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

Band: 66 (1986)

Heft: 1-2

Artikel: Very low-grade metamorphism of the Alps - an introduction

Autor: Frey, Martin

DOI: https://doi.org/10.5169/seals-50878

Schweiz. mineral. petrogr. Mitt. 66, 13–27, 1986

Very low-grade metamorphism of the Alps – an introduction

by *Martin Frey*[1]

Abstract

Until recently, studies of very low-grade metamorphism in the Alps have been based largely based on illite "crystallinity" and index mineral data and, to a lesser extent, on coal rank and fluid inclusion data. These four methods are briefly outlined and a correlation is presented in Fig. 7. The distribution of mineral assemblages in metabasites and metagraywackes as well as the location of reaction-isograds and mineral zone boundaries with respect to anchimetamorphic areas are shown on a large-scale map of the Alps (Plate 1). In the Eastern Alps, very low-grade metamorphism is predominantly of Eo-Alpine age, while in the Central and Western Alps, it is predominantly of Meso-Alpine and Neo-Alpine age. Finally, some suggestions for future work are given.

Keywords: low grade metamorphism, isograds, illite crystallinity, coal rank, fluid inclusion data, metagreywackes.

1. Introduction

Very low-grade metamorphism in the sense of WINKLER (1979) ranges from diagenesis to greenschist facies, an approximate temperature range of from 150–200 to 350–400 °C. In an orogenic belt, regional metamorphism is followed by uplift and erosion, yielding a clockwise pressure (P) – temperature (T) path (ENGLAND and RICHARDSON, 1977; ENGLAND and THOMPSON, 1984). Along this path there are three possible ways of passing through the P-T field of very low-grade metamorphism (Fig. 1): (A) during prograde metamorphism. In most cases, however, transformations at higher temperature will obliterate the imprint of very low-grade metamorphism; (B) during retrograde metamorphism. Such "late" overprints are important in unravelling a P-T path but will not be considered further here. (C) Maximum P and T are reached within the realm of

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

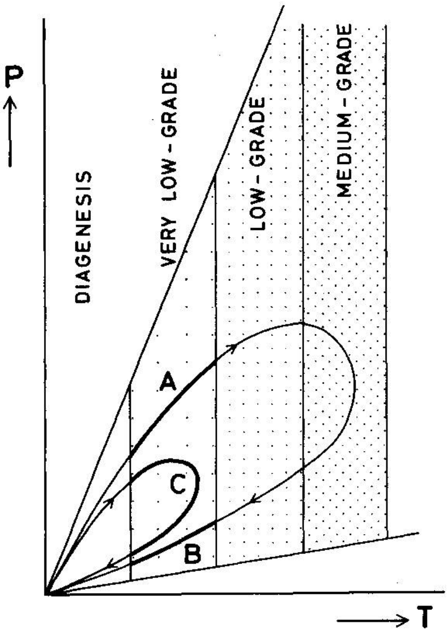

Fig. 1 Hypothetical pressure-temperature-time paths for two regionally metamorphosed rocks bodies. Transects through very low-grade metamorphism are shown in heavy lines: A, during prograde metamorphism; B, during retrograde metamorphism; C, during culmination of metamorphism. See text for discussion.

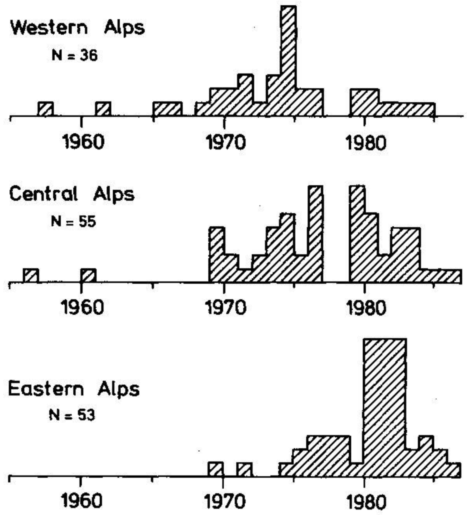

Fig. 2 Papers dealing with very low-grade metamorphism of the Alps grouped by year of publication.

very low-grade metamorphism. This paper deals exclusively with this final possibility.

In the Western and Central Alps, the study of very low-grade metamorphic rocks started some 25 years ago. However, research in this field in the Eastern Alps was initiated somewhat later (Fig. 2). While for this paper some 140 articles were consulted, only a few illustrative examples will be mentioned.

2. Four successful approaches

The following four methods have been successful in the investigation of very low-temperature metamorphism in the Alps: Illite "crystallinity", index minerals, coal rank, and fluid inclusion studies. The different variables of each method will be summarized, but for a detailed discussion the reader is referred to a forthcoming textbook (Frey, 1987b).

It has turned out that a combination of the various methods yields the most fruitful results, although usually only one or two methods were applied in any given study (Table 1). There exist only two studies where all of the four methods were combined (Barlier et al., 1974; Breitschmid, 1982).

Tab. 1 Correlations based on the number of methods employed for a given study. IC = illite "crystallinity", IM = index minerals, R = coal rank determination by reflectivity measurements, FI = fluid inclusion studies.

One method used		*Two methods used*	
IM	30	IM + IC	52
IC	8	IM + FI	1
R	6	IC + FI	1
FI	4		
Three methods used		*Four methods used*	
IC + R + FI	1	IM + IC + R + FI	2
IM + IC + R	5	BARLIER et al. (1974)	
IM + IC + FI	2	BREITSCHMID (1982)	

2.1. ILLITE "CRYSTALLINITY"

The determination of illite "crystallinity", i.e. the peak width at half height of the first illite basal reflection on X-ray diffractograms (KÜBLER, 1967), has become most popular in the Alps. This is because the method involves little analytical expense and because illite-bearing sediments are widespread. With the aid of illite "crystallinity" data the following three zones can be distinguished with increasing metamorphic grade: diagenetic (or unmetamorphosed) zone, anchizone, epizone. Note that the "anchizone" is recognized only on the basis of illite "crystallinity" data (KISCH, 1983, p. 309). In the Alps, the anchizone corresponds approximately to the temperature range between 200 and 300°C (Fig. 3) as derived from fluid inclusion studies (see below). The term "epizone" will be used in this paper only in connection with illite "crystallinity" data. In earlier Alpine studies, epizone and greenschist facies were regarded as synonymous. However, as discussed in section 3, this usage needs some revision.

