very great contrast in their viscosities and the slow diffusion rates of H_2O in silicate melts (Burnham, 1967). Thus the main influx of water from the sediments most likely occurred following fracturing in the crinanites when the sill was substantially consolidated.

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Department of Geology, The University C. M. B. HENDERSON
Manchester M13 9PL
Department of Geology, The University F. G. F. GIBB
Sheffield S1 3JD

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Piemontite schists from Upper Swat, north-west Pakistan

PIEMONTITE schists occur near to the contact between the Palaeozoic Lower-Swat-Buner schistose group and the epidote amphibolites of the Kohistan basic complex, located about 7 km east of Khwaza Khela (34° 55′ N., 72° 28′ E.), NW. Pakistan. Glaucophane schists, serpentinites, alpine ultramafites, and garnet gneisses have been previously reported along or near to this contact, which is probably a regional thrust fault. The piemontite schist horizon is at least a few hundred metres long and more than 10 m broad, and was previously described as tourmaline schist by Shah and Kahn (1971), without mention of the piemontite or other manganese-rich minerals present. The piemontite schists are associated with greenschists, calcareous schists, and quartz-mica schists of the Lower-Swat-Buner schistose group described by Martin *et al.* (1962). Epidote amphibolites are exposed about $\frac{1}{2}$ km to the north of the piemontite schists, while some glaucophane schists and serpentinites occurring within the schistose group occur a few kilometres to the east.

The piemontite schist is a fine grained rock with a distinct purplish colour and a silver-grey lustre associated with the schistosity. In thin section it is composed of quartz, albite, muscovite, margarite, tourmaline, piemontite, spessartine garnet, a Mn-rich chlorite ($MnO = 2{\cdot}24\%$), rutile, and magnetite. A crude segregation of quartz and albite from the muscovite, piemontite, tourmaline laminae occurs in the plane of the schistosity. The quartz grains are anhedral, interlocking and of even grain-size up to 0·25 mm in diameter and constitute modally 40 % of the rock. They commonly contain inclusions of small euhedral piemontite and magnetite crystals. Albite occurs as broadly twinned poikilitic patches up to 1 mm across and containing abundant inclusions of the associated minerals, which form a distinctly crenulated schistose fabric. The albite poikiloblasts often show rotational features suggestive of syntectonic growth.

Muscovite occurs as bundles of colourless or slightly rose-coloured grains. Margarite and the manganese-rich chlorite both occur in blebs of small colourless, radiating brushes.

Both the piemontite and the tourmaline occur as euhedral, elongated crystals sub-parallel to the dominant schistosity, the former being strongly pleochroic whereas the latter is colourless, or a very dull yellow dravite, showing some pleochroism in shades of pink. In the quartz-poor areas of the schistose fabric piemontite constitutes up to 15 % of the rock, some crystals being elongated up to 0·4 mm in length and 0·1 mm broad. The piemontite grains almost always carry tiny magnetite inclusions concentrated in their cores. Spessartine garnet is not common but forms occasional idioblastic crystals the habit of which seemingly indicates a late metamorphic growth, enclosing piemontite and tourmaline. Microprobe studies show that the disseminated magnetite is often intimately associated poikiloblastically with minute rutile grains.

The piemontite crystals in orientation suitable for optical examination consist mainly of 0·05–0·1 mm prisms elongated along [010]. Twinning on {100} was only rarely observed. However, two crystals twinned on {100} and lying parallel to the optic plane {010} were measureed for α, γ, and for the extinction angles. Dispersion of the indicatrix is strong and values are for Na*D* only: α 1·748, canary yellow, β 1·770, amethystine pink, γ 1·795, deep rose pink, γ–α 0·047, $2V\gamma$ calc $= 87° 29'$.

An XRF analysis of the whole rock, using pressed-powder discs, was carried out for major, minor, and a range of trace elements. H_2O^+ was determined by the Penfield method and FeO by Wilson's method. Accuracy should be within $\pm 2\%$ of the amounts present for the major elements. The values quoted in Table I for Co, Ga, Y, and Zr are expected to be correct to within 15 ppm, Cr, Ni, and Sr to within 20 ppm, and those for Ba, Cu, and Zn within 40 ppm. Owing to the over-all small grain-size and presence of magnetite inclusions the piemontite was not separated for chemical analysis, but analysed by electron-microprobe. The reported analysis of the piemontite is the average of three homogeneous grains free of inclusions and large enough to allow ten spot counts per grain. Total Mn has been expressed as Mn_2O_3 and total Fe as Fe_2O_3 following Deer *et al.* The analysis shown in Table I is expected to be accurate to $\pm 2\%$ of the amounts present for the major elements.

