

KEYWORDS: cosalite, sulbismuthinide mineral, Dunjeon gold mine, Korea

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MINERALOGICAL MAGAZINE, SEPTEMBER 1993, VOL 57, PP. 530-533

The breakdown of Zn-rich staurolite in a metabasite from the Betic Cordillera (SE Spain)

STAUROLITE is a characteristic mineral in medium and upper metamorphic grade rocks, most commonly found in metapelites; it has been reported occasionally in other rock types such as metabasites (Gibson, 1978; Moeen, 1991). Some natural staurolite specimens have a remarkable Zn-content, with up to 8 wt.% ZnO (Spry and Scott, 1986). Between the staurolite Zn-content and the *PT* stability field of this mineral, some empirical relationships have been proposed (Guidotti, 1970). He has shown that at higher metamorphic grades the Zn-content stabilizes the staurolite. In the present study, a staurolite with exceptionally high Zn-content in a metabasite sample with medium to low metamorphic grade assemblages is reported. Its textural relationships and transformation products to mineral assemblages rich in Zn are described also.

The metabasite outcrop studied (now amphibolites and amphibole-mica schists) belongs to the Bédar-Macael unit, from the Lubrín area (longitude 2°51'W, latitude 37°11'N). This is the uppermost unit of the Nevado-Filabride Complex, the lowest complex of the Alboran Domain in the Betic Cordillera (SE Spain) (García-Dueñas *et al.*, 1988). In the study area, two lithologic series can be distinguished in the Bédar-Macael unit. The lower one (to which a Paleozoic age has been attributed) consists essentially of graphite metapelites (quartz-mica-kyanite-chloritoid-garnet-staurolite schists), whereas the upper series (probably Permo-Triassic in age) is made up of albite metapelites (quartz-mica-albite-chloritoid-garnet-kyanite schists) and

marbles at the top. Within the latter lithologic assemblage, and preferentially along the contact between metapelites and marbles, a continuous band of metabasites with a maximum thickness of 200 m crops out. An Upper Jurassic age for the mafic protoliths was established by Hebeda *et al.* (1980).

The metabasites of the Bédar-Macael unit underwent alpine metamorphism characterized by a clockwise metamorphic evolution, in which three main mineral growing episodes can be distinguished. (1) A first episode under eclogite facies and blueschist facies (12 ± 2 kbar, 400 ± 50 °C); (2) a syn-kinematic retrograde episode under amphibolite facies, with a decrease in *P* at constant *T* (up to 5 kbar, 350 °C); and (3) a post-kinematic retrograde episode under greenschist facies, with a simultaneous decrease of *P* and *T* (Nijhuis, 1964; Bakker *et al.*, 1989; Soto, 1991).

Amphibolites together with amphibole-mica schists are the most common rock types in metabasites of the Bédar-Macael unit. Intercalated marbles, calcareous mica schist and quartzite veins appear in minor amounts. The mineralogy of the metabasites is characterized by several types of amphiboles (crossite, barroisite and minor Mg-hornblende), epidote, plagioclase (mean composition Ab₉₈), garnet (almandine > grossular > pyrope > spessartine), and opaque minerals (hematite-ilmenite intergrowths and magnetite; Nijhuis, 1964).

Metabasites exhibit a well-developed syn-kinematic schistosity generated during the second metamorphic event (amphibolite facies). A

