Coticules at Sulitjelma, Norway and their possible origin

NIGEL JOHN COOK & CHRISTOPHER HALLS

Cook, N. J. & Halls, C.: Coticules at Sulitjelma, Norway and their possible origin. *Norsk Geologisk Tidsskrift*, Vol. 70, pp. 153–158. Oslo 1990. ISSN 0029-196X.

Laterally continuous coticule horizons from Sulitjelma, Norway, related to the Cu-pyritic massive sulphide ores nearby contain zoned spessartine garnet within a matrix of quartz and Fe–Mn oxides. Electronprobe studies show that two compositionally distinct garnets exist, differentiated by Mn content. The high-Mn variety is interpreted as forming early during metamorphism, from chemical products of exhalite precipitation. The low-Mn type is attributed to regional metamorphism of a Fe–Mg silicate precursor mineral. Their coexistence is explained by lack of chemical equilibration allowed by the silicic matrix.

N. J. Cook, Department of Geological Sciences and the Mineral Exploration Research Institute, McGill University, Montreal, Quebec, Canada H3A 2A7; C. Halls, Department of Geology, Imperial College of Science and Technology, Prince Consort Road, London SW7 2BP, England.

Banded rock formations containing abundant Fe–Mn alumino-silicate minerals have been recognized in various localities around the world, and in metamorphosed rock sequences from throughout geological history, often in close spatial association with volcanogenic massive sulphide deposits. These horizons, which are characterized by spessartine garnet, are believed to have been formed as chemico-sedimentary layers of exhalite precipitation on the sea floor, simultaneously with, or shortly following, ore formation. They typically occur at well-defined stratigraphically conformable horizons lying directly above the stratabound ores. The horizons may sometimes cover lateral areas greater than 100 km^2 surrounding the massive ores and may be important guides to ore. As such, they have long been considered comparable to manganese rich varieties of banded iron formations (e.g. Stanton 1976).

Such Mn-rich sediments have been observed in areas of recent and currently active hydrothermal activity and mineralization on the present-day ocean floor, for example, in the black smoker area of the East Pacific Rise at 18.5°S, described by Marchig et al. (1986).

The ancient term coticule was re-introduced by Renard (1878) to describe a suite of metamorphosed rocks of this type in the Belgian Ardennes. Kennan (1986) has elaborated on the history of the term coticule and its usage. The rock should contain essential spessartine garnet in a matrix of sericite and/or quartz. The coticules may often be associated with a suite of rocks of ophiolitic affinity and be close to massive sulphide deposits.

Within the Caledonides of Scandinavia, such exhalite horizons were first recognized as the products of exhalative sedimentary activity at Skorovas, Nord Trøndelag by Halls et al. (1977) and more fully described by Ferriday et al. (1981). Several other occurrences in the Norwegian Caledonides have since been reported.

At Sulitjelma, northern Norway, a unit containing bands of garnet is found associated with a group of more than 20 pyritic massive sulphide deposits and was first reported by Boyle (1980). The Sulitjelma orebodies have a total tonnage of 35 million tonnes, and have been an important source of copper and pyrite in Norway since mining commenced more than 100 years ago. The stratigraphic sequence, which is of ophiolitic affinity (Boyle 1980), within which the deposits are located, lies in the upper allochthon of the Caledonides (Stephens et al. 1985).

Geological setting

The 20 or so orebodies which make up the ore field are recognized as stratiform stratabound massive ores, each with a well-developed subjacent zone of alteration (Cook 1987; Cook et al. 1990, in press). The orebodies are located at the junction between a sequence dominated by volcanic rocks of mostly basaltic composition, the Sulitjelma Amphibolite Group, and the stratigraphically overlying thick sedimentary unit, the Furulund Group. The basaltic segment of the Sulitjelma Amphibolite Group (Otervatn volcanics), together with the Mietjerpakte sheeted intrusive Complex and the Sulitjelma Gabbro are interpreted to form a possible ophiolite complex (Boyle 1980).

