Alpine Metamorphism of Pelitic and Marly Rocks of the Central Alps

By *Martin Frey* (Berne)*)

With 4 figures in the text

Abstract

The Central Alps offer the unique possibility to follow different formations from unmetamorphosed sediments to medium- and high-grade metamorphic rocks. This article summarizes the mineralogical changes of the following three formations with increasing Alpine metamorphic grade: The Keuper red-bed formation and the Lower Liassic black-shale formation from unmetamorphosed clays and marls to the beginning of the staurolite zone; and the Bündnerschiefer from the anchizone to the beginning of the sillimanite zone. Only few mineral reactions are known which interrelate these mineralogical changes. Therefore, most so-called isograds (based on reaction boundaries) postulated in pelitic and marly rocks of the Central Alps are at best mineral zone boundaries (first appearance of an index mineral).

Introduction

Studying the Alpine metamorphism on a regional scale is a very young science and dates back only to 1960 when Niggli presented the first zonal map for the Central Alps. Relevant to this study are his distribution maps for chloritoid, kyanite, and sillimanite. More recent distribution maps of these minerals, including also staurolite, can be found in Niggli and Niggli (1965) and Niggli (1970). In 1962 Wenk studied the mineral pair plagioclase-calcite in marly rocks and marbles of the Lepontine region. He was able to further subdivide the region within the kyanite zone with aid of the anorthite content in plagioclase.

None of the above mentioned boundaries can be regarded as isograds in the sense of Tilley (1924) nor in the sense of Carmichael (1970). According to

*) Author's address: Dr. M. Frey, Mineralogisch-Petrographisches Institut, Sahlistrasse 6, CH-3012 Berne, Switzerland.

Tilley (1924) an isograd represents a line of closely similar metamorphic grade. At this time metamorphic grade was thought to be dependent on temperature and pressure only. However, experimental and theoretical studies of the last twenty years made it clear that in addition to P_{total} and T the composition of the fluid phase plays a significant role in the formation of metamorphic rocks. For these reasons Carmichael (1970) uses the term isograd only if it is based on a specific metamorphic reaction.

Tilley (1924, p. 169) used the term isograd also in a more descriptive sense as "a line drawn on a map to represent a particular grade of metamorphism as indicated by the first appearance of an index mineral in rocks of some given composition" (Fyfe and Turner, 1958, p. 181). If the mineral reaction which leads to the appearance of an index mineral is known it may be possible to decide whether this boundary represents a line of closely similar temperature at a given total pressure as thought by Tilley. However, this is often not true because an index mineral may form by different reactions in different pelitic formations, due to different mineral assemblages in the unmetamorphosed sediment (e. g. the formation of chloritoid as discussed on p. 494 and p. 497). Therefore, the first appearance of an index mineral may be controlled by the distribution of the appropriate rock composition. This is, for example, the case for the outer limit of the chloritoid zone in the region between Aar- and Gotthard Massifs (Frey, 1969a, p. 116). Therefore, the term *zone boundary* will be used in this paper for the first appearance of an index mineral in rocks of approximately the same composition (e. g. pelitic rocks).

In this paper, the term *isograd* is used in the sense of Carmichael (1970), that is, it is based on a specific metamorphic reaction. Correlation on zone boundaries with isograds presupposes the knowledge of which mineral reaction[1]) is going on. This, on the other hand, can be done only if *complete* assemblages[2]) above, at, and below a zone boundary are known. This need for the knowledge of complete assemblages has only recently come to the mind of Alpine petrologists. As a result, very little data are available on complete assemblages in pelitic and marly rocks[3]) in the Central Alps. Provided information on such assemblages is available, one can work out possible reaction

---

[1]) Bearing in mind that balancing chemical reactions is only an approximation to what may actually have occurred in metamorphic rocks (see e. g. Carmichael, 1969).

[2]) For low- and medium-grade pelitic and marly rocks there is a critical need for X-ray work to detect phases as pyrophyllite, paragonite or margarite; in addition, staining techniques may be needed to detect k-feldspar.

