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Autor(en): Dalla Torre, Michael / Frey, Martin

- Objekttyp: Article
- Zeitschrift: Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie

Band (Jahr): 77 (1997)

Heft 2

PDF erstellt am: 26.09.2024

Persistenter Link: https://doi.org/10.5169/seals-58477

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The evolution from disordered Ad to ordered 2M₁ white K-mica polytype in low-temperature metamorphosed sedimentary rocks

by Michael Dalla Torre^{1,2} and Martin Frey¹

Abstract

Six sets of samples from five low-temperature regional metamorphic regions were investigated in order to determine the evolution of white K-mica polytypes as a function of temperature. The data show that disordered group A structures (Ad) associated with small amounts of mixtures of 1M and $2M_1$ structures occur in the diagenetic zone. The true 1Md structure was found to be less common than suggested by previous authors. At anchizonal grades, Ad and 1Md structures disappear and mixtures with variable amounts of 1M and $2M_1$ polytype prevail. In 90% of the samples the concentration of $2M_1$ varies between 70 and 90% at this grade. The largest proportions of the 1M structure are 40% and were found in a sample belonging to the diagenesis/anchizone boundary. At the onset of the epizone, 100% $2M_1$ are reached in most cases including a few exceptions. Our data suggest that the polytype transformation from Ad structures at the diagenetic zone to a mixture of 1M and $2M_1$ at the anchizone to 100% $2M_1$ at the epizone is a function of temperature and can be used as an indicator of grade in sedimentary rocks metamorphosed at lowtemperature conditions.

Keywords: white K-mica, illite, polytype, X-ray diffraction, Central Alps, SW-England, Jämtland, New Zealand.

Introduction

In order to determine different structures of white K-mica, several methods have been presented in the literature. In earlier studies, the 1Md structure was identified by the absence or low intensity of diagnostic 1M reflections (YODER and EUGSTER, 1955; LEVINSON, 1955) or by using different peak intensity ratios (VELDE and HOWER, 1963; REYNOLDS, 1963; MAXWELL and HOWER, 1967). Based on the methods developed in these early studies, several workers concluded that 1Md is the dominant structure in diagenetic samples (for a review, see FREY, 1987). Other criteria to identify disordered white K-mica material were presented by BAILEY (1988) and were later shown to be useful by AUSTIN et al. (1989): (1) the elevated background in X-ray powder diffraction (XRPD) patterns between 20 and 33° 2 Θ CuK α has been attributed to the presence of 1Md polytype (DRITS

et al., 1984; EBERL et al., 1987; BAILEY, 1988; AUSTIN et al., 1989), and (2) the 1Md polytype lacks discrete *hkl* reflections with $k \neq 3n$ (BAILEY, 1988). However, in samples where an elevated background is found in XRPD patterns and the nature of the ordered polytype cannot be established or a mixture of polytypes occurs, 1Md is no longer a useful term. This is because disorder is possible in all polytypes (AUSTIN et al., 1989) and, therefore, BAILEY (1988) proposed that the term Ad (disordered group A micas) is used in such cases. Although to date there is no method to quantitatively measure the content of Ad structures in a sample that contains mixtures of polytypes, estimates of the relative importance of disordered versus 1M and/or 2M1 structures can be made using the above-mentioned criterion.

In order to determine relative proportions of the ordered 1M and $2M_1$ polytype, recent studies (CAILLÈRE et al., 1982; MASSONNE and SCHREYER,

- ¹ Mineralogisch-Petrographisches Institut, Bernoullistrasse 30, CH-4056 Basel, Switzerland. E-mail: dallatorre@yogi.unibas.ch.
- ² Department of Geological and Environmental Sciences Stanford University, Stanford, CA 94305-2115 USA.

1986; TETTENHORST and CORBATO, 1993) used intensity ratios of different diagnostic 1M and 2M₁ reflections. Because quantitative determination of white K-mica polytypes is difficult, due to sample preparation procedures and their effects on XRPD patterns as well as due to sophisticated evaluation of specific diagnostic reflections, DAL-LA TORRE et al. (1994) experimentally reinvestigated the different methods developed by various researchers. The authors found that using the sample preparation procedure after HANDSCHIN and STERN (1989), the method by CAILLÈRE et al. (1982) yielded the best results to determine relative amounts of 2M₁ and 1M in absence of disordered polytype structures. However, their method is not applicable when disordered structures are present in a sample.

In this study, we used the criterion by BAILEY (1980, 1988) and AUSTIN et al. (1989) to determine the presence of disordered structures in a set of samples from different low-temperature metamorphic regions. In order to distinguish between the 1M and $2M_1$ white K-mica polytype, as well as to determine their relative amounts in samples free of disorder, the procedures proposed by DAL-LA TORRE et al. (1994) were applied. To date, there is no systematic study that investigated the distribution of different polytype structures in regionally metamorphosed rocks using the recently developed methods. Therefore, the goal of this investigation is to present data on the evolution of disordered to 2M1 white K-mica structures in sedimentary rocks metamorphosed under low-temperature conditions.

Experimental procedures

Fractions of the < 2 μ m fraction of 70 samples were investigated using XRPD on a Siemens D5000 diffractometer. Most of the samples studied were kindly provided by H.J. Kisch (< 2 μ m fraction) and L.N. Warr (rock chips), and were previously described by these authors (KISCH, 1980 a; 1980 b; 1994; WARR and RICE, 1994; WARR, 1996). Samples denoted with MF, F or L were collected by M. Frey and were described in HUN-ZIKER et al. (1986). ILC samples were collected by S. Krumm.

About 70 to 200 grams of MF, F, and L samples as well as those provided by L.N. Warr were ground in a tungsten-carbide swing-mill for 20 seconds. Samples containing calcite were treated with acetic acid. Fractions of the $< 2 \mu m$ fraction were obtained using settling tubes and millipore filters and were Ca-saturated. Mounts for the measurement of illite crystallinity (IC) values were prepared as sedimentation slides using 5 mg of material per cm² of sample surface. IC values were determined on air-dried specimens only. IC values for the diagenesis/anchizone and the anchizone/epizone boundary are 0.42° and 0.25° $\Delta 2\Theta$ CuK α , respectively (see FREY, 1988).

Disoriented mounts for the determination of polytypes were prepared using the procedure by HANDSCHIN and STERN (1989). Because this original publication may not generally be available, the reader is referred to DALLA TORRE et al. (1994). Unoriented mounts of diagenetic samples and of samples with an elevated background in XRPD patterns between 20 and 33° 2 Θ CuK α of air-dried mounts were glycolated for 128 hours. This procedure was proposed by AUSTIN et al. (1989), who found that diagnostic reflections of ordered polytypes are better resolved in XRPD patterns of ethylene-glycolated than of air-dried mounts.

According to the recommendations outlined by DALLA TORRE et al. (1994), a calibration curve was experimentally determined in order to quantitatively measure the relative proportions of 1M and $2M_1$. Different proportions of 1M and $2M_1$ white K-mica polytype were mixed together according to the procedures given by these authors. A description of the 1M and $2M_1$ polytype used may be found in DALLA TORRE et al. (1994) and SCHWANDER et al. (1968), respectively.

The XRPD measurements were performed on a Siemens D5000 diffractometer equipped with a graphite monochromator and a SICOMP 32-50 computer using the Siemens SOCABIM Diffrac AT V3.2 software. The divergence slits were variable during the measurements, whereas the secondary slit was fixed (0.2 mm). Earlier IC data were obtained on a Philips diffractometer at Basel University using CuKa radiation, a Ni primary filter, and divergence slits fixed at 2°. The receiving slit was fixed at 0.1 mm. The measurement conditions are given in table 1. According to the recommendations by DALLA TORRE et al. (1994), the 1M [112] and the $2M_1$ [025] reflections and the ratio $2M_1/(2M_1 + 1M)$ were used to determine the relative proportions of the two polytypes in samples free of disordered white K-mica structures. The areas of diagnostic peaks were estimated using computer-aided evaluation. In most cases, a single peak computation was applied. In a few samples, however, superposition of a small Kfeldspar reflection on the 1M [112] reflection was observed. In these cases, the white K-mica reflections were resolved by mathematical deconvolution techniques using a Pearson VII function.

diffractometer	measurement	20 rai	nge	scan speed	increment
		min	max	°20 min ⁻¹	°2Θ
D5000	IC	2.0	20.0	0.10	0.05
D5000	< 2 µm mineral assemblage	20.0	42.0	1.20	0.02
D5000	$< 2 \mu m$ mineral assemblage	42.0	48.0	0.75	0.02
Philips	IC	2.0	20.0	2.00	
D5000	$2M_1$ calibration	28.3	31.3	0.10	0.02
D5000	$2M_1$	18.0	33.0	0.10	0.02
D5000	$2M_1$ diagenetic samples	8.0	55.0	0.10	0.02

Tab. 1 Conditions for x-ray powder diffraction (XRPD).