The geological setting of the ore field has been given previously by Vogt (1927), Wilson (1973) and by Boyle et al. (1985). A simplified geological map of the area is given in Fig. 1 and the tectonostratigraphy of the area and of the Sulitjelma Amphibolite Group is summarized in Fig. 2.

Extensive penetrative tectonic deformation of the sequence, dominated by simple shear during

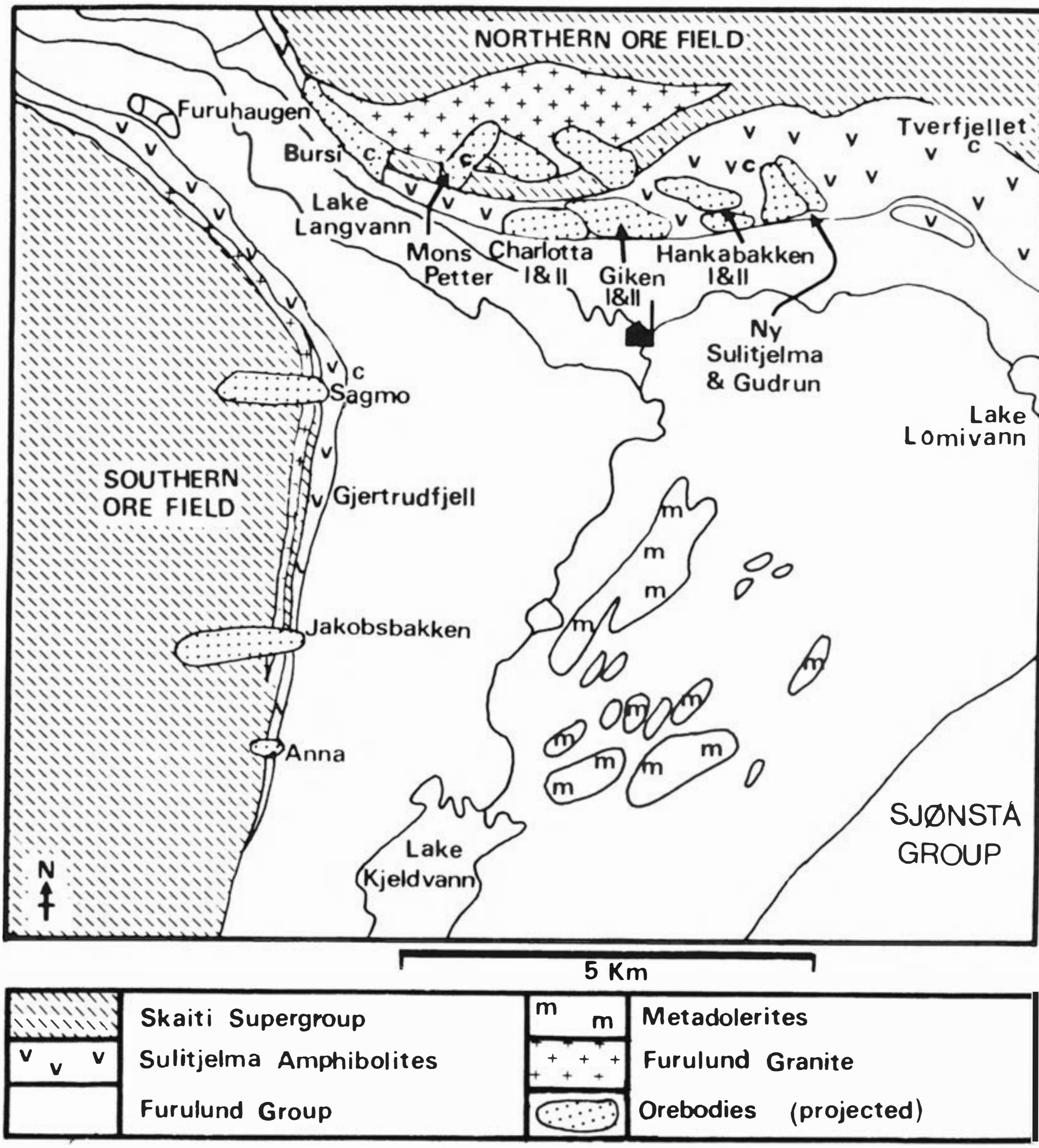

Fig. 1. Simplified geological map of the Sulitjelma area, indicating the main rock units and the location of coticules (c).

