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The Permian-Triassic of the Gartnerkofel-1 Core (Carnic Alps, Austria): Illite Crystallinity in Shaly Sediments and its Comparison with Pre-Variscan Sequences

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With 5 Text-Figures and 3 Tables

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Carinthia
Carnic Alps
Diagenesis
Very low-grade metamorphism
Illite crystallinity

Contents

Zusammenfassung

Mittelwerte der Illit-Kristallinität [IC] (KUBLER-Index) aus permischen (Bellerophon Formation) und skythischen (Werfen Formation) marinen Mergelschiefern der Forschungsbohrung Gartnerkofel-1 (Zentrale Karnische Alpen, Österreich) lassen generell auf die pT-Bedingungen einer fortgeschrittenen Diagenese schließen (n = 56; IC_{Mean} = 0,62°δ2Θ; Standardabweichung = 0,091). Die Proben wurden innerhalb einer vertikalen Distanz von 241,12 Metern entnommen. Unabhängig von Präparationseffekten (jeweils gleiche Belegungsdichten der sedimentierten Präparate, Fraktion<2 µm) festgestellte Trends zeigen mit steigenden Karbonatgehalten (Gesamtgestein) bei Illiten bzw. Muscoviten jeweils bessere Gitterordnungsgrade sowie kleinere b_0-Werte. Wenn auch die karbonatreicheren Gesteine an der Perm/Trias-Grenze (Tesero-Horizont, 6,5 Meter mächtig) generell bessere Gitterordnungsgrade (mit Werten im anchizonalen Feld) aufweisen, so liegt die Streuung sämtlicher Mittelwerte (IC: 0,74–0,34°δ2Θ) doch innerhalb der natürlichen Varianz von Küsten- und Schelfsedimenten, was auch in nicht metamorphen vergleichbaren permoskythischen Abfolgen der Ostalpen beobachtet wurde: Dabei haben sich in den Glimmer-Detrituskernen die ererbten metamorphen Prägungsgrade der jeweiligen terrestrischen Liefergebiete mit guten Gitterordnungsgraden (IC<0,42°δ2Θ) erhalten, wohingegen die Illit-Anwachssäume die physikalisch-chemischen Bedingungen der postdiagenetischen Sedimententwicklung widerspiegeln. Dies bedeutet bei dem relativ geringen Sedimentstapel über dem südalpinen Permoskyth also mäßige bis schlechte Gitterordnungsgrade (IC>0,42°δ2Θ). „Echte" anchizonale Bedingungen (im Zuge einer etwa frühalpinen Regionalmetamorphose) hätten ausgereicht, die Gitterbauordnungen der Kalihellglimmerindividuen und -populationen des südalpinen Permoskyth der Karnischen Alpen je nach Ionenverfügbarkeit mit zunehmender Versenkungstiefe weitgehend zu äquilibrieren. Eine solche regionalmetamorphe Angleichung beginnt jedoch erst in den liegenden präpermischen Formationen (Devon/Karbon-Grenze).

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Für die Deutung einer „transportierten“ Anchimetamorphose im südalpinen Permoskyth sprechen auch die geringe Beteiligung von Muscovit 1Md Polytypen gegenüber den $2M_1$–Typen sowie vereinzelt noch nicht wegreagierte mixed-layer Anteile von Montmorillonit (bis 10 %) im höheren Abschnitt der Werfen Formation. Auch wenn die Smektit-Phasen teilweise im Zuge postdiagenetischer Degradationsprozesse (bis rezent) gebildet worden sein könnten, wird aufgrund der hiesigen Gesamtdaten verglichen mit anderen Lokalitäten (siehe H.J. KISCH, 1987: Tab. 7.1 ff.) auf eine thermische Beeinflussung im Bereich zwischen mindestens 130°C und maximal 180–200°C geschlossen. Dies entspräche einer maximalen Gesteinsüberlagerung um 4000 Meter, wovon im Gartnerkofelbereich bis rezent bereits rund 3300 Meter abgetragen worden wären.

Mit der Anlieferung eines entsprechenden detritischen Materials werden die deutlich besseren, gleichzeitig geringer streuenden IC-Werte (< 0,42°δ2Θ) an der Perm/Trias-Grenze (Tesero-Horizont: 6,5 Meter) in Zusammenhang gebracht. Neben der Interpretation durch selektive Detrituslieferung (Detrituskerne mit „ererbter“ Anchimetamorphose und diagenetischen Anwachssäumen) sind auch Wachstumseffekte der extrem feinkörnigen Illite zu „dickeren“ Kristalliten („Ostwald ripening“) denkbar. Der Deutung durch Überlagerungsdruck (sedimentär und tektonisch), oder durch wie auch immer verursachten erhöhten Wärmefluß (200–250°C), widerspricht die in der darunterliegenden Bellerophon Formation schlechtere und wiederum stärker streuende IC.

Abstract

Illite crystallinity [IC] data (KUBLER-index) in Upper Permian (Bellerophon Formation) and Lower Triassic (Werfen Formation) marine shaley sediments from the drill-core Gartnerkofel-1 (central Carnic Alps, Austria) mainly indicate advanced diagenetic conditions (n = 56; IC_{mean} = 0.62°δ2Θ; standard deviation = 0.091). Independent of any preparation effects, the samples of lower carbonate content had poorer IC. The variance of all IC_{mean} values from bottom to top (IC 0.74–0.34°δ2Θ) is caused mainly by lithological factors and is typical for the diagenetic realm.

Thus, cores of detrital white micas preserved the inherited metamorphic conditions from their continental source areas and show good IC orderings (IC<0.42°δ2Θ). In post-diagenetic illite growth fringes poor crystallinity (IC>0.42°δ2Θ) is manifest, due to the small overburden overlying the south-Alpine Permo-Triassic. The thermal conditions during Alpine metamorphism, however, have been too low to approximate the varying grades of IC in the Permian/Lower Triassic sediments of the Carnic Alps.

