Tourmalinization in the Skiddaw Group around Crummock Water, English Lake District

N. J. FORTEY

British Geological Survey, 64 78 Gray's Inn Road, London WC1X 8NG

AND

D. C. COOPER

British Geological Survey, Keyworth, Nottingham NG12 5GG

ABSTRACT. Veins of tourmalinite were formed by wall-rock alteration adjacent to steep fractures in bleached, indurated Skiddaw Group metasedimentary rocks around Crummock Water, north-west Lake District. The vein rock is a fine-grained granoblastic mosaic of tourmaline, quartz, and minor rutile in which bedding is preserved. Brecciation, in which tourmalinite fragments are set in a coarser quartz-tourmaline matrix, is present in some veins. Networks of cross-cutting quartz veinlets with tourmaline, chlorite, and muscovite are very common. The tourmaline is intermediate schorl dravite and mostly brown in plane polarized light, though prisms in breccia matrix and veinlets have blue, low-Ti cores and brown rims. Comparison of tourmalinite and host-rock analyses indicates almost complete loss during tourmalinization of K, Rb, Li, Ba, As, and La, plus depletion in Ce, Y, Na, Sr, P, and Mn. The elements Si, B, Mo, and erratically, minor F, W, and Sn were introduced. Cu, Pb, Zn, and Ca show both gains and losses probably due to initial depletion and subsequent local enrichment. Reduction in Al, Zr, and Ti concentrations relates to dilution by introduced silica. The tourmalinite veins were formed by the action of hydrothermal fluids derived from the concealed late-Caledonian granitic intrusion responsible for the thermal metamorphism of the country rocks.

KEYWORDS: tourmalinization, Skiddaw Group, Lake District, England.

TOURMALINITE veins occur in Skiddaw Group metasedimentary rocks of Lower Ordovician age (Jackson, 1978) in the English Lake District. They are confined to pale, indurated and often spotted pelitic and semi-pelitic rocks formerly called the Blake Fell Mudstone (Dixon, 1925) but subsequently interpreted as a thermal metamorphic aureole related to a concealed granitic intrusion (Eastwood et al., 1931; Rose 1954). The first description of the veins was given by Jeans (1973), who concluded that they formed late in the sequence of end-Silurian Caledonian folding.

Field relationships. The tourmalinite veins, whose attitude is controlled by closely spaced jointing in the aureole rocks, are most common east of Crummock Water (fig. 1), where they are steeply inclined to vertical. Most trend between N50°E and E10°S, the mode lying between N80°E and E-W (A. H. Cooper, pers. comm.); a small number trend at about 90° to this mode. They range in thickness from about 3 m to less than 1 cm. The veins extend vertically some 900 m from the shore of Crummock Water [e.g. NY 154 186] to the summit of Grasmoor [NY 178 204]. Laterally, they extend at least 7 km from Grasmoor westwards through Melbreak [NY 148 185] and Hen Comb [NY 135 182] to Croasdale [NY 102 180]. Tourmaline is also present in As-Co-bearing veins in the eastern part of the aureole at Scar Crag Mine [NY 206 206] (Ixer et al., 1979), and in veinlets at the summit of Causey Pike [NY 218 209].

Sedimentary bedding can be traced through the thicker veins indicating that they have a metasomatic replacement origin. In addition, dark tourmalinite forms selvages to dilational quartz+tourmaline veinlets. These selvages pass into lobes which may extend several metres along the bedding in the host rocks. Associated quartz veins may contain fragments of tourmalinite and, in extreme cases, quartz veins in otherwise tourmaline-free rock are charged with transported tourmalinite fragments.

