Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 72 (1979)

Heft: 3

Artikel: Deformation, metamorphism and texture development in Permian mudstones of the Glarus Alps (Eastern Switzerland)

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DOI: https://doi.org/10.5169/seals-164856

Eclogae geol. Helv.	Vol. 72/3	Pages 601-621	9 figures in the text and 2 tables	Basle, November 1979

Deformation, metamorphism and texture development in Permian mudstones of the Glarus Alps (Eastern Switzerland)

By ANDREW W. B. SIDDANS[1])

ABSTRACT

Mudstones near the top of the Permian Verrucano have been studied in the Glarus Alps. Measurements of green spots enabled finite strain estimates to be made. These confirm earlier observations that the flattening planes dip gently south and that the extension direction is oriented north-south. Calculation of the reciprocal quadratic elongation parallel to the trace of the Glarus Thrust, along a north-south profile plane, enables an estimate of the bulk extension to be made. This evaluates at 14%.

Measurements on the cristallinity, the intensity ratios $I_{5Å}/I_{10Å}$ and $I_{2.80Å}/I_{2.58Å}$ and $d(060)$ of illite enable metamorphic grade in the Verrucano to be estimated. This is found to increase from north to south, with the growth of phengite and increase in the proportion of the $2M$ polymorph of illite.

Textures were studied optically, using very thin sections and by texture goniometry. Evidence was found that suggested a phase of syntectonic metamorphism during which the regional cleavage was formed, by a combination of pressure solution of quartz grains, crystallization of phyllosilicates and grain boundary sliding. This was followed by a phase of static crystallization during which new phyllosilicates grew across the pre-existing cleavage.

Published data on the structural and metamorphic evolution of the Glarus Alps is reviewed, together with the geochronological evidence. It is concluded that the Verrucano of the Glarus nappe was deformed in a ductile way during low-grade metamorphism to produce the regional cleavage and strain pattern, during Upper Oligocene times, prior to displacement of at least 35 km along the Glarus Thrust and the second phase of crystallization, which may have been of Miocene age.

RÉSUMÉ

Cette étude porte sur les argiles situées au sommet du Verrucano dans les Alpes de Glaris. Des estimations de la déformation finie ont été faites en mesurant les taches vertes de réduction. Ces mesures confirment les observations antérieures montrant que les plans d'aplatissement ont un léger pendage sud et que la direction d'allongement est orientée nord-sud. Le calcul du «reciprocal quadratic elongation» parallèle à la trace du plan de charriage de Glaris, le long d'une coupe orientée nord-sud, permet une estimation de la totalité de l'allongement qui est évalué à 14%.

Une estimation du degré de métamorphisme du Verrucano a été faite en mesurant la cristallinité, les valeurs des rapports $I_{5Å}/I_{10Å}$ et $I_{2.80Å}/I_{2.58Å}$ et $d(060)$ de l'illite. Le métamorphisme croît du nord au sud avec le développement de la phengite et l'augmentation de la proportion d'illite $2M$.

Les textures ont été étudiées au microscope, grâce à des coupes très minces, ainsi qu'au goniomètre. D'après ces observations, on peut montrer qu'une phase de métamorphisme syntectonique est synchrone de la schistosité régionale développée par dissolution par pression des grains de quartz, cristallisation des phyllosilicates et glissement des limites des grains. Cette phase est suivie par une phase de cristallisation

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statique pendant laquelle de nouveaux phyllosilicates se développent au travers de la schistosité préexistante.

Les données publiées sur l'évolution structurale et métamorphique des Alpes de Glaris, ainsi que les données géochronologiques sont passées en revue. En conclusion, le Verrucano de Glaris a été déformé d'une manière ductile pendant un métamorphisme faible qui a produit la schistosité et la déformation régionale au cours de l'Oligocène supérieur, avant un déplacement d'au moins 35 km le long du plan de charriage de Glaris et la seconde phase de cristallisation, peut-être d'âge Miocène.

Introduction

The Glarus Alps are situated in Eastern Switzerland (Fig. 1), occupying the area south of the Molasse basin and north and west of the river Rhine. The area of study (Fig. 1) comprised a broad north-south traverse, extending some 35 km from Walensee to Ilanz. The geology of this area is well documented, recent reviews being given by TRÜMPY (1969), SCHMID (1975), MILNES & PFIFFNER (1977) and MILNES (1978). An excellent geologic map was produced by OBERHOLZER (1942).

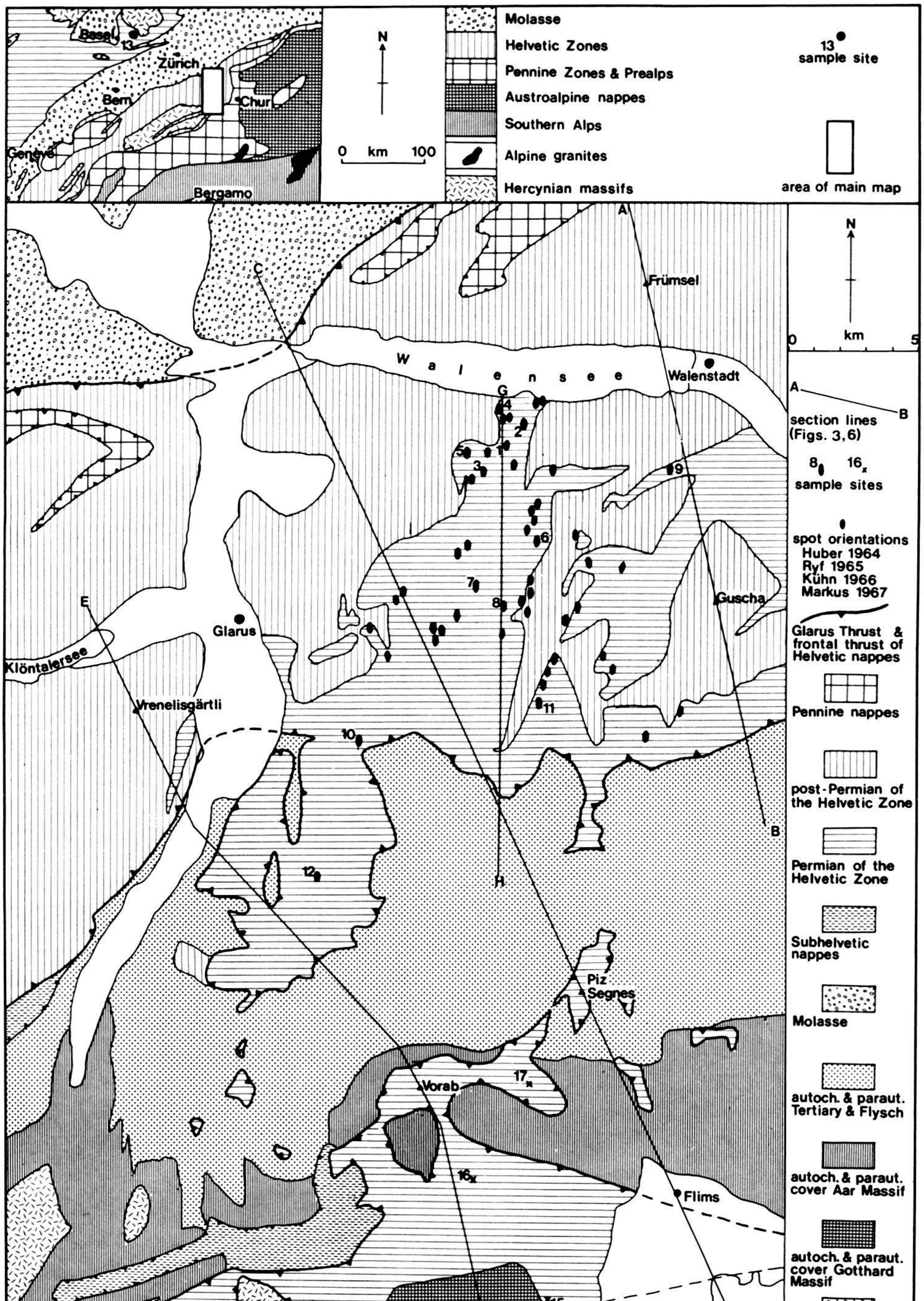
The area is divided tectonically into five major units (Fig. 1 and 3):

1. Structurally highest and of the most internal origin are rocks of the Pennine Zone, Bündnerschiefer to the south and east and flysch units of Upper Cretaceous to Lower Eocene age to the south and in klippen to the north and west of Walensee.
2. Structurally below the allochthonous Pennine Zone rocks is the Helvetic thrust block (SCHMID 1975). This is a sheet of rocks ranging from Permian to Eocene in age, that root in the Rhine valley between the Aar and Gotthard Massifs, from where they have been displaced northwards at least 35 km, to rest on Molasse of Oligocene and Miocene age north and west of Walensee. Their remnant thickness is 3¾ km on Glärnisch, but TRÜMPY (1969) suggested 5 to 6 km as their original thickness. The basal thrust, the Glarus Thrust, forms a broad, open, east-west trending arch (Fig. 3), that was probably an original feature (SCHMID 1975). TRÜMPY (1969, 1973) suggested that the age of displacement along the Glarus Thrust was Miocene, which post-dates the main fold- and cleavage-producing deformation (Calanda Phase, MILNES & PFIFFNER 1977) in Upper Oligocene times (Table 1). Thrusting in the frontal parts of the sheet has divided it up into a number of discrete nappes - Säntis, Axen, Mürtschen, Glarus (Fig. 3).

