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Alpine metamorphism in the North Helvetic Flysch of the Glarus Alps, Switzerland

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Key words: Glarus Alps, North Helvetic flysch, Glarus thrust plane, very low-grade metamorphism, Taveyannaz sandstone, illite crystallinity, vitrinite reflectance, fluid inclusion microthermometry

ZUSAMMENFASSUNG

Die alpine Metamorphose der Wageten-Schuppe und des nordhelvetischen Flysches der Glarner Alpen wird mit Hilfe kritischer Mineralparagenesen in den Taveyannaz-Sandsteinen, Daten zur Illit-Kristallinität und Inkohlung, sowie Homogenisierungstemperaturen (T_h) aus Fluideinschlüssen beschrieben. In der Wageten-Schuppe zeigen die Taveyannaz-Sandsteine Zeolith-Fazies (Laumontit, Korrensit), die Illite sind diagenetisch, die Inkohlung liegt bei $R_{max} \leq 2\%$. Fluideinschlüsse zeigen kleinere Mengen höherer Kohlenwasserstoffe und T_h zwischen 160 und 190 °C. Im nordhelvetischen Flysch variieren die Werte zwischen Illiten der höchstgradigen Diagenese, $R_{max} = 3–4\%$ und methanhaltigem Fluid mit T_h = 230 °C im Norden (Lochsiten) und Prehnit-Pumpellyit-, Pumpellyit-Aktinolith-Fazies, Illiten an der Anchi-Epizonengrenze, $R_{max} > 8\%$, und wasserreichen Fluideinschlüssen mit Einschlusstemperaturen von 270–300 °C im Süden. Die Daten dokumentieren die inverse metamorphe Zonierung entlang der Glarner Hauptüberschiebung und erlauben die Abschätzung eines postmetamorphen Überschiebungsbetrages von 10 km. Die metamorphe Entwicklung der Wageten-Schuppe deutet auf eine frühe Trennung vom paläogeographisch benachbarten nordhelvetischen Flysch hin und weist ihr dadurch eher eine helvetische als subhelvetische Stellung zu.

Innerhalb des südlichen nordhelvetischen Flysches zeigen sich an kartierten Schuppengrenzen Sprünge in den Inkohlungswerten, was für die Schuppentektonik einen zumindest partiell postmetamorphen Zeitraum vermuten lässt. Die Kombination verschiedener Datenmuster erlaubt für die südlichen Glarner Alpen die Annahme eines zeitlich kurzen Metamorphosehöhepunktes.

ABSTRACT

Mineral assemblages of the Taveyannaz sandstone, illite crystallinities, vitrinite reflectance data, and fluid inclusion homogenization temperatures (T_h) are presented for the Wageten slice and the North Helvetic flysch in the Glarus Alps. The Wageten slice reached zeolite facies (laumontite, corrensite), characterized by a diagenetic illite crystallinity, $R_{max} \leq 2\%$, and higher hydrocarbons-bearing fluid inclusions with T_h = 160–190 °C. Within the northern part of the North Helvetic flysch (Lochsiten locality) uppermost diagenetic illites coincide with $R_{max} = 3–4\%$, and methane-bearing fluid inclusions with T_h = 230 °C. Prehnite-pumpellyite/pumpellyite-actinolite facies, upper anchizone/lowermost epizone, $R_{max} > 8\%$, water-rich fluid inclusions with trapping temperatures of 270–300 °C are found in the southernmost outcrops of the North Helvetic flysch. Transported metamorphism along the Glarus overthrust is confirmed by the data presented, and a post-metamorphic displacement of approximately 10 km can be estimated. The Wageten slice must have been separated from the North Helvetic flysch before the onset of metamorphism in the Infrahelvetic units. This supports a Helvetic rather than a Subhelvetic position for this tectonic unit.

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Data from a vertical profile in the North Helvetic flysch suggest post-metamorphic movements of flysch slices along discrete tectonic boundaries within the flysch, presumably during post-metamorphic overthrusting of the Helvetic nappes. A correlation of the different methods indicates a short metamorphic event in the southern study area.

Introduction

Very low-grade metamorphism has become a topic of increasing interest in the external parts of the Swiss Alps (for review see Frey 1986). A variety of methods has been applied to quantify the degree of metamorphism during Alpine orogenesis such as illite crystallinity, coalification, fluid inclusion microthermometry, and critical mineral assemblages in the Taveyannaz sandstone and other lithologies. Application of several methods allowed a correlation between the data pattern of these methods (e.g. Kübler et al. 1979; Stalder 1979; Frey et al. 1980; Kisch 1980).

The northern external parts of the Alps are dominated by limestones and marls of the Helvetic nappes. While there is a general lack of volcanic sediments within the Mesozoic stratigraphy, they do occur in the Tertiary flysch units (e.g. Winkler et al. 1990). During the early Oligocene, all the way along the Alpine arc from southeastern France to eastern Switzerland, and also at some places in the Appenines (Stalder 1979), a strong andesitic input can be observed within the flysch sediments deposited in front of the northwards propagating Alpine orogen (Lateltin & Müller 1987). For a long time geologists have studied the often mottled sandstones containing large amounts of volcanogenic detritus. In Switzerland they were named Taveyannaz sandstones after an occurrence at the "Alp Taviglianaz" in the Western Alps (Studer 1834). A first overview and detailed petrographic description was given by De Quervain (1928), and a classification of the Taveyannaz sandstones into four types (I–IV) was proposed by Vuagnat (1952). A short summary of the characteristic features for each type is given in table 1.

The aim of this study is: (i) a review of earlier published data on metamorphism in the Glarus Alps, (ii) a description of metamorphism with the help of illite crystallinity, vitrinite reflectance, fluid inclusion data, and mineral assemblages from the Taveyannaz sandstones within the North Helvetic flysch of the Glarus Alps, and (iii) a discussion of the data and their tectonic and geological implications.

Regional setting and review of existing data

For a simplified description, the area of the Glarus Alps can be divided into a northern and a southern part. North of Schwanden (Fig. 1) the field area is dominated by the stack of Helvetic nappes. A tectonic slice at the northern Alpine border, called Wageten slice, may be considered as a Helvetic nappe unit situated above the Glarus thrust plane due to its "Helvetic" stratigraphic profile. However, the presence of Taveyannaz sandstone within the Tertiary of this slice reveals a paleogeographic origin close to the North Helvetic flysch presently found below the Glarus thrust plane (Frey 1965; Trümpy 1969; Siegenthaler 1974).

South of Schwanden the tectonic units below the Glarus main thrust (= Infrahelvetic units, Fig. 1) are exposed as well. Permian Verrucano, which represents the base of the Helvetic nappes is found in the "Glarner Freiberge", in some small klippen on top of the