Thick tourmalinite veins occur in areas containing ramifying quartz-vein networks, suggesting that both represent passage of hydrothermal fluids along the same zones of structural weakness. The massive, fine-grained, replacement tourmalinite is usually crossed by quartz-fracture veinlets which tend to lie both in and perpendicular to the plane of the host vein, imparting a blocky character to the
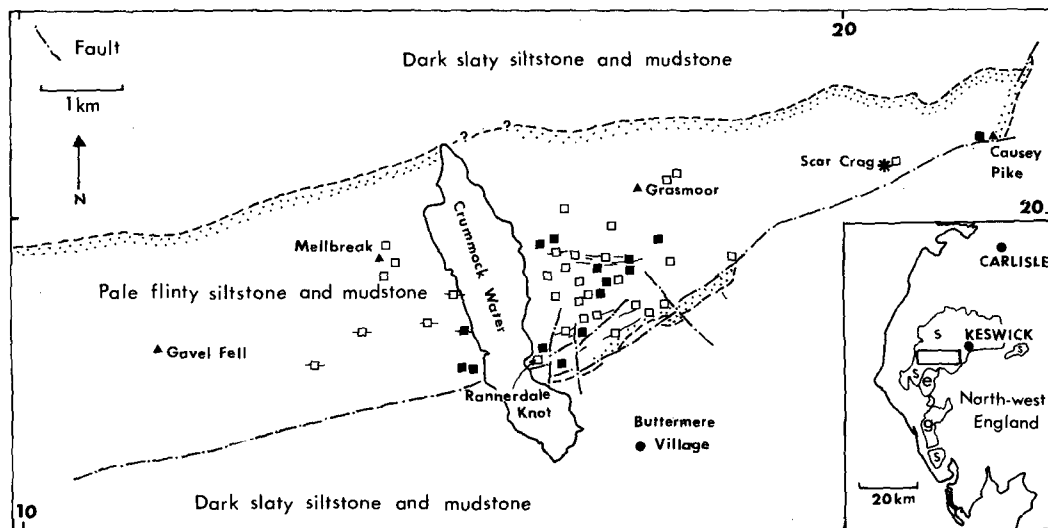
FIG. 1. Location map showing sites of tourmaline veins. Closed squares indicate veins sampled for mineralogical study and analysis; open squares, other veins; asterisk, site of Scar Crag mine. Boundaries of the Crummock Water aureole are shown stippled where gradational, and as faults. In the inset the research area is boxed; 's'—outcrop of the Skiddaw Group, 'g'—Eskdale Granite and Granodiorite; 'e'—the Ennerdale Granophyre.
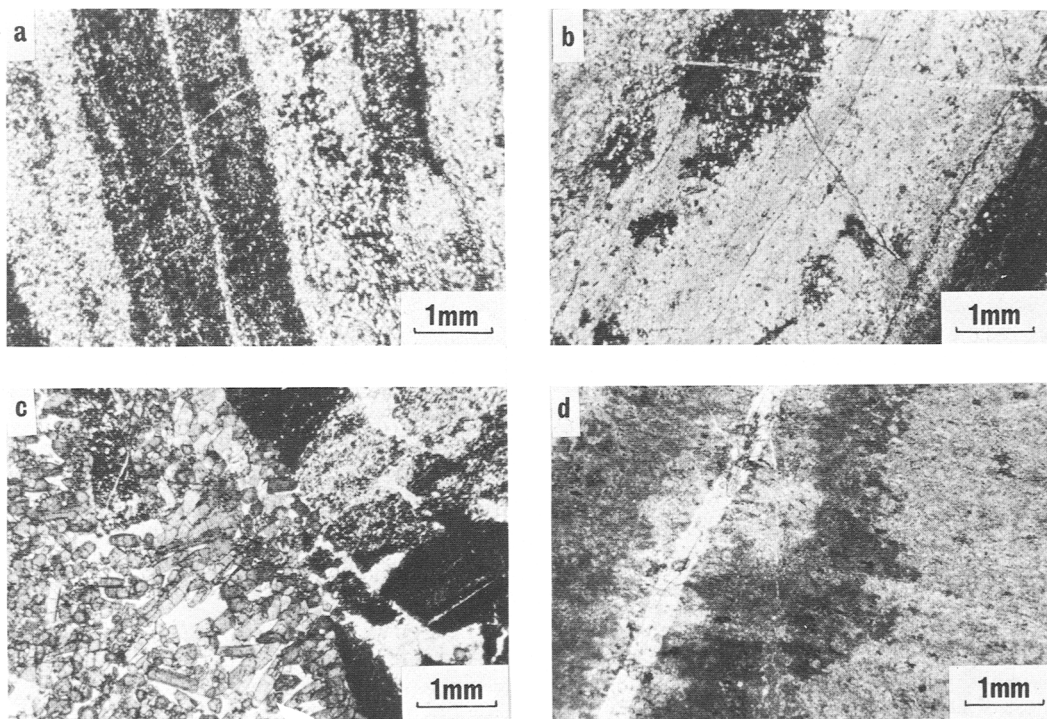

FIG. 2. Photomicrographs (plane polarized light) of: (a) bedding preserved in fine tourmalinite; (b) siliceous margin to a tourmalinite vein with clots of fine tourmaline and the transition to darker mudstone (bottom right); (c) detail of brecciated tourmalinite in which tourmalinized sediment fragments are set in quartz–tourmaline matrix; (d) oligoclase–tourmaline veinlet flanked by pale siliceous and dark chloritic zones in siltstone wallrock.

rock and often obscuring the original fracture about which the tourmalinite developed. In some cases the perpendicular veinlets are dominant, producing a ladder-vein structure. Quartz veining also occurs in other parts of the aureole where tourmalinite is only a minor constituent, and locally contains oxidized patches of pyritic sulphide, as in the network of anastomosing quartz veins at Cinderdale Common [NY 1632 1950] described by Jeans (1973).

The metamorphosed sedimentary rocks also contain numerous veinlets up to 4 mm thick of chlorite, muscovite, quartz, minor tourmaline, and other minerals. Examples studied came from the flank of Grasmoor north of the main group of tourmalinite veins, and from the summit of Causey Pike.

Mineralogy. The massive tourmalinite consists of a fine-grained mosaic of tourmaline and quartz with scattered, anhedral grains of rutile. The grain-size can be as small as 5 μm. Banding expressed by rapid changes in the tourmaline to quartz ratio preserves fine sedimentary lamination (fig. 2a) and cross-lamination, indicating that tourmaline formed by the replacement of pre-existing muscovite and chlorite. The outer boundaries of massive tourmalinite veins are marked by a transition over one or two millimetres into wallrock. In places, patches of fine tourmaline occur within thin (cm-scale) silicified zones which flank the tourmalinite (fig. 2b).