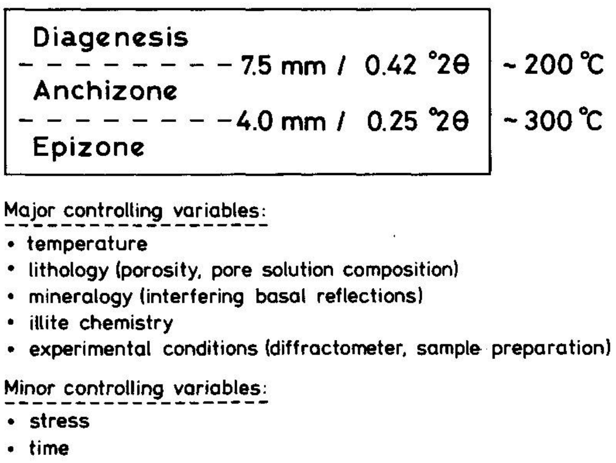

Fig. 3 Illite "crystallinity": division of metamorphic grade and controlling variables.

Illite "crystallinity" data have facilitated the mapping of an almost continuous zone of anchimetamorphic grade all the way from the Mediterranean Sea to Vienna (see Plate 1). In a few areas, it was possible to map lines of equal "crystallinity" or isocrysts (MERRIMAN and ROBERTS, 1985), as for example in the Northern Calcareous Alps near Innsbruck (KRUMM, 1984). In other areas, discontinuities in illite "crystallinity" were detected at nappe boundaries, with the higher tectonic unit showing higher metamorphic grade. This phenomenon was referred to as "transported metamorphism" (e.g. FREY et al., 1980a; BREITSCHMID, 1982), but "inverse metamorphic zonation" seems to be a more appropriate designation.

2.2. INDEX MINERALS

Very low-grade index minerals encountered in four different lithologies are given in Table 2. Investigations in the Taveyanne graywacke of Eocene-Oligocene age have produced a regular mineral zonation in the Western and Central Alps (MARTINI and VUAGNAT, 1965; MARTINI, 1968; MARTINI and VUAGNAT, 1970; SAWATZKI and VUAGNAT, 1971; MARTINI, 1972; KÜBLER et al., 1974; SAWATZKI, 1975; STALDER, 1979; KISCH, 1980; LIPPMANN and ROTHFUSS, 1980; BUSSY and EPARD, 1984), see Fig. 4. The facies series encountered is typical for an intermediate pressure regime (compare with LIOU et al., 1987). In the Western Alps metabasites have yielded useful index minerals, including lawsonite and glaucophane, which are indicative of a high pressure—low temperature re-

Tab. 2 Very low-grade index minerals from the Alps

Metabasites	*Metagraywackes*
Prehnite	Heulandite
Pumpellyite	Laumontite
Epidote	Prehnite
Lawsonite	Pumpellyite
Actinolite	Epidote
	Actinolite
	Corrensite
Metaclastites	*Fe-rich metalimestones*
Kaolinite	Glauconite
Pyrophyllite	Stilpnomelane
Paragonite	Biotite
Mg-Fe-carpholite	
Chloritoid	

Presence of Index Mineral = $f(T, P, X_{rock}, X_{fluid}, \ldots)$

gime. In comparison, metabasites and metagraywackes are extremely rare in the anchimetamorphic zone of the Eastern Alps (see Plate 1). Two comments are offered regarding pumpellyite-bearing mineral assemblages mentioned in the Plate caption. First, it is not always evident from the literature with which phases pumpellyite coexists. Secondly, these assemblages may not belong to the same Alpine regional metamorphic event and some may even have originated during ocean-floor metamorphism.

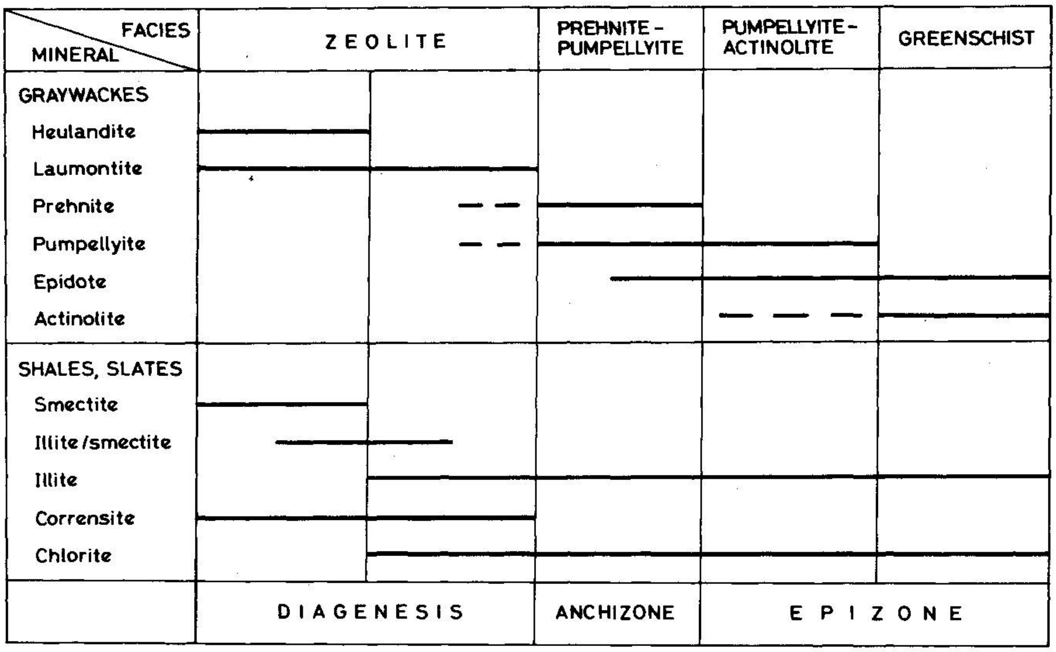

Fig. 4 Distribution of secondary minerals in the Taveyanne graywacke of the Western and Central Alps. See text for sources of data.

