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A survey of white mica crystallinity and polytypes in pelitic rocks of Snowdonia and Llŷn, North Wales

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ABSTRACT. Pelitic rocks in North Wales, ranging in age from late Precambrian to Silurian were sampled. XRD analysis was used to determine the mineralogy and white mica crystallinity of separated < 2 μm fractions. Results show that three stages of metapelite recrystallization can be distinguished. Stage I metapelites are uncleaved or feebly cleaved with crystallinities $> 0.43\Delta°2\theta$; the $1M_d$ polytype dominates < 2 μm fractions, occurring as K- and Na-micas. Stage II metapelites show variable cleavage development and crystallinities in the range 0.26–0.43$\Delta°2\theta$; $1M_d$ and $2M_1$ polytypes occur and K- and Na-micas are commonly regularly interstratified. Stage III metapelites are strongly cleaved with crystallinities $< 0.26\Delta°2\theta$; the $2M_1$ polytype is dominant, occurring as K-mica and paragonite. Pelites bearing pyrophyllite, rectorite, and corrensite are found close to plug-like intrusions and were contact altered prior to regional metamorphism. $1M$ mica is common in deeply buried but relatively undeformed volcaniclastic rocks of the Arfon Group.

Contours of equal crystallinity (isocrysts) are plotted with metabasite zones on a metamorphic map. This shows that stage I metapelites are equivalent to the sub-pumpellyite zone ($\equiv$?laumontite zone). Stage II metapelites are equivalent to the prehnite–pumpellyite facies and stage III metapelites to the clinozoisite and biotite zones of the greenschist facies.

KEYWORDS: pelitic rocks, mica, crystallinity, Snowdonia, Llŷn, Wales.

RECENT work by Roberts (1981) on assemblages in Ordovician metabasic extrusive and intrusive rocks of Snowdonia and Llŷn indicated a range in metamorphic grades from the lowest in which prehnite occurred in the absence of pumpellyite, through rocks in which pumpellyite entered, then clinozoisite and, at the highest grades, biotite (fig. 1). The range was shown to span the prehnite–pumpellyite facies into the lowermost greenschist facies. Broadly, highest grade rocks appeared to be confined to central Snowdonia and grade was shown to fall northeast towards Conwy and southwest towards Pwllheli.

The distribution of metabasites across the area is by no means ideally suited to the delineation of metamorphic grade. Although widely distributed in the Ordovician of Snowdonia, basic rocks are less widespread in Llŷn and in Arfon, where they occur mainly as sporadic dykes in Cambrian and 'Precambrian' strata, and are absent altogether from the Silurian outcrops. Pelitic rocks, on the other hand, are widely distributed throughout the entire area and range in age from late Precambrian to Silurian. The principal hindrances to a comprehensive cover are thus reduced to areas of thick drift covering parts of Llŷn and Arfon; and to areas occupied by Caradocian acid volcanic rocks in western and central Snowdonia. Hence a study of white mica crystallinity was undertaken to amplify the earlier work with the additional aim of providing a much needed link (Kisch, 1983), between metabasite and metapelite grades.

A summary of the geology of Snowdonia and Llŷn was given by Roberts (1979) so that only an outline incorporating modifications made necessary by BGS mapping of the Bangor Sheet (British Geological Survey, 1985) is given here.

The succession sampled is summarized in Table I. Late Precambrian and possibly Lower Cambrian (Comley Series) rocks of the Mona Complex are exposed in the southwest in Llŷn where the rocks are mostly in the form of a mélange: the Gwna Group consists mostly of basic tuffs and pillow lavas but includes blocks of quartzite, dolomite,

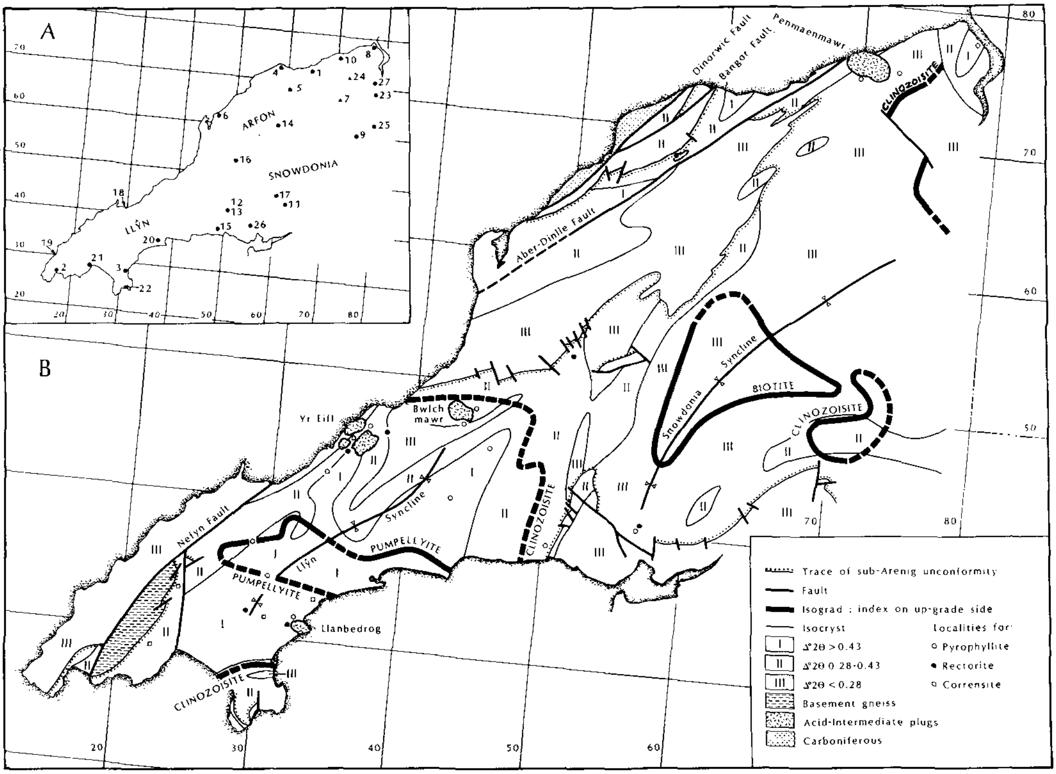

FIG. 1. (A) Inset map showing localities mentioned in the text. 1. Aber; 2. Aberdaron; 3. Abersoch; 4. Bangor; 5. Bethesda; 6. Caernarfon; 7. Carneddau; 8. Conwy; 9. Crafnant; 10. Craig-lwyd; 11. Croesor; 12. Cwm Pennant; 13. Dolbenmaen; 14. Llanberis; 15. Llanystumdwy; 16. Nantlle; 17. Nantmor; 18. Penrhyn Nefyn; 19. Porth Oer; 20. Pwllheli; 21. Rhiw; 22. St Tudwal's; 23. Tal-y-bont; 24. Tal-y-fan; 25. Trefriw; 26. Tremadog; 27. Tyn-y-groes. (B) Metamorphic map showing metabasite isograds, metapelite stages, and geological features mentioned in the text.

greywacke, and pelite; the younger Gwyddel Felsitic Beds are mostly fine grained, well bedded, acid tuffs. An area of garnetiferous acid and basic gneiss (fig. 1) probably represents an older basement (Matley, 1928).

Rocks of Eocambrian-Lower-Cambrian (Comley Series) age crop out in Arfon where they constitute the 4 km thick Arfon Group (Reedman *et al.*, 1984). The Padarn Tuff Formation at the base consists of acid ash-flow tuffs. The overlying Minffordd Formation crops out between the Dinorwic and Aber-Dinlle faults and consists of conglomerates, sandstones, siltstones, thin pelites, and a few thin tuffs. Similar lithologies are found in the succeeding Bangor Formation. East of the Aber-Dinlle fault the Fachwen Formation occupies a similar stratigraphical position to the Minffordd and Bangor Formations and is similar lithologically. Much of the detritus in all three formations is volcaniclastic.

Wood (1969) showed that the Arfon Group passes upward through Lower to Middle Cambrian (Comley-St David's Series) greywackes, siltstones, and slates of the Llanberis Slate Formation and thence into the turbidite sandstones and thin pelites of the Bronllwyd Grit; the succeeding pelites, greywackes, and quartzites of the Marchlyn Formation are Upper Cambrian (Merioneth Series) in age. Cambrian rocks also crop out in St Tudwal's peninsula where representatives of the Comley, St David's, and Merioneth Series are present and include greywackes, shales, and mudstones. Tremadoc Series slates and siltstones crop out near Porthmadog and along the Vale of Ffestiniog.

