a thickness of 0.5 to 3 m. Locally, such iron-formations rest directly upon massive sulphide ore; their precise mode of deposition is as yet unknown, although some sort of hydrothermal-exhalative origin seems inevitable in view of their spatial relationship to the massive sulphides (Sand 1986).

In the Gjersvik Group arc sequence (Fig. 12), massive sulphide deposition is largely confined to the middle volcanic unit, i.e. the early stages of rifting of the oceanic arc. There is a close spatial relationship between the ores and the andesitic and rhyodacitic metavolcanites. Several deposits of the order of 1 to 10 Mt are found in the area, including Skorovas, Skiftesmyr, Visletten, Gjersvik and Godejord. Their compositions range from pyritic Cu-Zn types similar to those of the SSZ ophiolites, to Zn-dominated Zn + Cu ± Pb ores. Zonation is observed in some of the deposits, showing a pyritic ore with variable Cu contents overlying a stockwork feeder zone, and with upper and peripheral parts characterised by Zn and local Pb enrichments. Pb isotope compositions of the massive sulphides are close to mantle values and only slightly enriched in radiogenic lead compared to the ophiolite-hosted ones, a feature which is in accordance with the primitive nature of the ore-hosting magmatic sequence. The *Skorovas* deposit (Halls et al. 1977; Reinsbakken 1980, 1992) was the biggest deposit in the Gjersvik Group, containing about 10 Mt of massive and minor disseminated pyritic ore averaging 1.0% Cu and 1.5% Zn with relatively low contents of Pb, Ag and Au. The Gjersvik deposit to the northeast, which was worked between 1993 and 1997, provided about 0.5 Mt of supplementary feed to the Joma mill. Calculated reserves were roughly 1.6 Mt at c.1.7% Cu and 1.0% Zn (company figures, Arve Haugen, personal communication 1998).

Distal exhalites are characteristically associated with VMS ores in the ophiolite-hosted as well as in the arc-related sequences. They comprise layers of jasper, consisting essentially of silica with up to 20% microcrystalline hematite, and sulphide/oxide/silicate/carbonate iron-formations of the *vasskis* type (see earlier), forming horizons which occur on top of and extend laterally from the massive sulphides and can be followed along strike for several kilometres (Halls et al. 1977; Sand 1986).

Orthomagmatic mineralisation

Known magmatic ores in the Early Ordovician immature arc-SSZ ophiolite setting are confined to two main types:

1. PGE mineralisation in ultramafic cumulates in the basal parts of ophiolites
2. Cu-Ni-PGE mineralisation in isolated, minor mafic intrusions in the higher parts of the plutonic-volcanic complexes

The former type has been the object of recent detailed investigations in the *Leka* ophiolite (Fig. 13). Here, several stratiform Pt and Pd enrichments occur within the layered ultramafic series. Cyclic chromite-rich horizons show a minor enrichment of Os + Ir + Ru (IPGE), whereas higher-grade Pt + Pd enrichment is found up to a few metres above the chromitite horizons. Fractionation of the PGE probably occurred due to crystallisation of IPGE-enriched chromite en route from the depleted mantle to the magma chamber. This process is reflected in very small and economically insignificant enrichments of up to 8 ppm PGE + Au in chromite-rich central zones of minor dykes, veins and tabular bodies of dunite and pyroxenite situated in mantle harzburgite (Pedersen et al. 1993).

The more extensive and interesting cumulate-hosted Pt + Pd enrichments were formed by exsolution of PGE-rich immiscible melts of base-metal sulphides, alloys and/or platinum group minerals immediately after influx of parental magma into the magma chamber. Individual horizons are up to 1.5 m thick and can be traced laterally for at least 1.5 km, with PGE + Au contents up to 1 ppm over 1 m intervals. The PGE enrichments are locally associated with trace levels of sulphide but with insignificant base metal enrichment (Pedersen et al. 1993). Pt + Pd + Au enrichments comparable to the cumulate-type PGE mineralisation at Leka have been detected also in the Lyngen Ophiolite associated with a more significant enrichment of copper-bearing sulphides (Vokes et al. 1991).

Minor gabbro bodies situated in the volcanic sequence of the Gjersvik Group in the Grong District contain massive or disseminated sulphides with significant PGE + Au enrichment in the small

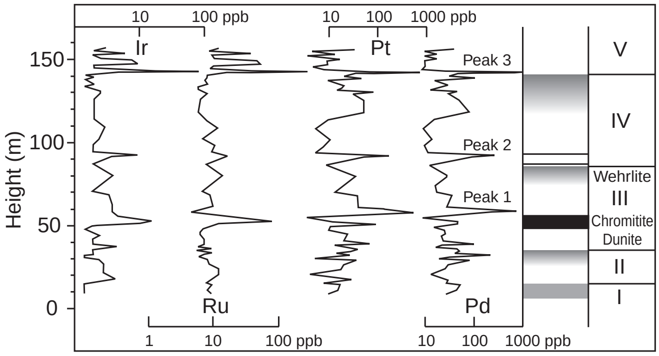


Fig. 13 Stratigraphic variation in iridium, ruthenium, platinum and palladium across a part of a sub-zone of olivine cumulates in the Leka Ophiolite, central Norway. Macrorhythmic units are marked *I – V*. Simplified after Pedersen et al. (1993)

Lillefjellklumpen and *Stormyrplutten* occurrences (Grønlie 1988; Larsen and Grenne 1995). A similar mineralisation, the *Fæøy* deposit, is found in the sheeted dyke complex of the Karmøy Ophiolite (Foslie and Høst 1932). The occurrences contain Cu and Ni in highly varying proportions and levels, but all three have similar, Pt-Pd-dominated, noble metal patterns. PGE + Au contents of the order of 5 ppm are typical of massive varieties. Sperrylite is the dominant Pt mineral, together with a wide range of Pd minerals.

Recent investigations at Stormyrplutten (Larsen and Grenne 1995) shows a 7 m thick mineralised zone, comprising essentially disseminated sulphides, and local, thin, semimassive bands or layers. The richest part contains about 2 ppm total PGE, 3% Cu and 0.3% Ni over a 1.5 m thick interval. A vertical section through this occurrence displays an upwards decrease in the Pt and Pd contents of the sulphide phase, which is thought to have exsolved from the parental melt in an open magmatic system with repeated periods of magma replenishment.

The gabbros which host the Cu + Ni + PGE in the Gjersvik Group have a boninitic geochemical signature which suggests that they formed part of the feeder system to the upper volcanic unit (Larsen and Grenne 1995). The Fæøy deposit is also intimately associated with high-Mg mafic dykes of boninitic affinity (R.B. Pedersen personal communication 1994), indicating a common origin for these deposits during arc rifting.

Mature arc development

Mature arc lithologies are confined to the sequences stratigraphically overlying the immature arc-SSZ ophiolite complexes of Laurentian affinity (Fig. 2). These volcanic-sedimentary sequences and their plutonic counterparts are most extensively developed in the Hølonda and Smøla-Snåsa districts of central Norway, and in association with the southwest Norwegian ophiolites (the Karmøy-Bømlo-Hardanger area). The underlying oceanic arc and ophiolite complexes, where preserved, show evidence of uplift and erosion and in some places inversion, prior to subsequent mature arc development, a feature which may be ascribed to accretion of the oceanic complexes on to the Laurentian plate margin in Arenig times (Grenne and Roberts 1998).

The mature arc sequences of this stage, at least as far as the important ore-hosting units in central Norway are concerned, are generally of the shoshonitic to high-K calc-alkaline association; however, MORB-type tholeiites and alkali basalts also occur and indicate a complex history of the mature arc-arc basin system (Roberts 1980; Pedersen and Hertogen 1990; Grenne and Roberts 1998). U-Pb zircon and fossil ages from such sequences in southwest Norway and the Hølonda and Smøla-Snåsa terranes (Pedersen et al. 1992; Grenne and Roberts 1998, and references therein) suggest that this type of volcanism was active in Arenig-Early Llanvirn times (c.480–470 Ma) and that felsic-dominated intrusive activity continued at least through the Middle Ordovician. These volcanic rocks and felsic intrusions are unconformably overlain by assumed Silurian sequences.

The lithology of the mature arc sequences is highly variable. Those of the Bømlo-Hardanger region in southwest Norway comprise predominantly subaerial lavas of basaltic to intermediate composition along with abundant felsic pyroclastic rocks often in the form of welded ash-flows and thick pyroclastic flows (Nordås et al. 1985). Sedimentary units are subordinate. Further south, a several thousand metre thick volcano-sedimentary sequence on Karmøy is thought to be an arc-basin equivalent to the mature arc development (Sivertsen 1992).

In the Løkken-Hølonda district in the western Trondheim Region, shoshonitic lavas of mafic to intermediate composition formed local islands, with surrounding shallow, carbonate-rich shelves, in a dominantly sedimentary basin characterised by rapid facies changes (Bruton and Bockelie 1980; Roberts et al. 1984; Grenne and Roberts 1998). The mixed sedimentary-volcanic succession, which contains a varied fauna of Laurentian affinity, rests upon the Løkken SSZ ophiolite (Grenne 1989a).

Further west and north, the Smøla-Fosdalen-Snåsa region contains thick volcanic sequences (Fig. 10) of similar shoshonitic basalts and andesites as well as large volumes of rhyolite, forming lava flows and pyroclastic deposits (Roberts 1980, 1982; Smith 1995). In the northeastern part of this volcanic belt, Roberts (1982) interpreted MORB-WPB-type basalts, which were supposedly overlying the shoshonitic volcanites, as reflecting a change-over from normal subduction-related magmatism to that of extensional processes.

Stratabound mineralisation

In southwest Norway, several small (< 1 Mt) stratiform deposits in the Varaldsøy-Ølve area in the Hardanger district, seem to be related to this setting, occurring as extensive, banded, horizons up to a few metres thick in close association with felsic units (Foslie 1926, 1955). Modern investigations are lacking, but the ores are known to be pyrite-dominated with varying but generally rather low Cu and Zn contents. Along strike, pyritic deposits often pass into magnetite ores; interbanded sulphide-oxide horizons comprise common transitional types. Very extensive zones of pyrite ± chalcopyrite dissemination is reported, but their metallogenic significance is not known.

In the Smøla-Snåsa terrane, several deposits resembling those of the Hardanger district are known. These range from magnetite- to pyrite-dominated types with or without minor amounts of chalcopyrite, and are hosted by shoshonitic lavas, rhyolites and various pyroclastic rocks (Figs. 14 and 10). *Fosdalen* is the biggest deposit and the only one which has given rise to any continuous and significant production; mining took place from 1906 to1997, during which period more than 35 Mt of ore was produced, carrying 50–70% magnetite, 3% of a cobaltiferous pyrite (0.25% Co) and minor amounts of chalcopyrite. Pyrite and copper concentrates were produced when marketing conditions were favourable (Carstens 1955; Vokes 1960; Bugge 1978; Smith 1995).

A possible equivalent of the metavolcanic Smøla-Snåsa sequence hosts the small *Skrattås* Zn-Pb-Cu deposit. Irregular, highly tectonised, thin layers or lenses of massive ore contain an average of about 34% Zn, 10% Pb, 2% Cu and 270 ppm Ag (unpublished NGU data). The sulphides were deposited directly above rhyolitic tuffs or tuffites in a sequence of rhyolitic to basaltic metavolcanites and were in turn overlain by sediments of mixed volcanic derivation as well as andesitic metavolcanites. Significant amounts of barite have been reported in the ore, and calcite is abundant both as a major matrix phase and as separate carbonate lenses adjoining the sulphide ore.

Epigenetic deposits

The large felsic plutons related to the later stages of this, essentially calc-alkaline, mature arc evolution show evidence of more deep-seated hydrothermal processes. Vein- and stockwork-type Cu-Mo-deposits were developed in association with some of the plutons, in particular the Follafoss tonalite-granodiorite and the Møklevatn granodiorite which have yielded U-Pb zircon ages of 460 ± 5 Ma (T. Thorsnes, personal communication 1994) and 456 ± 2 Ma (Roberts and Tucker 1991), respectively. The Follafoss pluton contains only subordinate mineralisation of chalcopyrite, pyrite, bornite and molybdenite in association with aplite dykes and sheared quartz veins in its endo- and exocontacts (Ørsjødalen and Skaudalen), but potentially economic porphyry-type Cu-Mo mineralisation has been investigated at *Fremstfjell* in the Møklevatn pluton (Fig. 12) (Martinsen and Vokes 1987).

The mineralisation at Fremstfjell is developed in the contact zone of the pluton, both within the porphyritic granodiorite with associated aplite dykes and in the metavolcanic wall-rocks. The mineralisation shows a crude zonal arrangement of ore minerals and alteration types within a 750 m × 1400 m halo of fracture-bound and disseminated pyrite. The halo is centred on an elliptical area (50 m × 200 m) with quartz-sericite alteration and with an intense stockwork of K-feldspar and quartz ± anhydrite veins. The latter veins are the main carriers of chalcopyrite and/or molybdenite. The highest grades (about 0.3% Cu and 0.1% Mo) are confined to the margin of the stockwork which is surrounded by pervasive albite alteration and superimposed by late propylitic alteration.

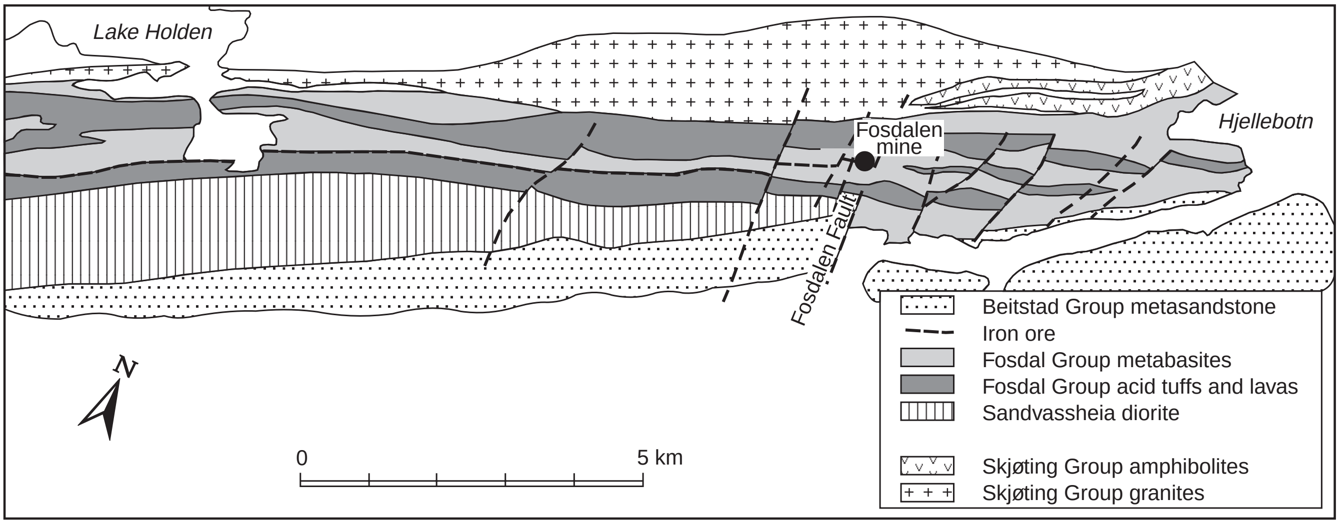
Igneous and sedimentary development of the remaining ocean basin

A regional marine transgression above the deformed Early to Middle Ordovician sequences was followed by deposition of clastic sequences probably related to the formation of fault-controlled basins (Thon 1985; Pedersen et al. 1992). This was coeval with a new phase of igneous activity and accompanying metallogenic processes. Representatives of this varied magmatic and metallogenetic history (Fig. 15) of the Late Ordovician to Early Silurian are preserved throughout the nappe pile of the Scandinavian Caledonides (Fig. 3).

Detailed volcanostratigraphic investigations in presumably *UA* units in the Bømlo district of southwest Norway (Brekke et al. 1984; Nordås et al. 1985) denote that this phase commenced with the eruption of subaerial calc-alkaline basalts and was succeeded by submarine basalts of alkaline to tholeiitic (partly transitional to calc-alkaline) rifting affinity, in a progressively deepening basin. Further north along the west coast of Norway, in the Solund-Stavfjord area, a similar range of volcanic and intrusive rocks has been dated to 443 ± 3 Ma (Dunning and Pedersen 1988) and has been interpreted in terms of spreading-ridge and subduction-related magmatism in a sediment-dominated setting close to a continental margin (Furnes et al. 1990).

Several large, predominantly mafic, intrusions related to this stage are found in the Gula Complex and Fundsjø-Stekenjokk metavolcanites. U-Pb zircon ages of the Fongen-Hyllingen, Artfjell, Sulitjelma and Råna layered intrusions (Fig. 15) all indicate emplacement in the Late Ordovician to Early Silurian and cluster within the combined analytical uncertainty at about 435–440 Ma (Pedersen et al. 1991 and references therein). Some of these intrusions were emplaced at crustal depths of 15–20 km in rocks which had suffered an earlier

Fig. 14 Geological map of the Fosdalen district showing the distribution of the stratiform magnetite horizon. After Smith (1995)



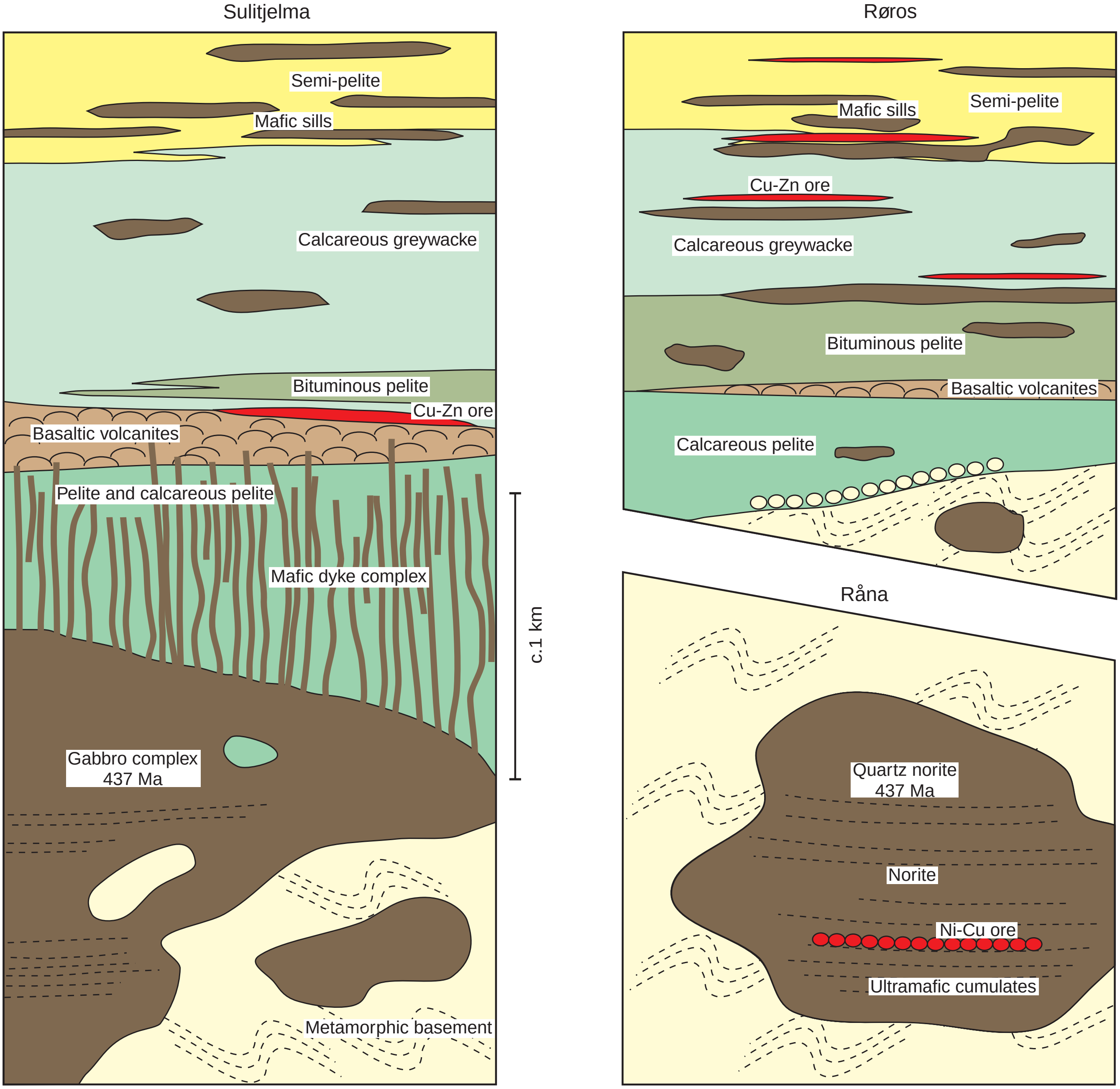


Fig. 15 Schematic, interpreted sections from the central (Røros) and the northern (Sulitjelma and Råna) Caledonides illustrating the igneous and sedimentary development of the remaining, narrow ocean basin during the stage of ocean closure. Mafic intrusions occur in the Late Ordovician-Silurian volcanosedimentary cover and underlying Early Caledonian basement

Caledonian tectonothermal event. Similar and coeval intrusive activity is represented in the Kalak Nappe Complex of the *MA* in northern Scandinavia (Sipilä 1991). A close association with dyke swarms and locally with sheeted dyke complexes showing MORB-dominated geochemical signatures indicates a tensional tectonic regime, and these complexes have locally been referred to as ophiolites (e.g. at Solund-Stavfjord and Sulitjelma, Furnes et al. 1990; Boyle 1989).

Thick, presumably Ordovician, clastic sequences overlying the immature arc systems of the Stekenjokk-Fundsjø zone, are intruded by numerous mafic and subordinate felsic magmas of predominantly tholeiitic to alkaline, MORB or WPB, composition with a superimposed subduction signature (Stephens et al. 1985a; Grenne and Hertogen unpublished data). These intrusions are particularly abundant in the thick, often calcareous psammitic and pelitic sequences (Fig. 15) in the Røros and Meråker districts, in the comparable Blåsjö Phyllite further north in Sweden, in the Furulund Schist sequence at Sulitjelma and the Ankerlia Schists of the Birtavarre-Vaddas area in northernmost Norway (Fig. 3). Age constraints on this magmatism are limited; local fossiliferous units overlying the gabbro-intruded sequences indicate that the magmatic activity is not younger than Llandovery (about 430 Ma). In the same sedimentary sequences, local volcanic rocks of supposed Late Ordovician age have compositions which indicate a genetic relationship to the MORB- to WPB-type intrusions, or show clear calc-alkaline compositions (Stephens 1980; Grenne and Lagerblad 1985; Stephens et al. 1985b; Boyle 1989). The situation thus appears to be analogous to that seen at a tectonostratigraphically higher position, in the Bømlo-Hardanger and Solund-Stavfjord districts.

Available data thus suggest that the Late Ordovician/ Early Silurian boundary was a period of widespread, mainly rift-related, magmatic activity throughout the, by now narrow, remainder of the Iapetus ocean (Fig. 2). The exact paleotectonic significance of this is debated. Pedersen et al. (1992) indicate a rifting event in a continent-based arc system situated on the Laurentian side of the basin. However, the apparent basin-wide distribution of this magmatic period may suggest that it was not limited to only one of the continental margins. In this context it is interesting that paleomagnetic data (Torsvik et al. 1992, 1996; Dalziel 1997) indicate that the plate tectonic pattern at the Ordovician-Silurian boundary was dominated by a rapid anti-clockwise rotation of Baltica and a lateral relative movement of the converging Baltic and Laurentian plate margins. On this basis it is tempting to suggest that the basin-wide magmatism at this time was related to transcurrent movements during the initial interference or suturing of the Baltic and Laurentian continent margins, a process which may have resulted in alternating transtensional and transpressional regimes (Harland 1971) with the development of a series of fault-controlled sedimentary basins and associated magmatism along the continent-continent interface.