Geological settings of the different regions

70 samples from five different metamorphic settings were investigated in this study. The mineral assemblages of $< 2 \mu m$ fractions are shown in table 2. K-feldspar, albite, and dolomite are present as minor or trace amounts in the $< 2 \mu m$ fractions only and did therefore not hinder XRPD evaluation of diagnostic 1M and 2M₁ reflections. Sample localities can be found in table 2. In the following, we outline briefly the geological settings of the different sets of samples. For additional information, the reader is referred to the publications listed in table 2.

Two sets of the samples are from Switzerland and were previously studied by KISCH (1980b) and HUNZIKER et al. (1986). The first set of samples was provided by H.J. Kisch and contains shales associated with Taveyanne graywacke or flysch. The shales and associated rock types are of Upper Eocene and Lower Oligocene age and represent the youngest clastic sedimentary rocks in the North Helvetic nappes of Switzerland. KISCH (1980b) provides data on diagnostic metamorphic minerals in the different rock types as well as vitrinite reflectance values for some samples. IC values obtained during the course of this study cover the range from the diagenetic zone to the epizone (Tab. 2).

The second set of samples, previously described by HUNZIKER et al. (1986), is from a Mesozoic sequence of sedimentary rocks that can be traced from the Jura Mountains beneath the Swiss Molasse Basin to the Glarus Alps. The sequence is largely undeformed in the Jura Mountains and probably was never buried more than 500 m. In the Molasse Basin, the sequence is covered by up to 5000 m rock that reached minimum temperatures of 100 to 150 °C (HUNZIKER et al., 1986). In the Glarus Alps, the Mesozoic sequence is largely deformed and experienced anchizonal to epizonal metamorphic conditions. The majority of the samples are from a Triassic red-bed formation referred to as Keuper in the Jura Mountains and Quartenschiefer in the Alps. IC values (Tab. 2) cover the whole range from the diagenetic zone to the epizone and are associated with increasing metamorphic conditions from the north to the south of the sequence (HUNZIKER et al., 1986).

Another set of samples also provided by H.J. Kisch is from Jämtland, Sweden, and was previously described by this author (KISCH, 1980a, 1994). The samples studied belong to the Jämtland Supergroup, which is a late-Precambrian and Lower-Paleozoic sedimentary sequence that covers a Precambrian basement. Three main tectonic divisions may be distinguished within the Jämtland Supergroup: these are (i) the autochthon of undeformed Precambrian basement and Cambro-Ordovician platform sediments, (ii) the parautochthonous cover nappes that include the entire Precambrian and Lower-Paleozoic sequence (Jämtland nappes), and (iii) the allochthon of the major long-transported nappe units including basement and cover. The samples investigated in this study are from the parautochthonous Lower Paleozoic units within the Jämtland nappes and have Middle Cambrian to Upper Ordovician, and Silurian ages (KISCH, 1980a). The Silurian sediments represent a largely undeformed sequence and cover weakly foliated Upper Ordovician to Middle Cambrian units. In addition, there is an increase in metamorphic grade from the diagenetic autochthon westward toward the allochthonous sequences.

Most samples from the South Island of New Zealand were provided by L.N. Warr. The South Island consists of accreted terranes that were metamorphosed during Jurassic and Cretaceous times (COOMBS et al., 1976). One of the most extensively investigated areas is the Torlesse terrane, which consists mostly of Permian to early Cretaceous graywackes intercalated with shales. The shales studied are from four different metamorphic grades: zeolite, prehnite-pumpellyite, pumpellyite-actinolite, and greenschist facies. IC values decrease with increasing metamorphic

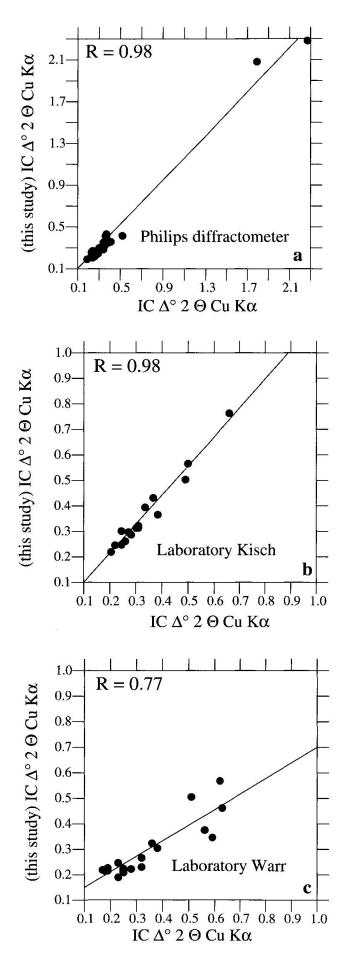
of samples investigated in this study.
$\frac{2M_{1,}}{2M_{1}+1M}$
2 Localities, mineral assemblages of fractions $< 2 \mu m$, IC, and
Tab. 2

4	(mpor	1		416				1	1			this study	$\frac{2M_1+1M}{2M_1+1M}$	
Jämtland													2	
N78-59B	N Norderän	0	0	0		0					.31	.31	.58	KISCH (1980a; 1994)
N78-66B	Brännåsen. NE Östersund	0	0	0		0					39	37	68	
N78-47A	Mörsil-Järpen	С	С	С		C	<u></u>				22	30	11	
N78-47B	Mörsil-Iärnen	C	C	C		C	-				27.	90°	75	
L CON	Döda N Alsansiön) (\circ	\circ) (i 7C	36	00	
1-76		0) () (07.	07.	6.	~ `
6-76N	Undersäker	0	0	0		2					.21	.22	<i>LL</i> .	
N92-10	Undersåker	0	0	0		0	0				.22	.25	-97	KISCH (1980a; 1994)
N92-13C	Ange	0	0	0		0					.31	.32	.73	KISCH (1980a; 1994)
Dachschiefer														
Z74-3B	Kiental	0	0	0		0	4	0			.50	.57	PA	KISCH (1980b)
Z75-22C	Mus, Urnerboden	0	0	0		0	~				.25	.25	.84	Kisch (1980b)
Z75-29B	Oberalp-Äsch, Schächental	0	0	0		0					.30	.31	.95	KISCH (1980b)
Z75-34B	Oberalp-Äsch, Schächental	0	0	0		0	5				.28	.29	.85	K_{ISCH} (1980b)
Z75-40C	Grube Gasperini. Seedorf	0	0	0		0	2				34	39	75	
Z75-40D	Grube Gasperini. Seedorf	0	0	0		C					37	43	75	
Z75-85H	Sattelhorn, Kanderprind	C	C	C		C	-	С			99	76	Ad Ad	
IZ75-90A	Balme, W Kandergrund	0	0	0		0)			.49	50	.82	
Keuper Quartenschiefer	ıfer													
F103	Frick	0		0	0	0						1.23	Ad	this study
F108	Frick	0	0	0	0	0						1.96	PA	HUNZIKER et al. (1986)
F176	Frick	0		0	0	0					2.27	2.28	1Md	HUNZIKER et al. (1986)
L10	Lindau	0	0	0	0	0						1.74	1Md	this study
L12	Lindau	0	0	0	0	0	0				1.79	2.08	PA	HUNZIKER et al. (1986)
L17	Lindau	0		0	0	0						1.30	PA	HUNZIKER et al. (1986)
MF131	Garvera	0	0	0	0	0				ctd		.42	1.00	this study
MF4	Ouarten	0	0	0		0					.52	.42	Ad	HUNZIKER et al. (1986)
MF15	Quarten	0	0	0			0	0				.57	PA	this study
MF20	Flissen	0	0	0		0		0				1.15	PY	HUNZIKER et al. (1986)
MF23	Flissen	0		0	0	0					.37	.43	.42	HUNZIKER et al. (1986)
MF34	Schwarzstöckli	0	0	0	0	\sim					.37	.41	89.	
MF341	Panüöl	0		0	0	~					.33	.28	<i>LL</i> :	HUNZIKER et al. (1986)
MF48	Limmernboden	0	0	0	0	<u> </u>					.23	.26	1.00	HUNZIKER et al. (1986)
MF52	Bifertengletscher	0	0	0	0	0						.22	.61	
MF53	Bifertengletscher	0	0	0	0	0					.29	.25	1.00	HUNZIKER et al. (1986)
MF54	Bifertengletscher	0	0	0	0	0					.27	.23	1.00	HUNZIKER et al. (1986)
MF56	Schafleger	0	0	0								.51	.58	this study
MF58	Schafteger	0	0	0		0						.42	.91	this study
MF59	Schafleger	0	0	0	0	0					.41	.36	<u>.</u>	HUNZIKER et al. (1986)
MEGO		(1											