The remaining three tectonic units all lie structurally below the Glarus Thrust and are themselves separated by thrusts:

3. The autochthonous and parautochthonous Mesozoic and Tertiary cover of the Aar Massif.
4. "Flysch" units (SCHMID 1975) of south Helvetic, Ultrahelvetic or Pennine Zone origin, emplaced on *3* early in the tectonic evolution of the area, both units then

Fig. 1. Outline map of the Glarus area showing the main tectonic divisions, section lines (Fig. 3 and 6), sample sites and sites of published spot shape studies. The axial orientations of the spots are correct, but the axial ratios have no significance. After OBERHOLZER (1942) and SCHMID (1975).


Molasse
Helvetic Zones
Pennine Zones & Prealps
Austroalpine nappes
Southern Alps
Alpine granites
Hercynian massifs
13 sample site
area of main map
0 km 100
Basel
Zürich
Bern
Chur
Genève
Bergamo
N
0 km 5
A
B
C
D
E
F
G
H
Walensee
Frümsel
Walenstadt
Glarus
Klöntalersee
Vrenelisgärtli
Guscha
Piz Segnes
Vorab
Flims
Rhein
section lines (Figs. 3, 6)
sample sites
spot orientations
Huber 1964
Ryf 1965
Kühn 1966
Markus 1967
Glarus Thrust & frontal thrust of Helvetic nappes
Pennine nappes
post-Permian of the Helvetic Zone
Permian of the Helvetic Zone
Subhelvetic nappes
Molasse
autoch. & paraut. Tertiary & Flysch
autoch. & paraut. cover Aar Massif
autoch. & paraut. cover Gotthard Massif
Crystalline massif

being subject to the same Oligocene deformation that also affected the Helvetic thrust block.

5. Allochthonous slices of the Mesozoic cover of the Aar Massif, displaced northwards onto *3* prior to movement along the Glarus Thrust to form the Subhelvetic nappes.

This study was made in Permian red beds, the Verrucano, of the Glarus nappe. It was chosen as an area to study the interrelationships of deformation, metamorphism and texture development, as there is a wealth of published information on the Verrucano (OBERHOLZER 1933, WYSSLING 1950, FISCH 1961, SCHIELLY 1964, HUBER 1964, RYF 1965, KÜHN 1966, MARKUS 1967, RICHTER 1968, WERNER 1973), on the metamorphism of adjacent formations, which has been studied in great detail by FREY (1969, 1970, 1978) and FREY et al. (1973) and the pattern of regional metamorphism and geochronology has been extensively documented (NIGGLI & NIGGLI 1965, FREY et al. 1973, 1974). Some of this information is summarized in Figures 2 and 4.

The Zürich theses, cited above, describe the stratigraphy of the Verrucano in great detail. It is very variable, up to 1½ km thick, with much lateral facies change in its lower parts (e.g. RICHTER 1968, Fig. 9). Broadly speaking it can be described as a group of post-Hercynian red beds that accumulated in intermontane basins under semi-arid climatic conditions. They fine upwards into a red mudstone formation, the Schönbühl-Schiefer, now red slates, that is particularly well-endowed with green spots. The overlying Trias succession contains a very similar lithology in the Quarten-Schiefer. The same penetrative cleavage, dipping gently south (Fig. 3), with a north-south extension direction, as indicated by the green spots (Fig. 1), passes up from the Verrucano through the Trias, but dies out upwards in the Jurassic.

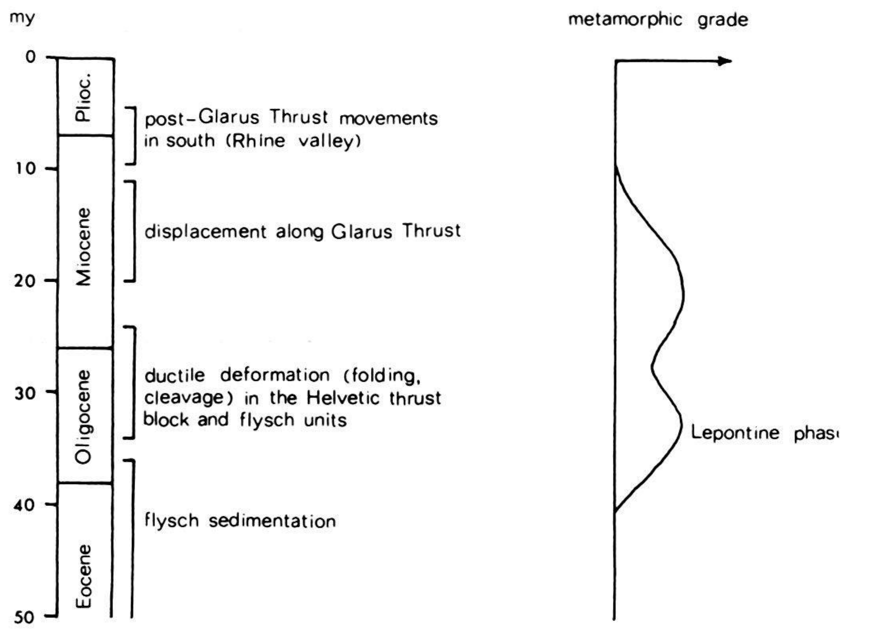


Fig. 2. Table showing the times of ductile deformation of the Verrucano, displacement along the Glarus Thrust and the metamorphic history of the Helvetic thrust block. Based on selected data from SCHMID (1975), FREY et al. (1973, 1974) and HUNZIKER (1974, personal communication).

