Hydrothermal subsilicic sodium gedrite from the Gåsborn area, West Bergslagen, central Sweden

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Abstract

Subsilicic sodium gedrite has been found in a hydrothermal vein together with sekaninaite (Fe-cordierite), andalusite, plagioclase, topaz, sillimanite, quartz, biotite, magnetite, ilmenite, hercynite, wolframite, pyrrhotite, chalcopyrite and pyrite. This vein is part of a hydrothermal vein system consisting predominantly of quartz–feldspar veins, some of which contain andalusite, sekaninaite, biotite, muscovite, fluorite and accessory oxides and sulphides, which was formed during the later stages of crystallization of a high-level anorogenic Svecofennian granite. Petrographic observations suggest the following crystallization sequence for the quartz–feldspar veins: plagioclase–quartz–andalusite–sekaninaite–microcline–biotite–albite–oxides and sulphides–muscovite–fluorite, and for the subsilicic sodium gedrite-bearing vein: andalusite–sekaninaite–subsilicic sodium gedrite–biotite–quartz–albite–sillimanite–topaz–oxides and sulphides. Electron microprobe analysis revealed that all subsilicic sodium gedrite is relatively homogeneous with only the following compositional variation: Na(A) 0.57–0.81, $\mathrm{Al^{iv}}$ 2.31–2.57, X_{Mg} 0.15–0.21. The temperature (T) for the formation of the hydrothermal vein system is estimated at 550–600 °C and the pressure (P) is estimated to be less than 3 kbar.

KEY WORDS: hydrothermal vein, andalusite, sekaninaite, subsilicic sodium gedrite, albitization, sodium.

Introduction and geological setting

SUBSILICIC sodium gedrite (amphibole nomenclature after Leake, 1978) has been described previously from only two locations (Kroonenberg, 1976; Schumacher, 1980). This paper presents the petrogenesis of a third occurrence and demonstrates its hydrothermal origin.

The factors that control the K + Na, A-site $A/\mathrm{Al^{iv}}$ ratio and the related edenite/tschermakite ratio (Berg, 1985) in orthorhombic amphiboles have been the subject of several studies (Robinson and Jaffe, 1971; Robinson *et al.*, 1982; Berg, 1985), in which general agreement exists that these ratios are crystal–chemically and crystallographically controlled by the incorporation of Mg and Fe in the $M1$–$M3$ sites of the amphibole. A comparison of site occupancies of the Gåsborn gedrite with gedrite from other localities with similar $A/\mathrm{Al^{iv}}$ ratios (Abraham and Schreyer, 1973; James *et al.*, 1978: Schumacher, 1980; Spear, 1980) shows a wide variation in X_{Mg}, indicating that the previously proposed control on $A/\mathrm{Al^{iv}}$ and the related edenite/tschermakite ratio by X_{Mg} is unjustified.

The Gåsborn area in the Bergslagen region of central Sweden (Fig. 1) consist of 1.9–1.8 Ga Svecokarelian (Svecofennian) rocks, comprising the following lithological units:

(1) A volcano–sedimentary sequence of acid metavolcanics with intercalated marbles, metacherts, and metamorphosed iron- and manganese-formations and basic lavas (Magnusson, 1930; Damman, 1985) belonging to the upper leptite–hälleflinta and slate group of the Bergslagen supracrustal series (Oen *et al.*, 1982; Oen, 1987). This volcano–sedimentary sequence was in sequence intruded by: (2) basic sills and dykes associated with the basic lavas; (3) a granite (Östra Höjden granite, Fig. 1) belonging to the group of older granites of the Bergslagen district (Åberg *et al.*, 1983*a, b*; Oen *et al.*, 1984; Baker, 1985); (4) gabbros and tonalites (Fig. 1) belonging to the Hyttsjö gabbro–tonalite suite (Oen *et al.*, 1982; Oen and Wiklander, 1982; Oen, 1987).