Equilibration of IC, as a result of regional anchimetamorphism, begins stratigraphically deeper – as noted in the nearby Kronhofgraben section – at the Devonian/Carboniferous boundary. Scarce 1Md illite polytypes ($2M_1$ illite polytypes are common) as well as the presence of mixed-layer illite/smectite (<10 %) in the uppermost parts of the Werfen Formation are in good agreement with this interpretation. Setting one result against the other, the thermal conditions – generally suffered in the Gartnerkofel-1 core – can be constrained to between 130°C and 200°C by comparison with various well-studied localities (H.J. KISCH, 1987: Tab. 7.1 f.). This corresponds to an estimated Mesozoic overburden of about 4000 meters, of which about 3300 meters have been eroded up to the present.

At the Permian/Triassic boundary (6.5 m Tesero Horizon) IC increases distinctly. Burial and heat flow cannot explain the temperature rise (200–250°C), especially as the IC in the underlying Bellerophon Formation (undisturbed contact with the Tesero Horizon) are also low, with large variance. There is no evidence of shear – influencing IC – just confined to the Tesero Horizon.

The anomaly may be interpreted as follows:

1) Detrital mica-cores (preserving inherited anchimetamorphism from continental source areas) predominate against post-diagenetic illite growth-fringes (with poor IC).

1. Introduction

In the Carnic Alps no detailed study of the degree of metamorphic alteration has been carried out previously. This investigation, based on core material, is therefore of intrinsic interest, and supplements the other research described in this volume.

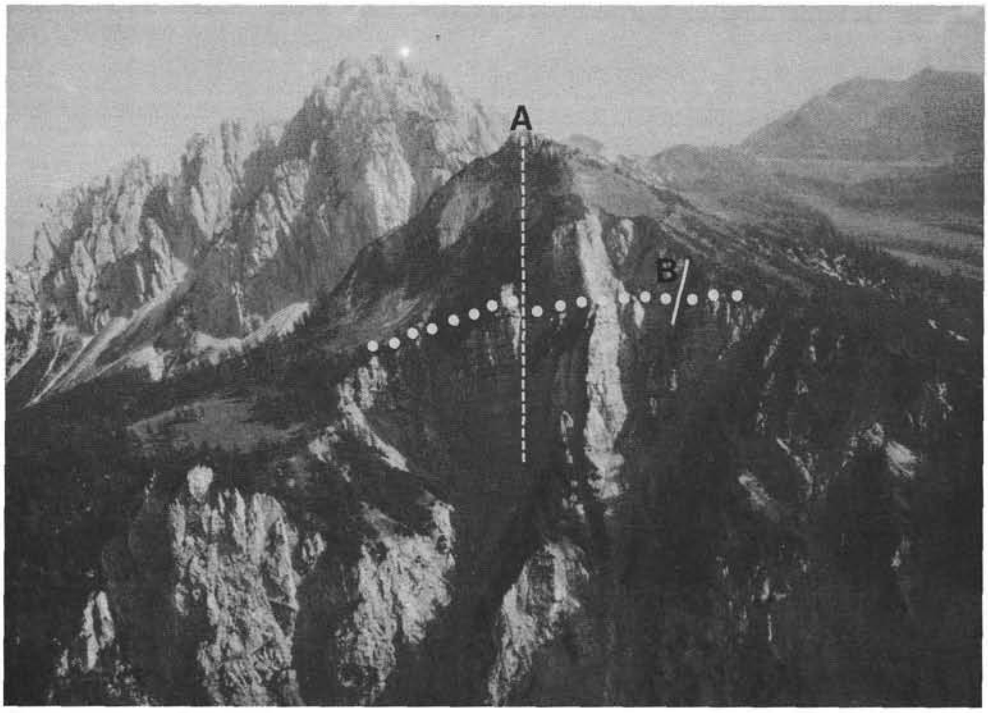
The intent was to study illite crystallinity and to determine the illite polytypes and selected lattice constants of illite or muscovite to provide information about the degree of metamorphism. The results allow comparison with adjacent very low-grade metamorphic regions on both sides of the Periadriatic Line (Devonian/Carboniferous sediments of Kronhofgraben and Grüne Schneid, and Permo-Mesozoic sediments of the Drauzug: G. NIEDERMAYR et al., 1984, and Middle and Eastern Carinthia: J.-M. SCHRAMM et al., 1982, and the Northern foreland of the Karawanken: W.v. GOSEN, J. PISTOTNIK & J.-M. SCHRAMM, 1987), and to consider the question of heat transfer in that region during the Alpine orogeny. For this purpose 85 samples have been analysed, of both clastic and carbonate rocks (56 samples from the Gartnerkofel-1 core [Text-Fig. 1], 29 samples from outcrops in the Kronhofgraben and Grüne Schneid [provided by H.-P. SCHÖNLAUB]).

2. Methods

Sets of 56 samples from the 330 m core at Gartnerkofel-1 and 29 samples from the sections at Kronhofgraben and Grüne Schneid were selected for investigating the diagenetic and very low grade metamorphic conditions.

For analysis all samples were ground to powder. Any carbonate was removed with HCl (dilution 1 : 10). The residues were separated by sedimentation in ATTERBERG cylinders to obtain clay fractions (<2 µm). Oriented samples were prepared by air-drying the clay suspension on glass slides.