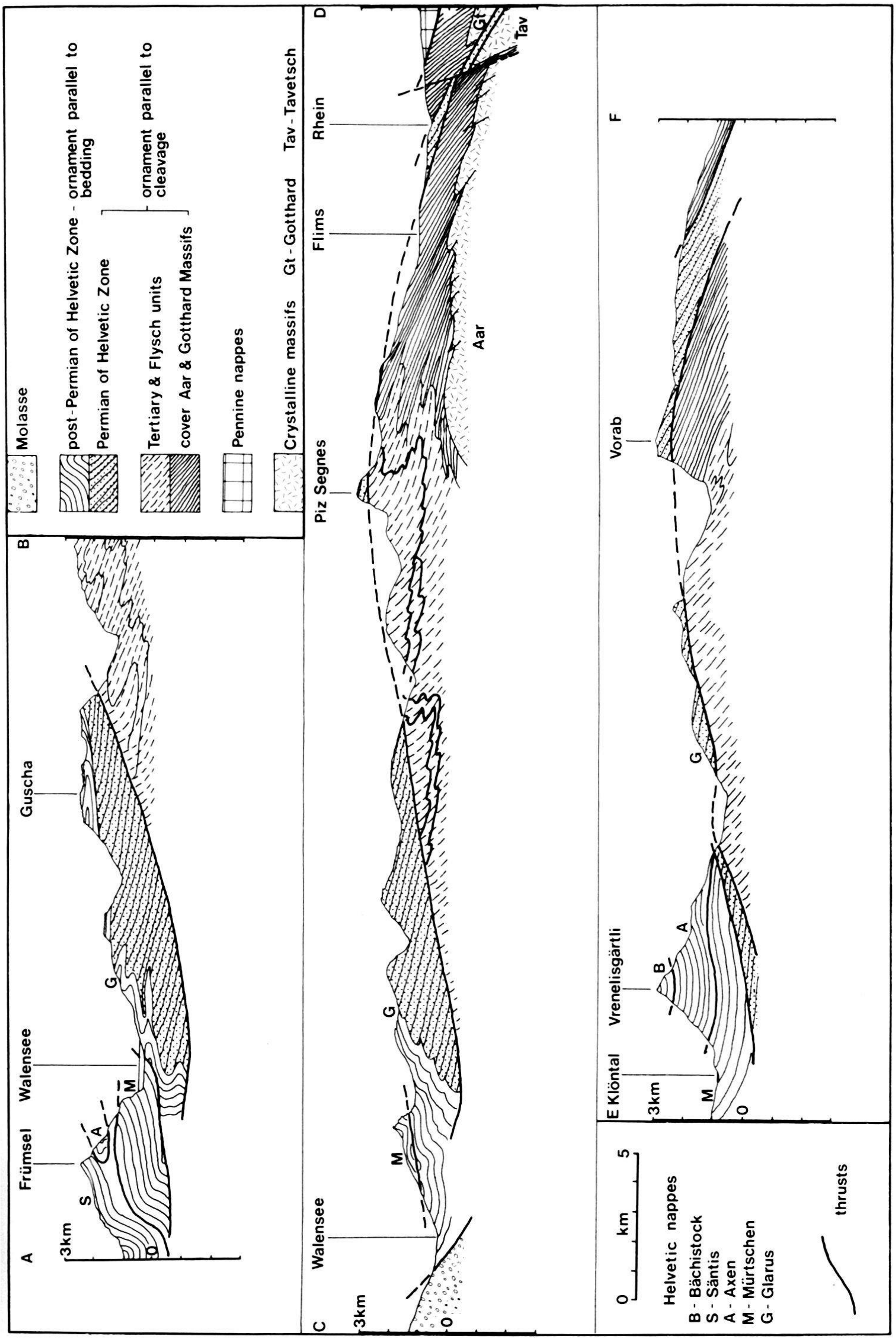


Fig. 3. Cross sections through the Glarus Alps after WYSSLING (1950), MARKUS (1967), TRÜMPY (1969), FREY et al. (1973) and SCHMID (1975).

Sampling sites referred to in the text are shown in Figure 1. Note that site 13 is located near Schopfheim, on the southern border of the Schwarzwald (Black Forest). This site was sampled in an attempt to provide some control on the non-metamorphic, but diagenetic, mineralogy and tectonically undeformed texture of the red mudstones. This was thought necessary because the northernmost Verrucano exposed in the Glarus Alps is both metamorphosed and deformed. Any stratigraphic correlation between site 13 and the others is quite unknown.

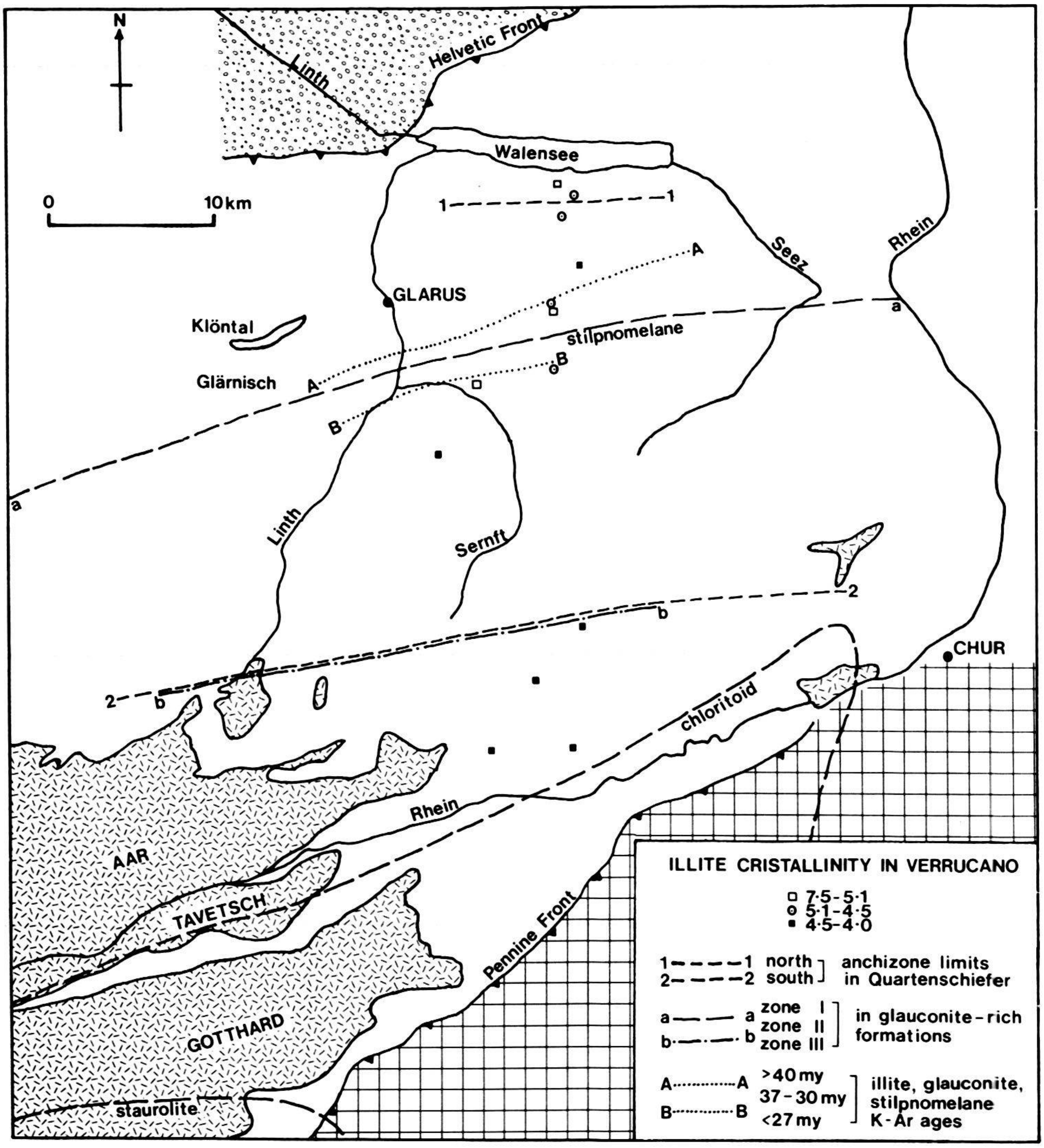


Fig. 4. Map of the Glarus area summarizing metamorphic zones recognized in the Quarten-Schiefer (FREY 1970), in glauconite-bearing formations (FREY et al. 1973), index minerals (NIGGLI & NIGGLI 1965) and geochronological data (FREY et al. 1973, HUNZIKER 1974, personal communication). The distribution of illite crystallinity in the Verrucano (this study) is also shown.

Deformation

HUBER (1964), RYF (1965), KÜHN (1966), MARKUS (1967), RICHTER (1968) and WERNER (1973) all describe green spots in the Verrucano that are flattened in the plane of the penetrative, gently south-dipping, slaty cleavage and extended in the cleavage in a north-south direction (Fig. 1). Unfortunately no three-dimensional spot shapes were described. In practice it is impossible to study spot shapes south of the "flysch" unit outcrops, since the red colour of the slates becomes green, due to pro-grade reactions that destroy hematite, so that the spots disappear.

Strain analysis using green spots is difficult and rather unsatisfactory. On close inspection it was found that the elliptical sections that result on smooth joint or cleavage surfaces always showed fluctuation to some extent, in both axial ratio and orientation. This suggested that one of the synoptic methods of strain analysis be used on three mutually perpendicular sections (SIDDANS, in press). However, this proved impossible, due to the large volumes of rock that would have been involved in even the most prolifically spotty rocks. Measurement of the two-dimensional strain data was thus done largely in the field, or on photographs, of smooth joint surfaces that form parallel to cleavage and normal to cleavage including the extension direction. The strain ratios on the two principal section planes were estimated using the Rf/φ method (DUNNET 1969), then combined to calculate the axial ratio of the strain ellipsoid assuming no volume change during deformation. The results are given in Table 1 and a deformation plot shown in Figure 5. These