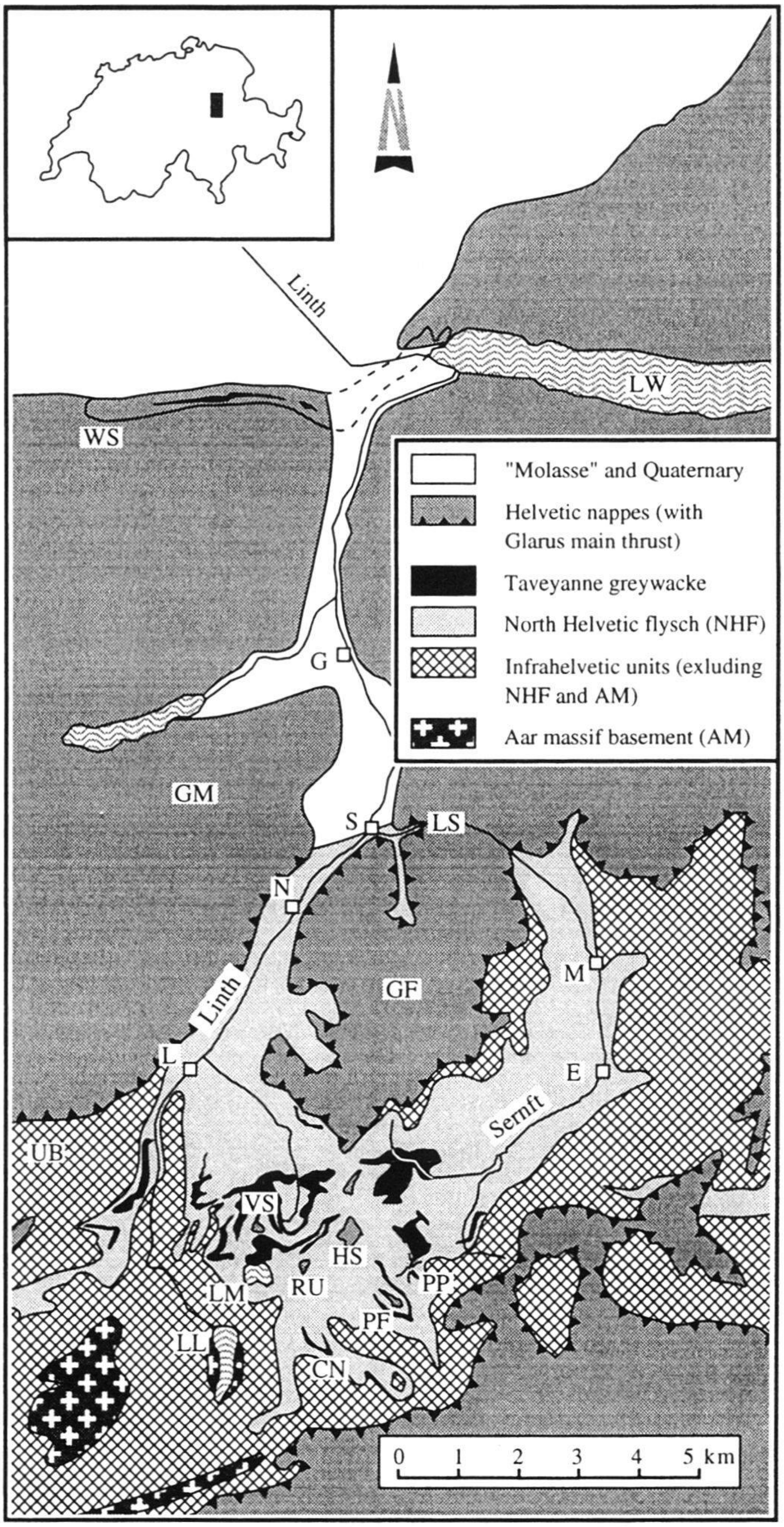

Fig. 1. Simplified tectonic map of the Glarus Alps (after Oberholzer 1942 and Pfiffner & Schmid, unpubl.). Local names: E Elm, G Glarus, L Linthal, M Matt, N Nidfurn, S Schwanden; CN Crap Ner, GF "Glarner Freiberge", GM Glärnisch massif, HS Hausstock, LL lake Limmern, LM lake Mutt, LS Lochsiten, LW lake Walen, PF Piz Fluaz, PP Panix pass, RU Ruchi, UB Urnerboden, VS Vorstegstock, WS Wageten slice.

Tab. 1. Definition and field appearance of the various types of Taveyannaz sandstone according to Vuagnat (1952).

Type	Description	Field occurrence
I	true andesites, basalts	does not exist in Switzerland
IIa	50–90% of andesitic material, mafic minerals (augite, amphibole) present, no alteration of volcanogenic material	homogeneous dark green colour
IIb	50–90% of andesitic material, metastable mafic minerals still present, partial alteration of volcanogenic material	patched or more rarely homogeneous greenish grey colour
III	50–90% of andesitic material, mafic minerals absent, strong alteration of the volcanogenic material	patched or more rarely homogeneous greenish grey colour
IV	> 50% of andesitic material, no mafic minerals, alteration by albite, chlorite, calcite, no Ca-silicates	moderate to dark grey colour, sometimes milky quartz grains

Infrahelvetics (Hausstock, Ruchi) and east and south of the Sernft valley. The Infrahelvetic units include the crystalline and polymetamorphic basement of the Aar massif, its autochthonous/parautochthonous mesozoic cover and three allochthonous flysch units (from bottom to top: North Helvetic, Blattengrat, and Sardona flysch). Between Linth and Sernft valley the North Helvetic flysch is the dominant unit. North Helvetic flysch sandstones include the Taveyannaz sandstone and the Altdorf sandstone (also called "Elm formation", "Matt sandstone", "Engi shales"; "grès de Val d'Illiez" after Vuagnat 1952).

Detailed maps of the area of the southern North Helvetic flysch are available from several Ph. D. theses from the University and ETH in Zürich (Styger 1961; Wegmann 1961; Frey 1965; Siegenthaler 1974). Outcrops of Taveyannaz sandstone forming the base of the North Helvetic flysch were used to distinguish several tectonic slices ("Schollen", Styger 1961; Siegenthaler 1974) that were thrusted onto each other during the Alpine orogeny. Detailed sedimentological studies within the Taveyannaz sandstone were performed by Sinclair (1992). He proposed the Taveyannaz sandstone to have been deposited into a deeper northern basin and a shallower southern piggy-back basin (Ori & Friend 1984) in front of the northwards propagating Alpine front. The sedimentation type was turbidite-like and sediment transport during early Oligocene within the outer basin was mainly from WSW to ENE (Radomski 1961; Siegenthaler 1974).

First details on Alpine metamorphism within the Glarus Alps were given by Niggli et

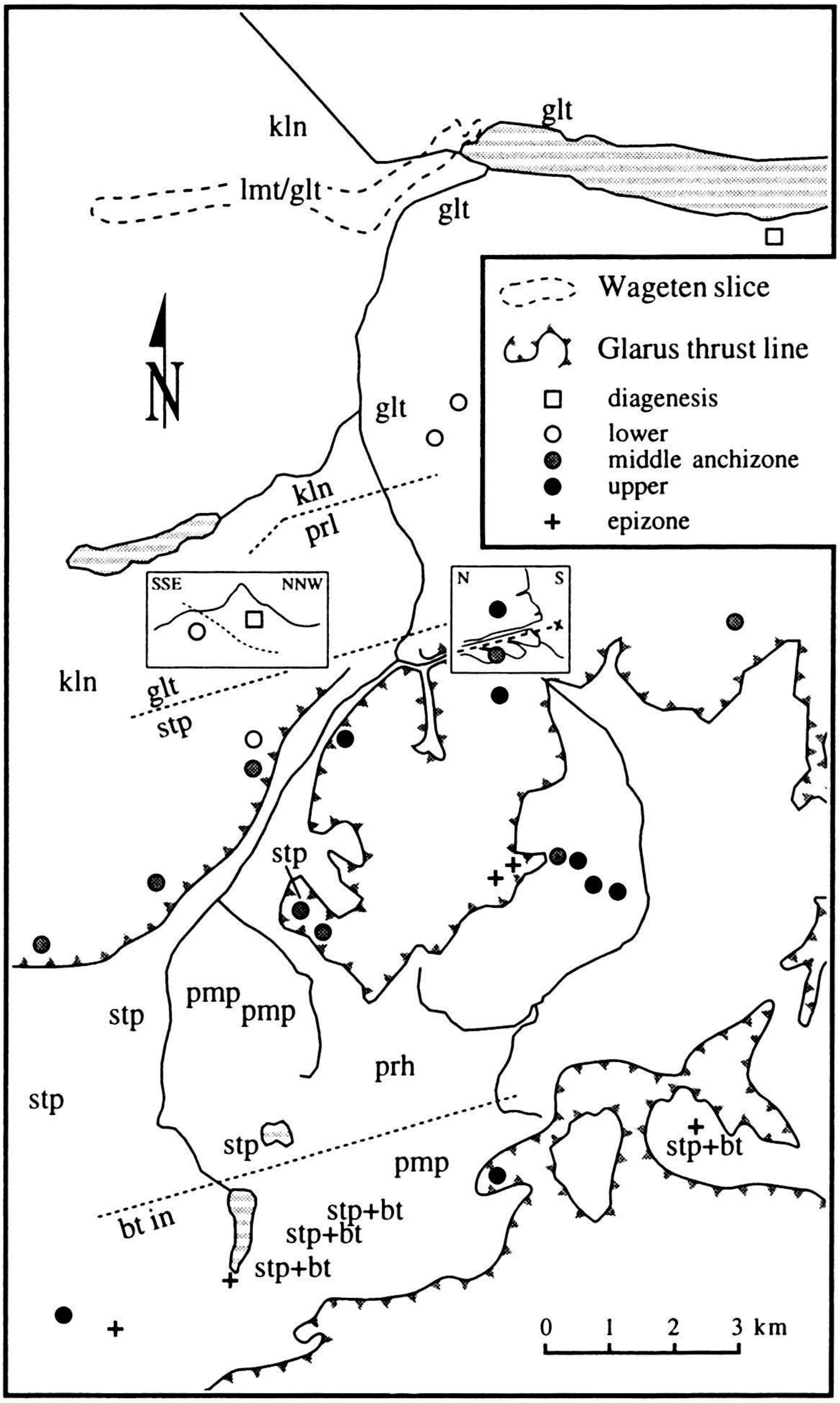

Fig. 2. Tectonic sketch of the Glarus Alps with synthesis of former published data on Alpine metamorphism (Frey 1970, 1987, 1988; Frey & Niggli 1971; Frey et al. 1973, 1980; Siegenthaler 1974; Siddans 1979). Mineral abbreviations: bt biotite, glt glauconite, kln kaolinite, lmt laumontite, prh prehnite, pmp pumpellyite, stp stilpnomelane. Two insets show local distributions of illite crystallinity data for a profile of the Glärnisch massif (left) and a profile of the Lochsiten outcrop (right). For conversion of IC data from mm into $\Delta°2\theta$ see Frey & Burkhard (1992).

al. (1956) who mentioned stilpnomelane and blue amphibole (Mg-riebeckites) as newly-grown metamorphic minerals within the Helvetic sediments, which were previously considered as non-metamorphic. Illite crystallinity was introduced as a technique to quantify very low-grade metamorphism in clay-rich sediments (Kübler 1967), and much detailed work has been carried out in the Glarus Alps since then by Frey (1969a, 1970, 1971, 1978, 1987, 1988), Frey et al. (1971, 1973, 1980), Siddans (1979) and Hunziker et al. (1986). A summary of the published results is shown in figure 2.