After treating the preparate in an ethyleneglycol steam bath at 50°C overnight, illite crystallinity (IC) was determined on a SIEMENS X-ray diffractometer type F under the following recording conditions: $CuK_{\alpha1}$–radiation, 40 kV, 30 mA, Ni-filter, scintillation counter, slits 1°/0.25°, time constant 2 sec, sensitivity 1×10^3–4×10^2, goniometer 2.5°/min, chart speed 50 mm/min. The “illite crystallinity ordering” was measured at the half-height width of the 10 Å basal reflection at least 10 times and converted to °δ2Θ. The system was calibrated with the interlaboratory standard MF1046–1, provided by M. FREY, Basle. The proportions of the $2M_1$ il-



Text-Fig. 1.
Aerial photograph from the north of the Reppwand with the Gartnerkofel (2195 m) in the background.
A: Drill site on Kammleiten (1998 m); B: Top of the outcrop section.
Dotted line indicates the Permian–Triassic boundary between the Bellerophon Formation (below) and the Werfen Formation above.
Photo: G. FLAJS, Aachen.

lite polytype were estimated according D.T. MAXWELL & J. HOWER (1967) from the illite peak ratio I(2.80 Å)/I(2.58 Å).

The *b* unit cell dimensions were determined by visually measuring (average error ± 0.005°2Θ) the positions of (060) reflections using quartz as an internal standard. Guinier-Camera (ENRAF-NONIUS FR522) conditions: $\mathrm{CuK}_{\alpha 1}$–radiation, 40 KV, 20 mA, Johanson quartz-monochromator.

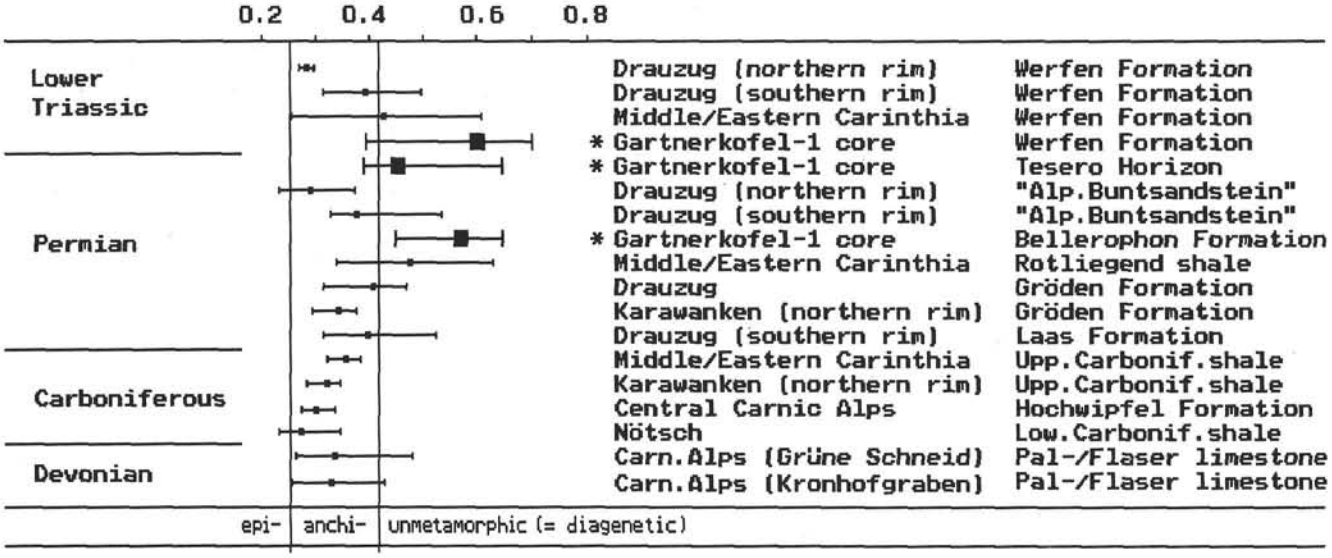
3. Results and Discussion

3.1. Illite Crystallinity (IC)

According to B. KUBLER (1967, 1984) the IC is defined by the angular half-height width in °δ2Θ of the first order "illite" (K-mica) basal reflection at half-maximum intensity. M. FREY (1987) summarizes the limiting values for the high-grade and low-grade boun-

Table 1.
Limiting values of IC (KUBLER-index).
W. SMYKATZ-KLOSS & E. ALTHAUS (1975) suggested that temperature – crystallinity correlations obtained in experiments can not yet be applied to any natural occurrence, but show the order of magnitude in which changes are to be expected.

DIAGENESIS	
	7.5 mm = 0.42°δ2Θ ≈ ca. 200°C
ANCHIZONE	= very low-grade metamorphism
	4.0 mm = 0.25°δ2Θ ≈ ca. 300°C
EPIZONE	= low-grade metamorphism (sensu H.G.F. WINKLER)