The analyses of the whole rock, piemontite, and spessartine garnet are presented in Table I. Compared to an average Palaeozoic shale, from which the piemontite schist is probably formed (Clarke, 1924), the rock has higher SiO_2, MgO, CaO, and K_2O and lower TiO_2, Na_2O, and P_2O_5. The values for Ba, Cr, Ga, and Zr are lower, and those for the other trace elements higher than those given for an average shale by Turekian and Wedepohl (1961). The significant difference of the Swat rock from the average values is in its nickel (2 × the average content), copper (> 11 times that of the average), and especially Mn (20 ×). The high manganese value reflects special circumstances, which precipitated abundant manganese at the time of the deposition of the shale horizon. Local volcanic or hydrothermal activity may have been the contributory factor.

TABLE I. *Analyses of the piemontite schist, piemontite, and spessartine*

1				2		2′			3		3′		
SiO_2	62·67	p.p.m.		SiO_2	36·75	On the basis of twelve oxygens			SiO_2	36·78	On the basis of twenty-four oxygens		
TiO_2	0·68	Ba	520	TiO_2	0·02	Si	2·878	3·00	TiO_2	0·37	Si	5·997	6·00
Al_2O_3	16·45	Co	27	Al_2O_3	19·59	Al	0·122		Al_2O_3	19·62	Al	0·003	
Fe_2O_3	4·60	Cr	67	Cr_2O_3	n.d.	Al	1·687		Cr_2O_3	n.d.	Al	3·768	
FeO	2·00	Cu	520	Fe_2O_3*	8·17	Fe^{3+}	0·482	2·92	FeO	2·14†	Cr	—	
MnO	2·11	Ga	10	Mn_2O_3*	12·55	Mn^{3+}	0·748		MnO	36·04†	Fe^{3+}	0·256	4·069
MgO	3·32	Ni	163	MgO	0·07	Ti	0·001		MgO	0·37	Ti	0·045	
CaO	2·19	Sr	377	CaO	19·90	Mg	0·008		CaO	5·12	Mg	0·090	
Na_2O	0·81	Y	37	Na_2O	n.d.	Ca	1·670	1·69	Na_2O	n.d.	Fe^{2+}	0·036	6·00
K_2O	4·42	Zn	125	K_2O	0·13	K	0·013		K_2O	0·02	Mn	4·979	
H_2O	2·00	Zr	115	Total	97·18						Ca	0·895	
P_2O_5	0·08								Total	100·46	Alm =	0·6	
Total	101·33										An =	1·1	
											Gr =	13·8	
											Py =	1·5	
											Sp =	83·0	

1. Piemontite schist.
2 and 2′. Piemontite.
3 and 3′. Spessartine.

* Total Fe and Mn as Fe_2O_3 and Mn_2O_3.
† Total Fe and Mn as FeO and MnO.

The manganese content of the piemontite ($Mn_2O_3 = 12{\cdot}55\%$) is high for this mineral although Bilgrami (1956) has reported up to $17{\cdot}78\%$ Mn_2O_3 from a piemontite in a pegmatite from Chikla, India.

The analysis has been recalculated on the basis of twelve oxygens in Table I. From this it appears that all the Mn^{3+} and Fe^{3+} are in octahedral co-ordination. However, a survey of the analysed epidote group minerals in the literature suggests that the Mn occurs in different oxidation states, most of it being octahedral but some also occupying some of the large cation sites (Hutton, 1942; Bilgrami, 1956; Cooper, 1971; Marmo *et al.*, 1959; Short, 1933). This also seems to be the case of the Swat piemontite, if the formula is recalculated on the basis of 13 (O, OH) after adding $1{\cdot}84\%$ H_2O to the analysis to give 1 (OH) in the formula $(Ca_{1{\cdot}74}Mg_{0{\cdot}01}Mn_{0{\cdot}16}K_{0{\cdot}01})$ $(Al_{1{\cdot}88}Fe_{0{\cdot}50}Mn_{0{\cdot}62})Si_{3{\cdot}00}O_{12}(OH)_{1{\cdot}00}$. In this formula Mn is about four times as abundant in the octahedral site as in the large cation site and is in accordance with most of the earliest piemontite analyses (see Short, 1933).

Cooper (1971) argues that bulk chemistry (especially oxidation state) rather than the metamorphic conditions controls the occurrence of piemontite. Further determinations of Mn_2O_3 and MnO contents of the piemontite-bearing rocks are needed to verify this, because, as pointed out by Cooper, most metamorphic occurrences of piemontite are in high-pressure or in high-pressure to intermediate-facies series terrains. The Swat rock seems also to have formed under high-pressure conditions. Apart from its closeness to the thrust fault and the glaucophane schist it occurs in a belt of schists that in places contain chloritoid, garnet, staurolite, and kyanite.

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Department of Geology, King's College, Strand
London W.C.2 — M. Qasim Jan

British Museum (Natural History)
London S.W.7 — R. F. Symes

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