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PRIMARY SCAPOLITE IN A GRANITIC PEGMATITE, WESTERN CHEROKEE COUNTY, SOUTH CAROLINA

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ABSTRACT

Rare primary scapolite has been discovered in a body of granitic pegmatite from the Inner Piedmont belt (Piedmont terrane) in northwestern South Carolina. The scapolite consists of 2–3 cm long, 2–6 mm wide, white to off-white, subhedral to euhedral, prismatic crystals. Electron-microprobe analyses document two types of scapolite within the granitic material, with compositions of ~70% and 59% *Me*. The overall mineralogy of this peraluminous body, including andesine (~An_{40}) and Ca-rich tourmaline as well as accessory allanite, epidote, titanite and apatite, and the high Ca content (>3% CaO) of the granitic material, are atypical of granitic pegmatites.

Keywords: scapolite, andesine, tourmaline, granitic pegmatite, Inner Piedmont belt, South Carolina.

SOMMAIRE

De rares cristaux de scapolite ont été découverts dans un massif de pegmatite granitique de la ceinture interne du Piedmont (socle du Piedmont), dans le secteur nord-ouest de la Caroline du Sud. Les cristaux de scapolite sont de 2 à 3 cm de long et de 2 à 6 mm de large, blanchâtres, de subidiomorphes à idiomorphes, et prismatiques. Les données obtenues à la microsonde électronique démontrent deux groupes de scapolite dans le matériau granitique, avec environ 70% et 59% du pôle *Me*, respectivement. Cette suite granitique hyperalumineuse contient andésine (~An_{40}), tourmaline riche en Ca, ainsi que les accessoires allanite, épidote, titanite et apatite; cet assemblage, et la haute teneur en Ca dans ces roches (>3% CaO), ne sont pas courants dans les granites pegmatitiques.

(Traduit par la Rédaction)

Mots-clés: scapolite, andésine, tourmaline, pegmatite granitique, ceinture interne du Piedmont, Caroline du Sud.

INTRODUCTION

Scapolite is generally considered a metamorphic or metasomatic mineral typically found in granulite- and amphibolite-facies rocks. It is most common in high-grade gneiss, marble, amphibolite, in skarns or similar contact metamorphic settings, and in granulite inclusions in igneous pipes (Shaw 1960a, Newton & Goldsmith 1975, and references therein). The scapolite in most "metamorphic" occurrences is typically viewed as secondary, after plagioclase (Goldsmith 1976), as in altered basic igneous rocks (*e.g.*, in the Humboldt lopolith, Nevada; Vanko & Bishop 1982).

Primary scapolite only rarely occurs in igneous rocks, for example, in aplite (Calkins 1909) and granitic pegmatite (Lacroix 1919, Safronova 1978 and references therein; Sinha & Swarnakar 1971), as phenocrysts in latite (Goff *et al.* 1982), and as megacrysts in tephra from potassic basanites (Boivin & Camus 1981). In this report, I describe primary scapolite in a body of granitic pegmatite, consider the unusually calcic mineral assemblage, and evaluate the petrogenesis of the granitic rock.

LOCATION AND GEOLOGICAL SETTING

The body of granitic pegmatite formerly cropped out in the bed of County Road 131 in western Cherokee County, South Carolina, 4.67 km N76°E of the intersection of South Carolina Highway 110 and U.S. Alternate 29 in the town of Cowpens. The sample locality is roughly 175 m west of the bridge over Rocky Ford Creek. During road maintenance the outcrop was destroyed, but representative blocks of material are preserved at the South Carolina Geological Survey and the McKissick Museum, University of South Carolina (catalog no. 1992.1.1.).

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The granitic body cropped out in what has historically been called the Inner Piedmont belt, amphibolite-facies rocks (Glover *et al.* 1983) assigned to the suspect Piedmont terrane (Williams & Hatcher 1982). Recently, this part of the southern Appalachian Piedmont has been designated the Inner Piedmont (tectonic) block (Horton & McConnell 1991) and the Inner Piedmont composite terrane (Horton *et al.* 1991). Felsic to intermediate gneisses (which locally grade into migmatite) and pelitic schist dominate the structurally complex and typically poorly exposed (<5%) sequence. Lesser amounts of impure quartzite, calc-silicate rock and amphibolite also are present.