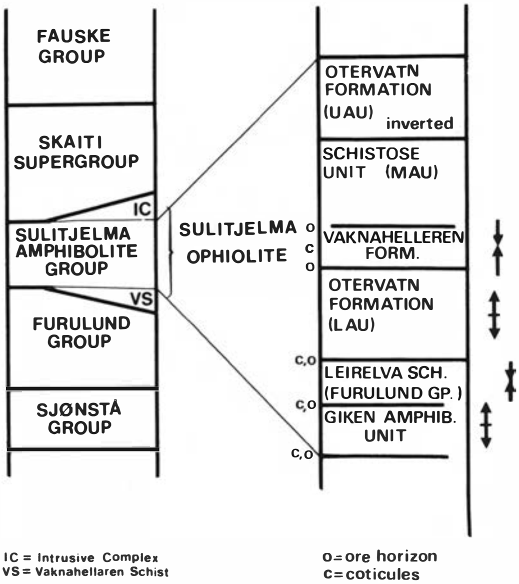

Fig. 2. Simplified tectono-stratigraphic column of the Sulitjelma area and of the Sulitjelma Amphibolite Group.

the Scandian Orogeny, coupled with the development of a sheath-fold geometry (Boyle 1987) has resulted in widespread inversion of both the stratigraphy and of the garnet isograd. The relative incompetence of the zones of hydrothermal alteration subjacent to the massive ores has led to them acting as major zones of weakness, along which tectonic transport has been allowed to take place (Cook 1987). The majority of the sulphide bodies and the coticule horizons are interpreted by unravelling of the stratigraphy to have possibly formed at a single stratigraphic interval (Cook 1987; Cook et al. 1990, in press) at or close to the junction of the Sulitjelma Amphibolite Group with the Furulund Group. They are now located at various structural levels. By virtue of their stratabound character, the coticule horizons are recognized as valuable guides to ore-bearing horizons at Sulitjelma.

The Sulitjelma Amphibolite Group is composed of four subformations, The Upper (UAU), Middle (MAU), Lower (LAU) and Giken Amphibolite units (Hansen 1984). The UAU and LAU form the limbs of the Vaknahellaren Synform, a major flat-lying fold, and can be correlated with the Otervatn Formation of Boyle (1982). The MAU is a mixed volcanic-sedimentary unit and forms the lower part of the upper limb of the fold (Fig. 2).

The rocks of the Sulitjelma Amphibolite Group are extensively chloritized, a result of the ore-forming hydrothermal activity which modified the chemical composition of the rock, in particular removing Ca from the system and preventing crystallization of minerals characteristic of the amphibolite facies, especially Ca-amphiboles. Widespread retrograde metamorphism and abnormally high water/rock ratios are also recognized (Cook 1987; Cook et al. 1990, in press). The chloritization of the Sulitjelma Amphibolite Group has given the suite the appearance of greenschist grade lithologies, with only the presence of small amounts of grossular garnet throughout all rock types, indicating the identity of the sequence as amphibolite grade. Only in the manganiferous garnet horizons, however, is garnet a major component mineral, largely due to chemical composition.