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Tab. 2 continued.

WFV65 Resentach 0 0 0 0 Howards et al. (1986) WFV15 Resentach 0 0 0 0 0 10 Howards et al. (1986) WFV13 Bursicok 0 0 0 0 0 0 19 10 Howards et al. (1986) WF731 Bursicok 0 0 0 0 0 0 19 10 Howards et al. (1986) WF731 Bursicok 0 0 0 0 0 0 10 Howards et al. (1986) WF731 Bursicok 0 0 0 0 0 0 0 10 Howards et al. (1986) WF731 Bursicok 0 0 0 0 0 0 0 10 Howards et al. (1986) WF731 Bursicok 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 <td< th=""><th>Mrtrist Mrtrist Rusentheth Riterion 0 0 0 0 100 Huxdress et al. (1986) Huxdress et al. (1986) Huxdress et al. (1986) Huxdress et al. (1986) Mrtrist Huxdress et al. (1986) Huxdress et al. (1986) Huxdress et al. (1986) Huxdress et al. (1986) Mrtrist Huxdress et al. (1986) Huxdress (1986) Huxdress</th><th>sample #</th><th>locality</th><th>sm</th><th>chl</th><th>qtz d</th><th>dol hem</th><th>m ab</th><th>kfs</th><th>i/s</th><th>stp</th><th>sm (</th><th>other</th><th>IC‡</th><th>IC this study</th><th>$\frac{2M_1}{2M_1+1M}$</th><th>reference</th></td<>	Mrtrist Mrtrist Rusentheth Riterion 0 0 0 0 100 Huxdress et al. (1986) Huxdress et al. (1986) Huxdress et al. (1986) Huxdress et al. (1986) Mrtrist Huxdress et al. (1986) Huxdress et al. (1986) Huxdress et al. (1986) Huxdress et al. (1986) Mrtrist Huxdress et al. (1986) Huxdress	sample #	locality	sm	chl	qtz d	dol hem	m ab	kfs	i/s	stp	sm (other	IC‡	IC this study	$\frac{2M_1}{2M_1+1M}$	reference
Chromin Bach Chromin Bach<	MF79 fritem Rath 7 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	MF65	Rusenbach	0										.35	.32	.86	HUNZIKER et al. (1986)
Frittern Butsicok Frittern Frittern Frittern Butsicok Britisiok 38 100 Paniver Rotstock 0 0 0 0 0 38 39 Butsicok Butsicok 0 0 0 0 0 38 39 Butsicok 0 0 0 0 0 0 38 37 Butsicok 0 0 0 0 0 0 38 37 Butsicok 0 0 0 0 0 0 0 38 37 38 37 38 37 38 37 37 38 37	MFT1 Filter 30 30 100 House Res et al. (1986) MT731 Bursitock 0 0 0 0 0 10 100 House Res et al. (1986) MT731 Bursitock 0<	MF703	Chrumm Bach	0	_									39	.35	1.00	HUNZIKER et al. (1986)
Paintexitock 0 </td <td>MT71 Bittistick. 0</td> <td>MF71</td> <td>Frittern</td> <td>0</td> <td>_</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td>-30</td> <td>.30</td> <td>1.00</td> <td>HUNZIKER et al. (1986)</td>	MT71 Bittistick. 0	MF71	Frittern	0	_									-30	.30	1.00	HUNZIKER et al. (1986)
Haniter Rotstock 0 0 0 0 0 19 19 100 Bultzitock 0 0 0 0 0 0 19 19 10 Bultzitock 0 0 0 0 0 0 23 34 23 35 Bultzitock 11* Deep Creek (Waimate Gorge) 0 0 0 0 0 0 0 23 25 25 35 Bultzitock 13C* Bernnore dam (shore platform) 0 0 0 0 0 0 23 25 36 21 26 27 36 21 26 27 36 23 23 36 23 23 36 100 100 10	WT711 Painter Rostock 0 0 0 0 19 10 100 Hystanse rad. (1986) MT731 Buristock 0	MF73	Bützistock	0	_				0						.38	.91	this study
Butistick 0	MIT3 Butastock 0 <t< td=""><td>MF731</td><td>Panixer Rotstock</td><td>0</td><td>_</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>.19</td><td>.19</td><td>1.00</td><td>HUNZIKER et al. (1986)</td></t<>	MF731	Panixer Rotstock	0	_									.19	.19	1.00	HUNZIKER et al. (1986)
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ealand 238 22 70 9: 111* Deep Creek (Waimate Gorge) 0 0 0 28 22 70 9: 113* Deep Creek (Waimate Gorge) 0 0 0 28 28 22 70 11.* Deep Creek (Waimate Gorge) 0 0 0 0 28 23 26 41 Add 11.* Deep Creek (Waimate Gorge) 0 0 0 0 26 28 27 70 70 11.* Deep Creek (Waimate Gorge) 0 0 0 0 23 26 41 Add 11.* Deep Creek (Waimate Gorge) 0 0 0 23 26 41 Add 27 26 41 27 26 41 21 23 23 23 23 23 23 23 23 24 24 27 26 41 41 23 23 24 24 24 24 23 23 100 23 23 100 23 23 24 24 24 24	New Zealand New Zealand NZ4 11* Deep Creek (Wainate Gorge) 0	MF82	Curaglia	0	And Date	0.000		0							.21	1.00	HUNZIKER et al. (1986)
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1.3B* Bermore dam 0 0 0 0 36 41 Ad 1.3C* Bermore dam (shore platform) 0 0 0 0 351 51 59 41 Ad 1.3C* Bermore dam (shore platform) 0 0 0 0 351 51 59 41 Ad 1.3C* Bermore dam (shore platform) 0 0 0 0 351 51 59 51 59 51 59 51 59 51 59 51 56 17 56 17 56 21 59 51 56 17 56 23 23 23 23 23 23 23 59 56 19 50 55 31 14* Datachine Bridge (Longslip Creek) 0 0 0 0 0 0 0 0 0 0 0 0 0 56 31 33 31 34 66 100 31 34 56 57 23 100 100 100 100 100 100 100	MP2843 1.33* Beimore dam 0 0 0 0 36 41 Ad Mis study MP286 1.37* Bermore dam (store platform) 0 0 0 0 35 34 35 70 this study MP286 1.37* Bermore dam (store platform) 0 0 0 0 32 27 55 WARK (1966) MP286 1.5* Longship Creek) 0 0 0 24 27 55 this study MP286 1.5* Longship Creek) 0 0 0 0 24 27 55 this study MP286 3.1* Lake Howden 0 <td< td=""><td>MF2839</td><td>1.1* Deep Creek (Waimate Gorge)</td><td>0</td><td>0</td><td>0</td><td></td><td>0</td><td>0</td><td></td><td></td><td></td><td></td><td>.26</td><td>.22</td><td>99.</td><td>this study</td></td<>	MF2839	1.1* Deep Creek (Waimate Gorge)	0	0	0		0	0					.26	.22	99.	this study
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	NTS8 13.5° Bennore dam (shore platform) 0 0 0 21 53 Wask (196) NT284 1.4* Datractime Bridge (Longslip Cresk) 0 0 0 22 23 23 34 Wask (196) NT259 1.7* Lindis River (S Goodger Road) 0 0 0 0 23 23 39 Wask (196) NT259 4.1* Datractime Bridge (Longslip Cresk) 0	MF2843	1.3B* Benmore dam	0	0	0		0	0	0				.36	.41	PA	this study
