Discontinuous inverse metamorphic zonation, Glarus Alps, Switzerland : evidence from illite "crystallinity" data

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by *Martin Frey*[1]

Abstract

The "crystallinity" of illite was determined on 60 slates located between 2450 m and 1000 m altitude along a sample traverse in the Glarus Alps, eastern Switzerland. Contrasting Kübler indices of 0.22 ± 0.03 (two sigma) and 0.32 ± 0.05 $\Delta°2\theta$ were found in the Verrucano of the lower Helvetic nappes and the Flysch units of the Infrahelvetic complex, respectively. This indicates epimetamorphic conditions in the upper tectonic unit and medium-grade anchimetamorphic conditions in the lower tectonic unit. The discontinuity in metamorphic grade coincides with the Glarus overthrust. Therefore, the discontinuous inverse metamorphic zonation is explained by post-metamorphic thrusting along the Glarus thrust.

The average illite b_0 value for 44 flysch samples is 9.0133 ± 0.0065 Å, indicating conditions of an intermediate-pressure facies series.

Examples of continuous and discontinuous inverted metamorphic zonations are compiled in an appendix.

Keywords: Illite, "crystallinity", illite b_0-geobarometry, inverted metamorphic zonation, Glarus Alps.

1. Introduction

Temperature in the earth's crust generally increases with depth. However, inversion of metamorphic zonation is a rather common feature of many orogenic belts, as can be seen from the compilation in the appendix. Inverted zonal sequences may be classified as continuous or discontinuous. Continuous inverse metamorphic zonation has been explained in many different ways, e.g. by post-metamorphic recumbent folding, by thrusting of hot rocks over colder ones, or by shear heating on crustal thrusts (see appendix). Discontinuous inverse metamorphic zonation, on the other hand, seems always to be related to major overthrusts in low-grade areas and is sometimes referred to as "transported metamorphism".

This study aims to document a clear-cut example of a discontinuous inverted metamorphic gradient based mainly on illite "crystallinity" data. Preliminary results were published by Frey et al. (1974) and incorporated in the metamorphic map of the Alps (Niggli, 1973). This inversion was already postulated by Martini and Vuagnat (1970, p. 59) based on mineral assemblages in metabasites and greywackes. However, the mineral assemblages from the Verrucano metabasites discussed in section 4.2 are not critical, and therefore, the conclusion of Martini and Vuagnat is not well founded.

2. Geologic setting

The investigated area is characterized by the Glarus overthrust separating the Infrahelvetic complex (below) from the Helvetic Nappes (above), see Fig. 1. The Infrahelvetic complex consists in the study area mainly of carbonate bearing slates of the parautochthonous North Helvetic Flysch and the allochthonous South Helvetic Units. The Glarus thrust is marked by a layer of calc-mylonite (Lochseiten limestone). The Helvetic Nappes are represented in the study area by the Permian Verrucano and minor Mesozoic sediments. The Verrucano

[1] Mineralogisch-Petrographisches Institut der Universität, Bernoullistrasse 30, CH-4056 Basel.