An increase of metamorphic grade from north to south is found in all tectonic units. Because displacement along the Glarus main thrust plane and intra-Helvetic thrust planes partly took place after metamorphism (Schmid 1975; Milnes & Pfiffner 1977), the metamorphic pattern is complicated by the different thrust planes (Groshong et al. 1984; Erdelbrock 1994). Along the Glarus thrust plane transported metamorphism, due to post-metamorphic stacking from Helvetic on top of Infrahelvetic units, was documented (Frey 1988, and right inset in Fig. 2).

From north to south within the Glarus Alps, the following reaction isogrades were published (Fig. 2): pyrophyllite-in close to the town of Glarus (Frey 1987), stilpnomelane-in at the village of Nidfurn (Frey et al. 1973) and biotite-in south of lake Mutt (Frey et al. 1973). Illite crystallinity (IC) data are available from the Helvetic Verrucano nappe (Siddans 1979; Frey 1988), for the other Helvetic nappes (Frey 1969a, 1970; Frey et al. 1973) and for the autochthonous cover of the Aar massif (Frey 1969a, 1970). In profile view the Helvetic nappes exhibit a rather complex illite crystallinity pattern, as has been shown for the Glärnisch massif (inset in Fig. 2 from Frey et al. 1973): Crystallinity values vary between lower diagenesis in the summit area and middle anchizone in the valley, the metamorphic zone boundaries crosscutting the tectonic boundaries between different individual Helvetic nappes. The Verrucano in the eastern part of the Glarus Alps shows increasing metamorphism from diagenesis close to lake Walen to anchizone in the area north of Lochsiten and uppermost anchizone to epizone within the "Glarner Freiberge" (Siddans 1979; Frey 1988). Within the autochthonous cover of the Aar massif around lake Limmern, the crystallinity reaches epizonal values.

Vitrinite reflectance (VR) data are given by Groshong et al. (1984) and correlated with inter- and intra-granular strain indicators. These authors review existing data on metamorphism along a N-S profile through the Glarus Alps, but no sample localities are given. VR data of Frey et al. (1980) indicate a R_{max} of 5.5% for the area of Urnerboden, and 4.9% for the Helvetic nappe close to Panix pass.

A large quantity of new IC and VR data were produced by Wang (1994) and Erdelbrock (1994) for the Helvetic Alps between Appenzell and Chur. A restricted amount of data (10) has also recently been published by Rahn et al. (1994). These 10 data are included in the diagrams of this study.

In the Western Alps newly-grown minerals such as laumontite, prehnite, pumpellyite and actinolite have been shown to reflect increasing metamorphic conditions between zeolite- and lowermost greenschist-facies (Martini & Vuagnat 1965; Kübler et al. 1974; Coombs et al. 1976; Kisch 1980; Bussy & Epard 1984). A similar zonation within outcrops of Taveyannaz sandstone (not shown in Fig. 2) has recently been presented for the Glarus Alps with zeolite-facies in the Wageten slice, prehnite-pumpellyite facies in the North Helvetic flysch and one outcrop of pumpellyite-actinolite-facies at Crap Ner in the south (Rahn et al. 1994).

Dating of the Alpine metamorphism within the Glarus Alps is mainly based on K/Ar and Ar/Ar age determinations on sheet silicates such as illite and glauconite; a few data are derived from blue amphiboles (Frey et al. 1973; Hunziker et al. 1986). Data indicate a metamorphic peak at 30–35 Ma for the Helvetic nappes above the Glarus thrust (Calanda phase, Milnes & Pfiffner 1977) and a second event at 20–25 Ma (Ruchi phase), which was correlated with the overthrust of the Helvetic nappes on top of the Infrahelvetic units. Detailed time-temperature paths, modelled with the help of fission track data, allowed to establish different metamorphic and uplift histories for different flysch localities (Rahn 1994).

Methods

Sampling procedure. 120 greywacke specimens from the Taveyannaz sandstone were sampled, and 108 thin sections examined. 36 thin sections were supplied by H. Sinclair. 38 samples and thin sections belong to three complete stratigraphic sections. A total of 127 shale samples were prepared for the determination of the IC (air-dried and glycolated), and 47 clay samples for VR. Most of the IC and VR determinations were performed on "Dachschiefer" interlayering the flysch sandstones or belonging to the underlying Globigerina marls (Priabonian). Additionally, a subhorizontal N-S profile of Helvetic samples (Eocene shales/Valanginian marls) has been added in order to connect outcrops of the Wageten slice with the North Helvetic flysch south of Schwanden. At the Lochsiten and south of Schwanden, only the underlying flysch was sampled (with two exceptions: see Fig. 3).

Illite crystallinity. The IC index was determined as the angular peak width at half height of the first illite basal reflection (Kübler index), following the recommendations of the IGCP 294 working group (Kisch 1991). Corrensite or detrital mica bearing samples have been avoided, as both factors have been reported to markedly influence the IC of the intercalated shales from the Taveyannaz sandstone (Kübler et al. 1974). From the sample preparation procedure two details shall be mentioned: (i) for grinding a disc mill was used, but grinding times of >30 seconds were avoided to prevent damage of the crystal lattice; (ii) sedimented slides of the 0.1–2 μm fraction contained a fixed quantity of 5 mg cm^{-2} to avoid preparate thickness effects (Krumm & Buggisch 1991). The Kübler index was measured on a Philips PW 1360 diffractometer and each measurement was repeated six times, with a precision of $\pm 0.04°$ (2σ). Measuring of the half width was done by hand on a paper chart-strip. The limits used for the anchizone are 0.25 and 0.42° $\Delta 2\theta$ Cu K_α for air-dried samples (Kübler et al. 1979).

Coal rank. Coal rank and illite crystallinity investigations were performed on samples from the same hand specimen. Coal rank was determined by reflectivity measurements on finely dispersed vitrinite particles. Polished blocks of rocks, cut perpendicular to the cleavage were used. Working conditions with a ZEISS photometer microscope were as follows: oil-immersion, monochromatic polarized light (546 nm), magnification × 1250. Data are given as maximum reflectance values (R_{max}).

Fluid inclusions. Fluid inclusions were studied by microthermometry on fibre, prismatic and skeletal quartz from syn-metamorphic joints. Microthermometric measurements were performed on the Chaixmeca freezing-heating stage, designed to work in the −180 °C to +600 °C range by Poty et al. (1976). The precision of the measurements is on the order of ± 0.1 °C in the −60 to +40 °C range and ± 1 °C outside this range. The method is described in Roedder (1984), Shepherd et al. (1985) and Mullis (1987). Homogenization temperatures from the earliest fluid inclusion population were used to estimate minimum to approximate peak temperatures, an approach that was tested by Mullis (1979).

It is important to note that all the correlations made between the results of the different methods are based on the assumption, that fluid inclusions were trapped at the same time as the formation of the illites and the maturity of the organic matter take place. For the Glarus Alps maximum metamorphic conditions were reached together with the developement of the main schistosity (Calanda phase, Milnes & Pfiffner 1977).