6 1.3C* Bermore dam (shore platform) 0 0 0 34 35 70 8 1.4* Datrachine Bridge (Longslip Creek) 0 0 0 24 27 55 9 1.4* Datrachine Bridge (Longslip Creek) 0 0 0 24 27 55 9 1.7* Longslip Creek 0 0 0 0 24 27 55 9 1.7* Longslip Creek 0 0 0 0 24 27 55 9 1.7* Longslip Creek 0 0 0 0 24 27 55 9 1.7* Lindis River (S Goodger Road) 0 0 0 0 23 19 100 2.1* Shotover River Bidge 0 0 0 0 0 23 19 100 5.5* Taieri Mouth 1.40* Road section 0 0 0 0 25 21 100 1.46< Hawes to Lake Wanaka road section	MP3846 1.3C* Bernance data (store platform) 0	NZ8	1.3C* Benmore dam (shore platform)	0	0	0		0	0	0				.51	.51	69.	WARR (1996)
1.4* Dalrachine Bridge (Longslip Creek) 0 0 32 27 55 1.4* Dalrachine Bridge (Longslip Creek) 0 0 0 24 27 56 1.1* Lindis River (S Goodger Road) 0 0 0 23 23 23 24 27 56 1.7* Lindis River (S Goodger Road) 0 0 0 0 0 23 23 23 24 27 56 6 31* Lake Howden 0 0 0 0 0 0 23 23 23 23 23 23 24 27 56 34 5 3.1* Lake Howden 0 0 0 0 0 0 0 23 23 19 100 5.5.7 Taieri Mouth 0 0 0 0 0 18 21 100 Lake Hawea to Lake Wanaka road section 0 0 0 0 19 22 100 Lake Hawea to Lake Wanaka road section 0 0 0 10 10 10 100 <tr< td=""><td>NZ39 1.4* Datachine Bridge (Longsh) Creek) 0 0 0 24 27 55 Wark (1996) MF2348 1.4* Longily Creek) 0 0 0 0 24 27 54 this study MF2345 1.4* Longily Creek) 0 0 0 0 23 27 54 this study NZ15 1.1* Lindis River (5 Goodger Road) 0 0 0 23 25 100 Wark (1996) NZ15 3.1* shower River Bridge 0</td><td>MF2846</td><td>1.3C* Benmore dam (shore platform)</td><td>0</td><td>0</td><td>0</td><td></td><td>0</td><td>0</td><td></td><td></td><td></td><td></td><td>.34</td><td>.35</td><td>.70</td><td>this study</td></tr<>	NZ39 1.4* Datachine Bridge (Longsh) Creek) 0 0 0 24 27 55 Wark (1996) MF2348 1.4* Longily Creek) 0 0 0 0 24 27 54 this study MF2345 1.4* Longily Creek) 0 0 0 0 23 27 54 this study NZ15 1.1* Lindis River (5 Goodger Road) 0 0 0 23 25 100 Wark (1996) NZ15 3.1* shower River Bridge 0	MF2846	1.3C* Benmore dam (shore platform)	0	0	0		0	0					.34	.35	.70	this study
8 1.4^* Dalrachine Bridge (Longslip Creek) 0 0 0 24 27 64 9 1.5^* Longslip Creek 0 0 0 23 23 23 98 9 1.7^* Liongslip Creek 0 0 0 0 23 23 23 98 2 1.7^* Liongs River Bridge 0 0 0 0 23 23 23 98 98 2 4.0^* Rocky Point Quarry, Mossburn 0 0 0 0 0 23 23 23 23 23 98 98 98 98 98 99 100 23 100 23 23 23 100 23 23 13 100 23 13 100 23 23 23 100 23 23 100 23 23 100 23 23 100 23 23 100 23 100 23 100 23 100 23 100 23 100 23 100 23 23 23 <td>MT2845 1.4* Datrachine Bridge (Longili) Creek) 0 0 24 27 64 this study NZ157 1.7* Longili Creek 0 0 0 23 23 94 Wast (1996) NZ157 2.1* stortower Bridge 0 0 0 0 23 23 94 Wast (1996) NZ157 2.1* stortower Bridge 0 0 0 23 23 23 94 Wast (1996) NZ154 2.1* stortower Bridge 0 0 0 0 0 23 23 23 94 Wast (1996) NZ153 1.1* ake Have to Lake Wanaka road section 0 0 0 0 0 23 23 23 24 27 24 24 27 24 24 27 24</td> <td>6ZN</td> <td>1.4* Dalrachine Bridge (Longslip Creek)</td> <td>0</td> <td>0</td> <td>0</td> <td></td> <td>0</td> <td>0</td> <td></td> <td></td> <td>0</td> <td></td> <td>.32</td> <td>.27</td> <td>.55</td> <td>WARR (1996)</td>	MT2845 1.4* Datrachine Bridge (Longili) Creek) 0 0 24 27 64 this study NZ157 1.7* Longili Creek 0 0 0 23 23 94 Wast (1996) NZ157 2.1* stortower Bridge 0 0 0 0 23 23 94 Wast (1996) NZ157 2.1* stortower Bridge 0 0 0 23 23 23 94 Wast (1996) NZ154 2.1* stortower Bridge 0 0 0 0 0 23 23 23 94 Wast (1996) NZ153 1.1* ake Have to Lake Wanaka road section 0 0 0 0 0 23 23 23 24 27 24 24 27 24 24 27 24	6ZN	1.4* Dalrachine Bridge (Longslip Creek)	0	0	0		0	0			0		.32	.27	.55	WARR (1996)
90 $1.5*$ Longslip Creek 0 0 0 24 21 98 P $1.7*$ Lindis River (S Goodger Road) 0 0 0 23 24 21 98 6 $1.7*$ Lindis River (S Goodger Road) 0 0 0 0 0 23 25 100 56 $3.1*$ Shotovern River (S Goodger Road) 0 0 0 0 0 23 25 100 23 25 100 23 25 100 23 25 100 23 25 100 23 25 100 23 23 100 100 23 23 100 100 23 23 100 100 23 23 100 100 23 100 23 23 100 23 100 23 100 23 100 23 100 23 100 23 100 23 100 23 100 23 100 23 100 23 100 23 100 23 100 23 100 23	MT2850 1.5* Longslip Creek 0 0 0 0 0 0 0 0 0 0 0 Wark (1966) Wark war (196	MF2848	1.4* Dalrachine Bridge (Longslip Creek)	0	0	0		0	0					.24	.27	.64	this study
P $1.7*$ Lindis River (S Goodger Road) 0 0 0 0 23 94 56 $3.1*$ Lake Howden 0 0 0 0 23 23 23 94 56 $3.1*$ Lake Howden 0 0 0 0 0 23 23 23 23 23 23 23 23 23 23 23 23 23 23 23 23 23 100 23 23 23 100 23 23 139 100 23 130 23<	NZ15-P 1.7* Lindis River (S Goodger Road) 0 0 0 23 24 WARR (1996) NZ17 2.1* Shotover River Bridge 0 0 0 23 25 100 WARR (1996) MF2255 5.4* Taken tover River Bridge 0 0 0 0 23 23 100 WARR (1996) NZ43 5.5* Taken Mouth 0 0 0 0 0 0 WARR (1996) NZ43 5.5* Taken Mouth 0 0 0 0 0 WARR (1996) NZ43 5.5* Taken Mouth 0 0 0 0 0 WARR (1996) NZ45 Lake Hawea to Lake Wanaka road section 0 0 0 0 WARR (1996) NZ46 Lake Hawea to Lake Wanaka road section 0 0 0 0 WARR (1996) NZ46 Lake Hawea to Lake Wanaka road section 0 0 0 MARR (1996) NZ46 Lake Hawea to Lake Wanaka road section 0 0 0 MARR (1996) SW1 Widemouth Bay K WARR and Ri	MF2850	1.5* Longslip Creek	0	0	0		0	0					.24	.21	<u> 98</u>	this study