Some massive veins are brecciated, with disoriented tourmalinite fragments cemented by coarser quartz charged with tourmaline prisms (fig. 2c). The brecciation is confined to the massive tourmalinite and indicates vigorous fluid passage during the hydrothermal activity.

Cross-cutting relationships between fracture-controlled veinlets within the replacive tourmaline indicate that at least four sets are present. Two early sets comprise tourmaline stringers and rutile + quartz veinlets < 1 mm thick. Later veinlets consist of quartz with irregularly distributed patches and sprays of tourmaline prisms, chlorite, muscovite, albite, and rarely apatite and arsenopyrite. Both tourmaline and albite show embayed forms which partially enclose grains of the host quartz. Last-formed veinlets consist almost entirely of quartz in which vuggy comb structure is frequent.

Mineral assemblages in other veinlets in the aureole include: quartz only (common), chlorite + muscovite + quartz (common), chlorite + muscovite + tourmaline + quartz + Ti-oxide, chlorite + quartz + apatite + Ti-oxide and oligoclase + tourmaline (apparently rare). Chloritic veinlets are locally flanked by thin zones of wallrock silicification and of darkening caused by chloritization and destruction of muscovite (fig. 2d).

Tourmaline composition. Analysis of tourmaline was carried out by EPMA in energy-dispersive mode (Table I). Application of this technique to tourmaline is discussed by Ethier and Campbell (1977) who point out the need to avoid burning off volatile elements. In the present work instrument conditions were set at 15.0 kV beam potential and 0.2×10^{-7} amps specimen current. This specimen current is an order of magnitude lower than that quoted by Ethier and Campbell (*op. cit.*) and no surface damage was observed optically.

Table I. Microprobe analyses of tourmaline, summarised as three representative analyses plus the ranges and median values for eighty analyses; results given as atoms per formula unit of 24.5 oxygens (anhydrous).

	1	2	3	Range	Median
Si	5.951	5.939	5.887	5.254 – 6.329	5.997
B	- - - 3.0 - - - - - - - - - - - - - - - - -				
Al^{IV}	6.000	6.000	5.942	5.563 – 6.0	6.0
Al^{VI}	0.470	0.687	-	0.0 – 0.951	
Fe	1.340	1.179	0.698	0.599 – 1.667	1.334
Mg	0.832	0.944	2.163	0.291 – 2.310	0.704
Ti	0.149	0.032	0.137	n.d. – 0.199	0.044
V	n.d.	0.016	0.012	n.d. – 0.017	n.d.
Cr	n.d.	0.013	n.d.	n.d. – 0.030	n.d.
Mn	0.037	0.017	0.017	0.014 – 0.047	0.027
Na	0.452	0.553	0.709	0.341 – 0.842	0.534
Ca	0.159	0.069	0.272	n.d. – 0.318	0.054
Total	18.391	18.448	18.853	18.182 – 18.871	18.408

Energy-dispersive analysis by BGS Cambridge Instruments Microscan V microprobe modified with Canberra solid-state detection equipment. Results are calculated using the ZAF correction program WARE2 (after Ware, 1980). Total iron is treated as Fe^{2+}. Three boron atoms per formula unit is assumed. Aluminium is allocated to Al^{VI} up to six atoms, any excess being allocated to Al^{IV}.

The tourmaline is predominantly tan brown when seen in plane polarized light, especially where fine-grained and massive. Prismatic crystals frequently possess pale blue cores, and rhythmic blue-brown zoning may be present. Paired core and rim analyses indicate that usually Na decreases and Ca and Ti increase into the rim zone. Changes in Mg and Fe content are usually minor, but some crystals show a zonation in which Mg increases with little change in Ca into the rim zone. Following Black (1971) it is suggested that the colour zoning is related to the higher Ti concentrations in the rims.