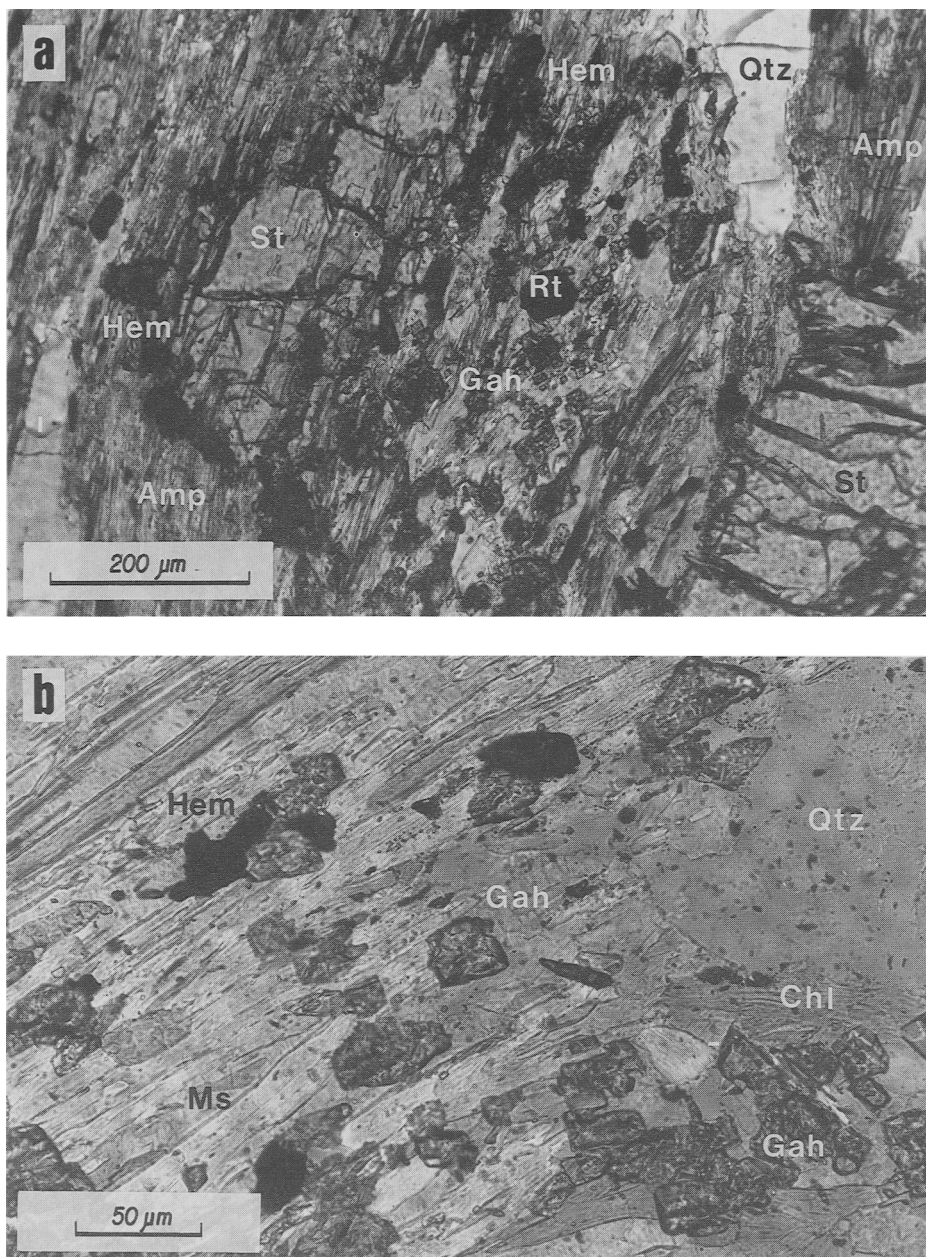


FIG. 1. Photomicrographs of: (a) Zincian-staurolite (St) with inclusions of rutile (Rt), quartz (Qtz) and amphibole (Amp), growing on a foliated matrix, with schistosity defined by elongated barroisite crystals. Gahnite (Gah) and hematite (Hem) aggregates grow at staurolite edges. (b) Squared crystals of gahnite showing cross-like twinning, surrounded by elongated crystals of muscovite (Ms) and chlorite (Chl).

mineral lineation with an E-W mean trend often appears. This lineation is defined by the preferred orientation of prismatic amphibole and epidote

crystals, as well as by the elongation of fusiform aggregates of plagioclase and epidote.

In the studied outcrop (longitude 2°51'54" W,

latitude 37°11'20" N), metabasites appear as a band of amphibolitic schists with a N-S trend and shallow dip to the E. Intercalations of marbles and calcite-rich schist become progressively more abundant toward the top of the band. Amphibole-mica schists consist mainly of green-blue barroisite crystals and colourless epidote crystals, defining the syn-kinematic schistosity. Some barroisite crystals are zoned and have blue crossite cores and dark green Mg-hornblende rims. In the matrix, post-kinematic albite and chlorite crystals developed at the expense of barroisite. Euhedral garnet crystals are frequent, growing over amphibole aggregates in the matrix. Accessories are hematite, quartz, rutile, and tourmaline. Along some amphibole crystals defining the schistosity, post-kinematic elliptical crystals (300–700 μ) of staurolite appear. These are pleochroic crystals, that vary from yellow to yellow-pink in colour. They contain inclusions of rutile, barroisite, hematite, and quartz, parallel to the schistosity in the matrix (Fig. 1a).

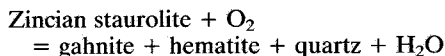
The analysed staurolite crystals show exceptionally high Zn content, with a maximum value up to 13.1 wt.% ZnO. Fe and Mg are present in subordinate amounts. This zincian staurolite has the highest ZnO content yet described in natural staurolite (cf. 7.16–8.77 wt.%; Miyake, 1985; Spry and Scott, 1986; Zaleski *et al.*, 1991). Occasionally high values of TiO₂ (up to 1.0 wt.%) and SiO₂ detected in some staurolite crystals are due to contamination produced by the presence of multiple rutile and quartz inclusions. Zincian staurolite crystals show a strong variation in composition from core to rim. Selected examples of core and rim compositions are shown in Table 1. Whereas cores are comparatively rich in Zn and poor in Fe with respect to rims, Mg content is constant throughout the crystals.