[3]) Pelitic rocks have been defined in two different manners: as calcium-free, aluminous sediments in the anglo-american sense, and as a sediment composed mainly of particles of the clay fraction ($< 2\ \mu$), but possibly also including carbonates etc. as in European usage. In this paper the term "pelitic" rocks is used in the first sense. Carbonate-bearing aluminous sediments are called marly rocks.

paths for a petrogenetic grid in a given chemical system. This has been done in the Central Alps for quartz-bearing carbonate rocks (TROMMSDORFF, 1966, 1972) and ultramafic rocks (EVANS and TROMMSDORFF, 1970). However, pelitic and even more marly rocks represent very complicated systems with too many components to be treated by graphical methods. Admittedly, important results can still be gained by introducing meaningful simplifications as has been done for pelitic rocks by THOMPSON (1957).

The Central Alps offer a unique possibility to determine the mineralogical changes of at least three different stratigraphic formations with increasing regional Alpine metamorphism, from unmetamorphosed sediments to medium- and high-grade metamorphic rocks. These rocks include an Upper Triassic red-bed formation (= Keuper, Quartenschiefer), a Liassic black-shale formation and the Bündnerschiefer. This review article is restricted to the three above mentioned formations, neglecting other informative metamorphic rocks as for example the paraschists and -gneisses in the Lucomagno nappe (BOSSARD, 1929) and the Simano nappe (Pizzo Forno-Campo Tencia region, see e. g. KELLER, 1968). Many of these paragneisses are highly aluminous and frequently contain segregations of quartz with kyanite and/or andalusite and/or sillimanite (KELLER, 1968; WENK, 1970; P. THOMPSON, personal communication 1973). These rock units would be well suited to find out whether the second sillimanite zone (breakdown of muscovite in the presence of quartz) is reached in the Central Alps. The writer apologizes that all the work in pre-Mesozoic rocks is not reviewed in this paper.

Dealing with Mesozoic sediments has the great advantage that these rocks underwent only Alpine metamorphism. However, the Alpine orogeny (and its metamorphism) was plurifacial (DE ROEVER, 1963) and at least two or even three different phases can be distinguished (BEARTH, 1958, 1967; VAN DER PLAS, 1959; NIGGLI, 1970; DAL PIAZ et al., 1972; ERNST, 1973; JÄGER, 1973; TRÜMPY, 1973; HUNZIKER, 1973; see also p. 247, this volume). An early high pressure, low temperature event occurred in Upper (late) Cretaceous time, followed by a lower pressure, higher temperature event at the Eocene-Oligocene boundary which is called the Lepontine phase in the Central Alps; finally, the external zones (Helvetic zone, Prealpes) seem to have been also affected by a phase at the Oligocene-Miocene boundary. The traverses studied in this article (Fig. 1) received their main imprint by the Lepontine phase. However, relicts of the early Alpine event are preserved in some Bündnerschiefer and some post-Lepontine recrystallization may have occurred in the low-grade external regions of all three formations discussed in this paper.

One of the main goals of metamorphic petrology is to decipher the physicochemical conditions under which a rock was formed. Regarding the meagre data available at present for pelitic and marly rocks in the Central Alps, the modest aims of this paper are: (1) to present the distribution of the phases