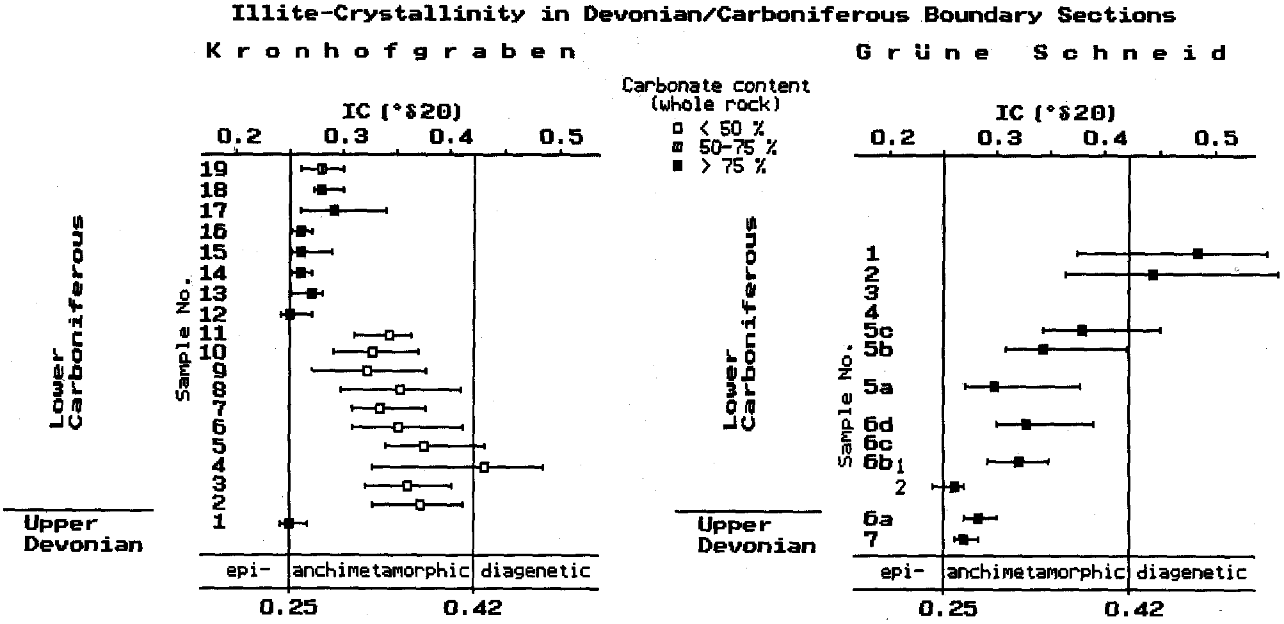


Text-Fig. 2.
Distribution of IC (KUBLER-Index) in Devonian, Carboniferous (Grüne Schneid, Kronhofgraben), Permian and Lower Triassic (Gartnerkofel-1 core, subdivided) shaley sediments of the Carnic Alps in comparison with IC data of the Drauzug (G. NIEDERMAYR et al., 1984), Middle and Eastern Carinthia (J.-M. SCHRAMM et al., 1982) as well as the Northern foreland of the Karawanken (W.v. GOSEN, J. PISTOTNIK & J.-M. SCHRAMM, 1987).
Squares represent mean values, lines indicate the range of IC values.

Table 2.
IC data from the sections Kronhofgraben (n = 19; mean = 0.32; standard deviation = 0.0513) and Grüne Schneid (n = 10; mean = 0.33; standard deviation = 0.0731). IC_{mean} of each sample computed from at least 10 measurements. Samples provided by H.P. Schönlaub. The horizontal position represents stratigraphically equivalent samples.

Kronhofgraben					Grüne Schneid				
Sample no.	IC_{min} °δ2Θ	IC_{mean} °δ2Θ	IC_{max} °δ2Θ	Carbonate content [%]	Sample no.	IC_{min} °δ2Θ	IC_{mean} °δ2Θ	IC_{max} °δ2Θ	Carbonate content [%]
19	0.26	0.28	0.30	74.1					
18	0.27	0.28	0.30	85.0					
17	0.26	0.29	0.34	91.6					
16	0.25	0.26	0.27	94.4					
15	0.25	0.26	0.29	92.3	1	0.37	0.48	0.56	96.0
14	0.25	0.26	0.27	75.2	2	0.36	0.44	0.57	96.9
13	0.25	0.27	0.28	86.8	3		---		
12	0.24	0.25	0.27	77.7	4		---		
11	0.31	0.34	0.36	2.1	5c	0.34	0.38	0.45	95.4
10	0.29	0.33	0.37	1.6	5b	0.31	0.34	0.42	95.6
9	0.27	0.32	0.38	2.1					
8	0.30	0.35	0.41	5.0	5a	0.27	0.30	0.38	91.4
7	0.31	0.33	0.38	1.2					
6	0.31	0.35	0.41	3.0	6d	0.30	0.35	0.39	90.5
5	0.34	0.37	0.43	1.5	6c		---		
4	0.33	0.43	0.47	1.6	6b	0.29	0.32	0.35	93.2
3	0.32	0.36	0.40	1.5		0.24	0.26	0.27	93.2
2	0.33	0.37	0.41	2.0					
1	0.24	0.25	0.27	80.9	6a	0.27	0.28	0.30	96.8
					7	0.26	0.27	0.28	96.7

dary of the anchimetamorphic zone (Table 1). The high-grade limit of the anchimetamorphic zone can be narrowed to around 300°C (by fluid inclusion data), and the low-grade limit by correlation with the onset of the prehnite-pumpellyite facies around 200°C (H.J. Kisch, 1987). Factors affecting IC are: temperature (as the most important physical influence), lithology (especially in the diagenetic realm), stress; and additionally: time, illite chemistry, fluid pressure, interfering basal reflections and experimental conditions.



Text-Fig. 3.
Vertical trends of IC in Devonian and Carboniferous shaley sediments of the Carnic Alps (sections Kronhofgraben and Grüne Schneid).
Vertical intervals in the Kronhofgraben section (sample no. 1–19): 1.39 m; in the Grüne Schneid section (sample no.7–1): 1.40 m; distances between samples not to scale! Each square represents a mean calculated from at least 10 IC measurements. The higher the carbonate contents, the higher generally the IC.

Not long ago D.D. EBERL & B. VELDE (1989) proposed a modified "crystallinity" index, using REYNOLD'S NEWMODE computer program to construct a grid with which the illite X-ray scattering domain size and illite structural distortions (especially swelling) can be determined indepentently from measurements of the 001 peak width at half-height and the SRODON intensity ratio. This method was not applicated in this study.