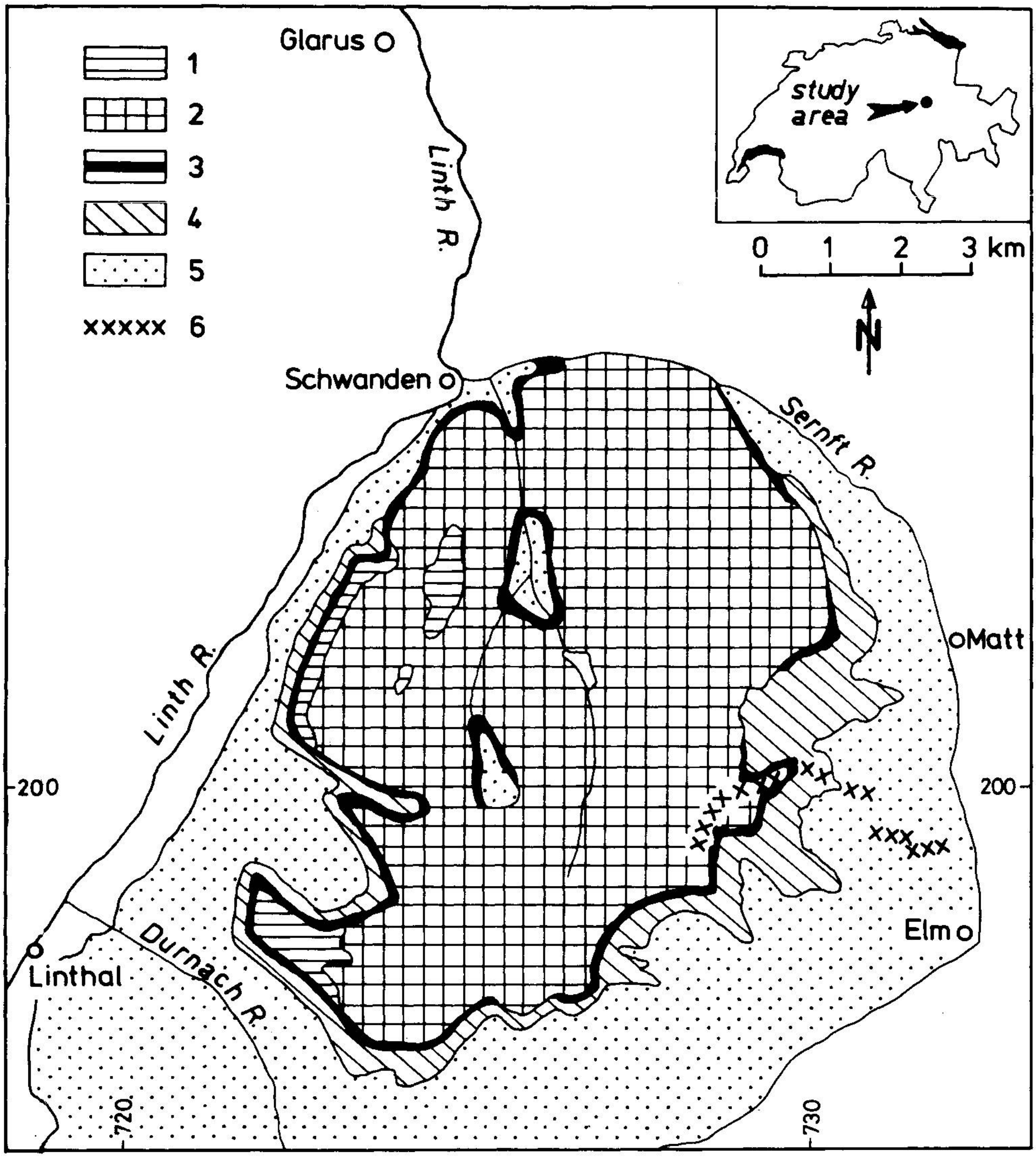

Fig. 1 Geologic map of the region between Linth and Sernf valleys, Glarus Alps, eastern Switzerland (after TRÜMPY, 1967).

1 Mesozoic 2 Permian Verrucano 3 Lochseiten calc-mylonite	Lower Glarus Nappe Complex	4 South Helvetic Units 5 North Helvetic Flysch 6 Sample traverse	Infrahelvetic Complex

comprises mainly slates and minor mafic and acid low-grade metavolcanics, and detailed lithologic descriptions are provided by AMSTUTZ (1954, 1957) and NIO (1972).

The rocks have suffered a well-defined sequence of deformation phases (TRÜMPY, 1969; SCHMID, 1975; MILNES and PFIFFNER, 1977; PFIFFNER, 1986). During the first phase, the Pizol phase, strip sheets of the South Helvetic Units were emplaced onto the North Helvetic Flysch. Penetrative ductile deformation, major folding and thrusting, as well as the development of a slaty cleavage are attributed to a second and mainly a third deformation phase, the Cavistrau and the Calanda phases, respectively. Complex heterogeneous, less ductile deformation occurred during a fourth, Ruchi phase. It is genetically related to continued movement along the Glarus overthrust and affected the Calanda phase structures in a zone about 200–300 m thick below the thrust.

A low-temperature metamorphism is well documented in the Glarus Alps, based mainly on mineral assemblages and illite "crystallinity" data and minor coal-rank and fluid inclusion data (MARTINI and VUAGNAT, 1965; FREY, 1969, 1970; KÜBLER, 1970; FREY et al., 1973, 1974, 1980; FREY, 1978; SIDDANS, 1979; KISCH, 1980; GROSHONG et al., 1984; HUNZIKER et al., 1986; FREY, 1987a). SIDDANS (1979) presented textural evidence suggesting two thermal peaks in the Glarus Alps, and these were provisionally dated at 35–30 Ma (Calanda phase) and 25–20 Ma (Ruchi phase) by HUNZIKER et al. (1986).

3. Methods

3.1. SAMPLE PREPARATION

Approximately 100–200 g of sample were ground in a tungsten-carbide Sieb Mill (Scheibenschwingmühle) for 30 s. Carbonate was removed by treatment with cold HCl 2N. The size fraction 0.1–2 μm was prepared using differential settling tubes and millipore filters. The X-ray mounts were prepared by sedimentation, and air-dried or glycolated. Glycolated mounts were prepared in a glycol steam bath at 70 °C overnight.

3.2. X-RAY ANALYSES

Mineral identification in shales and slates was performed using X-ray powder diffractometry and Guinier camera techniques. Sheet silicate abundance in Fig. 3 was determined semiquantitatively by X-ray diffractometry; the method used was that outlined by FREY (1978, Tab. 1).