Stratabound sulphides

Massive stratiform sulphides are commonly associated with the volcanic rocks of supposed Late Ordovician age. Similar massive or disseminated deposits are hosted by the thick clastic sequences, often with a close spatial relationship to mafic intrusions. The overall likeness between these mixed clastic-volcanic-intrusive sequences and the setting of the Besshi type of sulphide mineralisation is striking.

The once very important sediment-hosted ores of the *Røros* District (Fig. 16) comprise pyrrhotite- or pyrite-dominated, often stratiform, Cu-Zn bearing massive sulphides (Rui and Bakke 1975; Bugge 1978) situated in calcareous phyllites and metagreywackes containing local interlayers of possible volcaniclastic origin. The sequence is heavily intruded by minor gabbros or mafic sills. The deposits range up to 3 Mt in size and are often located near the contact to the gabbros. Cu/Zn ratios are highly variable; very Zn-rich as well as Cu-rich types being present (Bjørlykke et al. 1980). The ores are clearly concordant to the layering of the folded metasediments, which often are chloritic or quartz-sericite-pyrite-rich near the ore bodies. Pyrrhotite-dominated varieties (e.g. *Storwartz*) usually show a breccia-like structure containing a high proportion of wall-rock inclusions, and this type sometimes occurs together with massive pyritic ore in the same deposit. The deposits form thin plates or ruler-shaped bodies up to 2.5 km long, and with thicknesses commonly in the order of 1 m except for local increases in fold hinges. The *Kongens* deposit contained about 1.5 Mt of ore averaging 3% Cu and 4% Zn, whereas the last-mined deposit of *Lergruvbakken* contained 0.8 Mt with 0.7% Cu and 7.8% Zn (Bjørlykke et al. 1980). Together, the mines of the Røros District were worked continuously from 1644 to 1977.

Copper-zinc rich massive ores and disseminated Cu-dominated mineralisation in the eastern *Meråker* district further north (Fig. 7) have a very similar mode of occurrence and are linked with those of the Røros District through a belt of abundant but smaller, similar deposits, some of which carry significant amounts of magnetite partly in the form of massive bands (Rui and Bakke 1975). The most important deposit in the eastern Meråker area was that at *Lillefjell* Mine which was probably the most copper-rich of the regularly worked Scandinavian stratabound sulphides, the main part of the ore body containing 6% Cu (Foslie 1926) and uncertain but probably equal or higher amounts of zinc (Karlstrøm 1990).

Deposits in the Blåsjö Phyllite include the Zn-rich *Ankarvattnet* deposit (Sundblad 1980). This pyritic to pyrrhotitic massive deposit is situated in calcareous turbidites near a gabbroic intrusion; adjacent, sulphide-disseminated, quartz-chlorite-, quartz-white mica-, and dolomite-rich rocks have been interpreted as hydrothermal alteration products of the sediments in a feeder zone. Ore potential has been calculated to 0.75 Mt averaging 5.5% Zn and nearly equal amounts of Cu and Pb at about 0.4%.

The deposits of the *Sulitjelma* and *Birtavarre-Vaddas* districts in northern Norway are comparable to those of the districts just mentioned in their mode of occurrence as well as in metal contents, forming thin semi-massive plates and ruler-shaped bodies with associated dissemination. Mineralisation is found in gabbro-intruded calcareous sediments, commonly at the contact with basalt-dominated metavolcanic units. The deposits of the Birtavarre-Vaddas district (Vokes 1957) ranged up to 3 Mt, whereas the once very important Sulitjelma ore-field (worked between 1887 and 1991) comprised more than 20 separate pyritic deposits with a total tonnage in excess of 35 Mt (Cook et al. 1990) grading an average of 1.8% Cu, 0.4% Zn, 10 ppm Ag and 0.25 ppm Au. The Sulitjelma volcanites have an E-MORB chemistry with a superimposed sub-

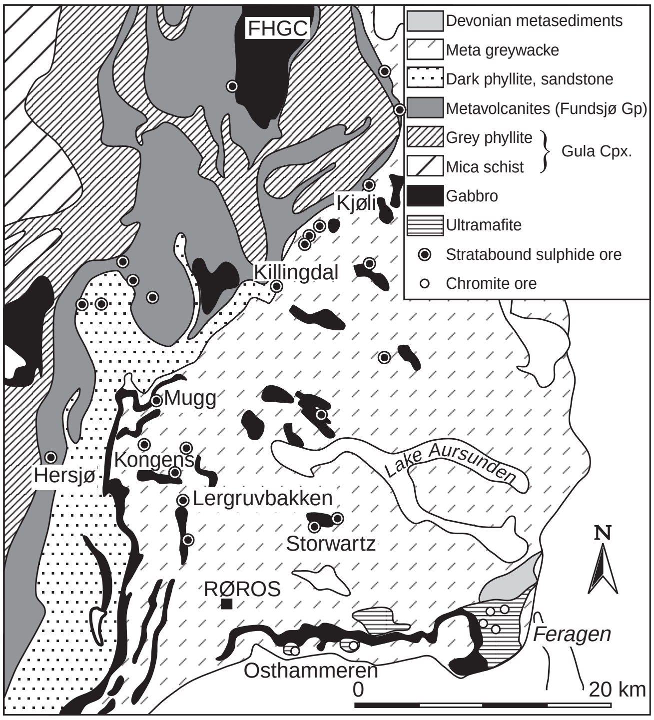


Fig. 16 Geological map of the Røros District, central Norway, showing ore deposits. *FHGC* = Fongen-Hyllingen Gabbro Complex. Geology after Nilsen and Wolff (1989)

duction signature (Boyle 1989; Pedersen et al. 1991) similar to much of the igneous activity at the Late Ordovician/Early Silurian boundary. Although it is generally agreed that the volcanism was related to a tensional setting, litho- and tectono-stratigraphic relationships to underlying and overlying sequences are controversial. Available evidence suggests a cogenetic relationship to the tectonostratigraphically overlying, 437 ± 2 Ma Sulitjelma Gabbro although, as pointed out by Pedersen et al. (1991) the term Sulitjelma Ophiolite (Boyle 1989) is inappropriate for the rock assemblage.

Mineralisation belonging to this stage in the southwestern part of the Caledonides is hosted by more volcanite-dominated sequences. The *Stordø* (Litlabø) deposit in southwest Norway was an about 9 Mt *vasskis* type mineralisation hosted by a sequence of various clastic sediments and bedded radiolarian cherts with basaltic units of shallow marine origin (Nordås et al. 1985). The ore horizon, ranging in thickness between 5 and 50 m, comprises extremely fine-grained pyritic sediments with interbands of magnetite, Fe-silicates and significant amounts of recrystallised chert (Foslie 1926). The deposit was mined for pyrite from 1865 to 1968. The *Solund-Stavfjord* complex (Furnes et al. 1990) further north contains minor and fairly low-grade, massive stratiform to disseminated sulphides hosted by basalts.

Orthomagmatic Ni-Cu deposits

Significant Ni-Cu mineralisation is found in the Råna layered intrusion near Narvik (Fig. 17). The intrusion was emplaced at 437^{+1}_{-2} Ma in a previously deformed sedimentary sequence (Barnes et al. 1988; Tucker et al. 1990), a part of the Narvik Group correlatable with the Gula Complex, and was itself later deformed during the Scandian orogeny. The intrusion has a MORB affinity compatible with the rift-signature of the other major mafic intrusions formed at this time.

The Råna complex is distinctly layered above a noritic contact zone, showing an up to 800 m thick ultramafic zone overlain by a noritic zone which is 300 to 2000 m thick and finally a quartz norite zone. A cyclic repetition of olivine-orthopyroxene-plagioclase-clinopyroxene is inferred, and local reversals and cross-cutting relationships indicate multiple magma replenishment from a deeper-lying reservoir which itself was undergoing fractional crystallisation (Boyd and Nixon 1985). The presently mined *Bruvann* deposit (Boyd and Mathiesen 1979; Barnes 1989), comprising mainly disseminations of pyrrhotite, pentlandite and chalcopyrite in peridotite, is the only major ore body in the Råna intrusion. Since 1989, some 5.7 Mt of ore have been mined; the tonnage remaining is estimated at just over 1 million, at 0.53% Ni and 0.10% Cu (L. Storhaug, personal communication 1998). The PGE contents of the ore are very low (Boyd et al. 1987). Ni-Cu ore of similar composition and geological setting occurs in the *Skjækerdalen* deposit in central Norway (Boyd and Nixon 1985). Production, which took place in the period 1876–1891, was based on the richer parts of the mineralisation and yielded 19 000 tonnes of ore containing 1.26% Ni and 0.63% Cu.

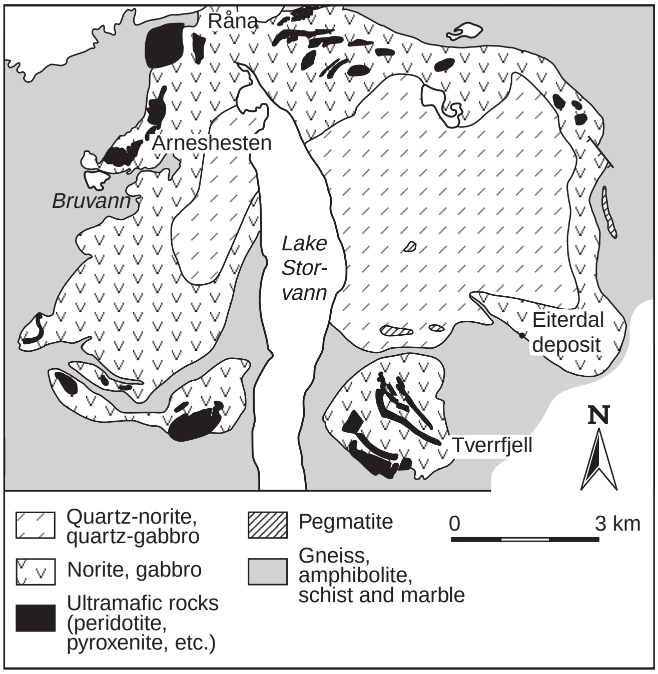


Fig. 17 Geological map of the Råna intrusive complex, northern Norway, after Boyd and Mathiesen (1979)

Batholith development

Batholiths and smaller bodies of granitoid intrusives are distributed throughout the Scandinavian Caledonides though most of them occur in the *UmA* and *UA* in Norway (Fig. 3). The present location of the batholiths above the Baltic continental crust is the result of eastward nappe translation during the Scandian phase. The most prominent of these are the Sunnhordland Batholith (Andersen and Jansen 1987), the Smøla-Hitra Batholith (Gautneb and Roberts 1989), the Bindal Batholith (Nordgulen 1992, 1993) and the abundant granitoid intrusives of the Beiarn region (Tørudbakken and Brattli 1985; Solli 1990; Solli et al. 1992).

The batholiths and other major granitic intrusives seem to have been emplaced during the Late Ordovician and Early Silurian into a previously imbricated pile of nappes. U-Pb and Rb-Sr dating yields ages within the interval 430–450 Ma. (Andersen et al. 1982; Tørudbakken and Brattli 1985; Andersen and Jansen 1987; Fossen and Austrheim 1988; Gautneb 1988; Tucker 1988; Nordgulen and Schouenborg 1990; Nordgulen et al. 1993). They contain a wide spectrum of intrusive rock types ranging from olivine gabbros to leuco-granites. The Sunnhordland Batholith comprises mainly granodiorites and granites (Andersen and Jansen 1987) whereas the Smøla-Hitra Batholith is dominated by high-K calc-alkaline to alkali-calcic quartz monzodiorites, granodiorites and granites (Gautneb and Roberts 1989; Nordgulen 1993). Equigranular and porphyritic granites and granodiorites are the most common rock types in the Bindal Batholith. The majority of the rocks in this latter area are high-K calc-alkaline and metaluminous, but calcic to alkali-calcic, and evolved, peralminous, varieties are also present (Nordgulen 1992).

Geochemical and isotope studies of the Bindal Batholith (Nordgulen 1992; Nordgulen and Sundvoll 1992; Birkeland et al. 1993b) suggest that the intrusions were derived by partial melting of multiple sources, such as depleted mantle and mafic lower crust, Th-enriched lower crust and various upper crustal rocks, over a west-dipping Benioff zone. The paleotectonic setting of the Bindal Batholith, and probably most of the other batholiths, is thought to be that of a convergent plate margin. The petrogenesis, ascent and emplacement of the granitoid magmas were controlled by oblique subduction, combined with strike-slip movements and thrusting along deep-seated fault systems (Nordgulen 1993).

Epigenetic deposits

No prominent mineralisation or potentially economic ore deposits seem to have been formed during the Batholith development. This may be an artifact caused by the difficulty of separating batholith-associated deposits from the granite-associated deposits related to the stage of syn- to post-collision development (see later).

The batholith-related deposits are mainly pegmatites, quartz-veins and skarn deposits carrying Fe-sulphides, base-metal sulphides, molybdenite and scheelite. Minor deposits of molybdenite-bearing pegmatites (Oftedahl 1967) and quartz-tourmaline veins are found locally in the western part of the Bindal Batholith (Fig. 18). The predominant mineralisation type, however, is fracture-bound trains of scheelite grains which are found in a wide spectrum of metamorphic and intrusive rocks in the Bindal Batholith and its country rocks. In addition, scheelite disseminations occur along ptygmatic quartz veins, boudinaged pegmatite dykes, calc-silicate lenses and zones of skarn alteration in marbles as well as quartz veins in the granites (Nissen 1969; Bowitz-Ihlen 1973; Skaarup 1974; James 1991; James et al. 1993). The most prominent of the scheelite skarn mineralisations occurs in altered marbles at *Målvika* (Fig. 18). According to James (1991) and James et al. (1993) the mineralisation is located along a 10 m wide and 700 m long marble horizon in hornblende-biotite gneisses. Scheelite is mainly concentrated in up to 1.5 m wide heterogeneous zones of plagioclase, clinopyroxene, garnet and/or wollastonite skarns and particularly where these skarns are retrograded to assemblages of epidote, quartz, amphibole and/or chlorite.

Comparable retrogradation is also found associated with small bodies of garnet-clinopyroxene skarns hosting disseminations and semi-massive ores of pyrrhotite and subordinate chalcopyrite at the contacts of both the Smøla-Hitra (Fediuk and Siedlecki 1977) and the Bindal Batholiths. The largest of the base-metal skarn deposits is found at *Husvika* in the northwestern part of the Bindal Batholith (Fig. 18). The Husvika deposit contained, prior to small-scale mining, approximately 100 000 tonnes with 24% Zn and 10% Pb, over a strike length of about 1.5 km (Vogt 1900; Torgersen 1928; Bjørlykke 1951). According to Birkeland and Bjørlykke (1993) base-metal sulphides, pyrrhotite and arsenopyrite occur as disseminations and massive lenses, pods and veins in grünerite-cummingtonite and almandine-tschermakitic amphibole skarns. The 1–2 m wide skarn zones occur in a 4–40 m thick sequence of interbanded amphibolites, calcareous mica schists, quartzites and impure marbles. The mineralisation both pre- and post-dates granitic dykes occurring abundantly in the wallrocks of the mineralised unit (Vogt 1900).

Stage 3: continent collision

The Scandian orogenic phase, related to the continent collision between Laurentia and Baltica (Fig. 2), occurred mainly during the Silurian, although crustal thickening due to interaction between the two plates may have started in the Late Ordovician. The passive margin of Baltica was subducted below the overriding margin of Laurentia which carried accreted nappe complexes punctured by batholith massifs and covered by sequences deposited during the final closure of the Iapetus ocean. This resulted in depression of the Meso- to Paleoproterozoic crystalline basement of the Baltic margin to depths where eclogites could form, i.e. at 40–60 km or more. The formation of eclogites in western Norway ranges from about 450 Ma in the Bergen arc (Boundy et al. 1996) to about 425 Ma in the Western Gneiss Complex (WGC) (Krogh et al. 1973; Griffin and Brueckner 1980). Granulites in the Vestranden Gneiss Complex (VGC) further north developed at 432 ± 6 Ma (Dallmeyer et al. 1992). Ilmenite-bearing gabbros of Proterozoic age occurring in the WGC are frequently metamorphosed to eclogites enriched in rutile which may represent a future source of raw material for TiO_2 pigment and Ti-metal production (Korneliussen et al. 1985).

During the subduction of the Baltic margin, the composite outboard terranes of the *UmA* and *UA* were displaced for hundreds of kilometres eastwards on to the Baltoscandian platform where molasse started to build up in the Silurian (Bjørlykke 1974). The underlying platformal sequences, together with their crystalline basement, became strongly folded and imbricated during the Scandian thrusting, leading to the formation of several orogen-parallel antiformal stacks of basement-cover complexes now exposed in tectonic windows, mainly in the *MA* and *LA* (Romer and Bax 1992). Seismic reflectors interpreted as thrusts and decollement structures, are present in the crystalline basement to a depth of 15–18 km below one of these antiformal stacks (Hurich et al. 1989), indicating involvement of the upper to middle crust in the deformation of the foreland. $^{40}Ar/^{39}Ar$ dating indicates that the main episode of nappe translation occurred at 420–410 Ma (Dallmeyer et al. 1988; Hames and Andresen 1996; Fossen and Dunlap 1997). This episode was subsequently followed by a long period of extension and tectonic unroofing related to gravity-driven collapse of the orogenic root. In the upper and middle crust, gravitational backsliding of the nappe units was followed by development of west-vergent and crustal-scale extensional detachment horizons which were active during the Devonian in southern Norway, i.e about 410–370 Ma (Chauvet and Dallmeyer 1992; Wilks and Cuthbert 1994; Fossen and Dunlap 1997). The tectonic uplift and decompression of the WGC was initially near isothermal, followed by a phase of rapid cooling. By the Middle Devonian, the present surface of the WGC lay at about 10–20 km depth and the crust had almost returned to isostatic equilibrium (Wilks and Cuthbert 1994).

Intramontane basins with Old Red Sandstone (ORS) formed in response to the late orogenic extension during the Early and Middle Devonian (Steel et al. 1985). Much of the uplift in the WGC took place before the deposition of the ORS-sediments (Andersen and Jamtveit 1990; Cuthbert 1991). However, final exposure of the high-grade rocks formed at or below 80 km (Cuthbert et al. 1983; Griffin et al. 1985) was accomplished at a late stage in the basin evolution (Cuthbert 1991).

Tectonic deformation of the ORS strata consists of open folding along E-W to NE-SW axes with concom-

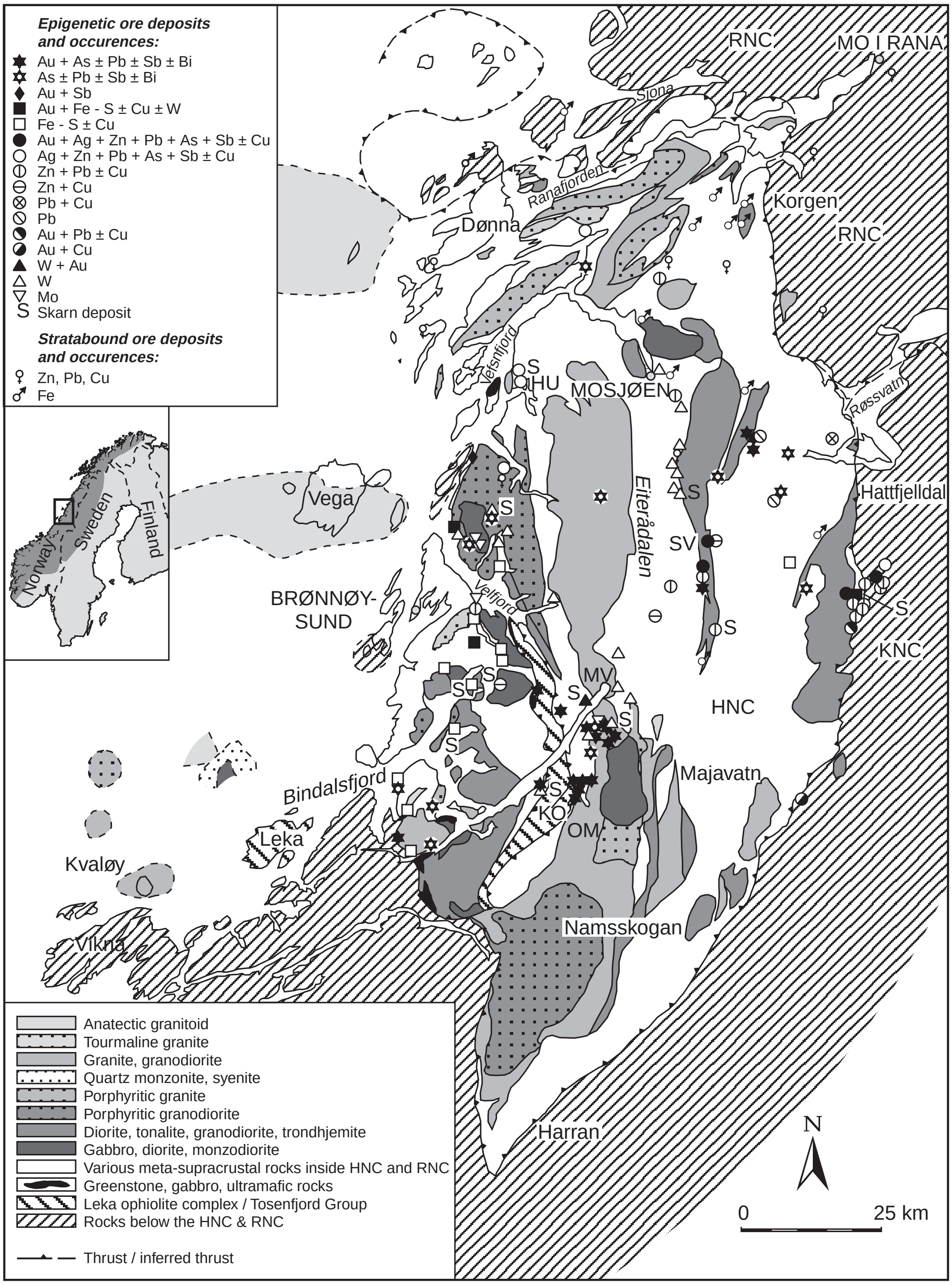


Fig. 18 Simplified geological map of the Bindal Batholith, showing the distribution of epigenetic ore deposits relatable to the batholith development and to the stage of continent collision. Geology after Nordgulen (1992). *HNC* = Helgeland Nappe Complex; *HU* = Husvika; *KNC* = Köli Nappe Complex; *KO* = Kolsvik; *MV* = Målvika; *OM* = Oksdal granite massif; *RNC* = Rödingsfjäll Nappe Complex; *SV* = Svenningdal

itant, and later, high and low-angle faults, mesoscopic thrusts, bedding-parallel mylonites, pebble-stretching lineation and penetrative cleavage in the finer-grained rocks (Steel et al. 1985; Bøe et al. 1989). The nature and timing of the deformation in the ORS basins is a controversial subject. In the extensional basin models it is contended that the observed deformation features can be explained in terms of a tensional syndepositional tectonic framework (Hossack 1984; Norton 1986; Chauvet and Séranne 1994). Other models advocate that folding, thrusting and metamorphism was the result of post-depositional and compressive N-S shortening (Nilsen 1968; Roberts 1983; Torsvik et al. 1987; Bøe et al. 1989). The last-mentioned authors provide strong evidence for a separate Late Devonian tectonothermal event affecting the ORS sequences in the coastal areas of Trøndelag. This event is regarded by the present authors as the ultimate termination of the Caledonian orogeny.