The Ordovician succession begins with sandstones of the Arenig Series which overstep all members of the Cambrian and late Precambrian succession to rest with strong unconformity on the Precambrian amphibolite facies gneisses. Graptolitic pelites of the Arenig and Llanvirn Series succeed the sandstones which, together, constitute

Table I. Generalised geological succession in Snowdonia and Llŷn

Formation/Group	Series	System
Pale Slates	Llandovery	Silurian
Bron y graig Formation		
Conwy Mudstone	Ashgill	
Cadnant Shales		
Dolgarrog Volcanic Formation		
Snowdon Volcanic Group (≡ Crafnant Volcanic Group)	Caradoc	Ordovician
Cwm Eigiau Formation		
Llewelyn Volcanic Group		
Nant Ffrancon Formation	Arenig-Llanvirn	
------------- Unconformity		
Tremadoc Slates	Tremadoc	
Marchlyn Formation	Merioneth	
Bronllwyd Grit	St David's	
Llanberis Slate Formation		
Bangor Formation (≡Fachwen Fm.)	Comley	Cambrian
Minffordd Formation (≡Fachwen Fm.)		
------------- Unconformity		
Padarn Tuff Formation		
------?------?------		
Gwyddel Felsitic Beds		
Gwna Group		
------------- Unconformity		
Acid and basic gneiss		Late Precambrian

the Nant Ffrancon Formation in northern Snowdonia. Sediments of Llandeilo age have not been proved in the area. The Caradoc Series is dominated by acid, intermediate, and basic volcanic rocks but also includes thick developments of sandstones, siltstones, and pelites most of which are largely volcaniclastic. Ashgill Series sediments are mainly marine mudstones which pass upward into turbidite sandstones. Deposition of turbidite sands continued into the Silurian and intensified to give the greywacke-pelite sequence of the Llandovery Series.

In Llŷn a suite of basic sills are emplaced within the Arenig and Llanvirn Series, but in Snowdonia the sills lie within Caradoc Series beds. Basic dykes cut rocks ranging from Comley Series to Caradoc Series. Sills and dykes are folded and cleaved and the consensus is that most are related to the Caradocian magmatism. Several small plug-like bodies, intermediate to acid in composition, cut strata ranging up to Caradocian in age; the largest is about 4 km wide. They were emplaced before the main deformation and are believed to be related to the Caradocian volcanism (Roberts, 1979; Croudace, 1982).

The distribution of the major rock groups has been controlled by two major downfolds (the Snowdonia and Llŷn synclines) and by a series of major strike faults, the most important of which are the Bangor and Dinorwic faults, the Aber-Dinlle fault, and the Nefyn fault. Folding occurred probably during the Middle Devonian but may have been as early as end-Silurian. An axial-planar cleavage, often slaty, associated with the folds is presented in many pelitic and pyroclastic rocks.

Sampling and analytical methods

Samples were spaced about 1.5 km apart where the geology suggested gradual change could be reasonably expected, but very much closer adjacent to the traces of certain faults, unconformities, and across belts of known high strain (Coward and Siddans, 1979). The sampling interval was also close in the better exposed contact aureoles of some acid and intermediate intrusions. In total 314 pelite samples were collected and analysed by XRD techniques, supplemented by electron microprobe and XRF analyses and thin section petrography.

Pelite samples were disaggregated in the laboratory initially by hand-grinding in an agate pestle and mortar to pass a 72-mesh sieve; frequent sieving was employed to minimize overgrinding. The resulting powders were further disaggregated in an ultrasonic bath prior to separation of the < 2 μm (e.s.d.) fraction by gravity settling. It was rarely necessary to use a dispersant, but records were kept of the few samples where 1–2 ml of Calgon were added. Suspensions of the < 2 μm fraction were centrifugally compacted, without the addition of flocculating agents, and the resulting clay pellets smeared on to two glass slips (1 × 1.5 mm) and allowed to air-dry overnight at 20–25 °C. These were analysed on a Philips diffractometer (PW1130) using Ni-filtered Cu-$K\alpha$ radiation 40 kV, 30 mA, scanning the range 2–35°2θ at 0.5°2θ/min. Over 90% of the diffraction peaks diagnostic of the white mica polytypes (Bailey, 1980, p. 58), are within the 2θ range scanned.

Mica crystallinity determinations on the < 2 μm fractions measured the half-height width of the 10 Å peak, the technique introduced by Kubler (1967). In this study crystallinity is regarded as the fundamental thickness of mica crystallites consisting of a stack of N 10 Å unit cells. The relationship between N and peak width at half height, B (measured in radians 2θ), is given by the Scherrer equation:

$$B = K\lambda/Nd\cos\theta$$

where K is a constant (0.91), λ is the radiation wavelength, and d is the unit cell spacing, i.e. 10 Å (Brindley, 1980). XRD peaks tend to be sharp and intense for values of $N > 20$, and appreciably broadened when $N < 15$; Bragg reflection is not possible when $N = 1$. In deriving N from the 10 Å peak width there are two potential sources of error (apart from instrumental effects, dealt with below). The work of Nadeau *et al.* (1984, 1985) indicates that an interparticulate diffraction effect from sedimented aggregates (< 0.1 μm) of oriented particles can give rise to XRD *peak-width crystallite thicknesses* which are considerably larger than crystallite thicknesses recorded by TEM. However, given the recrystallized nature of the samples and the coarser size fraction used for this study, interparticulate diffraction effects are probably unimportant. Of much greater importance are potential errors arising from peak broadening caused by overlapping peaks or interstratification and for this reason mica crystallinity is quoted here as the half height width of the 10 Å peak. Future work clearly requires an integrated TEM and XRD investigation of mica crystallinity.

Early crystallinity measurements by Kubler (1967, 1968), and others, were highly dependent on machine operating conditions and were not reproducible without standards. Kisch (1980) partially overcame this problem by measuring peak widths in degrees 2θ, rather than millimetres, and recommended standard machine conditions which were used in this study. These are: Ni-filtered Cu-$K\alpha$ radiation, 40 kV; 30 mA. Slits: $\frac{1}{2}$° divergence, 1° scatter, 0.1 mm receiving. Chart speed, 1°2θ = 40 mm on paper. Scan speed 0.5°2θ/minute. Ratemeter 1×10^3 cps (rarely 4×10^2), at time constant 4. Untreated < 2 μm smears were scanned forward and reverse in the range 7.5–10°2θ, and the widths of the 10 Å peak at half height measured to the nearest 0.1 mm, averaged and converted to degrees 2θ. Each group of twenty-five samples analysed using a Philips (PW1170) cassette-type automatic sample changer was accompanied by two standards positioned at the start and finish of a continuous run. These monitored changes in machine conditions and indicated maximum errors of $\pm 0.02\Delta°2\theta$ for machine variation between different runs.

Several < 2 μm smears were analysed on the electron microprobe using a Link energy dispersive X-ray analyser. Prior to analysis the < 2 μm smears were heated to 550 °C for 1 h and subsequently coated with carbon. Analysis

Table II. Electron microprobe analyses of <2μm fractions

Wt%	BRM 295	BRM 257	BRM 297	BRM 68	BRM 201	BRM 260	BRM 267	BRM 282	BRM 168	BRM 169	BRM 202	BRM 97	BRM 198	BRM 104	BRM 9	BRM 11
SiO_2	51.84	52.92	48.12	46.05	50.68	46.37	48.41	46.90	46.74	46.48	44.51	46.14	47.78	51.69	49.67	49.39
Al_2O_3	26.52	27.44	29.78	34.27	29.57	30.91	29.26	29.52	30.80	33.61	28.77	30.84	32.06	28.29	31.82	31.34
TiO_2	0.85	0.92	0.24	0.31	0.83	1.48	1.25	0.94	1.79	1.62	0.62	0.62	0.90	0.54	0.47	0.38
FeO^t	2.73	4.37	1.78	6.15	5.85	6.92	7.39	9.25	6.16	4.05	8.35	8.70	7.16	1.98	2.30	2.38
MgO	1.70	2.42	0.62	1.17	1.36	1.31	1.27	1.98	1.12	0.96	1.92	1.22	1.57	0.92	0.88	1.09
MnO	0.07	0.13	0.00	0.54	0.13	0.52	0.19	0.09	0.06	0.33	0.03	0.16	0.25	0.01	0.23	0.01
CaO	0.13	0.23	0.33	1.05	0.21	0.20	0.05	0.20	0.16	0.37	2.65	0.16	0.18	0.01	0.22	0.74
Na_2O	0.85	2.84	1.09	1.73	2.72	1.96	1.52	2.59	1.74	2.22	1.06	3.04	1.36	0.19	1.15	0.54
K_2O	8.53	4.36	8.34	4.04	3.21	5.06	3.61	3.82	4.88	5.31	3.65	2.95	4.16	9.76	8.46	8.67
S	0.53	0.13	0.24	0.13	0.40	0.35	0.30	0.22	0.30	0.15	3.55	0.42	0.15	0.06	0.40	0.63
Total	93.74	95.75	90.53	95.43	94.97	95.10	93.24	95.51	93.75	95.10	95.12	94.24	95.57	93.45	95.61	95.66
Na/(Na+K)	0.13	0.50	0.17	0.40	0.56	0.37	0.39	0.48	0.35	0.39	0.31	0.60	0.34	0.03	0.17	0.09
MCΔ°2θCuKα	0.27°	0.20°	0.33°	0.33°	0.54°	0.30°	0.40°	0.62°	0.36°	0.37°	0.58°	0.83°	0.73°	0.14°	0.24°	0.71°