The overall composition varies considerably, but is generally intermediate between schorl and dravite,
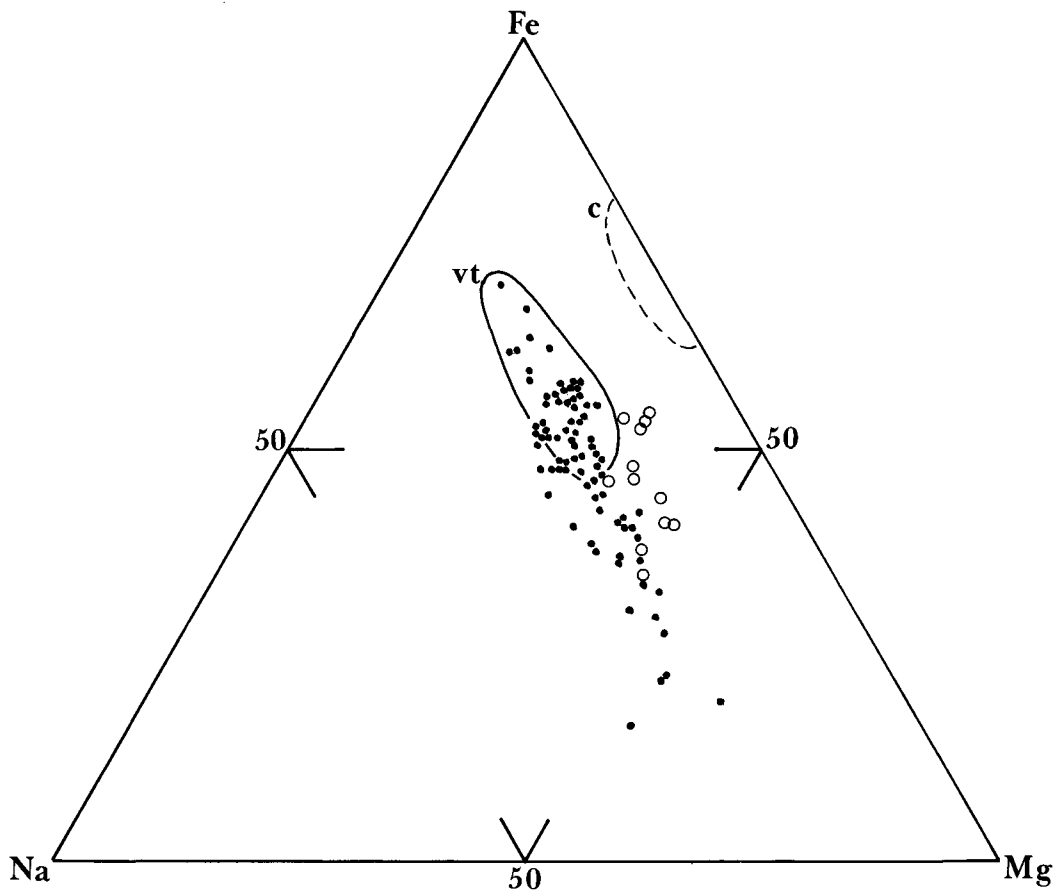
FIG. 3. Fe–Mg–Na proportions in tourmaline and tourmalinite. Tourmaline in chloritic and feldspathic veinlets is confined to the field 'vt' and coexisting chlorite plots in field 'c'; dots — tourmaline analyses; open circles — tourmalinite . rock analyses.

the principal variation being between Fe and Mg (fig. 3). Ca tends to increase with Mg, but the behaviour of Ti is erratic with respect to this variation. Tourmaline in chloritic and feldspathic veinlets falls at the schorlitic end of the overall range of compositions, having values of Fe/(Fe + Mg) between 0.58 and 0.85 (Fig. 3). Values for coexisting chlorite and the host rock also fall in this range, suggesting that mineral compositions in these veinlets reflect the chemistry of the host rock.

Tourmaline from hydrothermal veins in SW England is less sodic and Fe-rich than that in granite and related aplite and pegmatite (Power, 1968). Similar variation is seen in tourmaline from British Columbia (Ethier and Campbell, 1977) where examples from hydrothermal and sedimentary environments are markedly more dravitic than those from an associated granite stock. In B-metasomatism of wallrock to the Tip Top pegmatite, South Dakota (Shearer et al., 1984) tourmaline becomes progressively less dravitic as the pegmatite is approached. The Crummock Water tourmaline, which is hydrothermal in its general character and setting, shows no such precise trend; it covers the range from 'granitic' Fe- and Na-rich compositions to a more 'hydrothermal' type, locally within individual hand specimens.

Geochemistry. Samples of massive, tourmalinized rock from the veins were analysed by X-ray fluorescence spectrometry (analysts P. Harvey and B. Atkin, University of Nottingham) using beads prepared by the Norrish and Hutton (1969) method as modified by Harvey et al. (1973) for major elements, and pressed powder pellets with PVP/methyl-cellulose binder for trace elements. In addition, B, Be, and Li were determined by inductively