The half-height width of the first illite basal reflection at 10 Å on an X-ray diffractogram was measured as representing the Kübler index of the so-called illite "crystallinity" (KÜBLER, 1967). Standards were included in the diffractometer runs. A measure of the precision of the method was obtained by operating the goniometer in an oscillating mode and by measuring the Kübler index of each sample six times. The average standard deviation (two sigma) was

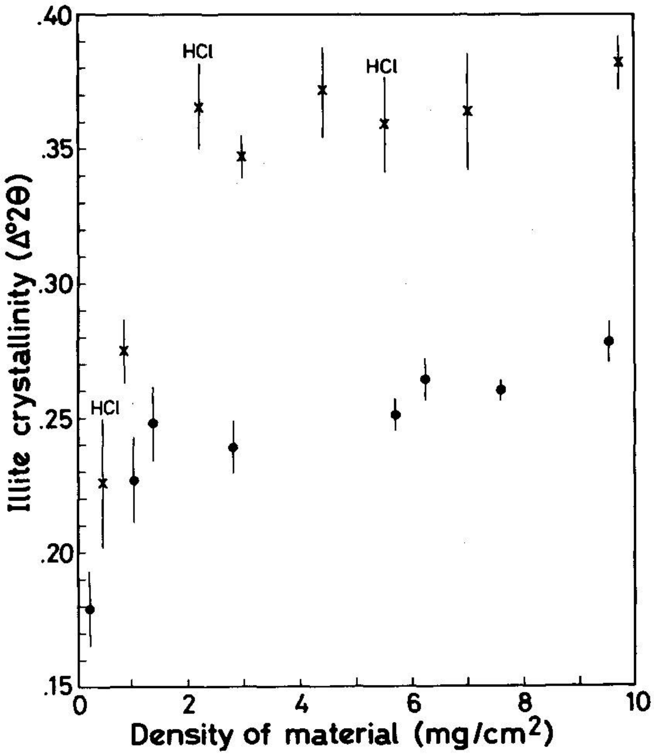

Fig. 2 The Kübler index of illite "crystallinity" with two sigma standard deviations is plotted against the density of material used to prepare X-ray diffraction slides. Note that the Kübler index decreases rapidly with a density of material < 2 mg/cm². HCl = sample treated with cold HCl 2N for 24 h.

0.016 Δ°2θ. The terms "anchimetamorphic", "anchizone", "epimetamorphic" and "epizone" are used in the sense of Kübler, that is only in connection with illite "crystallinity" data. The non-metamorphic/anchimetamorphic and the anchimetamorphic/epimetamorphic boundaries were defined at indices of 0.42 and 0.25 Δ°2θ CuKα respectively.

The d (060,$\bar{3}$31) spacing of white K-mica was measured on a Guinier film, which was then transformed to a diffratogram with aid of a densitometer. The (060) and the ($\bar{3}$31) peaks could not be resolved. The (211) quartz reflection served as an internal standard.

The effect of sample preparation on the measured 10 Å peak width of illite has recently been reviewed by KISCH and FREY (1987). We shall briefly focus here on the effect of acid treatment and the method of slide preparation. The effect of acid treatment was tested on a carbonate-poor sample and was found to be insignificant (Fig. 2). The effect of sample material of sedimentation slides on the Kübler index is shown in Fig. 2. It was found than thin slides (< 2–3 mg/cm^2) show distinctly smaller values of the Kübler index (better "crystallinity") than thicker slides, a result which is in accordance with the findings of WEBER (1972). For the present study, therefore, the time-consuming check of slide thickness was not carried out, but care was taken to avoid thin slides.

4. Results and discussion

Evidence for an inverse metamorphic gradient in the study area comes mainly from illite "crystallinity" data, and is further supported by mineral assemblages and radiometric age data.

4.1. ILLITE "CRYSTALLINITY"

67 samples were collected at regular intervals of altitude along an E-W sample traverse from Blistock (2447 m) to Chüebodenrus (1010 m) northwest of Elm (Fig. 1). The Kübler index was determined on 14 Verrucano samples and on 53 flysch samples. If samples containing paragonite and/or paragonite/muscovite mixed-layer are neglected for the moment, then the Verrucano samples with a Kübler index ranging from 0.20 to 0.25 $\Delta°2\theta$ belong to the epizone while the flysch samples with a Kübler index ranging from 0.28 to 0.37 $\Delta°2\theta$ belong to the middle anchizone. Note that the gap in illite "crystallinity" values coincides with the main Glarus overthrust, but there is no such gap between the South Helvetic Unit and the North Helvetic Flysch which are separated by an early, Pizol phase thrust fault (Fig. 3).

The effect of glycolation on the Kübler index was tested on three samples having the largest $\Delta°2\theta$ values in the air-dried state. For all three cases a slightly lower Kübler index (improved "crystallinity") was obtained (see Fig. 3, samples indicated with "Gl"). For two samples the effect of glycolation was found to be negligible, while for the third sample it was found to be minor (0.341 ± 0.007 $\Delta°2\theta$ for the glycolated state versus 0.357 ± 0.007 $\Delta°2\theta$ for the air-dried state).

The significance of this illite "crystallinity" distribution pattern will be discussed next. It should be remembered that the Kübler index is dependent on many factors (see e.g. FREY, 1987b, pp. 18–21, for a recent review). The following variables are considered to be relevant to this study: Temperature, lithology, and interfering basal reflections.

(i) Temperature is generally believed to be the most important physical factor affecting illite "crystallinity", a conclusion which seems to be valid for this study as well, as dicussed below.