Magmatic activity relatable to crustal thickening and to concomitant collision-related rifting represented by the ORS basins has so far only been documented in the form of small intrusive bodies, as well as minor trachytic and rhyolitic lava flows interbedded with fluvial conglomerates in the central part of the Solund basin, in the oldest part of the succession (Furnes and Lippard 1983). Numerous granitic pegmatites are found in the Early Proterozoic crystalline rocks of the WGC and VGC. Rb-Sr whole-rock dating of such pegmatites in the WGC yields ages in the range 371–424 Ma (Pidgeon and Råheim 1972; Kullerud et al. 1986) whereas those of the VGC have given U-Pb ages of 398 ± 3, 401 ± 3 and 404 ± 2 Ma (Schouenborg 1988; Schouenborg et al. 1991). The largest of the Devonian intrusives so far encountered is the Gåsøy Intrusion on the coast of western Norway (Nordfjord), which is composed of coarse-grained gabbroic to dioritic rocks. The geochemistry of these rocks is transitional between tholeiitic and calc-alkaline. Sm-Nd dating of the intrusive gives an age of 380 ± 26 Ma (Middle Devonian) believed to represent the time of crystallisation (Furnes et al. 1989).

All ore deposits formed during the syn- to post-collision development are epigenetic (Fig. 3) and comprise:

1. Sandstone lead deposits
2. Carbonate-hosted base-metal deposits
3. Vein deposits

These deposits will be described in order of apparent decreasing age though the timing of the ore-forming events is poorly constrained.

Sandstone-hosted base-metal deposits

The Neoproterozoic to Cambrian platformal and rift-basin sequences, consisting dominantly of arenites, are hosts to a number of stratabound and disseminated to semi-massive ores of galena, lesser sphalerite, and minor pyrite, chalcopyrite, bornite, chalcocite, calcite, fluorite and barite. The most prominent of these are the sandstone lead deposits which have constituted one of the most important metal sources in the Caledonides. The majority of the known sandstone lead deposits occurs in close proximity to the present thrust front of the Caledonides and along its whole length (Fig. 19) (Grip 1954, 1967, 1978; Tegengren 1962; Christofferson et al. 1979; Rickard et al. 1979; Bjørlykke and Sangster 1981; Nordrum and van der Wel 1981; Bjørlykke 1983; Romer 1992). In addition, minor, but genetically important, Pb- and Cu-dominated deposits are found near the margin of allochthonous and parautochthonous basement windows in the more interior parts of the Caledonides (Johansson 1983a, b; Pharaoh et al. 1983; Krause and Bakke 1986) as well as inside Neoproterozoic rift-basins (Lake Vättern and Gulf of Bothnia) far east of the Caledonian front (Ödman 1942; Grip 1978).

By far the major part of the resources of sandstone lead ore lies in the Swedish sector, being concentrated in three main areas centred around Laisvall, Dorotea and Vassbo. Grip and Frietsch (1973) reported the following total original quantities (resources) of lead metal: the Laisvall area 5.4 Mt, the Dorotea area 3.1 Mt, the Idre area (including Vassbo) 0.3 Mt. Production has taken place at two of the Swedish deposits in the past; *Vassbo*, which was worked from 1960 to 1982 produced some 5 Mt of ore at 4.6% Pb and 14 g/t Ag. *Laisvall*, with an original geological reserve of about 60 Mt at 4% Pb, has been in operation since 1942. For many years it was the largest European producer of primary lead. Total production to end 1992 amounted to some 50 Mt with 4% Pb and 0.7% Zn; in more recent years, production has been running at between 1 and 2 Mt of ore per year.

These galena-dominated ores are found both in autochthonous and allochthonous sedimentary sequences (Fig. 20), the latter being part of the *LA*. They are in most cases situated at a short distance above Precambrian crystalline rocks which may be capped by an up to 10 m thick zone of altered rocks, interpreted as a weathered paleo-surface or regolith. The deposits invariably occur stratigraphically below a sub-Middle Cambrian sedimentary break defined by conglomerates overlain by black alum shales (Bjørlykke and Sangster 1981; Bjørlykke 1983). The major ores are located in units of quartz sandstones with poorly and irregularly mineralised interbeds of arkoses, feldspathic sandstones, siltstones, shales and conglomerates, filling local depressions in the basement (e.g. at Laisvall and Vassbo).

Within the ore-bearing quartz sandstones the ore minerals fill interstices between the sand grains and micro-fractures in them, as well as fissures and other tectonic structures. Disseminated to semi-massive ores occur dominantly in the autochthonous sedimentary sequences (as at Laisvall and Vassbo) whereas fracture-bound mineralisation is more common in the allochthonous sequences, locally constituting the main ore type (e.g. Dorotea). In addition to the ore minerals, intergrown calcite, barite, fluorite and quartz form the cement of the mineralised sandstones. In high-grade ores, both the detrital quartz grains and the cementing gangue minerals appear to have been replaced to varying degrees. Ore contacts are commonly diffuse, although sharp and locally crosscutting contacts between high-grade ores and barren sandstone can be found, e.g. at Laisvall where the mineralisation is grossly discordant in respect to the whole sandstone sequence.

Pyrite is ubiquitously present as a minor mineral whereas Cu-sulphides are rare in the deposits along the Caledonian front. However, Cu-sulphides represent an important constituent in low-grade deposits occurring in basal arenites at the margin of basement domes in the Lower Allochthon of the Hedmark region and

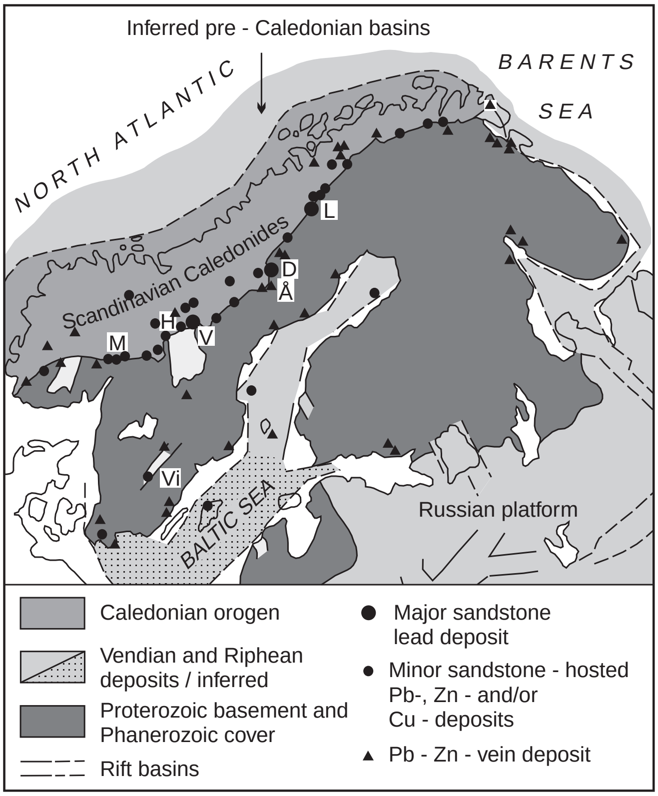


Fig. 19 Distribution of sandstone lead deposits and lead-bearing quartz-carbonate veins in the Scandinavia Caledonian orogen and its foreland. Geology redrawn from Kumpulainen and Nystuen (1985). Ore deposits compiled from Grip (1978), Rickard et al. (1979), Johansson (1980), Bjørlykke (1983), Krause and Bakke (1986), Fedotova (1990), Romer (1992) and unpublished NGU data. *D* = Doretea; *H* = Hedmark region; *L* = Laisvall; *M* = Mjøsa district; *V* = Vassbo; *Vi* = Visingsö-Vättern basin

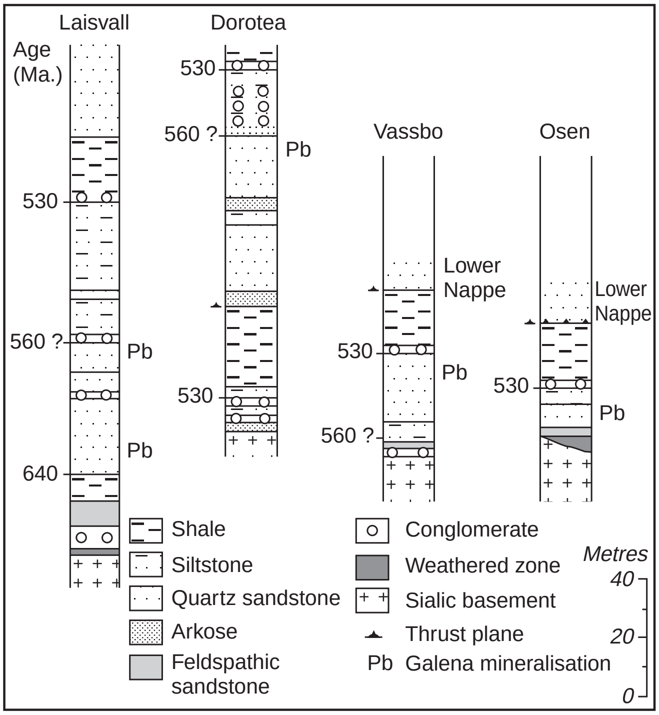


Fig. 20 Lithostratigraphy in four areas along the Caledonian front containing sandstone lead deposits. See Figs. 3 and 19 for location. Modified after Bjørlykke and Sangster (1981)

further northwest in central south Norway (Krause and Bakke 1986; K. Isbrekken personal communication 1994). In addition, Cu-sulphides are found to replace the cement and form veinlets in the basal quartz sandstones of the Neoproterozoic Visingsö group in the Vättern basin (Ödman 1942).

The autochthonous sandstones along the Caledonian front occur in a nearly non-metamorphic state and show fabrics indicative of only moderate pressure solution. Deformation textures ascribable to Caledonian thrusting or extension are occasionally found in sericite, calcite, galena and sphalerite (Rickard et al. 1979; Johansson 1983b; Lindblom 1986). Fracture-bound sulphide mineralisation, which is conspicuous in the *LA* deposits at Dorotea, becomes even more prominent towards the interior of the orogen where also quartz-sulphide and barren quartz veins start to occur in quartzitic sandstones together with disseminated ores (Krause and Bakke 1986). Locally, the mineralisation consists solely of barren quartz veins enveloped by galena disseminations (Kautsky and Tegengren 1952). Although it may be argued that the fracture-bound sulphides represent mobilisates of primary disseminated ores, this is less likely due to the similar range of fluid compositions and homogenisation temperatures for fluid inclusions in sphalerite from these two ore types at Laisvall (Lindblom and Rickard 1978). Therefore, it is possible that the quartz-sulphide veins in the sandstone lead deposits west of the Caledonian front may represent a link to granite-associated and basement-dome related vein deposits (see later).

Fluid inclusion studies on the Laisvall deposit (Roedder 1968; Lindblom and Rickard 1978; Lindblom 1986), have given homogenisation and freezing temperatures of calcite, fluorite and sphalerite which indicate that the ore minerals precipitated from saline Na-Ca-Cl-brines (20–29 equivalent wt. % NaCl with up to 9% $CaCl_2$) at 130–180 °C and 200 bar.

The stable isotope compositions ($\delta^{13}C$, $\delta^{18}O$, and $\delta^{34}S$) of calcite, barite and sulphides in the Laisvall deposit demonstrate that the gangue minerals are mostly of non-diagenetic origin and that the ore minerals were not precipitated from the same solutions under equilibrium conditions (Rickard et al. 1979, 1981; Lindblom 1984). This is consistent with textural relationships between the minerals (Rickard et al. 1979; Lindblom 1986) which suggest a series of pulses of solutions with somewhat varying compositions. Rickard et al. (1979) interpreted the isotope data as indicating the involvement of two main types of solutions in the ore formation. One solution was rather homogeneous and sulphide-bearing whereas the other was a heterogeneous metal-bearing sulphate solution comparable with basinal, oil-field, brines, the comparison to oil-field brines being suggested by the presence in the fluid inclusions of dark phases interpreted as hydrocarbons. Some of the sulphate was assumed to be formed by oxidation of sedimentary pyrite in shales, e.g. in the alum shales. Sulphur isotope ratios reported from the Norwegian sector by Bjørlykke (1983) are also consistent with oil-field brines as a source for the sulphur, although he proposed an alternative source, that of sea-water sulphate locally reduced by bacteria.

The Pb-isotope composition of galenas in the sandstone lead deposits is highly radiogenic (Rickard et al. 1981; Bjørlykke and Thorpe 1982; Johansson 1983a; Johansson and Rickard 1984; Romer 1992). Although the data points for the individual sandstone lead deposits show little spread, highly variable Pb-isotope ratios were recognised on intra- and inter-crystal scale in the Laisvall deposit (Rickard et al. 1979). It is generally accepted that the ore lead was derived mainly from the Paleoproterozoic rocks in the basement.

Although the various sandstone base-metal deposits on the Baltic shield share many common features, they may have different origins or may represent parts of a continuous spectrum of ore-forming processes operating throughout the Caledonian orogeny. For example, the sandstone copper deposits could represent a red-bed type of mineralisation in fluvial to sub-tidal sediments, whereas the sandstone lead deposits in the Gulf of Bothnia and possibly related vein deposits occurring further east in Russia (Grip 1978; Sundblad 1989; Fedotova 1990; Fig. 19) could be related to Neoproterozoic rifting. Regarding the sandstone lead deposits along the Caledonian front, there seems to be a general consensus that these are epigenetic with respect to their hosting sediments. Published views on their genesis may be summarised as advocating the following four genetic models:

1. Pre-orogenic, diagenetic precipitation of Pb (Zn, Cu)-sulphides from groundwaters permeating sub-tidal sandstones containing organic substances. The Pb is assumed to have been released from K-feldspar in the granitic basement during a prolonged period of chemical (tropical) weathering (Bjørlykke 1980, 1983; Bjørlykke and Sangster 1981).
2. Ore deposition in relation to convecting brines above high-heat-producing (HHP) granites and under a cap rock composed of alum shales. The circulating fluids leached base-metals from the HHP granites and other rocks in the granitic basement (Bjørlykke et al. 1991).
3. Thrust- and fault-controlled migration of ore fluids from the interior of the orogen and through the Caledonian sediments (Grip 1954, 1967) or underlying crystalline basement (Gee 1972; Romer 1992) at the climactic (Scandian) phase of the orogeny.
4. Tectonic expulsion of metal-bearing connate waters (brines) from the Neoproterozoic-Cambrian basinal and platformal sedimentary sequences (Lindblom 1986) during the period of continental collision and nappe translation (Rickard et al. 1979; Duane and de Wit 1988).

Most of these models have also been advocated for other strata-bound and epigenetic Pb-Zn-F-Ba-deposits occurring world-wide in carbonate and/or arenite sequences overlying major unconformities. The genesis of such deposits, including the MVT deposits, has also been ascribed to fluid migration during crustal attenuation and intracontinental rifting (Sawkins 1976; El Aref and Amstutz 1983) and to different mechanisms of basin dewatering during diagenesis (Jackson and Beales 1967; Cathles and Smith 1983; Garven and Freeze 1985) and subsequent tectonism (Colman et al. 1989).

Available data show that the sandstone lead deposits along the Caledonian front were formed subsequently to sedimentary compaction and diagenesis, but prior to the latest nappe translations and orogenic collapse during the Scandian collision. Mixing of two compositionally different fluids, i.e. a hot basinal Na-Ca-Cl brine and a less saline fluid of uncertain origin was probably the main mechanism for the ore deposition which occurred by the filling of micro-vugs/pores and fractures and by replacement of gangue-mineral cement in the sandstone. The data can, in the opinion of the present authors, best be fitted to the listed models 2, 3 and 4, whereas model 1 can be excluded on the basis of similar fluids in both the disseminated and fracture-bound sphalerite ores. Although model 2 cannot be totally ruled out, we would argue that the balance of evidence is in favour of a formation related to tectonic expulsion of fluids during the Scandian orogeny, i.e. models 3 and 4.

Carbonate-hosted base-metal deposits

Subordinate dolomite-hosted Zn-(Pb) deposits occur along unconformities in the Upper Allochthon of the Sagelvvatn area in the central part of the Scandinavian Caledonides in northern Norway (Fig. 3). These deposits are hosted by Llandoverian calcareous dolomites with sphalerite, pyrite and galena (3:1:1) occurring as cement in dissolution breccias and as disseminations and thin bedding-parallel layers (Bjørlykke and Olaussen 1981). Comparable breccia deposits in the Ofoten area (Tårstad, Sinklia and Melkedalen deposits) contain only minor galena (Foslie 1949). All of these deposits have been affected by late Caledonian deformation, although the exact nature of this deformation is at present uncertain. The geology of the deposits indicates that they may represent examples of MVT ore formation and could possibly be of similar age and related to the same process of large-scale fluid migration that formed the lead sandstone deposits.

Vein deposits

Numerous generations of quartz veins, some of which are strongly folded, can be distinguished in the metamorphic rocks (Johansson 1980; Bennet and Barker 1992) and the granitic intrusives of the allochthons, indicating repeated fluid migration during the orogeny. However, only a small fraction of these veins contains any metallic mineralisation, and this almost invariably occurs associated with later shearing and fracturing. Available data indicate that most of the vein deposits formed subsequently to the main phase of Scandian nappe translation, but prior to the latest episode of extension when the formation of the foreland vein deposits (see later) is assumed to have occurred.

The deposits can be subdivided according to the dominant ore mineral(s), or into U, Be, Mo, W, polymetallic Ag-Au, Au, base metal and Fe deposits. When their geological environment of deposition is considered, most of them can be grouped into three categories: (1) deposits in areas with granitic intrusives and batholiths (granite-associated vein deposits, Fig. 21a), (2) deposits spatially related to dome structures and antiforms, frequently with cores of allochthonous and parautochthonous basement gneisses (basement-dome related vein deposits, Fig. 21b) and (3) deposits mainly in the autochthonous basement along and east of the Caledonian front (foreland vein deposits). Deposits occurring along thrust zones are present only locally. This subdivision does not imply that the modes of genesis of these groups of deposits are necessarily fundamentally different.

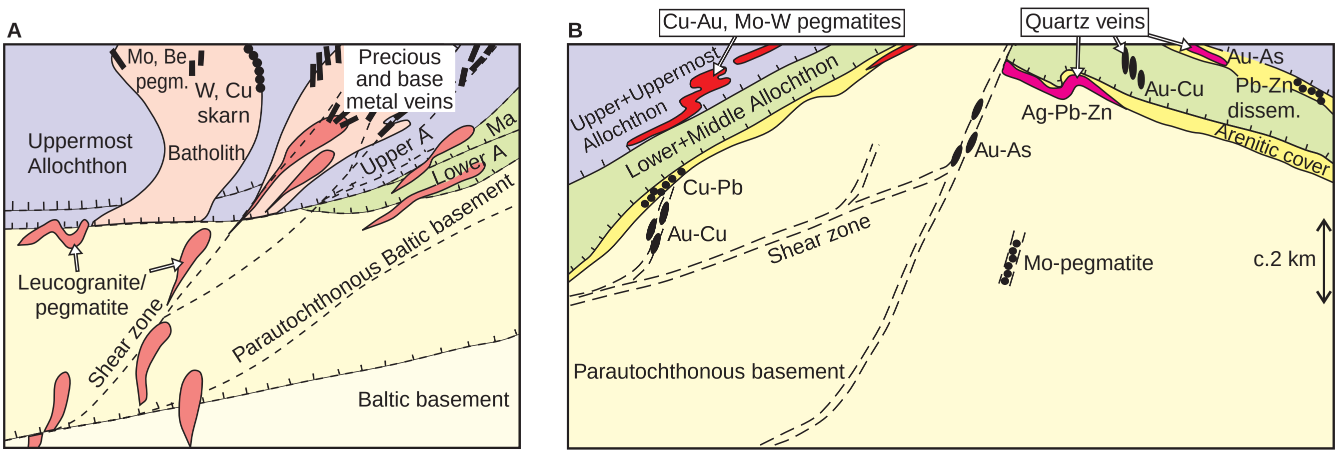
Granite-associated vein deposits

Granite-associated vein deposits occur within Late Ordovician and Early Silurian granitic batholiths and their country rocks. They show a wide spectrum of metals and metal ratios. However, only a few of them have so far been exploited, mainly for their contents of precious metals, e.g. the Svenningdal silver mines in the Bindal Batholith (Fig. 18) and the Bømlo gold mines at the margin of the Sunnhordland batholith (Fig. 22). Over the last decade, a number of the deposits has been re-investigated for their gold potential. They comprise mineralised fractures and quartz veins carrying mainly iron- and base-metal sulphides and in certain areas precious metals, and are invariably confined to high-angle ductile to semi-brittle shear zones and associated dilatational structures which are enveloped by wall-rock alteration such as silicification, sericitisation, carbonatisation and/or chloritisation.

The vein deposits spatially associated with the Bindal Batholith in the Helgeland Nappe Complex (HNC of *UmA*, Fig. 18) are characterised by one or more telescoped parageneses which comprise in order of decreasing age: (1) pyrrhotite with minor base-metal sulphides, (2) arsenopyrite, (3) pyrite and base-metal sulphides (Cu, Zn, Pb), (4) Sb-, As- and/or Bi-sulphosalts including Ag-rich phases and (5) marcasite with subordinate uraninite and thorite. Native gold is found associated with all of these assemblages except the last one, although it precipitated mainly together with arsenopyrite. Economic grades of Au, however, are only present in arsenopyrite mineralisation occurring in the endo- and exo-contact zones of the batholith massifs.

In the western part of the HNC, sulphide mineralisation is almost invariably hosted by competent rocks such as granitoids, granitic dykes and pre-existing metamorphic quartz veins, and not by supracrustal rocks which behaved ductilely during the formation of brittle ore structures in the potential host-rocks (Ihlen 1995). This suggests that these deposits, e.g. the Kolsvik Au-As deposit, formed at the transition between brittle and ductile tectonic regimes at a depth of 8–10 km, if a geothermal gradient of 35 °C/km is

Fig. 21a, b Schematic cross-sections showing the lithological and structural setting of **a** granite-associated deposits and **b** basement-dome related deposits



assumed (Sibson 1983). This feature is less pronounced in the eastern part of the HNC and the underlying nappe where the sulphides (e.g. Svenningdal, Fig. 18) locally fill fractures in marbles or form veins together with co-precipitated quartz in the metasedimentary rocks, suggesting a crust sufficiently cooled and unroofed to behave in a more brittle manner.

The *Kolsvik* deposit is the largest of the known shear-zone related Au-As deposits (Fig. 18) (Birkeland et al. 1993a) with an estimated ore potential of 0.5 Mt with 5 g/t Au (Ihlen 1993). The up to 2 m wide ore zones, which follow individual splays of a regional N-S trending shear zone at the contact of a granite massif, are hosted mainly by late leuco-granites and leuco-tonalites which intersect early mylonites relatable to the Scandian thrusting. As depicted in Table 2 the ores are affected by ductile shearing and brecciation as a consequence of late Caledonian extension and subsequent normal faulting.