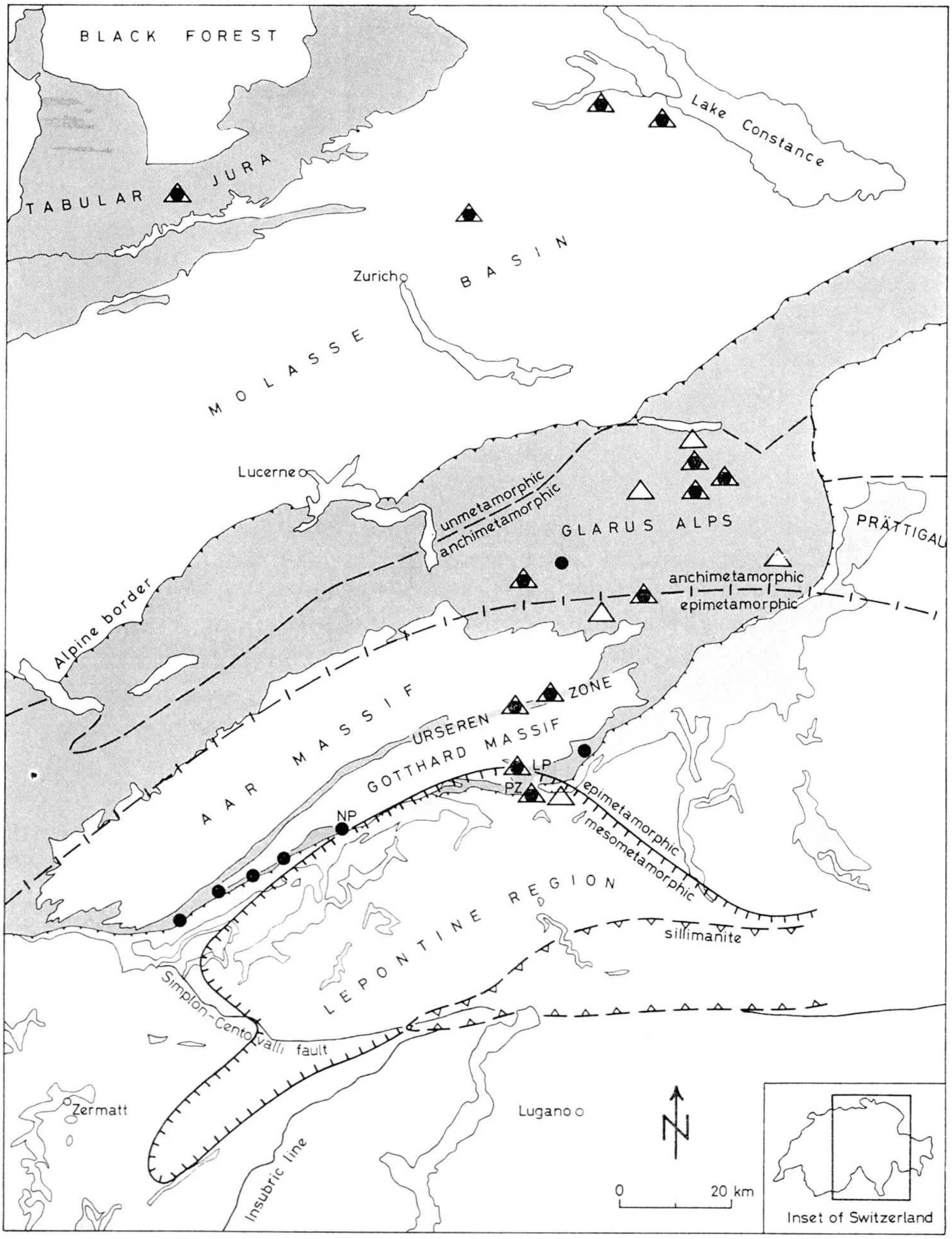

Fig. 1. Location of traverses studied in this paper. Main sample localities are shown with triangles for the Upper Triassic red-bed formation and with filled circles for the Lower Liassic black-shale formation. Bündnerschiefer outcrops are shown by light stippling. The dark stippled areas represent the Jura and Helvetic domains. Metamorphic zone boundaries are drawn according to the definition in footnote 4. The unmetamorphic-anchimetamorphic boundary is poorly defined.

Abbreviations for localities: NP = Nufenenpass; LP = Lukmanierpass; PZ = Piora Zone.

occurring in three formations; (2) to discuss some critical mineral assemblages; and (3) to derive some possible mineral reactions.

Progressive metamorphism of Mesozoic sediments

UPPER TRIASSIC (QUARTENSCHIEFER)

This formation was studied in detail by FREY (1969a). Additional data for unmetamorphic[4]) and anchimetamorphic[4]) rocks were given in a later paper (FREY, 1970). In the following a brief summary is given with some additional new data. For detailed references the reader is referred to FREY (1969a).

The traverse chosen for the Upper Triassic formation (Fig. 1) was dictated by the available outcrops (FREY, 1969a, Fig. 1). It is a red-bed formation made up originally of marls, clays, sand- and dolostones. The mean thickness varies from 30 to 70 m. Since the sediments may have been deposited in an alluvial fan near the water table, chemical variation is heterogeneous at a scale of a single outcrop. However, analyzed anchimetamorphic and epi- to mesometamorphic rocks occupy the same areas in AKNF, ACF and AFM plots (FREY, 1969a, Fig. 27). It can be safely stated that every high-grade rock has a lower-grade counterpart in terms of bulk composition.