Table II Analyses of tourmalinites from around Crummock Water

Anal. no.	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	63.79	64.34	65.23	68.03	67.41	68.65	65.30	70.11	81.78	71.63	73.24	67.27
Al_2O_3	18.46	17.67	17.64	16.22	16.60	16.59	17.64	15.58	9.82	14.33	14.47	16.65
TiO_2	0.78	1.03	1.07	1.16	0.93	1.00	0.69	0.92	0.51	0.87	0.63	0.91
Fe_2O_3	4.97	5.25	5.71	4.86	5.55	4.27	5.99	5.29	2.89	5.51	3.80	6.05
MgO	3.31	3.03	2.24	2.66	1.89	2.36	2.29	1.78	1.40	1.90	1.58	1.90
CaO	0.56	0.47	0.31	0.31	0.36	0.35	0.27	0.29	0.19	0.30	0.23	0.33
Na_2O	1.13	1.01	0.68	0.67	0.43	0.56	0.92	0.37	0.35	0.44	0.49	0.56
K_2O	0.03	0.06	0.04	0.03	0.03	0.02	0.01	0.09	0.17	0.57	1.21	0.30
MnO	0.01	0.03	0.03	0.02	0.02	0.01	0.03	0.02	0.02	0.03	0.03	0.03
P_2O_5	0.14	n.d.	0.13	n.d.	0.09	0.12	n.d.	0.07	n.d.	0.06	0.06	0.07
B_2O_5	5.66	5.56	5.31	4.95	4.95	4.79	5.34	4.37	2.64	3.18	2.80	4.66
LOI	1.15	1.30	1.32	1.40	1.68	1.30	1.41	1.35	0.86	1.50	1.61	1.43
Total	99.99	99.72	99.57	100.39	99.92	100.04	99.88	100.04	100.62	100.33	100.17	100.16
Cr	129	137	133	222	147	144	154	158	120	115	97	144
V	122	128	117	125	117	177	130	100	61	91	87	104
Ni	47	45	32	41	38	44	34	45	39	38	43	46
Co	17	18	16	8	13	11	15	15	5	14	9	10
Cu	3	8	8	10	10	16	6	15	7	10	12	8
Zn	21	27	28	14	17	13	19	19	3	15	18	14
As	n.d.	2	n.d.	5	11	64	2	n.d.	n.d.	n.d.	n.d.	2
Mo	3	26	16	10	12	30	7	9	34	60	79	11
Sb	n.d.	3	2	3	3	3	3	3	7	3	2	4
W	5	8	8	11	13	13	7	10	7	12	5	5
Sn	5	3	8	3	3	3	7	7	20	14	13	14
Li	6	7	7	5	28	10	13	6	4	29	8	22
Pb	16	16	17	15	20	30	13	13	12	14	16	12
Rb	3	3	5	4	4	2	2	7	10	38	78	19
Th	11	9	8	7	8	11	8	12	6	8	7	12
Ba	43	47	60	63	42	51	38	58	37	78	225	89
Sr	72	66	55	59	48	42	53	54	33	47	40	60
Nb	12	15	20	21	16	18	8	18	11	16	14	18
Ce	30	n.d.	35	17	39	18	26	29	17	60	37	26
Y	14	8	13	8	11	12	7	11	10	20	13	11
Ga	36	29	25	28	24	22	28	23	15	23	23	27
Be	1.6	2.4	2.8	2.2	2.0	2.4	2.4	2.0	2.0	1.4	2.0	2.0
Zr	176	176	198	238	159	258	137	205	95	117	46	155
F	871	848	795	927	968	675	1305	428	367	502	580	641

Sample locations: 1 - NY 1635 1837; 2 - NY 1709 1907; 3 - NY 1715 1914; 4 - NY 1715 1930; 5 - NY 1742 1943; 6 - NY 1741 1945; 7 - NY 1775 1977; 8 - NY 1646 1824; 9 - NY 1545 1820; 10 - NY 1554 1821; 11 - NY 1548 1865; 12 - NY 1686 1861.

n.d. - not detected. Detection limits were; As 2 ppm, Sb 2 ppm, and Ce 6 ppm. In addition, La (<4ppm), Bi (<2ppm) and S (<5ppm) were below detection, and U (≤3ppm) was below detection (<2ppm) in all but three samples.

coupled plasma emission spectrometry (analysts B. Tait and L. Ault, BGS) and F by an automated colorimetric method (analyst R. Fuge, University College of Wales, Aberystwyth). Results are set out in Table II. Wallrock adjacent to three tourmalinites (3, 8, and 12 in Table II) were also analysed together with a suite of the host rocks collected on a 200 m grid east of Crummock Water (Table III). The small number of samples (twelve) precluded determination of element distributions, and so non-parametric statistical methods (Conover, 1980; Hall, 1983) were employed to assess the data.

Variation in tourmalinite composition and inter-element relationships closely reflect the mineralogy of the rocks. The elements Al, Mg, Ca, Na, Ga, Sr, V, F, and B display very similar variation patterns, confirming their concentration in tourmaline (e.g. Spearman Rank rho statistic (ρ): B–V = 0.91 : MgO–Na$_2$O = 0.88 : B–Al$_2$O$_3$ = 0.94). Fe shows a weaker correlation with these elements, as do Co and Zn which are not closely correlated with Fe. Ni displays independent variation.

K, Rb, and Ba, though severely depleted, form a closely inter-correlated group. Si, Mo, and Sn are enriched yet show significant Spearmen Rank correlations with the K-group and each other at the 95 % confidence level (e.g. for K$_2$O–Mo, ρ = 0.59; Rb–Sn, ρ = 0.75; K$_2$O–SiO$_2$, ρ = 0.51). Both these groups display strong negative correlations with elements concentrated in tourmaline, suggesting an association with quartz and muscovite in veinlets. Ti, Cr, Nb, and Zr form a positively correlated group largely ascribed to rutile, though Ti also shows a significant correlation with the tourmaline group reflecting its presence in that mineral. Th, Y, Ce, and P form a covarying group related to apatite.

On the Fe–Mg–Na diagram (fig. 3) the wholerock data are less sodic than the tourmaline mineral analyses, reflecting a contribution from chlorite in crosscutting veinlets. Similarly, muscovite in these veinlets is considered to be responsible for the relatively high concentrations of K$_2$O (> 0.1 %) in some specimens. Li and F are not enriched in the more potassic rocks, and F shows positive correlations with all the tourmaline group of elements, confirming its presence in that mineral. Simple extrapolation of the Li, F, and B results to a nominal schorl boron content of 10 % B$_2$O$_3$ (after Deer et al., 1962) suggests that the tourmaline contains about 20 ppm Li and 1750 ppm F.

