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Greenalite, Mg-rich minnesotaite and stilpnomelane from the Ösjöberg and Sirsjöberg iron-ore mines, Hjulsjö, W. Bergslagen, Sweden

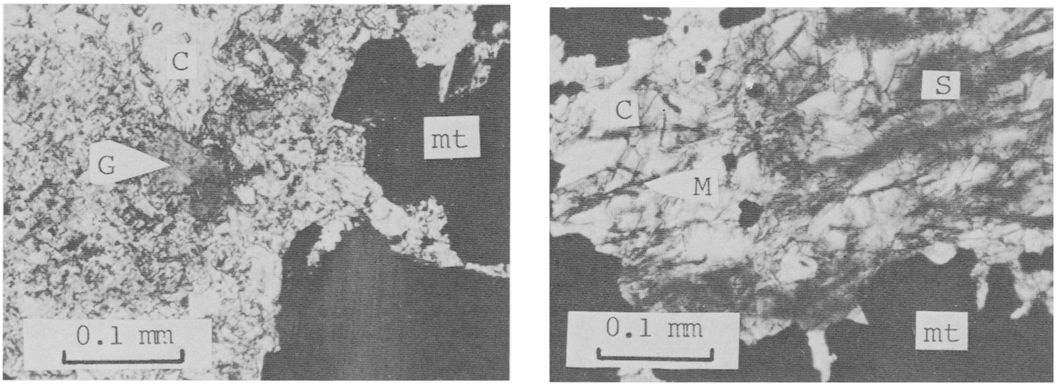
GREENALITE, Mg-rich minnesotaite, and stilpnomelane have been identified by electron microprobe analysis in samples taken from dumps of the abandoned Ösjöberg and Sirsjöberg mines 5 km NW of Hjulsjö, Bergslagen. This is the first report of the occurrence of these minerals in the Proterozoic iron ores of Central Sweden. The two mines, some 700 m apart, worked a large, 7 km long, meta-rhyolite-hosted, magnetite ore horizon—one of the many concordant skarn iron ores in the 1.8–1.9 Ga Proterozoic Bergslagen Supracrustal Series (Oen *et al.*, 1982). They were amongst the largest iron producers of this area.

The subsurface geology of the mines has been described by Geijer and Magnusson (1944); earlier descriptions are given by Blomberg (1879) and Sundius (1923). According to Geijer and Magnusson (1944) the massive magnetite ore horizon in the Ösjöberg mine is 15–20 m wide and 850 m long, strikes E–W and dips steeply 60–70 °N. Talc, chlorite, and actinolite form schistose zones (sköls) in the iron ore, running parallel to the country rocks (felsic metavolcanics), and separating the northern contact of the iron ore from the metavolcanics.

The Sirsjöberg iron ore is massive magnetite, forming a uniformly 50 m thick and 650 m long subvertical body which strikes approximately E–W and is considered by Baker and de Groot (1983*b*) to be continuation of the Ösjöberg ore horizon. The ore is separated from an underlying limestone horizon by a garnet–pyroxene–amphibole skarn. Magnetite is present in the skarn and the limestone. Epidote and calcite are later minerals filling tectonic fissures and cracks.

Greenalite occurs in a sample from Ösjöberg mine which comprises a fine grained aggregate of magnetite grains (±0.05 mm) with some larger grains up to 0.5 mm in a matrix composed predominantly of talc with minor green chlorite. Talc also fills fractures in the larger magnetite grains. Very minor pyrite and rare chalcopyrite are seen enclosing magnetite. Olive green greenalite forms platy growths up to 0.2 mm replacing calcite (up to 1 mm grains) which is generally in contact with magnetite, though greenalite is rarely seen in contact with magnetite (fig. 1). Small quartz grains are also present in the calcite.