Coticule horizons are exposed underground at the northern end of Sagmo mine (Fig. 1), some 1–10 m above the massive ores, and in the recently closed Mons Petter Mine in the Northern ore field. A number of field outcrops of coticules have been noted within the Vaknahellaren Schist Formation near Ny Sulitjelma in the eastern part of the ore field. This formation is a thin but distinctive unit composed of mixed sediments and tuffitic rocks at the junction between the Sulitjelma Amphibolite Group and the Furulund Group, as shown in Fig. 2. A thin garnetiferous horizon previously interpreted by Boyle (1980) and Hansen (1984) as belonging to the Vaknahellaren Schist Formation is noted at Bursi in the northwestern part of the ore field, and a somewhat thicker unit is seen on Tverfjellet to the northeast. The Tverfjellet examples, located

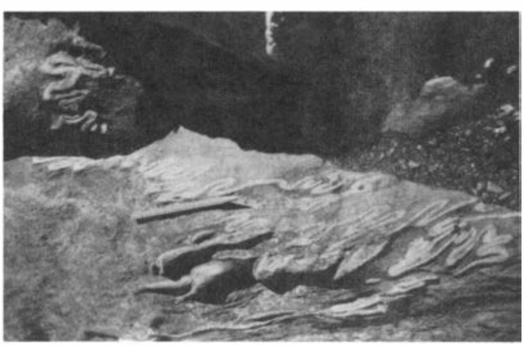

Fig. 3. Field exposure of coticule horizon, Tverfjellet, East of Ny Sulitjelma.

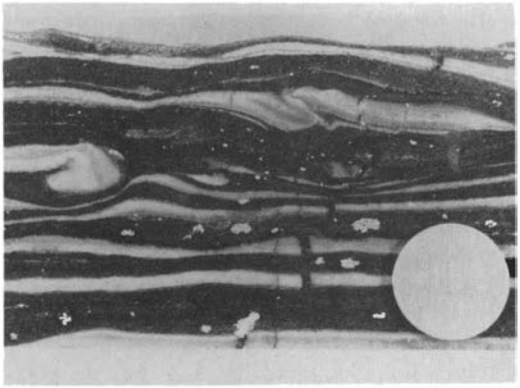

Fig. 4. Photograph of hand specimen of coticule from Tverfjellet, showing banding and structural features.

10 km from the ore field, are the most spectacular, and were first described by Boyle (1980, 1982). The intervals in which the coticule horizons appear are about 2–5 m thick, although lack of adequate outcrop in the field severely limits assessment of the units' true thickness. The individual bands (Figs. 3 and 4) are usually less than 1 cm in thickness, but are as thick as 1 m at certain outcrops at Bursi. Small quantities of dravoitic tourmaline have been observed from the equivalent horizon at Gjertrudfjell in the Southern Orefield.

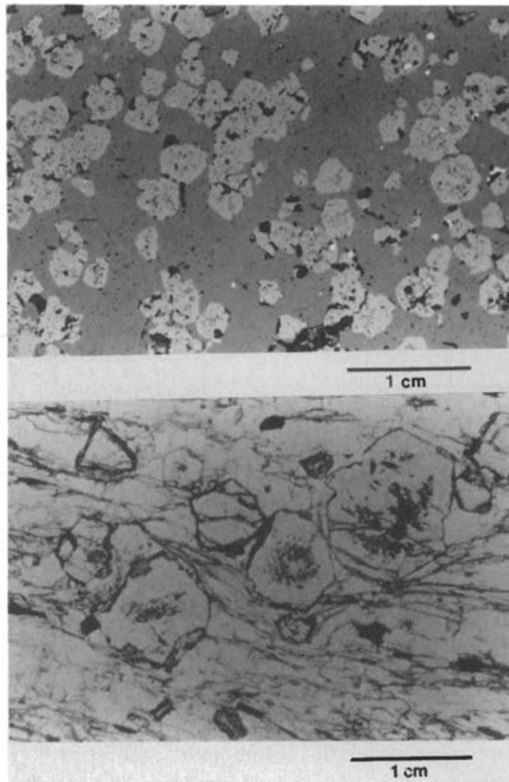

Fig. 5. Photomicrographs of banded coticule under transmitted light, showing (a) the pink and (b) the dark band types.