Similar effects of late extension are also found in the polymetallic *Svenningdal* Ag-Au deposit which comprises a system of parallel quartz-ankerite-sulphide veins, confined to ESE-WNW trending dilatational structures at the margin of a granodiorite-tonalite massif (Vogt 1900; Birkeland 1993a). The up to 1 m wide sulphide veins which intersect deformed (D_1–D_3) schists and marbles as well as the granodiorite, yielded hand-cobbed ore containing about 400 g/t Ag, 5 g/t Au, 3% Zn, 1% Pb and 0.3% Cu. The total production of precious metals was 17 700 kg Ag and 37 kg Au (Poulsen 1964).

Numerous gold-bearing vein deposits are found in the Sunnhordland region both at the margin of the batholith and on both sides of the Hardangerfjord Fault Zone (Wulff and Stendal 1995), a major extensional detachment zone in the Caledonides of southwest Norway (Fig. 22) (Andersen and Andresen 1994). The highest density of gold-rich deposits is found within intrusives of the Lykling ophiolite on the island of Bømlo (Amaliksen 1980; Christensen and Stendal 1995) in the hanging-wall of the Sunnhordland Fault Zone. Mining took place during the last decades of the nineteenth century (Reusch 1888). Total production is estimated at 140 kg gold. Typical gold contents of 2.5 g/t are reported for bulk-samples of the veins, specimens of which have become well-known as museum exhibits. The gold mineralisation occurs along silicified and carbonatised faults and shear zones which are frequently located at the contacts of dolerite dykes. Up to one metre thick dilatational milky quartz veins and breccias are developed in the shear zones; both the veins and the altered wall-rocks contain native gold accompanied by Cu-sulphides and pyrite (Reusch 1888; Amaliksen 1980; E. Curti personal communication 1989; Wulff 1993; Christensen and Stendal 1995; Wulff and Stendal 1995).

Fluid inclusion and stable isotope data presently available for the vein and alteration minerals in the deposits in the Sunnhordland batholith (E. Curti personal communication 1989; Berg and Segalstad 1989; Wulff 1993; Christensen and Stendal 1995) indicate formation temperatures in the range 200 °C to 350 °C for the mineralisation. Precipitation seems to have occurred from low-salinity fluids with generally low, but highly variable, contents of

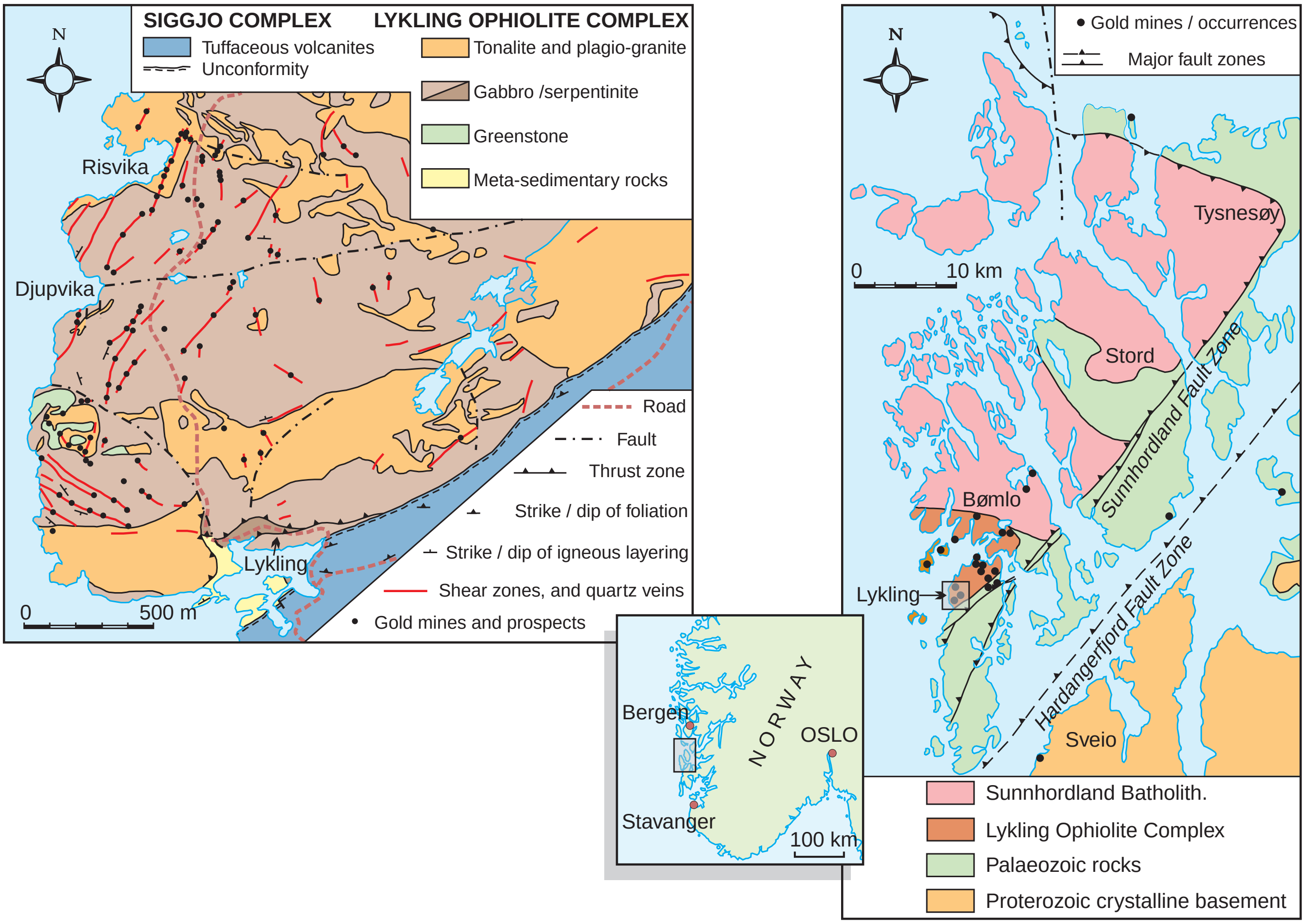


Fig. 22 Simplified geological map of the Sunnhordland region showing the distribution of registered gold mines and occurrences (*right*) with close-up map of the gold-vein system in the Lykling Ophiolite Complex at Bømlo (*left*). Compilation based on Reusch (1888), Amaliksen (1980), Andersen and Andresen (1994), and Wulff and Stendal (1995)

Table 2 Tectonic, intrusive and hydrothermal events in the evolution of the Kolsvik Au-As deposit. After Ihlen (1993)

Time	Tectonic	Intrusive	Hydrothermal
? Mesozoic ?	*Late faulting* Development of early breccias and late crush zones along reactivated faults		Clay gouge formation and argillic alteration. Stilbite-calcite-Chlorite cemented breccias and veins in granite with brick-red envelopes
Devonian	*Normal faulting (extension)* Reactivation of regional shear zone and related ore structures with early ductile and late brittle deformation along fault planes. Ductile shearing of tonalite dykes and mineralised (Au-As) cataclasites and breccias		Red granite alteration around quartz-chlorite and/or epidote veins. Marcasite ± uraninite veins. Pyrite deposition. Chlorite alteration, veining and cementation of late fault breccias. Chlorite-sericite veining and alteration
	Strike-slip faulting Semi-brittle dextral shearing with associated cataclasis, brecciation and opening of dilatational structures in the intrusives along a regional N-S trending shear zone off-setting early mylonite zones	*Post-D_3 intrusives* Dolerite dykes. Tonalite dykes.	Gold-arsenopyrite ± quartz veining and breccia cementation. Sericite alteration. Quartz-muscovite veining and associated muscovite alteration. Biotite alteration of monzodiorites. Milky quartz veins
Silurian	*D_3: Scandian deformation* Open folding with N- to NE-plunging axes affecting granite dykes. Mylonites formed along high-angle reverse faults (E dip) in the two-mica granite (Oksdal granite massif, Fig. 18)	Leuco-granite *Batholiths* Pegmatite dykes	Quartz veining and silicification with minor associated scheelite
Ordovician	*D_2: Nappe stacking* Isoclinal folding with associated nappe imbrication during medium-grade metamorphism	Two-mica granite. Quartz monzonite. Monzodiorite Anatectic tonalite Granodiorite	Skarn alteration (garnet-clinopyroxene) with associated pyrrhotite-chalcopyrite dissemination. Locally some scheelite. Late pyritisation and retrogradation

CO_2, i.e. typical mesothermal gold veins (Nesbitt et al. 1986). A magmatic source is considered for the carbon whereas the oxygen isotope ratios can be interpreted as representing a mixture of magmatic/metamorphic fluids and meteoric waters.

Basement-dome related vein deposits

Veins and, locally, skarn deposits occur associated with a number of domes in the interior of the Scandinavian Caledonides. The deposits are confined mainly to the basement-cover contacts and immediately overlying cover sequences, though deposits with a similar mineralogy are also found in the underlying basement (Fig. 21b).

The basement domes between Rana and Ofoten in northern Norway (Fig. 3) are known for their abundant occurrences of molybdenite mineralisation both in the basement rocks and in their cover sequences (Bugge 1963). Deformed granitic pegmatites occur in the Laksådalen area immediately above the contact to the basement gneisses and contain molybdenite, beryl, scheelite and uraninite (Bugge 1963; Lindahl 1984; Neumann 1985). They were mined for molybdenite which occurs together with subordinate scheelite along fractures and in carbonate breccias. In addition, scheelite-bearing skarns with minor molybdenite occur along the contact between marbles and hornblende gneisses above or at the same tectonostratigraphic level as the pegmatite swarm. Fluid inclusion studies and thermodynamic considerations suggest that the skarns were formed from extremely CO_2-rich solutions at 400–500 °C and above 2 kbar (Larsen 1991). Pegmatites comparable to those in the Laksådalen area are also found in the cover sequence to the Vestranden Gneiss Complex (VGC) in the Bindal district. One of them, bearing molybdenite, crosscuts the basement-cover contact and yields a U-Pb zircon age of 401 ± 3 Ma, i.e. Early Devonian (Schouenborg 1988). Fracture-bound uraninite-pitchblende mineralisation containing locally subordinate arsenopyrite, molybdenite and base-metal sulphides, is encountered in Paleoproterozoic granitic rocks of the windows in northern and north-central Norway. Pb-isotope systematics suggest deposition during the span of the Scandian orogeny (Stuckless et al. 1982; Lindahl 1983).

Base-metal deposits which generally contain small and erratically distributed concentrations of base-metal sulphides, comprise mainly mineralisation associated with quartz-dominated veins (Johansson 1980, 1983b) and semi-ductile shear zones. The latter type is invariably located in the interior of the basement domes and locally contains visible gold which is intergrown with Cu-sulphides (Tysfjord and Glomfjord domes in northern Norway, I. Lindahl personal communication 1994; the Åmotsdal dome in southern Norway, K. Isbrekken personal communication 1994) and arsenopyrite (Gautelis deposit in the Rombak window of northern Norway, Skyseth and Reitan 1995). The two latter authors argue that the gold and arsenic were introduced by mesothermal (220–320 °C), highly saline, brines (34–40 wt. % equivalent NaCl) related to late Caledonian retrogradation and were precipitated in response to fluid reactions with Early Proterozoic marbles.

The quartz-vein deposits are especially well developed along the tectonised basement-cover contacts in the autochthonous and allochthonous units of the Nasafjell window (Fig. 23) (Johansson 1980, 1983b; Often 1982) and the Grong-Olden culmination (unpublished NGU data). Close to and at the basement contact, the mineralisation occurs associated with sheared, fractured and vuggy parts of milky quartz veins and lenses. Some veins are Ag-rich and dominated by galena, sphalerite and Sb-sulphosalts (Nasafjell, Johansson 1980, 1983b) whereas others contain gold together with arsenopyrite (Graddis, Often 1982) or pyrite-chalcopyrite (Sibirien, unpublished NGU data).

Johansson (1980, 1983a) considered the vein deposits of the Nasafjell basement dome to be of Late Caledonian age, and that the veins post-date the main episode of Scandian thrusting but were affected by reversed nappe movements probably related to late gravity collapse of the nappe pile. Sulphur isotope data suggest a mixture of sulphide and sulphate sulphur leached both from the granitic basement and the supracrustal and intrusive rocks of the Caledonian nappes (Johansson 1984). It is noteworthy that the basement-dome and granite-associated deposits show similar mineral parageneses and temporal development in relation to the late Caledonian tectonites. This may indicate that the fluids and related ore-forming processes were not fundamentally different in the two geological environments.

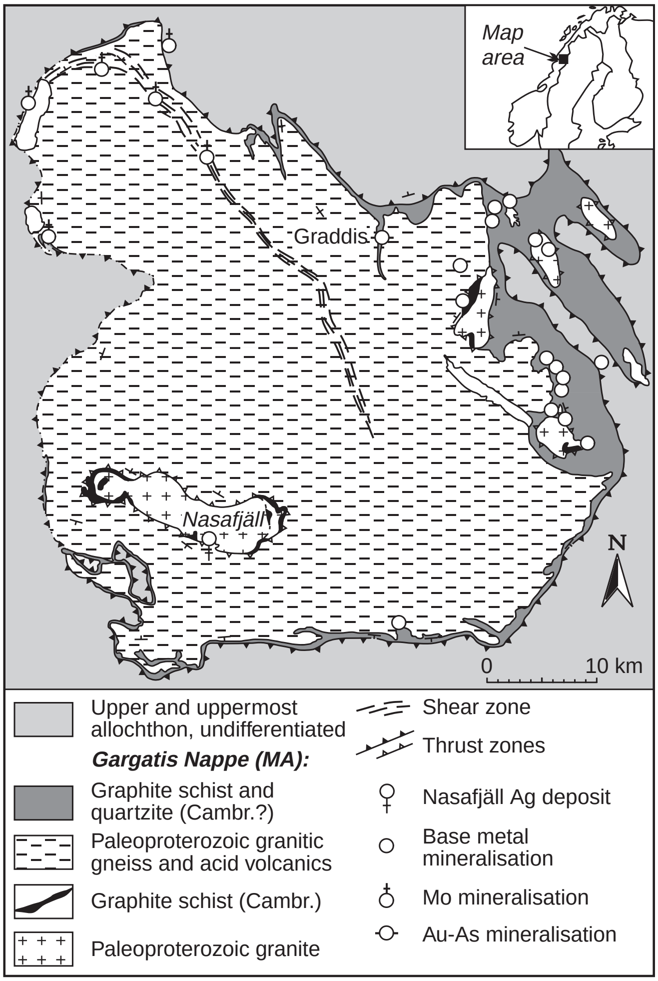


Fig. 23 Simplified geological map of the Nasafjäll basement dome, showing the distribution of epigenetic ore deposits. Geology compiled from Thelander et al. (1980) and Gjelle (1988). Ore deposits from Johansson (1980), Often (1982) and unpublished NGU-data

Foreland vein deposits

The foreland vein deposits comprise centimetre- to metre-wide veins and fault-breccias containing galena and sphalerite in a gangue of mainly calcite and, usually, subordinate amounts of quartz, fluorite and/or barite. They are related to basement faults in areas where these intersect Caledonian thrust planes and the Neoproterozoic erosional unconformity along the Caledonian front (Bjørlykke 1973; Nordrum and van der Wel 1981; Johansson 1983b, 1984; Romer 1992). Some deposits are also found at the margin of Neoproterozoic rift-basins further to the east (Grip 1978; Sundblad 1989; Fedotova 1990) whereas a few occur associated with basement domes in the interior of the Caledonides (H. Stendal personal communication 1988; Romer 1992, 1994).

The veins in the *Åkerlandet* deposit, at the Caledonian front just east of Dorotea, give fluid-inclusion homogenisation temperatures between 75 °C and 165 °C. The mineralisation is probably caused by mixing of two hot saline brines (32–37% and 14–20% wt. equivalent NaCl, respectively). The stable isotope ratios indicate a significant contribution of reduced carbon to the ore-forming fluids which probably derived their sulphur by leaching of sulphides in the granitic basement (Johansson 1984). The veins are apparently unaffected by deformation and locally occur along normal faults offsetting the sandstone lead deposits (Johansson 1983b, 1984). Therefore, it is assumed that the foreland deposits along the Caledonian front post-date the formation of the sandstone lead deposits. The age of the deposits occurring further to the east is more uncertain. The occurrences of both sandstone lead deposits and calcite-vein deposits along the Caledonian front may indicate a genetic link between them (Romer 1992). In addition, both seem to have been formed by fluid mixing. The foreland vein deposits probably represent the cessation of tectonically induced fluid flow associated with the continental collision.

Source rocks of the vein deposits

The source rocks for the metals in the vein deposits have been studied by means of Pb-isotope analyses of sulphides and native gold (Johansson 1983a; E. Curti personal communication 1989; Romer 1992, 1994; Birkeland et al. 1993a). The Pb-isotope ratios of the vein deposits fall on the same linear trend as the sandstone lead deposits with the granite-associated and basement-dome deposits being less radiogenic and the foreland deposits being generally more radiogenic than the sandstone deposits.

Pb-isotope ratios of galena, chalcopyrite and arsenopyrite in the Kolsvik and Svenningdal deposits fall within the range of ratios for feldspar in the surrounding granitic massifs (Birkeland et al. 1993a, b). This indicates that the ore lead is derived from the granitic intrusives, either through exsolution and expulsion of magmatic water during crystallisation of Devonian leuco-granites and pegmatites or through leaching by fluids of unknown origin. A similar conclusion was also drawn by Curti for the Bømlo gold deposits. The Svenningdal deposits also contain sulphides with higher ^{206}Pb/^{204}Pb ratios (Birkeland et al. 1993a). The low ^{208}Pb/^{204}Pb ratios of these sulphides indicate contribution from an additional source where selective leaching of uranogenic lead had occurred.

The Pb-isotope composition of galena in the basement-dome related and foreland vein deposits in the Rombak and Nasafjell basement domes and elsewhere in the Swedish Caledonides gives indication of mixed sources (Johansson 1983a; Romer 1992, 1994). The lead in the veins represents mixing between Caledonian (non-radiogenic) and Svecokarelian or Paleoproterozoic (radiogenic) lead in various proportions between 0 and 100%. The lead in the Nasafjäll deposits is considered to be derived totally from the surrounding granitic basement rocks. The strong enrichment of radiogenic lead in the foreland veins is inferred to be caused by selective leaching of radiogenic non-feldspar lead (Johansson 1983a).

Summary and comparison with other sectors of the Caledonian-Appalachian Orogen

The framework of Caledonian metallogeny in Scandinavia is a period of plate movements which started with Neoproterozoic rifting and break-up of a megacontinent, followed by formation of an extensive Iapetus ocean between a northwestern (Laurentia) and a southeastern (Baltica) plate. Plate convergence with subduction of oceanic crust commenced before the Early Ordovician and led to the development of arcs and arc-basins of varying maturity and at different locations within the ocean basin. By the end of the Ordovician, the remaining basin had become narrow and experienced a similar history of sedimentation. Initial, oblique, interference of the converging continent edges led to a period of rift-type magmatism in the sedimentary basin at about the Ordovician-Silurian boundary and coeval emplacement of granitic batholiths into the continental crust and accretionary prism of the Laurentian plate margin. The batholithic magmatism, which was associated with the westward subduction of Baltica, progressively moved inland from the outer margin of Laurentia. This caused the present dominance of Middle Silurian to Late Devonian intrusives and Devonian volcanics in the Caledonides outside Scandinavia, and Late Ordovician to Early Silurian plutons in the obducted terranes of the Scandinavian sector. The ultimate destruction of the subduction system and cessation of the Caledonian orogeny occurred during the Late Devonian. A synthesis of this complex paleotectonic-metallogenic framework is shown in Fig. 24 (see also Fig. 2).

Although comparable ore-forming processes operated in different parts of the Caledonian-Appalachian belt they differ in age and importance, due to the somewhat diachronous and diversified evolution of the individual segments. The metallogeny of the Scandinavian Caledonides therefore shows large contrasts as well as significant similarities when compared to other parts of the orogen and other Early Paleozoic mountain belts.

Sedimentary ores

Fe deposits

Stratabound, mainly stratiform, deposits of oxidic iron ores are important aspects of the metallogenic development of the Scandinavian Caledonides. They comprise two main types; the metasedimentary magnetite-hematite ores in the Dunderland Group of the *UmA* in Nordland and Troms, and the volcanite-hosted magnetite-(pyrite-chalcopyrite) ores in the *UA* of the Fosen district of Trøndelag (see later).

Correlation and comparison of the Dunderland-type iron ores with iron formations in other Caledonide-type orogens has been difficult, due to uncertainty regarding their age (both Cambro-Silurian and late Precambrian ages have been suggested in the past). Although their lithological and paleotectonic environments of deposition appear comparable to those of the early Phanerozoic iron ores of the Clinton-Wabana type of the Appalachians of Canada and the USA (see, e.g. Gross 1965; Kimberley 1978; Guilbert and Park 1986), the recent age dating of associated metacarbonate formations in the *UmA*, strongly indicates a Latest Precambrian (Neoproterozoic) age.

Sedimentary iron formations of this age are scarce on a world scale (see, e.g. Meyer 1981). There is a marked peak in the number of occurrences of this type of ore between about 2.75 Ga and about 1.9 Ga, none between 1.8 Ga and 0.8 Ga, but a minor peak from here to about 0.6 Ga. This renewal of BIF formation in the Neoproterozoic coincided approximately with global low-latitude glaciation during which anoxic oceans could have developed again on a large scale (Kirschvink 1992).

A recent study by Klein and Beukes (1993) mentions only three examples of Neoproterozoic iron formations in the world; in the Rapitan Group of northern Canada, in the Urucum region of Brazil and in the Damara Supergroup, Namibia. Again, according to Klein and Beukes (1993), these Neoproterozoic banded iron formations "are unique in their intimate association with glaciogenic siliciclasts ...." among other features. So far no evidence of glaciogenic components has been found in the Dunderland Group and its correlatives in Scandinavia. However, a complicating factor is the intense deformation and metamorphism that the ores and their host rocks have undergone. These latter effects also make it difficult to reconstruct the original, depositional fabrics, and perhaps mineralogy, of the *UmA* ores, and to compare these with the well-described, "virtually unmetamorphosed" ores of, e.g. the Rapitan Group (Klein and Beukes 1993).

Sediment-hosted sulphide deposits

Stratabound sulphide ores hosted by sedimentary sequences, with or without extrusive or intrusive magmatic additions, were formed at several stages of the orogenic development. Due to later deformation and metamorphism it is not possible always to be certain of the proportion of magmatic components; the distinction between VMS and SMS (Sedex) character is sometimes rather artificial. Recent work on the host rocks of the Bleikvassli ore, for example, (Bjerkgård et al. 1997) indicates that there may be a greater proportion of magmatic (volcanic) components than hitherto recognised.

