Characterisation of the low-grade metamorphism in the Nambucca block (NSW, Australia)

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ABSTRACT

Investigation of the crystallinity of K-white micas in early Permian rocks from the Nambucca Block, NSW, reveals a metamorphic pattern with the highest grade (epizonal) rocks in an east-west trending zone which changes transitionally to lower grade (anchizonal) rocks to the south and north. Chlorite crystallinity values show a similar pattern, but in some cases do not agree with the Kübler index values from the same location owing to peak broadening caused by the overlap of the (002) chlorite-vermiculite peak and the (001) peak of chlorite. The usefulness of this parameter as a grade indicator is thus limited, unless deconvolution programs are applied.

b_0 cell parameters of K-white micas in slates indicate intermediate P facies series metamorphism (b_0=9.023; sd=0.020), which accords with an interpretation based on mineral assemblages in metabasites. The much wider range in b_0 values noted in these rocks, compared to those formed under similar metamorphic conditions in other terrains, is attributed to a wide range in bulk chemical composition. Temperatures of formation based on Al^{IV} contents of chlorites and chlorites in mixed-layer clays, range from 216°-231°C in the anchizonal rocks to 244-349°C in epizonal rocks.

Key words: Low grade metamorphism, Kübler index, Chlorite crystallinity, Chlorite geothermometry.

RESUMEN

Caracterización del metamorfismo de muy bajo grado en el bloque Nambucca (NSW, Australia). El estudio de la cristalinidad de las micas blancas potásicas en rocas del Pérmico Inferior del Bloque Nambucca, Nueva Gales del Sur, ha puesto en evidencia un modelo metamórfico con las rocas de grado más alto (epizona) con una distribucion este-oeste, cambiando gradualmente a rocas de grado menor (anquizona) hacia el sur y el norte. Los valores de la cristalinidad de la clorita muestran una distribucion similar, pero son más variables y con frecuencia no coinciden con los valores de la cristalinidad de las micas blancas potásicas de la misma zona, debido al ensanchamiento producido por el solapamiento del pico (002) de la clorita-vermiculita y el (001) de la clorita. La utilidad de este parámetro como indicador de grado es, por tanto, limitada, a no ser que se utilicen métodos de descomposición de los diagramas de difracción de rayos X. El parámetro b_0 de las micas blancas potásicas de las pizarras indica series de metamorfismo de presión intermedia (b_0 9.023; sd=0.020), que está de acuerdo con la interpretación basada en las asociaciones minerales en las metabasitas. Los valores máximos de b_0 observados en esta zona, en comparación con los que se obtienen en otros terrenos afectados por condiciones metamórficas similares, se atribuyen a un intervalo mayor de la composición química global. Las temperaturas de formación, obtenidas a partir de los contenidos en Al^{IV} de las cloritas y de las cloritas en los interestratificados, oscilan entre 216° y 231°C en las rocas anquizonales y 244-349°C en las rocas epizonales.

Palabras claves: Metamorfismo de bajo grado, Indice de Kübler, Cristalinidad de la clorita, Geotermometría de la clorita.

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INTRODUCTION

The Nambucca Block (NB) is one of the several fault-bounded blocks that make up the eastern part of the southern New England Fold Belt (SNEFB, Fig 1). These blocks developed late in the history of the SNEFB during Permian orogenesis which disassembled a once contiguous Devonian-Carboniferous accretion-subduction complex. The NB contains early Permian clastic and silicic volcanic rocks, basalts of tholeiitic and slightly alkaline affinity and minor limestones (Leitch, 1988; Asthana and Leitch, 1985). These rocks were deformed under low grade metamorphic conditions (prehnite-pumpellyite to greenschist facies), *ca.* 260 Ma ago (Leitch, 1976; Leitch and McDougall, 1979; Fukui *et al.*, 1990).