A mineralized vein system is developed in the granite, in adjacent gabbro- and tonalite plugs and in the country rock (Fig. 1). The most abundant minerals in these veins are quartz, plagioclase and microcline, together with sekaninaite, andalusite,

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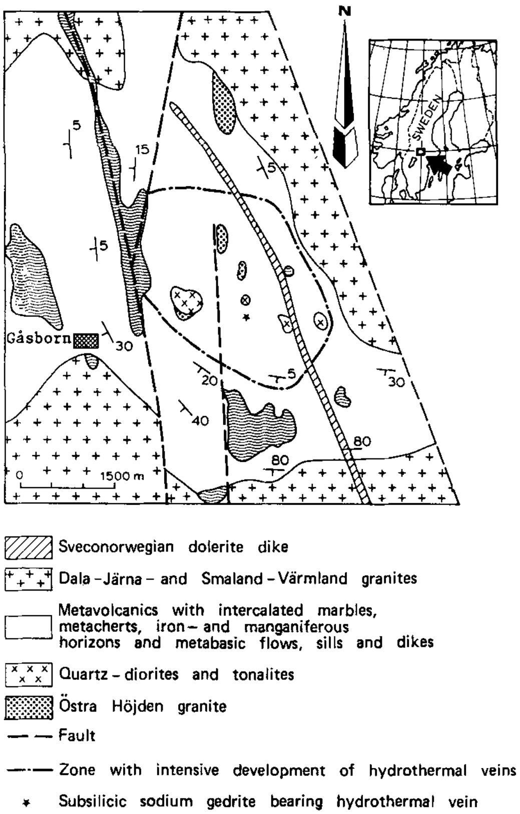

FIG. 1. Simplified geological sketch map of the Gåsborn area.

biotite, muscovite, fluorite and accessory oxides and sulphides. In one of the veins quartz, plagioclase and microcline are almost absent and andalusite and sekaninaite constitute about 90 vol. % of the vein material, together with accessory subsilicic sodium gedrite, sillimanite, quartz, biotite, albite, topaz, oxides and sulphides.

Comparison of the mineralogy of this vein system with the mineralogy of the granite suggests that it was formed from a hydrothermal fluid associated with the granite.

This Svecokarelian complex was intruded to the N, E and S (Fig. 1) by younger, 1.7–1.6 Ga granites of the Småland–Värmland (Filipstad) and Dala–Järna groups (Welin *et al.*, 1977) and a 1.2–0.9 Ga Sveconorwegian dolerite dyke (Oen and Verschure, 1982) which is found cross-cutting all older rocks in the central part of the Gåsborn area (Fig. 1).

Petrographic descriptions of the Östra Höjden granite and associated hydrothermal veins

The Östra Höjden granite is a fine- to medium-grained, leucocratic, reddish granite which shows a weak biotite foliation in outcrops. It consists of fine- to medium-grained plagioclase, quartz, microcline, and accessory biotite, wolframite, magnetite, ilmenite, pyrrhotite, chalcopyrite, pyrite, zircon, apatite and allanite. The first mineral to crystallize was subhedral plagioclase, showing an increasing Na content from the cores to the rims of the crystals (cores An_{30}, rims An_{10}). The plagioclase has a patchy appearance due to microclinization. Quartz occurs as anhedral, medium-grained crystals in between the plagioclase. Microcline occurs as tiny, anhedral crystals interstitial between the quartz and the plagioclase and as megacrysts up to 6 cm replacing plagioclase and quartz, some of which contain graphic intergrowths of quartz. A thin rim of albite has been developed around many of the microcline megacrysts, which shows optical continuity with albite lamellae occurring within the microcline. Biotite, the oxides and sulphides, zircon, apatite and allanite occur as tiny crystals in between the other minerals.