HOST-ROCK GNEISS

The granitic body intruded hornblende – epidote – microcline – quartz – biotite – plagioclase gneiss (Table 1). Clots 3–5 mm across of subhedral plagioclase are a conspicuous feature of the host gneiss. The foliation clearly wraps around these clots, indicating that they are prekinematic.

Two samples of gneiss from outcrops approximately 50 m apart were taken near the pegmatitic body. Gneiss sample A (gnA) is relatively biotite-rich, and gneiss sample B (gnB) is relatively hornblende-rich. The gneiss samples, though superficially similar in texture, are markedly different in their compositions (Table 2). Compositionally, both of these samples resemble calc-alkaline igneous rocks (Table 2); gnA plots as a rhyolite, and gnB plots as an andesite on the Jensen (1976) cation plot, as modified by Grunsky (1981). These compositions compare favorably with average rhyolite–rhyodacite and andesite, respectively (Le Maitre 1976). Although the sum for gnA is somewhat low, a duplicate analysis yielded a similarly low total.

With respect to volatile contents, neither sample is enriched in S or Cl compared to normal volcanic and plutonic rocks of similar bulk-composition. Only sample gnB appears to contain CO_2 (0.13%). These results show that the country-rock gneiss in the vicinity likely was not the source of volatiles for the scapolite in the body of pegmatitic granite. Very few compositions have been published on the high-grade metamorphic rocks of the Piedmont terrane in South Carolina. Secor *et al.* (1986) considered the schists and paragneisses of the Piedmont terrane to be derived from upper Proterozoic and lower Paleozoic continental slope and rise sediments deposited off the southeastern edge of the Laurentian plate. However, there is increasing evidence that some of these rocks had igneous precursors (Mittwede 1990).

TABLE 1. MODAL ANALYSES OF THE HOST-ROCK GNEISS AND THE PEGMATITIC GRANITIC MATERIAL

	gn avg.	range	peg avg.	range
Plagioclase	34.7	27.27 - 44.13	18.9	5.70 - 35.10
Biotite	24.2	18.07 - 29.80		
Quartz	22.6	20.73 - 24.20	34.5	24.40 - 48.60
Microcline	7.5	3.27 - 17.07	33.0	17.60 - 50.70
Scapolite			7.6	0 - 25.80
Tourmaline			4.9	tr - 14.30
Epidote	6.2	4.40 - 8.00		
Hornblende	3.6	2.20 - 4.67		
Σ vol.%	98.8		98.9	

In the gneiss, accessories (each <1.0%) include titanite (0.55%), apatite, sericite, tourmaline, unidentified opaque phases, and trace zircon and allanite. In the pegmatite, accessories (each <1.0%) include muscovite, biotite, epidote, allanite (typically rimmed by epidote), titanite (including some alteration to leucoxene?), apatite, and zircon. Also, some micrographic intergrowth of quartz and feldspar is present, as well as some late alteration of plagioclase to sericite. Four thin sections of gneiss were examined, and 1500 points were counted per thin section. Eight thin sections of pegmatite were examined, and 1000 points were counted per thin section.

TABLE 2. WHOLE-ROCK CHEMICAL COMPOSITIONS OF TWO SPECIMENS OF THE COUNTRY-ROCK GNEISS AND A SPECIMEN FROM THE PEGMATITIC GRANITIC BODY

	gnA	gnB	peg	peg norm	
SiO_2	68.50	54.30	71.20	Q	31.54
TiO_2	0.36	1.08	0.16	C	0.62
Al_2O_3	14.80	17.40	14.97	or	33.95
Fe_2O_3*	2.03	7.85	1.77	ab	12.09
MnO	0.04	0.16	0.02	an	15.73
MgO	0.90	4.13	0.81	hy	5.69
CaO	1.65	6.75	3.19	il	0.30
Na_2O	2.23	2.87	1.43	ap	0.04
K_2O	5.13	1.89	5.74		
P_2O_5	0.19	0.29	0.02		
BaO	-	-	0.27		
CO_2	0.02	0.13	-		
S	<0.01	0.01	-		
B	-	-	0.50		
LOI	1.55	1.95	0.37		
Σ wt.%	97.40	98.81	100.45		99.96
Cl (ppm)	225	323			
Rb	102	72			
Sr	576	472			
Y	<10	12			
Zr	87	178			
Nb	13	21			
Ba	3750	733			
Cr	207	286			
Be			4		
Li			4		
Sn			<1		