BRM 295: Pelitic matrix from mélange, Gwna Group; Llanbadrig, Anglesey [SH 376 947]
BRM 257: Blue slate, Llanberis Slate Formation; Marchlyn Qy. [SH 603 628]
BRM 297: Mudstone, Arenig Series; Llanbadrig, Anglesey [SH 376 947]
BRM 68: Rectorite-bearing mudstone, Arenig Series; in 'aureole' of Yr Eifl intrusion [SH 351 440]
BRM 201: Mudstone, Arenig Series; Caernarfon [SH 481 617]
BRM 260: Pencilled slate, Llanvirn Series; Trefor, Llŷn [SH 363 470]
BRM 267: Pyrophyllite-bearing mudstone, Llanvirn Series; in 'aureole' of Bwlch Mawr intrusion [SH 437 477]
BRM 282: Mudstone, Llanvirn Series; Botwnnog, Llŷn [SH 263 317]
BRM 168: Blue-grey slate, Llanvirn Series; Cwm Pennant [SH 530 459]
BRM 169: Blue-grey slate, Llanvirn Series; Cwm Pennant [SH 534 485]
BRM 202: Mudstone, Llanvirn Series; Caernarfon [SH 489 613]
BRM 97: Siltstone, Llanvirn Series; Garn Fadrun, Llŷn [SH 286 351]
BRM 198: Rectorite-bearing mudstone, Llanvirn Series; Nanhoron, Llŷn [SH 286 317]
BRM 104: Pelitic sandstone, Caradoc (Crafnant Volcanic Formation); Tal y bont [SH 754 663]
BRM 9: Cleaved silty mudstone, Caradoc Series; Conwy [SH 749 770]
BRM 11: Mudstone, Caradoc Series; Conwy [SH 781 782]

Table III. Whole-rock analyses of pelites from Snowdonia and Llŷn

Wt%	BRM 46	BRM 398	BRM 257	BRM 49	BRM 147	BRM 68	BRM 267	BRM 168	BRM 202	BRM 198	BRM 34	BRM 9	BRM 98
SiO_2	72.70	61.04	62.60	57.33	54.71	54.15	55.06	54.40	52.08	49.94	60.61	65.28	57.22
Al_2O_3	11.88	17.24	18.29	21.00	23.32	25.10	25.84	24.31	24.90	25.76	18.26	20.24	21.02
TiO_2	0.57	0.69	0.86	0.80	1.07	0.99	1.05	1.24	1.07	1.07	0.74	0.94	0.96
Fe_2O_3	4.39	7.92	7.38	9.07	9.13	6.16	6.02	8.20	9.36	10.21	8.25	2.35	8.65
MgO	1.85	2.79	2.23	2.24	2.19	1.17	1.13	1.13	2.01	1.86	1.68	0.48	1.47
CaO	0.11	0.35	0.24	0.54	0.46	0.58	0.04	0.06	0.34	0.10	0.45	0.06	0.09
Na_2O	1.05	2.99	2.53	1.31	1.32	1.31	0.95	1.03	0.75	0.86	1.02	0.32	0.64
K_2O	2.78	3.38	2.73	3.86	3.44	3.68	3.16	3.70	3.22	3.30	4.44	6.00	4.27
MnO	0.02	0.12	0.12	0.14	0.06	0.27	0.20	0.35	0.14	0.29	0.48	0.10	0.12
P_2O_5	0.05	0.12	0.09	0.06	0.10	0.09	0.07	0.11	0.13	0.12	0.16	0.12	0.08
LOI	2.69	3.39	3.24	3.87	4.50	4.76	6.23	5.59	6.51	6.46	4.07	4.19	5.98
Total	98.08	100.03	100.33	100.22	100.32	98.26	99.74	100.12	100.52	99.99	100.17	100.09	100.49

BRM 46: Purple pelite (MC=0.26$\Delta°2\theta$), Gwna Group; Aberdaron, Llŷn [SH 145 248]
BRM 398: Purple volcaniclastic semi-pelite (MC=0.30$\Delta°2\theta$), Bangor Formation; Bangor [SH 584 721]
BRM 257: Blue slate (MC=0.20$\Delta°2\theta$), Llanberis Slate Formation; Marchlyn Qy. [SH 603 628]
BRM 49: Purple slate (MC=0.24$\Delta°2\theta$), Llanberis Slate Formation; Llanberis [SH 575 607]
BRM 147: Grey cleaved pelite (MC=0.22$\Delta°2\theta$), Tremadoc Slates; Tan-y-bwlch [SH 650 416]
BRM 68: Mudstone (MC=0.33$\Delta°2\theta$), Arenig Series; in 'aureole' of Yr Eifl intrusion [SH 351 440]
BRM 267: Mudstone (MC=0.40$\Delta°2\theta$), Llanvirn Series; in 'aureole' of Bwlch Mawr intrusion [SH 438 474]
BRM 168: Blue-grey slate (MC=0.36$\Delta°2\theta$), Llanvirn Series; Cwm Pennant [SH 530 459]
BRM 202: Mudstone (MC=0.58$\Delta°2\theta$), Llanvirn Series; Caernarfon [SH 489 613]
BRM 198: Mudstone (MC=0.73$\Delta°2\theta$), Llanvirn Series; Nanhoron, Llŷn [SH 286 317]
BRM 34: Grey cleaved pelite (MC=0.22$\Delta°2\theta$), Caradoc Series; Llyn Ogwen [SH 673 605]
BRM 9: Cleaved silty mudstone (MC=0.24$\Delta°2\theta$), Caradoc Series; Conwy [SH 749 770]
BRM 98: Mudstone (MC=0.50$\Delta°2\theta$), Caradoc Series; Nefyn, Llŷn [SH 290 397]

employed a beam defocused to approximately 200 μm in diameter and the mean composition from at least three analysis points on each sample was taken (Table II). XRF whole rock analyses were made on thirteen pelites for ten major elements (Table III).

Mineralogy of < 2 μm fractions

Late Precambrian–Cambrian. Eighty-four pelites were analysed, including eighteen samples from the Gwna Group of the Mona Complex of Llŷn (figs. 2 and 8). Gwna schists and phyllites from the area west of Aberdaron give crystallinity values in the range 0.21–0.28$\Delta°2\theta$ and are rich in dioctahedral $2M_1$ K-mica and chlorite. Minor amounts of albite and rutile are also present in the separations, and hematite is detectable in purple-coloured pelites. Gwna pelites from coastal or near-coast exposures between Porth Oer and Penrhyn Nefyn, show lower values (and therefore higher crystallinities) 0.19–0.22$\Delta°2\theta$, and are generally more chloritic; indeed, some basic schists contain no mica but show traces of amphibole in the separations.

Most of the twenty samples from the Arfon Group contained a $1M$ K-mica identified by non-basal peaks at 4.35, 3.66, 3.07, and 2.93 Å. $1M$ mica is the dominant polytype in many samples although it is commonly accompanied by $2M_1$ mica. The range of values obtained from the Arfon samples, 0.17–0.36$\Delta°2\theta$, is in fact the product of two groups of values related to the formations within the Arfon Group. Samples from the Padarn Tuff Formation, are mostly in the range 0.17–0.29$\Delta°2\theta$, possess $2M_1 \geqslant 1M$ white mica populations and commonly contain significant amounts of albite and, less commonly, traces of anatase in the < 2 μm fractions. Two samples from the Fachwen Formation show similar mineralogical characteristics, but higher values. The latter fall in the range 0.24–0.36$\Delta°2\theta$, that characterizes the Minfordd and Bangor Formations. Samples from these strata commonly possess $1M \geqslant 2M_1$ white mica populations, minor albite, and, in two cases, little or no chlorite.

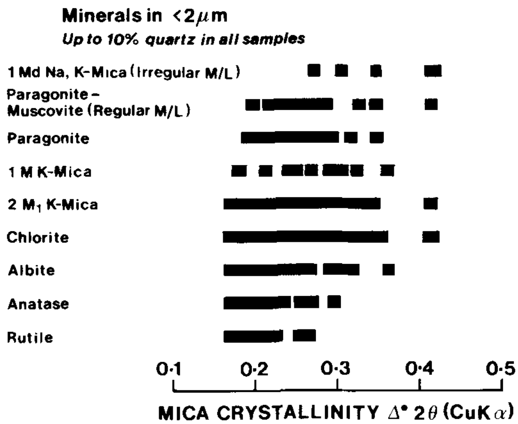

FIG. 2. Mica crystallinity and < 2 μm mineralogy of eighty-four pelites from the Cambrian of Snowdonia and Llŷn.

The < 2 μm mineralogy of the succeeding Llanberis Slate Formation is distinctly different from that of the Arfon Group. $1M$ K-mica is absent and instead $2M_1$ paragonite occurs extensively together with $2M_1$ muscovite in white mica populations. Chlorite is more abundant, though invariably subordinate to K-mica; minor amounts of anatase (±rutile) are commonly present and, rarely, hematite occurs in purple slates. Paragonite may be sufficiently abundant to give a sharp 9.6 Å peak on the shoulder of the more intense K-mica 10.0 Å peak. Other basal reflections at 4.82 Å and 3.21 Å, are more readily resolved from K-mica reflections, and are therefore useful indicators of small amounts of paragonite. Well-resolved 9.6 Å peaks are easily excluded from 10.0 Å peak width measurements, resulting in a relatively narrow range of crystallinity values (0.18–0.29$\Delta°2\theta$) for this formation. About 60 % of the samples analysed contain paragonite, most of these being typical roofing slates from the Bethesda, Llanberis, and Nantlle areas. One of the more paragonitic < 2 μm separations, BRM 257 was analysed in the electron microprobe and the results are shown in Table II. Total alkalis indicate that approximately 70 % is white mica of which nearly half is paragonitic (allowing for 2–3 % albite in the separation). XRD shows that quartz forms 10 % whilst probe analysis indicates anatase forms 1 % thus leaving chlorite forming up to 17 %. Paragonite was not detected in several slate samples, nor in pelitic material from the Glog Grit and other psammites from the base of the Llanberis Slate Formation. Albite is significantly more plentiful in slate samples containing no paragonite.