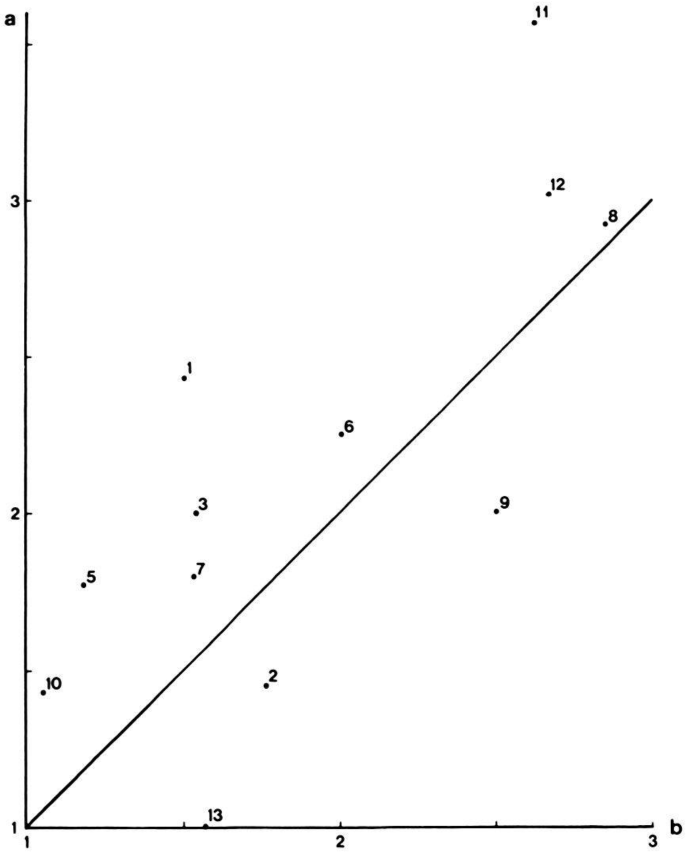


Fig. 5. Deformation plot of finite strain analyses in the Verrucano. $a = X/Y$, $b = Y/Z$, $X \geqslant Y \geqslant Z$. The line $k = 1$ is also shown, $k = (a-1)/(b-1)$.

results confirm earlier observations that the spots have a consistently north–south oriented extension direction (Fig. 1).

The extent to which the spot shapes actually represent the geometry of the finite strain ellipsoid remains uncertain. Spot shapes at the tectonically undeformed site 13 are oblate in bedding, indicating 26% compaction during lithification. Presumably the red mudstones of the Glarus Alps also underwent a similar compaction. Superposition of a tectonic strain obliquely on the compaction shape fabrics would be expected to produce the Rf/φ patterns characteristic of deformed semi-planar fabrics (DUNNET & SIDDANS 1971). In fact this was not detected. This may be partly due to the failure to detect bedding orientation at some localities and partly due to insufficient two-dimensional data being used in the Rf/φ analyses. The only checks available on the finite strain results come from study of buckled pre-tectonic quartz veins. The amount of shortening indicated by both methods is similar.

As noted by SCHMID (1975) and MILNES & PFIFFNER (1977) ductile deformation of the Verrucano, producing the cleavage, pre-dated emplacement of the Glarus nappe. The amount of north–south extension in the Verrucano, on a regional scale during this Oligocene deformation, may be estimated using the method of HOSSACK (1978). This is illustrated in Figure 6. A profile of the Glarus Thrust is shown in Figure 5*a*, constructed from the stratum contour map of SCHMID (1975) and information given by TRÜMPY (1969). The profile extends along north–south grid line 734 (Fig. 1). The strain data is projected onto this profile plane, whose orientation closely approximates ZX sections through the finite strain ellipsoids. The angles between X-axes of the ellipsoids and the trace of the thrust plane are given in Table 1 and shown in Figure 6*a*. The reciprocal quadratic elongation parallel to the trace of the thrust plane was calculated and plotted against distance along the section (Fig. 6*b*). Measurement of the area under the resulting curve suggests that the amount of bulk extension along this line, between sites 2 and 12, now a distance

Table 1: *Table of finite strain analyses in the Verrucano.*
"k" is defined in Figure 5, the angles θ are those between the orientation of the trace of the Glarus Thrust and the strain ellipsoid long axis (see Fig. 6a).

Site	X	Y	Z	k	θ(°)
1	2.07	0.85	0.57	2.84	30
2	1.55	1.07	0.60	0.59	30
3	1.83	0.92	0.59	1.86	30
5	1.55	0.87	0.74	4.22	35
6	2.16	0.96	0.48	1.25	25
7	1.70	0.95	0.62	1.51	25
8	2.90	0.99	0.35	1.04	15
9	2.15	1.08	0.43	0.67	-
10	1.29	0.90	0.86	8.57	20
11	3.21	0.90	0 34	1.58	15
12	2.89	0.96	0.36	1.20	10
13	1.16	1.16	0.74	0.00	-

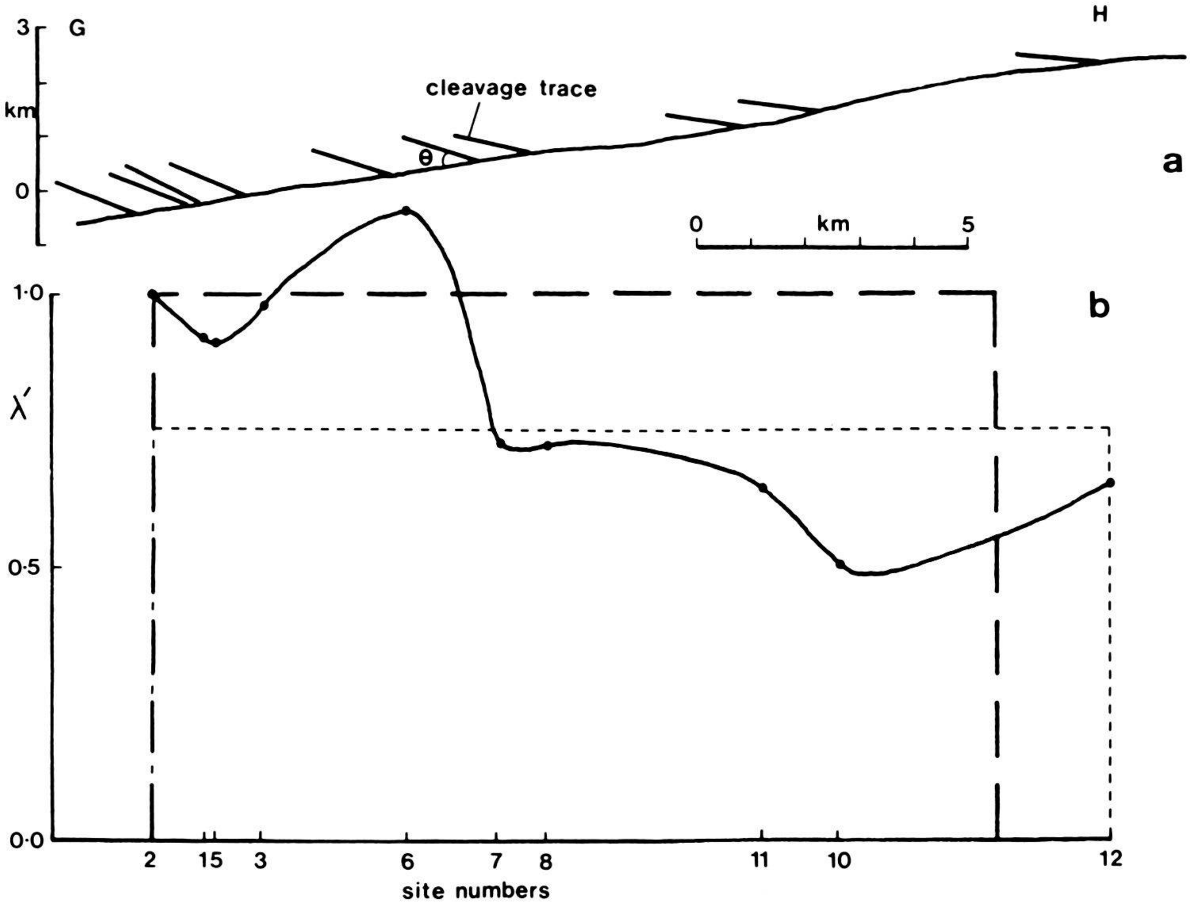


Fig. 6. Calculation of the bulk extension along section line *GH* (Fig. 1), using the method of HOSSACK (1978). Diagram *a* shows the trace of the Glarus Thrust, constructed using data given by TRÜMPY (1969) and SCHMID (1975), the oblique lines are the orientations of strain ellipse long axes projected onto the section plane.

of 17.6 km, was 14%, corresponding to a mean reciprocal quadratic elongation of 0.75. This extension is unevenly distributed along the profile plane, increasing generally to the south.