(ii) Lithology plays an important role in determining illite "crystallinity". There exist two main lithologic differences between samples above and below the Glarus overthrust, that is carbonate content which is generally higher in the flysch samples (up to 55 wt% calcite, see Fig. 3), and the colouring pigment which is hematite in the purple Verrucano and organic matter in the gray to black Flysch. A high carbonate content may retard the aggradation of illite due to a deficiency in potassium. However, in the Flysch samples there exists no correlation between the highly variable calcite content and the rather uniform values of the Kübler index (Fig. 4). Therefore, carbonate content is not regarded as a determinant factor in this study.

Increased illite "crystallinity" in red and green shales as compared to interbedded black and gray shales has been variously mentioned from the late diagenetic zone (e.g. OGUNYOMI et al., 1980, p. 568; ISLAM et al., 1982, p. 182). This retardation in organic-matter-rich shales is attributed to the isolation of illite crystals from circulating ionic solutions by a mantle of hydrophobic organic material, or to the persistence of acidic pore fluids. Both possibilities may retard "crystallinity" improvement. Because the hematite-bearing Verrucano red-beds and the organic matter-bearing Flysch are separated by the Glarus overthrust and are not interbedded in the study area, it cannot be decided whether the gap in illite "crystallinity" values at this tectonic boundary is controlled by different metamorphic grade or, at least in part, by the organic matter content in the flysch. However, in our experience, organic material does not seem to affect illite "crystallinity" in anchi- and epimetamorphic slates of the Glarus Alps. At several localities the Kübler index was determined in red and black slates of neighbouring formations belonging to the same tectonic unit, and no significant difference was noted (M. FREY, unpublished data).

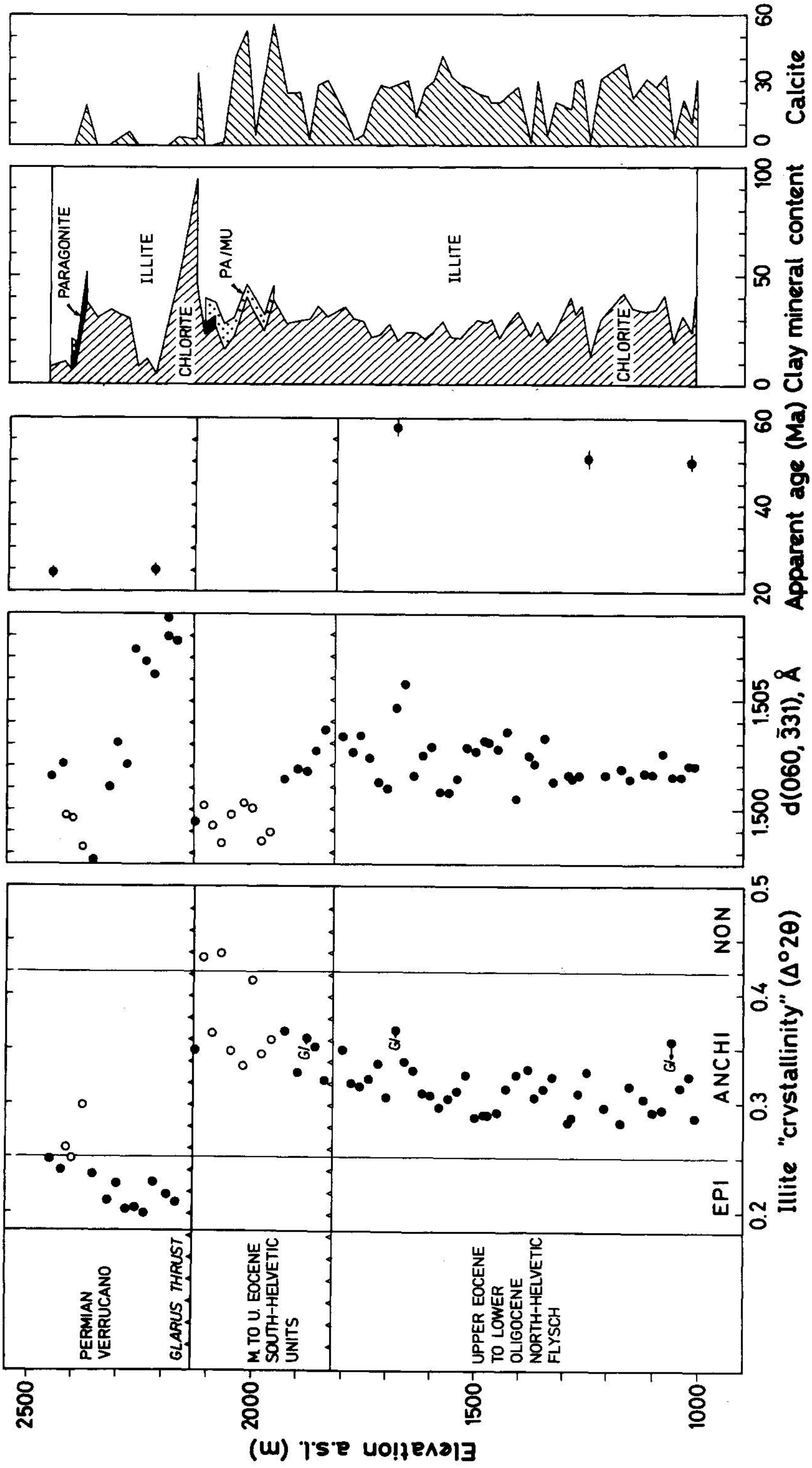

Fig. 3 Kübler indices of illite "crystallinity", illite d(060, 331̄) spacing, clay mineral distribution (fraction 0.1–2 μm) and calcite content (wt%) for 67 samples along the traverse indicated in Fig. 1. 5 K-Ar apparent ages on illites (fraction 0.1–2 μm) are also shown. Illite "crystallinity" values determind on three glycolated (Gl) samples are indicated by arrows. Open circles refer to samples containing sodium-bearing micas. Pa/Mu = paragonite/muscovite mixed-layer.