Samples from the Middle Cambrian mudstones of St Tudwal's give the largest values of any Cambrian pelites, viz. 0.30–0.41$\Delta°2\theta$. In the Manganese Beds $2M_1$ K-mica is dominant, giving the lower values, whereas $1M_d$ mica is abundant in the conchoidally fracturing Caered Mudstones; chlorite and minor paragonite and albite are also present in both formations. Pelites from both the Maentwrog and Ffestiniog Beds (Merioneth Series) show a very limited range of values (0.17–0.24$\Delta°2\theta$). Tremadocian pelites have a much larger range of crystallinity values, 0.18–0.35$\Delta°2\theta$, due mainly to the occurrence of paragonite regularly interstratified with muscovite. This mineral, first described by Frey (1969) from the Glarus Alps, is not previously recorded from British rocks. Detection of typically subordinate amounts of the paragonite/muscovite mineral in many Tremadocian pelites is difficult. Fig. 3 illustrates a diffractometer trace of one of the more paragonitic Tremadoc samples. A diagnostic peak at 3.26 Å is usually resolved from the adjacent paragonite (006) and muscovite (006) peaks, but other diagnostic peaks at 4.88 Å and at 1.96 Å (not illustrated) are easily lost by rapid scanning or reduced concentrations of the mineral. The position of (00*l*) peaks at 1.96 and 3.26 Å indicate a paragonite : muscovite ratio of about 6 : 4 for the mixed-layer mineral in fig. 3, similar to the ratio reported by Frey (1969). This ratio is fairly typical of Cambrian pelites and appears to result in a regular interlayered mineral. Mixed-layer and discrete paragonite occur in eight of the ten Tremadocian pelites analysed, in amounts invariably subordinate to $2M_1$ K-mica; chlorite with minor albite and anatase are also present.

Ordovician. The < 2 μm mineralogy and white mica crystallinity values of 109 pelites from the Arenig and Llanvirn Series are summarized in fig. 5. Pelites from both series of rocks are characterized by widespread and abundant paragonitic white mica populations with 62 % of Arenig pelites and 98 % of Llanvirn pelites containing Na-micas. The $1M_d$ mica polytype occurs widely with both regular and irregular interstratifications of K-mica, Na-mica, and smectite, and as a result the range of crystallinity values is considerably wider than that obtained from Cambrian pelites (fig. 8). The most feebly metamorphosed Arenig and Llanvirn pelites occur mainly in two areas; the strip between the Dinorwic and Aber-Dinlle faults, and in the area of Llŷn lying east of the Nefyn fault and west of Abersoch–Pwllheli. Typical pelites in these areas are mudstones or micaceous, silty shales with clay assemblages dominated by $1M_d$ micas, subordinate chlorite, $2M_1$ or $1M$ K-micas, and regular paragonite/muscovite mixed-layer mica. In the crystallinity range 0.50–0.73$\Delta°2\theta$ only the $1M_d$ mica polytype is detected, but it is characteristic both of regular 6 : 4 paragonite/muscovite and an irregular interstratification of Na-mica/K-mica and minor smectite. Identification of the irregular mixed-layer mica is based on XRD and electron microprobe data. On XRD traces it is characterized by pronounced low-angle broadening of the 10 Å peak, and high-angle broadening of 5 Å and 3.3 Å peaks (fig. 4). Glycerol saturation resulted in slightly less broadened 10 Å peaks in some samples, indicating that interlayered smectite forms possibly less than 15 % of the mica. Heating to 550 °C for 1 hr reduced the 10 Å peak width, but also, in many cases, increased the 3.3 Å peak width at the expense of both the 3.26 Å paragonite/muscovite peak and the 3.20 Å paragonite peak. The sodic nature of the mineral was revealed by electron microprobe analysis of separations containing only the broadened peaks of the irregularly interstratified mica (±chlorite and pyrophyllite, but no paragonite either discrete or in regular mixed layers). These are shown in Table II (BRM 97, 201, 202,

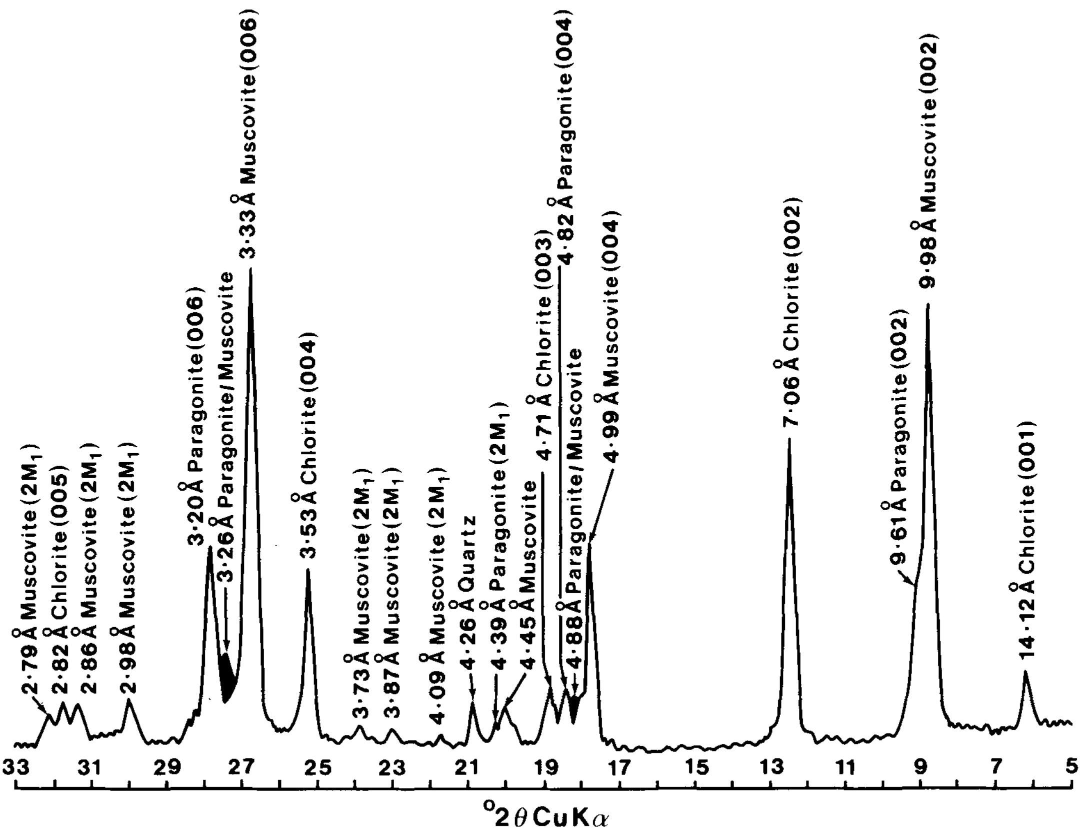

FIG. 3. XRD trace of the < 2 μm fraction of a stage III metapelite from the Tremadoc Series. Sample no BRM 147; NGR SH 650 416.

267, 282). All contain significant amounts of Na_2O, and Na/(K+Na) ratios range from 0.31–0.60. Ca is significant in only one Llanvirn pelite (BRM 202), indicating that the small amounts of expansible material in these samples is predominantly a sodium-smectite. The mineral is considered to be an irregularly interstratified Na-mica/K-mica with less than 15% Na,Ca-smectite interlayers.

The appearance of a poorly developed cleavage in Arenig and Llanvirn pelites is accompanied by changes in the white mica population. $2M_1$ K-mica ($\pm 1M$ K-mica) becomes dominant and $1M_d$ regular 6:4 paragonite/muscovite replaces irregular Na-mica/K-mica. Discrete paragonite appears in pelites with values less than 0.42Δ°2θ; minor albite, anatase, and rutile appear when values are below 0.36Δ°2θ. Arenig and Llanvirn pelites characterized by these mineral assemblages (plus chlorite) are widely distributed, from Aber and the Carneddau (in the Nant Ffrancon Formation), through western Snowdonia and northern Llŷn, to Aberdaron and St Tudwals. Slaty cleavage is very variably developed in these rocks: in Arenig mudstones it may be conspicuous when values are less than 0.35Δ°2θ; shaly and more paragonitic Llanvirn pelites show cleavage development when values are below 0.40Δ°2θ.

The occurrence of $1M$ K-mica is restricted to Arenig pelites cropping out in two areas. In the Ordovician outcrop lying between the Dinorwic and Aber-Dinlle faults $1M$ K-mica occurs in uncleaved and weakly cleaved Arenig mudstones. The $1M$ polytype also occurs in weakly cleaved Arenig mudstones outcropping west of the Nefyn fault, around Aberdaron.