Petrography and mineral chemistry

The coticule horizons are composed of rhythmically alternating pink and dark bands, each band of between 0.3 and 1.0 cm in thickness. Both band types contain garnet and quartz. Garnets account for 40–80% of the rock; they are of 'pyralspite' type and are rounded and blastic in appearance. The garnets range in size from microscopic (less than 0.1 mm) to approximately 1 mm as shown in Fig. 5a and b. The main mineralogical distinction between the two bands is that the dark bands additionally contain biotite, chlorite, magnetite and hematite. The biotite and chlorite are both highly Mg rich, with Mg/(Fe + Mg) ratios of about 0.75. Trace Mn oxides have been noted. These other minerals make up 30% of the rock by volume. On the hand specimen scale, the coticules are characterized by ptygmatic folding, micro-scale shear zones, boundinaging and other micro-structures.

Electronprobe microanalysis was carried out to determine the chemical compositions of the garnet phases. Representative analyses and stoichiometry are given in Table 1. A strong dichotomy in chemical composition was revealed between the populations of garnets in the pink bands and those in the dark bands. Those in the pink bands were highly rich in Mn, and each contained 22–35% of the spessartine molecule. The Mn content systematically decreases from core to rim and this is typical of garnets produced within a single prograde metamorphic event, and has been widely reported, by Woodsworth (1977) amongst others. Zonation of Fe, Mg and Ca varies from grain to grain, sometimes increasing towards the rim and sometimes decreasing.

The garnets in the dark bands were also 'normally' zoned, but were appreciably lower in Mn content, which was in the range of 10–20% of the spessartine molecule. Profiles of chemical composition across the two distinct types of garnet grains from a sample containing both types are shown in Fig. 6.

Table 1. Electronprobe microanalyses of garnet.

	Pink bands		Dark bands	
	6541/13 (core)	6541/30 (rim)	6541/23 (core)	6541/27 (rim)
SiO_2	40.69	37.54	37.21	34.25
TiO_2	0.26	0.04	0.08	1.66
Al_2O_3	18.66	22.14	20.30	19.49
FeO	21.60	25.60	27.43	28.10
MnO	14.85	9.77	10.26	5.48
MgO	1.09	1.71	0.96	4.21
CaO	3.37	6.31	4.82	3.99
Total	100.52	102.11	101.06	97.18
Si	6.47	5.94	5.99	5.68
Ti	0.03	0.01	0.01	0.21
Al^{iv}	0.00	0.05	0.00	0.11
Al^{vi}	3.50	3.89	3.85	3.70
Fe	2.87	3.38	3.70	3.89
Mn	2.00	1.31	1.40	0.77
Mg	0.26	0.40	0.23	1.04
Ca	0.58	1.07	0.83	0.71
O	24.00	24.00	24.00	24.00
Almandine	50	55	64	61
Grossular	10	18	15	11
Pyrope	5	7	5	16
Spessartine	35	21	17	12

Formulae are calculated on basis of 24 oxygens.
Cambridge mark V electron probe, Imperial College, London.

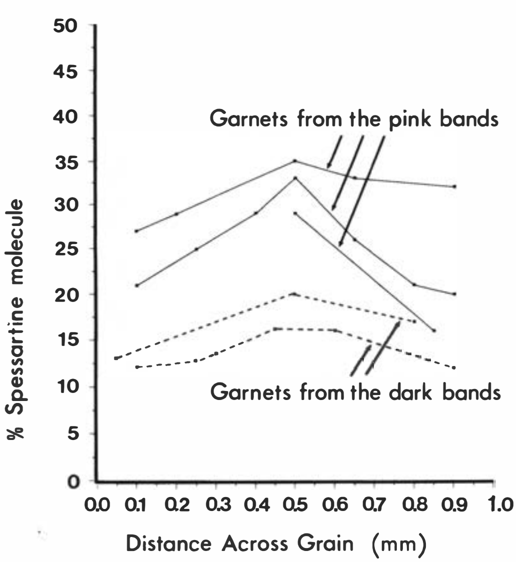

Fig. 6. Profiles of garnet composition expressed in relative percentages of the spessartine molecule. Contents of the other components (Fe, Mg and Ca) behave unsystematically and zonation patterns vary from grain to grain.