The earliest representatives of ores until recently regarded as Sedex occur in the nappes of the *UmA*, where the interpreted paleotectonic environment of deposition was that of the Laurentian plate margin during initial break-up and rifting of the Proterozoic supercontinent in Neoproterozoic to Cambrian times. The

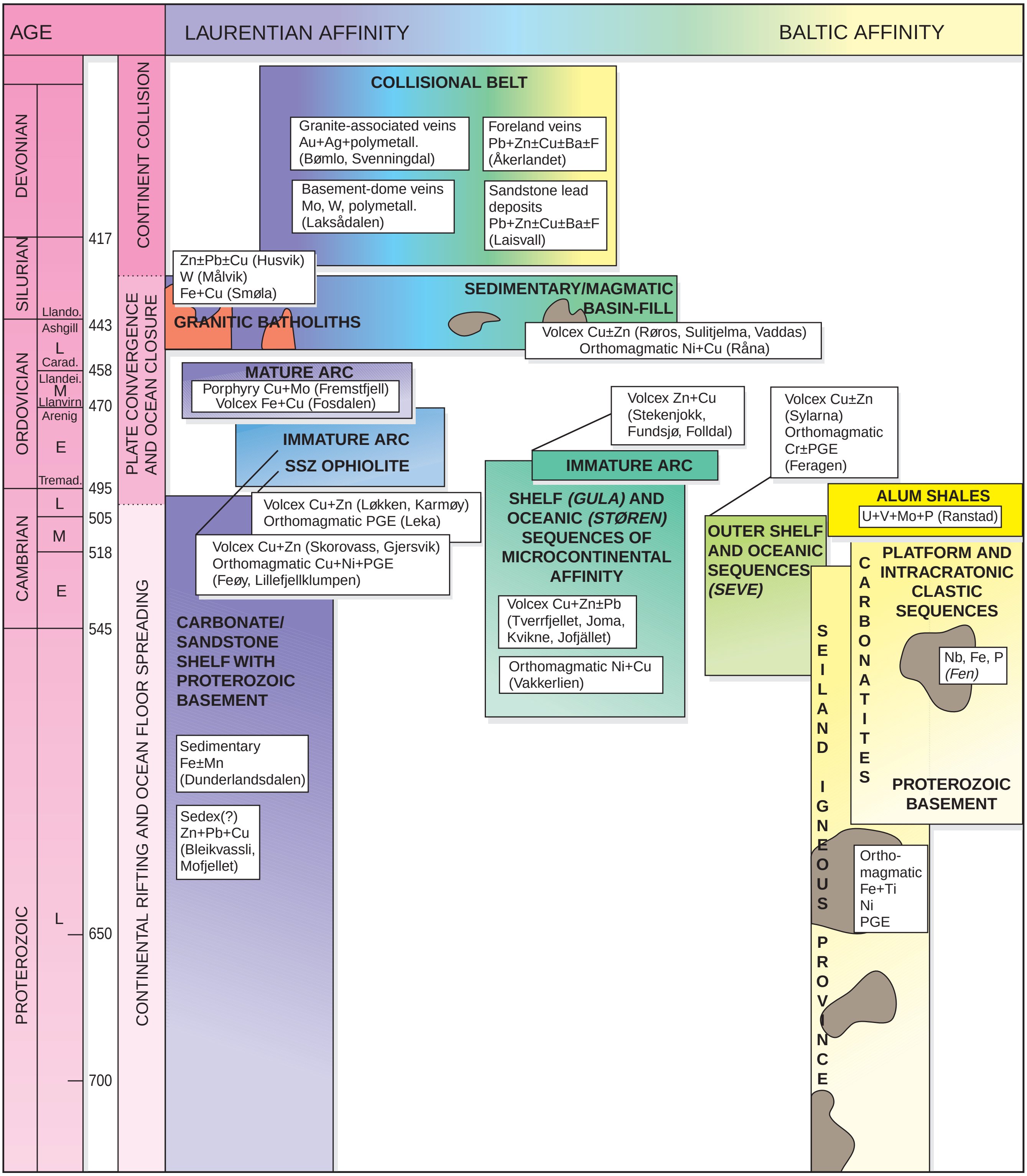


Fig. 24 Diagram illustrating the relationship between the temporal and the paleotectonic/paleogeographic development of metallogenetically significant settings in the Scandinavian Caledonides. Time scale used here and in the text is from Tucker and McKerrow (1995)

problems of age determination of the rocks of the *UmA* have been pointed out earlier in this study; we are up against the same problems as we met when trying to compare the metasedimentary iron ores of the *UmA* with examples outside Scandinavia.

Massive, stratiform sulphide ores of the Zn-Pb-(Cu) and Cu-Zn types are representative of this stage, with the most important examples, such as Bleikvassli and Mofjell, belonging to the first type. However, pyritic deposits with low Cu-Zn values are also numerically important in the *UmA* and maybe of more significance from a correlation point of view. Stephens et al. (1984) for example, correlate the *UmA* stratabound sulphide ores and their lithological-paleotectonic environments with, among others, the major Neoproterozoic Cu-Zn pyritic/pyrrhotitic deposits of the Ducktown, Great Gossan Lead and Ore Knob districts of the southern USA Appalachians. A similar setting is also assigned to important barite and base-metal (Pb-Zn) deposits, such as Aberfeldy, in the Middle Dalradian rocks of the Scottish Caledonides. Barite is not an important component of the Scandinavian *UmA* stratabound sulphides, though its presence (2–3%) in the Mofjell ore points to a geochemical similarity with the Scottish Dalradian ores.

Metalliferous black shales

Considerable potential resources of U, V, Mo and Ni as well as of shale oil, exist in Scandinavia in the form of Middle Cambrian to Tremadocian shale facies sediments (alum shales). These were deposited on the Baltic plate following the establishment of a passive, Atlantic-type plate margin during a period of gradual submergence and very slow marine deposition (Andersson et al. 1985).

This shale facies can be recognised all the way from Finnmark in the north to Skåne in the extreme south. Equivalents are also present in the Anglo-Welsh Region of Great Britain, the Avalon zone of Newfoundland and in Nova Scotia, indicating that the facies accumulated along the southeastern margin of the early Iapetus ocean. This was separated by a considerable distance from the more equatorial Laurentian margin on which a westwards-onlapping Lower Cambrian sandstone facies was succeeded by a monotonous carbonate bank facies, extending at least from east Greenland via northern Scotland to the western front of the Appalachians in North America, and lasting from the Middle Cambrian into the Middle Ordovician (Gee et al. 1974).

Little information is available regarding the resources of the alum shale equivalents in the Anglo-Welsh and Canadian areas. The highest U content quoted by Andersson et al. (1985), 150 ppm, occurred in the Upper Cambrian Monk's Park Shales of Warwickshire, which compares unfavourably with maximum contents in the Scandinavian shales.

Volcanogenic massive sulphide deposits

By far the most important Caledorian ores in Scandinavia, in a historic-economic perspective as well as in abundance, are the numerous volcanogenic massive sulphide deposits, in a broad sense, representatives of which entered the scene at intervals through most of the Caledonian orogenic cycle. Five types of paleotectonic environments have been identified as prolific hosts to VMS deposits:

Ocean basin extension (1)

Their earliest representatives playing a significant role were inferably formed in an ocean crust to continent margin transition zone in relation to ocean basin extensional volcanism. Including major ores such as Joma and Tverrfjell and smaller ores such as at Kvikne, these mixed volcanic- and sediment-hosted ores constitute one of the most important VMS subtypes in the Scandinavian Caledonides, yet are perhaps the least constrained as regards exact paleotectonic and paleogeographic position. Their general lithological setting compares to that of the Gander Terrane of the northern Appalachians, where similar but metallogenically less important successions, are interpreted to represent an apron of continental shelf, rise, slope and abyssal-plain sediments that accumulated along the northwestern margin of the Avalon microcontinent in Neoproterozoic and Early Paleozoic times (Schwab et al. 1988; Van Staal and Fyffe 1991). The significance of this similarity is uncertain, however, since rock successions with characteristic Avalonian affinity such as Neoproterozoic-Cambrian, bimodal, ensialic arc-type volcanites are not known in the Scandinavian Caledonides.

Ophiolites (2)

The important class of *Cyprus-type* or ophiolite-hosted VMS deposits also played an important role in Caledonian metallogeny, being represented, among others, by the Løkken ore-body (30 Mt) which is a world-class deposit. In contrast to the above-mentioned group of mixed sediment-volcanite related deposits, the ophiolite-hosted ones are situated in oceanic crust consisting of a thick basaltic sequence underlain by sheeted dykes and corresponding plutonic rocks. They entered the scene after the onset of regional plate convergence in Late Cambrian-Early Ordovician times. Thus, on a regional scale they were obviously related to a destructive plate margin, probably on the Laurentian side of the Iapetus ocean, although on the more local scale these deposits were associated with tensional processes within back-arc or intra-arc basins. Their age and setting is similar to that of VMS deposits of supra-subduction zone (SSZ) ophiolites in the Notre Dame Subzone of the Dunnage Zone of the Newfoundland Appalachians, such as Tilt Cove and Rambler (Swinden 1991 and references therein). However, all these are small in comparison with the Løkken deposit.

Immature arc (3)

Immature, oceanic arc-type, volcanism was broadly coeval with the Early Ordovician SSZ ophiolites and represents one of the most prolific VMS settings in the Caledonides. One arc system developed in close spatial association with the SSZ ophiolites on the Laurentian side of Iapetus and comprised thick volcanic sequences which are hosts to several Zn-Cu massive sulphides of the order of 1–10 Mt, of which Skorovas is the biggest known. Ore deposition was related to arc rifting characterised by felsic or intermediate volcanism within the mafic-dominated sequences. The similarity in age and paleotectonic setting to that of major VMS deposits such as Point Leamington in the Notre Dame Subzone of the Dunnage Zone of central Newfoundland (Swinden 1991) is noteworthy.

Another Early Ordovician, immature, arc system is thought to have developed closer to the Baltic side of the Iapetus ocean where bimodal volcanism was accompanied by deposition of thick, often graphitic, tuffite sequences. VMS deposits of the Zn-Cu, often Zn-rich, type are numerous and commonly related to volumetrically significant felsic magmatism. The largest deposit is Stekenjokk-Levi (26 Mt). Correlation with other parts of the Caledonian-Appalachian orogen is uncertain although there are similarities to Late Cambrian-Early Ordovician arc sequences of the Exploits Subzone of the Dunnage Zone (Tally Pond and Tulks Hill volcanics).

Mature arc (4)

Mature arc and arc basin sequences, of active continental margin affinity, comprising mafic and intermediate through to felsic calc-alkaline and shoshonitic volcanic rocks mixed with sedimentary, often calc-rich, lithologies continued to evolve above the Laurentian margin at least through the Middle Ordovician. Such sequences are represented several places in the Central and Southern Scandinavian Caledonides, though major VMS ores seem to be scarce or absent. Mineralisation is mainly in the form of extensive and very abundant Fe-formation with variable sulphide and base metal content; *Kuroko-type* Zn-Pb-Cu VMS deposits, characteristic of this type of setting elsewhere in the world (Franklin et al. 1981), seem to be economically insignificant in Scandinavia. Nevertheless these sequences represent a setting and time period of potential interest, being directly correlatable with the very important ore-hosting Buchans-Roberts Arm volcanic belt in the Notre Dame Subzone of the Dunnage Zone of central Newfoundland (Kirkham 1987; Swinden 1991).

Stratabound deposits of Fe oxides (mainly magnetite), with varying proportions of iron and base-metal sulphides, are more abundant than VMS ores in the mature arc and arc-basin sequences in the Scandinavian Caledonides. In places, magnetite-rich layers are interbanded with massive, base-metal-rich sulphide layers in deposits which must be classed as of the VMS type, and consensus now (following Carstens 1955) regards these Fe-formations as a mainly oxide facies of the general VMS deposition. Magnetite-dominated deposition is especially well developed in the Fosen district of central Norway.

These volcanite-hosted magnetite-(sulphide) ores have many features in common with the Ordovician iron formation along the massive sulphide-bearing *Brunswick horizon* (Luff et al. 1993) of the Bathurst Camp, N.B., although their paleotectonic setting is probably different, the latter being related to felsic and mafic rift magmatism during back-arc basin opening along the continental margin of Avalonia on the southeastern side of Iapetus (Fyffe et al. 1990; Van Staal et al. 1992). A large mass of such an iron formation carrying a small, footwall, body of massive sulphides, was formerly worked at the Austin Brook Mine, about 1 km south along strike from the large (12 + Mt) Brunswick No. 6 ore body (see e.g. Boyle and Davis 1964; Saif 1983). Gross (1965) cites the Austin Brook iron formation as a Phanerozoic example of Algoma-type iron-formation, while Kimberley (1978) lists the Austin Brook occurrences in his paleoenvironmental classification of iron formations as "shallow-volcanic-platform iron formation". This is the same group in which the Devonian Lahn-Dill (Germany) iron formation is placed; a comparison between the latter and the Fosen ores was suggested by Vokes (1988), though the German ores appear to show no relation to VMS deposition.

Direct correlatives of the New Brunswick deposits and the paleotectonically comparable Avoca orebody in the Irish Caledonides (Stephens et al. 1984; McConnell et al. 1991) have not been identified within the Scandinavian sector of the mountain belt. Sequences of comparable lithology and age, including significant volumes of felsic volcanites of Middle to Upper Ordovician age (Roberts et al. 1984 and references therein), occur in the western Trondheim Region directly east and south of the Hølonda terrane from which they are separated by a thrust fault. However the exact paleogeographic position and metallogenic significance of these units remain to be solved.

Mixed sedimentary-volcanic sequences (Besshi-type deposits) (5)

The sequentially latest type of important, often rich, Cu-Zn or Zn-Cu VMS deposits entered the metallogenic scene near the Ordovician-Silurian boundary. Their association with rift-type, mafic and more local felsic, volcanism and intrusions in thick clastic sequences is interpreted by the present authors to reflect a paleotectonic setting characterised by transcurrent movements and development of local transtensional regimes and fault-controlled sedimentary basins during the initial suturing of the Baltic and Laurentian continent margins. Numerous individual deposits, such as those of the Røros and Sulitjelma districts, have been important past-producers. These ores show many similarities of lithological setting, age and deposit-characteristics to some of the copper-dominated ores of the USA Appalachians, for example, those of the Vermont Copper Belt (Slack 1993) and have sometimes been referred to as Besshi-type sulphides. Their depositional setting compares to some extent to that of presently-forming sulphides in the Guaymas basin in the Gulf of California and the western Woodlark Basin, where rapidly accumulated sediments covering a spreading ridge have a strong control on ore formation (Binns et al. 1987; Koski 1990).

Orthomagmatic deposits

In Scandinavia, orthomagmatic deposits are thought to be related to several stages of the development of the Caledonides. Intrusive carbonatite-alkaline complexes dating from the period of initial rifting and continent separation (late Neoproterozoic-Early Cambrian) are present both within the Caledonides (Seiland Igneous Complex) and on the Baltic plate to the east (Fen, Alnö). Ores of both Fe and Nb have been worked at Fen in the past, but the other complexes have so far shown limited economic potential.

The approximately 30 carbonatite complexes in Northern Europe range in age from about 2500 to 356 Ma (Wooley 1989). Of these, only those mentioned have yielded early Caledonian ages, though Wooley considers that eight carbonatites in northern Finland and on the Kola Peninsula, ranging in age from 430 to 356 Ma can be considered as 'a late Caledonian group'. In North America, the area between the western Appalachian Front and the Grenville Front is the locus of a large number of carbonatite complexes (Wooley 1989). These include several which have been dated to the period we are considering here, but others, including the economically important Oka deposit, are of a much younger age. The only carbonatite within the North American Appalachians is a minor occurrence in New Jersey, where associated nepheline syenites fall age-wise in the interval 437–424 Ma, similar, says Wooley, to those associated with the Late Ordovician Taconic orogenic phase.

Scandinavia is poorly endowed with Fe-Ti-V deposits of strictly Caledonian age; the very important deposits of these metals in this region are dominantly of Mesoproterozoic age, a feature also shared with the equally important North American examples on the Laurentian Plate. The only unequivocal examples of Caledonian (*sensu stricto*) deposits of this type are disseminated Fe-Ti-oxides in mafic intrusive rocks of the SIP in northern Norway.

Orthomagmatic Ni-Cu-S deposits are, on the other hand, numerous and widespread along almost the whole length of the orogen in Scandinavia. While some are undoubtedly of Precambrian age, others can be referred to one or other of the three main stages in the Caledonian cycle. The most important ones (e.g., Bruvann, Råna) despite their extremely low PGE values, are associated with mafic-ultramafic intrusions related to the initial plate collision at the Ordovician-Silurian boundary. Smaller, but sometimes relatively PGE-rich, Ni-Cu deposits are found in intrusive bodies related to the stage of ocean spreading or to SSZ ophiolites; ultramafic cumulates in the latter also contain more extensive, but low-grade, PGE mineralisation.

Orthomagmatic mineralisation analogous to that in the Scandinavian Caledonides is present, e.g., in variably disrupted ophiolite suites of Early Ordovician age in the Dunnage/Gander zones of the Canadian Appalachians (Swinden 1993). Deposits present in the ultramafic and mafic plutonic parts of these ophiolites include occurrences of chromite in Newfoundland and Eastern Quebec; minor occurrences of nickeliferous, locally PGE-rich, sulphides in the Bay of Islands (NF) complex and numerous Ni occurrences associated with dismembered ophiolitic rocks in Gaspé. Analogous deposits of copper-nickel and chromite, by modern standards of only minor importance, occur sporadically along most of the length of the US Appalachians (Feiss and Slack 1989). Ni-bearing deposits in southeast Quebec may be related to the early stages of the Taconic orogenic phase, corresponding in time to the emplacement of the Råna Complex in northern Norway.

Epigenetic deposits

The epigenetic ore deposits in the Scandinavian Caledonides comprise porphyry-type, skarn, sandstone lead, carbonate-hosted base-metal, and syn- to post-collision vein deposits in order of decreasing age.

Porphyry-type Cu-Mo-deposits

Porphyry-type Cu-Mo mineralisation occurs relatively widespread in the Caledonian-Appalachian belt (Hollister et al. 1974; Rice and Sharp 1976; Schmidt 1978; Plant et al. 1983; Talbot and Max 1984; Feiss and Slack 1989; Ruitenberg and McCutcheon 1993), though few of them are of economic importance. The mature arc setting of the Fremstfjell deposit in Norway is possibly comparable with that of the Mariner deposit in the Avalon terrane of Nova Scotia (Hollister et al. 1974). Both deposits conform to the plutonic-type porphyry model defined by McMillan and Panteleyev (1980).

Most porphyry-type mineralisation in the belt, including the economic porphyry Cu deposit at Mines Gaspé, Quebec (Allcock 1982) and the porphyry W-Mo-Sn deposit at Mount Pleasant, New Brunswick (Kooiman et al. 1986; Sinclair et al. 1988), is related to Devonian plutons and sub-volcanic intrusives which are generally absent in the Scandinavian Caledonides.

Skarn mineralisation

Contact-metasomatic skarn deposits in the Caledonian-Appalachian belt are generally small and of no economic importance. The only exception is the porphyry-related copper skarns at Mines Gaspé (Einaudi et al. 1981;

Allcock 1982). The Målvika W deposit, is comparable with scheelite-bearing skarns at the contacts of Late Ordovician granodiorite plutons in East Greenland (Harpøth et al. 1986). The abundance of ferrous minerals in the Caledonian scheelite skarn deposits indicates that they belong to the class of reduced tungsten skarns as defined by Newberry (1979), formed at great depth or in carbonaceous host rocks. Oxidised skarns formed at shallower depth are apparently missing in the Scandinavian sector of the belt.

Sandstone-hosted base-metal deposits

Sandstone-hosted base-metal deposits of major economic importance seem to be unique for the Scandinavian sector of the Caledonian-Appalachian belt. Disseminated Pb-Zn-(Cu)-Ba ores in sandstones are rare in the Laurentian succession, though basinal and platformal arenite-shale sequences of comparable age and geotectonic setting were deposited on both sides of Iapetus (Scott 1976; Harpøth et al. 1986). However, as indicated by Rickard et al. (1979), the lead sandstone deposits along the Caledonian front may represent an aberrant member of the MVT deposits which locally are underlain by mineralised Cambrian sandstones in the Appalachian foreland (Snyder and Gerdemann 1968).

The proposed models for the formation of sandstone lead deposits in Scandinavia are in broad terms similar to suggestions made for the formation of Pb-Zn-Ba vein deposits, which are hosted in allochthonous Cambrian sandstones at the margin of the Appalachian belt along the lower Saint Lawrence, Quebec (Beaudoin et al. 1989; Williams-Jones et al. 1992). These authors argue that the veins, locally surrounded by minor sulphide dissemination, were formed in response to large scale, tectonically-induced expulsion of reduced metalliferous brines which interacted with sulphate-bearing fluids at the site of ore deposition. The fluid migration is assumed to be related to the late stages of the Taconic orogenic phase. In this scenario, the Pb-Zn vein deposits, which occur along the sub-Cambrian peneplane in the Ottawa Valley region (Sangster and Bourne 1982) and at Rossie, New York (Ayuso et al. 1987), could be correlated with the foreland veins in the Scandinavian Caledonides.

The carbonate-hosted base-metal deposits found in the northern and axial part of the Scandinavian Caledonides, represent possible examples of MVT deposits occurring widespread along the western margin of the Appalachian orogen (Laurence 1968).

Vein deposits

Syn- to post-collisional vein deposits, mainly of Devonian age, occur scattered throughout the length of the Caledonian-Appalachian belt (Dunham et al. 1978; Williams and McArdle 1978; Stendal and Ghisler 1984; Harpøth et al. 1986; Feiss and Slack 1989; Kish and Stein 1989; McArdle 1989; Ruitenberg and McCutcheon 1993). The vein deposits, which are of some interest in view of their contents of gold, and to a lesser extent, silver, were precipitated in association with transpressive tectonism during the late stages of the continental collision (Plant et al. 1991; Kontak and Smith 1993; Ruitenberg et al. 1990).

Though the auriferous veins differ considerably on an inter-deposit scale, they can be grouped according to their regional characteristics, which are apparently specific for the individual segments of the orogen. The gold-vein deposits in Scandinavia which occur mainly at the margin of allochthonous batholith massifs, are different from those in East Greenland (Harpøth et al. 1986) and the Orthotectonic Caledonides of United Kingdom (Simpson et al. 1989; Plant et al. 1991) and Ireland (McArdle 1989) where the majority of the deposits are found within Neoproterozoic meta-sedimentary successions (Eleonore Bay and Dalradian supergroups) and in close proximity to major faults and underlying basement structures. Most of the auriferous deposits in the Appalachian belt in Canada are situated in Paleozoic volcanic-sedimentary sequences proximal to major wrench and thrust faults defining terrane boundaries (Tuach et al. 1988; Ruitenberg et al. 1990; Tuach 1992; Dubé and Lauzière 1993). In spite of the widespread development of turbidites in parts of the Scandinavian Caledonides, turbidite-hosted gold deposits (Boyle 1986) analogous to those in the Meguma Terrane of Nova Scotia (Kontak and Smith 1993) and in the Paratectonic Caledonides of Wales (Annels and Roberts 1989) are apparently missing.

Acknowledgements The authors are most grateful to the late Dr. Georg Bauer for his patience and inspiration through the many stages leading to completion of the present contribution, and to Mr. and Mrs. Bauer, without whose fruitful initiative this would never have come into being. We also wish to express our thanks to the many colleagues, especially at the Geological Survey of Norway, with whom we have dicussed the various aspects of Caledonian geology during the compilation of this manuscript. We are particularly indebted to I. Lundquist and A.I. Johannessen for their help with the drafting. Support provided by the Geological Survey of Norway is gratefully acknowledged.

"I have omitted all those things which I have not myself seen, or have not read or heard of from persons upon whom I can rely. That which I have neither seen, nor carefully considered after reading or hearing of, I have not written about. The same rule must be understood with regard to all my instruction, whether I enjoin things which ought to be done, or describe things which are usual, or condemn things which are done." Georgius Agricola (1556).