A few reaction-isograds have been mapped in metaclastites and Fe-rich metalimestones. The reaction-isograd kaolinite + quartz = pyrophyllite + H_2O was mapped in the high-grade anchizone of the Eastern Alps (SCHRAMM, 1978) and in the low-grade anchizone of the Central Alps (FREY, 1987a; see Plate 1). The difference in metamorphic grade is ascribed to the effect of different fluid compositions. In the fist example, the presence of hematite points to a water-rich fluid while in the second example organic material produced a methane-rich fluid with a water activity much less than unity (FREY, 1978). The appearance of chloritoid in metaclastites is governed by the reaction: pyrophyllite + chlorite = chloritoid + quartz + H_2O, and a corresponding reaction-isograd has been mapped at the beginning of the epizone of the Eastern and Central Alps (SCHRAMM, 1978; FREY and WIELAND, 1975). It is interesting to note that chloritoid appears at considerably higher grade in the polymetamorphic basement of the Ötztal nappe. In this case early Alpine chloritoid formed by a hydration-reaction at the expense of pre-Alpine staurolite (PURTSCHELLER, 1969).

Similar observations have also been made in the Western Alps: in "wet" Mesozoic metasediments, chloritoid appears at lower metamorphic grade than in the "dry" pre-Alpine basement (J. DESMONS, pers. comm. 1986).

The following two reaction-isograds have been established in Fe-rich limestones of the Helvetic nappes: glauconite ± chlorite + quartz = stilpnomelane + K-feldspar + H_2O + O_2 near the beginning of the anchizone and stilpnomelane + chlorite + K-feldspar = biotite + H_2O near the anchizone– epizone boundary (FREY et al., 1973; BREITSCHMID, 1982; FREY, 1987c), see Plate 1.

2.3. COAL RANK

In the Alps, the determination of coal rank through reflectivity measurements on phytoclasts has proved to be a reliable method of determining very low-grade metamorphic conditions (e.g. BARLIER et al., 1974; KÜBLER et al., 1979; STALDER, 1979 in the Western Alps; KÜBLER et al., 1979; STALDER, 1979; FREY et al., 1980a; KISCH, 1980; DORTMANN, 1982; GROSHONG et al., 1984 in the Central Alps; EGGERT et al., 1976; TEICHMÜLLER and TEICHMÜLLER, 1975, 1978; HUFNAGEL et al., 1981 in the Eastern Alps). In the diagenetic realm and at the beginning of very low-grade metamorphism, coal rank from sub-bituminous coal to anthracite (Fig. 5) is a more reliable method than illite "crystallinity" measurements.

Just a few interesting results will be mentioned here. DORTMANN (1982) determined an increase in coal rank with depth within the 2 km thick Niesen nappe from 3% to 5% maximum reflectivity. In the Vorderriss 1 borehole through the Northern Calcareous Alps (see Plate 1, No 12, for location) the intermediate Lechtal nappe I showed mean reflectivity (Rm) values of 1.5–2.0 while the Lechtal nappe II above and the Allgäu nappe below showed considerably lower coal ranks with 0.4–1.1% Rm (HUFNAGEL et al., 1981). Obviously, the Lechtal nappe I was exposed to higher temperatures before it was tectonically emplaced between the other two nappes.

Besides coal rank determination, a few other methods to determine the maturation of organic material have been applied in the Alps. GAUPP and BATTEN (1985) established a gradient in metamorphic grade based on colour changes of palynomorphs in Cretaceous pelitic rocks in the western part of the Eastern Alps. Conodont colour changes (e.g. EPSTEIN et al., 1977), on the other hand, has seen very little application in the Alps, but is of potential use in Triassic and Paleozoic limestones of the Eastern Alps.

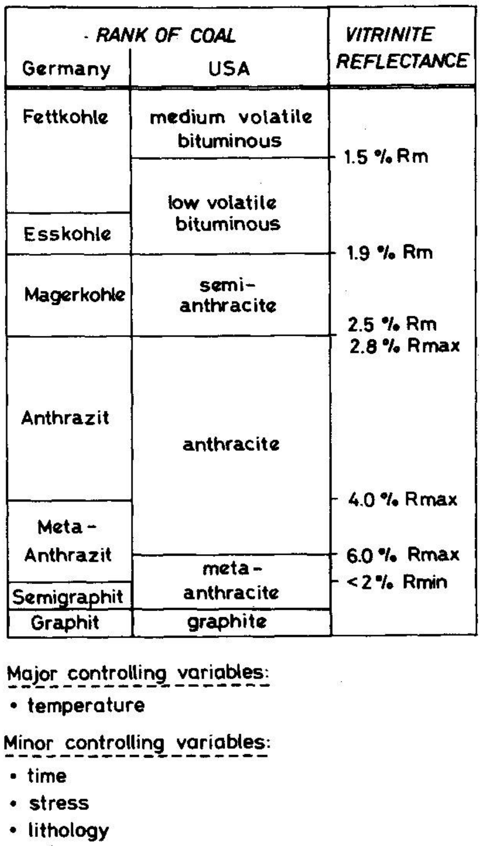

Fig. 5 Coal rank: division of metamorphic grade and controlling variables.

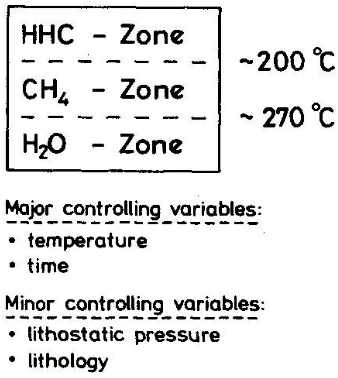

Fig. 6 Fluid inclusions: division of metamorphic grade and controlling variables.