The tectonic setting in which these rocks accumulated is a subject of controversy. Current consensus favours a rift setting for them and for those of similar age elsewhere in the SNEFB. However, there is some disagreement as to whether deposition occurred in a single, major basin, the Barnard Basin (Leitch, 1988) or a series of smaller basins of pull-apart origin (Aitchison and Flood, 1993).

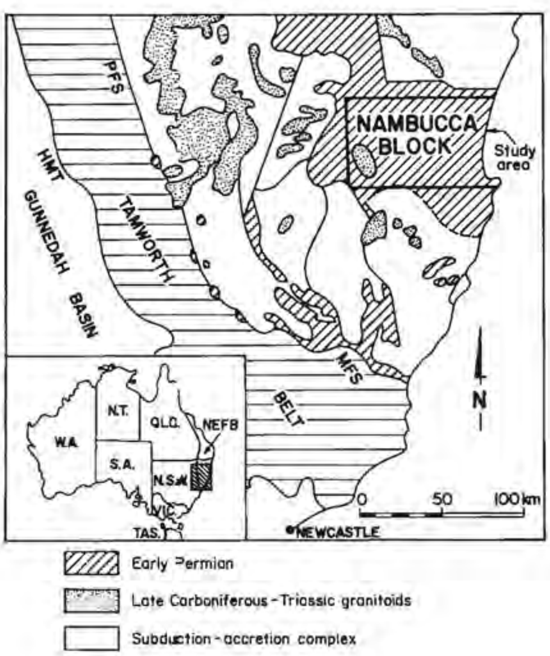

FIG. 1. Location map of Nambucca Block in the Southern New England Fold Belt; **inset**- position of study area within the New England Fold Belt (NEFB); **PFS**: Peel Fault System; **MFS**: Manning Fault System; **HMT**: Hunter Mooki Thrust.

Metamorphic studies on the NB have concentrated on the regional and contact metamorphic aspects (Leitch, 1976). However, these studies were of a reconnaissance nature only and were based primarily on calc-silicate assemblages in metabasites and sandstones. Leitch (1976) defined four zones of regional metamorphism based on the presence of prehnite only in Zone 1, stilpnomelane and pumpellyite in Zone 2, pumpellyite-actinolite assemblages and lack of prehnite in Zone 3, and disappearance of pumpellyite in Zone 4.

To obtain a better understanding of the metamorphism, a detailed sampling of the slates in the NB was carried out. These rocks are extremely common in the block and are ideal for metamorphic studies as they contain abundant K-white mica, less common chlorite and a variety of clay types including chlorite-smectite, chlorite-vermiculite, chlorite-illite and illite-smectite (Brime and Offler, 1993). These minerals can be useful indicators of grade, particularly K-white mica (Kübler, 1968; Kisch, 1987) and chlorite (Arkai, 1991), the crystallinity of which increases with temperature. Additional information can be obtained from the lateral spacing b_0 of K-white mica which increases with increasing P (Sassi and Scolari, 1974; Guidotti and Sassi, 1986) and thus gives some indication of the style of metamorphism.

In the present investigation, the crystallinity of chlorite and K-white mica, and the b_0 values of K-white mica were determined as well as the composition of chlorite, chlorite-vermiculite and chlorite-smectite; most analyses were carried out on slates and a few on meta-sandstones and fine-grained white mica schists. The data obtained are presented here and their interpretation compared with that of Leitch (1976).

METHODS

More than 300 samples of slate and a small number of white mica schists and metasandstones were collected for analysis. Fractions (<2 μm) were prepared from whole rock powders and sedimented onto glass slides for X-ray diffraction determinations carried out on a Philips automated PW 1732/10 X-ray diffractometer, using CuKα radiation, graphite monochromator, 40 KV and 30 Ma. Samples were scanned over the range 2θ=6.5-10° at 0.5° 2θ/min using divergent and scatter slits of 1°, and receiving slits of 0.2 mm and Kübler index (KI; Kübler, 1968) determined. Peak width was calculated in terms of Δ°2θ and samples with IC>0.20Δ°2θ were glycolated to test for the presence of smectite interlayered with the illite. Similar machine conditions were used for the determination of the crystallinity of chlorite. Scanning ranges of 2θ=5-7° and 11-13.5° respectively were used for the (001) and (002) peaks.