References

Agricola G (1556) De Re Metallica. Translated by Herbert Clark Hoover and Lou Henry Hoover, Dover Publications, New York 1950, pp XXX-XXXI

Allcock JB (1982) Skarn and porphyry copper mineralization at Mines Gaspé, Murdochville, Quebec. Econ Geol 77: 971–999

Amaliksen KG (1980) Gullforekomster på Bømlo. Nor Geol Unders Rpt 1750/35A, 48 pp

Andersen T (1983) Iron ores in the Fen central complex, Telemark (S. Norway): petrography, chemical evolution and conditions of equilibrium. Nor Geol Tidsskr 63: 73–82

Andersen T, Taylor PN (1988) Pb isotope geochemistry of the Fen carbonatite complex, SE Norway: age and petrogenetic implications. Geochim Cosmochim Acta 52: 209–215

Andersen TB, Jansen ØJ (1987) The Sunnhordland Batholith, W. Norway: regional setting and internal structure with emphasis on the granitoid plutons. Nor Geol Tidsskr 67: 159–183

Andersen TB, Jamtveit B (1990) Uplift of deep crust during orogenic extensional collapse: a model based on field studies in the Sogn-Sunnfjord region of western Norway. Tectonics 9: 1097–1111

Andersen TB, Andresen A (1994) Stratigraphy, tectonostratigraphy and the accretion of outboard terranes in the Caledonides of Sunnhordland, W. Norway. Tectonophys 231: 71–84

Andersen TB, Austrheim H, Sturt BA, Pedersen S et al. (1982) Rb-Sr whole rock ages from Magerøy, North Norwegian Caledonides. Nor Geol Tidsskr 62: 79–85

Andersson A, Dahlman B, Gee DG, Snäll S (1985) The Scandinavian alum shales. Sver Geol Unders Ca 56, 42 pp + append

Andreasson PG (1994) The Baltoscandian margin in Neoproterozoic – early Palaeozoic times. Some constraints on terrane derivation and accretion in the Arctic Scandinavian Caledonides. Tectonophys 231: 1–32

Andreasson PG, Svenningsen O, Johansson I, Solyom Z, Xiaodan T (1992) Mafic dyke swarms of the Baltica-Iapetus transition, Seve Nappe Complex of the Sarek Mts., Swedish Caledonides. Geol Fören Stockh Förh 114: 31–45

Annels AE, Roberts DE (1989) Turbidite-hosted gold mineralisation at the Dolaucothi gold mines, Dyfed, Wales, United Kingdom. Econ Geol 84: 1293–1314

Armands G (1972) Geochemical studies of uranium, molybdenum and vanadium in a Swedish alum shale. Stockh Contrib Geol 27, 148 pp

Ayuso RA, Foley NK, Brown CE (1987) Source of lead and mineralizing brines for Rossie-type Pb-Zn veins in the Frontenac axis area, New York. Econ Geol 82: 489–496

Barnes S-J (1989) The sulphide-segregation history of the Tverrfjell portion of the Råna layered intrusion. In: Prendergast MD, Jones MJ (eds) Magmatic sulphides – The Zimbabwe Volume, London, Institution of Mining and Metallurgy, pp 107–116

Barnes S-J, Sawyer EW, Boyd R, Tucker RD (1988) The tectonic setting of the Råna layered intrusion. Geol Ass Can, Min Ass Can, Can Geophys Union, Progr with Abstr, 13: a5

Barth TFW, Ramberg IB (1966) The Fen circular complex. In: Tuttle OF, Gittins J (eds) Carbonatites. Wiley-Interscience, New York, pp 225–257

Beaudoin G, Schrijver K, Marcoux E, Calvez J-Y (1989) A vein and disseminated Ba-Pb-Zn deposit in the Appalachian thrust belt, St.-Fabien, Quebec. Econ Geol 84: 799–816

Berg H-J, Segalstad TU (1989) Geochemical conditions for deposition of some hydrothermal gold deposits in Norway. Gold'89 in Europe. Toulouse, Abstr vol., Blackwell Scientific Publications, Oxford, p 25

Bergman S (1993) Geology and geochemistry of mafic-ultramafic rocks (Köli) in the Handöl area, central Scandinavian Caledonides. Nor Geol Tidsskr 73: 21–42

Bergström J, Gee DG (1985) The Cambrian in Scandinavia. In: Gee DG, Sturt BA (eds) The Caledonide Orogen – Scandinavia and related areas. Wiley, Chichester, pp 247–271

Bergstøl S, Svinndal S (1960) The carbonatite and per-alkaline rocks of the Fen area: petrology. Nor Geol Unders 208: 99–105

Billett MF (1987) The geology of the northern Sulitjelma area and its relationships to the Sulitjelma ophiolite. Nor Geol Tidsskr 67: 71–83

Binns RA, Scott SD, Burne RV, Chase RL et al. (1987) Western Woodlark Basin; potential analogue setting for volcanogenic massive sulfide deposits. In: Brennan E (ed) Procs Pacific Rim Congress 87. Australian Institute of Mining and Metallurgy, pp 531–535

Birkeland A, Bjørlykke A (1993) Pb isotopic constraints on the origin of the Husvika Zn-Pb deposit in Nordland, north-central Norway. Nor Geol Tidsskr 73: 43–54

Birkeland A, Ihlen PM, Bjørlykke A (1993a) The source of metals in sulfide deposits in the Helgeland Nappe Complex, north-central Norway: Pb isotope evidence. Econ Geol 88: 1810–1829

Birkeland A, Nordgulen Ø, Cumming GL, Bjørlykke A (1993b) Pb-Nd-Sr isotopic constraints on the origin of the Caledonian Bindal Batholith, central Norway. Lithos 29: 257–271

Bjerkgård T, Bjørlykke A (1994) The geology of the Folldal area, southern Trondheim Region Caledonides, Norway. Nor Geol Unders Bull 426: 53–75

Bjerkgård T, Bjørlykke A (1996) Sulfide deposits in Folldal, southern Trondheim Region Caledonides, Norway: source of metals and wall-rock alterations related to host rocks. Econ Geol 91: 676–696

Bjerkgård T, Larsen R, Marker M (1997) Regional setting of the Bleikvassli Zn-Pb deposit in Nordland, Norway. Nor Geol Unders Bull 433: 34–35

Bjørlykke A (1973) Dokka. Berggrunnskart 1816-4, 1:50 000. Nor Geol Unders (Map)

Bjørlykke A (1980) Galena occurrences in late Precambrian/Cambrian sandstones in Norway. Nor Geol Unders 360 (Bull 57): 95–97

Bjørlykke A (1983) Sulphur isotope composition of the sandstone-lead deposits in southern Norway. Nor Geol Unders 380 (Bull 70): 143–158

Bjørlykke A, Sangster DF (1981) An overview of sandstone lead deposits and their relation to red-bed copper and carbonate-hosted lead-zinc deposits. In: Skinner BJ (ed) Econ Geol 75th Anniv vol, pp 179–213

Bjørlykke A, Olaussen S (1981) Silurian sediments, volcanics and mineral deposits in the Sagelvvatn area, Troms, North Norway. Nor Geol Unders Bull 365: 1–38

Bjørlykke A, Thorpe RI (1982) The source of lead in the Osen sandstone lead deposit on the Baltic Shield. Econ Geol 77: 430–440

Bjørlykke A, Sangster DF, Fehn U (1991) Relationship between high heat-producing (HHP) granites and stratabound lead-zinc deposits. In: Pagel M, Leroy JL (eds) Source, transport and deposition of metals, Balkema, Rotterdam, pp 257–260

Bjørlykke A, Grenne T, Rui I, Vokes FM (1980) A review of Caledonian stratabound sulphide deposits in Norway. Geol Surv Ireland Spec Pap 5: 29–46

Bjørlykke A, Vokes FM, Birkeland A, Thorpe RI (1993) Lead isotope systematics of strata-bound sulfide deposits in the Caledonides of Norway. Econ Geol 88: 397–417

Bjørlykke H (1951) Sink og blyforekomster i Nord-Norge. Tidsskr Kjemi, Bergves Metall 11 (6): 85–89

Bjørlykke H, Svinndal S (1960) The carbonatite and per-alkaline rocks of the Fen area: mining and exploration work. Nor Geol Unders 208: 105–110

Bjørlykke K (1974) Depositional history and geochemical composition of Lower Paleozoic epicontinental sediments from the Oslo Region. Nor Geol Unders 305 (Bull 24): 1–81

Boundy TM, Essene EJ, Hall CM, Austrheim H, Halliday AN (1996) Rapid exhumation of lower crust during continent-continent collision and late extension; evidence from $^{40}Ar/^{39}Ar$ incremental heating of hornblendes and muscovites, Caledonian Orogen, Western Norway. Geol Soc Am Bull 108: 1425–1437

Bowitz-Ihlen PM (1973) En malmgeologisk undersøkelse av scheelittmineraliseringer i strøket Ravannene-Øvre Laksfors i Vefsn. Dipl thesis, NTH, University of Trondheim, 101 pp

Boyd R, Mathiesen CO (1979) The nickel mineralization of the Råna mafic intrusion, Nordland, Norway. Can Mineral 17: 287–298

Boyd R, Nixon F (1985) Norwegian nickel deposits: a review. In: Papunen H, Gorbunov GI (eds) Nickel-copper deposits of the Baltic Shield and Scandinavian Caledonides. Geol Surv Finland Bull 333: 363–394

Boyd R, McDade JM, Millard Jr, HT, Page NJ (1987) Platinum metal geochemistry of the Bruvann nickel-copper deposit, Råna, North Norway. Nor Geol Tidskr 67: 205–213

Boyle AP (1989) The geochemistry of the Sulitjelma ophiolite and associated basic volcanics: tectonic implications. In: Gayer RA (ed) The Caledonide geology of Scandinavia. Graham and Trotman, London, pp 153–164

Boyle RW (1986) Gold deposits in turbidite sequences: their geology, geochemistry and history of the theories of their origin. In: Keppie J, Boyle RW, Haynes SJ (eds) Turbidite hosted gold deposits. Geol Assoc Can Spec Pap 32: 1–15

Boyle RW, Davies JL (1964) Geology of the Austin Brook and Brunswick No 6 sulphide deposits, Gloucester County, New Brunswick. Geol Surv Can Pap 63–64, 23 pp

Brekke H, Furnes H, Nordås J, Hertogen J (1984) Lower Palaeozoic convergent plate margin volcanism on Bømlo, SW Norway, and its bearing on the tectonic environments of the Norwegian Caledonides. J Geol Soc London 141: 1015–1032

Brueckner HK, Rex DC (1980) K-A and Rb-Sr geochronology and Sr isotopic study of the Alnö alkaline complex, northeastern Sweden. Lithos 13: 111–119

Bruton DL, Bockelie JF (1980) Geology and paleontology of the Hølonda area, western Norway, a fragment of North America? In: Wones DR (ed) Procs of 'The Caledonides in the USA'. Va Polytech Inst Dept Geol Sci Mem 2: 41–47

Bryhni I, Andreasson PG (1985) Metamorphism in the Scandinavian Caledonides. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 763–782

Bugge A (1963) Norges molybdenforekomster. Nor Geol Unders 217: 1–134

Bugge JAW (1948) Rana Gruber. Geologisk beskrivelse av jernmalmfeltene i Dunderlandsdalen. Nor Geol Unders 171, 149 pp

Bugge JAW (1978) Norway. In: Bowie SHU, Kvalheim A, Haslam HW (eds) Mineral deposits of Europe, vol 1, North-west Europe. Institution of Mining and Metallury/Mineral Society, London, pp 199–249

Bøe R, Atakan K, Sturt BA (1989) The style of deformation in the Devonian rocks on Hitra and Smøla, Western Norway. Nor Geol Unders Bull 414: 1–19

Cadow R (1993) Sm-Nd and Rb-Sr ages of hornblende clinopyroxenite and metagabbro from the Lillebukt alkaline complex, Seiland Igneous Province. Nor Geol Tidskr 73: 243–249

Carstens CW (1923) Der unterordovicische Vulkanhorizont in dem Trondhjemgebiet mit besonderer Berucksichtigung der in ihm auftretenden Kiesvorkommen. Nor Geol Tidsskr 7: 185–269

Carstens H (1955) Jernmalmene i det vestlige Trondheimsfelt og forhold til kisforekomstene. Nor Geol Tidsskr 35: 211–221

Cathles LM, Smith AT (1983) Thermal constraints on the formation of Mississippi Valley-type lead-zinc deposits and their implications for episodic basin dewatering and deposit genesis. Econ Geol 78: 983–1002

Chauvet A, Dallmeyer RD (1992) ^{40}Ar/^{39}Ar mineral dates related to Devonian extension in southwestern Scandinavian Caledonides. Tectonophys 210: 155–177

Chauvet A, Séranne M (1994) Extension-parallel folding in the Scandinavian Caledonides: implications for late orogenic processes. Tectonophysics 238: 31–54

Christensen K, and Stendal H (1995) Gold mineralization at Lykling, Bømlo, the Caledonides of southwestern Norway. In: Ihlen PM, Pedersen M, Stendal H (eds) Gold mineralization in the Nordic countries and Greenland. Extended abstracts and fieldstrip guide, Grønl Geol Unders Open File Series 95/10: 20–24

Christofferson HC, Wallin B, Selkman S, Rickard DT (1979) Mineralization controls in the sandstone lead-zinc deposits at Vassbo, Sweden. Econ Geol 74: 1239–1249

Claesson S, Stephens MB, Klingspor I (1988) U-Pb zircon dating of felsic intrusions, Middle Køli Nappes, central Scandinavian Caledonides. Nor Geol Tidsskr 68: 89–97

Colman TB, Jones DG, Plant JA, Smith K (1989) Metallogenic models for carbonate-hosted (Pennine- and Irish-style) mineral deposits. In: JA Plant, DG Jones (eds) Metallogenic models and exploration criteria for buried carbonate-hosted ore deposits – a multidisciplinary study in eastern England, London, Institution of Mining and Metallurgy, British Geological Survey Keyworth, Nottingham, pp 123–133

Cook NJ, Halls C, Kaspersen PO (1990) The geology of the Sulitjelma ore field, northern Norway; some new interpretations. Econ Geol 85: 1720–1737

Cook NJ, Spry P, Vokes FM (1998) Mineralogy and paragenetic relationships among sulphosalts and related minerals in the Bleikvassli Zn-Pb-(Cu) deposit, Nordland, Norway. Mineralium Deposita 34: 35–56

Cuthbert SJ (1991) Evolution of the Devonian Hornelen Basin, west Norway; new constraints from petrological studies of metamorphic clasts. Geol Soc London Spec Publ 57: 343–360

Cuthbert SJ, Harvey MA, Corswell DA (1983) A tectonic model for metamorphic evolution of the basal gneiss complex, western south Norway. J Metam Geol 1: 63–90

Dallmeyer RD, Mitchell JG, Pharaoh TC, Reuter A, Andresen A (1988) K-Ar and ^{40}Ar/^{39}Ar whole-rock ages of slate/phyllite from allochthonous basement and cover in the tectonic windows of Finnmark, Norway: evaluating the extent and timing of Caledonian tectonothermal activity. Geol Soc Am Bull 100: 1493–1501

Dallmeyer RD, Johansson L, Møller C (1992) Chronology of Caledonian high-pressure granulite-facies metamorphism, uplift, and deformation within northern parts of the Western Gneiss Region, Norway. Geol Soc Am Bull 104: 444–455

Daly JS, Aitcheson SJ, Cliff RA, Gayer RA, Rice AHN (1991) Geochronological evidence from discordant plutons for a Late Proterozoic orogen in the Caledonides of Finnmark, northern Norway. J Geol Soc London 148: 29–40

Dalziel IWD (1997) Neoproterozoic-Paleozoic geography and tectonics: review, hypothesis, environmental speculation. Geol Soc Am Bull 109: 16–42

Duane MJ, deWit MJ (1988) Pb-Zn ore deposits of the northern Caledonides; products of continental scale fluid mixing and tectonic expulsion during continental collision. Geology 16: 999–1002

Dubé B, Lauziére K (1993) Structural setting and controls of gold mineralization in Western Newfoundland. In: CIM Geol Field Conf, BATHURST'93. Progr with Abstr, vol 3: 60–62

Dunham KC, Beer KE, Ellis RA, Gallagher MJ et al. (1978) United Kingdom. In: Bowie SHU, Kvalheim A, Haslam HW (eds) Mineral Deposits of Europe. Vol I. Northwest Europe. London, Institution of Mining and Metallurgy/Mineralogical Society, pp 263–317

Dunning GR, Pedersen RB (1988) U/Pb ages of ophiolites and arc-related plutons of the Norwegian Caledonides: implications for the development of Iapetus. Contrib Mineral Petrol 98: 13–23

Einaudi MT, Meinert LD, Newberry RJ (1981) Skarn deposits. In: Skinner BJ (ed) Econ Geol; Seventy-fifth Ann Vol: pp 317–391

El Aref MM, Amstutz GC (1983) Lead-zinc deposits along the Red Sea coast of Egypt. New observations and genetic models on the occurrences of Um Geigh, Wizr, Essel and Zug El Bohar. Monograph Series on Mineral Deposits No 21. Gebrüder Borntraeger, Berlin, pp 1–103

Fediuk F, Siedlecki S (1977) Smøla. Beskrivelse til det berggrunnsgeologiske kart 1321-1. Nor Geol Unders 320: 1–23

Fedotova MG (1990) Caledonian vein mineralization of the Murmansk and Belomorian coasts of Kola Peninsula. Kola Science Centre, USSR Academy of Sciences, Apatity, 32 pp (in Russian)

Feiss PG, Slack JF (1989) Mineral deposits of the US Appalachians. In: Hatcher RD Jr, Thomas WA, Viele GW (eds) The geology of North America, vol F-2, The Appalachian-Ouachita Orogen in the United States. Geological Society of America, pp 471–494

Foslie S (1925) Syd-Norges gruber og malmforekomster. Nor Geol Unders 126: 1–89

Foslie S (1926) Norges svovelkisforekomster. Nor Geol Unders 127: 1–122

Foslie S (1949) Håfjellsmulden i Ofoten og dens sedimentære jernmangan-malmer. Nor Geol Unders 174: 1–129

Foslie S (1955) Kisdistriktet Varaldsøy-Ølve i Hardanger og bergverksdriftens historie. Nor Geol Unders 147: 1–106

Foslie S, Høst MJ (1932) Platina i sulfidisk nikkelmalm. Nor Geol Unders 137: 1–71

Fossen H, Austrheim H (1988) The age of the Krossnes Granite, west Norway. Nor Geol Unders Bull 413: 61–65

Fossen H, Dunlap WJ (1997) Thermal evolution of the southern Norwegian crust: orogeny, collapse and prolonged slow cooling. Geonytt 1–97: 38

Franklin JM, Lydon JW, Sangster DF (1981) Volcanic-associated massive sulfide deposits. In: Skinner BJ (ed) Econ Geol 75th Anniv Vol, 485–627

Frietsch R (1975) Brief outline of the metallic mineral resources of Sweden. Sver Geol Unders C718, 64 pp

Furnes HJ, Lippard SJ (1983) Devonian lavas from Solund, West Norway: field relations and geochemistry. Nor Geol Unders 382 (Bull 71): 1–15

Furnes H, Roberts D, Sturt BA, Thon A, Gale GH (1980) Ophiolite fragments in the Scandinavian Caledonides. In: Payayiotou A (ed) Procs Internat Ophiolite Symp Cyprus 1979. Geol Surv Dept, Nicosia, pp 582–600

Furnes H, Nystuen JP, Brunfelt AO, Solheim S (1983) Geochemistry of Upper Riphaean-Vendian basalts associated with the "sparagmites" of southern Norway. Geol Mag 120: 349–361

Furnes H, Pedersen RB, Stillman CJ (1988) The Leka Ophiolite Complex, central Norwegian Caledonides: field characteristics and geotectonic significance. J Geol Soc London 145: 401–412

Furnes H, Pedersen RB, Sundvoll B, Tysseland M, Tumyr O (1989) The age, geochemistry and tectonic setting of the Caledonian Gåsøy intrusion, west Norway. Nor Geol Tidsskr 69: 273–289

Furnes H, Skjerlie KP, Pedersen RB, Andersen JB, et al. (1990) The Solund-Stavfjord ophiolite complex and associated rocks, west Norwegian Caledonides: geology, geochemistry and tectonic environment. Geol Mag 127: 209–224

Fyffe LR, van Staal CR, Winchester JA (1990) Late Precambrian-Early Paleozoic volcanic regimes and associated massive sulphide deposits in the northeastern mainland Appalachians. Can Inst Min Met Bull 83, No 938: 70–78

Gale GH, Roberts D (1974) Trace element geochemistry of Norwegian lower Palaeozoic basic volcanics and its tectonic implications. Earth Plan Sci Lett 22: 380–390

Garven G, Freeze RA (1985) Theoretical analysis of the role of groundwater flow in the genesis of stratabound ore deposits. 1. Mathematical and numerical model. 2. Quantitative results. Am J Sci 284: 1095–1124; 1125–1174

Gautneb H (1988) Structure, age and formation of dykes on the island of Smøla, Central Norway. Nor Geol Tidsskr 68: 275–288

Gautneb H, Roberts D (1989) Geology and petrochemistry of the Smøla-Hitra Batholith, Central Norway. Nor Geol Unders Bull 416: 1–24

Gee DG (1972) The regional geological context of the Tåsjö Uranium Project, Caledonian Front, Central Sweden. Sver Geol Unders C671, 36 pp

Gee DG (1980) Basement-cover relationships in the central Scandinavian Caledonides. Geol Fören Stockh Förh 102: 455–474

Gee DG, Karis L, Kumpulainen R, Thelander T (1974) A summary of Caledonian front stratigraphy, northern Jämtland, southern Västerbotten, central Swedish Caledonides. Geol Fören Stockh Förh 96: 389–397

Gee DG, Guezou J-C, Roberts D, Wolff FC (1985) The central-southern part of the Scandinavian Caledonides. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 109–133

Geis HP (1971) A short description of the iron-titanium provinces in Norway with special reference to those in production. Minerals Sci Eng July, pp 13–24

Gjelle S (1988) Geologisk kart over Norge, berggrunnskart Saltdal – 1:250 000. Nor Geol Unders (Map)

Grenne T (1986) Ophiolite-hosted Cu-Zn deposits at Løkken and Høydal, Trondheim Nappe Complex, Upper Allochthon. In: Stephens MB (ed) Stratabound sulphide deposits in the central Scandinavian Caledonides. Sver Geol Unders Ca 60: 55–64

Grenne T (1988) Marginal basin type metavolcanites of the Hersjø Formation, eastern Trondheim District, Central Norwegian Caledonides. Nor Geol Unders Bull 412: 29–42

Grenne T (1989a) Magmatic evolution of the Løkken SSZ ophiolite, Norwegian Caledonides: relationships between anomalous lavas and high-level intrusions. Geol J 24: 251–274

Grenne T (1989b) The feeder zone to the Løkken ophiolite-hosted massive sulfide deposit and related mineralizations in the central Norwegian Caledonides. Econ Geol 84: 2173–2195

Grenne T, Lagerblad B (1985) The Fundsjø Group, central Norway: a lower Palaeozoic island arc sequence, geochemistry and regional implications. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 745–760

Grenne T, Vokes FM (1990) Sea-floor sulfides at the Høydal volcanogenic deposit, central Norwegian Caledonides. Econ Geol 85: 344–359

Grenne T, Roberts D (1998) The Hølonda Porphyrites, Norwegian Caledonides: geochemistry and tectonic setting of Early-Mid-Ordovician shoshonitic volcanism. J Geol Soc London 155: 131–142

Grenne T, Grammeltvedt G, Vokes FM (1980) Cyprus-type sulphide deposits in the western Trondheim District, central Norwegian Caledonides. In: Panayiotou A (ed) Proc Int Ophiolite Symp Cyprus 1979. Geological Survey Department, Nicosia, pp 727–743