* Total iron reported as Fe_2O_3. For gneiss, analyst: X-ray Assay Laboratories, Don Mills, Ontario. Methods: major elements (lower reporting limit 0.01%) and trace elements (detection limit 10 ppm) by XRF spectrometry; S determined using a Leco analyzer, and CO_2 by coulometry. For pegmatite, analyst: Paul E. Burgener, Technical Service Laboratories, Mississauga, Ontario. Method: inductively coupled argon plasma (ICAP) spectrometry. Norm calculated assuming all Fe as FeO.

THE BODY OF GRANITIC PEGMATITE

The body of granitic pegmatite is tabular in form, 28–36 cm wide, and 13–21 cm thick. The margins of the body are diffuse, rather schistose, biotite-rich, and gradational with the gneissic host-rock. However, beyond the biotite-rich selvages, the granitic material lacks a fabric and has the appearance of typical granitic pegmatite. Its mineralogy and chemical composition (Tables 1, 2) are roughly consistent with that of "normal" granite (Le Maitre 1976). Its average mode (Table 1) plots in the monzogranite field, but very near the boundary of the syenogranite field (QAP diagram of Streckheisen 1976). The pegmatitic material is peraluminous, with A/CNK (molar) = 1.44.

The modal mineralogy, based upon detailed petrographic study of eight thin sections (Table 1), is in excellent agreement with a norm based upon a single whole-rock composition of a sample of material considered representative of the granitic body (Table 2). Scapolite appears as plagioclase in the norm, so that the sum of ab and an in the norm approximates the sum of plagioclase + scapolite in the mode.

The mineralogy and composition of the pegmatite reflect its unusually calcic nature. In addition to scapolite, the plagioclase ($\sim An_{40}$) and tourmaline in this granitic body are both calcic (Table 3) relative to the plagioclase and tourmaline typical of simple (barren) granitic pegmatite dikes (*e.g.*, Černý 1982). Among the accessory minerals of the granitic body, the calcium-rich phases include epidote, allanite, titanite and apatite (Table 1).

Two textures are prominent: 1) quartz, microcline and plagioclase occur in patches or zones (henceforth termed "matrix") of anhedral (tending toward polygonal), roughly equigranular, 5–10 mm grains; 2) scapolite, plagioclase, quartz (with strongly undulatory extinction), microperthitic microcline (approximately $Or_{88.5}$; Table 3), recognized by its grid twinning, and tourmaline (with two color zones, typically dark olive green in the core and lighter olive green toward the rim) occur in larger (2–3 cm), discrete, usually subhedral to euhedral crystals (except for the quartz grains, which are consistently anhedral). The accessory phases are present within both, as distinct grains within the "matrix", and as inclusions within the coarser grains. For example, euhedral crystals of allanite (with a rim of epidote) and titanite occur in the "matrix", but euhedral allanite and anhedral titanite crystals also occur as inclusions in scapolite. Furthermore, subhedral to anhedral biotite, epidote and muscovite grains are present as inclusions within some of the largest grains of scapolite and plagioclase. Inclusions of biotite are found in microcline, and inclusions of zircon occur in plagioclase.