Whereas the Devonian and Lower Carboniferous sequence of the Carnic Alps (Kronhofgraben and Grüne Schneid sections) has suffered chiefly anchimetamorphic conditions, the majority of IC-values from the Permian/Lower Triassic sequence (Gartnerkofel-1 core) is distributed in the advanced diagenetic realm and indicates very low-grade conditions (Text-Fig. 2).

3.1.1. Upper Devonian and Lower Carboniferous Sediments (Kronhofgraben and Grüne Schneid Sections)

In the Kronhofgraben section anchimetamorphic influence continues up to the top (Lower Carboniferous), whereas in the Grüne Schneid section the anchimetamorphic conditions decrease to diagenetic in its uppermost part. The very low-grade metamorphic overprint caused moderate equilibrations of the sheet-silicate crystallinity ordering. Table 2 summarizes IC-data of Upper Devonian/Lower Carboniferous sequences from the Kronhofgraben and Grüne Schneid sections.

The anchimetamorphic realm shows vertical trends of decreasing IC ordering (with typically increasing variances) from the bottom to the top of the observed sections (Text-Fig. 3), also regarding the carbonate contents. Besides, the trend in the uppermost part of the Kronhofgraben section differs from that of Grüne Schneid section due to the further fact, that the Devonian/Carboniferous formations of Kronhofgraben are in a deeper tectonic position in the pile of thrust sheets of the Carnic Alps.

3.1.2. Upper Permian and Lower Triassic Sediments (Gartnerkofel-1 Core)

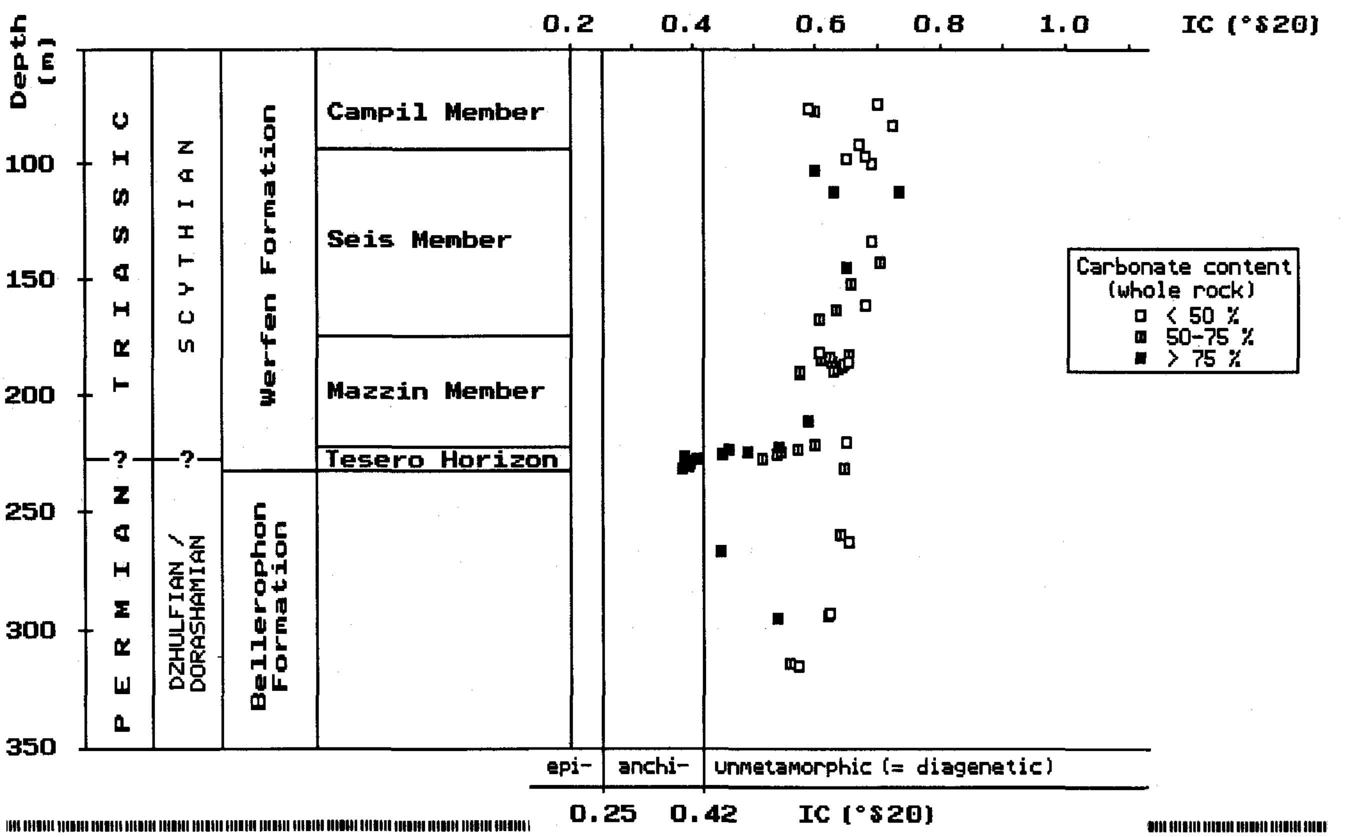
Table 3 contains the complete data-set of IC, b_0, illite intensity ratio I(002)/I(001) and carbonate content ordered according to depth in the Gartnerkofel-1 core. Generally these higher stratigraphic formations of the central Carnic Alps have not been affected by anchimetamorphism.