Grenne T, Hertogen J, Solli A, Birkeland A, Erichsen E, Sandstad JS (1995) The sequential development of magmatic and ore-forming processes in the Fundsjø Group, Meråker district, Central Norway. Nor Geol Unders Bull 427: 108–111

Griffin WL, Brueckner HK (1980) Caledonian Sm-Nd ages and a crustal origin for Norwegian eclogites. Nature 258: 319–321

Griffin WL, Austrheim H, Brastad K, Bryhni I et al. (1985) High-pressure metamorphism in the Scandinavian Caledonides. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 783–801

Grimm K, Stendal H (1991) Geological setting of the Pb-Zn-Cu mineralization in the Mjønesfjell area, Nordland, northern Norway. Nor Geol Unders Bull 420: 1–12

Grip E (1954) Blymalmen vid Laisvall, dess geologi og en jämførelse med några utländska förekomster. Geol Fören Stockh Förh 76: 357–380

Grip E (1967) On the genesis of the lead ores of the eastern border of the Caledonides in Scandinavia. Econ Geol Monogr 3: 208–218

Grip E (1978) Sweden. In: Bowie SH, Kvalheim A, Haslam HW (eds) Mineral deposits of Europe. Vol 1, Northwest Europe. London, Institution of Mining and Metallurgy/Mineralogical Society, pp 93–198

Grip E, Frietsch R (1973) Malm i Sverige 2. Norra Sverige. Stockholm, Almqvist and Wiksell Läromedel, 295 pp

Gross GA (1965) Geology of iron deposits in Canada. Vol 1 General geology and evaluation of iron deposits. Geol Surv Can Econ Geol Rpt 22, 181 pp

Grønlie A (1988) Platinum-group minerals in the Lillefjellklumpen nickel-copper deposit, Nord-Trøndelag, Norway. Nor Geol Tidsskr 68: 65–72

Guézou JC (1978) Geology and structure of the Dombås-Lesja area, southern Trondheim Region, south-central Scandinavian Caledonides, Norway. Nor Geol Unders Bull 340: 1–34

Guilbert JM, Park CF Jr (1986) The geology of ore deposits. WH Freeman and Co, New York, 985 pp

Halls C, Reinsbakken A, Haugen A, Ferriday I (1977) Geological setting of the Skorovas ore body within the allochthonous volcanic stratigraphy of the Gjersvik nappe, central Norway. In: Volcanic processes in ore genesis. London, Institution of Mining and Metallurgy, pp 128–151

Hames WE, Andresen A (1996) Timing of Paleozoic orogeny and extension in the continental shelf of north-central Norway as indicated by laser $^{40}Ar/^{39}Ar$ muscovite dating. Geology 24: 1005–1008

Harland WB (1971) Tectonic transpression in Caledonian Spitsbergen. Geol Mag 108: 27–42

Harpøth O, Pedersen JL, Schønwandt HK, Thomassen B (1986) The mineral occurrences of central East Greenland. Medd Grønl (Grønl Geosci) 17, 139 pp

Heim M, Grenne T, Prestvik T (1987) The Resfjell ophiolite fragment, southwest Trondheim Region, Central Norwegian Caledonides. Nor Geol Unders Bull 409: 49–71

Hill T (1980) Geochemistry of the greenschists in relation to the Cu-Fe deposits in the Ramundberget area, central Sweden. Nor Geol Unders 360 (Bull 57): 195–210

Hollister VF, Potter RR, Barker AL (1974) Porphyry-type deposits of the Appalachian orogen. Econ Geol 69: 618–630

Horne GS (1979) Mélange in the Trondheim Nappe suggests a new tectonic model for the central Norwegian Caledonides. Nature, London, 281: 267–270

Hossack JR (1984) The geometry of listric growth faults in the Devonian basins of Sunnfjord, W Norway. J Geol Soc London 141: 629–637

Hurich CA, Palm H, Dyrelius D, Kristoffersen Y (1989) Deformation of the Baltic continental crust during Caledonide intracontinental subduction: views from reflection data. Geology 17: 423–425

Ihlen PM (1993) The Kolsvik Au-As-deposit, Bindal, North-Central Norway. I: Corelogs. Nor Geol Unders Rep 93.003, 322 pp

Ihlen PM (1995) Gold mineralization in relation to batholith magmatism in the Helgeland Nappe Complex and its immediate substrate, the Caledonides of North-Central Norway. In: Ihlen PM, Pedersen M, Stendal H (eds) Gold mineralization in the Nordic countries and Greenland. Extended abstracts and field-trip guide, Grønl Geol Unders Open File Series 95/10: pp 42–46

Ihlen PM, Grenne T, Vokes FM (1997) The metallogenic evolution of the Scandinavian Caledonides. Trans Inst Min Met Sect B 106: 194–203

Jackson SA, Beales FW (1967) An aspect of sedimentary basin evolution: the concentration of Mississippi Valley-type ores during the late stages of diagenesis. Bull Can Petrol Geol 15: 393–433

James DW (1991) The geology and geochemistry of the Målvika tungsten skarn deposit, Central Norway. PhD Thesis, University of Sheffield

James DW, Mitchell JG, Ineson PR, Nordgulen Ø (1993) Geology and K/Ar chronology of the Målvika scheelite skarns, Central Norwegian Caledonides. Nor Geol Unders Bull 424: 65–74

Johansson Å (1980) Occurrence and deformation of some sulphide-bearing quartz veins in the Nasafjället area, Swedish Caledonides. Nor Geol Unders 360 (Bull 57): 113–122

Johansson Å (1983a) Lead isotope composition of Caledonian sulfide-bearing veins in Sweden. Econ Geol 78: 1674–1688

Johansson Å (1983b) Descriptions of Caledonian sulfide-bearing veins in Sweden. In: Lindblom S (ed) ORG 83 – Ann Rep of the Ore Research Group, Stockholm University, pp 151–166

Johansson Å (1984) Fluid inclusion and stable isotope studies on some Caledonian sulfide-bearing veins in Sweden. Econ Geol 79: 1736–48

Johansson Å, Rickard D (1984) Isotopic composition of Phanerozoic ore leads from the Swedish segment of the Fennoscandian Shield. Mineral Deposita 19: 249–255

Juve G (1967) Zinc and lead deposits in the Håfjell syncline, Ofoten, northern Norway. Nor Geol Unders 244, 54 pp

Juve G (1977) Metal distribution at Stekenjokk: primary and metamorphic patterns. Geol Fören Stockh Förh 99: 149–158

Juve G, Grenne T (1993) Malmgeologi. Nasjonalatlas for Norge, kartblad 2.2.4. Oslo, Nor Geol Unders, Trondheim (map)

Karlstrøm H (1990) Edelmetaller i norske kaledonske sulfidforekomster. BVLI's Tekniske Virksomhet, Trondheim, Teknisk Rep 77, 264 pp

Kautsky F, Tegengren FR (1952) Die Geologie der Umgebung des Tuoddarjaure am Südrande des Sjanglifensters. Geol Fören Stockholm Förh 74: 455–474

Kimberley MM (1978) Paleoenvironmental classification of iron formations. Econ Geol 73: 215–229

Kirkham RV (1987) Tectonic setting of the Buchans Group. In: Kirkham RV (ed) Buchans geology, Newfoundland. Geol Surv Can Pap 86-24: 23–34

Kirschvink JL (1992) Late Proterozoic low-latitude global glaciation: The snowball earth. In: Schopf JW, Klein C (eds) The Proterozoic biosphere: a multidisciplinary study. Cambridge University Press, Cambridge, pp 51–53

Kish SA, Stein HJ (1989) Post-Acadian metasomatic origin for copper-bearing vein deposits of the Virgilina district, North Carolina and Virginia. Econ Geol 84: 1903–1920

Klein C, Beukes NJ (1993) Sedimentology and geochemistry of the glaciogenic Late Proterozoic Rapitan iron-formation in Canada. Econ Geol 88: 542–565

Knoll AH, Walter MR (1992) Proterozoic stratigraphy and Earth history. Nature 356: 673–677

Kolderup CF (1926) Solunds devonfelt. Bergens Museum Årbok 1924–25, 8: 1–73

Kollung S (1979) Stratigraphy and major structures of the Grong District, Nord-Trøndelag. Nor Geol Unders Bull 354: 1–51

Kontak DJ, Smith PK (1993) An overview of Meguma gold deposits in the Meguma Terrane of southern Nova Scotia, Canada. In: CIM Geol Field Conf, BATHURST'93. Progr with Abstr, vol 3, pp 63–66

Kooiman GJA, McLead MJ, Sinclair WD (1986) Porphyry tungsten-molybdenum orebodies, polymetallic veins and replacement bodies, and tin-bearing greisen zones in the Fire Tower zone, Mount Pleasant, New Brunswick. Econ Geol 81: 1356–1373

Korneliussen A, Geis HP, Gierth E, Krause H et al. (1985) Titanum ores; an introduction to a review of titaniferous magnetite, ilmenite and rutile deposits in Norway. Nor Geol Unders Bull 402: 7–24

Koski RA (1990) A comparison of sulfide deposits from modern sediment-covered spreading axes with Besshi-type deposits of Japan. In: McMurray GR (ed) Gorda Ridge: a sea-floor spreading center in the United States' Exclusive Economic Zone. Springer-Verlag, New York, Berlin Heidelberg, pp 117–130

Krause M, Bakke O (1986) Exploration for sandstone lead deposits in the sparagmite region, southern Norway – some case histories. Nor Geol Unders Bull 406: 1–15

Kresten P (1986) The Alnö alkaline area. In: Lundqvist T et al. The Enåsen Au deposit and the Alnö alkaline complex. Sver Geol Unders Ca 67: 20–22

Krill AG (1989) Further notes on the rift hypothesis for the Seiland Igneous Province. Geol Fören Stockh Förh 111: 395–398

Krill AG, Zwaan B (1987) Reinterpretation of Finnmarkian deformation on western Sørøy, northern Norway. Nor Geol Tidsskr 67: 15–24

Krogh EJ, Elvevold S (1990) A Precambrian age for an early gabbro-monzonitic intrusive on the Øksfjord peninsula, Seiland Igneous Province, northern Norway. Nor Geol Tidsskr 70: 267–273

Krogh TE, Mysen BO, Davis GL (1973) A Paleozoic age for the primary minerals of a Norwegian eclogite. Carnegie Institute Washington Yearbook 1973, pp 575–576

Krupp R, Krupp G (1985) Geological setting of the Tverrfjell copper/zinc deposit central Norway. Geol Rundsch 74: 467–482

Kullerud L, Tørudbakken BO, Ilebekk S (1986) A compilation of radiometric age determinations from the Western Gneiss Region, South Norway. Nor Geol Unders Bull 406: 17–42

Kumpulainen R, Nystuen JP (1985) Late Proterozoic basin evolution and sedimentation in the westernmost part of Baltoscandia. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 213–232

Larsen RB (1991) Tungsten skarn mineralizations in a regional metamorphic terrain in northern Norway: a possible metamorphic ore deposit. Mineral Deposita 26: 281–289

Larsen RB, Grenne T (1995) Character and tectonic setting of an Ordovician boninite hosted Cu-Ni-PGE ore in the Norwegian Caledonides. Trans Inst Min Met Sect B104: 87–98

Laurence RA (1968) Ore deposits of the Southern Appalachians. In: Ore deposits of the United States, 1933–1967 (Graton-Sales Volume), vol 1. pp 155–168

Lindahl I (1984) Uran, uranprospektering og uranmineralisering i Norge. Nor Geol Unders Skr 51, 29 pp

Lindahl I, Bjørlykke A (1988) The Gjeitvann lead-copper-(zinc) mineralization, Porsangerhalvøya, Finnmark, northern Norway. Nor Geol Tidsskr 68: 125–132

Lindblom S (1984) Calcite carbon and oxygen isotope evidence for ore formation at Laisvall, Sweden. Bull Mineral 107: 241–253

Lindblom S (1986) Textural and fluid inclusion evidence for ore deposition in the Pb-Zn deposit at Laisvall, Sweden. Econ Geol 81: 46–64

Lindblom S, Rickard DT (1978) Fluid inclusions in sphalerite at Laisvall, Sweden. Geol Fören Stockh Förh 100: 177–180

Luff WM, Lentz DR, van Staal CR (1993) The Brunswick No 12 and No 6 mines, Bathurst Camp, northern New Brunswick. In: McCutcheon SR, Lentz DR (eds) Guidebook to the metallogeny of the Bathurst Camp. (Fieldtrip 4) 3rd Ann Field Conf Geol Soc of CIM, Bathurst, New Brunswick, pp 75–105

Lutro O (1979) The geology of the Gjersvik area. Norges Geol Unders 354: 53–100

Martinsen M, Vokes FM (1987) Porphyry-type Mo-Cu mineralization in the Norwegian Caledonides. SINTEF, Div. of Rock and Mineral Engineering, Rep STF36 F87023, 21 pp

McArdle P (1989) Geological setting of gold mineralization in the Republic of Ireland. Trans Inst Min Met Sect B 98: 7–12

McConnell BJ, Stillman CJ, Hertogen J (1991) An Ordovician basalt to peralkaline rhyolite fractionation series from Avoca, Ireland. J Geol Soc London 148: 711–718

McMillan WJ, Panteleyev A (1980) Ore deposit models – 1 Porphyry copper deposits. Geosci Can 7: 52–63

Melezhik VA, Roberts D, Pokrovsky G, Gorokhov IM, Ovchinnikova GV (1997) Primary isotopic features in metamorphosed Caledonian carbonates: implications for depositional age. Nor Geol Under Bull 433, 22–23

Meyer C (1981) Ore-forming processes in geologic history. In: Skinner BJ (ed) Econ Geol 75th Anniv Vol, pp 6–41

Moorbath S, Vokes FM (1963) Lead isotope abundance studies on galena occurrences in Norway. Nor Geol Tidsskr 43: 283–344

Moore AC, Hultin I (1980) Petrology, mineralogy and origin of the Feragen ultramafic body, Sør-Trøndelag, Norway. Nor Geol Tidsskr 60: 235–254

Mørk MBE, Stabel A (1990) Cambrian Sm-Nd dates for an ultramafic intrusion and for high-grade metamorphism on the Øksfjord pensinsula, North Norway. Nor Geol Tidsskr 70: 275–291

Nesbitt BE, Murowchick JB, Muehlenbachs K (1986) Dual origins of gold lode deposits in the Canadian Cordillera. Geology 14: 506–509

Neumann H (1985) Norges mineraler. Nor Geol Unders Skr 68, 278 pp

Newberry RJ (1979) Systematics in W-Mo-Cu skarn formation in the Sierra Nevada: an overview. Geol Soc Am, Abstr with Progr, 11, 486 pp

Nilsen O (1974) Mafic and ultramafic inclusions from the initial (Cambrian?) volcanism in the central Trondheim Region, Norway. Nor Geol Tidsskr 54: 337–359

Nilsen O (1978) Caledonian sulphide deposits and minor ironformations from the Southern Trondheim Region, Norway. Nor Geol Unders Bull 340: 35–85

Nilsen O, Mukherjee AD (1972) Geology of the Kvikne mines with special reference to the sulphide ore mineralization. Nor Geol Tidsskr 52: 151–192

Nilsen O, Wolff FC (1989) Geologisk kart over Norge, berggrunnskart Røros and Sveg – 1:250 000. Nor Geol Unders (Map)

Nilsen TH (1968) The relationship of sedimentation to tectonics in the Solund Devonian district of southwestern Norway. Nor Geol Unders 259: 1–108

Nilsson LP (1990) Platinum-group mineral inclusions in chromite from the Osthammeren ultramafic tectonite body, south-central Norway. In: Stumpfl EF, Papunen H (eds) Procs 5th Int Plat Symp. Mineral Petrol 42: 249–263

Nilsson LP, Sturt BA, Ramsay DM (1997) Ophiolitic ultramafites in the Folldal-Røros tract, and their Cr-(PGE) mineralisation. Nor Geol Unders Bull 433: 10–11

Nissen AL (1969) A new Norwegian occurrence of scheelite. Nor Geol Unders 258: 116–123

Nordenskiöld AE (1893) Remarques sur le fer natif d'Ovifak et sur le bitumen des roches crystallines de Suède. C R Acad Sci 116: 666–678

Nordgulen Ø (1992) A summary of the petrography and geochemistry of the Bindal Batholith. Nor Geol Unders Rep 92.111, 103 pp

Nordgulen Ø (1993) The Caledonian Bindal Batholith: regional setting based on geological, geochemical and isotopic data. PhD Thesis, University of Bergen, Norway, 133 pp

Nordgulen Ø, Schouenborg B (1990) The Caledonian Heilhornet pluton, north-central Norway: geological setting, radiometric age and implications for the Scandinavian Caledonides. J Geol Soc London, 147: 439–450

Nordgulen Ø, Sundvoll B (1992) Strontium isotope composition of the Bindal Batholith, Central Norwegian Caledonides. Nor Geol Unders Bull 423: 19–39

Nordgulen Ø, Bickford ME, Nissen AL, Wortman GL (1993) U-Pb zircon ages from the Bindal Batholith, and the tectonic history of the Helgeland Nappe Complex, Scandinavian Caledonides. J Geol Soc London 150: 771–783

Nordrum FS, Van der Wel D (1981) Mineral-, stein- og ertsforekomster innen kartblad Sauda (1:250 000). Nor Geol Unders Skr 35, 58 pp

Nordås J, Amaliksen KG, Brekke H, Suthren RJ et al. (1985) Lithostratigraphy and petrochemistry of Caledonian rocks on Bømlo, southwest Norway. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 679–692

Norton MG (1986) Late Caledonian extension in western Norway; a response to extreme crustal thickening. Tectonics 5: 195–204

Odling NE (1988) Deformation of the Joma sulphide deposit, Caledonides of Nord-Trøndelag, Norway. In: Zachrisson E ed) Procs 7th Quad IAGOD Symp Luleå. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, pp 513–524

Ödman OH (1942) Copper ores of the "red beds" type from Visingö, Sweden. Sver Geol Unders C444: 1–26

Oftedahl C (1967) Note on a molybdenite-dolomite-bearing pegmatite in Velfjord, Nordland, Norway. Nor Geol Unders 247: 147–149

Often M (1982) Orienterende undersøkelser og diamantboring av grensesonen Prekambrium/Kaledon i Saltdal-Sørfold-regionen. Nor Geol Unders Rep 1650/30 A, 26 pp

Page NJ (1963) The sulfide deposit of Nordre Gjetryggen gruve, Folldal, Norway. Nor Geol Unders 228: 217–269

Pedersen RB, Hertogen J (1990) Magmatic evolution of the Karmøy Ophiolite Complex, SW Norway: relationships beween MOR-IAT boninitic-calc-alkaline and alkaline magmatism. Contrib Mineral Petrol 104: 277–293

Pedersen RB, Dunning GR (1997) Evolution of arc crust and relations between contrasting sources: U-Pb (age), Nd and Sr isotope systematics of the ophiolitic terrain of SW Norway. Contrib Mineral Petrol 128: 1–15

Pedersen RB, Dunning GR, Robins B (1988) U-Pb ages of nepheline syenite pegmatites from the Seiland Magmatic Province, N. Norway. In: Gayer RA (ed) The Caledonide geology of Scandinavia, Graham and Trotman, London, pp 3–8

Pedersen RB, Furnes H, Dunning G (1991) A U/Pb age for the Sulitjelma Gabbro, north Norway: further evidence for the development of a Caledonian marginal basin in Ashgill-Llandovery time. Geol Mag 128: 141–153

Pedersen RB, Bruton DL, Furnes H (1992) Ordovician faunas, island arcs and ophiolites in the Scandinavian Caledonides. Terra Nova 4: 217–222

Pedersen RB, Johannesen GM, Boyd R (1993) Stratiform PGE mineralizations in the ultramafic cumulates of the Leka Ophiolite Complex, Central Norway. Econ Geol 88: 782–803

Pedersen SAS (1979) Structures and ore genesis of the Grimsdalen sulphide deposits, southern Trondheim Region, Norway. Nor Geol Unders 351 (Bull 51): 77–98

Pharaoh TC, Ramsay DM, Jansen Ø (1983) Stratigraphy and structure of the northern part of the Repparfjord-Komagfjord window, Finnmark, northern Norway. Nor Geol Unders 377 (Bull 68): 1–45

Pidgeon RT, Raaheim A (1972) Geochronological investigation of the gneisses and minor intrusive rocks from Kristiansund, west Norway. Nor Geol Tidsskr 52: 241–256

Plant JC, Simpson PR, Green PM (1983) Metalliferous and mineralized Caledonian granites in relation to regional metamorphism and fracture systems in northern Scotland. Trans Inst Min Met Sect B 92: 33–42

Plant JC, Cooper DC, Green PM, Reedway AJ, Simpson PR (1991) Regional distribution of As, Sb and Bi in the Grampian Highlands of Scotland and English Lake District: implications for gold metallogeny. Trans Inst Min Met Sect B 100: 135–147

Poulsen A (1960) Exploitation of mineral raw materials in Norway. In: Holtedahl O (ed) Geology of Norway. Nor Geol Unders 208: 532–540

Poulsen A (1964) Norges gruver og malmforekomster. II: Nord-Norge, med malmkart og geologiske oversiktskart over Nord-Norge. Nor Geol Unders 204, 191 pp

Prestvik T (1980) The Caledonian ophiolite complex of Leka, north-central Norway. In: Panayiotou A (ed) Procs Int Ophiolite Symp Cyprus 1979. Geological Survey Department, Nicosia, pp 555–566

Pringle I (1973) Rb-Sr age determinations on shales associated with the Varanger ice age. Geol Mag 109: 465–472

Ramberg IB (1973) Gravity studies of the Fen complex, Norway, and their petrological significance. Contrib Mineral Petrol 38: 115–134

Ramsay DM (1971) Stratigraphy of Sørøy: In: Caledonian Geology of Northern Norway. Nor Geol Unders 269: 314–317

Reinsbakken A (1980) Geology of the Skorovas mine: a volcanogenic massive sulphide deposit in the central Norwegian Caledonides. Nor Geol Unders 360 (Bull 57): 123–154

Reinsbakken A (1986) The Joma Cu-Zn massive sulphide deposit hosted by mafic metavolcanites. In: Stephens MB (ed) Stratabound sulphide deposits in the central Scandinavian Caledonides. Sver Geol Unders Ca 60: 50–54

Reinsbakken A (1992) The Skorovas volcanogenic massive sulphide deposit – volcanostratigraphy, petrochemistry, hydrothermal alteration and paleotectonic setting. Dr.ing. Thesis, UNIT-NTH, 363 pp

Reinsbakken A, Stephens MB (1986) Lithology and deformation in the massive sulphide-bearing Gelvenåkko and Leipikvattnet Nappes. In: Stephens MB (ed) Stratabound sulphide deposits in the central Scandinavian Caledonides. Sver Geol Unders Ca 60: 42–44

Reusch H (1888) Bømmeløen og Karmøen med omgivelser. Nor Geol Unders, 422 pp

Rice R, Sharp GJ (1976) Copper mineralization in the forest of Coed-y-Brenin, North Wales. Trans Inst Min Met Sect B 85: 1–13

Rickard DT, Willdén MY, Marinder N-E, Donnelly TH (1979) Studies on the genesis of the Laisvall sandstone lead-zinc deposit, Sweden. Econ Geol 74: 1235–1285

Rickard DT, Coleman M, Swainbank I (1981) Lead and sulphur isotopic composition of galena from the Laisvall sandstone lead-zinc deposit, Sweden. Econ Geol 76: 2042–2046