The andalusite–sekaninaite-bearing quartz–feldspar hydrothermal veins cross-cut the Östra Höjden granite, adjacent gabbros and tonalites and the country rock. The veins have a width between 2 cm and 7 m and a length up to several hundreds metres. Most are weakly boudinaged and show a mineral zoning from the rims to the centres of the veins. They consist of fine- to coarse-grained plagioclase (An_{30-05}), quartz, microcline, biotite, muscovite, fluorite and accessory oxides and suphides (wolframite, tantalite, ilmenite, pyrrhotite, pyrite, molybdenite), pyrochlore and titanite. Andalusite and sekaninaite are locally found in these veins. At the contact with the wall-rocks a rim of biotite of variable thickness is invariable developed. Local occurrences of open cavities within the veins suggest that they are probably infillings of fractures formed during the emplacement of the granite. The first mineral to crystallize was sub-euhedral plagioclase, which increases in grain size and albite content from the walls to the centres of the veins (Wall: grain size up to 6 mm; core An_{30}, rim An_{20}. Centre: grain size up to 2 cm; core An_{20}; rim An_{05}). The plagioclase has a patchy appearance due to microclinization. Subhedral quartz up to 5 mm occurs between plagioclase in the margins of the veins. In the centres of the veins quartz and subhedral microcline up to 2 cm in size occur between the plagioclase, while subhedral sekaninaite and andalusite

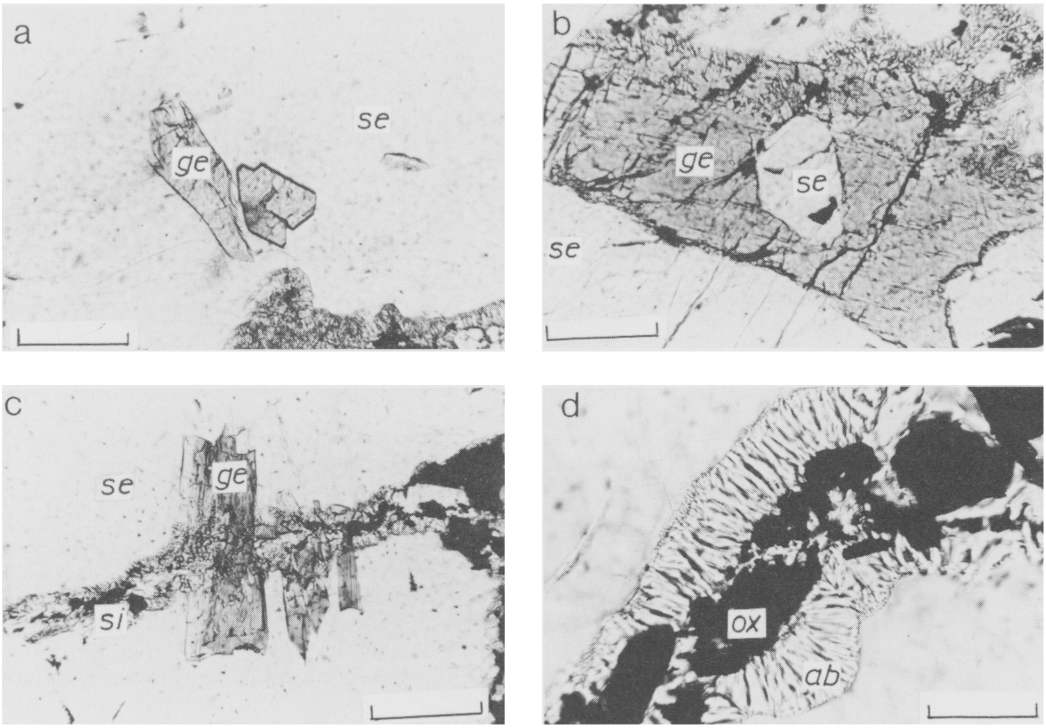

FIG. 2(*a–d*). (*a*) Inclusions of subsilicic sodium gedrite (ge) in the outer margin of a sekaninaite (se) crystal; the coronitic rim to the lower right marks the boundary of the sekaninaite crystal; bar = 200 μm. (*b*) Inclusion of sekaninaite (se) in subsilicic sodium gedrite (ge) in the outer margin of a sekaninaite(se) crystal; bar = 200 μm. (*c*) Replacement of subilicic sodium gedrite (ge) and sekaninaite (se) by a coronitic rim of sillimanite, quartz, oxides and sulphides (si); bar = 200 μm. (*d*) Intergrowths of sillimanite and albite (ab) radiating outwards from oxide- and sulphide crystals (ox); bar = 20 μm.