In the most strongly cleaved Arenig and Llanvirn pelites $2M_1$ K-mica and $2M_1$ paragonite become the dominant white micas, whereas regular paragonite/muscovite is present in minor amounts or absent. As a result of what appear to be prograde unmixing of regular paragonite/muscovite into

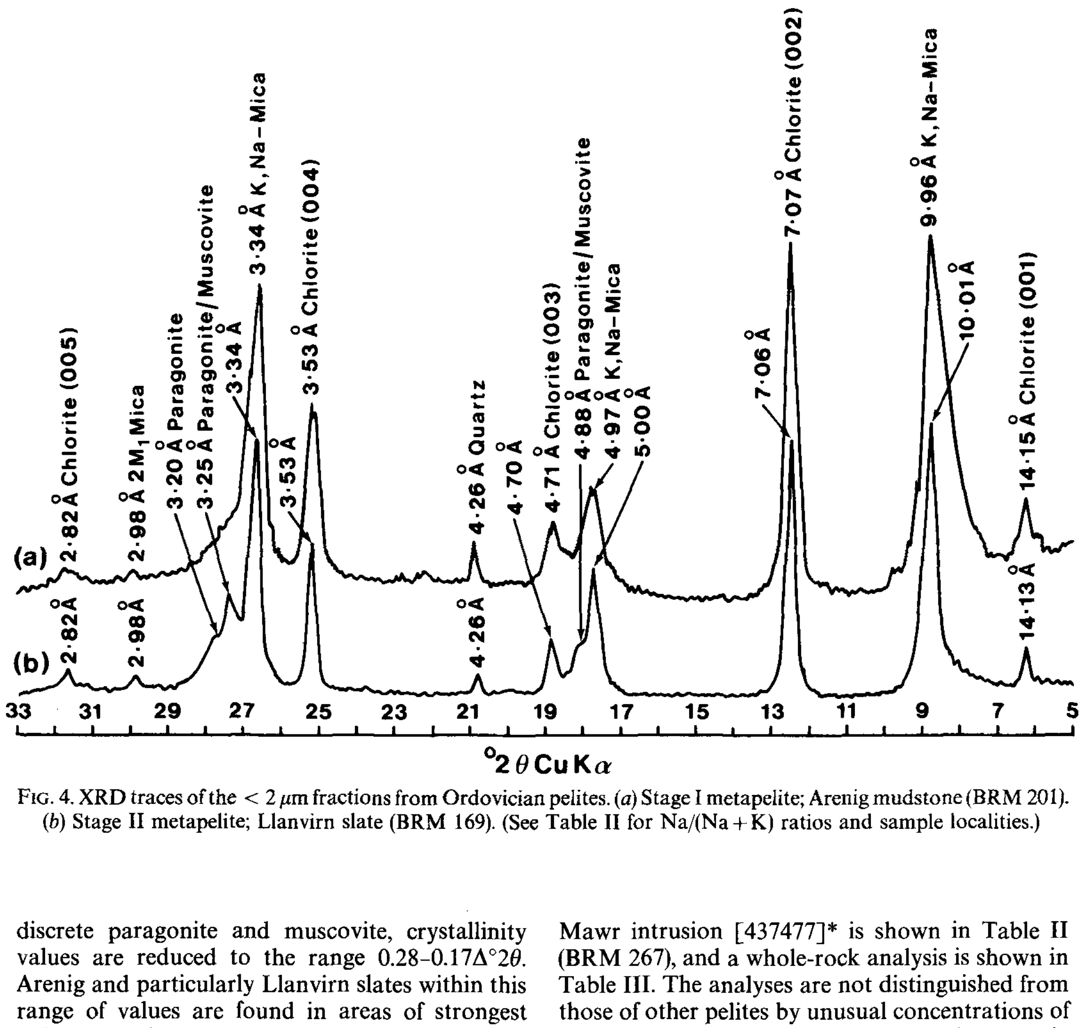

FIG. 4. XRD traces of the < 2 μm fractions from Ordovician pelites. (*a*) Stage I metapelite; Arenig mudstone (BRM 201). (*b*) Stage II metapelite; Llanvirn slate (BRM 169). (See Table II for Na/(Na+K) ratios and sample localities.)

discrete paragonite and muscovite, crystallinity values are reduced to the range 0.28–0.17Δ°2θ. Arenig and particularly Llanvirn slates within this range of values are found in areas of strongest deformation including Cwm Pennant, and parts of the Carneddau.

Some of the least deformed Arenig and Llanvirn pelites are closely associated with the numerous sub-volcanic intrusions of central and northern Llŷn. These indurated mudstones and shales lack conspicuous cleavage, and, in some areas are a distinctive khaki colour. Pyrophyllite is present in nine samples of Llanvirn pelite, most of them located close to outcrops of intrusions (fig. 1). The mineral is readily identified in < 2 μm fractions by basal reflections at 9.2, 4.46, and 3.07 Å. It occurs in pelites with values ranging from 0.38 to 0.74Δ°2θ and with clay assemblages commonly consisting of irregular Na-mica/K-mica and subordinate regular paragonite/muscovite and chlorite. Discrete paragonite and 2M_1 K-mica may also occur with pyrophyllite. An analysis of a pyrophyllite-bearing clay fraction from mudstones close to the Bwlch Mawr intrusion [437477]* is shown in Table II (BRM 267), and a whole-rock analysis is shown in Table III. The analyses are not distinguished from those of other pelites by unusual concentrations of major elements; the samples are not significantly silica- or alumina-rich, nor depleted in alkalis so that metasomatic alteration seems unlikely. The existence of pyrophyllite does suggest that kaolinite was initially present in the pelite and that temperatures of 200–300 °C were attained in order for the reaction; kaolinite + quartz → pyrophyllite + H_2O, to take place (Kisch, 1983, p. 362).

Rectorite is also present in several Arenig and Llanvirn pelites, similarly close to outcrops of intrusions (fig. 1). The mineral is a regularly interstratified Na-mica/Na,Ca-smectite characterized by a very low angle peak at 22–25 Å; glycerol saturation expands the peak to 27.5 Å and heating to 550 °C causes collapse to 9.8–10 Å. Rectorite-bearing pelites possess values in the range 0.32–

* All National Grid References are in the 100 km square SH.

$0.73\Delta°2\theta$, and clay assemblages dominated by irregular Na-mica/K-mica, but with subordinate regular paragonite/muscovite and chlorite. Microprobe analyses of two rectorite-bearing separations are shown in Table II. In the Arenig sample (BRM 68), the CaO content of 1.05% indicates that the expansible component of the rectorite is mainly a Ca-smectite, whereas in the Llanvirn sample (BRM 198), CaO is significantly lower (0.18%), indicating that, in this case, Na-smectite forms the interlayers in the rectorite.

Regularly interstratified chlorite/vermiculite and chlorite/smectite also occurs in Arenig and Llanvirn pelites closely associated with intrusions. For brevity these minerals are collectively referred to as corrensite in figs. 1 and 5. Pelites containing chlorite/vermiculite appear to be associated with the basic intrusions of the Rhiw area; chlorite/smectite occurs in pelites in the vicinity of the more acid Llanbedrog and Yr Eifl intrusions.

The $< 2\ \mu m$ mineralogy and white mica crystallinity values of 121 pelites from the Caradoc, Ashgill, and Llandovery Series are summarized in fig. 6. White mica populations in Caradoc pelites (103 samples) are consistently less paragonitic than those in Llanvirn pelites; Na-micas, always considerably less abundant than K-micas, occur in only 30% of the samples. However, the range of crystallinity values obtained is similar to that of Arenig and Llanvirn pelites, reflecting a similar range of metapelitic lithologies, from least altered mudstones and shales to strongly recrystallized phyllitic slates. The least altered Caradoc pelites possess values ranging from 0.38 to $0.71\Delta°2\theta$ and are found in several areas. Around Conwy, Caradoc shales, siltstones, and mudstones possess white mica populations dominated by $1M_d$ K-mica ($\pm$ irregular Na-mica interlayers), with subordinate $2M_1$ K-mica and regular paragonite/muscovite. Chlorite is also present in most samples. In similar pelites pyrophyllite occurs adjacent to the Penmaenmawr intrusion [698747], and also beneath a rhyolite sheet (Conwy Rhyolite Formation), south of Craig-lwyd [726750]. A third occurrence of pyrophyllite in pelites within Caradocian sandstones near Conwy [783735], has no apparent close connection with intrusive rocks. Feebly metamorphosed Caradocian pelites also occur over a large area of central Llŷn extending eastwards to Llanystumdwy. Further to the east at Tremadog, pyrophyllite and rectorite occur in bladed (cleaved) mudstones between thick basic sills [567404].