Roberts D (1980) Petrochemistry and palaeogeographic setting of the Ordovician volcanic rocks of Smøla, Central Norway. Nor Geol Unders 359 (Bull 56): 43–60

Roberts D (1982) Disparate geochemical patterns from the Snåsavatn greenstone, Nord-Trøndelag, central Norway. Nor Geol Unders 373 (Bull 66): 63–73

Roberts D (1983) Devonian tectonic deformation in the Norwegian Caledonides and its regional perspectives. Nor Geol Unders 380 (Bull 70): 85–96

Roberts D (1988a) The terrane concept and the Scandinavian Caledonides: a synthesis. Nor Geol Unders Bull 413: 93–99

Roberts D, Gale GH (1978) The Caledonian-Appalachian Iapetus Ocean. In: Tarling DH (ed) Evolution of the Earth's crust. Academic Press, London, pp 255–342

Roberts D, Gee DG (1985) An introduction to the structure of the Scandinavian Caledonides. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 55–68

Roberts D, Tucker RD (1991) U-Pb zircon age of the Møklevatnet granodiorite, Gjersvik Nappe, Central Norwegian Caledonides. Nor Geol Unders Bull 421: 33–39

Roberts D, Tucker RD (1998) Late Cambrian U-Pb zircon age of a metatrondhjemite from Ytterøya, Trondheimsfjorden, Central Norwegian Caledonides. Nor Geol Tidsskr 78: 253–258

Roberts D, Grenne T, Ryan PD (1984) Ordovician marginal basin development in the central Norwegian Caledonides. Geol Soc London Spec Publ 16: 233–244

Roberts D, Sturt BA, Furnes H (1985) Volcanite assemblages and environments in the Scandinavian Caledonides and the sequential development history of the mountain belt. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 919–930

Robins B (1985) Disseminated Fe-Ti oxides in the Seiland Magmatic Province of Northern Norway. In: Korneliussen A, Robins B (eds) Titaniferous magnetite, ilmenite and rutile deposits in Norway. Nor Geol Unders Bull 402: 79–91

Robins B, Gardener PM (1974) Synorogenic layered basic intrusions in the Seiland petrographic province, Finnmark. Nor Geol Unders 312: 91–130

Robins B, Gardener PM (1975) The magmatic evolution of the Seiland province, and Caledonian plate boundaries in northern Norway. Earth Plan Sci Lett 26: 167–178

Roedder E (1968) Environment of deposition of the disseminated lead ores at Laisvall, Sweden, as indicated by fluid inclusions. Int Geol Congr, 23rd Session Prague Procs Rep-Sect 7: 389–401

Romer RL (1992) Sandstone lead-zinc mineral deposits and their relation to the tectonic mobilization of the Baltic Shield during the Caledonian orogeny – a reinterpretation. Mineral Petrol 47: 67–85

Romer RL (1994) Deformation-related Paleozoic radiogenic lead and strontium additions in Proterozoic marbles from the Rombak-Sjangeli basement culmination, Scandinavian Caledonides. GFF 116: 23–29

Romer RL, Bax G (1992) The rhombohedral framework of the Scandinavian Caledonides and their foreland. Geol Rundsch 81: 391–401

Rui IJ (1973) Structural control and wall rock alteration at Killingdal Mine, central Norwegian Caledonides. Econ Geol 68: 859–883

Rui IJ (1974) Geology and structures of the Røstvangen sulphide deposit in the Kvikne district, central Norwegian Caledonides. Nor Geol Tidsskr 53: 433–442

Rui IJ, Bakke I (1975) Stratabound sulphide mineralization in the Kjöli area, Røros District, Norwegian Caledonides. Nor Geol Tidsskr 55: 51–75

Ruitenberg AA, Johnson SC, Fyffe LR (1990) Epigenetic gold deposits and their tectonic setting in the New Brunswick Appalachians. Bull Can Inst Min Met 83: 43–55

Ruitenberg AA, McCutcheon SR (1993) Syn- and post-collisional mineral deposits in the Canadian Appalachians. In: CIM Geol Field Conf, BATHURST'93. Progr with Abstr, vol 3, pp 7–9

Saager R (1967) Drei Typen von Kieslagerstätten im Mofjell-Gebiet, Nordland und ein neuer Vorschlag zur Gliederung der Kaledonischen Kieslager Norwegens. Nor Geol Tidsskr 8: 68–73

Saif SI (1983) Petrographic and geochemical characteristics of iron-rich rocks and their significance in exploration for massive sulfide deposits, Bathurst, New Brunswick, Can J Geochem Explor, 19: 705–721

Sand K (1986) A study of paleozoic iron-formations in the Central Norwegian Caledonides. Rep 23b, Geological Institute NTH-University Trondheim, 23 pp

Sandwall J (1981a) Caledonian geology of the Jofjället area, Västerbotten county, Sweden. Sver Geol Unders C778, 105 pp

Sandwall J (1981b) The Zn-Pb-Cu sulphide deposits of the Jofjället area, Västerbotten county, Swedish Caledonides. University of Luleå, Research Rep 1981: 27, 133 pp

Sangster AL, Bourne JH (1982) Geology of the Grenville province, and regional metallogenesis of the Grenville Supergroup. Geol Assoc Can Spec Pap 25: 91–125

Sawkins FJ (1976) Metal deposits related to intercontinental hotspot and rifting enviroments. J Geol 84: 653–671

Schmidt RG (1978) The potential for porphyry copper-molybdenum deposits in the eastern United States. US Geol Surv Prof Pap 907E, 31 pp

Schouenborg BE (1988) U/Pb-Zircon datings of Caledonian cover rocks and cover-basement contacts, northern Vestranden, central Norway. Nor Geol Tidsskr 68: 75–87

Schouenborg BE, Johansson L, Gorbatschev R (1991) U-Pb zircon ages of basement gneisses and discordant felsic dykes from Vestranden, westernmost Baltic Shield and central Norwegian Caledonides. Geol Rundsch 80: 121–134

Schwab FL, Nystuen JP, Gundersen LC (1988) Pre-Arenig evolution of the Appalachian-Caledonide orogen: sedimentation and stratigraphy. In: Harris AL, Fettes DJ (eds) The Caledonian-Appalachian orogen. Geol Soc Spec Publ 38: 75–91

Scott B (1976) Zinc and lead mineralization along the margins of the Caledonian orogen. Trans Inst Min Met Sect B 85: 200–204

Sibson RH (1983) Continental fault structure and the shallow earthquake source. J Geol Soc London 140: 741–767

Sigmond EMO, Gustavson M, Roberts D (1984) Berggrunnskart over Norge (Bedrock map of Norway) 1:1 mill. Nor Geol Unders, Trondheim

Simpson PR, Gallagher MJ, Green PM, Middleton RS et al. (1989) Gold mineralization in relation to the evolution of extensional volcano-sedimentary basins in the Scottish Dalradian and Abitibi belt, Canada. Trans Inst Min Met Sect B 98: 102–117

Sinclair WD, Kooiman GJA, Martin DA (1988) Geological setting of granites and related tin deposits in the North zone, Mount Pleasant, New Brunswick. Can Geol Surv Pap 88-1B, 201–208

Sipilä P (1991) Mafic and ultramafic rocks of the Raisduoddar-Halti area in the Finnish-Norwegian Caledonides: petrography, mineralogy and geochemistry. Bull Geol Soc Finland 63: 15–24

Sivertsen J-E (1992) Stratigraphy and geochemistry of the extrusives of the Torvastad Group; marginal basin deposits associated with Karmøy Ophiolite Complex, SW Norway. Cand. Scient. Thesis, University of Bergen

Skaarup P (1974) Stratabound scheelite mineralization in skarns and gneisses from the Bindal area, northern Norway. Mineral Deposita 9: 299–308

Skauli H, Bjørlykke A, Thorpe RI (1992) Lead-isotope study of the sulphide ore and alteration zone, Bleikvassli zinc-lead deposit, northern Norway. Mineral Deposita 27: 276–283

Skyseth T, Reitan P (1995) Geology and genesis of Gautelisfjell gold deposit, Rombak Window, northern Norway: a link between retrograde Caledonian metamorphism and saline fluids. In: Ihlen PM, Pedersen M, Stendal H (eds) Gold mineralization in the Nordic countries and Greenland. Extended abstracts and field-trip guide, Grønl Geol Unders Open File Series 95/10: 94–97

Slack JF (1993) Besshi-type massive sulfide deposits of the Vermont copper belt. In: Slack JF, Offield TW (eds) Selected mineral deposits of Vermont and the Adirondack Mountains, New York, II Besshi-type massive sulfide deposits of the Vermont Copper Belt. Soc Econ Geol, Guidebook Series, vol 17: 32–73

Smethurst MA, Khramov AN, Torsvik TH (1998) The Neoproterozoic and Palaeozoic palaeomagnetic data for the Siberian platform. Earth Sci Rev 43 (1–2), 1–24

Smith PM (1995) Geological setting of mineralization along the Verran Fault Zone, central Norway. PhD Thesis, University of London, 304 pp

Snyder FG, Gerdemann PE (1968) Geology of the Southeast Missouri Lead District. In: Ridge JD (ed) Ore deposits of the United States, 1933–1967 (Graton-Sales Volume), Am Inst Min Met Petr Eng, New York, vol 1, pp 326–358

Solli A (1990) Saltstraumen. Berggrunnskart 2029-3, 1:50 000. Nor Geol Unders (Map)

Solli A, Farrow CM, Gjelle S (1992) Misvær. Berggrunnskart 2029-2, 1:50 000, Nor Geol Unders (Map)

Spjeldnaes N (1985) Biostratigraphy of the Scandinavian Caledonides. In: Gee DG, Sturt BA (eds) The Caledonide orogen: Scandinavia and related areas. Wiley, Chichester, pp 317–329

Steel R, Siedlecka A, Roberts D (1985) The Old Red Sandstone basins of Norway and their deformation. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 293–315

Stendal H, Ghisler M (1984) Strata-bound copper sulfide and non-strata-bound arsenopyrite and base metal mineralization in the Caledonides of East Greenland – a review. Econ Geol 79: 1574–1584

Stephens MB (1980) Occurrence, nature and tectonic significance of volcanic and high-level intrusive rocks within the Swedish Caledonides. In: Wones DR (ed) Procs Caledonides in the USA. VPI, Dept Geol Mem 2: 289–298

Stephens MB (1982) Field relations, petrochemistry and petrogenesis of the Stekenjokk volcanites, central Swedish Caledonides. Sver Geol Unders C75, 111 pp

Stephens MB (1986) Stratigraphy and deformation in the massive sulphide-bearing Stikke Nappe, Upper Allochthon. In: Stephens MB (ed) Stratabound sulphide deposits in the central Scandinavian Caledonides. Sver Geol Unders Ca 60: 24–29

Stephens MB, Gee DG (1985) A tectonic model for the evolution of the eugeoclinal terranes in the central Scandinavian Caledonides. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 953–970

Stephens MB, Gee DG (1989) Terranes and polyphase accretionary history in the Scandinavian Caledonides. Geol Soc Am Spec Pap 230: 17–30

Stephens MB, Swinden HS, Slack JF (1984) Correlation of massive sulfide deposits in the Appalachian-Caledonian orogen on the basis of paleotectonic setting. Econ Geol 79: 1442–1478

Stephens MB, Furnes H, Robins B, Sturt BA (1985a) Igneous activity within the Scandinavian Caledonides. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 623–656

Stephens MB, Gustavson M, Ramberg IB, Zachrisson E (1985b) The Caledonides of central-north Scandinavia – a tectonostratigraphic overview. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 135–162

Stephens MB, Kullerud K, Claesson S (1993) Early Caledonian tectonothermal evolution in outboard terranes, central Scandinavian Caledonides: new constraints from U-Pb zircon dates. J Geol Soc London 150: 51–56

Stuckless JS, Troëng B, Hedge CE, Nkomo IT, Simmons KR (1982) Age of uranium mineralization at Lilljuthatten in Sweden. Sver Geol Unders C 798: 1–49

Sturt BA, Roberts D (1991) Tectonostratigraphic relationships and obduction histories of Scandinavian ophiolitic terranes. In: Peters T et al. (eds) Ophiolite genesis and evolution of the ocean lithosphere. Min Petrol Mineral, Sultanate Oman, pp 745–769

Sturt BA, Ramsay DM (1994) The structure and regional setting of the Skei Group, Leka, north-central Norway. Nor Geol Unders Bull 426: 31–46

Sturt BA, Pringle I, Ramsay DM (1978) The Finnmarkian phase of the Caledonian orogeny. J Geol Soc London 135: 597–610

Sturt BA, Ramsay DM, Neuman RB (1991) The Otta Conglomerate, the Vågåmo Ophiolite – further indications of early Ordovician Orogenesis in the Scandinavian Caledonides. Nor Geol Tidsskr 71: 107–115

Sturt BA, Ramsay DM, Bjerkgård (1997) Revisions of the tectonostratigraphy of the Otta-Røros tract. Nor Geol Unders Bull 433: 8–9

Sundblad K (1980) A tentative "volcanogenic" formation model for the sediment-hosted Ankarvattnet Zn-Cu-Pb massive sulphide deposit, central Swedish Caledonides. Nor Geol Unders 360 (Bull 57): 211–227

Sundblad K (1989) Precambrian metal sources in sulphide deposits in the northernmost part of the Scandes. Proc 1988 Swedish Ann Meeting IGCP-TCAPO project. Geol Fören Stockh Förh 111: 415–418

Sundblad K, Stephens MB (1983) Lead isotope systematics of stratabound sulfide deposits in the higher nappe complexes of the Swedish Caledonides. Econ Geol 78: 1090–1107

Sundblad K, Gee DG (1985) Occurrence of a uraniferous-vanadiniferous graphitic phyllite in the Köli Nappes of the Stekenjokk area, central Swedish Caledonides. Geol Fören Stockh Förh 106: 269–274

Swinden HS (1991) Paleotectonic settings of volcanogenic massive sulphide deposits in the Dunnage Zone, Newfoundland Appalachians. Bull Can Inst Min Met 84 (946): 59–69

Swinden HS (1993) Metallogeny of the pre-accretion Appalachian orogen. In: Can Inst Min Met Geol Field Conf, BATHURST'93. Progr with Abstr 3: 4–6

Sæther T, Nystuen JP (1981) Tectonic framework, stratigraphy, sedimentation, and volcanism of the Late Precambrian Hedmark Group, Østerdalen, South Norway. Nor Geol Tidsskr 61: 193–211

Søvegjarto U (1977) Kaledonske jernmalmer i Nordland. In: Bjørlykke A, Lindahl I, Vokes FM (eds) Kaledonske malmforekomster. BVLI's Tekniske Virksomhet, Trondheim, pp 95–106

Talbot V, Max MD (1984) Application of various geophysical exploration techniques to Cu and Mo mineralization in Galway granite, Ireland. Trans Inst Min Met Sect B 93: 109–113

Tegengren FR (1962) Vassbo blymalmsfyndighet i Idre och dess geologiska intramming. Sver Geol Unders C586: 1–61

Thelander T, Bakker E, Nicholson R (1980) Basement-cover relationships in the Nasafjället Window, central Swedish Caledonides. Geol Fören Stockh Förh 102: 569–580

Thon A (1985) Late Ordovician and Early Silurian cover sequences to the west Norwegian ophiolite fragments: stratigraphy and structural evolution. In: Gee DG, Sturt BA (eds) The Caledonide orogen – Scandinavia and related areas. Wiley, Chichester, pp 407–415

Torgersen JC (1928) Sink- og blyforekomster på Helgeland. Nor Geol Unders 131: 1–79

Torgersen JC (1935) Sink- og blyforekomster i det nordlige Norge. Nor Geol Unders 142, 60 pp

Torske T (1965) Geology of the Mostadmarka and Selbustrand area, Trøndelag. Nor Geol Unders 232: 1–83

Torsvik TH, Sturt BA, Ramsay DM, Vetti V (1987) The tectonomagnetic signature of the Old Red Sandstone and pre-Devonian strata in the Hasteinen area, western Norway, and implications for the later stages of the Caledonian orogeny. Tectonics 6: 305–322

Torsvik TH, Smethurst MA, Van der Voo R, Trench A, Abrahamsen N, Halvorsen E (1992) Baltica. A synopsis of Vendian-Permian palaeomagnetic data and their palaeotectonic implications. Earth Sci Rev 33: 133–152

Torsvik TH, Smethurst MA, Meert JG, Van der Voo R, McKerrow WS, Brasier MD, Sturt BA, Walderhaug HJ (1996) Continental break-up and collision in the Neoproterozoic and Palaeozoic – a tale of Baltica and Laurentia. Earth Sci Rev 40: 229–258

Trønnes R (1994) Marmor forekomster i Midt-Norge. Nor Geol Unders Rep 94.042, 53 pp

Trønnes RG, Sundvoll B (1995) Isotopic composition, deposition ages and environments of central Norwegian Caledonian marbles. Nor Geol Unders Bull 427: 44–47

Tuach J (1992) List of gold occurrences and deposits on the island of Newfoundland. Geological Survey Branch, Department of Mines and Energy, Government of Newfoundland and Labrador, Open file Rep NFLD 2188, 108 pp

Tuach J, Dean PL, Swinden HS, O'Driscoll CF et al. (1988) Gold mineralization in Newfoundland: a 1988 review. In: Current Research 1988, Newfoundland Department of Mines, Mineral Development Division, Rep 81-1, pp 279–306

Tucker RD (1988) Contrasting crustal segments in the Norwegian Caledonides; evidence from U-Pb dating of accessory minerals. GAC-MAC meeting, St John's, Progr with Abstr, A127

Tucker RD, McKerrow WS (1995) Early Paleozoic chronology: a review in light of new U-Pb zircon ages from Newfoundland and Britain. Can J Earth Sci 32: 368–379

Tucker RD, Boyd R, Barnes S-J (1990) An U-Pb zircon age for the Råna Intrusion, northern Norway: new evidence of basic magmatism in the Scandinavian Caledonides in Early Silurian time. Nor Geol Tidsskr 70: 229–239

Tørudbakken B, Ramberg IB (1982) Statusrapport ved Nordlandsprosjektet. Geolognytt 17: 55–56

Tørudbakken BO, Brattli B (1985) Ages of metamorphic and deformational events in the Beiarn Nappe Complex, Nordland, Norway. Nor Geol Unders Bull 399: 27–39

Van Staal CR, Fyffe LR (1991) Dunnage and Gander zones, New Brunswick: Canadian Appalachian region. New Brunswick Department of Natural Resources and Energy, Mineral Resources, Geoscience Rep 91-2, 39 pp

Van Staal CR, Fyffe LR, Langton JP, McCutcheon SR (1992) The Ordovician Tetagouche Group, Bathurst Camp, Northern New Brunswick, Canada: history, tectonic setting, and distribution of massive-sulphide deposits. Explor Mining Geol 1: 93–103

Vogt JHL (1894) Dunderlandsdalens jernmalmfelt i Ranen. Nor Geol Unders 15: 1–103

Vogt JHL (1900) Søndre Helgeland. Nor Geol Unders 29: 1–178

Vogt JHL (1902) Det nordlige Norges malmforekomster og bergverksdrift. Kristiania

Vogt JHL (1910) Norges jernmalmforekomster. Nor Geol Unders 51: 1–225

Vokes FM (1957) The copper deposits of the Birtavarre district, Troms, northern Norway. Nor Geol Unders 199: 1–239

Vokes FM (1960) Mines in south and central Norway. Guide to excursion C10, Int Geol Cong, Oslo, 1960

Vokes FM (1963) Geological studies on the Caledonian pyritic zinc-lead ore body at Bleikvassli, Nordland, Norway. Nor Geol Unders 222: 1–126

Vokes FM (1966) On the possible modes of origin of the Caledonian sulfide ore deposit at Bleikvassli, Nordland, Norway. Econ Geol 61: 1130–1139

Vokes FM (1988) Latest Proterozoic and Phanerozoic metallogeny in Fennoscandia. In: Zachrisson E (ed) Procs 7th Quad IAGOD Symp Luleå. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, pp 41–58

Vokes FM (1996) Geological factors influencing the utilization of the Løkken Cu-Zn-Fe-S deposit, Meldal. Det Kongelige Norske Videnskabers Selskabs Forhandlinger, 1995, pp 179–189

Vokes FM, Gale GH (1976) Metallogeny relatable to continental drift in southern Scandinavia. Geol Assoc Can, Spec Pap 14: 413–444

Vokes FM, Rundhovde E, Boyd R, Grenne T et al. (1991) The metallogeny of early Ordovician ophiolites in the Norwegian Caledonides. In: Pagel M, Leroy JL (eds) Source, transport and deposition of metals. Procs 25th Anniv Meet, SGA, Nancy. AA Balkema, Rotterdam, pp 627–630

Wilks WJ, Cuthbert SJ (1994) The evolution of the Hornelen Basin detachment system, western Norway: implications for the style of late orogenic extension in the southern Scandinavian Caledonides. Tectonophysics 238: 1–30

Willden MY (1980) Paleoenvironment of the autochthonous sedimentary rock sequence at Laisvall, Swedish Caledonides. Stockholm Contrib Geology, XXXIII, 100 pp

Williams CE, McArdle P (1978) Ireland. In: Bowie SHU et al. (eds) Mineral deposits of Europe. vol I Northwest Europe. London, Institution of Mining and Metallurgy/Mineralogical Society, pp 319–345

Williams-Jones AE, Schrijver K, Doig R, Sangster DF (1992) A model for epigenetic Ba-Pb-Zn mineralization in the Appalachian thrust belt, Quebec: evidence from fluid inclusions and isotopes. Econ Geol 87: 154–174

Wooley AR (1989) The spatial and temporal distribution of carbonatites. In: Bell K (ed) Carbonatites. Genesis and evolution. Unwin Hyman, London, pp 15–37

Wulff P (1993) En klassifikation af mineraliseringer på Bømlo, Sunnhordland, SV-Norge. Master Thesis, University of Copenhagen, 139 pp

Wulff P, Stendal H (1995) Gold in Sunnhordland, the Caledonides of southwestern Norway. In: Ihlen PM, Pedersen M, Stendal H (eds) Gold mineralization in the Nordic countries and Greenland. Extended abstracts and fieldtrip guide, Grønl Geol Unders Open File Series 95/10: 116–119

Zachrisson E (1969) Caledonian geology of northern Jämtland-southern Västerbotten. Köli stratigraphy and main tectonic outlines. Sver Geol Unders C644, 33 pp

Zachrisson E (1971) The structural setting of the Stekenjokk ore bodies, central Swedish Caledonides. Econ Geol 66: 641–652

Zachrisson E (1980) Aspects of stratabound base metal mineralization in the Swedish Caledonides. Geol Surv Ireland Spec Pap 5: 47–61

Zachrisson E (1984) Lateral metal zonation and stringer zone development, reflecting fissure-controlled exhalations at the Stekenjokk-Levi stratabound sulfide deposit, central Scandinavian Caledonides. Econ Geol 79: 1643–1659

Zachrisson E (1986a) Scandinavian Caledonides. Stratabound sulphide deposits (Map 1:1.5 M) Sver Geol Unders Ba 42

Zachrisson E (1986b) The Stekenjokk Zn-Cu(-Pb) massive sulphide deposit in a bimodal metavolcanic sequence. In: Stephens MB (ed) Stratabound sulphide deposits in the central Scandinavian Caledonides. Sver Geol Unders Ca 60: 34–41

Zartman RE, Doe BR (1981) Plumbotectonics – the model. Tectonophysics 75: 135–162