(iii) Interfering basal reflections of other associated phyllosilicates with basal reflections close to 10 Å may cause a broadening of the illite (001) peak, leading to apparently higher Kübler indices. In the present study such minerals include paragonite, mixed-layer paragonite/muscovite and possibly also NH_4-bearing illite (JUSTER et al., 1987). Illite "crystallinity" values of samples containing sodium-bearing micas are indicated by open circles in Fig. 3, and include three samples from the Verrucano as well as eight samples from the South Helvetic Unit.

In conclusion it can be said that the contrasting illite "crystallinity" values above and below the Glarus overthrust were presumably caused by a discontinuity in metamorphic grade (temperature) but lithologic control (organic matter in flysch) cannot be completely excluded. Further evidence for the presence of a discontinuous inverse metamorphic zonation is provided by information from mineral assemblages and radiometric age data as discussed below.

4.2. MINERAL ASSEMBLAGES

Mineral assemblages from metapelites and metamarls of the study area yield only limited information on metamorphic grade. Metabasites and metagraywackes, on the other hand, are often very useful indicators of metamorphic conditions at low temperatures (see e.g. LIOU et al., 1987).

4.2.1. Mineral assemblages from the Verrucano

The maximum assemblage in the Verrucano slates is illite (to muscovite)-paragonite-mixed-layer paragonite/muscovite-chlorite-albite-quartz-calcite-hematite. Note that paragonite from Blistock has already been reported by KÜBLER (1970). This mineral assemblage is stable both under greenschist and subgreenschist facies conditions.

Spilitic metabasites are widespread in the study area and comprise the following maximum assemblage: albite-chlorite-muscovite-epidote-quartz-calcite-dolomite-hematite-titanite (MILCH, 1892; AMSTUTZ, 1954; FREY, unpublished results). This mineral assemblage is not very useful to determine metamorphic grade and occurs both in the prehnite-pumpellyite and the greenschist facies. No prehnite, pumpellyite or actinolite have so far been reported from these rocks. The lack of index Ca-Al silicates and the stabilization of carbonates may be a consequence of the presence of CO_2 in the fluid phase (e.g. LIOU et al., 1987, p. 85).

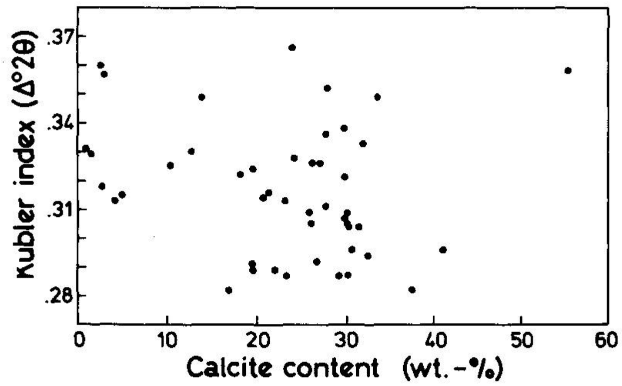

Fig. 4 The Kübler index of illite "crystallinity" is independent of the whole rock calcite content. The data of 46 Flysch samples are plotted.

4.2.2. Mineral assemblages from the Flysch units

The common assemblage in slates from the Flysch units is illite-chlorite-albite-quartz-calcite-organic material. Additional paragonite/muscovite mixed-layer and paragonite are found in some samples from the South Helvetic Unit (Fig. 3). As for the Verrucano slates, these assemblages do not allow discrimination between lower greenschist and subgreenschist facies conditions.

The andesitic Taveyanne metagraywacke is widespread in the North Helvetic Flysch between the Linth and Sernf valleys, although it does not outcrop along the sample traverse of Fig. 1. Prehnite and pumpellyite are mentioned from the Linth-Sernf area by MARTINI and VUAGNAT (1965, Fig. 1). Our own observations in metagreywackes from the Linth and Durnach valleys (south and southeast of Linthal, respectively) yielded the following maximum assemblage: pumpellyite-prehnite-epidote-chlorite-illite-quartz-albite-calcite-titanite. This buffered assemblage is characteristic of the prehnite-pumpellyite facies, spanning an approximate pressure-temperature range of 1.5–3 kbar and 250–350 °C (LIOU et al., 1987, Fig. 3.6) in the Fe-free model system. These temperatures may be lowered by up to 50 °C by the presence of Fe^{3+} (LIOU et al., 1987, Figs. 3.8 and 3.9). However, in the absence of mineral chemical data this effect cannot be quantified for the Glarus Alps at present.