b_o cell dimensions on K-white micas were obtained from rocks containing the nonlimiting assemblage quartz-albite-muscovite-chlorite (Guidotti and Sassi, 1976), and of higher grade than middle anchizonal conditions, in order to obtain values truly reflecting the baric conditions (Padan *et al.*, 1982). All analyses were made on powdered samples packed into aluminium mounts, similar in design to that of Robinson (1981), to enhance the (060) peak relative to the (331) peak (Guidotti, 1984). The range 2θ=59.5-63° was step scanned at 0.005° 2θ/sec using a counting time of 1 second and b_o determined from the (060) peak using the (211) quartz reflection as an internal standard. Machine settings were: slits 2°, 0.1 mm, 2°, time constant 2.

Deconvolution of the white mica and chlorite basal reflections was carried out using a line profile fitting routine (Philips APD 1700).

Major and trace element analyses of 24 slates were determined on a Philips PW 1404 XRD spectrometer, using fused glass discs. A low dilution fusion technique was employed in the production of the discs (Eastell and Willis, 1990).

Mineral analyses were carried out on a JEOL JSM-840 scanning electron microscope attached to a LINK EDS system. The settings were 2.5nA and 15kV, counting time 60 seconds, and data reduction was by an on-line computer using the SPEED (Software Package for Empirical Energy Dispersive spectroscopy) program of N. Ware (Research School of Earth Sciences, Australian National University).

KÜBLER INDEX

Kübler indexes of K-white mica were obtained for over 300 samples, but only 80 were deemed to be suitable for the determination of the metamorphic pattern in the NB, the others being affected by detrital white mica which is common in many specimens. Those used were chosen on the basis that:

- microscopic examination revealed neocrystalline white mica defining slaty cleavage and/or that detrital white micas were minor or absent.
- the samples were phyllitic or showed evidence of high strain. It was considered that in these samples neocrystalline white mica would dominate.

Those that were rejected, contained white mica with KI values higher than the grade indicated by the types of clays present and the degree of interlayering in them, and by the mineral assemblages in the metabasites and sandstones.

The Kübler indexes define a similar metamorphic pattern to that presented by Leitch (1976). The grade increases towards the centre of the area from the south and possibly from the north, although the pattern is less well defined in this part of the NB. In addition, rocks of higher grade cover a larger area than that shown by Leitch, 1976, Fig. 2) and local areas of higher grade are present. The development of higher grade rocks in the lower grade zones delineated by Leitch (1976), could be due to the presence of subsurface granitoids which are common in the NB and adjacent blocks. However, b_o values obtained from samples showing the higher grade indexes, do not support this proposition because they are rarely <9.012 and range from 9.010 to 9.045. Under contact metamorphic conditions, b_o would be much lower (Briand, 1980). Further, the fabric of hornfelsic rocks in the NB is quite distinctive and readily identified.