up to 3 mm in size occur interstitially between the quartz and the feldspars. Small inclusions of euhedral quartz and plagioclase in sekaninaite and andalusite show that the latter minerals have crystallized later than the plagioclase and the quartz. Microcline also occurs as megacrysts up to 6 cm across, some of which contain graphic intergrowths of quartz, replacing plagioclase, sekaninaite, andalusite and quartz. A thin rim of albite is developed around some of these megacrysts, showing optical continuity with albite lamellae occurring in the microcline. Late biotite and muscovite occur between feldspar and quartz and in reaction rims around the sekaninaite and the andalusite crystals. Muscovite rims around biotite suggest that the crystallization of muscovite outlasted that of biotite. Accessory oxides and sulphides form tiny interstitial grains which often show intergrowths with biotite. Fluorite occurs in late-crystallizing, panidiomorphic aggregates. A rim of highly variable thickness is always developed along the vein walls, consisting of biotite and accessory sulphides and oxides.

The subsilicic sodium gedrite-bearing vein consists for over 50 vol. % of medium-grained (up to 4 mm) andalusite crystals, often rimmed by intergrowths of andalusite and sekaninaite, which themselves are rimmed by a mantle of sekaninaite containing up to 300 μm pale blue and green pleochroitic inclusions of subsilicic sodium gedrite in its outer margins (Fig. 2*a, b*). These two intergrowth types comprise up to 45 vol. % of the vein. Optical continuity between (1) andalusite from the cores with andalusite from the andalusite–sekaninaite intergrowths and (2) sekaninaite from the andalusite–sekaninaite intergrowths with sekaninaite from the sekaninaite–subsilicic sodium gedrite intergrowths suggests the following crystallization sequence: andalusite–andalusite + sekaninaite–

sekaninaite + subsilicic sodium gedrite. Plagioclase occurs locally as anhedral grains between the andalusite, sekaninaite and subsilicic sodium gedrite intergrowths. Topaz occurs as colourless, euhedral inclusions in the andalusite and plagioclase crystals.

Albite, sillimanite, quartz, magnetite, ilmenite, hercynite, wolframite, pyrrhotite and pyrite occur in thin coronitic rims, surrounding and cross-cutting the andalusite-, sekaninaite- and subsilicic sodium gedrite crystals (Fig. 2*c*). The oxides and sulphides form tiny sub-euhedral crystals up to 100 μm. Albite, sillimanite and quartz are intergrown in aggregates that radiate outwards from the oxides and sulphides (Fig. 2*d*). Electron microprobe analyses revealed two types of aggregates, one consisting of about 40 vol. % sillimanite and 60 vol. % quartz, and the other consisting of about 35 vol. % albite, 50 vol. % sillimanite and 15 vol. % quartz. The intergrowths occur along separate rims. At intersections of both types of rims a dense mass was found, the exact composition of which could not be determined. Sillimanite forms euhedral crystals up to 200 μm, quartz and albite show vermicules up to 50 μm. The vein wall consists of a thin rim of 1–4 mm sub-euhedral biotite poikiloblasts containing numerous inclusions of zircon. These biotite crystals also replace the sekaninaite along cracks and rims. Around some of the biotite poikiloblasts coronitic rims similar to those occurring around andalusite, sekaninaite and the subsilicic sodium gedrite are found. Dark red, up to 5 mm, almandine-rich garnets (Alm_{85-90}) containing inclusions of sekaninaite, biotite, sillimanite, oxides and sulphides in their outer rims are locally found in the vein walls.

Chemical compositions

Electron microprobe analyses were made with a Cambridge Instrument Co, Microscan 9 operated at an acceleration potential of 20 kV and a sample current of 25 nA. Raw data were corrected with the Mark 9 online ZAF correction computer program. Standards used for Cl, K, Ca, Si, Ti, Mn, Fe, Na, Mg, Al and Zn were marialite, orthoclase, diopside, ilmenite, rhodonite, fayalite, jadeite, forsterite, corundum and synthetic ZnO. Fluorine was measured as a sample current of 40 nA using fluorite as a standard.