2.4. FLUID INCLUSIONS

Until a few years ago fluid inclusion studies concentrated on large quartz crystals from late Alpine clefts. Recently, MULLIS (1979) developed a method that leads to a three-fold zonation of very low-grade regional metamorphic areas using fluid inclusions from tiny fissure quartz. Three fluid zones were defined, namely (i) a zone of higher hydrocarbons covering the diagenetic or nonmetamorphic range; (ii) a methane zone covering the low- and medium-grade anchizone as defined by illite "crystallinity" data; and (iii) a water zone beginning in the high-grade anchizone and extending into the epizone (Fig. 6). The precise boundary values used to define the fluid composition of the three mentioned fluid zones are tabulated in FREY et al. (1980b). It is believed that the early inclusions from the nonmetamorphic zone and the anchizone have a fluid composition approximately related to peak metamorphic conditions. Based on homogenization temperatures, the lower and upper boundaries of the methane zone were determined to be about 200° at 1.2 kbar and 270 °C at 1.7 kbar, respectively (MULLIS, 1979; see Fig. 6). This method, which has been applied so far only in a few subsequent studies (MULLIS in FREY et al., 1980a, 1980b; MULLIS in NIEDERMAYR et al., 1984) seems to be very promising.

3. Correlation of methods

As mentioned earlier, very few studies have applied all of the four methods discussed above. Illite "crystallinity" data, mineral assemblages and fluid zones yield a homogeneous picture. Even so, there is still some uncertainty as to how coal rank correlates with the other three methods. Fig. 7 shows the presently available scheme as worked out in the Alps (subject to slight modification in the future). This correlation supersedes an earlier attempt (FREY and NIGGLI, 1971; see also FREY et al., 1980a, p. 197 for a correction) and is in general agreement with the correlation proposed by KISCH (1983). According to data from the Western and Central Alps (Plate 1), the majority of occurrences of pumpellyite ± prehnite + chlorite + albite ± quartz are located in the anchizone, whereas all occurrences with pumpellyite + actinolite (or glaucophane) + chlorite ± albite + quartz are located in the epizone as defined by illite "crystallinity" data.

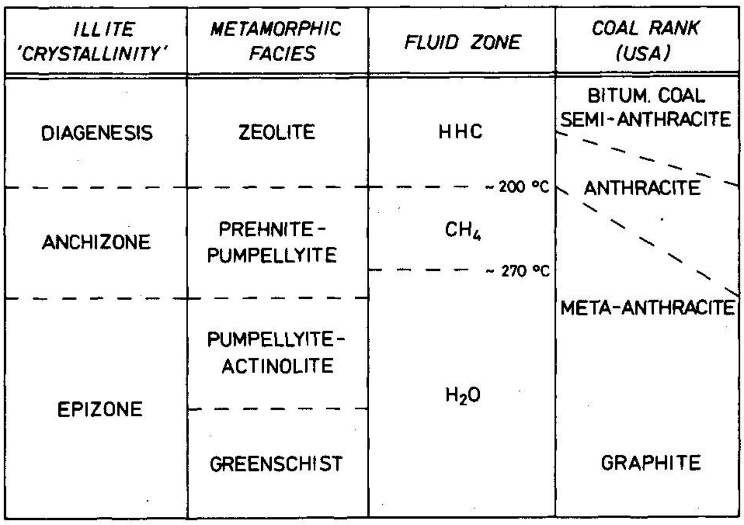

Fig. 7 Correlation between different indicators of very low-grade metamorphism based on data from the Alps.

4. Geothermometry and geobarometry

The derivation of temperature-pressure conditions in very low-grade metamorphism is a difficult undertaking. The analyses of mineral assemblages in very low-grade metabasites and metagraywackes provides tight constraints on P-T conditions (LIOU et al., 1987), but relevant mineral chemical data are very scarce in the Western and Central Alps (e.g. COOMBS et al., 1976). Some reaction-isograds in metaclastites and iron-rich metalimestones have been located in the Central and Eastern Alps as mentioned earlier, but only the univariant reaction kaolinite + quartz = pyrophyllite + H_2O has been located in P-T space. Unfortunately, this dehydration reaction cannot be used for temperature estimates as long as the activity of water remains unknown. The calcite-dolomite geothermometry is limited at temperatures below 300 °C because of low degree of solid-solution. Vitrinite reflectance data have yielded reasonable temperature estimates (e.g. STALDER, 1979) and the same may become true by application of the conodont colour method in the Eastern Alps. In this author's opinion, the most reliable temperature and pressure estimates can presently be extracted from fluid inclusion data (see section 2.4. for references). The b_o geobarometer proposed originally by SASSI and SCOLARI (1974) for greenschist facies metapelites has been extended to anchizonal metaclastites of the Central Alps by PADAN et al. (1982) and needs further testing.

5. Radiometric dating

Radiometric dating of very low-grade metamorphic rocks is fraught with many difficulties (for a review see HUNZIKER, 1987). Notwithstanding these reservations, radiometric dating in the Alps has yielded important but sometimes conflicting results. Most commonly, the K–Ar and the Rb–Sr methods have been applied (Western Alps: BONHOMME et al., 1980; Central Alps: FRANK and STETTLER, 1979; HUNZIKER et al., 1986; Eastern Alps: JUNG, 1980; KRALIK et al., 1981; KRALIK, 1982, 1983a, b; HAMMERSCHMIDT, 1982), and in a few cases the $^{39}Ar/^{40}Ar$ method was used (FRANK and STETTLER, 1979; HAMMERSCHMIDT, 1982; HUNZIKER et al., 1986). These studies indicate that most very low-grade metaclastites of the Eastern Alps were metamorphosed during the Eo-Alpine orogenic phase in late Cretaceous time. In the Central and Western Alps, on the other hand, the Meso-Alpine and Neo-Alpine phases of middle and late Tertiary age, respectively, seem to be predominant.