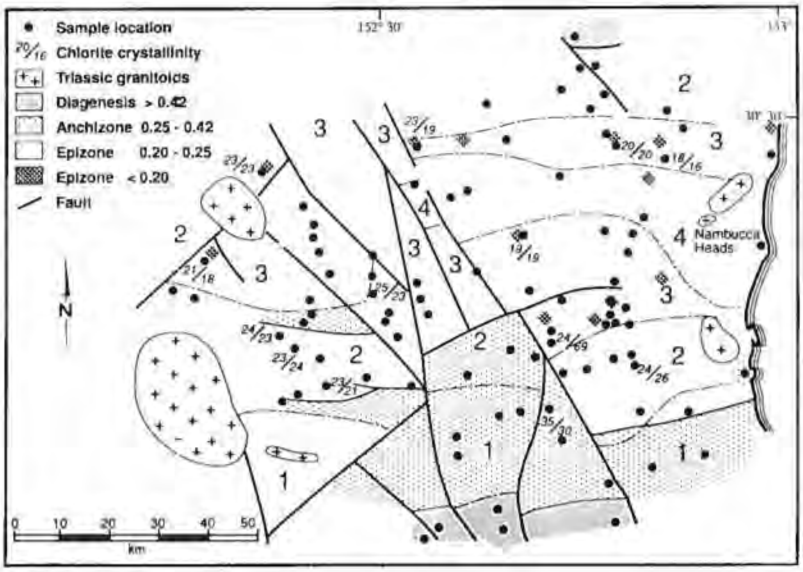

FIG. 2. Metamorphic map of the Nambucca Block showing the metamorphic zones 1 to 4 delineated by Leitch (1976) (metamorphic boundaries shown by long dash-short dash lines) and the position of the diagenetic zone (KI>0.42), anchizone (KI 0.42-0.25) and epizone (KI<0.25). The chlorite crystallinity values are also given: numerator (001), denominator (002). The upper and lower boundaries of the anchizone are those defined in Kisch (1991).

CHLORITE CRYSTALLINITY

Arkai (1991) has suggested that chlorite crystallinity can be used as a grade indicator, complementary to or instead of the illite crystallinity method, in low grade metamorphic terrains. In view of the paucity of Kübler index data in many areas of the NB, owing to the problems encountered with detrital white mica, chlorite crystallinity determinations were carried out on 12 samples containing illite, chlorite and no detectable interlayered smectite or vermiculite according to XRD (Fig. 2). The aim was to obtain data reflecting the grade in these areas and thus to allow a better definition of the metamorphic pattern in the NB.

Examination of figure 2 shows that overall, the chlorite crystallinity values confirm the pattern defined by the Kübler indexes. Further, in some specimens there is agreement between the Kübler index and chlorite crystallinity, and between the crystallinity obtained from the width of the (001) and (002) peaks of the chlorite. However, in others, the chlorite crystallinity is lower (Fig. 3). In the specimens exhibiting this difference, the (001) and the (002) peaks are broad and asymmetrical towards the low 2θ end of the diffractogram, suggesting that two or more minerals phases may be overlapping. To investigate this further, a deconvolution program was applied to the diffraction data obtained from specimens exhibiting markedly asymmetrical (001) and (002) peaks. Figure 4 illustrates the results obtained from NB 79, a sample

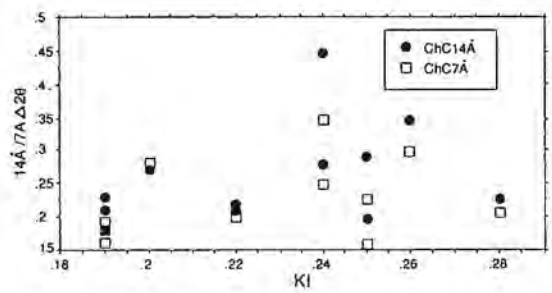

FIG. 3. Kübler index (KI) *versus* Chlorite cristallinity (Chc) (14°A and 7°A).

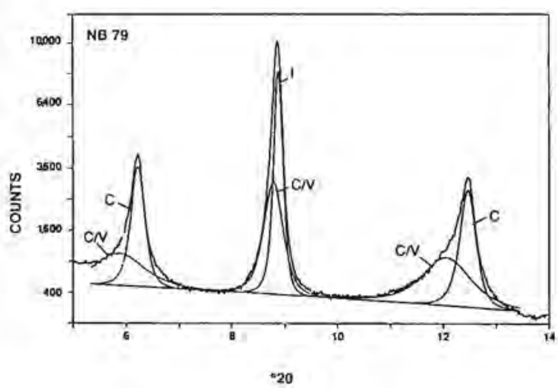

FIG. 4. Deconvolution of NB79 (air dried) pattern. C: chlorite; CV: chlorite-vermiculite.