Representative analyses of andalusite, sekaninaite and subsilicic sodium gedrite are given in Tables 1 and 2. More than 50 analyses of the subsilicic sodium gedrite were made, but only 8 representative analyses are given here, with the structural formulae calculated on the basis of 23 O. A full list of analyses is available from the author on request.

Table 1. Representative electron microprobe analyses of andalusite and sekaninaite.

	Andalusite		Sekaninaite	
SiO_2	36.65	0.98	47.00	5.00
Al_2O_3	62.25	2.01	31.78	3.99
FeO	0.97	0.01	15.09	1.34
MnO	–	–	0.91	0.08
MgO	–	–	3.39	0.54
Na_2O	–	–	0.39	0.08
Total	99.87	3.00	98.57	11.03

In the calculations, total tetrahedral Si + Al were constrained to 8. Because the total of cations in the *M*1, *M*2, *M*3 and *M*4 sites was below seven, it was assumed that all Fe is Fe^{2+}. To bring the total of the *M*1, *M*2, *M*3 and *M*4 sites to 7. Na was taken from the *A* site to the *M*4 site, following the procedure described by Berg (1985).

Microprobe analyses along traverses from core to rim in several subsilicic sodium gedrite crystals revealed that these crystals are relatively homogeneous in composition with only the following compositional variation: Na(*A*) 0.57–0.81, Al^{iv} 2.31–2.57, X_{Mg} 0.15–0.21.

The factors that control the K + Na, *A*-site A/Al^{iv} ratio and the related edenite/tschermakite ratio (Berg, 1985) in orthorhombic amphiboles have received considerable study in the literature. Based on data available Berg (1985) showed the existence of a moderate inverse correlation between the A/Al^{iv} ratio (and thus the related edenite/tschermakite ratio) and X_{Mg} in orthorhombic amphiboles (Fig. 3, after Berg, 1985), suggesting that these ratios are influenced by incorporation of Fe and Mg in the *M*1–*M*3 sites of orthorhombic amphiboles.

Robinson *et al.*, (1982) have suggested that such a correlation may result from a slight collapse of the *M*1–*M*3 sites due to an increasing Mg-content. As Mg replaces Fe^{2+} in the *M*1 and *M*3 sites, these would collapse somewhat, causing concomitant shrinking of the *M*2 site, and favouring the enhancement of Al instead of Mg in this site, or in other words, the tschermakite substitution would be favoured. Conversely, replacement of Mg by Fe^{2+} in the *M*1 and *M*3 sites may result in expansion of these sites, which might cause a change of the *A*-site, resulting in easier accommodation of Na, or in other words, the edenite substitution would be favoured.

Table 2. Representative electron microprobe analyses of subsilicic sodium gedrite. X_{Mg} = Mg/(Mg+Fe).

	E7.27	E7.56	E7.12	E7.33	E7.17	E7.10	E7.39	E7.14
SiO_2	34.41	34.56	34.66	34.87	35.19	35.43	35.69	36.05
Al_2O_3	24.01	23.70	22.26	23.16	23.34	21.23	24.68	21.20
TiO_2	—	—	0.11	—	–	–	–	–
FeO	30.58	29.86	32.07	30.89	29.23	31.99	29.61	30.31
MnO	1.70	1.84	1.73	1.75	1.96	1.51	1.83	1.80
MgO	3.38	3.82	3.12	3.61	4.05	3.24	3.43	4.49
CaO	—	—	0.11	0.08	0.08	0.07	0.05	0.08
Na_2O	2.31	2.79	2.77	2.22	2.49	2.61	2.35	2.63
F	0.57	0.85	0.54	0.85	0.60	0.59	0.82	0.58
Total	96.96	97.42	97.37	97.43	96.94	96.67	98.46	97.14
Si	5.43	5.44	5.51	5.51	5.53	5.64	5.51	5.69
Al^{IV}	2.57	2.56	2.49	2.49	2.47	2.36	2.49	2.31
Al^{VI}	1.90	1.84	1.68	1.82	1.86	1.64	2.00	1.63
Ti	—	—	0.02	—	–	–	—	–
Fe	4.04	3.93	4.27	4.08	3.84	4.30	3.83	4.00
Mn	0.23	0.25	0.23	0.23	0.26	0.21	0.24	0.24
Mg	0.80	0.90	0.74	0.85	0.95	0.77	0.79	1.05
Ca	—	—	0.02	0.01	0.01	0.01	0.01	0.01
Na	0.71	0.85	0.85	0.68	0.85	0.81	0.70	0.80
Total	15.68	15.77	15.81	15.67	15.77	15.74	15.57	15.73
Na(a)	0.68	0.77	0.81	0.67	0.77	0.74	0.57	0.73
X_{Mg}	0.16	0.19	0.15	0.17	0.20	0.15	0.17	0.21