As common in non-metamorphic series (for instance Northern rim of the Northern Calcareous Alps: J.-M. SCHRAMM, 1982b; M. KRALIK, H. KRUMM & J.-M. SCHRAMM, 1987; external parts of the Swiss Alps: M. FREY et al., 1980; North Wales: R.J. MERRIMAN & B. ROBERTS, 1985; northwestern Morocco: E. WYBRECHT et al., 1985; southwestern Gaspé/Quebec: D. DUBA & A.E. WILLIAMS-JONES, 1983), IC ordering in the Gartnerkofel-1 core varies widely among adjoining samples at intervals of centimeters to few meters. The determined values of any single sample vary due to the specific petrology of the source area, and environmental conditions. Nevertheless a slight trend of decreasing IC may be detected from bottom to the top of the Permo-Scythian sequence within an interval of 241.12 meters (Text-Fig. 4). Scarce 1Md illite polytypes ($2M_1$ illite polytypes are common) as well as <10 % mixed-layer illite/smectite in the uppermost parts of the Werfen Formation emphasize this trend. The trend, the lower the carbonate content (whole rock) the poorer the IC, was recognized independant of any preparation effects. M. KRALIK, H. KRUMM & J.-M. SCHRAMM (1987) observed that same feature earlier in Mesozoic pelites of the Northern Calcareous Alps.

Table 3.
IC and b_0 data from the Gartnerkofel-1 core.
Intensity ratio 002/001 according to J. ESQUEVIN (1969).

Sample no.	Depth [m]	IC_{min} °δ2Θ	IC_{mean} °δ2Θ	IC_{max} °δ2Θ	b_0 [Å]	Int.ratio 002/001	Carbonate content [%]
12	74.40	0.56	0.70	0.75	9.004	0.22	27.4
14	75.90	0.50	0.59	0.72	9.019	0.25	40.1
15	76.30	0.49	0.60	0.71	9.015	0.28	54.4
19	82.60	0.66	0.72	0.80	9.019	0.25	9.2
25	90.30	0.64	0.67	0.74	9.012	0.27	42.4
28	95.30	0.60	0.68	0.74	9.016	0.24	37.1
29	95.90	0.55	0.65	0.77	9.022	0.19	31.0
31	97.40	0.64	0.69	0.79	9.025	0.23	31.7
37	103.78	0.54	0.60	0.71	9.023	0.30	74.6
44	113.20	0.67	0.73	1.01	9.015	0.22	82.9
44A	113.20	0.55	0.63	0.98	9.022	0.24	81.9
59	134.53	0.60	0.69	0.83	9.017	0.23	37.5
66	142.74	0.64	0.70	0.86	9.014	0.22	73.4
69	145.08	0.59	0.65	0.81	9.019	0.17	84.0
74	152.57	0.61	0.66	0.79	9.021	0.22	54.6
81B	162.36	0.59	0.68	0.72	9.015	0.22	48.7
82	163.88	0.60	0.63	0.72	9.017	0.24	57.6
86	167.98	0.53	0.60	0.64	9.015	0.20	60.8
100	181.57	0.52	0.60	0.63	9.023	0.36	37.0
101	182.00	0.64	0.65	0.83	9.012	0.27	46.9
104B	183.28	0.60	0.62	0.78	9.016	0.28	50.1
106	183.51	0.53	0.61	0.75	9.008	0.23	61.7
112	184.80	0.59	0.63	1.02	9.025	0.24	46.3
117	185.57	0.57	0.65	0.78	—	—	8.9
118B	185.65	0.59	0.64	0.73	9.011	0.20	10.4
124	186.85	0.61	0.64	0.82	9.006	0.22	60.9
131	188.15	0.51	0.64	0.72	9.014	0.25	15.2
133	188.52	0.47	0.63	0.66	9.021	0.16	22.0
136	189.30	0.52	0.57	0.78	9.015	0.33	68.0
138	189.80	0.55	0.57	0.87	9.015	0.21	80.3
175	211.85	0.56	0.59	0.76	9.001	0.28	77.8
190	220.35	0.52	0.65	.70	9.010	0.24	44.9
190C	220.90	0.58	0.60	0.77	9.013	0.17	68.8
191B	221.34	0.41	0.54	0.60	9.014	0.23	75.8
191E	221.80	0.48	0.57	0.69	9.006	0.18	68.0
191F	222.05	0.38	0.54	0.56	8.993	0.19	69.8
193	222.20	0.50	0.54	0.68	—	—	67.4
194A	222.46	0.36	0.46	0.57	8.996	0.20	88.8
194C	223.02	0.38	0.49	0.58	0.003	0.19	84.0
194D	223.33	0.34	0.45	0.51	9.003	0.18	92.9
195A	224.04	0.28	0.39	0.46	9.003	0.18	84.8
196	224.52	0.51	0.52	0.67	9.009	0.19	54.5
196B	225.01	0.35	0.41	0.48	8.999	0.19	98.2
198C	227.02	0.37	0.40	0.44	9.002	0.19	99.3
201A	229.22	0.32	0.40	0.46	—	—	95.1
202A	229.74	0.34	0.40	0.48	9.002	0.21	92.6
204A	230.04	0.26	0.39	0.49	8.994	0.20	92.2
205	230.95	0.54	0.65	0.78	9.009	0.23	58.0
232	259.50	0.59	0.64	0.75	9.006	0.30	63.0
236	263.54	0.60	0.65	0.75	9.010	0.30	40.2
238	266.80	0.42	0.45	0.61	9.017	0.19	82.3
262	292.30	0.37	0.62	0.64	—	—	26.0
265	294.80	0.49	0.62	0.84	9.021	0.21	47.0
267	295.95	0.38	0.54	0.77	9.011	0.25	76.0
284	314.86	0.54	0.56	0.73	—	—	68.2
286	315.52	0.56	0.57	0.79	0.012	0.21	2.3