There are no problems of compatability now in accomodating this strain downwards, as the Oligocene strain trajectories are discontinuous across the Glarus Thrust. Upwards, however, where the deformation dies out in the Jurassic so that Cretaceous strata are quite undeformed, it would be interesting to study how the strain variations are accomated. Presumably either the cleavage steepens and dies out upwards, or there are decollement horizons within the Mesozoic strata. MILNES & PFIFFNER (1977) describe the geologic evolution of this part of the Alps. According to their reconstructions the penetrative deformation of the Glarus nappe and its underlying basement, the Tavetsch Massif, during Upper Oligocene times, was due to the Austroalpine and Pennine nappes overthrusting the Aar Massif and its cover, so that they were involved in a broad shear zone dipping steeply south. They describe a bulk strain ellipsoid in the infrahelvetic complex with axial ratio 2:1:½, but note that the strains are very heterogeneous. Integrating the extensions along the cleavage seen in this study gives a bulk reciprocal quadratic elongation of 0.26, which is identical with that of MILNES & PFIFFNER (1977).

Metamorphism

The regional pattern of Lepontine metamorphism in the Central Alps was described by NIGGLI & NIGGLI (1965) and dated as 35–40 my by JÄGER (1970) and HUNZIKER (1970). Modern reviews of alpine metamorphism and geochronology are given by FREY et al. (1974), HUNZIKER (1974) and PURDY & JÄGER (1976). Low-grade metamorphism in the Glarus Alps has been studied in great detail, in the Quarten-Schiefer by FREY (1969, 1970), in the Lias by FREY (1970, 1978) and in glauconite-bearing formations by FREY et al. (1973). It was found that low-grade metamorphism in the Quarten-Schiefer could be zoned using the cristallinity of illite (KUBLER 1967). It appears that the lower and upper limits of the anchizone outcrop as east–west traces just south of Walensee and just north of the Aar Massif, respectively (Fig. 4). With increasing grade three zones were recognized in glauconite-bearing formations:

I. unmetamorphosed sediments containing K-rich glauconite and Fe-rich chlorite;
II. in which green stilpnomelane is formed at the expense of glauconite;
III. in which biotite appears.

Zone boundaries were found to outcrop as east–west traces, the I/II boundary about midway through the anchizone, the II/III boundary approximately coincides with the upper limit of the anchizone (Fig. 4). FREY et al. (1973, Fig. 6), in a detailed study on Glärnisch, show "isograds" of illite cristallinity crossing nappe boundaries obliquely and relate the I/II boundary to the thickness of the nappe pile, showing that the individualization of the various nappes within the Helvetic thrust block predates the metamorphism. FREY et al. (1974), however, note that post-metamorphic displacements along the Glarus Thrust have produced an inversion of zones. This is based on a detailed study on Glarner Freiberge (M. Frey, personal communication, 1979).

K–Ar ages on glauconite, stilpnomelane, riebeckite and illite (FREY et al. 1973, 1974; HUNZIKER, in FREY 1978) decrease systematically southwards (Fig. 4), from presumably sedimentary ages, >40 my, in the north, to <20 my in the south. It remains uncertain whether this pattern represents a single thermal culmination and cooling, the Lepontine phase at around 35 my, or is the product of that and a later metamorphic event at around 20 my in southern parts. Textural evidence to be presented lends some support to the latter hypothesis, so that Figure 2 is shown accordingly.

Mineral assemblages found in the Verrucano were established optically and by X.R.D. methods. These vary systematically from north to south. In non-metamorphic samples from site 13 the assemblage is quartz - chlorite - illite/montmorillonite - hematite - plagioclase - calcite. In the northern Glarus Alps mixed-layer illite/montmorillonite is replaced by illite, in the southern Glarus Alps hematite disappears and paragonite, oxychlorite and an opaque mineral appear. With the disappearance of hematite the rocks change colour from red to green.

Oriented and unoriented mounts of the clay fractions, $<2\ \mu$, were prepared for analysis by X.R.D. techniques. Clay fractions were obtained from whole rock powders in settling columns, the oriented mounts were prepared by sedimenting the clay fraction fast, under pressure, onto porous tiles. X.R.D. traces were run slowly, 0.5° 2θ/min., using CoK_α radiation. Illite cristallinity was measured as the peak width at half height above background of the 10 Å diffraction peak on the oriented mounts. These measurements were standardized against samples of known cristallinity from the Quarten-Schiefer, kindly provided by Prof. M. Frey and prepared by the same method. The ratio of illite polymorphs $2M/(2M+1Md)\times 100$ was obtained by measuring the areas under the 2.80 and 2.58 Å diffraction peaks above background on the unoriented mounts, calculating their intensity ratio and using the calibration curve of MAXWELL & HOWER (1967, Fig. 2). Two methods were used to estimate the composition of the illites:

1. The areas under the 5 and 10 Å diffraction peaks above background were measured on the oriented mounts. According to ESQUEVIN (1969) their intensity ratio enables aluminous and magnesian illites to be distinguished.
2. The ranges and maxima of the illite (060) diffraction peaks were accurately measured on the unoriented mounts, using quartz (211) as an internal standard. According to MAXWELL & HOWER (1967, Fig. 4) this enables the $Mg+Fe_{total}$ content of octahedral sites to be estimated.

The results of these analyses are shown in Table 2 and Figures 4 and 7.

Table 2: *Results of X.R.D. studies of clay fractions from the Verrucano. For details see text.*

	cristallinity index	$\left(\frac{2M}{2M+1Md}\right)100$	range of d(060) (Å)	d(060) maxima (Å)	$\frac{I_{5Å}}{I_{10Å}}$
			corresponding values of $(Mg+Fe_{tot})_n/O_{10}(OH)_2$		
13	11.40	30	1.509 - 1.502 0.7 - 0.4	1.509, 1.498 0.7, 0.0	0.258
4	6.95	59	1.510 - 1.500 0.7 - 0.1	1.510, 1.498 0.7, 0.0	0.254
2	4.70	52	1.510 - 1.502 0.7 - 0.4	1.510, 1.504, 1.498 0.7, 0.5, 0.0	0.280
3	4.90	60	1.510 - 1.498 0.7 - 0.0	1.510, 1.505, 1.498 0.7, 0.5, 0.0	0.286
6	4.35	57	1.505 - 1.498 0.5 - 0.0	1.505, 1.498 0.5, 0.0	0.337
7	4.40	63	1.510 - 1.498 0.7 - 0.0	1.508, 1.505, 1.498 0.65, 0.5, 0.0	0.301
8	6.35	72	1.510 - 1.498 0.7 - 0.0	1.510, 1.505, 1.498 0.7, 0.5, 0.0	0.317
11	4.50	70	1.510 - 1.500 0.7 - 0.1	1.510, 1.505, 1.500 0.7, 0.5, 0.1	0.236
10	6.35	55	1.510 - 1.505 0.7 - 0.5	1.508, 1.503, 1.498 0.65, 0.4, 0.0	0.400
12	4.15	52	1.510 - 1.498 0.7 - 0.0	1.510, 1.503, 1.498 0.7, 0.4, 0.0	0.357
17	4.00	100	1.505 - 1.498 0.5 - 0.0	1.505, 1.501, 1.498 0.5, 0.2, 0.0	0.320
16	4.00	100	1.505 - 1.498 0.5 - 0.0	1.505, 1.501, 1.498 0.5, 0.2, 0.0	0.393
15	4.40	100	1.510 - 1.498 0.7 - 0.0	1.510, 1.498 0.7, 0.0	0.243
14	4.15	100	1.508 - 1.498 0.65 - 0.0	1.508, 1.503, 1.498 0.65, 0.4, 0.0	0.288

As in the Quarten-Schiefer, illite cristallinity decreases from north to south across the Glarus Alps (Fig. 4). The variation, however, is not as great as that reported by FREY (1970) for the Quarten-Schiefer. The northernmost Verrucano outcrops are in the anchizone, while the southern samples are at the anchi-/epizone boundary. The northwards extension of the anchizone in the Verrucano, relative to the Quarten-Schiefer may perhaps be explained in terms of their relative stratigraphic positions and "isograd" dips. The apparent southern extension of the anchizone probably arises from a combination of insufficient sampling and failure to resolve paragonite in all samples, so that illite basal reflection peak widths are over estimated. A wealth of illite cristallinity data (M. Frey, personal communication, 1979) clearly shows that the Verrucano of the Glarner Freiberge is in the epizone.