The above suggestion of Robinson *et al.*, (1982) is not supported by plotting the data of Table 2 in Fig. 3; the gedrites from Gåsborn fall away from the general trend between X_{Mg} and A/Al^{iv} proposed by Berg (1985).

A comparision of site occupancies of 2 subsilicic sodium gedrites taken from Table 2 with other orthorhombic amphiboles described in the literature is presented in Table 3, using the site occupancy scheme of Robinson *et al.*, (1982). All orthorhombic amphiboles presented in this table have similar A/Al^{iv} ratios (0.31–0.36), and edenite/tschermakite ratios (0.45–0.55), but show a wide variation in X_{Mg} (0.15–0.62), indicating that both Fe^{2+} and Mg can be substituted in the $M1$–$M3$ sites of orthorhombic amphiboles at similar A/Al^{iv} ratios, showing that there cannot be a correlation between the A/Al^{iv} ratio and the related edenite/tschermakite ratio and X_{Mg} as proposed by Robinson *et al.*, (1982) and Berg (1985).

Estimation of *P*, *T* conditions during the formation of the hydrothermal vein system

The stability fields of andalusite (Holdaway, 1971) and sekaninaite (Fe-cordierite) (Holdaway and Lee, 1977; Lonker, 1981) show that these two minerals can crystallize in hydrothermal veins at temperatures between about 480 and 780 °C and at a pressure less than 3 kbar. Hellingwerf *et al.* (1987) estimated the temperature of solidification of granites similar to the Östra Höjden granite occurring elsewhere in the Bergslagen district at 650 °C and the temperature of formation of pegmatites and high-temperature garnet–pyroxene skarns associated with these granites at 550–600 °C. In the Gåsborn area the formation of garnet–pyroxene skarns is spatially related to the hydrothermal vein system (Damman, 1985), limiting the temperature of formation of the hydrothermal vein system to 550–600 °C. Because none of the breakdown reactions of Fe-cordierite given by Holdaway and Lee (1977) and Lonker