As recognized in numerous thin sections of Permo-Scythian pelites (with similar IC) of the Northern Calcareous Alps (J.-M. SCHRAMM, unpublished), also in the GK-1 samples cores of detrital micas may have preserved the inherited metamorphic conditions from their continental source areas and tend therefore to better illite crystallinity orderings (IC<0.42°δ2Θ), as confined



Text-Fig. 4.
Variation and general trend of IC data (n = 56; mean = 0.62; standard deviation = 0.0912) in the Gartnerkofel-1 core.
Each square represents the mean of at least 10 measurements. Note the extraordinary IC values at the Permian/Triassic boundary, as well as the trend, the higher the carbonate content the better the IC.

to the Tesero Horizon. On the other hand, illite growth fringes may suggest younger formations, and reflect the physical conditions of burial history of the sediments better. Due to the small overburden at the top of the southalpine Permo-Scythian, estimated at about 4000 meters (maximum burial depth), the post-depositionally formed illites have poor crystallinity ($>0.42°\delta 2\Theta$). The thermal conditions during Alpine metamorphism, however, were insufficient to account for the varying grades of IC in the Upper Permian/Lower Triassic sediments of the Carnic Alps.

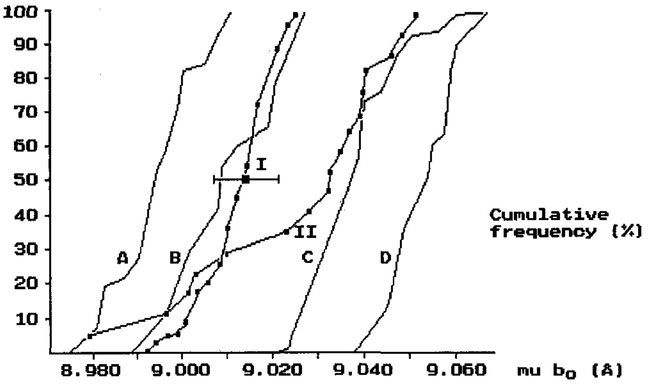
At the Permian/Triassic boundary (Tesero Horizon) IC distinctly increases for 6.5 meters (sample 204A: lowest IC-value of 10 measurements: 0.26, IC_{mean} = 0.39).

3.2. K-mica b_0 Spacings

A series of authors attempted to calibrate the b_0 cell parameter of K-mica ("illite") as a geobarometer for pelitic rocks in the epi- and anchizone (C.V. GUIDOTTI & F.P. SASSI, 1976, 1986; A. PADAN, H.J. KISCH & R. SHAGAM, 1982). Although M. FREY et al. (1983) and M. FREY (1987) express some reservations regarding the K-mica b_0 geobarometer, the method should be valid, if the b_0 spacings of a large number of samples with similar alteration grade are determined with a small standard deviation – as is the case in the Gartnerkofel-1 core. M. FREY (1987) summarizes the relation between b_0 and pressure:

$b_0 < 9.000$ Å: low-pressure facies series
9.000 Å $< b_0 < 9.040$ Å: intermediate-pressure facies series
$b_0 > 9.040$ Å: high-pressure facies series

The K-mica b_0 parameters of 53 samples (listed in Table 3) vary between 8.993 and 9.025 Å (standard deviation: 0.0079 Å). Therefore all analysed micas of the Gartnerkofel-1 core are muscovites (the phengite field after C. CIPRIANI et al., 1968, lies above 9.025 Å). The mean b_0 value of 9.012 Å and the cumulative frequency curve I (Text-Fig. 5) correspond with the reference curve B (New Hampshire) (F.P. SASSI & A. SCOLARI,



Text-Fig. 5.
Cumulative frequency curves of b_0 cell parameters of muscovites from the Gartnerkofel-1 core shales (I) in comparison with those of low- and very low-grade Permoscythian pelites of the Northern Calcareous Alps (II) (J.-M. SCHRAMM, unpublished) and reference curves A (Bosost), B (New Hampshire), C (Eastern Alps) and D (Sanbagawa) (F.P. SASSI & A. SCOLARI, 1974).

1974), pointing to a low- to intermediate-pressure metamorphism. A series of authors observed the correlation, that the higher the carbonate content, the lower the b_0 value. Taking this trend into account (shifting the frequency curve I to higher b_0 values between reference curve B and C), the estimate of pressure doubles. Applying the method uncritically, pressures of more than 2 kb would be deduced. But the overburden of about 4000 meters, as reconstructed for the post-Scythian sequences of the Carnic Alps, corresponds to pressures of 1.0–1.5 kb, which seems a more realistic conclusion.

3.3. Illite Polytypes

With advanced diagenesis or incipient metamorphism illite polytypes transform from 1Md towards $2M_1$. This progression has been noted by many authors (D.T. MAXWELL & HOWER, 1967; J.-M. SCHRAMM, 1982a; R.J. MERRIMAN & B. ROBERTS, 1985; J.C. HUNZIKER et al., 1986).

3.3.1. Upper Devonian and Lower Carboniferous Sediments (Kronhofgraben and Grüne Schneid sections)

Only $2M_1$ illite (respectively muscovite) polytypes have been detected; 1Md illite polytypes have been completely converted to $2M_1$ polytypes.

3.3.2. Permian and Lower Triassic sediments (Gartnerkofel-1 Core)

The $2M_1$ illite (muscovite) polytype is common. In the uppermost parts of the Werfen Formation the 1Md illite polytype is scarce.

4. Conclusions

4.1. Upper Devonian and Lower Carboniferous Sediments (Kronhofgraben and Grüne Schneid Sections)

IC orderings and variances in both sections indicate very low grade metamorphic (= anchimetamorphic) conditions. The very first beginning equilibration of muscovite chemistry in the carbonates and shales typically manifests the onset of anchimetamorphism. Due to the deeper tectonic position of the section Kronhofgraben IC_{mean} remains constant, whereas in the Grüne Schneid section anchimetamorphism deceases in its very uppermost part (Lower Carboniferous).