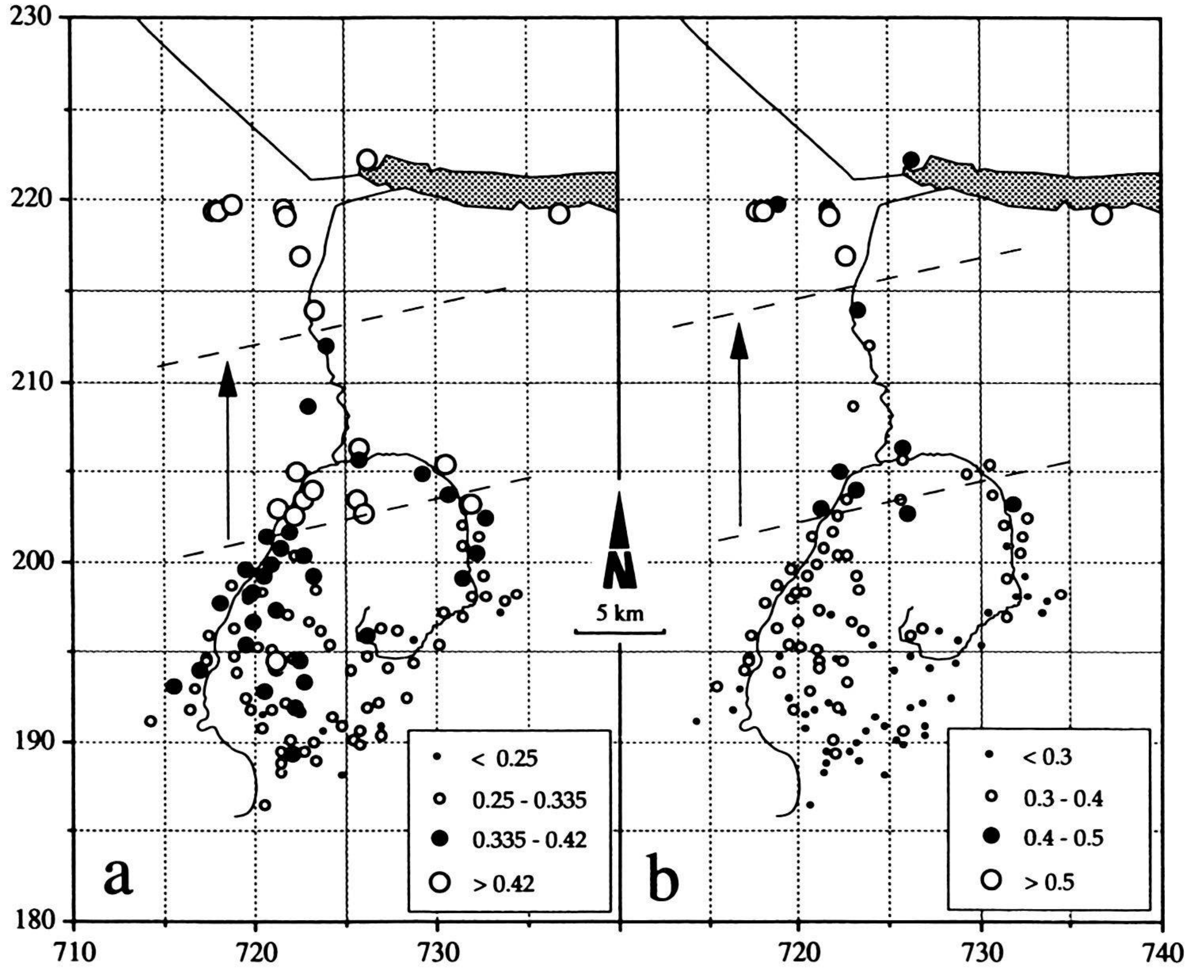

Fig. 3. Distribution of air-dried (a) and glycolated (b) illite crystallinity data (Δ°2θ) in the Glarus Alps. Samples have been taken above the Glarus thrust plane north of Schwanden, and below the Glarus thrust at Lochsiten and south of Schwanden (exceptions: Helvetic "Kieselkalk" above Nidfurn, Verrucano sample from the Ruchi summit). The used limits for air dried IC values define the following metamorphic zones: < 0.25: epizone, 0.25–0.335: upper anchizone, 0.335–0.42: lower anchizone, > 0.42: diagenesis. The limits of the glycolated IC data have been chosen arbitrarily. The two dashed lines indicate the lower limits of the anchizone (air-dried data) or 0.4 Δ°2θ isocryst (glycolated data) within the Helvetic nappes and the North Helvetic flysch. The distance between both lines corresponds to the post-metamorphic transport distance. The grid corresponds to the Swiss coordinate system (1 unit = 1 km).

Results

Illite crystallinity (IC)

IC values are given for air-dried and glycolated samples and are shown in figure 3. For the air-dried values the zone limits according to Kübler et al. (1979) were chosen to group the data and, in addition, the anchizone has been divided into a lower and an upper anchizone (boundary at 0.335° Δ2θ). For glycolated values no internationally accepted limits do exist. A division with limits of 0.3, 0.4, 0.5° Δ2θ was chosen.

In the Wageten slice and the northern part of the profile within the Helvetic nappes (between the Wageten slice and Lochsiten), air-dried IC values are within the diagenetic range. In the southern part of the profile within the Helvetic nappes, IC enters the anchizone. Transported metamorphism at the Glarus main thrust (Frey 1988) is indicated by the reappearance of several diagenetic values within the northernmost outcrops of the North Helvetic flysch, tectonically situated below the Helvetic nappes that are characterized by values of middle to upper anchizone (Fig. 2). With the help of the appearance of the diagenesis-anchizone boundary in the Helvetic units and the Infrahelvetic flysch, the distance of transported metamorphism can be estimated to be about 10 km (Fig. 3, cf. also Groshong et al. 1984, Wang 1994).

The boundary between lower to upper anchizone occurs between Matt and Elm at the bottom of the Sernft valley and around Linthal in the Linth valley, but data exhibit a strong overlap. There is an unexplained diagenetic value in the quarry of Matt. Additional sampling within the quarry revealed a range of 0.43 to 0.63° $\Delta 2\theta$ in shale samples devoid of detrital white mica. While in the area between the upper Sernft valley and the Panix pass lower anchizonal values are very rare, they still exist in the upper Linth valley and the area around lake Mutt. Epizonal values were found in the upper Sernft valley and in the southeasternmost outcrops of the North Helvetic flysch around Piz Fluaz and Crap Ner (Fig. 1). One single diagenetic value north of the Vorstegstock can partly be explained by small amounts of paragonite. Generally, however, sodium micas or mixed-layers paragonite/muscovite (Frey 1969b) are not detectable in the < 2 µm fraction.

The pattern of glycolated IC values with the chosen range limits are very similar to the air-dried values. From Linthal to the uppermost flysch outcrops, sampling covers a range in altitude from 650 to 3,100 metres, but not altitude gradient within IC values can be observed.

Vitrinite reflectance (VR)

A regular increase of metamorphic grade, i.e. maximum temperature, is displayed by the data pattern of VR from north to south within the Helvetic nappes and within the North Helvetic flysch (Figs. 4a, 5). In the Subalpine Molasse north to the Wageten slice a R_{max} of 0.77% indicates maximum temperatures of 100–120 °C (Rahn 1994). The Wageten slice has a mean R_{max} below 2.0%, while values within the Helvetic nappes increase towards south, from 2.5% close to the Wageten slice to 4.6% in the Glarus nappe above Nidfurn. The northernmost outcrops of the North Helvetic flysch start with values between 3 and 4%, and increase along both valleys to values > 8%, where a large part of the measured organic material is of semigraphitic rank. Because of the increasing measurement error, values > 5% are only indicated with one decimal digit, values above 8 as > 8. Between Linth and Sernft valley R_{max} data show a shift of iso-reflectance lines of about 5 km in N-S direction (Fig. 5). This is consistent with the WSW-ENE orientation of reaction isogrades in the Glarus Alps (Frey et al. 1973; Frey 1987).

Fluid inclusions

Within the flysch sandstone layers, the opening of joints perpendicular to the sedimentological layering and main schistosity within the intercalated schists can be correlated

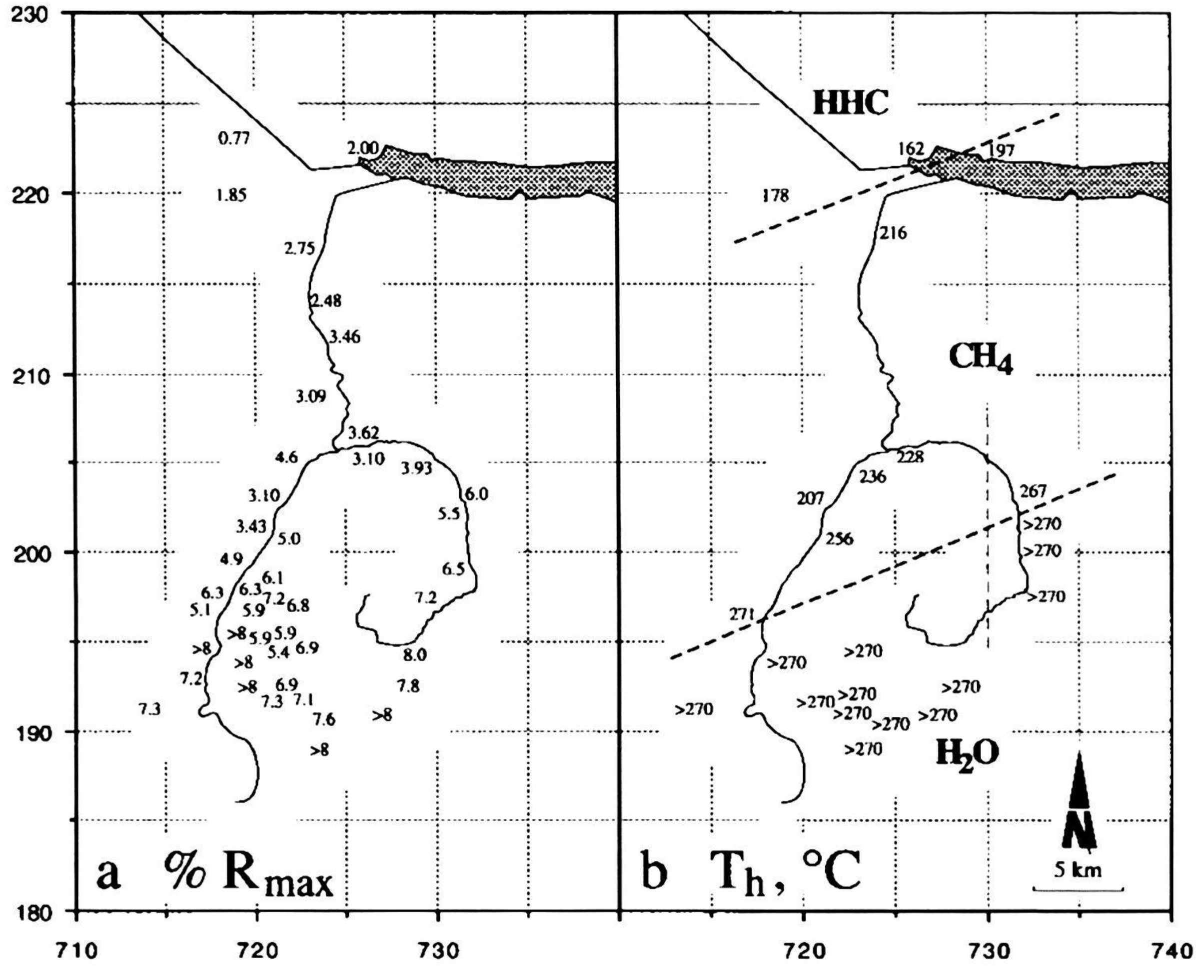

Fig. 4. Data pattern of vitrinite reflectance (a) and fluid inclusions (b), values given as % R_{max}, and °C for the mean homogenization temperature, respectively. Sample localities are above the Glarus thrust plane north of Schwanden (exception: coal rank datum from the Subalpine Molasse) and below the Glarus thrust at Lochsiten and south of Schwanden. Fluid zones are after Mullis (1979), HHC = fluid zone of higher hydrocarbons. Temperature values > 270 °C indicate a minimum temperature for all samples of the H_2O zone.

with the main metamorphic event. Thus, fibre quartz that formed during the opening of these joints, trapped fluids with homogenization temperatures close to the metamorphic peak (Mullis 1979).