	NZ17 2.1* Shotover River Bridge 0 0 0 23 25 1.00 Wark (1996) NZ29 5.5* Taieri Mouth 0 0 0 0 0 0 Mark (1996) NZ43 1.st Lake Hawea 0.1 ake Warak aroad section 0 0 0 0 Mark (1996) NZ43 1.ake Hawea to Lake Waraka road section 0 0 0 0 Mark (1996) NZ46 1.ake Hawea to Lake Waraka road section 0 0 0 0 Mark (1996) NZ46 1.ake Hawea to Lake Waraka road section 0 0 0 0 Mark (1996) NZ46 1.ake Hawea to Lake Waraka road section 0 0 0 0 Mark (1996) NZ46 1.ake Hawea to Lake Waraka road section 0 0 0 0 Mark (1996) NZ46 1.ake Hawea to Lake Waraka road section 0 0 0 0 Mark (1996) NZ46 1.ake Hawea to Lake Waraka road section 0 0 0 100 Wark (1996) SW1 Widemouth Bay SW1 <td< td=""><td>NZ15-P</td><td>1.7* Lindis River (S Goodger Road)</td><td>0</td><td>0</td><td>0</td><td></td><td>0</td><td>0</td><td></td><td></td><td></td><td></td><td>.19</td><td>.23</td><td>.94</td><td>WARR (1996)</td></td<>	NZ15-P	1.7* Lindis River (S Goodger Road)	0	0	0		0	0					.19	.23	.94	WARR (1996)
56 $3.1*$ Lake Howden 0 0 0 0 0 1 23 23 23 89 4.0* Rocky Point Quarry, Mossburn 0 0 0 0 1 10 23 19 100 5.5* Taieri Mouth 1.40* Rocky Point Quarry, Mossburn 0 0 0 0 18 21 100 1.ake Hawea to Lake Wanaka road section 0 0 0 0 0 18 21 100 I.ake Hawea to Lake Wanaka road section 0 0 0 0 0 18 21 100 I.ake Hawea to Lake Wanaka road section 0 0 0 0 0 25 21 100 I.ake Hawea to Lake Wanaka road section 0 0 0 0 0 26 46 61 I.ake Hawea to Lake Wanaka road section 0 0 0 0 25 21 100 I.ake Hawea to Lake Wanaka road section 0 0 0 26 36 56 56 56 56 56 56 56 <t< td=""><td>MF2356 3.1* Lake Howden 0</td><td>NZ17</td><td>2.1* Shotover River Bridge</td><td>0</td><td>0</td><td>0</td><td></td><td>0</td><td>0</td><td></td><td></td><td></td><td></td><td>.23</td><td>.25</td><td>1.00</td><td>WARR (1996)</td></t<>	MF2356 3.1* Lake Howden 0	NZ17	2.1* Shotover River Bridge	0	0	0		0	0					.23	.25	1.00	WARR (1996)
4.0* Rocky Point Quarry, Mossburn 0 0 0 0 0 1 62 57 Ad $5.5*$ Taieri Mouth 0 0 0 0 0 1 62 57 Ad $5.5*$ Taieri Mouth 0 0 0 0 0 1 62 57 Ad $1.46e$ Hawea to Lake Wanaka road section 0 0 0 0 1 25 21 100 $1.4ke$ Hawea to Lake Wanaka road section 0 0 0 0 0 2 1 100 $1.4ke$ Hawea to Lake Wanaka road section 0 0 0 0 0 2 1 100 $1.2ke$ Hawea to Lake Wanaka road section 0 0 0 0 2 1 1 0 $1.2ke$ Hawea to Lake Wanaka road section 0 0 0 0 2 1 1 0	NZ29 4.0* Rocky Point Quarry, Mosburn 0 0 0 0 1 62 57 Ad Wark (1996) NZ42 Lake Havea to Lake Wanaka road section 0 0 0 1 23 19 100 Wark (1996) NZ45 Lake Havea to Lake Wanaka road section 0 0 0 19 22 100 Wark (1996) NZ46 Lake Havea to Lake Wanaka road section 0 0 0 0 23 21 100 Wark (1996) NZ46 Lake Havea to Lake Wanaka road section 0 0 0 0 0 23 21 100 Wark (1996) NZ46 Lake Havea to Lake Wanaka road section 0	MF2856	3.1* Lake Howden	0	0	0		0	0					.23	.22	.89	this study
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	NZ42 5.5* Taieri Mouth 0 0 0 0 0 0 0 0 Wark (1996) NZ43 Lake Havea to Lake Wanaka road section 0 0 0 25 21 1.00 Wark (1996) NZ46 Lake Havea to Lake Wanaka road section 0 0 0 0 25 21 1.00 Wark (1996) NZ46 Lake Havea to Lake Wanaka road section 0 0 0 0 25 1.00 Wark (1996) NZ46 Lake Havea to Lake Wanaka road section 0 0 0 0 19 22 1.00 Wark (1996) NZ46 Lake Havea to Lake Wanaka road section 0 0 0 0 0 19 22 1.00 Wark (1996) SW England Nidemouth Bay 0 0 0 0 0 0 10 Wark and Rice (1994) SW England Nidemouth Bay 0 0 0 0 0 10 Wark and Rice (1994) SW England Nidemouth Bay Nidemouth Bay 0 0 10 <td< td=""><td>NZ29</td><td>4.0* Rocky Point Quarry, Mossburn</td><td>0</td><td>0</td><td>0</td><td></td><td>0</td><td>0</td><td>0</td><td></td><td></td><td>lmt</td><td>.62</td><td>.57</td><td>Ρq</td><td>WARR (1996)</td></td<>	NZ29	4.0* Rocky Point Quarry, Mossburn	0	0	0		0	0	0			lmt	.62	.57	Ρq	WARR (1996)
Lake Hawea to Lake Wanaka road section 0 0 0 0 25 21 1.00 Lake Hawea to Lake Wanaka road section 0 0 0 0 0 0 25 21 1.00 Lake Hawea to Lake Wanaka road section 0 0 0 0 0 0 22 1.00 Iake Hawea to Lake Wanaka road section 0 0 0 0 0 23 346 61 Widemouth Bay 0 0 0 0 0 0 38 30 93 Widemouth Bay 0 0 0 0 0 0 38 36 56 57 100 Portgaverne 0 0 0 0 0 36 32 100 36 36 37 56 38 56 56 38 56 37 74	NZ43 Lake Hawea to Lake Wanaka road section 0 0 0 0 25 21 1.00 WARR (1996) NZ46 Lake Hawea to Lake Wanaka road section 0 0	NZ42	5.5* Taieri Mouth	0	0	0		0	0		0		dmd	.23	.19	1.00	WARR (1996)
Lake Hawea to Lake Wanaka road section 0 0 0 0 0 19 21 100 ngland Lake Hawea to Lake Wanaka road section 0 0 0 0 0 19 22 100 ngland Widemouth Bay 0 0 0 0 0 9 23 100 Widemouth Bay 0 0 0 0 0 9 53 30 93 Portgaverne 0 0 0 0 0 9 25 100 Rebarwith Strand 0 0 0 0 0 9 38 36 56 Adorf 0 0 0 0 0 35 37 74 Ncoblenz 0 0 0 0 36 56 38 56 Ncoblenz 0 0 0 0 0 32 37 74 rink way station Oos 0 0 0 0 59 35 74	NZ45 Lake Havea to Lake Wanaka road section O O O O O O O O MAR (196) NZ46 Lake Havea to Lake Wanaka road section O O O O 19 22 1.00 WARR (196) SW1 Widemouth Bay O O O O O O Sig 46 61 WARR (1996) SW4 Portgavene O O O O O O Sig 46 61 WARR and RICE (1994) SW4 Portgavene O O O O O Sig 38 30 93 WARR and RICE (1994) SW6 Trebarwith Strand O O O O O Sig 38 56 KRUMM (written comm., 1955) SW6 Trebarwith Strand O O O O Sig 38 56 KRUMM (written comm., 1955) ILC1 Adorf Adorf ILC3 Well Biach ILC4 Kelbeach IS5 37 37 38 56 KRUMM (written com	NZ43	Lake Hawea to Lake Wanaka road section	0	0	0		0	0			10000		.25	.21	1.00	WARR (1996)