4.2. Upper Permian and Lower Triassic Sediments of the Gartnerkofel-1 Core

The majority of IC-data from the Gartnerkofel-1 core indicate diagenetic conditions ($IC_{mean} > 0.42°\delta 2\Theta$). Also in view of the disappearence of smectite bearing phases, and the nearly complete $1Md \rightarrow 2M_1$ illite polytype conversion, in comparison with numerous well studied localities (H.J. KISCH, 1987: Fig. 7.1 f.), the thermal conditions can be narrowed to a range between 130°C and 200°. The sharply increased IC ordering (corresponding to anchimetamorphic grades: $< 0.42°\delta 2\Theta$) at the Permian/Triassic boundary (Tesero Horizon) might be interpreted in several ways:

1) Detrital muscovites were transported from an anchimetamorphic continental source area to their present position and preserve an inherited anchimetamorphism. According to Text-Fig. 2, many outcrops of Carboniferous–Lower Permian sediments could have been the source of very low grade altered illite – assuming that a majority of those rocks at Late Permian already have been metamorphosed, but not all. These rocks probably cropped out very generally in the drainage, throughout the Bellerophon–Werfen time. A strong regression at the Permian/Triassic boundary (W. T. HOLSER & M. MAGARITZ, 1987) may have increased erosion on the continental source area, transporting and depositing the specific metamorphosed, detrital micas. During their syn- and postdepositional history the detrital muscovites resp. illites underwent differing evolutions (aggradation, degradation), dependent on chemical and physical factors, controlled by exo-and endogenic mutual effects in the paleogeographical environment. The present IC values are partial results of those specific evolutions of illites.
2) Detritus with very fine grained distribution evolved to thicker crystals. As D. D. EBERL & J. SRODON (1988) carried out, the mechanism of Ostwald ripening can account for alteration processes of illite, characterized by the simultaneous growth and dissolution of particles (minerals) within a single medium.
3) Overburden was increased by Alpine overthrusting, which raised the temperature and caused aggradation of illites. This interpretation seems unlikely, because an increased overburden would also affect the underlying sequence. The Bellerophon Formation underlies the Tesero Horizon undisturbed, but nevertheless shows only diagenetic alteration.
4) Similarly locally limited, temporary increase of the thermal gradient (enhanced heat flow) would also trigger anchimetamorphic reactions in the underlying formations. The lower grade of alteration in the Bellerophon Formation takes this consideration out of question.
5) Increasing IC may have been caused by local tectonic strain and heating in shear zones, as observed by L. RATSCHBACHER & K. KLIMA (1985) in the Grauwackenzone of Styria. But on the one hand there is no evidence (based on studies of macro- and microfabrics [K. BOECKELMANN, this volume]) of a shear zone in the Tesero Horizon, and on the other hand known zones of shearing and brecciation (e. g. 207–210 m) do not increase IC.
6) There is also only minimal evidence of hydrothermal veining. Most of the pyrite is early diagenetic.

The anomalous zone of low IC (zone of good crystallinity of illite) that is found in Gartnerkofel-1 (224.5–231 m) may be related to a similar occurrence at Lozzo in the Italian Dolomites, 70 km to the west. At that locality S. KRUMM (1987, 1990) described a section of low IC, extending from the base of the studied section in the Bellerophon Formation, up to a level near the top of the Buchenstein Limestone in the Ladinian. Above that level the IC jumps sharply to higher values more like those expected from the depth of burial. The similarity of the two occurrences suggests a common origin in a post-Ladinian injection of thermal waters. Such a fluid front may have originated either from an igneous intrusion such as the Monzoni (S. KRUMM, 1990), or from evaporite brines expressed from the Bellerophon Basin west of Lozzo, similar to those postulated to account for illitization of Paleozoic clays in the Midcontinent USA (W.C. ELLIOTT & J.L. ARONSON, 1987; R.L. HAY et al., 1988). Any such fluid injection must have been episodic in order the account for the sharp temperature rise (L.M. CATHLES & A.T. SMITH, 1983; L.M. CATHLES, 1987). Thus while the anomalous illitization happens to concentrate near the P/Tr boundary in Gartnerkofel, the more extensive incidence of illite at Lozzo indicates that it did not originate in volcanism at the boundary. Furthermore, although the illite may thus be of hydrothermal origin, it is apparently not related to the occurrences of trace metals near the P/Tr boundary, which are early diagenetic on textural and isotopic grounds (W.T. HOLSER, this volume). On the other hand, the post-Ladinian fluid front could be related to a second late cycle of dolomitization (K. BOECKELMANN & M. MAGARITZ, this volume) and/or to a chemogenic overprint of the remanent magnetization (W. ZEISSL & H.J. MAURITSCH, this volume).

7) An acid rain event, consequent to an impact, volcanic or global fire event would affect (without regard to carbonates) the chlorites first. The occurrence of oolites as well as varying, but throughout the GK-1 section distributed chlorite contents between 0 and about 15 % (related to fractions <2 µm) largely exclude this interpretation.
8) An ephemeral exogenic temperature rise to about 200–250°C, eventual in the marginal area of an impact, triggering the illite crystallinity ordering processes in the near-surface beds, is difficult to imagine. There is no paleogeographic evidence of disturbed surface sediments or layers of debris (ejecta) around (Tesero Horizon).

With the present state of investigation the author prefers the interpretations 1) (detrital) and 2) (Ostwald ripening) as cause for the improved IC just confined to the Tesero Horizon. These propositions are not contradictory to all geological evidences.

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