Fluid inclusion data from quartz are given in figure 4b. Inclusions of the Wageten slice contain higher hydrocarbon-bearing fluids, and their T_h are below 200 °C (HHC zone). Methane-bearing fluid inclusions were found from the northern border of lake Walen to Linthal village (methane zone). At Lochsiten the lowermost mean T_h within the North Helvetic flysch indicates 228 °C, and along the Linth valley values increase steadily to 271 °C at Linthal. Along the Sernft valley the transition from methane to water zone was fixed within a kilometer by two samples NE and SE of Matt. In both valleys further south fibre quartz contains water dominated fluid inclusions (water zone). Joint systems in the water zone are filled by early fibre or prismatic quartz and younger

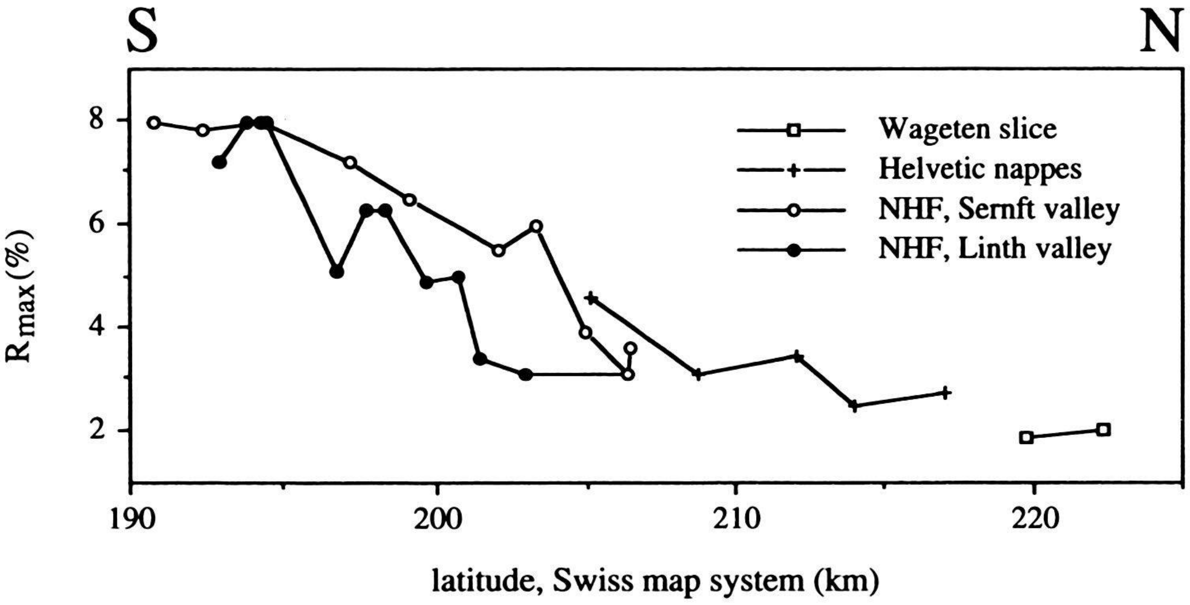

Fig. 5. Vitrinite reflectance data (R_{max}) projected along a N-S profile. Note the difference in coal rank between upperlying Helvetic nappes and North Helvetic flysch at a latitude of 206 and the shift of VR values between Linth and Sernft valley.

calcite. Some large fluid inclusions are decrepitated, indicating fluid inclusion trapping before the temperature peak was reached.

The limits between the three fluid zones (Mullis 1979) run ENE-WSW (Fig. 4b). Thus, they are parallel to iso-reflectance lines and to the border of the Helvetic nappes, i.e. the Alpine border in this area (Fig. 1).

Taveyannaz sandstone

A typical mineralogical feature is the almost total absence of primary volcanic amphiboles, which are common in the Western Alps (Bussy & Epard 1984, Fischer & Villa 1990) and a general scarcity of newly-grown epidote. The neoformation of the latter is restricted to small overgrowths on detrital epidote/clinozoisite grains in the zeolite and prehnite-pumpellyite facies and nucleation of small grains in the pumpellyite-actinolite facies (Rahn et al. 1994).

In the North Helvetic flysch of the southern Glarus Alps, most Taveyannaz sandstones of type IIb or III (Tab. 1) are prehnite- and pumpellyite-bearing. Occurrences of only pumpellyite were rarely found. Only one locality with pumpellyite and actinolite was found (Crap Ner, Rahn et al. 1994).

In the Glarus Alps, the Taveyannaz sandstone types can be described as follows: type I (totally absent in Switzerland, Vuagnat 1952) and IIa have not been found. Type IIb contains markedly more than 50% of andesitic components. Prehnite is rather scarce and restricted to larger grains within albite, rarely K-feldspar or quartz. Pumpellyite is found as small aggregates within the matrix (dark green pleochroism) or prismatic grains within albite (colourless). Generally prehnite and pumpellyite make up less than 5% of the rock volume, which is dominated by albite (former plagioclase) and a matrix of chlorite and calcite. Volcanogenic clinopyroxenes, that represent the only primary mafic phase, are partially replaced by chlorite, quartz and calcite.

In type III volcanogenic clinopyroxenes are totally replaced by quartz, calcite and white mica (remaining shadows). Pumpellyite and prehnite occur in larger amounts, and are mainly concentrated within the brighter patches. Newly-grown white mica occupies up to 10% of the volume.

Type IV is characterized by the absence of metastable mafic minerals, but also of prehnite and pumpellyite. Alteration comprises total albitization of former plagioclase and parts of the K-feldspars. Chlorite and calcite are found within the matrix, the latter indicating very late overgrowth (Stalder 1979). This type is mainly found in thin sandstone layers and at the edges of thick layers. A common feature in a complete Taveyannaz sandstone sequence is the occurrence of layers with less than 50% of andesitic material, but with large amounts of clastic and newly-grown calcite.

While type IIb and III are mostly faintly greenish and commonly patched in colour, type IV and interlayered sandstones with less than 50% of andesitic material are generally moderate to dark grey. The occurrence of patched types, and therefore the presence of ciritical minerals is restricted to thick sandstone layers (Styger 1961), they are normally not found within thin layers.

Discussion

Relation between Taveyannaz sandstone classification, sedimentary parameters and metamorphism

Within the North Helvetic flysch the Taveyannaz sandstone represents a sedimentological facies with strong lateral and vertical variation (Oberholzer 1933; Styger 1961). The occurrence of types IIb and III is reported to be dependent on layer thickness of the sandstone beds, content of interlayered "Dachschiefer" and grain size (Styger 1961, Siegenthaler 1974): Type IIb and III never occur close to interlayered "Dachschiefer". This is consistent with type successions along vertical profiles W and NE of the Vorstegstock (Fig. 1), where types vary within less than 1 m. Within one single turbidite layer the basis often is of type IV, towards the top followed by type II or III sandstones whereas the uppermost part again passes into type IV due to the increasing amount of silty material. This observation obviously indicates a small scale limit for the classification after Vuagnat (1952) (Tab. 1), when applied to rapidly changing sedimentation sequences as they are common in the Taveyannaz sandstone (Siegenthaler 1974; Sinclair 1992).