Cleavage becomes increasingly conspicuous in Caradoc pelites possessing values of less than $0.38\Delta°2\theta$. In paragonitic pelites cleavage development is accompanied by an increase in both $2M_1$ K-mica and regular 6:4 paragonite/muscovite

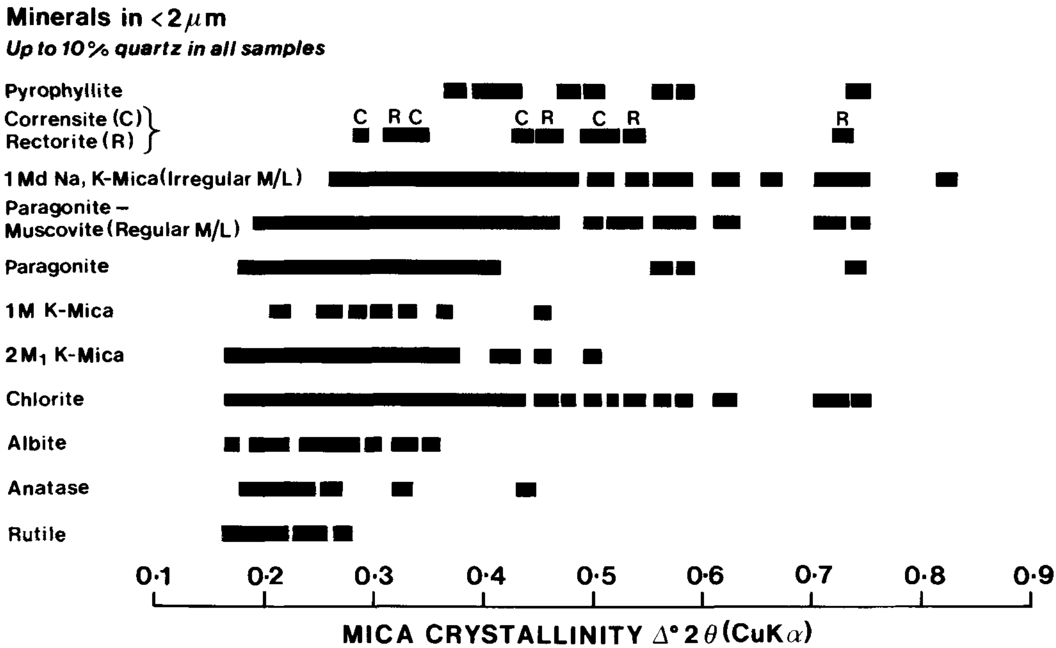

FIG. 5. Mica crystallinity and $< 2\ \mu m$ mineralogy of 109 pelites from the Arenig and Llanvirn Series of Snowdonia and Llŷn.

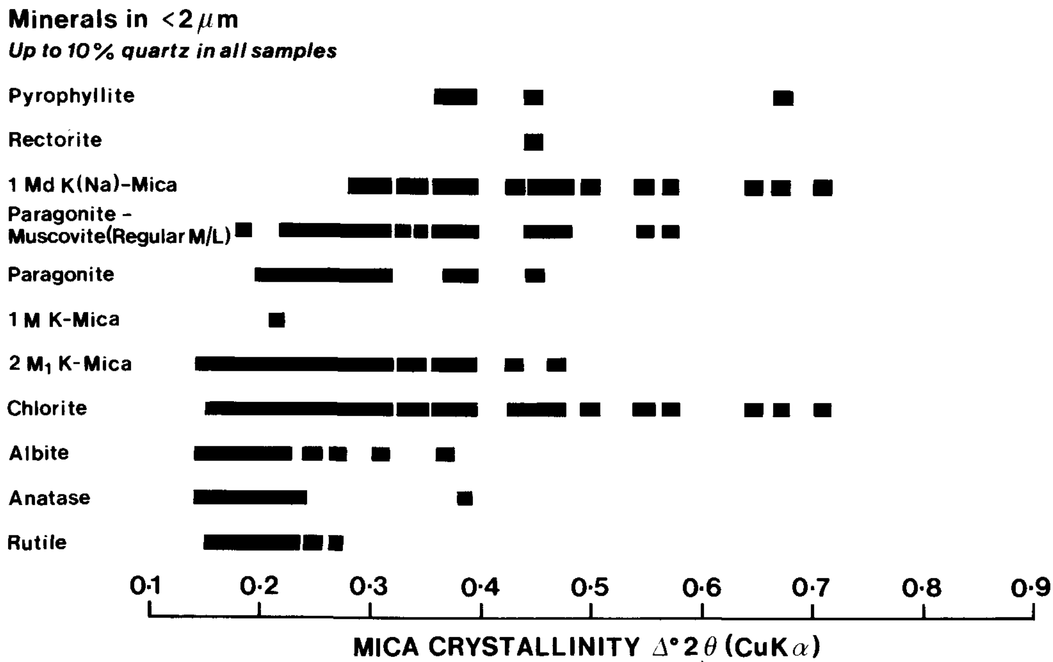

FIG. 6. Mica crystallinity and < 2 μm mineralogy of 121 pelites from the Caradoc, Ashgill, and Llandovery Series of Snowdonia and Llŷn.

in white mica populations. Discrete paragonite appears in slates with values of less than $0.32\Delta°2\theta$; it also occurs with pyrophyllite in contact-altered shales having values of $0.38\Delta°2\theta$. Paragonite-bearing Caradocian slates are mainly confined to the country south and east of Snowdon, from Cwm Pennant and Dolbenmaen, through Nantmor, Croesor, and Blaenau Ffestiniog to Penmachno. Paragonite-poor slates crop out over a wide area of central, eastern, and northeastern Snowdonia. Typically they possess values of $< 0.24\Delta°2\theta$ and consist of $2M_1$ K-mica ($\pm$minor paragonite), subordinate chlorite, minor albite, and anatase or rutile, or both. Two types of paragonite-free pelites are notable for their lack of chlorite. First, siliceous pelites interbedded with rhyolitic tuffs commonly contain a single phyllosilicate, $2M_1$ K-mica, with minor albite, $\pm$anatase. Second, dark-grey and pyritic, black pelites of the Upper Caradocian Llanrhychwyn Slates in the Crafnant area, contain very little or no chlorite and separations largely consist of $2M_1$ K-mica with minor albite, $\pm$anatase. Very similar black, pyritic pelites of the Upper Caradocian Dolwyddelan Slates, contain no chlorite, but here K-feldspar accompanies $2M_1$ K-mica. Crystallinity values of both types of chlorite-poor slates are in the range 0.14–$0.24\Delta°2\theta$.

Ten Ashgillian pelites were collected from the three known areas of outcrop. The least altered Crugan Mudstones in the Llanbedrog area show little evidence of cleavage development, and give crystallinity values of 0.47–$0.58\Delta°2\theta$; they consist largely of $1M_d$ K-mica (with possibly Na-mica interlayers), regular paragonite/muscovite and chlorite. A similar mudstone from the Llanystumdwy area is poorly cleaved and possesses a value of $0.36\Delta°2\theta$; the < 2 μm mineralogy is similar to the Llanbedrog pelites, but $2M_1$ K-mica is now significantly more abundant. In northeastern Snowdonia, Ashgillian pelites range from poorly cleaved mudstones around Conwy to thoroughly cleaved Grinllwm Slates near Trefriw. The Bodeidda Mudstones from Conway are poorly cleaved with a value of $0.38\Delta°2\theta$, and consist of $1M_d$ K-mica with subordinate chlorite and minor regular paragonite/muscovite. Southwest of Trefriw, the Grinllwm Slates possess values of 0.19–$0.25\Delta°2\theta$ and < 2 μm fractions consist largely of $2M_1$ K-mica with chlorite and minor paragonite, albite, anatase, and rutile.

Silurian. Six Llandovery pelites were analysed for this study. Two samples of poorly cleaved mudstones from the Llanystumdwy area gave crystallinity values of 0.36–$0.39\Delta°2\theta$, and separations consisting mainly of $1M_d$ K-mica, subordinate $2M_1$ K-mica, regular paragonite/muscovite, and chlorite.

A pencilled (poorly cleaved) mudstone (?Gyffin Shale), from Conwy [7845 7735] gave a value of $0.48\Delta°2\theta$ and contains no $2M_1$ mica in a separation dominated by $1M_d$ K-mica and regular paragonite/muscovite. South of Conwy (Tyn-y-groes), cleaved mudstones and slates with values of 0.25–$0.30\Delta°2\theta$, contain much $2M_1$ K-mica in separations, with $1M_d$ K-mica, regular paragonite/muscovite, chlorite, and minor albite.

Metapelite recrystallization

In this section mineral assemblages are interpreted in terms of prograde recrystallization and cleavage development. For reasons of space the geological interpretation of these results will be presented elsewhere.

Metapelite stages. In Snowdonia and Llŷn, the development of slaty cleavage is the clearest field evidence of the metamorphic recrystallization of pelitic rocks. Least altered pelites are mudstones and shales of Arenig, Llanvirn, and Caradoc age. Feeble development of cleavage in these rocks takes the form of a splintery fracture in mudstones or a fine crenulation in laminated shales. At the appearance of these structures significant changes occur in the white mica population present in < 2 μm fractions. In particular the $2M_1$ polytype, absent or sparingly present in the least altered pelites, is detected in increased amounts, whereas the $1M_d$ polytype is relatively less abundant; mixed-layer mica in paragonitic pelites shows an increasing regularity of interstratifications and discrete $2M_1$ paragonite appears. Crystallinity values recorded from these feebly cleaved pelites range from $0.48\Delta°2\theta$ for paragonitic Llanvirn pelites, to $0.35\Delta°2\theta$ for Arenig mudstones. With the exception of hydrothermally altered pelites (dealt with below), discrete $2M_1$ paragonite is not detected in samples with crystallinity values greater than $0.42\Delta°2\theta$, and $2M_1$ K-mica is not a significant component of clay-size white micas giving values greater than $0.43\Delta°2\theta$. Accordingly the development of these micas in poorly cleaved mudstones and shales is recognized as an important stage in pelitic recrystallization. In fig. 7 this is the basis of the