Interpretation of the illite 5 and 10 Å intensity ratios and *d*(060) data is difficult, due to uncertainty about the usefulness of the ESQUEVIN diagram (M. Frey, personal communication, 1979) and the unknown contribution that hematite (214) makes to the spectrum of *d*(060) values. Tentatively it is concluded that the illite content of the non-metamorphic samples is a mixture of biotite-muscovite compositions of diagenetic origin and detrital muscovites. In the anchizone rocks of the northern Glarus Alps the *d*(060) maxima at 1.503-1.505 Å are thought to be due to the growth of phengite. In the southern Glarus Alps the *d*(060) maxima at 1.501-1.498 Å are throught to be due to the growth of muscovite at the higher metamor-

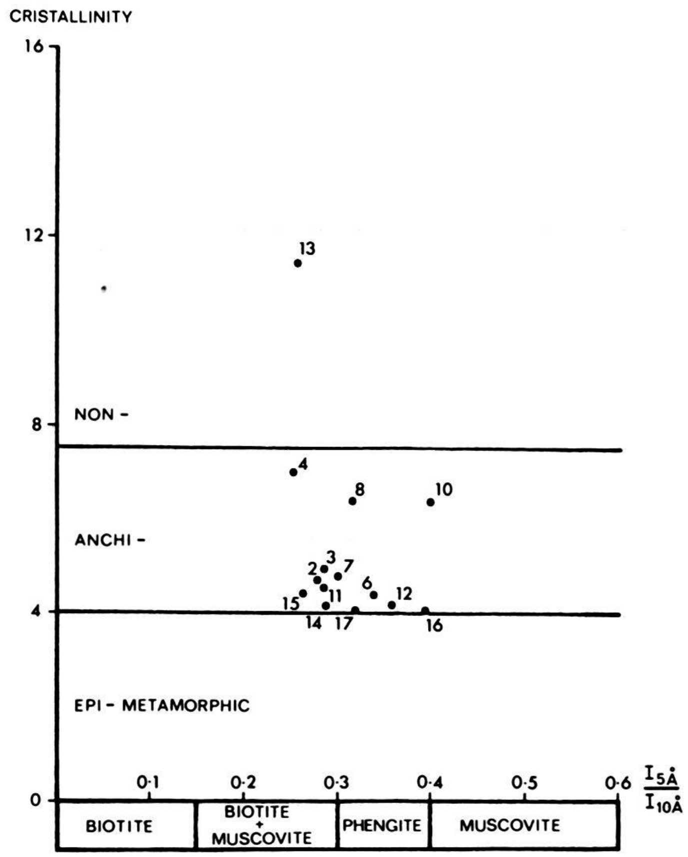


Fig. 7. Cristallinity of illite versus intensity ratio $I_{5Å}/I_{10Å}$ in the Verrucano (diagram after ESQUEVIN 1969).

phic grades. It is thought that this pattern of crystallization, progressively replacing the diagenetic illites, together with the persistence of detrital muscovites, would account for the observed distribution of polymorph ratios, which increases in an irregular way from north to south.

Textures

Oriented samples were collected for texture analysis. Very thin sections, approximately 5 μ, were cut normal to cleavage and parallel to the extension direction for optical examination. The single exception to this was a sample from site 13, which being tectonically undeformed, was cut normal to bedding. This sample shows a weak fabric parallel to bedding, defined by the preferred orientation of chlorite, illite and hematite, which is cut by randomly oriented illites (Fig. 8*a*). Detrital quartz grains and lithic fragments are approximately equidimensional.

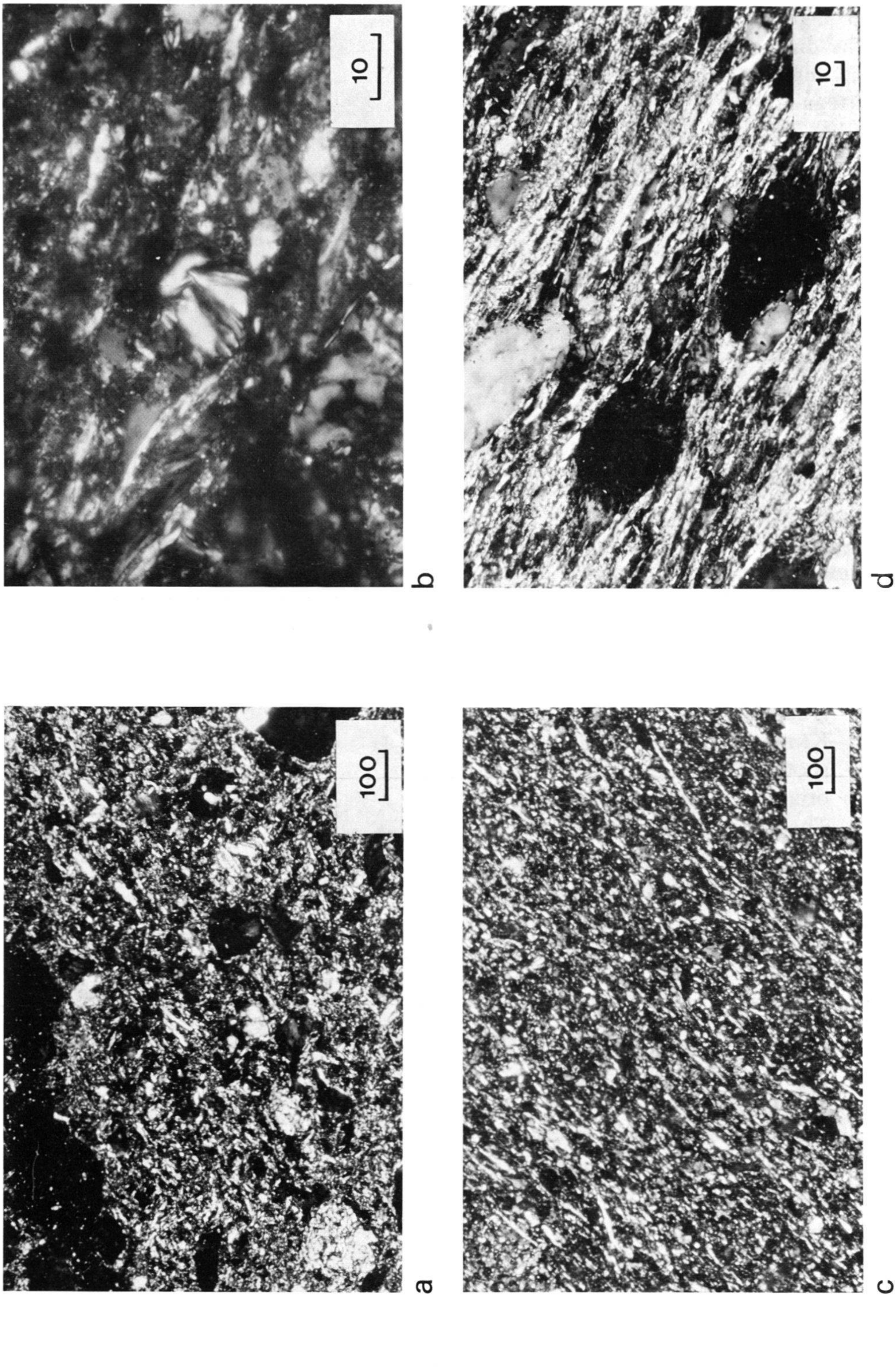
Samples from the red slates of the northern and central Glarus Alps consistently show a number of optical features:

1. The cleavage fabric is defined by the preferred orientation of illite, chlorite and hematite (Fig. 8*c*).
2. Detrital quartz grains are elongate parallel to the cleavage trace and have fibrous quartz also parallel to the cleavage trace developed in strain shadows (Fig. 8*d*). The quartz grains show no optical features indicative of internal strain.
3. Discrete bands of quartz occur parallel to the cleavage trace.
4. Pods of differently oriented phyllosilicates occur as sub-elliptical aggregates oriented parallel to the cleavage trace (Fig. 8*b*). The structure of these slates thus is similar to those with a domainal structure described by WILLIAMS (1972) and KNIPE & WHITE (1976). The orientation of the pods is similar to that of the green spots but there is no correlation of axial ratios. The internal phyllosilicate orientation within the pods is different from pod to pod.
5. The cleavage fabric is cut by randomly oriented illites (Fig. 8*c*). These cross-cutting illites have not been observed to cut across pods.