known to contain chlorite, illite and chlorite-vermiculite (Brime and Offler, in prep.). It is clear in this sample, that the asymmetry is due to the overlap of chlorite and chlorite-vermiculite, and that the chlorite crystallinity is higher than the original trace would suggest. Similar results were obtained from other specimens. These studies show that interpretations made on data obtained from asymmetrical (001) and (002) peaks of 'chlorite' are misleading and that chlorite crystallinity can only be used successfully as a grade indicator if deconvolution programs are applied to peaks showing asymmetry.

b_o CELL PARAMETER DATA

On the basis of a study of the alteration assemblages in metabasites and sandstones, Leitch (1976) suggested that regional metamorphism took place under a moderately low geothermal gradient, with temperatures of 360°-370° and pressures of 4-7 kilobars being attained at the pumpellyite-actinolite/greenschist boundary.

Since b_o cell parameters of K-white micas in low grade metamorphic rocks are known to reflect baric conditions (Sassi and Scolari, 1974, Guidotti and Sassi, 1986), 73 samples were analysed to test the interpretation of Leitch (1976). Those chosen for analysis contained little or no detrital white mica and abundant regional metamorphic white mica. The results are presented in figure 5 along with cumulative curves based on data from other metamorphic terrains (Sassi and Scolari, 1974; Guidotti and Sassi, 1986). The mean b_o value (x=9.023; sd=0.020) indicates an intermediate P facies series metamorphism supporting the interpretations of Leitch (1976). However, the standard deviation is higher than the one normally obtained in these types of studies and the slope of the cumulative curve is oblique to the other curves (Fig. 5).

The reason for the high standard deviation became clear when chemical analyses (Table 1) of samples containing K-white mica showing the complete range in b_o, were carried out. When the b_o value for each

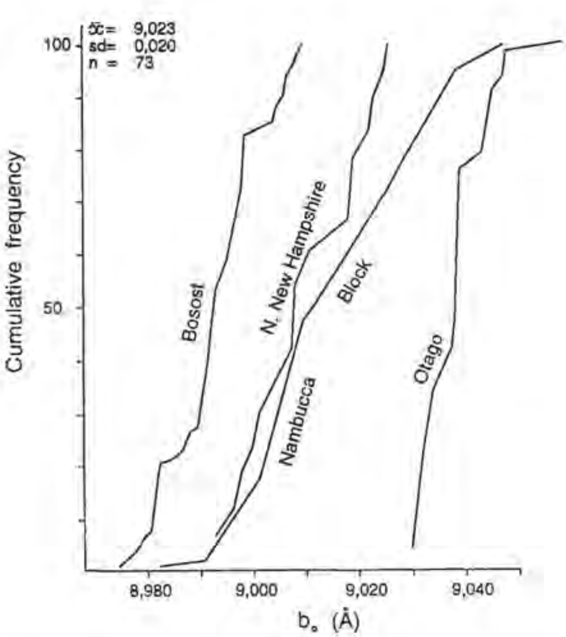

FIG. 5. Diagram showing b_o cumulative frequency curve obtained from slates in the NB relative to curves obtained from samples in other metamorphic terrains.

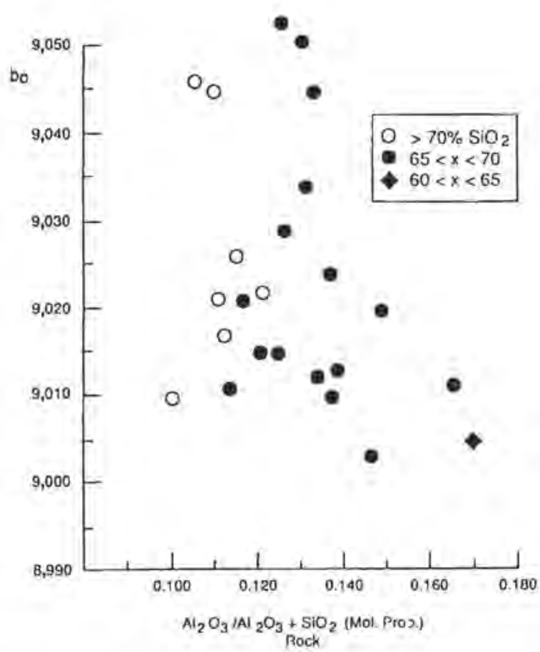

FIG. 6. b_o *Versus* $Al_2O_3/Al_2O_3+SiO_2$ (molecular proportions) of slates in the Nambucca Block.