The inverse relationship observed between Zn and Fe contents along crystal profiles, shows that the major substitution in these zincian staurolites is a Zn=Fe substitution. Substitutions of this type have previously been described in other natural Zn-rich staurolite (e.g. Griffen and Ribbe, 1973; Miyake, 1985; Holdaway *et al.*, 1991). Apparently, Mg does not substitute for Fe.

The edges of staurolite crystals show evidence of incipient transformation to dark aggregates formed by spinel (gahnite) and opaque minerals (hematite only), which grew at the expense of staurolite. In the vicinity of staurolite, some isolated gahnite crystals show squared sections with occasional cross-like twinning (Fig. 1b). In the studied samples, this type of twinning has not been found in staurolite crystals. The gahnite composition is rich in Fe and poor in Mg, with

amounts of ZnO greater than 35 wt.% (mean composition: gahnite = 83 mol.%; hercynite = 12 mol.%; and spinel = 5 mol.%). The transformation of staurolite to gahnite is consistent with the decrease in Zn-content towards the rim of the staurolite. Part of the Fe released by the breakdown of staurolite formed hematite.

The textural relationships described, and the compositional variation of staurolite towards the crystal-rims are consistent with an oxidation reaction for the breakdown of the zincian staurolite. The unbalanced reaction involved in the staurolite to gahnite transformation is:



Similar oxidation reactions with water release have been proposed by Zaleski *et al.* (1991).

The *PT* conditions of the post-kinematic staurolite growth and its subsequent transformation to gahnite, may be qualitatively constrained by the stability field of the syn-kinematic barroisite assemblage during the second phase of metamorphism, and the presence of kyanite in surrounding albite-metapelites. The barroisite + garnet + plagioclase association stabilized between 5–10 kbar and 450 °C (Soto, 1991). The subsequent zincian-staurolite growth would have, therefore,

Table 1. Electron microprobe analyses of staurolite and gahnite.

	Staurolite		Gahnite
	Rim	Core	
SiO ₂	28.13	27.84	0.00
Al ₂ O ₃	50.21	49.49	54.89
TiO ₂	0.71	0.53	0.01
MgO	2.74	2.83	0.76
FeO	7.05	4.34	3.22
MnO	0.03	0.01	0.02
ZnO	9.63	13.13	40.70
Total	98.52	98.18	99.60
	44 (O) + 4 (OH)		32 (O)
Si	7.92	7.92	0.00
Al (4)	0.08	0.08	
Al (6)	16.61	16.53	15.81
Ti	0.15	0.11	0.00
Mg	1.15	1.20	0.28
Fe	1.66	1.03	0.41
Mn	0.01	0.00	0.01
Zn	2.00	2.76	7.34
Total	29.58	29.64	23.85
XFe	0.34	0.21	0.05
XMg	0.24	0.24	0.04
XZn	0.42	0.55	0.91

occurred at lower P and similar or slightly lower T . The low X_{Mg} value in this zincian-staurolite indicates that it formed at medium to low P conditions, as high Mg content stabilizes this mineral at high P and T conditions (Schreyer, 1988).

Acknowledgements. We wish to thank Dr. C. Chopin and Dr. A. Crespo-Blanc for their valuable comments on this paper, and the editors of the Mineralogical Magazine for their review and many improvements to the manuscript. The work was financed by the project PB-87-0461-01-CICYT.

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- [Manuscript received 11 September 1992:
revised 4 November 1992]

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KEYWORDS: zincian-staurolite, gahnite, metabasite, metamorphism, Betic Cordillera.

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MINERALOGICAL MAGAZINE, SEPTEMBER 1993, VOL 57, PP. 533–538

Namansilite, $\text{NaMn}^{3+}\text{Si}_2\text{O}_6$: a widespread clinopyroxene?

NAMANSILITE, the manganese analogue of aegirine, jadeite, and kosmochlor, has been named and described by Kalinin *et al.* (1992) from the Irnimiski deposit in the Far East of Siberia. An $\text{Na}(\text{Mn}^{3+}, \text{Fe}^{3+})$ clinopyroxene with up to 88.3 mol. % of the Mn (namansilite) end-member had previously been described by Ashley (1986) from a Lower Paleozoic stratiform manganese ore body at the Hoskins mine near Grenfell in the Lachlan Fold Belt of New South Wales, Australia (also mentioned by Eggleton and Ashley, 1989), and the same mineral, referred to as 'Na-Mn-clinopyroxene', has also been described by Basso *et al.* (1989) from Val di Vara in the Northern

Apennines, Italy. Here we report namansilite from the Woods mine manganese deposit in the Woolomin Formation of the New England Fold Belt, New South Wales. Electron microprobe elemental distribution maps for Na, Mn, Si, and Ca in the new mineral, in association with kuzulite, have already been presented by Kawachi (1991).

Occurrence at Woods Mine and physical properties

The Woolomin Formation contains metabasalt, chert, ash-fall tuffs, siliceous sandstone, and