6. Suggestions for future work

The study of very low-grade metamorphic during the last two decades has enhanced the knowledge of metamorphism in the external regions of the Alps to a considerable extent. Our knowledge of the boundary between very low-grade and low-grade metamorphism is fairly complete, but much less is known about the lower temperature realm encompassing advanced diagenesis to the beginning of very low-grade metamorphism. What is particularly needed, besides careful X-ray diffraction studies, are (i) microstructural and chemical information on the fine grained sheet silicates through the application of electron microscopy (SEM, TEM, HRTEM); (ii) more detailed studies of the organic matter, not only reflectivity studies on phytoclasts, but also using organic chemical methods and applying the method of conodont colours (Eastern Alps). (iii) Fluid inclusion studies on quartz from open fissures initiated by J. Mullis should be extended to the Western and Eastern Alps. In addition, such studies may also be applied to vein and rock forming quartz with a well defined structural history. (iv) Fission track dating with its low closure temperatures has much potential for dating the very low-grade metamorphism and subsequent uplift history but has, to the author's best knowledge, not yet been applied to Alpine areas covered in this review.

Acknowledgments

I would like to thank Doug Robinson for inviting me to the conference on "Diagenesis and Low-Temperature Metamorphism" in Bristol in April 1984. This rearoused my interest in very low-grade metamorphism. Discussions with Jacqueline Desmons, Johannes Hunziker, Josef Mullis, Michael Schramm and Marlies Teichmüller were important for the preparation of this manuscript. Martin Burkhard and Martin Kralik made unpublished manuscripts available. Marc Handy kindly improved the English. Thoughtful reviews were provided by Daniel Bernoulli, Jacqueline Desmons, Adrian Pfiffner and Stefan Schmid. To all these friends and colleagues my sincere thanks.

References

SMPM = Schweiz. mineral. petrogr. Mitt.

APRAHAMIAN, J. (1974): La cristallinité de l'illite et les minéraux argileux en bordure des massifs cristallins externes de Belledonne et du Pelvoux (variations et relations possibles avec des événements tectoniques et métamorphiques alpins). Géol. Alpine 50, 5–15.

APRAHAMIAN, J. and PAIRIS, J.-L. (1981): Very low grade metamorphism with a reverse gradient induced by an overthrust in Haute-Savoie (France). Thrust and Nappe Tectonics. The Geol. Soc. London 159–165.

APRAHAMIAN, J., PAIRIS, B. et PAIRIS, J.-L. (1975): Nature des minéraux argileux et cristallinité des illites dans le massif de Platé et le revers occidental des Aiguilles Rouges. Implications possibles d'un point de vue sédimentaire, structural et métamorphique. Annales Centre Univ. Savoie II, Sci. Nat. 95–119.

BARLIER, J., RAGOT, J.-P. et TOURAY, J.-C. (1974): L'évolution des Terres Noires subalpines méridionales d'après l'analyse minéralogique des argiles et la réflectométrie des particules carbonées. Bull. B.R.G.M. (2e série), Section II/6, 533–548.

BECHTOLD, D., KLEBERGER, J. und SCHRAMM, J.-M. (1981): Zur Metamorphose der Grauwackenzone in Salzburg/Österreich – Ein Exkursionsführer. Geol. Paläont. Mitt. Innsbruck 10, 305–353.

BOCQUET-DESMONS, J. (1971): Cartes de répartition de quelques minéraux du métamorphisme alpin dans les Alpes franco-italiennes. Eclogae geol. Helv. 64, 71–103.

BOCQUET-DESMONS, J. (1974): Etudes minéralogiques et pétrologiques sur les métamorphismes d'âge alpin dans les Alpes françaises. Thèse Univ. Grenoble, 489 pp.

BONHOMME, M.G., SALIOT, P. and PINAULT, Y. (1980): Interpretation of potassium-argon isotopic data related to metamorphic events in south-western Alps. SMPM 60, 81-98.

BREITSCHMID, A. (1982): Diagenese und schwache Metamorphose in den sedimentären Abfolgen der Zentralschweizer Alpen (Vierwaldstättersee, Urirotstock). Eclogae geol. Helv. 75, 331–380.

BURKHARD, M. (1986): L'Helvétique de la bordure occidentale du Massif de l'Aar, Tectonique, Déformation et Métamorphisme. Thèse Univ. Neuchâtel.

BUSSY, F. et EPARD, J.-L. (1984): Essai de zonéographie métamorphique entre les Diablerets et le massif de l'Aar (Suisse occidentale) basée sur l'étude des Grès de Taveyanne. SMPM 64, 131–150.

CARON, J.-M. (1977): Lithostratigraphie et tectonique des Schistes lustrés dans les Alpes cottiennes septentrionales et en Corse orientale. Sci. Géol. Mémoire 48, 326 pp.

COOMBS, D.S., NAKAMURA, Y. and VUAGNAT, M. (1976): Pumpellyite-actinolite facies schists of the Taveyanne formation near Loèche, Valais, Switzerland. J. Petrol. 17, 440–471.

CORTESOGNO, L., LUCCHETTI, G. e PENCO, A.M. (1974): Associazione a laumontite, prehnite e apofillite in vene nelle anfiboliti di Ellera (massicci cristallini della Liguria Occidentale). Ann. Mus. civ. Storia Nat. Genova 80, 58–80.

CORTESOGNO, L., LUCCHETTI, G. and SPADEA, P. (1984): Pumpellyite in low-grade metamorphic rocks from Ligurian and Lucanian Apennines, Maritime Alps and Calabria (Italy). Contrib. Mineral. Petrol. 85, 14–24.

DAVIES, V.M. (1983): Alpine structure and metamorphism in a traverse from the Grandes Rousses Massif to the internal Briançonnais. Unpubl. Ph. D. thesis Univ. Liverpool, 223 pp.

DIETRICH, V., VUAGNAT, M. and BERTRAND, J. (1974): Alpine metamorphism of mafic rocks. SMPM 54, 291–332.