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ingland Widemouth Bay 0 0 0 0 63 46 61 Videmouth Bay O 0 0 0 0 9 33 30 93 Portgaverne 0 0 0 0 0 9 33 30 93 Irebarwith Strand 0 0 0 0 0 9 33 30 93 nisches Schiefergebirge Ndorf S 36 36 33 36 36 37 30 36 37 36 37 36 <	SW England SW1 Widemouth Bay 0 0 0 0 0 0 93 WARR and RUCE (1994) SW4 Portgaverne 38 30 93 WARR and RUCE (1994) SW6 Trebarwith Strand 0 0 0 0 0 93 WARR and RUCE (1994) SW6 Trebarwith Strand 0 0 0 0 0 93 WARR and RUCE (1994) SW6 Trebarwith Strand 0 0 0 0 0 93 WARR and RUCE (1994) Rheinisches Schiefergebirge 1 Adorf 25 22 1.00 WARR and RUCE (1994) ILC1 Adorf 0 0 0 0 36 37 37 37 KRUMM (written comm., 1995) ILC3 Well Eibach 1LC4 N Koblenz 36 36 37 37 37 37 37 37 37 37 37 Mitten comm., 1995) 35 .17 KRUMM (written comm., 1995) 37 .17 KRUMM (written comm., 1995) 35 .37 .47 </td <td>NZ46</td> <td>Lake Hawea to Lake Wanaka road section</td> <td>0</td> <td>0</td> <td>0</td> <td></td> <td>0</td> <td>0</td> <td></td> <td>\circ</td> <td></td> <td></td> <td>.19</td> <td>.22</td> <td>1.00</td> <td>WARR (1996)</td>	NZ46	Lake Hawea to Lake Wanaka road section	0	0	0		0	0		\circ			.19	.22	1.00	WARR (1996)
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Portgaverne O <th< td=""><td>SW4 Portgaverne O Wark and RICE (1994) SW6 Trebarwith Strand O O O O O O Wark and RICE (1994) Rheinisches Schiefergebirge </td><td>SW1</td><td>Widemouth Bay</td><td>0</td><td>~</td><td>0</td><td></td><td>0</td><td></td><td>0</td><td></td><td></td><td></td><td>.63</td><td>.46</td><td>.61</td><td>WARR and RICE (1994)</td></th<>	SW4 Portgaverne O Wark and RICE (1994) SW6 Trebarwith Strand O O O O O O Wark and RICE (1994) Rheinisches Schiefergebirge	SW1	Widemouth Bay	0	~	0		0		0				.63	.46	.61	WARR and RICE (1994)
Trebarwith Strand 0 0 0 0 25 22 1.00 nisches Schiefergebirge Adorf 36 36 32 87 Well Eibach 0 0 0 0 36 38 56 N Koblenz 0 0 0 0 36 37 74 railway station Oos 0 0 0 0 35 37 74	SW6 Trebarwith Strand O O O O O Mark and RICE (1994) Rheinisches Schiefergebirge Rheinisches Schiefergebirge .25 .22 1.00 Wark and RICE (1994) RLC1 Adorf .36 .32 .87 KrubM (written comm., 1995) ILC3 Well Eibach .0 .0 .36 .32 .87 KrubM (written comm., 1995) ILC4 N Koblenz .0 .0 .32 .33 .56 KrubM (written comm., 1995) ILC4 N Koblenz .0 .32 .33 .56 KrubM (written comm., 1995) ILC4 N Koblenz .32 .37 .47 KrubM (written comm., 1995) ILC6 railway station Oos .0 .32 .35 .47 KrubM (written comm., 1995) Explanations: * denotes number of excursion stop in CooMBs and Cox (1991), ‡ denotes IC data from previous studies (see text), ms = white K-mica, chl = chlorite, chlorite	SW4	Portgaverne	0	0	0			0				pg	.38	.30	.93	
iisches Schiefergebirge Adorf Adorf 36 .32 .87 Well Eibach 0 0 0 0 .56 .38 .56 N Koblenz 0 0 0 0 .59 .37 .74 railway station Oos 0 0 0 .59 .35 .47	Rheinisches SchiefergebirgeILC1AdorfILC1AdorfILC1AdorfILC3Well EibachILC3Well EibachILC4N KoblenzILC4N KoblenzILC5railway station OosOOOOOOOOOOOOOOSectorsSe	SW6	Trebarwith Strand	0	0	0		0						.25	.22	1.00	
Adorf 0 0 0 0 36 32 87 Well Eibach 0 0 0 0 0 36 32 87 Well Eibach 0 0 0 0 0 36 32 37 56 N Koblenz 0 0 0 0 32 33 56 railway station Oos 0 0 0 0 59 .35 .47	ILC1 Adorf 0 0 0 0 0 0 0 36 32 87 Kruhn (written comm., 1995) ILC3 Well Eibach 0 0 0 0 0 36 38 56 Kruhn (written comm., 1995) ILC4 N Koblenz 0 0 0 0 0 32 23 74 Kruhn (written comm., 1995) ILC6 railway station Oos 0 0 0 0 32 33 35 37 74 Kruhn (written comm., 1995) ILC6 railway station Oos 0 0 0 0 0 35 .33 .35 .47 Kruhn (written comm., 1995) Explanations: * denotes number of excursion stop in CooMBs and Cox (1991), ‡ denotes IC data from previous studies (see text), ms = white K-mica, chl = chlorite, mice chlorite, chlori	Rheinisches	Schiefergebirge														
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N Koblenz 0 0 0 0 0 0 14 railway station Oos 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	ILC4N KoblenzOOOOOOILC4KRUMM (written comm., 1995)ILC6railway station OosOOOOOOILC6.32.33.47KRUMM (written comm., 1995)Explanations: * denotes number of excursion stop in CooMBs and Cox (1991), ‡ denotes IC data from previous studies (see text), ms = white K-mica, ch1 = chlorite, ms = white K-mica,	ILC3	Well Eibach	0	0	0		0						.56	.38	.56	KRUMM (written comm., 1995
railway station Oos O O O O O O .59 .35 .47	ILC6 railway station Oos O O O O S9 .35 .47 KRUMM (written comm., 1995) Explanations: * denotes number of excursion stop in CooMBs and Cox (1991), ‡ denotes IC data from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text), ms = white K-mica, ch = chlorite, mice from previous studies (see text)	ILC4	N Koblenz	0	0	0		0						.32	.23	.74	KRUMM (written comm., 1995
	Explanations: * denotes number of excursion stop in CooMBS and Cox (1991), ‡ denotes IC data from previous studies (see text), ms = white K-mica, ch1 = chlorite,	ILC6	railway station Oos	0	0	0		0						-59	.35	.47	KRUMM (written comm., 1995
$q_{1Z} = q_{1Z}$, $q_{0I} = q_{0IOMITC}$, $q_{0I} = $																	