4.3. ILLITE d(060,$\bar{3}$31) VALUES AND ILLITE b_o-GEOBAROMETRY

For Na-poor white K-micas the d(060,$\bar{3}$31) spacing provides a semi-quantitative determination of the Mg + total Fe content in the octahedral layer. Such correlations have been established both for muscovites (CIPRIANI et al., 1968; FREY et al., 1983) and for illites (HUNZIKER et al., 1986).

The illite d(060,$\bar{3}$31) values along the sample profile show the following features (Fig. 3):

(i) Illites coexisting with paragonite and/or paragonite/muscovite mixed-layer have the lowest d-values, that is these illites have a high muscovite component.

(ii) In the Verrucano and, though less pronounced, in the upper part of the South Helvetic Unit, the d(060,$\bar{3}$31) values increase towards the Glarus overthrust. The author has no explanation for this phenomenon at the present time.

(iii) Illites from the North Helvetic Flysch display rather uniform d(060,$\bar{3}$31) spacings, independent of the calcite content of their whole rocks (Fig. 5). This result contrasts with the findings of GEYSSANT et al. (1973) and ARKAI et al. (1981) who observed decreasing b_o values with increasing carbonate content.

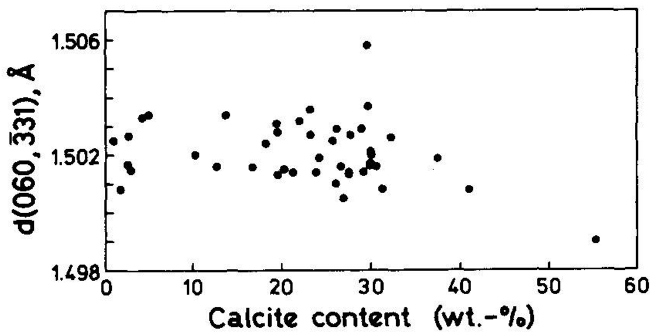

Fig. 5 The illite d(060,$\bar{3}$31) spacing is independent of the whole rock calcite content. The data of 44 flysch samples are plotted.

The method of using b_o of muscovite for geobarometric purposes in greenschist facies metapelites was developed by SASSI (1972) and SASSI and SCOLARI (1974). An overview of this qualitative geobarometer is given by GUIDOTTI and SASSI (1976, 1986). More recently, PADAN et al. (1982) extended the method to shales and slates of the high-grade anchizone.

For the illite b_o-geobarometry of this study the b_o parameter was calculated using the relation $b_o \approx 6 \times d(060,\bar{3}31)$. Some problems involved in this calculation have been discussed by GUIDOTTI and SASSI (1986, p. 374) and FREY (1987b, p. 57). The rocks used involved 39 samples from the North Helvetic Flysch and five samples from the lower part of the South Helvetic Unit (Fig. 3) containing the non-limiting assemblage illite + chlorite + quartz + albite + calcite + organic material. As discussed earlier, no disturbing effect of the varying calcite content on d(060,$\bar{3}$31) or b_o values was observed. The b_o frequency distribution of the chosen slate samples is unimodal (Fig. 6). The average

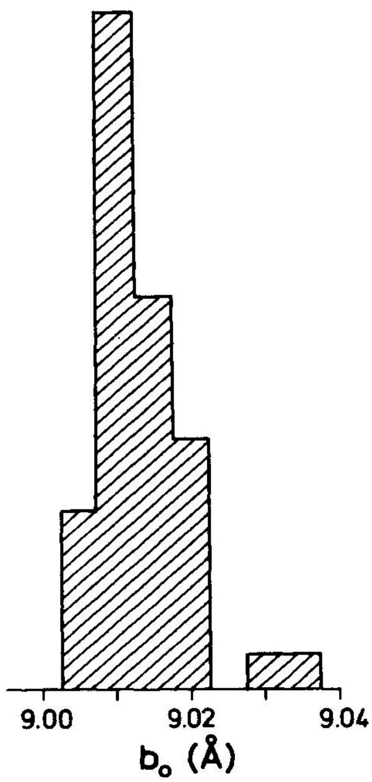

Fig. 6 Frequency distribution of the b_o lattice parameter of 44 illites from flysch samples.

b_o value was found to be 9.0133 ± 0.0065 Å. This value is slightly lower than the 9.023 ± 0.011 Å reported by PADAN et al (1982) for 19 widely scattered samples from the North Helvetic Flysch of the central Swiss Alps. A cumulative frequency plot is shown in Fig. 7, demonstrating the similarity to the intermediate-pressure facies series of the Ryoke area, Japan (mean b_o = 9.013 Å; SASSI and SCOLARI, 1974).