Calculating the greenalite formula on the basis of 14 oxygens results in excess Si, a common feature noted by Florian and Papike (1975) and Guggenheim *et al.* (1982). Calculation on the basis of 4.0 tetrahedral cations produces the general formula $(Fe_{5.86}Mg_{0.14})Si_4O_{10}(OH)_8$.



FIGS. 1 and 2. FIG. 1 (*left*). Sample Cab 328b, crossed nicols. Greenalite (g) replacing calcite (c), in magnetite (mt) carbonate rock. FIG. 2 (*right*). Sample Bj 13c, crossed nicols. Mg-rich minnesotaite (m) and stilpnomelane (s) in a matrix of calcite.

Mg-rich minnesotaite and *stilpnomelane* occur in a sample from the Sirsjöberg mine which comprises weakly banded aggregates of magnetite, with minor quartz and calcite. Mg-rich minnesotaite forms small, dark brown to colourless pleochroic needles up to 0.2 mm long in the calcite, running parallel to the magnetite banding (fig. 2). Stilpnomelane forms camel-brown platy aggregates together with minor green chlorite, particularly between the magnetite grains, but also overprinting Mg-rich minnesotaite, and forms bands and veins, parallel to the original banding.

Mg-rich minnesotaite shows an Si deficiency and excess of octahedral cations, suggesting some substitution of Fe^{2+} or Mg for Si. Minor amounts of Ca and Na are also present. Both Ca and Al show an irregular distribution in the Mg-rich minnesotaite grains. Several analyses have confirmed that the presence of Ca is not spurious. The general formula for this Mg-rich minnesotaite is $(Fe_{1.66}Mg_{1.54})Si_4O_{10}(OH)_2$ (see also Kager and Oen, 1983). Stilpnomelane is similar in composition to minnesotaite, except for a higher Al content, and the presence of alkalis, though their content is low (Table I). The identity of the stilpnomelane has been checked by X-ray diffraction. A general formula $(K,Ca)_{0.1}(Fe_{1.79}Mg_{0.91}Al_{0.21})\ Si_8O_{20}(OH)_4 \cdot xH_2O$ can be written for this stilpnomelane, which has a higher Fe/(Fe+Mg) ratio than the Mg-rich minnesotaite.

Greenalite in banded iron-formation is considered to be a relict primary mineral formed

Table I. Electron microprobe analyses for greenalite (sample Cab 328b) and Mg-rich minnesotaite and stilpnomelane (sample Bj 13c).

	Greenalite			Mg-rich Minnesotaite			Stilpnomelane		
	1	2	3	1	2	3	1	2	3
SiO_2	35.08	34.99	34.33	52.06	51.40	51.79	48.83	49.48	48.79
TiO_2	0.02	d.1	d.1	d.1	d.1	0.02	n.d	n.d	d.1
Al_2O_3	0.09	0.05	0.07	0.54	0.87	0.54	5.18	5.32	5.31
FeO*	52.37	51.95	51.14	27.01	27.79	26.39	27.46	29.21	27.40
MnO	0.18	0.19	0.09	0.68	0.56	0.70	0.24	0.36	0.27
MgO	0.79	0.65	0.65	14.39	13.70	14.37	7.82	7.98	8.21
CaO	0.33	0.24	0.76	1.16	1.31	0.87	0.33	0.78	0.74
Na_2O	0.02	d.1	d.1	0.15	0.19	0.12	d.1	0.06	0.04
K_2O	d.1	d.1	d.1	0.04	d.1	d.1	0.70	0.69	0.58
(H_2O)**	11.12	11.93	12.95	3.97	4.18	5.20	9.44	6.12	8.66
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
	on the basis of 14 oxygens			on the basis of 11 oxygens			on the basis of 11 oxygens		
Si	4.239	4.263	4.238	3.790	3.768	3.806	3.771	3.720	3.739
Al	0.000	0.000	0.000	0.046	0.075	0.047	0.229	0.280	0.261
Σ	4.239	4.263	4.238	3.836	3.843	3.853	4.000	4.000	4.000
Al	0.013	0.007	0.010	0.000	0.000	0.000	0.243	0.191	0.219
Ti	0.002	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
Fe^{2+}	5.293	5.294	5.279	1.644	1.704	1.622	1.773	1.836	1.756
Mn	0.018	0.020	0.009	0.042	0.035	0.044	0.016	0.023	0.018
Mg	0.142	0.118	0.120	1.561	1.497	1.574	0.900	0.894	0.938
Ca	0.043	0.031	0.101	0.090	0.103	0.069	0.027	0.063	0.061
Na	0.005	0.000	0.000	0.021	0.027	0.017	0.000	0.009	0.006
K	0.000	0.000	0.000	0.004	0.000	0.000	0.069	0.066	0.057
Σ	5.516	5.370	5.519	3.362	3.366	3.326	3.028	3.082	3.055
Fe/(Fe+Mg)	0.97	0.98	0.98	0.51	0.53	0.51	0.66	0.67	0.65