A summary of the distribution of some important minerals in marly and pelitic rocks is presented in Fig. 2. The data are based on 25 unmetamorphic samples from the Tabular Jura and three boreholes below the Molasse Basin; 180 anchimetamorphic samples from the Glarus Alps, 65 epimetamorphic samples from the eastern Urseren Zone between the Aar- and Gotthard Massifs, and about 100 epi- to mesometamorphic samples from the Lukmanierpass region. Marly rocks are predominant over pelitic rocks at all grades except in the epimetamorphic Urseren Zone.

The main mineralogical differences going from unmetamorphic to anchimetamorphic rocks are: expandable clay-minerals disappear, an Al-rich chlorite appears, and the illite becomes impoverished in Fe and Mg. From this it is concluded that the Al-rich chlorite and illite formed from the mixed-layer illite/montmorillonite. Whether a mixed-layer illite/chlorite/montmorillonite or illite/chlorite was involved in the formation of the chlorite as suggested by WEAVER and BECK (1971) is not known because of the absence of outcrops

[4]) The terminology used in this paper is as follows: unmetamorphic rocks (illite crystallinity > 7.5); anchimetamorphic rocks (illite crystallinity 7.5–4.0); epimetamorphic rocks (illite crystallinity < 4.0, $\approx$ greenschist facies); mesometamorphic rocks ($\approx$ amphibolite facies, beginning with the first appearance of staurolite). These terms are used in a descriptive sense and do not imply that the essential controlling factor is depth (GRUBENMANN, 1904).

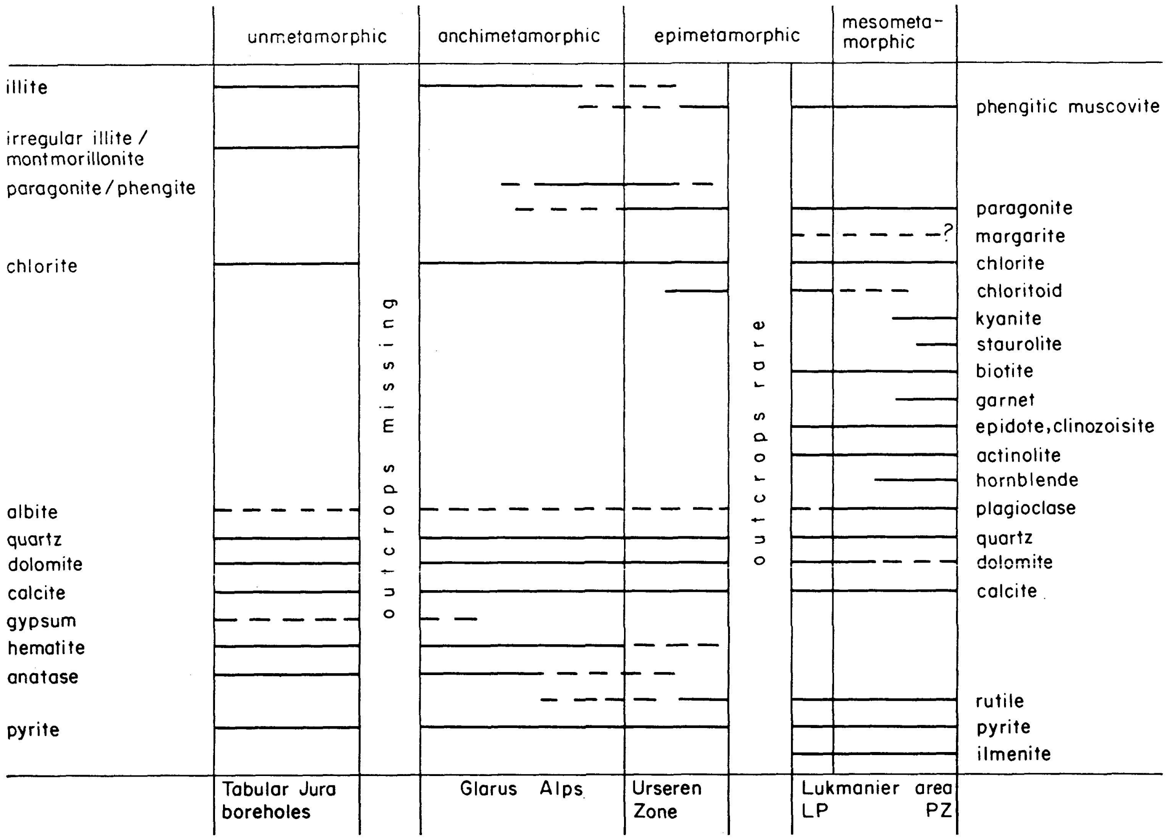

Fig. 2. Distribution of some important minerals of the Upper Triassic red-bed formation. Solid line = mineral is a major phase; dashed line = mineral is a minor phase; ? = distribution not clearly defined due to insufficient data. LP = Lukmanierpass; PZ = Piora Zone.