DORTMANN, T. (1982): Ein Querprofil durch die Niesendecke. Sedimente, Tektonik, Metamorphose und ihre Bedeutung für die Gebirgsbildung. Unveröffentl. Diplomarbeit Univ. Bonn.

EGGERT, P., GREBE, H., TEICHMÜLLER, M. und TEICHMÜLLER, R. (1976): Inkohlungsuntersuchungen an Treibholz aus der Unteren Junghansen-Serie (Unterkreide) der Feuerstätter Decke (Nordpenninikum) westlich Oberstorf/Allgäu. N. Jb. Geol. Paläont. Abh. 152, 112–136.

ENGLAND, P. and RICHARDSON, S.W. (1977): The influence of erosion upon the mineral facies of rocks from different metamorphic environments. J. geol. Soc. London 134, 201–213.

ENGLAND, P.C. and THOMPSON, A.B. (1984): Pressure-temperature-time paths of regional metamorphism. I. Heat transfer during the evolution of regions of thickened continental crust. J. Petrol. 25, 894–928.

EPSTEIN, G., EPSTEIN, J. and HARRIS, L. (1977): Conodont colour alteration – an index to organic metamorphism. Prof. Pap. U.S. Geol. Surv. 995, 27 pp.

FABER, E., SCHOELL, M. und STAHL, W.J. (1981): Geochemische Untersuchungen der gasförmigen Kohlenwasserstoffe der Tiefbohrung Vorderriss 1. Geol. Bavarica 81, 145–158.

FRANK, E. and STETTLER, A. (1979): K–Ar and ^{39}Ar–^{40}Ar systematics of white K-mica from an Alpine metamorphic profile in the Swiss Alps. SMPM 59, 375–394.

FREY, M. (1969): Die Metamorphose des Keupers vom Tafeljura bis zum Lukmanier-Gebiet. Beitr. geol. Karte Schweiz, NF 137, 160 pp.

FREY, M. (1970): The step from diagenesis to metamorphism in pelitic rocks during Alpine orogenesis. Sedimentology 15, 261–279.

FREY, M. (1978): Progressive low-grade metamorphism of a black shale formation, Central Swiss Alps, with special reference to pyrophyllite and margarite bearing assemblages. J. Petrol. 19, 95-135.

FREY, M. (1987a): The reaction-isograd kaolinite + quartz = pyrophyllite + H_2O, Helvetic Alps, Switzerland. SMPM 67.

FREY, M. (1987b): Very low-grade Metamorphism. Blackie, Glasglow.

FREY, M. (1987c): Very low-grade metamorphism of clastic sedimentary rocks. In M. Frey, ed., Very low-grade Metamorphism, Blackie, Glasgow.

FREY, M. und NIGGLI, E. (1971): Illit-Kristallinität, Mineralfazien und Inkohlungsgrad. SMPM 51, 229-234.

FREY, M. und WIELAND, B. (1975): Chloritoid in autochthon-parautochthonen Sedimenten des Aarmassivs. SMPM 55, 407-418.

FREY, M. HUNZIKER, J.C., ROGGWILLER, P. und SCHINDLER, C. (1973): Progressive niedriggradige Metamorphose glaukonitführender Horizonte in den helvetischen Alpen der Ostschweiz. Contrib. Mineral. Petrol. 39, 185-218.

FREY, M., TEICHMÜLLER, M., TEICHMÜLLER, R., MULLIS, J., KÜNZI, B., BREITSCHMID, A., GRUNER, U. and SCHWIZER, B. (1980a): Very low-grade metamorphism in external parts of the Central Alps: Illite crystallinity, coal rank, and fluid inclusion data. Eclogae geol. Helv. 73, 173-203.

FREY, M., BUCHER, K., FRANK, E. and MULLIS, J. (1980b): Alpine metamorphism along the geotraverse Basel-Chiasso - a review. Eclogae geol. Helv. 73, 527-546.

GAUPP, R. and BATTEN, D.J. (1985): Maturation of organic matter in Cretaceous strata of the Northern Calcareous Alps. N. Jb. Geol. Paläont. Mh. 3, 157-175.

GROSHONG, R.H., PFIFFNER, O.A. and PRINGLE, L.R. (1984): Strain partitioning in the Helvetic thrust belt of eastern Switzerland from the leading edge to the internal zone. J. Struct. Geol. 6, 5-18.

GRUNER, U. (1976): Geologie des Falknis-Glegghorn-Gebietes (W-Rhätikon): Unveröffentl. Liz.-Arbeit, Univ. Bern

GRUNER, U. (1981): Die jurassischen Breccien der Falknis-Decke und altersäquivalente Einheiten in Graubünden. Beitr. geol. Karte Schweiz. N.F. 154, 136 pp.

GUITARD, G. et SALIOT, P. (1971): Sur les paragenèses à lawsonite et à pumpellyite des Alpes de Savoie. Bull. Soc. fr. Minéral. Cristallogr. 94, 507-523.

GÜRLER, B. (1982): Geologie der Val Tasna und Umgebung (Unterengadin). Unpubl. Diss. Univ. Basel.

HAMMERSCHMIDT, K. (1982): K/Ar and $^{40}Ar/^{39}Ar$ age resolution from illites of the Trias of Mauls; Mesozoic cover of the Austroalpine basement, eastern Alps (South Tyrol). SMPM 62, 113-133.

HOEFS, J. and FREY, M. (1976): The isotopic composition of carbonaceous matter in a metamorphic profile from the Swiss Alps. Geochim. cosmochim. Acta 40, 945-951.

HOSCHEK, G., KIRCHNER, E., MOSTLER, H. and SCHRAMM, J.-M. (1980): Metamorphism in the Austroalpine units between Innsbruck and Salzburg (Austria) - A synopsis. Mitt. österr. geol. Ges. 71/72, 335-341.

HUFNAGEL, H., KUCKELHORN, K., WEHNER, H. und HILDEBRAND, G. (1981): Interpretation des Bohrprofils Vorderriss 1 aufgrund organo-geochemischer und geophysikalischer Untersuchungen. Geol. Bavarica 81, 123-143.