Chemical changes in tourmalinization were assessed by comparing three tourmalinite-wallrock pairs and the median compositions of the tourmalinite and host rock populations. All four comparisons show a consistent pattern (fig. 4). Differences in medians (Mann–Whitney U test) and overall

Table III

Analyses of wallrocks to tourmalinites

	3W	8W	12W	M
SiO$_2$	61.98	61.53	58.87	58.92
Al$_2$O$_3$	19.83	19.47	20.41	20.28
TiO$_2$	1.21	1.16	1.10	1.10
Fe$_2$O$_3$*	5.98	7.42	8.92	7.81
MgO	1.60	1.68	1.79	1.79
CaO	0.60	0.24	0.25	0.42
Na$_2$O	1.09	0.69	0.88	1.01
K$_2$O	3.78	3.35	3.61	3.35
MnO	0.13	0.06	0.12	0.12
P$_2$O$_5$	0.14	0.12	0.15	0.17
LOI	3.41	3.66	3.84	3.80
Total	99.75	99.40	99.93	
Cr	118	120	120	120
V	139	133	134	135
Ni	49	50	53	47
Co	19	21	31	24
Cu	9	9	25	18
Zn	89	16	22	27
As	16	7	27	27
Mo	n.d.	n.d.	n.d.	n.d.
Sb	n.d.	2	n.d.	3
W	6	8	5	4
Sn	2	6	n.d.	2
Li	50	64	70	73
B	320	398	170	103
Pb	9	3	15	11
Rb	168	148	167	161
U	3	4	3	3
Th	10	13	15	14
Ba	663	625	687	625
Sr	123	90	96	101
Nb	22	21	21	21
La	68	24	41	45
Ce	139	72	108	103
Y	43	28	35	38
Ga	24	24	25	25
Be	2.7	2.7	3.4	3.2
Zr	239	222	212	214
F	581	618	598	–

Sample numbers refer to corresponding tourmalinites in

Table II. M – median of 43 host rocks (not available for F).

* Fe as Fe$_2$O$_3$. Detection limits – Mo 2ppm, Sb 2ppm, Sn 2ppm.
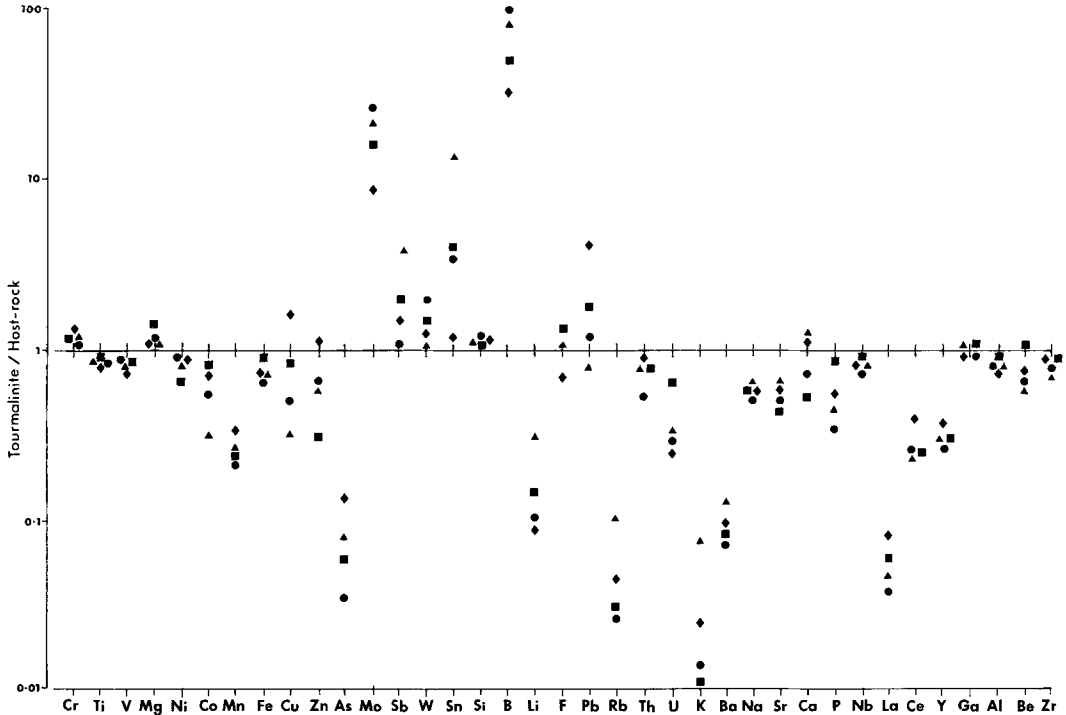
FIG. 4. Element ratio plot to compare tourmalinite with host rock compositions. Circles—ratio of medians of twelve tourmalinites and forty-three bleached pelitic and semipelitic host rocks; other symbols refer to three paired tourmalinite and wallrock analyses. Half detection limit values were used in calculations involving results below the detection limits.

distributions (Kolmogorov–Smirnov two sample test) between the host rock and tourmalinite sample populations are highly significant (> 99.95% confidence level) for most elements determined, while Mg, Na, Cr, Cu, Ni, Pb, Zn, and Zr show differences in the 95–99.95% confidence range. Only Ca, Ga, and Sb show no significant statistical differences. Two of the three paired analyses showed higher levels of F in the tourmalinites (fig. 4), and a small number (10) of F determinations carried out on other host rocks also suggest weak F enrichment in the tourmalinites.