Samples from the green slates of the southern Glarus Alps consistently show optical features that distinguish them from the northern red slates:

1. Discrete patches of oxychlorite, chlorite, high-relief white mica, calcite and an opaque mineral occur (Fig. 8*e*). These are approximately equidimensional in shape and cross-cut the cleavage fabric.
2. Elongate quartz grains show development of subgrains. The cross-cutting phyllosilicates include chlorite and white mica and where they occur in the elongated quartz grains their orientations appear to be controlled by subgrain boundaries (Fig. 8*f*).
3. The pods of differently oriented phyllosilicates have not been observed.

A limited number of samples were prepared for texture goniometry by the combined reflection/transmission mode technique. The analytical procedures are described by SIDDANS (1976). These samples were cut parallel to the mesoscopic planar fabric of the rocks and scanned for illite and chlorite basal planes and the



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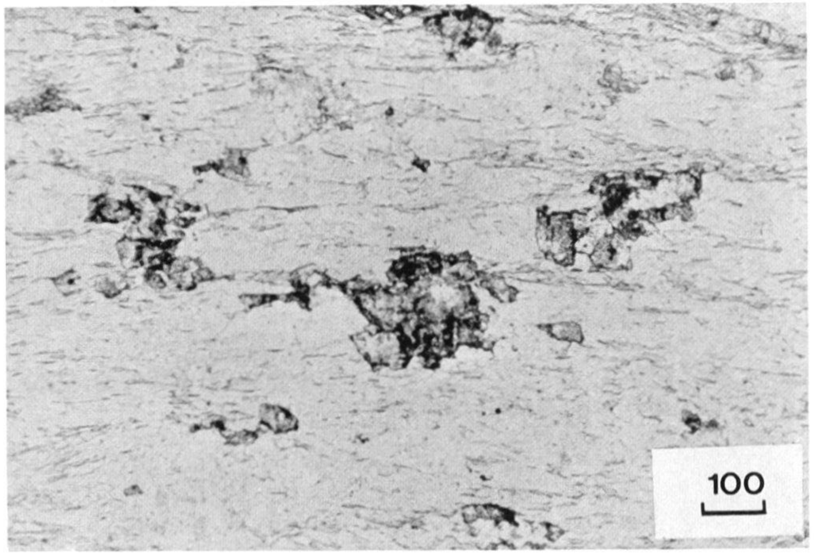

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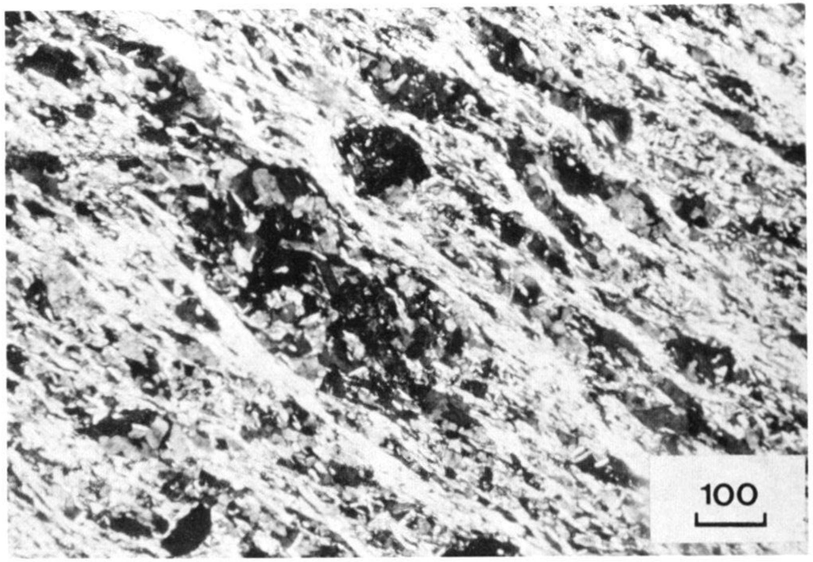

f

Fig. 8. Photomicrographs of samples from the Verrucano. Scale-bars calibrated in μ. All sections cut normal to cleavage and including the extension direction, except *a* which is normal to bedding. All sections viewed between crossed polars, except *e* which is in P.P.L.

a) Sample 13. Bedding fabric defined by chlorite, illite and hematite. Note cross-cutting illites and equidimensional detrital quartz grains and lithic fragments.
b) Sample 8. Pods of differently oriented phyllosilicates between anastomosing cleavage lamellae.
c) Sample 8. Cleavage fabric defined by chlorite, illite and hematite. Note cross-cutting illites.
d) Sample 11. Quartz grains elongated in the extension direction with fibrous quartz in the strain shadows.
e) Sample 14. Equidimensional patches of oxychlorite, chlorite, high-relief white mica, calcite and an opaque mineral cross-cutting the cleavage fabric.
f) Sample 15. Quartz grains elongated in the extension direction showing the development of subgrains and cross-cutting phyllosilicates along subgrain boundaries.

first two quartz diffraction peaks, 100 and 101. Low peak-to-background ratios precluded any study of hematite orientations by this technique. All samples produced pole-figures for quartz that did not differ significantly from random in orientation. This applies to a sample from site 15, whose elongate quartz grains were seen to show subgrain development optically.

Pole-figures for chlorite and illite basal planes are shown in Figure 9. As expected the tectonically undeformed sample from site 13 has maximum pole densities normal to bedding and contours are approximately concentric, though there is a difference in magnitude between the maximum pole densities that is not accountable by the errors arising from the counting statistics. In all the slaty rocks the maximum pole densities are within 5° of the pole to cleavage and the finite extension directions are in areas of very low pole densities on the pole-figures. Comparison of the data for samples from sites 2 and 11 shows an increase in preferred orientation with an increase in finite strain, though no direct correlations are possible. The difference in magnitude of maximum pole densities for chlorite and illite basal planes are explicable by the errors associated with the counting statistics in the cases of samples from sites 2 and 15, but not in that from site 11. All pole-figures have triclinic symmetry in detail, though those from site 15 approach monoclinic symmetry. The 3 and 6 times random contours for both chlorite and illite at site 2 have marked lobes extending approximately towards the pole to bedding; this sample has a relatively low finite strain state. The significance of these lobes and sub-maxima in lower-order contours is not understood. The lack of optically observed domainal structure in sample 15 and difference in orientation between sub-maxima and poles to bedding in samples 11 and 15, perhaps suggest they are produced by the optically observed cross-cutting phyllosilicates. The pole-figure for illite basal planes from sample 15, of course, represents the combined effects of the illite and paragonite, whose 10 Å diffraction peaks cannot be resolved in reflection mode texture goniometry.

Discussion

The deformation and metamorphic histories of the Glarus nappe have been outlined in earlier sections. It is apparent, however, that some uncertainties remain concerning the existence of a second metamorphic event at about 20 my, the extent to which penetrative, cleavage-producing deformation continued after the maximum metamorphic grade was attained and the extent of post-metamorphic displacements along the Glarus Thrust.

The evidence concerning the duration of ductile deformation and the peak of metamorphism is critical. It is, for example, used by MILNES & PFIFFNER (1977) to date the end of the Calanda Phase in the Infrahelvetic complex of Eastern Switzerland. Considering the petrographic evidence of cleavage and porphyroblast growth:

1. FREY (1969, Fig. 38 and 39) illustrates chloritoid and staurolite post-dating the cleavage fabric in the Quarten-Schiefer (now believed to be Liassic: M. Frey, personal communication, 1979) of the Lukmanier area.
2. BÜRGISSER & FELDER (1974) describe post-tectonic growth of stilpnomelane in the parautochthonous cover of the Aar Massif.