sample was plotted against $Al_2O_3/Al_2O_3+SiO_2$ (molecular proportions), it was found that b_0 increased with decreasing $Al_2O_3/Al_2O_3+SiO_2$ (Fig.6). Thus part of the range in b_0 values is due to the wide range in composition of the host rocks which, according to discriminant function analysis, is the result of detritus being contributed from two main sources to the rift basins during the early Permian, one rich in felsic igneous rocks, the other quartz-rich meta-sediments (Offler and Brime, in prep.).

TABLE 1. REPRESENTATIVE ANALYSES OF SLATES.

	NB89	NB137-1	NB305	NB351	NB359	9206
SiO_2	65.35	69.50	61.34	64.08	64.92	68.38
TiO_2	0.72	0.56	0.90	0.82	0.85	0.73
Al_2O_3	16.01	14.16	20.80	17.28	18.75	15.89
Fe_2O_3	2.30	0.22	3.77	4.23	3.14	1.58
FeO	2.43	3.54	1.01	0.56	0.44	1.57
MnO	0.05	0.10	0.02	0.01	0.00	0.01
MgO	2.06	1.58	0.96	1.56	0.88	0.81
CaO	0.03	1.14	0.03	0.09	0.05	0.05
Na_2O	1.33	1.72	0.78	1.02	0.89	2.33
K_2O	6.01	3.92	3.03	3.99	3.42	2.71
P_2O_5	0.15	0.11	0.04	0.06	0.07	0.02
LOI	2.80	2.55	6.42	5.23	5.74	4.90
Total	99.24	99.10	99.10	98.93	99.15	98.98
b_0	9.057	9.045	9.010	9.004	9.002	9.021
$Al_2O_3/Al_2O_3 + SiO_2$	0.126	0.105	0.166	0.137	0.146	0.121

CHLORITE GEOTHERMOMETRY

Studies of chlorites and chlorite in mixed-layer clays have shown that Al^{IV} increases with temperature (Bevins *et al.*, 1991; de Caritat *et al.*, 1993; Cathelineau, 1988). On the basis of this relationship, Cathelineau (1988) proposed a geothermometer using downhole temperatures and chlorite compositions obtained from drillhole samples in geothermal areas. Several authors have used this geothermometer, some have modified it (*e.g.*, Hillier and Velde, 1991) and recently de Caritat *et al.* (1993) have compared it with other chlorite geothermometers. The last noted that the bulk mineral composition and Fe/Fe+Mg ratio of the chlorite also exerted control over Al^{IV} contents in chlorites. These limitations have been kept in mind in determining the temperatures of formation of the rocks of the NB from the anchizone and epizone. Representative analyses of chlorites and mixed-layer clays (chlorite-smectite and chlorite-vermiculite) which have been used for the geothermometry are shown in table 2. Calculation of the Mg numbers (Table 3) for chlorite in the interlayered phyllosilicates and chlorite, indicates little variability between specimens. Further, the mineral assemblages in the samples are similar, apart from the presence of chlorite in the higher grade samples and chlorite-smectite in place of chlorite-vermiculite in the lower grade samples. In view of this, some confidence can be placed in the temperatures obtained from Al^{IV} contents of the chlorites and chlorite interlayered with smectite or vermiculite (Table 3).