K, Rb, and Ba are strongly depleted, whereas other LIL (large ion lithophile) elements such as Th probably held in resistate phases show only slight depletion. K/Rb decreases to give a low median value of ninety-five for tourmalinite, consistent with metasomatism by aqueous fluid of magmatic or meteoric origin (Armbrust and Gannicott, 1980). REE and Y are also depleted, La very strongly resulting in greatly enhanced Ce/La ratios. Hydrothermal REE-fractionation (Vlasov, 1966) is ascribed to the relative stabilities of REE carbonate,

sulphate, and fluoride complexes (Taylor and Fryer, 1982; Humphris, 1984). Relative depletion in La may be related to the absence of the 'true lanthanide' $4f$ configuration in La and the possibility of Ce^{3+} or Ce^{4+} oxidation states, resulting in the formation of contrasting alkali–REE–anion compounds. Though some REE are doubtlessly retained in apatite, more distant redeposition is suggested by an occurrence of euhedral allanite prisms up to 4 mm long in late-stage quartz–albite segregations in pelitic aureole rock at the foot of Rannerdale Knott [NY 1664 1864]. Mn and Li are strongly depleted in tourmalinite, though their levels in the Crummock Water tourmaline are similar to normal levels in schorl and dravite in both igneous and hydrothermal settings (Deer et al., 1962; Taylor and Slack, 1983).

Mo (≤ 79 ppm) and B are, in contrast, greatly enriched in the tourmalinite, and an appreciable amount of Si was added in forming silicified zones, quartzose breccia matrices and veins. Concentrations of Sn, W, Mg, and Cr are slightly higher than in wallrock (fig. 4). There is no evidence for any net

gain or loss of Be. Cu, Zn, Pb, and Ca display both enrichment and depletion, and it is suggested that initial removal was followed by some redeposition in the later veining. Arsenic is the only chalcophile element to show consistently strong depletion, but the local presence of arsenopyrite (in one thin section of tourmalinite) indicates that it too can be enriched in the later veining. Moreover, the As–Co-bearing quartz vein at Scar Crag mine, which Ixer *et al.* (1979) relate to the concealed granite, may also be an expression of the later veining.

Dilution by introduced silica is considered responsible for small net reduction in the Ti, Zr, and Al content of tourmalinites with respect to host rocks. TiO_2/Al_2O_3 and Zr/Al_2O_3 ratios show little change whilst the individual element concentrations move towards zero in the tourmalinites (fig. 5). Minor discrepencies in the trend probably reflect local mobility and redistribution of the elements, for example Ti is concentrated into rutile veinlets. Changes in Al_2O_3/Ga, however, indicate either a relative loss of Al or gain in Ga (fig. 5). Reduction in Al concentration by silica dilution and a relative gain in Ga are consistent with other element variation patterns. Similar plots, of other elements which correlate closely with Al_2O_3 in the host rocks and show a slight overall depletion in tourmalinites (V, Nb, and Be), indicate that whilst most changes are consistent with silica dilution one sample is apparently enriched in V and two depleted in Nb.