In addition, the classification of the Taveyannaz sandstone represents a mixture of sedimentary and metamorphic criteria according to the present knowledge on low-grade metamorphism of metagreywackes: types IIb and III are characterized by the presence of Ca-silicates that are not primary, but growed during Alpine metamorphism. In the Glarus Alps type IIa of Vuagnat (1952) was only found within very restricted areas in thin sections (e.g. within the "intrapatch" matrix, see Rahn et al. 1994), but on a larger scale this type IIa is thought to represent an unmetamorphosed Taveyannaz sandstone, which should be absent in metamorphic terranes. Type IIb corresponds to a partially al-

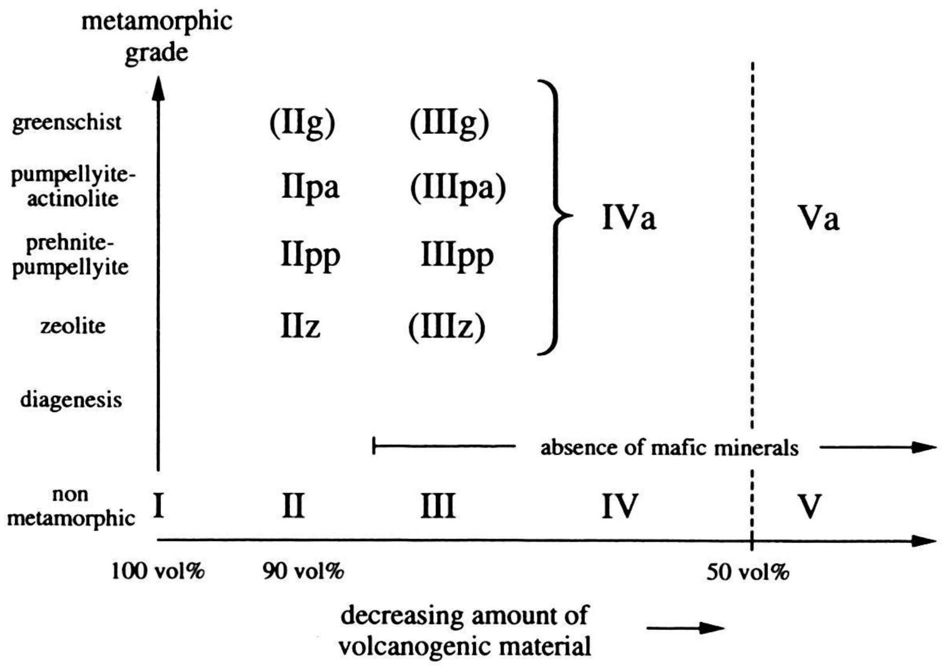

Fig. 6. Classification scheme for the Taveyannaz sandstone, modified after Vuagnat (1952). The used abbreviations for the metamorphic grade are z for zeolite, pp for prehnite-pumpellyite, pa for pumpellyite-actinolite, and g for greenschist facies. Due to the lack of critical minerals, metamorphic alteration in types IV and V is indicated by "a" for "altered". Metamorphic classification types, that are not found in the Glarus Alps, are given in brackets.

tered Taveyannaz sandstone with relicts of mafic minerals, whereas type III is the thoroughly altered sandstone with no remaining mafic igneous minerals. Thus, for the Glarus Alps, the occurrence of type III is exclusively the result of metamorphism. In addition, in type III a generally large amount of newly-grown H_2O-bearing phases suggests an enhanced fluid flux for these rocks.

With decreasing amount of andesitic material there is an increase of primary and secondary calcite within the sandstones. Increasing amounts of CO_2 in the fluid inhibit the formation of prehnite and pumpellyite within the rocks, as has been demonstrated in experiments by Plyusnina & Likhoydov (1977).

We therefore propose a modified classification scheme for the Taveyannaz sandstones that distinguishes between primary sedimentological and secondary metamorphic criteria (Fig. 6). The scheme considers the amount of primary volcanogenic material and the presence/absence of igneous mafic minerals (clinopyroxene, hornblende), where the type classification has mainly been adopted from Vuagnat (1952). As a transition to the interlayered siltstones and shales, a sedimentological type V has been added, that does not contain 50% of primary mafic igneous material. This type must not be mixed up with other flysch sandstones (e.g. "grès de Val d'Illiez", Vuagnat 1952) with low amounts of volcanogenic material. The occurrence of type V in the field is restricted to outcrops of Taveyannaz sandstones of type I to IV.

In the proposed classification scheme the metamorphic grade is indicated by the addition of the metamorphic facies abbreviation: z for zeolite facies, pp for prehnite-pumpellyite facies, etc. The Vuagnat type IIa is omitted, as it only exists for unmetamorphosed sandstones, which in the new classification simply are expressed without an addition. For the types IV and V, that do not show critical minerals, an abbreviation "a" for "altered" is proposed. This alteration mainly includes albitization, chloritization and the neoformation of calcite.

Metamorphism and origin of the Wageten slice

Trümpy (1969) proposed a paleogeographic origin of the Wageten slice between the Helvetic and North Helvetic sedimentation realm, but indicated a movement of the slice above the Glarus main thrust plane towards north. In a paleogeographic reconstruction of Siegenthaler (1974), the Wageten slice is found as the northernmost part of the Taveyannaz flysch basin, that was filled by a sediment input from SE or sedimentation transport along the trough axis (Radomski 1961; Siegenthaler 1974; Sinclair 1992).

Remnants of land plants within the Taveyannaz sandstone indicate a deposition close to a shore line of a possible volcanic andesitic island are (Trümpy 1960), which probably marked the southern margin of the WSW-ENE trending basin. Plant remnants also exist in the clay interlayers. Furthermore, very coarse grained Taveyannaz sandstone layers can be observed within the Wageten slice: single grains can reach sizes of more than 1 cm in diameter.

From these observations a depositional realm close to an ancient shore-line is proposed. This shore-line might have been the southern border of the piggy-back basin proposed by Sinclair (1992). Subsequent detachment of the Wageten slice and separation from the North Helvetic flysch was probably the result of a major south-dipping thrust plane in the thrust wedge in front of the northwards moving Alpine orogeny (Sinclair et al. 1991), that later has been reactivated by the Glarus main thrust.

Data of metamorphism show similar metamorphic grades for the Wageten slice and the surrounding Helvetic units, but a distinctly lower grade than the suggested paleogeographic neighbours of the slice within the North Helvetic flysch (Fig. 5). Initial detachment of the Wageten slice from the units of the North Helvetic flysch therefore occurred at a time before metamorphic peak conditions were reached. The post-metamorphic transport of 10 km (Groshong et al. 1984, Wang 1994) is considerably less than the total displacement along the Glarus thrust plane of 35 km (Schmid 1975).

The "vertical" profile Linthal – Ruchi

In figure 7, IC and VR data are plotted along a profile from Linthal (altitude 650 metres) to the Ruchi (3,109 metres) intersecting several slices within the North Helvetic flysch (Styger 1961; Siegenthaler 1974). IC data show no clear trend along the profile; one single value close to the epizone is found on top of the Ruchi and within the Verrucano. Additional data would be needed to express the metamorphic step between Verrucano (on top) and North Helvetic flysch (below), as shown by Frey (1988).

For R_{max} and R_{min} values, however, data show several offsets and are separated into four groups. R_{min} data even indicate trends of decreasing values from top to bottom between two offsets. Note that group boundaries of R_{max} and R_{min} occur at the same alti-

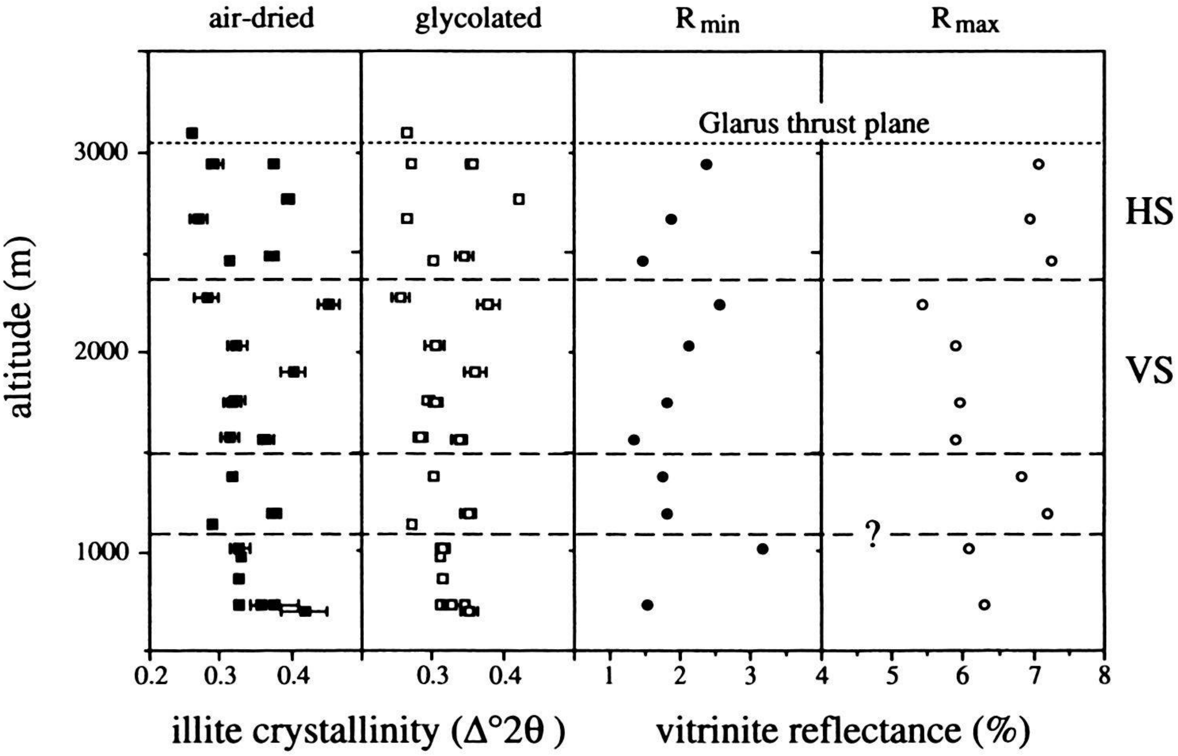

Fig. 7. Illite crystallinity (with measurement error bars) and coal rank data along a "vertical" profile from Linthal (650 m) to the Ruchi mountain (3,109 m). Due to strong oxidation, the uppermost sample (Verrucano) above the Glarus thrust plane provides no coal rank data. Vitrinite reflectance data show breaks along boundaries of the Hausstock (HS) and Vorstegstock slice (VS) (Siegenthaler 1974). The question mark indicates a third possible slice boundary within the Altdorf sandstone (Styger 1961).

tudes. In the meta-anthracite stage ($R_{max} > 4\%$), R_{min} decreases strongly with increasing R_{max} (see e.g. Teichmüller 1987, Fig. 4.30) and R_{min} values therefore are thought to represent the most sensitive method at this metamorphic grade. The trend shown by the R_{min} values is interpreted as an increasing metamorphic grade from top to bottom of each data group.