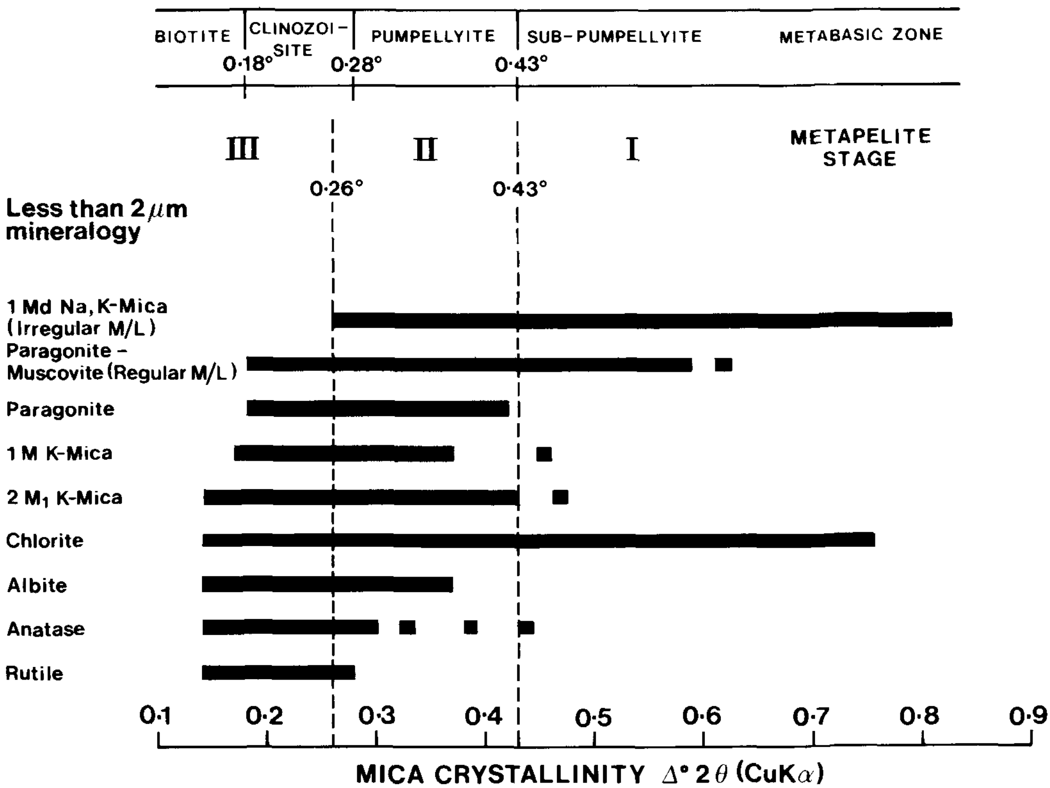

FIG. 7. Mica crystallinity and < 2 μm mineralogy of metapelite stages in Snowdonia and Llŷn. Equivalent metabasite zones from the same region are also shown.

division between metapelite stages I and II. Metapelites of stage I characteristically lack megascopic cleavage and possess values $> 0.43\Delta°2\theta$, with < 2 μm fractions dominated by the $1M_d$ mica polytype, plus subordinate chlorite. Paragonitic pelites of stage I contain both irregular and regular $1M_d$ mixed-layer micas, the regular 6:4 paragonite/muscovite appearing in pelites with crystallinities below $0.60\Delta°2\theta$. In paragonite-poor pelites of stage I the $1M_d$ polytype is a K-mica with minor interlayering of Na-mica. Less than 15% smectite interlayers may occur in the irregular mixed-layer micas of stage I metapelites.

In stage II metapelites progressive development of cleavage accompanies changes in the < 2 μm mineralogy. Irregular mixed-layer Na,K-mica in paragonitic pelites continue to show the ordering of stratifications recorded in stage I, and ultimately regular 6:4 paragonite/muscovite is the only mixed-layer mica in well-cleaved metapelites. At the same time increasing amounts of $2M_1$ Na- and K-mica are developed, derived either directly from recrystallization of irregular $1M_d$ Na,K-mica, or through 'unmixing' (longer-range ordering) of regular paragonite/muscovite. Thus in strongly cleaved paragonitic pelites of stage II, $2M_1$ K-mica and Na-mica dominate white mica populations, regular paragonite/muscovite is subordinate, and irregular mixed-layer Na, K-mica is all but eliminated. In paragonite-poor pelites of stage II progressive cleavage development is accompanied by increases in $2M_1$ K-mica at the expense of $1M_d$ K-mica. Albite may appear in < 2 μm fractions from siliceous and tuffaceous pelites lacking well-developed cleavage. Anatase, but less commonly rutile, appears in many well-cleaved stage II metapelites. Knipe (1981) described microchemical and microstructural changes resulting from cleavage formation in Ordovician pelites from Anglesey; they are similar to regional changes described here in stage II metapelites. Illites with variable Na-content (the irregular mixed-layer Na, K-mica, this study), occur throughout the pelite, but Fe- and Mg-depleted paragonite and Na-rich phyllosilicates (the regular paragonite/muscovite, this study), are found in the oriented cleavage domains. Large detrital muscovite grains also occur throughout the pelite, but small flakes (< 30 μm) in the oriented cleavage domains are considered to have formed from illites; phengites are confined to the cleavage (P) domains. (Both fine-grained muscovite and phengite are identified as $2M_1$ K-micas in this study.)

The division between stage II and III metapelites (fig. 7), is not one that can be related to field evidence since, in the higher grade part of stage II most pelitic rocks are well-cleaved. It is based on the survival of $1M_d$ K-mica in paragonite-poor pelites. The crystallinity value adopted, $0.26\Delta°2\theta$, was the lowest obtained from several cleaved siliceous pelites where no $2M_1$ (or $1M$) reflections were detected, indicating that the mica present is the $1M_d$ polytype. At lower values (i.e. increased crystallinity) $2M_1$ K-mica replaces $1M_d$ K-mica in paragonite-free slates of stage III. However, in paragonitic slates of stage III, $2M_1$ micas are accompanied by regular $1M_d$ paragonite/muscovite mixed-layer mica, but this mineral is much less abundant compared with typical paragonitic pelites of stage II. Furthermore, in many stage III paragonite-bearing pelites from the Llanberis Slate Formation, mixed-layer mica is apparently absent. Thus white micas in stage III metapelites are predominantly discrete K- and Na-rich $2M_1$ polytypes, and regular mixed-layer mica is very subordinate or absent. Albite is commonly detected in < 2 μm fractions, mostly in paragonite-free metapelites of stage III, but a few Cambrian slates contain paragonite and minor albite in separations. Both TiO_2 polymorphs, anatase, and rutile, are common in stage III metapelites, occurring together in some samples. Although chlorites were not studied in detail for this survey, a plot was constructed of the ratio 7 Å peak : 14 Å peak intensities against mica crystallinity. It shows a marked reduction in the ratio for crystallinities below $0.26\Delta°2\theta$, indicating that chlorites in stage III are Fe-depleted compared with those found in stages I and II metapelites.

*Survival of 1*M *K-mica.* The occurrence of a $1M$ mica polytype in the Arfon Group and the Arenig Series merits special mention. It occurs mostly in stage II metapelites but extends up-grade into stage III metapelites, thus spanning the anchizone-epizone bondary (fig. 7). Under these conditions of regional metamorphism the $1M$ polytype is metastable, the $2M_1$ mica being the stable polytype (Velde, 1965). The $1M$ polytype is not common in normal sediments, but is found in Fe-clay sediments as well-crystallized glauconite or as celadonite in tuffs. Much less commonly, the $1M$ polytype is reported as Fe-poor K-mica: Kisch (1966) described $1M$ K-mica and chlorite replacing vermicular kaolinite macrocrysts in tonsteins from Permian coal measures. This paragenesis was to some extent anticipated by Velde's (1965) experimental work which synthesized $1M$ (and $1M_d$) mica from kaolinite + KOH; it appears that the $1M$ structure of well-ordered kaolinite is inherited by the $1M$ mica. Pure, well crystallized $1M$ K-mica occurs in the matrix of Cambro-Ordovician sandstones recovered from well depths of up to 3 km (Triplehorn, 1967); the mica, it is suggested, formed authigenically by alteration of feldspar in the