Discussion and conclusions. Tourmaline occurrences in the English Lake District are associated with granitic intrusions forming part of the Early Silurian to Early Devonian (Rundle, 1979) composite batholith which underlies much of the area (Bott, 1974; Firman, 1978; Lee, 1984). Ansari (1983) regards some schorlitic tourmaline in the Eskdale granite as primary, but the amount of B fixed during primary crystallization of these intrusions is generally uncertain and the coarse-grained yellow-brown early tourmaline common in SW England granites is absent. P. R. Simpson (pers. comm.) found that the Ennerdale Granophyre contains less than 10 ppm B whereas the other intrusions contain appreciably more. Tourmaline occurs on joints in the Shap granite (Grantham, 1928) and the Eskdale granite (Simpson, 1934), and tourmaline is a minor secondary mineral in the Skiddaw granite (Rastall and Wilcockson, 1915; Hitchen, 1934). Tourmalinized breccia pipes in the Haweswater basic intrusive complex (Nutt, 1972, 1979) overlie the concealed roof of the Shap granite (Lee, 1984). Tourmalinite veins similar to those at Crummock Water occur in the contact aureole of the Skiddaw granite at Snab [NY 3054 3105] and Poddy Gill (Shackleton, 1975), and tourmalinized
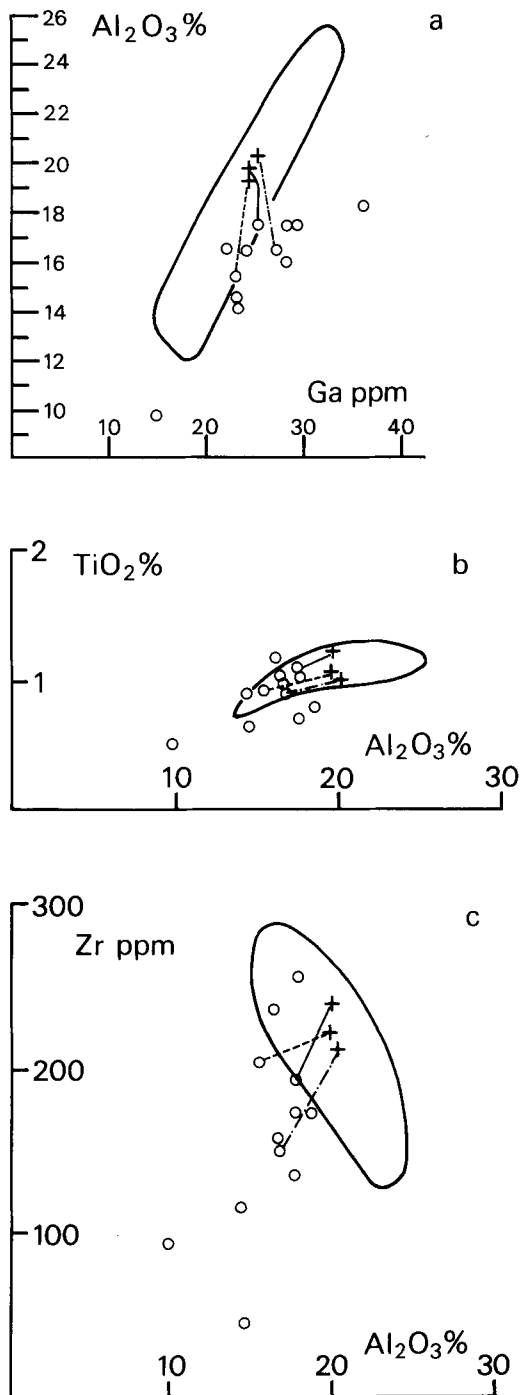

FIG. 5. Variation diagrams showing tourmalinites (open circles) and the field of host rock analyses. Three tourmalinites are tied to the corresponding wallrocks shown as crosses.

zones occur close to the Skiddaw granite in Skiddaw Group wallrocks adjacent to the W-lodes at Carrock Fell mine [NY 322 329] (N. J. Fortey, unpubl. data).

Tourmalinization of metasedimentary rocks aroud Crummock Water involved the introduction of B, Si, Mo, minor F and traces of Sn and W. Fluid–rock reactions resulted in near complete removal of K, Rb, Ba, Li, La, and As, plus depletion in Ce, Y, Fe, Na, Sr, P, Mn, and chalcophile elements, whilst Cr, Mg, and Ga show modest relative enrichment in tourmalinite with respect to host-rock compositions. Formation of additional tourmaline-, chlorite-, and muscovite-bearing quartz veinlets followed further fracturing and introduction of hydrothermal fluid. Weak Mo and Sn enrichments are associated with K which represents muscovite in these veinlets; minor redeposition of chalcophile elements took place at this stage. A few elements including Zr, Ti, and Al suffered minimal net changes in concentration except for dilution by introduced silica. This pattern of Al depletion and Si addition contrasts with the geochemistry of tourmalinization in more siliceous (75% SiO_2) metasediments at the Tip Top pegmatite (Shearer et al., 1984) where Si was lost and Al added.

Charoy (1982) explains the tourmaline-rich marginal facies of the Lands End granite at Cape Cornwall by the unmixing during late fractionation of an immiscible alkali–B–volatile-rich magma of low solidus temperature (following Chorlton and Martin, 1978 and Pichavant, 1979). Separation of a mobile, boron enriched aqueous phase can also result in metasomatism of solidified granite, as in luxullianite and similar rocks (e.g. Brammall and Harwood, 1925; Lister, 1978a, b), or give rise to boron metasomatism of country rocks. Release of volatile-rich fluids from apical parts of granites will take place when the volatile pressure exceeds the strength of the host rock envelope (Norton and Cathles, 1973). Tourmalinization is thus a feature of some breccia pipes related to granite ridges and cusps (e.g. Goode and Taylor, 1980; Allman-Ward et al., 1982). Tin, tungsten, and other metals may be enriched in such pipes and associated veins (e.g. Hosking, 1969; So and Shelton, 1983), having possibly been released from chlorite and biotite during alteration at greater depth (Bromley, 1983; Lister, 1984).

The Crummock Water tourmalinite veining therefore suggests a locus of hydrothermal flow consistent with the passage of B-rich aqueous fluid from a ridge-like granitic intrusion beneath the elongate Crummock Water aureole. Joints and fractures in the host aureole provided pathways for fluid movement, and explosive brecciation was not developed extensively. Though the veins are also

in close spatial proximity to the Ennerdale Granophyre there is no structural or other evidence for a genetic association with this intrusion. The ultimate source of the boron was probably the underlying granitic magma though, in view of the paucity of evidence for magmatic boron in Lake District granites, derivation from the Skiddaw Group country rocks (which have a median B content of about 65 ppm) cannot be excluded.

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