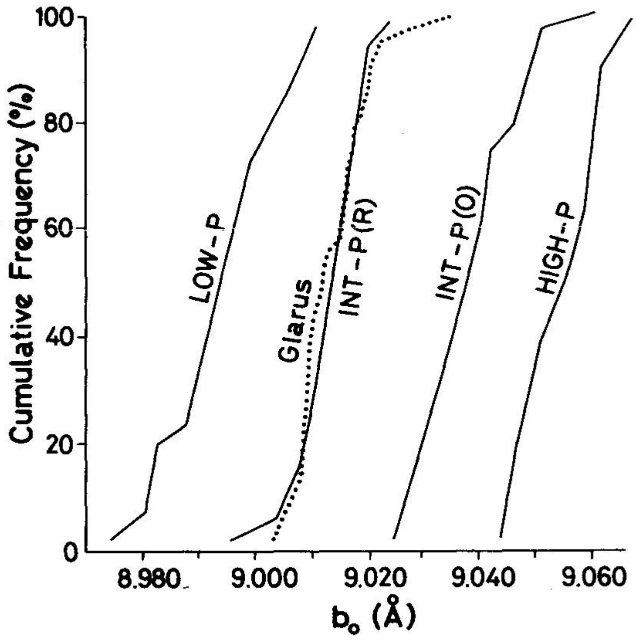

Fig. 7 Cumulative frequency curve of b_0 values for Glarus Flysch samples. Other curves as follows: Low-P: Low pressure curve of the Bosost area, INT-P (R): Low-intermediate pressure curve of the Ryoke area, INT-P (O): High-intermediate pressure curve of the Otago area, HIGH-P: High pressure curve of the Sanbagawa area. Curves taken from SASSI and SCOLARI (1974).

4.4. FLUID INCLUSION DATA

A microthermometric method to determine approximate pressure and temperature values of fluid trapping based on fluid inclusion studies from fissure quartz was developed by MULLIS (1979, 1987). One sample from the North Helvetic Flysch N of Matt (coordinates 731.950/203.170) yielded a homogenization temperature of 267 ± 2°C (J. MULLIS, pers. comm. 1988). This temperature value is believed to be near the peak conditions during regional metamorphism (MULLIS, 1979, p. 535).

4.5. RADIOMETRIC AGE DATA

Radiometric age data may provide, under certain circumstances, information on metamorphic grade of low-grade metamorphic rocks (e.g. HUNZIKER, 1987). Rb-Sr and/or K-Ar data are available for the 0.1–2 µm fraction of five illite-rich slates from the sample traverse described earlier. One Verrucano sample, located 300 m above the Glarus thrust, yielded a Rb-Sr age of 30.5 ± 1.9 Ma and a K-Ar age of 24.2 ± 1.3 Ma; a second Verrucano sample, located 90 m above the Glarus thrust, yielded concordant Rb-Sr and K-Ar ages of 25.7 ± 0.9 and 24.9 ± 1.5 Ma, respectively (HUNZIKER et al., 1986). The 30 Ma value may date the main (Calanda) phase of metamorphism or, alternatively, may be a partially reset age. The 24–25 Ma values may be attributed to movements on the main Glarus thrust during the Ruchi phase (HUNZIKER et al., 1986). K-Ar data for three North Helvetic Flysch samples gave considerably older "ages", that is 57.7 ± 2.0 Ma (450 m below the Glarus thrust), 50.7 ± 2.2 Ma (900 m), and 49.9 ± 1.8 Ma (1100 m), (J.C. HUNZIKER, pers. comm. 1988). These ages are considerably higher than the stratigraphic age of the North Helvetic Flysch of about 35 Ma and are interpreted, therefore, as "mixed ages" between the age of detrital muscovite and time of metamorphism. Obviously, temperatures were not high enough for a total resetting and were lower than in the overlying Verrucano.

4.6. REGIONAL SIGNIFICANCE

The discontinuous inverted metamorphic zonation as observed today between the Helvetic nappes and the Infrahelvetic complex may have originated as follows: Shortly after deposition the North Helvetic Flysch was covered by slip sheets of the South Helvetic Unit (Pizol phase). Subsequently all units of the study area were affected by intense internal deformation which formed the main cleavage (Calanda phase), accompanied by post-tectonic regional metamorphism with a thermal peak at about 30 Ma b.p. Metamorphic conditions were of epizonal grade in the Verrucano and of mid-anchizonal grade in the flysch units (see section 4.1). Maximum temperatures and pressures are only broadly constrained. For the Verrucano 300–350°C are assumed based on epizonal conditions (FREY, 1986, Fig. 7) and the absence of biotite. For the Flysch units 250–300°C are assumed based on a general correlation of mid-anchizonal conditions, prehnite-pumpellyte facies and fluid inclusion data from the Alps (FREY, 1986, Fig. 7; see also sections 4.2. and 4.4.). Pressures cannot be calibrated for the Verrucano at the present time. For the Flysch units a lithostatic pressure of

2–2.5 kbar is proposed assuming a mean geothermal gradient of 30 °C/km, which seems to be a reasonable value for an area belonging to a medium-pressure facies series (see section 4.3.). Finally displacement of up to 10–20 km (GROSHONG et al., 1984) along the Glarus overthrust during the Ruchi phase produced the inverse metamorphic zonation at about 25–20 Ma b.p.