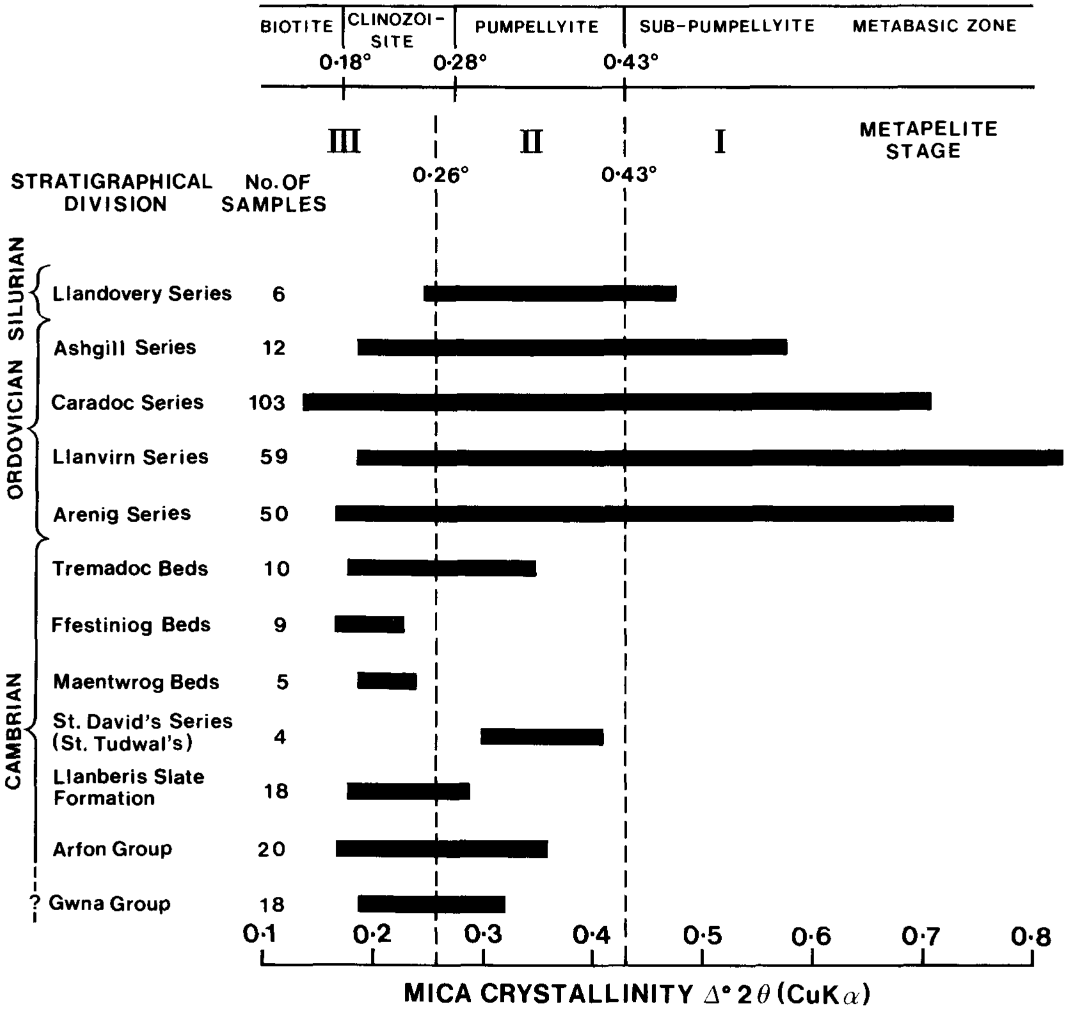

FIG. 8. Mica crystallinity and stratigraphical age of 314 metapelites from Snowdonia and Llŷn.

presence of sodic waters. In the Arfon Group, feldspar is a common constituent of $1M$ mica-bearing volcaniclastic sandstones and semipelites of the Minfordd and Bangor Formations. Thin sections of samples containing abundant $1M$ mica consist of fine clasts (< 0.3 mm) of alkali feldspar, acid lava particles (including pumice and shards), and fragments of former β-quartz phenocrysts, with rare biotite, magnetite, and tourmaline. The matrix of the coarser sediments is largely an intergrowth of $1M$ mica, subordinate $2M_1$ mica, and chlorite. These intergrowths may occur as interstitial, randomly oriented phyllosilicate stacks or fans, as a replacement of feldspar and lithic grains and as thin coatings on clasts. In more pelitic bands, fine clasts are enclosed in an anastomosing phyllosilicate network oriented sub-parallel to the bedding; incipient cleavage is restricted to discrete shears, also sub-parallel to bedding. The proportion of $1M$ to $2M_1$ mica is greatly reduced in samples rich in orthoclastic detritus (mostly polycrystalline metaquartzite grains and muscovite flakes), indicating that $1M$ K-mica is linked with volcaniclastic material, possibly having formed after early kaolinitic alteration of feldspars. Survival of metastable $1M$ K-mica and rock textures generally is consistent with deep burial rather than recrystallization associated with deformation and corresponds, perhaps, with the deep epigenetic to early metagenetic 'stages' of regional burial metamorphism of Kossovskaya and Shutov (1965).

The $1M$ K-mica occurring in Arenig pelites is generally less abundant than in the Arfon Group. A close spatial association of 1*M*-bearing Arfon and Arenig pelites in the Bangor area suggests that a local source of kaolinized volcanics may have been available at widely separated time. Thus the Padarn Tuff Formation, the most likely source of volcaniclastic detritus in the Minfordd and Bangor Formations (Reedman *et al.*, 1984), may have been exposed again by pre-Arenig uplift. In both the Arfon and Arenig rocks the development of 1*M* K-mica appears to result from deep burial of kaolinitized volcanic detritus within the half-graben bounded by the Aber-Dinlle and Dinorwic Faults. The survival of 1*M* K-mica appears to be linked with the low degree of deformation suffered by rocks within this fault system.

Survival of pyrophyllite, rectorite, and corrensite. Reported occurrences of pyrophyllite and rectorite-bearing pelites, particularly in Europe and Russia, suggest they are characteristic of anchizonal metapelites (Kisch, 1983). In Britain, pyrophyllite and rectorite occur in anchizone pelites associated with the anthracite area of the South Wales coalfield (Gill *et al.*, 1977). Some of the pyrophyllite and rectorite-bearing Ordovician pelites identified by this survey possess mica crystallinities characteristic of anchizonal stage II metapelites, but many others have mineral assemblages and mica crystallinities that belong to the least altered metapelites of stage I. Furthermore, nearly 90% of pelites containing these two minerals are located close to outcrops of igneous intrusions (fig. 1). Pyrophyllite and rectorite have been widely reported from hydrothermal zones associated with Tertiary or younger volcanic centres. On Goto Island, Japan, diaspore-pyrophyllite deposits occur in areas of hydrothermal alteration associated with late Miocene rhyodacitic intrusions into early Miocene sediments and tuffs. Rectorite occupies veinlets in rocks rich in diaspore-pyrophyllite and also in rocks rich in kaolinite (Sudo *et al.*, 1962). In the Ohaki-Broadland geothermal field of the Taupo Volcanic Zone, New Zealand, rectorite and corrensite occur in hydrothermally altered acid and intermediate tuffs of Quaternary age (Eslinger and Savin, 1973). Associated hydrothermal minerals include K-mica, alkali-feldspars, chlorite, calcite, quartz, and wairakite. Rectorite is present at measured well temperatures of 270 °C. Experimental work by Velde (1969) shows that pyrophyllite and regular mixed-layer K-mica/smectite (K-rectorite) coexist in the temperature range 310–420 °C at 1 kbar P_{H_2O}. However pyrophyllite has been synthesized from kaolinite and quartz under either low water-vapour pressures or increased acidity in the temperature range 200–300 °C (Kisch, 1983, p. 363). Given the low confining pressures existing at the time of emplacement of the subvolcanic intrusions of Llŷn and northern Snowdonia, temperatures of 200–300 °C are consistent with the usual absence of spotting or other features typical of hornfelses. Hydrothermal mineral assemblages formed at these temperatures would almost certainly survive very low grade regional metamorphism, and indeed some hydrothermally altered pelites are clearly stage II (anchizonal) metapelites. However, because of early contact induced hydrothermal induration, many hydrothermally altered pelites have failed to develop penetrative cleavage. As a result white mica populations are largely dominated by the $1M_d$ polytype typical of stage I metapelites. Knipe's (1981) study and this survey have clearly shown that deformation plays a crucial role in the very low grade recrystallization of white micas.

Correlation between metapelites and metabasites. The correlation between metapelitic stages and metabasite zones in Ordovician rocks shown in figs. 7 and 8 was derived by plotting diagnostic metabasite assemblages from Roberts (1981), on a contoured map of crystallinity values (isocrysts), a simplified version of which is shown in fig. 1. Pumpellyite- and pumpellyite + prehnite-bearing assemblages plot up-grade from the 0.43° isocryst and clinozoisite-bearing metabasites mostly plot up-grade from the 0.28° isocryst. However, around Taly-y-fan, southwest of Conwy, the clinozoisite isograd is associated with the 0.22° isocryst, reflecting the paragonite-poor nature of the pelites in this area. Field associations therefore indicate that the upper limit of stage II metapelites correlates with the beginning of the greenschist facies as defined in metabasites and the lower limit with the beginning of the prehnite-pumpellyite facies. Mineralogy, white mica crystallinity range and associated metabasites all indicate that stage II metapelites represent Kubler's 'anchizone' (Kisch, 1983). Metabasites associated with stage I metapelites lack diagnostic mineral assemblages. However the widespread occurrence of $1M_d$ micas, chlorite and mixed-layer phyllosilicates (irregular and regular), and the absence of kaolinite and a penetrative cleavage, all suggest that for the most part stage I correlates with the laumontite zone of the zeolite-facies (Kisch, 1983, pp. 376–7), despite the fact that laumontite has not yet been recognized. Biotite-bearing metabasites plot up-grade from the 0.18° isocryst but < 2 μm mineral assemblages giving mica crystallinities below $0.18\Delta°2\theta$ are not significantly different from those of other stage III metapelites. Pelites located within the biotite-isograd (fig. 1) are mostly paragonite-poor Caradocian slates consisting of $2M_1$ K-mica, chlorite, albite, and minor TiO_2. Paragonite-bearing slates do not possess crystallinities below $0.18\Delta°2\theta$. This is due to high-angle broadening of the 10 Å K-mica peak in the presence of Na-mica, rather than instability of paragonite in the biotite zone. As the limiting minimum 10 Å peak width ($0.144\Delta°2\theta$ from this study) is approached and machine errors become proportionately larger, the usefulness of the technique is diminished. Mica crystallinity measurements are a useful index of metapelitic grade up to the clinozoisite zone, but not beyond. Clearly, without details of the white micas producing the measurements such indices have limited value.

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