The offset of VR values can be explained by post-metamorphic movements along the slice boundaries, possibly related to post-metamorphic thrusting of the Helvetic nappes over the flysch. The offsets coincide with proposed slice boundaries mapped with the help of repeated Taveyannaz sandstone successions (Styger 1961, Siegenthaler 1974). An additional slice boundary within the North Helvetic flysch can be suggested for the lower part of the vertical profile. The results, however, are in contrast to structural indications for the post-metamorphic thrusting event (Ruchi phase). Ruchi phase deformation is only reported from the uppermost 300 metres of the flysch underneath the Glarus thrust plane (Schmid 1975, Milnes & Pfiffner 1977).

Correlation of different parameters of metamorphism

The correlation of different data patterns exhibits a linear relation between IC and VR from diagenesis to lowermost epizone (Fig. 8). A comparison with other regions of the

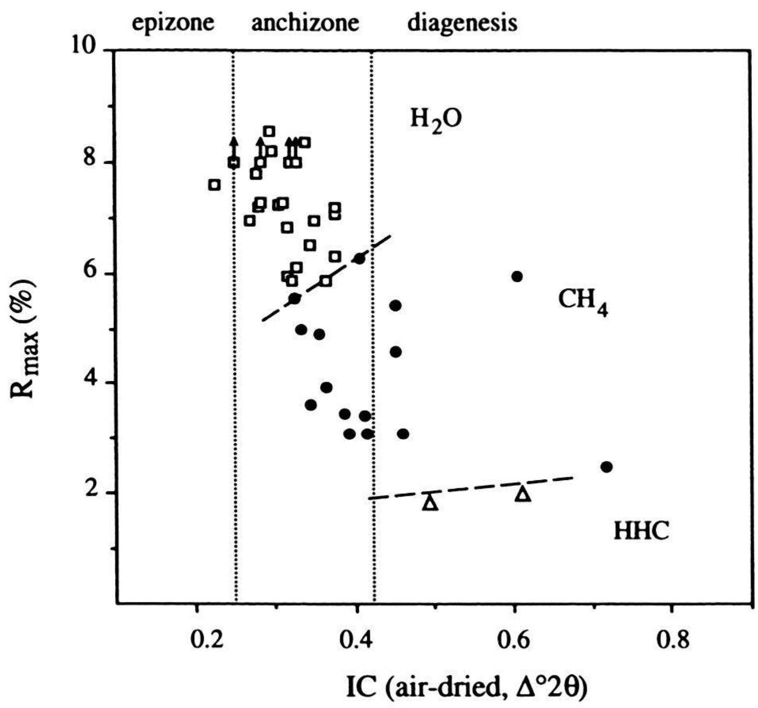

Fig. 8. Correlation between coal rank, illite crystallinity and fluid inclusion data from the Glarus Alps. Open triangles represent localities with higher hydrocarbons (HHC) bearing fluid inclusions, filled circles localities with CH_4-bearing fluid inclusions, and open squares are localities with H_2O-rich fluid inclusions; fluid zones after Mullis (1979). R_{max} values of "> 8%" are shown by vertical arrows. Limits of the anchizone after Kübler et al. (1979).

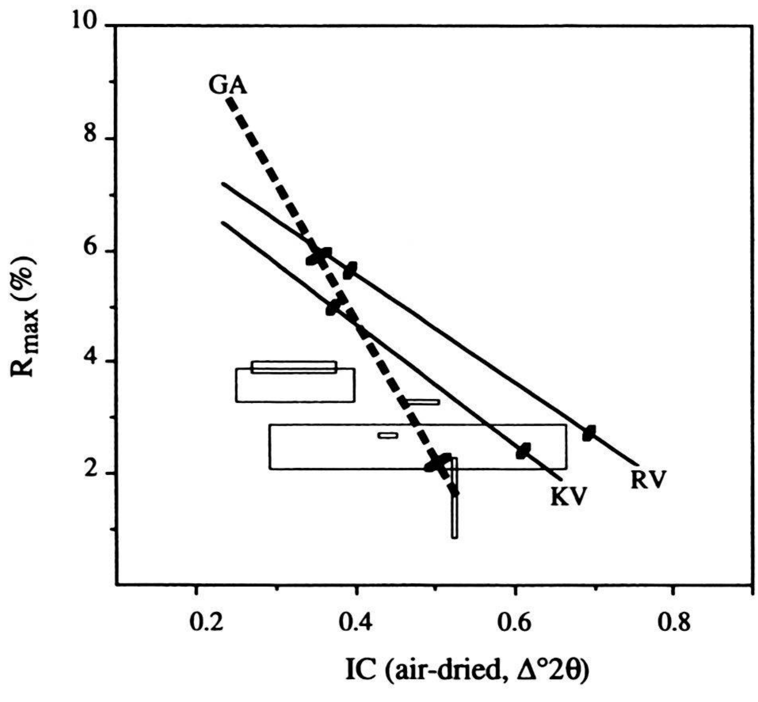

Fig. 9. Synthetic correlation diagram between coal rank and illite crystallinity data for several areas of the Helvetic Alps of Switzerland: GA Glarus Alps (41 localities), KV Kien Valley (Frey et al., 1980 21 localities), RV Reuss valley (op. cit., 41 localities), and six localities and their data scatter from Taveyannaz sandstone outcrops in the Western and Central Alps (Kisch 1980). Small black dashes on the correlation lines indicate the intersection between correlation lines and fluid zone boundaries (cf. Fig. 8).

Helvetic Alps is given in figure 9, where a general correlation line for the Glarus Alps is compared with two IC-VR correlation lines from the Reuss and Kien valley (Frey et al. 1980) and data from six Taveyannaz and Altdorf sandstone outcrops in the Western and Central Alps (Kisch 1980). Note the rather steep correlation for the Glarus Alps compared to other areas of the Helvetic Alps with R_{max} values increasing markedly for small changes of illite half widths. The steep slope expresses the rather restricted evidence of a

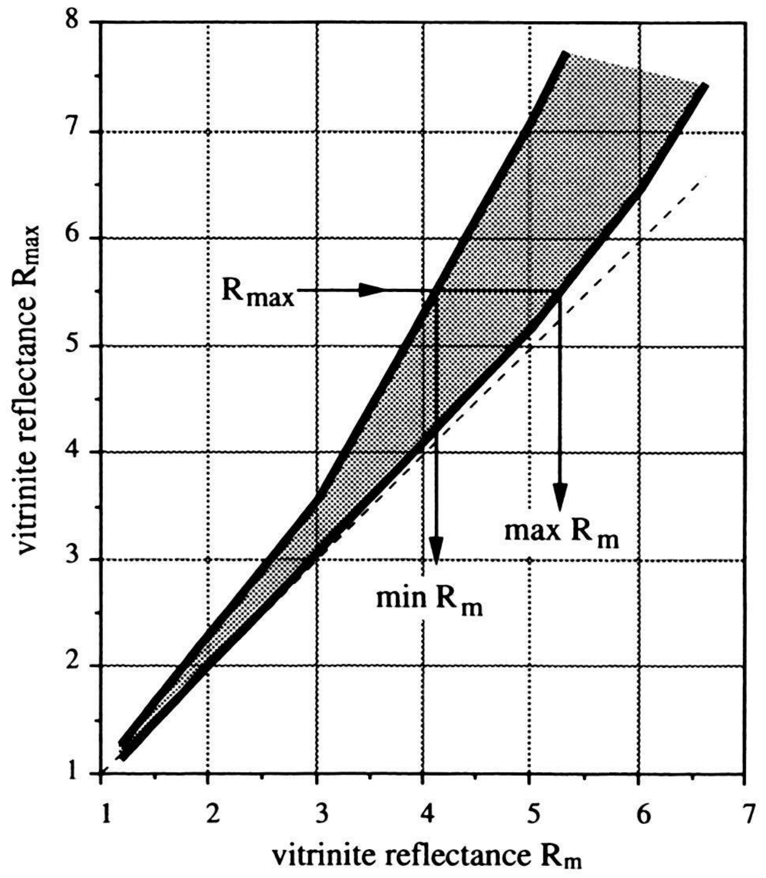

Fig. 10. Correlation diagram between maximum and mean vitrinite reflectance after Stach et al. (1982, Fig. 19a) and indicated example for the conversion of R_{max} into R_m values.

single IC value on one hand, and the better reliability of the VR data in the Glarus Alps on the other.