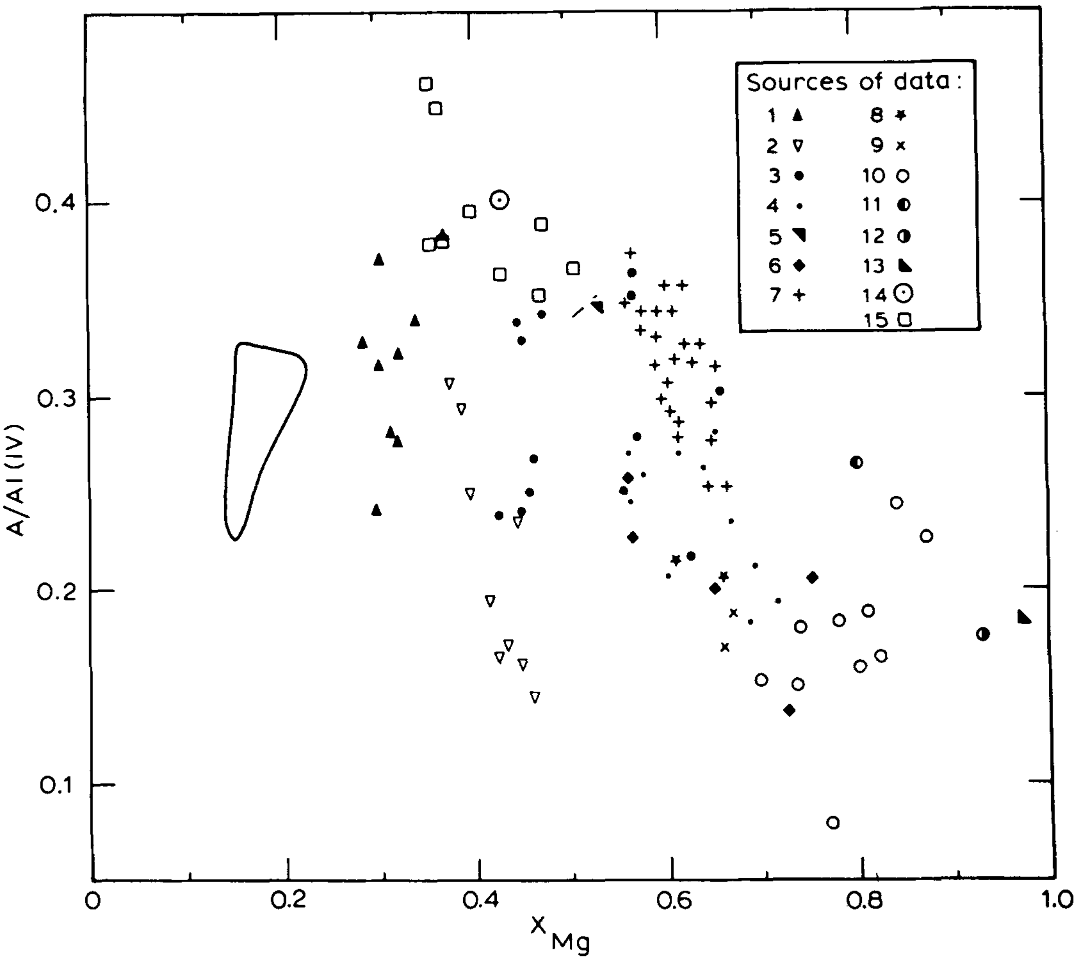

FIG. 3. $A/\mathrm{Al}^{\mathrm{iv}}$ *vs.* X_{Mg} for orthorhombic amphiboles from different localities. Line encloses field of Gåsborn gedrites. Sources of other data: (1) Abraham and Schreyer, 1973; (2) Kamineni, 1975; (3) Stout, 1972; (4) Spear, 1980; (5) James *et al.*, 1978; (6) Robinson and Jaffe, 1971; (7) Berg, 1985 (data from Schumacher, 1980); (8) Lal and Moorehouse, 1969; (9) Deer *et al.*, 1963; (10) Beeson, 1978; (11) Papike and Ross, 1970; (12) Rabbitt, 1948; (13) Zotov and Siderenko, 1967; (14) Otten, 1984; (15) Berg, 1985.

(1981) fit in with the observed breakdown reaction described in this paper, and no fluid-inclusion-bearing minerals were found in the subsilicic sodium gedrite-bearing hydrothermal vein, it is impossible to get a better pressure estimation than the 3 kbar upper limit given above.

Genetical considerations

The older granites of Bergslagen are high-level anorogenic granites showing a crystallization sequence starting with plagioclase, followed by quartz and microcline (Baker, 1985). Postmagmatic albitization, sometimes accompanied by the formation of Mg-chlorite is a well known phenomenon in many of these granites and surrounding host rocks (Baker, 1985). The Östra Höjden granite shows a similar crystallization sequence with microcline replacing plagioclase and quartz, and thin rims of albite replacing microcline. Occurrences of small amounts of molybdenite and wolframite in the Östra Höjden granite and scheelite, galena, Pb-Bi-Ag- and Pb-Bi-Cu-sulphosalts in skarns associated with the granite (Damman, 1985; Kieft and Damman, in prep.) suggest a close relationship between the Östra Höjden granite

Table 3. Site occupancies, A/Al^{iv} and X_{Mg} in orthorhombic amphiboles from different localities.