Discussion

The formation of the two types of garnets can be related to the formation of the layers in which they are found. The pink bands are thought to have been formed by precipitation from Fe–Mn rich plumes during periods of relatively intense hydrothermal exhalation from the focus of hydrothermal activity, probably following the intensive phase of massive ore formation. They are composed of a chemical component; Fe, Mn and silica exhaled from the hydrothermal vents, and a detrital component originating from non-chemical sedimentation; contributing the A1. The garnets were formed from either primary hydrothermal precursor minerals, with a similar composition, possibly from a Fe–Mn hydroxide gel, or from minerals which grew during diagenesis of exhalite precipitates close to the sea floor. A similar genesis has been proposed by Robinson (1984) for garnets in garnet-stilpnomelane rocks at Redstone, Timmins, Ontario, Canada.

Evidence from currently active hydrothermal systems has shown that the process of hydrothermal exhalation may be cyclic (Cann & Strens 1987). It is possible that the banded garnetites are a record of the cyclic nature of the latter part of the hydrothermal activity which produced the Sulitjelma deposits. The dark bands are believed to have been formed as mixtures of sedimentary and tuffitic material with possibly some hydrothermal component during periods of relative quiescence.

The garnets in the pink bands are proposed to have grown early during metamorphism, at relatively low temperatures, overprinting a fine-grained fabric. Boyle (pers. comm.) has observed that, in some samples, the grain size of garnet and quartz is comparable in the pink layers, demonstrating that textural equilibrium was established after garnet growth at higher metamorphic conditions when the supply of mineral forming components was exhausted. The pronounced zoning is consistent with garnet formation within a single prograde event (Robinson 1984). Preferential fractionation of Mn into the garnet structure leads to the progressive depletion of Mn in the rock during garnet growth (Woodsworth 1977).

The garnets in the 'dark' bands are believed to have originated as the reaction product of Fe–Mg silicates with Mn oxides under amphibolite facies conditions, comparable with those reactions outlined by Boyle (1986) for the more widely distributed basic and pelitic rocks of the Sulitjelma area. The establishment of chemical equilibrium between the two types of garnets has not been attained because of the barrier to fluid flow presented by the fine-grained siliceous matrix of the pink bands. The lack of chemical homogenization of garnet from one stratigraphic interval to another is due to metamorphism under closed system conditions on a micro-scale.

Comparable features of garnet mineralogy have been reported by Stanton (1976) from the Broken Hill area, N.S.W., Australia. His interpretation was that the spessartine garnets derived from the in situ closed system metamorphism of an early manganiferous chloride of chamosite-cronstedtite type. He also stressed that the composition of the garnets reflects the composition of the precursor minerals rather than the bulk-rock chemistry. A similar interpretation may be made for the coticules under discussion here.

Acknowledgements. – The authors thank A/S Sulitjelma Bergverk for their assistance during field work. The comments on an early version of the manuscript by Dr Alan Boyle are greatly appreciated and two anonymous *Norsk Geologisk Tidsskrift* reviewers are thanked for their most helpful reviews. The first author was in receipt of a United Kingdom NERC–CASE studentship at Imperial College, London during the duration of this research.

Manuscript received April 1990

References

Boyle, A. P. 1980: The Sulitjelma amphibolites, Norway: Part of a lower Palaeozoic ophiolite complex? *In* Panayioutou, A. (ed.): *Ophiolites: Proceedings International Ophiolite Symposium, Cyprus, 1979.* Cyprus Geological Survey Dept., Nicosia, 567–575.

Boyle, A. P. 1982: The structure, petrology and ophiolitic affinities of the Sulitjelma Amphibolites, Central Scandinavian Caledonides. Unpublished PhD thesis, University of London.