TABLE 3. CHEMICAL COMPOSITION OF FELDSPARS AND TOURMALINE FROM THE PEGMATITIC GRANITIC BODY

	plagioclase		microcline		tourmaline	
	$\bar{x}$ (n=3)	σ_{n-1}	$\bar{x}$ (n=3)	σ_{n-1}	$\bar{x}$ (n=3)	σ_{n-1}
SiO_2	57.98	0.609	63.89	0.156	34.37	0.196
TiO_2	-		<0.01		0.88	0.055
Al_2O_3	26.07	0.099	18.56	0.080	27.46	0.329
Fe_2O_3*	0.02	0.029	<0.01		12.80	0.645
MnO	<0.01		<0.01		0.12	0.044
MgO	-		-		7.46	0.332
CaO	8.14	0.054	0.01	0.023	2.50	0.150
Na_2O	6.68	0.065	1.28	0.098	1.45	0.065
K_2O	0.14	0.008	15.06	0.062	0.08	0.007
BaO	0.01	0.013	0.88	0.065	0.04	0.033
B_2O_3†					10.27	
Σ wt.%	99.04		99.68		97.43	
Structural Formulae Based on 8 (feldspar) and 29 (tourmaline) O atoms						
Si	2.615		2.974		B	3.000
Al	1.386		1.019		Si	5.695
Fe	0.001		-		Al	5.364
Ca	0.393		0.001		Ti	0.110
Na	0.585		0.116		Fe	0.798
K	0.008		0.894		Mn	0.017
Ba	-		0.016		Mg	1.842
					Ba	0.003
	4.988		5.020		Ca	0.444
					Na	0.466
					K	0.017
End-Member Feldspar, Mole %						
Ab	59.28		11.46			
An	39.88		0.06			
Or	0.84		88.48			

* Total iron reported as Fe_2O_3. † B_2O_3 in tourmaline calculated assuming 3 boron atoms in the structural formula (Henry & Guidotti 1985). Compositions obtained by electron-microprobe analysis on the Cameca SX-50 microprobe at the University of South Carolina. TAP, PET and LIF analyzing crystals, an accelerating voltage of 15 kV, and a beam current of 25 nA were used.

On the basis of textural information (inclusions and grain-boundary relationships), allanite, titanite, zircon, apatite, biotite and possibly some of the epidote and muscovite crystallized first. Then came an episode of crystallization in which quartz, plagioclase and K-feldspar formed as the "matrix" described above. The first of the larger, subhedral crystals to crystallize was scapolite, which was followed in sequence by plagioclase, quartz and K-feldspar. The last of the major phases to crystallize was tourmaline; it tends to be euhedral, more so than the other major phases. Because in one instance growth of tourmaline disrupted parallel exsolution-lamellae of albite in microcline, it is apparent that these lamellae formed before the tourmaline and that the tourmaline thus is subsolidus. Finally, on the basis of the presence of inclusions, it is clear that quartz was crystallizing throughout the formation of all of the other major phases, and that some feldspar continued to crystallize up until and during the crystallization of tourmaline.

Micrographic intergrowths (plagioclase with quartz "worms" or blebs) and sericitic alteration of plagioclase and, to a lesser extent, scapolite, were the latest products of crystallization, attributed to deuteric alteration.

SCAPOLITE

The scapolite occurs in elongate subhedral to euhedral prismatic crystals (Fig. 1), in most cases with cross-sections 2–6 mm across and with long dimensions up to 2–3 cm. Longitudinal sections show second-order birefringence, typically 0.024–0.026, but scapolite with a birefringence of up to 0.030 also is present in separate grains. Locally, the scapolite has a fibrous or "shredded" appearance along cleavages or crystal boundaries, but for the most part is very fresh. It also has a distinctive orange-pink fluorescence in short-wave ultraviolet radiation.

In the granitic body, scapolite is completely independent of plagioclase; it does *not* result from the alteration of plagioclase. No replacement textures are present (Fig. 1). In most cases, the scapolite is not in contact with plagioclase and, as has been already pointed out, the scapolite grains crystallized prior to the plagioclase.

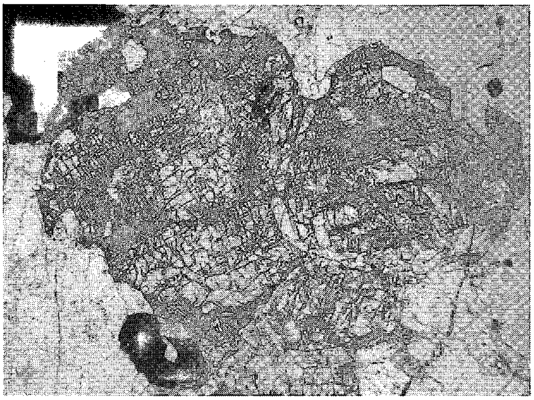

FIG. 1. Photomicrograph of scapolite in granitic pegmatite material (plane-polarized light). Width of the larger grain of scapolite is approximately 2 mm. The surrounding mineral phases are quartz (white) and tourmaline (black).