Table 3 lists the temperatures determined from chlorites and chlorites in interlayered phyllosilicates, using the regressive equation of Hillier and Velde (1991). The temperatures range from 216°-231°C in the anchizone and 244-349°C in the epizone with the majority of the latter exceeding 280°C. It is important to note that temperatures determined from Al^{IV} contents in chlorite interlayered with vermiculite tend to be lower than those obtained from chlorites (Table 3). This suggests that the mixed-layer clays have not reequilibrated chemically to the same degree as chlorite with rising temperature. Therefore, the temperatures obtained from the mixed layer clays must be treated with caution.

The temperature obtained for the epizone are in accord with those determined by Leitch (1976) and Liu *et al.* (1993). The latter authors estimated temperatures of 290-300°C for regional metamorphic assemblages formed during the first deformation (D_1), from the composition of epidote and chlorite in the buffered assemblage epidote-pumpellyite-chlorite-actinolite-quartz.

TABLE 2. REPRESENTATIVE ANALYSES OF CHLORITES (C) AND MIXED LAYER CLAYS (ML).

	NB57 (ML)		NB153 (ML)		NB158 (ML)		NB307 (ML)		NB238 (C)		NB45 (ML)		NB45 (C)		NB137 (ML)		NB137 (C)	
	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ
SiO_2	33.10	2.72	33.26	1.91	31.38	1.31	28.79	0.91	27.70	0.72	29.06	3.49	24.66	0.16	28.70	1.68	24.99	0.14
TiO_2	0.04	0.07	0.19	0.11	0.00	0.00	0.08	0.08	0.03	0.07	0.03	0.07	0.07	0.09	0.00	0.00	0.06	0.08
Al_2O_3	18.07	2.21	19.86	1.22	18.79	1.03	20.42	0.62	20.45	0.21	20.78	1.63	21.23	0.88	17.91	0.67	18.48	0.09
FeO	23.29	0.76	23.72	2.06	23.76	0.94	27.03	0.99	23.88	1.04	23.08	2.56	28.98	0.18	27.53	3.13	33.32	0.88
MnO	0.29	0.07	0.20	0.05	0.39	0.06	0.28	0.07	0.28	0.04	0.14	0.07	0.35	0.04	0.68	0.12	0.86	0.09
MgO	6.96	0.94	8.84	1.61	10.00	0.40	9.21	0.75	14.07	0.55	9.20	0.70	11.45	0.08	11.05	1.08	9.27	0.16
CaO	0.71	0.09	0.47	0.09	0.65	0.22	0.26	0.09	0.02	0.05	0.13	0.09	0.00	0.00	0.43	0.27	0.00	0.00
K_2O	0.41	0.23	0.73	0.36	1.13	0.94	0.95	0.21	0.03	0.06	1.39	1.02	0.04	0.06	0.55	0.12	0.00	0.00
Total	**82.86**	**5.24**	**87.26**	**0.72**	**86.10**	**1.92**	**87.02**	**1.38**	**86.45**	**0.58**	**83.81**	**4.19**	**86.77**	**0.62**	**86.85**	**1.27**	**86.97**	**1.15**
Formula on the basis of 28 (O)																		
Si	7.16	0.19	6.84	0.26	6.63	0.20	6.14	0.16	5.84	0.14	6.29	0.44	5.37	0.09	6.18	0.29	5.60	0.08
Ti	0.01	0.01	0.03	0.02	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01
Al^{IV}	0.84	0.19	1.16	0.26	1.37	0.20	1.86	0.16	2.16	0.14	1.71	0.44	2.63	0.09	1.82	0.29	2.41	0.08
Al^{VI}	3.76	0.24	3.66	0.17	3.31	0.15	3.28	0.10	2.92	0.17	3.60	0.42	2.82	0.10	2.73	0.11	2.47	0.09
Fe	4.24	0.40	4.09	0.43	4.20	0.19	4.83	0.22	4.21	0.19	4.21	0.64	5.28	0.01	4.97	0.63	6.24	0.11
Mn	0.05	0.02	0.04	0.01	0.07	0.01	0.05	0.01	0.05	0.01	0.03	0.01	0.07	0.01	0.12	0.03	0.16	0.01
Mg	2.24	0.17	2.71	0.45	3.15	0.12	2.92	0.19	4.42	0.18	2.98	0.33	3.72	0.06	3.54	0.30	3.09	0.03
Ca	0.17	0.03	0.10	0.02	0.15	0.05	0.06	0.02	0.00	0.00	0.03	0.02	0.00	0.00	0.10	0.06	0.00	0.00
K	0.11	0.06	0.19	0.09	0.30	0.26	0.26	0.06	0.01	0.02	0.37	0.25	0.01	0.01	0.15	0.03	0.00	0.00
Total	**18.59**	**0.16**	**18.82**	**0.09**	**19.18**	**0.23**	**19.41**	**0.10**	**19.62**	**0.16**	**19.24**	**0.31**	**19.90**	**0.00**	**19.62**	**0.19**	**19.96**	**0.07**
n	10		5		10		11		5		6		2		7		2	