Boyle, A. P. 1986: Metamorphism of basic and pelitic rocks at Sulitjelma, Norway. *Lithos 19*, 113–128.

Boyle, A. P. 1987: A model for the stratigraphic and metamorphic inversions at Sulitjelma, central Scandes. *Geological Magazine 124*, 451–466.

Boyle, A. P., Mason, R. & Hansen, T. S. 1985: A new tectonic perspective of the Sulitjelma region. *In* Gee, D. G. & Sturt, B. A. (eds.): *The Caledonide Orogen: Scandinavia and Related Areas,* 529–542. John Wiley & Sons Ltd.

Cann, J. R. & Strens, M. R. 1987: Venting evets in hot water. *Nature 329*, 104.

Cook, N. J. 1987: The volcanogenic massive sulphide deposits at Sulitjelma, Norway, a mineralogical and geochemical investigation. Unpublished PhD thesis, University of London.

Cook, N. J., Halls, C. & Kaspersen, P. O. 1990: The geology of the Sulitjelma ore field, Northern Norway – some new interpretations. Accepted for publication in *Economic Geology.*

Ferriday, I. L., Halls, C. & Hembre, O. S. 1981: The stratigraphy and mineralogical identity of exhalative sediments with relationship to the stratiform volcanogenic orebodies at Skorovas, Norwegian Caledonides. *In: Proceedings; Caledonian-Appalachian Stratabound Sulphides.* University of Strathclyde, Glasgow.

Halls, C., Reinsbakken, A., Ferriday, I., Haugen, A. & Rankin, A. 1977: Geological setting of the Skorovas orebody within the allochthonous volcanic stratigraphy of the Gjersvik nappe, Central Norway. *In: Volcanic Processes in Ore Genesis, Geological Society of London Special Publication no. 7*, 128–151.

Hansen, T. S. 1984: En geologisk undersøkelse av den Sulitjelma Gruvefeltet. Unpublished Dr Ing thesis, Norges Tekniske Høgskole, Trondheim.

Kennan, P. S. 1986: The coticule package: A common association of some very distinctive lithologies. *Aardkundige Medelingen 3*, 139–148.

Marchig, V., Erzinger, J. & Heinze, P. M. 1986: Sediment in the black smoker area of the East Pacific Rise (18.5°S). *Earth and Planetary Science Letters 79*, 93–106.

Renard, A. 1878: Sur la structure et la composition minéralogique du coticule et sur les rapports avec le phyllade oligistiére. *Mem. Cour. Acad. Roy. Belg 41*, 1–42.

Robinson, D. J. 1984: Silicate facies iron formations and stratabound alteration: Tuffaceous exhalites derived by mixing – Evidence from Mn garnet–stilpnomelane rocks at Redstone, Timmins, Ontario. *Economic Geology 79*, 1796–1817.

Stanton, R. L. 1976: Petrochemistry of the ore environment at Broken Hill, New South Wales 2. Regional Metamorphism of banded iron formations and their origin. *Transactions, Institute of Mining and Metallurgy B85*, 118–131.

Stephens, M. B., Gustavson, M., Ramberg, I. B. & Zachrisson, E. 1985: The Caledonides of Central-North Scandinavia – a tectonostratigraphic overview. *In* Gee, D. G. & Sturt, B. A. (eds.): *The Caledonide Orogen – Scandinavia and Related Areas.* 135–162. John Wiley & Sons Ltd.

Vogt, Th. 1927: Sulitjelmafeltets Geologi og Petrografi. *Norges Geologiske Undersøkelse 121*, 560 pp.

Wilson, M. R. 1973: The geological setting of the Sulitjelma orebodies, Central Norwegian Caledonides. *Economic Geology 68*, 307–316.

Woodsworth, G. J. 1977: Homogenisation of zoned garnets from pelitic schists. *Canadian Mineralogist 15*, 230–242.