grade from the zeolite to the greenschist facies (see Tab. 2, and WARR et al., 1996).

The SW samples are from a NE–SW trending traverse of the Variscan low-grade metamorphic belt of north Cornwall, south-west England (WARR and RICE, 1994). The diagenetic sample SW1 was taken from an Upper Carboniferous sequence, whereas samples SW4 and SW6 are Devonian in age. The SW samples were proposed to be used as interlaboratory standards for IC measurements (see WARR and RICE, 1994).

The samples ILC1, ILC3, and ILC5 are from the Rheinisches Schiefergebirge in Germany. Specimen ILC1 was collected near Adorf, sample ILC2 is from east and sample ILC5 from southwest of Dillenburg, Germany. Samples ILC1 and ILC3 are Upper Devonian in age, wheras sample ILC5 is of Lower Carboniferous age. The specimen ILC4 was collected north of Koblenz, Germany (all information by S. Krumm, written comm. 1995).

Results and discussion

IC DATA

In the first part of this section, we will briefly discuss IC data obtained by previous researchers and this study. The correlations between IC values obtained at Basel University and those found in other laboratoires are shown in figure 1. The best correlation coefficients were obtained with the data provided by Kisch (written comm., 1995) and with earlier data obtained at Basel University using the Philips diffractometer. A smaller correlation coefficient is observed between our data and those published by WARR and RICE (1994) and WARR (1996). Their IC values are generally larger than those obtained in this study. These observations suggest that the IC values for the diagenesis/anchizone and anchizone/epizone boundaries for data from Kisch (written comm., 1995) are very close to those from our laboratory using both the Siemens D5000 and the Philips diffractometer. Although WARR and RICE (1994) adopted limits of the anchizone of 0.42° and 0.25° $\Delta 2\Theta$ CuK α , our data are consistent with 0.37° and $0.23^{\circ} \Delta 2\Theta$ $CuK\alpha$, respectively. In addition, compared to the plots in figure 1A and B, figure 1C shows a rela-

Fig. 1 Correlations between illite crystallinity (IC) data obtained in different laboratories and this study. (a) Philips diffractometer (Basel University), (b) Kisch (written comm., 1995), (c) WARR and RICE (1994) and WARR (1996).

tively large scatter. The scatter and variability in correlations and thus in turn the different limits for the anchizone obtained from figure 1B and C presumably arose from different rock desaggregation and sample prepartion techniques used in the different laboratories. However, in order to enable interpretation of our results regarding white K-mica polytype transformation as a function of grade, the IC data obtained during the course of these investigations plus additional metamorphic indicators described in the literature were used.

The variation of IC within a single outcrop may be evaluated from table 2. The following pairs of samples show only a small variation in IC values when measurements from the same laboratory are compared: N78-47A and N78-47B, Z75-40C and Z75-40D, NZ4 and MF2839, as well as NZ9 and MF2848. A relatively large variation in IC values obtained in this study was found between samples NZ8 and MF2846 and may be due to peak broadening in sample NZ8 caused by increased mechanical grinding using a small sample size.

Ad, 1Md, 1M, AND 2M1 STRUCTURES

The percentage of $2M_1$ is obtained from the $2M_1/(2M_1 + 1M)$ ratio (see Tab. 2) and from figure 2. The calibration curve obtained in this study is similar to that provided by DALLA TORRE et al. (1994) and its quality may be estimated using the criterion suggested by these authors. They formu-

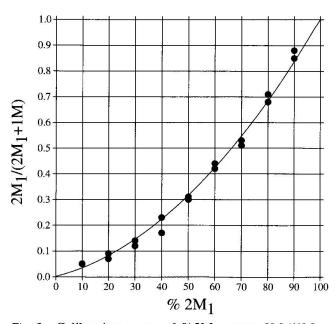


Fig. 2 Calibration curve of $\%2M_1$ versus $2M_1/(1M + 2M_1)$ used in this study.

lated an intensity factor written as $v = w_n(1-r)/r$ $(1-w_p)$, where w_p is the weight fraction of $2M_1$ in the mixture and r is the ratio $2M_1/(2M_1+1M)$ obtained from the measurements. According to DALLA TORRE et al. (1994), v should be constant for every combination of w_p and r. In the present study, we found that v is relatively constant in a range from 10 to 80% $2M_1$ polytype in the mixture. Outside this range, v displays a larger variation owing to the small amounts of $2M_1$ and 1Mpolytype in the mixture. This observation results in the fact that estimates of $\%2M_1$ outside this range $(2M_1/(2M_1+1M) < 0.15 \text{ and } > 0.7)$ display a larger uncertainty than those within this range. However, DALLA TORRE et al. (1994) estimated that the absolute error of the method lies around $\pm 2\%$ for a mixture containing equal proportions of both polytypes (see also below).

It has been agreed that IC is primarily a function of temperature and improves with increasing metamorphic grade (e.g., FREY, 1987). This statement is also true for the samples investigated here: IC values decrease with improving vitrinite reflectance in the Dachschiefer and increasing grade as determined by metamorphic mineral assemblages in the New Zealand samples (KISCH, 1980b; WARR, 1996). Moreover, chemical, XRPD, infrared, and petrological data from the Keuper and Quartenschiefer samples (HUNZIKER et al., 1986) as well as additional XRPD and petrological data from the Jämtland, SW England, and ILC samples (see KISCH, 1980a; WARR and RICE, 1994; S. Krumm, written comm., 1995) support this general trend. For these reasons, improving IC can be interpreted to reflect increasing metamorphic conditions, and it is therefore appropriate to correlate IC values with estimates of the amount of $2M_1$ in a sample.

Plots of %2M₁ versus IC for the various sample groups studied are shown in figure 3. Samples that contain disordered white K-mica structures were not considered in these plots because the amount of $2M_1$ can quantitatively not be determined (see above). In general, the data show that 100% $2M_1$ is reached at the onset of the epizone, a few exceptions excluded (see Tab. 2). Three anchizonal samples (MF131, MF703, and MF71) also contain 100% 2M₁. Except for the SW samples, the relationship between $\%2M_1$ and IC is not that obvious and correlation coefficients are generally small. However, the plots reveal that increasing $2M_1$ contents are related to decreasing IC values, i.e. increasing grade. This is even more evident if samples that contain disordered structures, established on the basis of an elevated background in XRPD patterns, are considered. Inspection of table 2 reveals that disordered polytypes prevail in samples belonging to the diagenetic zone. XRPD patterns of almost all of these samples reveal weak and diffuse 1M [112] and $2M_1$ [025] reflections indicating that a mixture of 1M and $2M_1$ is associated with a disordered polytype. XRPD patterns of ethylene glycolated preparates containing a mixture of 1M and $2M_1$ associated with disordered structures showed better resolved diagnostic ordered polytype reflections for a few samples only. No effect upon glycolation was observed for the majority of the preparates, indicating larger amounts of disordered structures than mixtures of ordered polytypes. The XRPD patterns of samples L10 and F176 show weak $2M_1$ [025] and no 1M [112] reflections upon glycolation (see Fig. 4a for diagenetic sample L10 – for comparison sample MF52 with a $2M_1/(2M_1+1M)$ ratio of 0.61 is shown in Fig. 4b). Using the criterion for the definition of the 1Md polytype (absence of diagnostic 1M reflec-

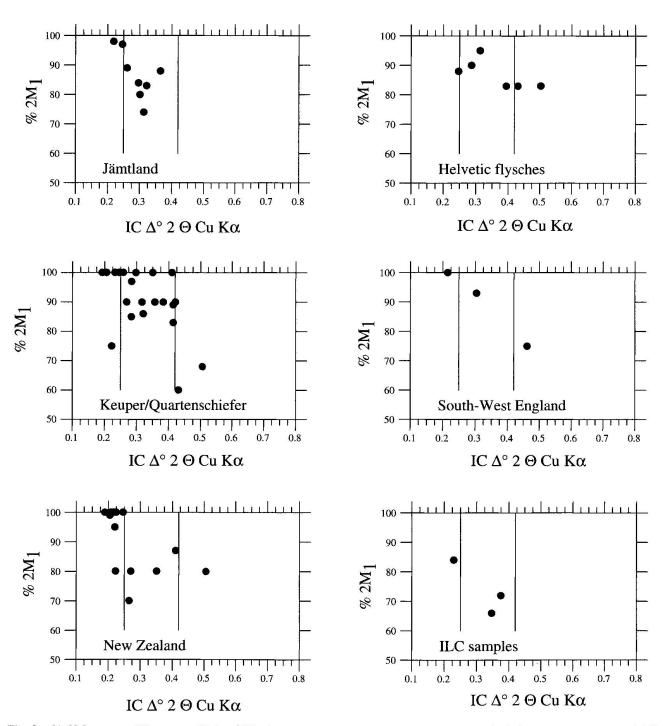


Fig. 3 % 2M₁ versus illite crystallinity (IC) data for the various sample groups studied. Solid lines between 0.25° and 0.42° $\Delta 2\Theta$ CuK α indicate the IC limits of the anchizone.

tions with $k \neq 3n$ in addition to the elevated background), this observation may indicate that both samples contain large proportions of 1Md and only a small amount of $2M_1$ structures.