Mixed layer clays are chlorite-smectite (NB 57); chlorite-vermiculite (NB 137, 153, 158, 307) according to XRD analyses.

TABLE 3. TEMPERATURES BASED ON Al^{IV} CONTENTS OF CHLORITE.

Spec. No.	x	Mg.No	Al^{IV}(ML) (av)	T°C	n	x	Al^{IV}(C) (av)	T°C	Mg.No	n	Assemblage
NB 57	19	35	2.09	196	11						I+C/S+I/S
NB 143	23	38	2.20	224	9						I+C/S
NB 153	27	40	2.23	231	5						I+C/V
NB 158	36	43	2.28	244	10						I+C/V
NB 246	45	40	2.54	309	7						I+C/V
NB 305	42	33	2.44	284	5						I+CV
NB 307	52	38	2.49	296	11						I+C/V
NB 117	57	40	2.60	324	9						I+CV
NB 238	78	51	2.43	281	5						I+C
NB 45	42	42	2.51	301	6	94 (91)	2.70	349	41	2	I+C
NB 375	64	35	2.62	328	4	98 (96)	2.68	329	35	3	I+C+C/V
NB 137	66	42	2.27	241	5	98 (95)	2.44	284	33	2	I+C+C/V

ML= Mixed layer clay; C= Chlorite; C/V=Chlorite/Vermiculite; I= Illite; I/S= Illite/Smectite; C/S= Chlorite/Smectite; n= number of analyses; x= % chlorite. Al^{IV} (ML) represents tetrahedral Al in chlorite interlayered with vermiculite or smectite; based on the method of Bettison-Varga *et al.* (1991) and assuming Z>Y. The small amount of white mica which appears to be intimately associated with the mixed layer clays (see K_2O contents, Table 1), has not been taken into consideration in these calculations.

CONCLUSIONS

Studies of the crystallinity of K-white micas indicate that rocks of anchizonal grade occur at the southern and northern margins of the NB and epizonal grade in the centre. This accords with the observations of Leitch (1976), although higher grade rocks are more widely distributed than he reported.

Chlorite crystallinity values show a similar pattern. However, broadening of the (001) and (002) peaks of chlorite by overlapping chlorite-vermiculite peaks occurs in some samples. The usefulness of this parameter is limited unless deconvolution programs are applied to samples in which this problem arises.

Intermediate P facies series metamorphism is suggested by the b_o cell parameters (b_o=9.023; sd=0.200) of the K-white micas, in agreement with the interpretation of Leitch (1976), based on calc-silicate assemblages. The unusually wide range in b_o values obtained from white micas in these rocks, is attributed to major variations in bulk chemistry which is the result of contributions from source areas dominated by felsic igneous rocks and quartz-rich sediments.

Al^{IV} contents in chlorite and chlorite in chlorite-vermiculite and chlorite-smectite show that temperatures ranged from 216-231°C in the anchizonal rocks and 244-349°C in the epizonal rocks.

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