TABLE 4. CHEMICAL COMPOSITION OF SCAPOLITE FROM THE PEGMATITIC GRANITIC BODY

	Scp - Group A		Scp - Group B	
	$\bar{x}$ (n=10)	σ_{n-1}	$\bar{x}$ (n=3)	σ_{n-1}
SiO_2	46.54	0.243	49.62	0.355
TiO_2	-		<0.01	
Al_2O_3	25.75	0.114	25.08	0.087
Fe_2O_3*	0.02	0.012	0.09	0.031
MnO	0.02	0.028	0.03	0.025
MgO	<0.01		<0.01	
CaO	16.46	0.149	13.63	0.034
Na_2O	3.98	0.073	5.16	0.062
K_2O	0.15	0.018	0.91	0.016
BaO	0.03	0.031	-	
Cl	0.21	0.013	1.44	0.018
SO_3	3.24	0.131	1.33	0.029
Σ wt.%	96.40		97.29	
	Structural formulae on the basis of 12 (Si, Al)			
Si	7.263		7.519	
Al	4.737		4.481	
Fe^{3+}	0.001		0.005	
Mn	0.003		0.004	
Ca	2.752		2.213	
Ba	0.002		-	
Na	1.204		1.516	
K	0.030		0.176	
Cl	0.056		0.370	
S	0.380		0.151	
C†	0.564		0.479	

* Total iron reported as Fe_2O_3. † C in structural formula by difference. Compositions obtained by electron-microprobe analysis. Instrumentation and operating conditions as in Table 3.

Electron-microprobe analyses document two types of scapolite, in separate grains, within the granitic body. No compositional zoning was detected in either type. On the basis of Ca/(Ca+Na) values, there are two types of scapolite in this rock, containing approximately 70% and 59% *Me* (Table 4). The presence of the more Ca-rich scapolite accounts for the higher birefrigence (Shaw 1960a).

Both types of scapolite contain significant amounts of SO_3 and Cl (Table 4). The low totals shown are attributed to CO_2. Insofar as the anion positions in the structural formulae for the scapolite analyses reported here (Table 4) are only about half-filled by SO_3 + Cl, the difference is attributed to CO_2. Scapolite with Ca contents similar to those reported here characteristically contain 2.5–3.5 wt.% CO_2 (Shaw 1960a, Evans *et al.* 1969).

It is significant that the Na/(Na+Ca) ratios for scapolite (0.30 for the more abundant Ca-rich type, 0.41 for the less calcic type) are appreciably lower than that of the plagioclase (0.60). As shown by Orville (1975), scapolite will be more calcic than the coexisting plagioclase for low-An bulk compositions; according to the data of Shaw (1960b), An_{40} appears to be the threshhold value below which this relationship generally holds.

In this granitic body, an overall trend of Ca depletion during crystallization is obvious from textural data, namely, the early appearance of allanite, apatite, and possibly some of the titanite and epidote, and the later sequential appearance of the Ca-bearing major phases scapolite, plagioclase, and tourmaline.

PETROGENESIS OF THE SCAPOLITE-BEARING GRANITIC PEGMATITE

What condition(s) facilitated the formation of primary igneous scapolite in this pegmatitic granitic body? In particular, what was the source for the CO_2, SO_3, and Cl?

Scapolite is a relatively high-temperature phase, as indicated by its typical occurrence in high-temperature metamorphic rocks, especially granulites and skarns. As noted by Goldsmith (1976, p. 164), "Although generally metamorphic minerals, the Ca-rich scapolites are obviously stable in a temperature range high enough to crystallize as primary magmatic phases at depth, assuming an adequate supply of CO_2 and sulfate." Millhollen's (1974) experimental work led to the formation of scapolite at about 6 kbar and 900°C. According to his findings and the conclusions of Goff *et al.* (1982), the formation of Ca-rich scapolite requires temperatures greater than or equal to 850°C and total pressures of 3–6 kbar. Furthermore, "the rarity of scapolite as a phenocryst mineral suggests that high partial pressures of CO_2 and SO_2 are rare in the magmatic environment" (Goff *et al.* 1982, p. 86).