HUNZIKER, J.C., FREY, M., CLAUER, N., DALLMEYER, R.D., FRIEDRICHSEN, H., FLEHMIG, W., HOCHSTRASSER, K., ROGGWILER, P. and SCHWANDER, H. (1986): The evolution of illite to muscovite: mineralogical and isotopic data from the Glarus Alps, Switzerland. Contrib. Mineral. Petrol. 92, 157-180.

HUNZIKER, J.C. (1987): Non-stable isotopes in very low-grade metamorphism. In M. Frey, ed., Very low-grade Metamorphism, Blackie, Glasgow.

JUNG, G. (1980): Radiometrische Altersdatierung und Metamorphoseuntersuchungen der Kalkalpenbasis und der Grauwackenzone in der Radmer und am steirischen Erzberg. Jber. 1979 Hochschulschwerpunkt S15, 1, 20–27.

KIRCHNER, E. (1979): Pumpellyitführende Kissenlavabreccien in der Gips-Anhydrit-Lagerstätte von Wienern am Grundlsee, Steiermark. Tschermaks Min. Petr. Mitt. 26, 149–162.

KIRCHNER, E. (1980): Natriumamphibole und Natriumpyroxene als Mineralneubildungen in Sedimenten und basischen Vulkaniten aus dem Permoskyth der Nördlichen Kalkalpen. Verh. Geol. Bundesanst. Wien, 249–279.

KISCH, H.J. (1980): Illite crystallinity and coal rank associated with lowest-grade metamorphism of the Taveyanne greywacke in the Helvetic zone of the Swiss Alps. Eclogae geol. Helv. 73, 753–777.

Kisch, H.J. (1983): Mineralogy and petrology of burial diagenesis (burial metamorphism) and incipient metamorphism in clastic rocks. In: G. Larsen and G.V. Chilingar, Diagenesis in sediments and sedimentary rocks, 2: 289–493. – Developments in sedimentology 25 B, Elsevier, Amsterdam.

KOLLER, F. (1985): Petrologie und Geochemie der Ophiolite des Penninikums am Alpenostrand. Jb. Geol. Bundesanst. Wien 128, 83–150.

KRALIK, M. (1982): Geochronologie der kretazischen Metamorphose in den Kalkalpen und der Grauwackenzone im Bereich von Bischofshofen. Jber. 1981 Hochschulschwerpunkt S15, 3, 9–22.

KRALIK, M. (1983a): Interpretation of K–Ar and Rb–Sr data from fine fractions of weakly metamorphosed shales and carbonate rocks at the base of the northern calcareous Alps (Salzburg, Austria). Tschermaks Min. Petr. Mitt. 32, 49–67.

KRALIK, M. (1983b): Anwendungsmöglichkeiten von K–Ar und Rb–Sr-Isotopenuntersuchungen an Sedimenten, Erz- und Erdöllagerstätten. Mitt. österr. geol. Ges. 76, 189–204.

KRALIK, M., THÖNI, M. und FRANK, W. (1981): Metamorphoseuntersuchungen in den feinklastischen und karbonatischen Sedimenten der Nördlichen Kalkalpen im Salzburger Bereich. Jber. 1980, Hochschulschwerpunkt S15, 2, 37–43.

KRALIK, M., KRUMM, H. and SCHRAMM, J.-M. (1986): Low grade and very low grade metamorphism in the Northern Calcareous Alps and the Greywacke zone: Illite crystallinity data and isotopic ages. In H. Flügel and P. Faupl, eds., The Geodynamics of the Eastern Alps.

KRUMM, H. (1981): Untersuchungen an Schichtsilikaten der Tiefbohrung Vorderriss 1 (Kalkalpen, Bayern). Geol. Bavarica 81, 193–206.

KRUMM, H. (1984): Anchimetamorphose im Anis und Ladin (Trias) der Nördlichen Kalkalpen zwischen Arlberg und Kaisergebirge – ihre Verbreitung und deren baugeschichtliche Bedeutung. Geol. Rdsch. 73, 223–257.

KUBLER, B. (1967): La cristallinité de l'illite et les zones tout à fait supérieures du métamorphisme. Etages tectoniques, Colloque de Neuchâtel, 105–122.

KUBLER, B., MARTINI, J. and VUAGNAT, M. (1974): Very low grade metamorphism in the western Alps. SMPM 54, 461–469.

KUBLER, B., PITTION, J.-L., HÉROUX, Y., CHAROLLAIS, J. et WEIDMANN, M. (1979): Sur le pouvoir réflecteur de la vitrinite dans quelques roches du Jura, de la Molasse et des Nappes préalpines, helvétiques et penniques. Eclogae geol. Helv. 72, 347–373.

KÜNZI, B. (1975): Geologie des hintersten Kientals (Berner Oberland). Unpublizierte Liz.arbeit Univ. Bern.

LEIMSER, W. und PURTSCHELLER, F. (1980): Beiträge zur Metamorphose von Metavulkaniten im Pennin des Engadiner Fensters. Mitt. österr. geol. Ges. 71/72, 129–137.

LIOU, J.G., MARUYAMA, S. and CHO, M. (1987): Very low-grade metamorphism of volcanic and volcaniclastic rocks – mineral assemblages and mineral facies. In M. Frey, ed., Very low-grade Metamorphism, Blackie, Glasglow.

LIPPMANN, F. und ROTHFUSS, H. (1980): Tonminerale in Taveyannaz-Sandsteinen. SMPM 60, 1–29.