The discontinuous inverted metamorphic zonation described in the present paper is not a local phenomenon but has been observed also in analogous tectonic situations further east and west. In the Klausenpass area, 25 km WSW of the study area, illite "crystallinity" data indicate epi- to anchizonal conditions for the Axen nappe thrust over the Infrahelvetic complex showing upper- to medium-grade anchizonal conditions (CHRISTE, 1985). In the Urirotstock area, some 15 km further west, a combined illite "crystallinity", mineral assemblage, coal rank and fluid inclusion study place the southern part of the Axen nappe within the high-grade anchizone, and the underlying North Helvetic Flysch in the medium-grade anchizone (BREITSCHMID, 1982; FREY et al., 1980). Whether such a discontinuity in metamorphic grade at the base of the Helvetic nappes exists further west remains to be detected.

5. Conclusions

The following conclusions can be drawn from this study:

(i) Inverse metamorphic zonation may be classified as continuous or discontinuous (see appendix).

(ii) A case study of discontinuous inverse metamorphic zonation from the Glarus Alps has been described, based on evidence from illite "crystallinity", mineral assemblages and radiometric age data.

(iii) Discontinuous inverse metamorphic zonation seems to be a rather common feature in low-grade external zones of many orogenic belts (appendix). Continuous inverse metamorphic zonation, on the other hand, seems to be restricted to areas of higher metamorphic grade, where original discontinuities have disappeared, due to partial, thermal re-equilibration.

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Appendix: Examples of inverted metamorphic zonation from regional metamorphic terrains

Region	Inverted zonal or isograd sequence
(A) Continuous inverted metamorphic zonation	
Appalachians West-Central New England, USA	sillimanite + K-feldspar/sillimanite/staurolite + kyanite/garnet
Wopmay orogen Northwest Territories, Canada	granitic melt/sillimanite/andalusite/biotite; or granitic melt/sillimanite - orthoclase/sillimanite/staurolite/biotite; or sillimanite + K-feldspar/muscovite + sillimanite/muscovite + andalusite
Scandinavian Caledonides Tømmerås Window, Norway	amphibolite facies/greenschist facies
Scandinavian Caledonides Sulitjelma, Norway	garnet/biotite
Scottish Dalradian, Balquhidder region, Scotland	garnet/biotite
East Greenland Scoresby Sund	staurolite+ kyanite/garnet + biotite/chlorite
Lower Himalayas Punjab, India	sillimanite + kyanite/kyanite/biotite or staurolite/biotite/chlorite
Lower Himalayas Kashmir, India	sillimanite + migmatite/sillimanite + kyanite/staurolite + kyanite/biotite + garnet/biotite/chlorite
Lower Himalayas Gangtok, Sikkim, India	staurolite/garnet/biotite
Lower Himalayas Central Nepal	sillimanite/kyanite/garnet/biotite/chlorite
Lower Himalayas Central Nepal	greenschist-amphibolite transitional facies/greenschist facies (biotite/chlorite)
Lower Himalayas Eastern Nepal	sillimanite + cordierite/sillimanite + kyanite/staurolite + kyanite/biotite + garnet/chlorite
(B) Discontinuous inverted metamorphic zonation	
Central Alps Préalpes, Switzerland and France	anchimetamorphic/diagenetic; or epi-metamorphic/anchimetamorphic
Central Alps Helvetic nappes, Switzerland	high-grade anchimetamorphic/low-grade anchimetamorphic; or epimetamorphic/medium-grade anchimetamorphic
Appalachians Quebec, Canada	late diagenetic/late middle diagenetic
Scandinavian Caledonides Northern Norway and Sweden	staurolite + kyanite/chlorite + biotite

* Includes references to earlier studies

(in part after WATKINS, 1985, Tab. 3).

uggested origin	References
Successive nappes carried successi-ely hotter rocks over colder ones" p. 216)	Thompson et al. (1968)*
ost-metamorphic recumbent folding, r thrusting of hot rocks over older ones; or shear heating on rustal thrusts; or emplacement of funnel-shaped intrusive complex	St-Onge (1981), St-Onge et al. (1984)
mplacement of high-grade nappes bove low-grade units	Andreasson and Lagerblad (1980)*
hear-zone deformation	Mason (1984)*
arm fold core rocks emplaced ver cool limb rocks	Watkins (1985*, 1987)
ntruduction of heat by the Cale-onian cover above	Wenk (1961, p. 31), Haller and Kulp (1962, p. 23), Talbot (1979)
ast overthrusting of a hot crystal-ine nappe upon its cooler foreland, ombined with synmetamorphic shearing	Frank et al. (1973, 1977), Thöni (1977)
lurifacial metamorphism, syn- to ost-metamorphic thrusting	Stäubli (1986, pers. comm. 1988)
verthrusting or underthrusting	Bhattacharyya and Das (1983)
arge scale underthrusting of two ontinental slabs	Le Fort (1975)*
hear heating	Arita (1983)
lurifacial metamorphism, syn- to ost-metamorphic thrusting	Brunel and Kienast (1986)
ost-metamorphic thrusting	Martini (1972); Mullis (1979); Frey et al. (1980); Mosar (1988)
ost-metamorphic thrusting	Mullis (1979); Frey et al. (1980); Breitschmid (1982); Groshong et al. (1984); Christe (1985); this study
ost-metamorphic thrusting	Hesse and Ogunyomi (1980); Ogunyomi et al. (1980)
plift, erosion and cooling between etamorphic peak and thrusting	Crowley (1988)