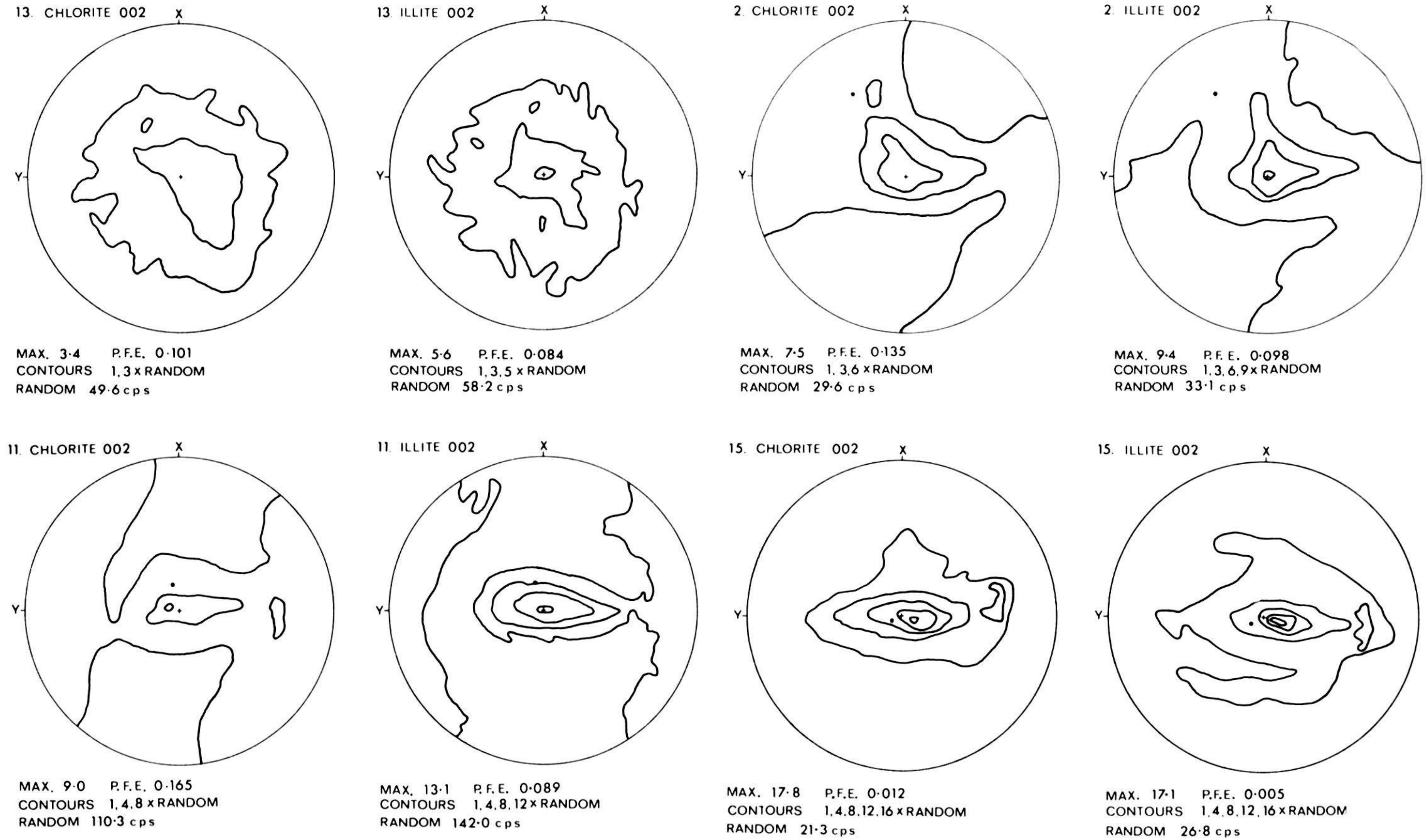

Fig. 9. Equal-area, upper-hemisphere pole-figures for chlorite and illite basal planes for samples from sites 13, 2, 11 and 15. For 13 the *XY*-plane is parallel to bedding, for the others the axes are finite strain ellipsoid axes, i.e. *Z* (up) is parallel to the pole to cleavage, *XY* is parallel to cleavage and *X* is parallel to the extension direction. The solid dots are poles to bedding, MAX. is the maximum pole density, P.F.E. is the probable fractional error associated with the maximum pole density. RANDOM is the random fabric intensity in counts per second.

3. MILNES & PFIFFNER (1977) describe chloritoid porphyroblasts cross-cutting the cleavage in the Infrahelvetic complex, but with renewed flattening of the matrix causing subsequent rotation during the Ruchi Phase, contemporaneous with displacements along the Glarus Thrust, but of only local extent.
4. In this study patches of oxychlorite, chlorite, high-relief white mica, calcite and an opaque mineral have been described cross-cutting the cleavage fabric in the Verrucano of the southern Glarus Alps and cross-cutting illites have been seen throughout the Glarus area.

It is thus concluded that while ductile deformation may have continued locally after porphyroblast growth in the Infrahelvetic complex, within the Helvetic thrust sheet itself the maximum metamorphic grade, associated with porphyroblast growth, post-dated the penetrative, cleavage-producing deformation. It appears that, as suggested by SCHMID (1975) and MILNES & PFIFFNER (1977), the observed and inferred tectonic evolution, metamorphism and geochronological data of the Glarus Alps can best be combined in a model that includes two thermal peaks:

1. Ductile, cleavage-producing deformation during Upper Oligocene times, accompanied by syntectonic metamorphism with a thermal peak at about 35 my.
2. Static heating, possibly resulting from the blanketing effect of the overthrust Austroalpine and Pennine Zone units that caused the earlier deformation, producing a thermal peak at about 20 my.
3. Displacement along the Glarus Thrust to produce the observed inversion of metamorphic zones.

The rest of this discussion aims to consider the development of the observed textures in the Verrucano in the light of the deformation and metamorphic history. The one ubiquitous feature seen optically in all samples is the presence of phyllosilicates cross-cutting an earlier planar fabric. The pre-existing fabric is bedding in the case of the Schwarzwald sample and cleavage in the Glarus Alps. The phyllosilicates are illites, except in the southern parts where cross-cutting chlorite and oxychlorite are also seen. The pattern of K-Ar ages, however, suggests that they cannot have a common origin. It appears that the cross-cutting illites of the Schwarzwald must be of diagenetic origin, those of the southern Glarus Alps may be of Miocene age, while those of the northern and central Glarus Alps may be either the product of the Oligocene metamorphic peak outlasting the cleavage-producing deformation, or the composite product of that and a later metamorphism.

The oriented phyllosilicates contributing to the planar fabric of the cleavage presumably formed by crystallization under non-hydrostatic stress, as the products of pro-grade metamorphic reactions. Some possible reactions have been suggested by FREY (1969, 1970) for the Quarten-Schiefer, which in view of the lithological similarity may also be applicable to the Verrucano. They are dehydration reactions. The sites of phyllosilicate crystallization are discussed by KNIPE & WHITE (1976) and the importance of dehydration reactions during deformation is discussed by SIDDANS (1978). The main points of these discussions may be summarized:

1. The margins of pods, or high-stress zones within pods, are sites of crystallization or recrystallization of phyllosilicates, where new phases grow in thermodynami-

cally stable orientations. Thus the cleavage lamellae, which anastomose around the pods, grow at the expense of the pods.

2. If water produced by pro-grade reactions cannot escape rapidly enough the pore-fluid pressure will rise with a number of consequences - rotation and grain boundary sliding will be facilitated, the solubilities of quartz and calcite will be increased and the presence of a migrating pore-fluid will facilitate transfer of material in solution into and out of local volumes of rock.

WHITE & KNIPE (1978) suggest that the production of new small grains at pod margins may produce a further weakening effect, leading to enhanced deformation in the cleavage lamellae.

With the development of analytical facilities on scanning transmission electron microscopes it would be a fascinating study to investigate the chemistry and crystallography of phyllosilicates in the pods and cleavage lamellae of these slates. It would also appear to be the only way of obtaining further information on the nature of the cross-cutting phyllosilicates. Such data should provide a new insight into metamorphic processes associated with deformation of fine-grained rocks at low metamorphic grades (e.g. KNIPE 1978).

In the northern and central Glarus Alps detrital quartz grains show all the optical features characteristic of deformation by pressure solution. They also show no preferred crystallographic orientation. Some of the quartz now present in the red slates is, of course, the product of reactions, so will not necessarily record the complete history of deformation in their shapes and strain features. Elongate quartz grains in the green slates of the southern Glarus Alps do show optical evidence of internal deformation, with the development of subgrains. However, the lack of any preferred crystallographic orientation suggests that this internal deformation was a very late stage event in the sequence of strain increments producing the net grain shapes and that the bulk of the deformation was achieved by pressure solution. Alternatively, or additionally, the possible 20 my thermal peak may have had an annealing effect on the quartz grains, prior to growth of the new phyllosilicates along subgrain boundaries.

Acknowledgments

I am extremely grateful to Prof. M. Frey and Dr. J.C. Hunziker for providing an invaluable introduction to the Geology of the Glarus Alps, its literature, a most enjoyable time in Bern whilst benefitting from them and for much subsequent stimulating discussion. Prof. Frey kindly provided clay fractions of known illite cristallinity, from the Quarten-Schiefer, against which my results were standardized and made available much unpublished illite cristallinity data. Dr. Hunziker kindly made available much unpublished K-Ar age data on the Glarus Alps. I am also grateful to Profs. M. Frey and J.G. Ramsay, Drs. J.C. Hunziker, A.G. Milnes and S.M. Schmid for their comments on an early draft of the manuscript.

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