Fluid inclusion data allow to correlate R_{max} and IC with fluid zones and homogenization temperatures (Fig. 8). At the boundary between the HHC and CH_4 fluid zones (temperature of 200 °C), IC values indicate a large range from 0.5 to 0.7° Δ2θ, whereas R_{max} values vary little around 2.2–2.6%. Thus, at lower degree vitrinite reflectance data are distinctly more sensitive than illite crystallinity values. For the boundary between CH_4 and H_2O zone (270 °C), R_{max} varies between 5 and 6%, and IC values show a narrow range from 0.36 to 0.40° Δ2θ (Fig. 9). This reflects the increasing reliability of IC with increasing temperature. In addition, the fluid zone boundaries found for the three regions (Fig. 9) coincide with the fluid zone boundaries in figure 8.

For the northernmost outcrops of prehnite-pumpellyite facies in the Taveyannaz sandstone, IC values indicate middle anchizone and R_{max} is above 6%. This is in contrast to results from the Western Alps indicating the occurrence of prehnite-pumpellyite facies already in the uppermost diagenesis and the lower anchizone and R_{max} of 3.5% (Kisch 1980). Kübler et al. (1974) indicate the stability of laumontite to lie entirely within the diagenesis (defined by IC). One can therefore assume that the beginning of the prehnite-pumpellyite facies lies markedly further north than the northernmost outcrops of Taveyannaz sandstones with critical minerals in the North Helvetic flysch.

The beginning of the pumpellyite-actinolite facies at Crap Ner coincides with the beginning of the epizone, where the organic matter is of semigraphitic rank (> 8%). This is

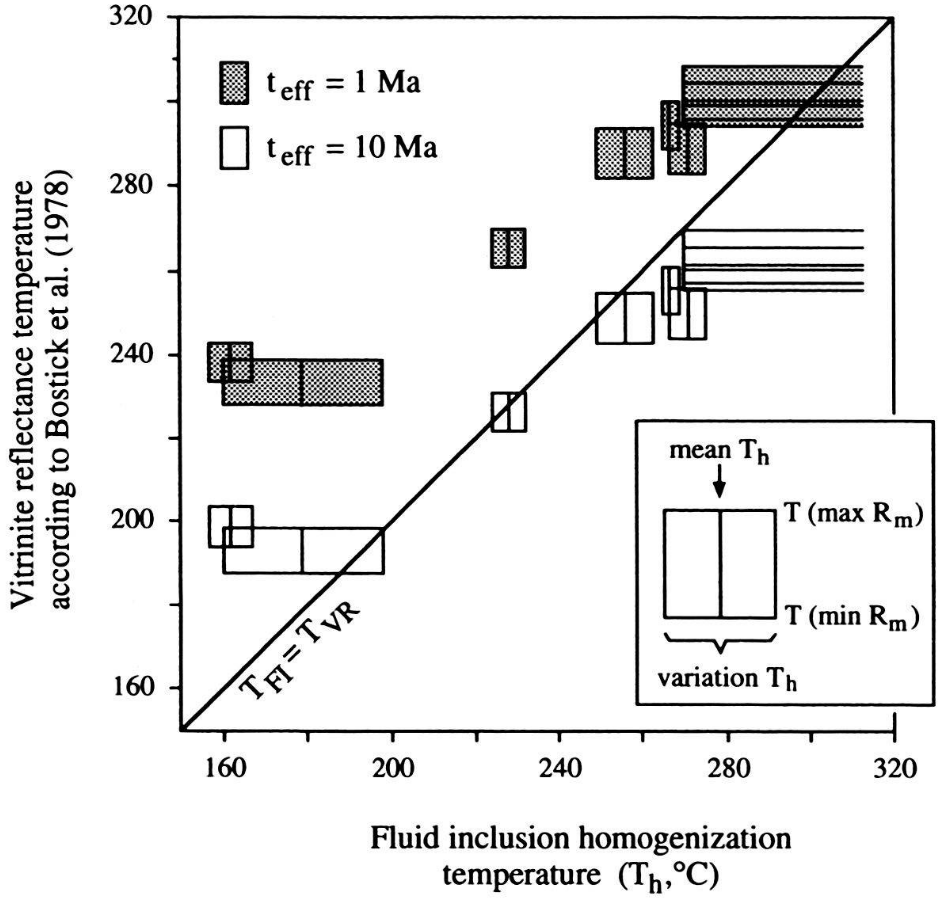

Fig. 11. Correlation between fluid inclusion homogenization temperatures and temperatures derived from coal rank data after Bostick et al. (1978), calculated for two different effective heating times t_{eff} = 1 and 10 Ma. For the samples of the H_2O zone, a minimum temperature of 270 °C can be assumed due to the absence of methane, but a range of 270–310 °C for the fluid inclusion trapping temperature has been estimated by chlorite thermometry (Rahn et al. 1994). For the conversion of R_{max} into R_m see figure 10, for interpretation see text.

concordant with findings of Kübler (1970) from the pumpellyite-actinolite facies of Leuk (Coombs et al. 1976).

A comparison between measured fluid T_h and temperatures derived from coal rank data (Bostick et al. 1978) can be used to estimate the duration of Alpine metamorphism. For this purpose measured R_{max} values were converted into mean reflectance (R_m) values, which was done with the help of the correlation between the two parameters from Stach et al. (1982): Each R_{max} value corresponds to a spread of R_m (Fig. 10). For the maximum and minimum R_m temperatures were calculated and this temperature range was compared with the fluid T_h. The depicted variation in fluid T_h corresponds to a mean T_h and the measured T_h variation. Both parameters are illustrated in the inset of figure 11.

VR temperatures have been calculated for two different effective heating times (t_{eff}), that are defined as the time period during which the organic material underwent a temperature above T_{max}–15 °C (Bostick et al. 1978). The chosen t_{eff} are 1 and 10 Ma and are thought to represent the duration of the Alpine metamorphic peak.

In the north conformity of temperature values is obtained for t_{eff} = 10 Ma, whereas towards south data tend to correlate better with VR temperatures calculated for t_{eff} = 1 Ma. For the southern Glarus Alps a short metamorphic event (t_{eff} < 10 Ma) can be proposed, which is in agreement with general textural and chemical disequilibrium within the Taveyannaz sandstones and a comparison between VR temperatures and chlorite thermometry (Rahn et al. 1994). A short metamorphic peak for the south of the eastern Helvetic Alps is also suggested from coal rank pattern further east (Erdelbrock 1994).

Conclusions

In the Glarus Alps a zonation from zeolite facies in the north (Wageten slice) to prehnite-pumpellyite and pumpellyite-actinolite facies (southern North Helvetic flysch) can be correlated with increasing IC values (upper diagenesis to beginning of the epizone), coal rank data (1.85 to >8% R_{max}) and fluid inclusion data (HHC zone, 170–190 °C, to H_2O zone, >270 °C). Transported metamorphism is found for illite crystallinity and coal rank data between the Helvetic nappes above the Glarus overthrust and the North Helvetic flysch below, but not between North and South Helvetic flysch units (Frey 1988). A combination of IC, coal rank and fluid inclusion data from the northern external Swiss Alps indicate the following values for the fluid zone boundaries:

HHC–CH_4 (= 200 °C):	IC (air-dried):	0.5–0.7° Δ2θ
	R_{max}:	2.2–2.6%
CH_4–H_2O (= 270 °C):	IC (air-dried):	0.36–0.40° Δ2θ
	R_{max}:	5–6%

The appearance of pumpellyite-actinolite assemblages coincide with the beginning of the epizone.

The occurrence of Taveyannaz sandstone types II to IV (according to Vuagnat 1952) is influenced by primary sedimentary aspects (content of andesitic material, layer thickness), metamorphism, fluid flux and fluid composition within the rock during alteration. Small scale type variations within vertical profiles indicate a limit of applicability of this typology, but show a strong dependence of critical minerals on the primary content of andesitic fragments. Therefore, a modified classification scheme is proposed that separates metamorphic alteration and sedimentological criteria.

The Wageten slice was initially detached from the sedimentation realm of the neighbouring North Helvetic flysch after sedimentation of the Taveyannaz sandstone (lower Oligocene), was metamorphosed and finally transported above the Glarus thrust plane towards north ("Helvetic" position). The presence of plant remnants within the Taveyannaz sandstone suggests a deposition close to a shore-line south of the sedimentary basin of the North Helvetic flysch.

VR data along vertical profiles in the North Helvetic flysch indicate postmetamorphic movements along slice boundaries. These movements are suggested to be related to the Ruchi event of the Glarus overthrust (Milnes & Pfiffner 1977).

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