As noted by Boivin & Camus (1981), crystallization of a sulfur-rich scapolite involves a high $f(SO_3)$ and, therefore, an exceptionally high $f(O_2)$, necessary to stabilize sulfate and carbonate species in the melt. They suggested that their scapolite megacrysts represent high-pressure phenocrysts from the host magma.

The modal mineralogy and chemistry of the host-rock gneisses do not appear to provide a reasonable source for the CO_2, SO_3, and Cl in the scapolite. The possibility that the body of granitic pegmatite is a simple leucosome would seem to be ruled out.

However, it is possible that the granitic body represents a partial melt that drew from a wider chemical reservoir. The contact relationship described above suggests that the granitic body may represent an anatectic melt that was produced during conditions of peak metamorphism or, alternatively, that the body may have had a deep-seated igneous source that was tapped during metamorphism. In either case, because the granitic body – country rock contacts are not sharp, it is not unreasonable to conclude that the gneiss was at elevated temperature (probably high-grade metamorphic conditions) when the granitic body was emplaced. Morphologically, the body of granitic pegmatite should be considered simply a vein, as there is not enough known of the field relations to define the body as either a sill or dike.

Alternative sources for the "exotic" anions in the scapolite include the following:

1) The granitic melt may have interacted with carbonate rocks prior to emplacement and crystallization. This hypothesis has been invoked previously to explain the presence of primary scapolite in aplite described by Calkins (1909) and in some of the pegmatites described by Safronova (1978).

Although no carbonate rocks have been found in the immediate vicinity of the granitic body, discontinuous beds or lenses of calcitic to dolomitic marble are not uncommon along the southeastern flank of the Inner Piedmont belt (Overstreet & Bell 1965). For example, the old Otterson marble quarry, described by Sloan (1908), is said to be located about 3 km east-southeast of the dike outcrop, although I was unable to locate that quarry in the field. A number of other marble occurrences, many of which were old quarries with limited production, are located along strike to the southwest, in Laurens County (Sloan 1908). The most notable occurrence is the Master's Kiln locality (Sloan 1908, Clarke 1957, Snipes 1969). At this locality, a granitic rock intruded a marble bed and produced a skarn characterized by diopside, scapolite, and actinolite. This is the only other significant occurrence of scapolite known in South Carolina. According to Clarke (1957), the scapolite at Master's Kiln has a composition of Me_{65} (based upon its indices of refraction).

2) The granitic body may have had a deep-crustal magmatic source in which the anions necessary to form scapolite, especially CO_2 and possibly SO_3, may be enriched (Newton & Goldsmith 1975, Goldsmith 1976).

It is possible that CO_2 coming from the earth's interior could be entrapped in scapolite present in intermediate or basic rocks and that remelting of these rocks could liberate the CO_2 to higher crustal levels (Newton & Goldsmith 1975, Lovering & White 1964). On the other hand, Moecher & Essene (1990) have argued persuasively against the role of CO_2 flooding or mantle outgassing (*e.g.*, Newton *et al.* 1980) as a general mechanism for the formation of granulites.

3) The widespread occurrence of tourmaline and particularly tourmalinites in the area (reviewed in Mittwede 1990), especially to the north, may reflect an evaporitic paleoenvironment in which not only B but also the anions necessary to form scapolite may have been abundant. As noted by Serdyuchenko (1975) and Slack (1982), ancient evaporitic terranes generally are marked by an abundance of diagnostic minerals such as anhydrite and scapolite. Although there is a tourmaline and, therefore, a boron anomaly in the area (Mittwede 1984), unusual amounts of scapolite have not been noted. Mittwede (1984) concluded that the tourmalinites have a volcanogenic-exhalative origin.

These alternatives are not directly testable at this time. Based upon the textural evidence and available geochemical data, it is clear that the mineral phases present did crystallize from a magma.

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