MARTINI, J. (1968): Etude pétrographique des Grès de Taveyanne entre Arve et Giffre (Haute-Savoie, France). SMPM 48, 539-654.
MARTINI, J. (1972): Le métamorphisme dans les chaînes alpines externes et ses implications dans l'orogenèse. SMPM 52, 257-275.
MARTINI, J. et VUAGNAT, M. (1965): Présence du faciès à zéolites dans la formation des «grès» de Taveyanne (Alpes franco-suisses). SMPM 45, 281-293.
MARTINI, J. und VUAGNAT, M. (1970): Metamorphose niedrigsttemperierten Grades in den Westalpen. Fortschr. Miner. 47, 52-64.
MERRIMAN, R.J. and ROBERTS, B. (1985): A survey of white mica crystallinity and polytypes in pelitic rocks of Snowdonia and Llŷn, North Wales. Min. Mag. 49, 305-319.
MORARIU, D. (1985): Deformation und Metamorphose der mesozoischen Metasedimente am West- und Südrand des Aarmassivs (Leukerbad-Ausserberg). Unpubl. Diss. Univ. Basel.
MOSER, H.-J. (1985): Strukturgeologische Untersuchungen in der Rawil-Depression (Helvetische Kalkalpen zwischen Berner Oberland und Wallis). Diss. Univ. Bern.
MULLIS, J. (1979): The system methane-water as a geologic thermometer and barometer from the external part of the Central Alps. Bull. Minéral. 102, 526-536.
NIEDERMAYR, G., MULLIS, J., NIEDERMAYER, E. und SCHRAMM, J.-M. (1984): Zur Anchimetamorphose permo-skythischer Sedimentgesteine im westlichen Drauzug, Kärnten-Osttirol (Österreich). Geol. Rdsch. 73, 207-221.
NIGGLI, E. und NIGGLI, C. (1965): Karten der Verbreitung einiger Mineralien der alpidischen Metamorphose in den Schweizer Alpen (Stilpnomelan, Alkali-Amphibol, Staurolith, Disthen, Sillimanit). Eclogae geol. Helv. 58, 335-368.
NIGGLI, E. and ZWART, H.J. (1973): Metamorphic map of the Alps, scale 1:1000000. Subcommission for the Cartography of the Metamorphic Belts of the World. Sheet 17 of the Metamorphic Map of Europe. Leiden/UNESCO, Paris.
PURTSCHELLER, F. (1969): Petrographische Untersuchungen an Alumosilikatgneisen des Ötztaler-Stubaier Altkristallins. Tschermaks Min. Petr. Mitt. 13, 35-54.
PADAN, A., KISCH, H.J. and SHAGAM, R. (1982): Use of the lattice parameter b_0 of dioctahedral illite/muscovite for the characterization of P/T gradients of incipient metamorphism. Contrib. Miner. Petrol. 79, 85-95.
RAUMER, J.F. VON (1974): Zur Metamorphose amphibolitischer Gesteine im Altkristallin des Mont-Blanc- und Aiguilles-Rouges-Massivs. SMPM 54, 471-488.
SALIOT, P. (1973): Les principales zones de métamorphisme dans les Alpes françaises. Répartition et signification. C.R. Acad. Sci. Paris 276, Série D, 3081-3084.
SASSI, F.P. and SCOLARI, A. (1974): The b_0 value of the potassic white micas as a barometric indicator in low-grade metamorphism of pelitic schists. Contrib. Mineral. Petrol. 45, 143-152.
SAWATZKI, G. (1975): Etude géologique et minéralogique des flyschs a grauwackes volcaniques du synclinal de Thônes (Haute-Savoie, France). Grès de Taveyanne et grès du val d'Illiez. Arch. Sci. Genève 28, 265-368.
SAWATZKI, G. et VUAGNAT, M. (1971): Sur la présence du faciès à zéolites dans les grès de Taveyanne du synclinal de Thônes (Haute-Savoie, France). C.R. Soc. Phys. Hist. Nat. Genève 6, 69-79.
SCHRAMM, J.-M. (1974): Vorbericht über Untersuchungen zur Metamorphose im Raume Bischofshofen-Dienten-Saalfelden (Grauwackenzone/Nördliche Kalkalpen, Salzburg). Anzeiger math.-naturw. Kl. Österr. Akad. Wiss. Jg. 1974/12, 199-207.
SCHRAMM, J.-M. (1977): Über die Verbreitung epi- und anchimetamorpher Sedimentgesteine in der Grauwackenzone und in den Nördlichen Kalkalpen (Österreich) - ein Zwischenbericht. Geol. Paläont. Mitt. Innsbruck 7, 3-20.
SCHRAMM, J.-M. (1978): Anchimetamorphes Permoskyth an der Basis des Kaisergebirges (Südrand der Nördlichen Kalkalpen zwischen Wörgl und St. Johann in Tirol, Österreich). Geol. Paläont. Mitt. Innsbruck 8, 101-111.

SCHRAMM, J.-M. (1980): Bemerkungen zum Metamorphosegeschehen in klastischen Sedimentgesteinen im Salzburger Abschnitt der Grauwackenzone und der Nördlichen Kalkalpen. Mitt. österr. geol. Ges. 71/72, 379–384.

SCHRAMM, J.-M. (1982): Zur Metamorphose des feinklastischen Permoskyth im Ostabschnitt der Nördlichen Kalkalpen (Ostösterreich). Verh. Geol. Bundesanst. Wien 2, 63–72.

SIDDANS, A. W. B. (1979): Deformation, metamorphism, and texture development in Permian mudstones of the Glarus Alps. Eclogae geol. Helv. 72, 601–621.

STALDER, P. (1979): Organic and inorganic metamorphism in the Taveyannaz sandstone of the Swiss Alps and equivalent sandstone in France and Italy. J. Sed. Petrol. 49, 463–482.

TEICHMÜLLER, M. und TEICHMÜLLER, R. (1975): Inkohlungsuntersuchungen in der Molasse des Alpenvorlandes. Geol. Bavarica 73, 123–142.

TEICHMÜLLER, M. and TEICHMÜLLER, R. (1978): Coalification studies in the Alps. In: H. CLOOS et al., eds. Alps, Apennines, Hellenides, Schweizerbart, Stuttgart, 49–55.

WINKLER, H. G. F. (1979): Petrogenesis of metamorphic rocks. Fifth ed., Springer, New York.

Manuscript received July 15, 1986; accepted July 29, 1986.

Leere Seite
Blank page
Page vide

Schweiz. mineral. petrogr. Mitt.
Band 66, 1/2, 1986