	A		M4				M1-M2-M3					T			
	Na	K	Na	Ca	Mn	Fe	Fe	Mg	Ti	Fe^{3+}	Al^{VI}	Al^{IV}	Si	A/Al^{IV}	X_{Mg}
1	0.81	—	0.04	0.02	0.23	1.71	2.56	0.74	0.02	—	1.68	2.49	5.51	0.32	0.15
2	0.77	—	0.08	0.01	0.26	1.65	2.19	0.95	—	—	1.86	2.47	5.53	0.31	0.19
3	0.55	—	—	0.07	0.03	1.96	2.17	1.78	0.02	—	1.03	1.74	6.26	0.32	0.30
4	0.52	—	—	0.05	0.02	2.01	2.14	1.97	0.02	—	0.80	1.61	6.39	0.32	0.32
5	0.65	—	0.02	0.06	0.02	1.90	1.17	2.50	0.02	—	1.30	1.98	6.01	0.33	0.45
6	0.55	—	—	0.08	0.04	1.88	1.33	2.59	0.02	—	1.05	1.65	6.35	0.34	0.56
7	0.44	0.06	—	0.06	0.02	1.99	0.88	3.21	0.02	—	0.89	1.29	6.71	0.34	0.53
8	1.00	—	0.12	0.01	0.05	1.83	0.04	3.05	—	0.60	1.31	2.80	5.20	0.36	0.62

(1,2) this paper; (3,4) Abraham and Schreyer, 1973; (5,6) Spear, 1980; (7) James et al., 1978; (8) Schumacher, 1980.

and the W–Mo group of the older granites of the Bergslagen district (Hellingwerf and Baker, 1985; Baker *et al.*, 1987).

The hydrothermal veins associated with the Östra Höjden granite always have a rim of biotite developed at the contact with the wall-rock. According to Murdoch (1936), Černý and Povondra (1967), and Krýza (1977) these biotite rims suggest that de-alkalinization of the vein-forming fluids and subsequent oversaturation with Si and Al are probably the processes which caused the formation of andalusite and sekaninaite in the hydrothermal veins. Inclusions of sekaninaite in subsilicic sodium gedrite and thin rims of sekaninaite around subsilicic sodium gedrite (Figs. 2*a, b*) suggest that the subsilicic sodium gedrite and the outer rims of the sekaninaite have crystallized simultaneously. Comparison of the chemistry of sekaninaite and subsilicic sodium gedrite (Tables 1 and 2) shows that both minerals have similar Si/Al ratios, implying limited mobility of these elements during the formation of these minerals. To form subsilicic sodium gedrite at these constant Si/Al ratios by means of a coupled edenite/tschermakite substitution, which is necessary to incorporate all Si and Al, requires a large intake of Na. As no other minerals capable of supplying Na have been found as inclusions in sekaninaite and subsilicic sodium gedrite, it is suggested that Na was taken from the fluid, indicating that subsilicic sodium gedrite must have been formed hydrothermally. The fact that subsilicic sodium gedrite only occurs in the outer rims of sekaninaite crystals suggests that Na must have been enriched in the fluid during the evolution of the hydrothermal system. This suggestion agrees with the observed occurrences of albite rims around microcline in the Östra Höjden granite and associated quartz–feldspar hydrothermal veins and the occurrence of rims of albite, sillimanite and quartz replacing sekaninaite and subsilicic sodium gedrite in the subsilicic sodium gedrite bearing vein, which also point to enrichment of Na in the hydrothermal fluid during its evolution.

The oxides and sulphides associated with the coronitic rims of albite, sillimanite and quartz are mainly magnetite, together with some ilmenite, hercynite, wolframite, chalcopyrite, pyrrhotite and pyrite. Most of the iron necessary to form magnetite, chalcopyrite, pyrrhotite and pyrite could be obtained from the breakdown of sekaninaite and subsilicic sodium gedrite as shown above. Other elements necessary to form the oxides and sulfides (S, W, Cu, Zn, Ti) are probably obtained from the hydrothermal fluid.

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