In summary, our results show that according to the criteria for the definition of different polytypes most of the diagenetic samples, except samples L10 and F176, contain large amounts of disordered group A white K-micas and small amounts of a mixture composed of 1M and 2M₁. These observations suggest that the low-grade diagenetic samples are generally free of 1Md structures and that the true 1Md structure is far less abundant than previously suggested (e.g., VELDE and HOWER, 1963). Moreover, our data also indicate that the 1M structure is not a very common form of white K-mica polytypes. The 2M₁ structure prevails in most samples free of disorderd white K-mica. The largest concentrations of 1M is around 40% (sample MF23). Our observations are generally consistent with results presented by AUSTIN et al. (1989). Based on a XRPD study of K-bentonites, which are entirely diagenetic in origin, these autors found that Ad and mixtures of 1M and 2M₁ structures are the dominant polytype forms, whereas the 1Md structure is relatively rare.

The reproducibility of the method as well as the variation in the content of a specific polytype within an individual outcrop may be estimated from table 2. As previously mentioned, there are five pairs of samples each of which was collected from the same outcrop. The variation in $\%2M_1$ for most of these samples is $\pm 2\%$ or smaller (N78-47A and N78-47B, Z75-40C and Z75-40D, NZ4 and MF2839, NZ8 and MF2846). For the pair of samples NZ9 and MF2848, the variation is of the order of $\pm 4\%$. These observations suggest that the method proposed by DALLA TORRE et al. (1994) is capable to estimate relative proportions of 1M and $2M_1$ in samples free of disordered white K-mica structures with a fairly high degree of reliability. Moreover, individual outcrops appear to be homogeneous with respect to a specific polytype concentration.

BRINDLEY (1980) as well as SRODON and EBERL (1984) suggested that 1Md structures may exist only if smectite is interlayered with white Kmica. AUSTIN et al. (1989), however, found that smectite interstratification is not a necessary condition for the presence of a disorderd polytype. During the course of this study, disordered structures were observed in 14 samples, 12 of which contain mixed-layer illite/smectite. This observation suggests that the presence of smectite interstratification favours disorder in white K-mica.

EVOLUTION OF WHITE K-MICA POLYTYPES AS A FUNCTION OF TEMPERATURE

In the laboratory, YODER and EUGSTER (1955), VELDE (1965), and MUKHAMET-GALEYEV et al. (1986) have found that the 1Md \rightarrow 1M \rightarrow 2M₁ white K-mica polytype transformation is a function of temperature. Also on a regional scale many workers found that increasing amounts of 2M₁ are related to an increase in metamorphic grade in terms of temperature (for references, see DALLA TORRE et al., 1994; RUIZ CRUZ and ANDREO, 1996). A literature compilation by FREY (1987) showed that the conversion from 1Md towards

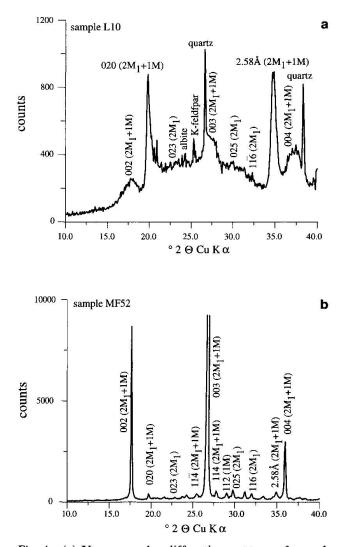


Fig. 4 (a) X-ray powder diffraction pattern of sample L10 after 128 hours in glycolated atmosphere. The elevated background between 20° and $33^{\circ} 2\Theta$ CuK α is clearly visible. No 1M [112] peak can be detected, however, a weak $2M_1[025]$ reflection does occur. For further details see text. (b) X-ray powder diffraction pattern of sample MF52 showing discrete 1M [112] and $2M_1[025]$ reflections in addition to a low background and well resolved 00l peaks.

2M₁ is completed at approximately the anchizone/epizone boundary. These previous studies based the evaluation of the relative amount of $2M_1$ versus 1Md or 1M on criteria developed by YODER and EUGSTER (1955) and LEVINSON (1955) or on methods that used different peak intensity ratios (VELDE and HOWER, 1963; REYNOLDS, 1963; MAXWELL and HOWER, 1967). However, two recent studies (AUSTIN et al., 1989; DALLA TORRE et al., 1994) showed that the criteria to distinguish between Ad, 1Md, 1M, and 2M₁ used in this study are more useful than the ones presented in earlier studies. On the basis of these criteria our data suggest that in the diagenetic zone Ad structures prevail and are transformed into mixtures of 1M and 2M₁ structures in the anchizone. As grade increases, the amount of 1M polytype decreases in favour of 2M1 structures until, at epizonal grades, all 1M is converted to 2M₁ structures.

Conclusions

Based on methods developed by previous researchers, many workers concluded that 1Md is a common structure of illite in sedimentary rocks under diagenetic conditions. A recent study by AUSTIN et al. (1989) proposed, however, based on new criteria to differentiate between 1Md and Ad structures, that 1Md is less common than previously suggested. The data obtained in this study are consistent with their observations. At diagenetic grade, newly formed white K-mica crystals generally exhibit disorder. In most cases, these structures belong to the disordered group A micas (Ad) according to the terminology by BAILEY (1988) and AUSTIN et al. (1989). At diagenetic grades, Ad structures prevail and are associated with small amounts of mixtures of 1M and 2M₁ polytypes. Our study further suggests that disorder in white K-mica is favoured by the presence of smectite interstratifications. Disordered structures do not occur at anchizonal grades, but a mixture of 1M and $2M_1$ white K-mica polytype with larger proportions of the latter prevails. 90% of the anchizonal samples studied exhibit 2M₁ concentrations that cover the range from 70 to 90%. At the onset of the epizone, 100% 2M₁ are generally reached, although there are a few exceptions to this rule. At IC values smaller than $0.2^{\circ} \Delta 2\Theta$ $CuK\alpha$, 1M structures were not found in any of the samples studied. The 1M polytype generally appears to be less common than the 2M₁ structure, even at lower grades. The results obtained in this study show that with improving illite crystallinities, white K-mica crystals evolve from Ad structures in the diagenetic zone to a mixture of 1M and $2M_1$ with variable but larger proportion of the latter in the anchizone to 100% $2M_1$ in the epizone. Thus, determination of white K-mica polytypes appears to be a useful indicator to determine the grade of metamorphism of sedimentary rocks metamorphosed at low-temperature conditions.

Acknowledgements

We wish to thank Hanan J. Kisch, Laurence N. Warr and Stefan Krumm for providing samples as well as IC data obtained in their laboratories. Without them this study would have been impossible. We also wish to thank Willem B. Stern for his help in various matters in the Xray lab. The manuscript benefitted from the critical reviews by Hanan J. Kisch, Laurence N. Warr, and Rolf Nüesch. This study was financed in part by the Swiss National Science Foundation, grant 20-37'344.93.

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Manuscript received October 14, 1996; revised manuscript accepted April 28, 1997.