* total Fe given as FeO.

** H_2O values obtained by subtracting electron microprobe analysis total from 100%. d.1 = value lies under detection limit of system, n.d = not determined. Analyses performed on a Cambridge Instruments Microscan 9 operating at 20 Kv using silicate standards and an on-line ZAF correction procedure.

during diagenesis, whereas minnesotaite is thought to be a prograde metamorphic mineral (Klein, 1974, 1983; Florian and Papike, 1978) unless there is clear evidence that they are retrograde (e.g. Gole, 1980). In the Ösjöberg and Sirsjöberg mines the paragenetic significance of greenalite, Mg-rich minnesotaite, and stilpnomelane is not clear. The presence of a garnet-pyroxene-amphibole skarn (Geijer and Magnusson, 1944) would normally be taken as indicative of high-grade metamorphism (e.g. Winkler 1979), while the presence of greenalite and minnesotaite is clearly indicative of lower grade metamorphism. Greenalite and Mg-rich minnesotaite are not seen replacing magnetite, though stilpnomelane is clearly later. The mineral paragenesis found in surrounding felsic metavolcanics indicates lower greenschist facies conditions (Baker, 1981). Large-scale development of greenalite in the La Union Fe-Pb-Zn deposit of Cartagena, Spain, has been shown to be a metasomatic replacement of limestone (Oen *et al.*, 1975), whereas Mg-rich minnesotaite developed at a later stage in the mineralization (Kager, 1980). The petrographic relationships of greenalite and Mg-rich minnesotaite to calcite in the Sirsjöberg and Ösjöberg ores tentatively suggest a similar metasomatic development.

Sundius (1923) divided the iron ores of Bergslagen into sedimentary and metasomatic types, the latter group containing the skarn-bearing ores to which Ösjöberg and Sirsjöberg belong. Geijer and Magnusson (1944) and Magnusson (1970) considered that all the iron ores in W. Bergslagen had a sedimentary origin, and that iron concentration and skarn development or metasomatism was a later, modifying event. Recently Oen *et al.* (1982) have proposed a model of submarine continental rifting to account for the association of skarn and ore-forming processes with bimodal igneous magmatism, and related hydrothermal-metamorphic events. The Sirsjöberg-Ösjöberg ore horizon, which is concordant with the felsic metavolcanics, is similarly considered to be the product of sedimentary-exhalative processes (Baker and de Groot, 1983*b*) related to sub-seafloor hydrothermal systems operating on the underlying felsic pyroclastics (Baker and de Groot, 1983*a*).

In the samples examined greenalite and Mg-rich minnesotaite are apparently not retrograde reaction products of magnetite, as they have not been observed preferentially in contact with the latter mineral. The greenalite and Mg-rich minnesotaite may well represent primary prograde metasomatic minerals formed during the sub-seafloor hydrothermal alteration of limestones intercalated in the felsic metavolcanics. Stilpnomelane is probably a later low-grade metamorphic mineral.

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