between the unmetamorphic clay- and marlstones below the Molasse Basin and the anchi-metamorphic shales in the Glarus Alps. The mixed-layer paragonite/phengite (Frey, 1969b) and paragonite are too scarce to obtain an insight into their formation.

In the epimetamorphic phyllites triclinic chloritoid appears. At the same time there is a color change in the rocks from purple to green, probably due to the consumption of hematite in the chloritoid-forming reaction: Al-rich chlorite + Ti-bearing hematite = chloritoid + ripidolite + rutile + $H_2O + O_2$. The iron reduction was probably caused by fluids originating in the adjacent Liassic black-shale formation (H. P. Eugster, personal communication 1969).

On the Lukmanierpass biotite is common in both pelitic and marly Quartenschiefer. However, scarcity of outcrops between Urseren Zone and Lukmanierpass (lying on the eastern border of the Gotthard Massif) prevent any conclusion regarding the formation of biotite. Almandine-rich garnet appears late in the sequence and again its formation is obscure. Armoured relicts of chloritoid in garnets document the prograde character of this metamorphism. The plagioclase directly north of the Lukmanierpass is albite, while oligoclase-andesine is found in the mesometamorphic metasediments south of the pass.

A detailed study regarding the peristerite gap in these rocks has not been done. Kyanite is abundant in the Piora Zone (Fig. 2) and occurs in Quartenschiefer rocks of a wide chemical composition, coexisting with many different phases; especially noteworthy is the coexistence of kyanite with hornblende (see below). Since pyrophyllite is absent from the epimetamorphic Urseren Zone and was found in only 4 samples out of 180 anchimetamorphic slates, kyanite was presumably not formed by a reaction involving pyrophyllite. Instead the following kyanite-producing reaction was proposed (FREY, 1969a, p. 117): Muscovite + chlorite + quartz = kyanite + biotite + H_2O. However, this reaction does not apply to the formation of kyanite in biotite-free chloritoid schists, outcropping e. g. in the Val di Campo east of Lukmanierpass.

The formation of actinolite and hornblende will now be discussed in some detail. On the Lukmanierpass the main rock-type in the Quartenschiefer consists of thin alternating layers (mostly in the cm range) of yellow-weathering dolomite and green chlorite schists; the latter sometimes biotite-bearing. At Camperio, at the eastern end of the Piora Zone, the dominating rock type is made up of alternating amphibole-rich and biotite-rich layers, respectively. Field relationships indicate that the rocks from both outcrops were originally the same. If this is true it can be concluded that (a) dolomite was involved in the formation of amphibole and (b) therefore a great loss of CO_2 must have occurred at the beginning of the mesozone.

The Hornblendegarbenschiefer is one of the famous rock types in the Quartenschiefer of the Piora Zone. The hornblende has the highest Al-content reported in the literature so far (LEAKE, 1971), and ANGEL (1967, p. 310) proposed the name "Gotthardit" for this amphibole. This hornblende coexists with staurolite and kyanite (KRIGE, 1918; BOSSARD, 1929; FREY, 1969a). A possible low-grade equivalent of this assemblage has been recently found in Val Campo by FOX (personal communication, 1972) in chloritoid-hornblende-bearing Quartenschiefer. It is striking that the Hornblendegarbenschiefer with its big porphyroblasts are geographically restricted to a relatively narrow zone south of the Gotthard Massif. This may be due to chemical control but could be also caused by a large production of a fluid phase at this particular metamorphic grade due to the consumption of dolomite in the marly Quartenschiefer (see above) as suggested by NIGGLI (1973, p. 238).

LOWER LIASSIC

Preliminary results on the progressive metamorphism of this black-shale formation were given by FREY (1970, 1972), FREY and NIGGLI (1972) and FREY and ORVILLE (1974). Further results can be obtained from local studies by NIGGLI (1912), JUNG (1963), J. D. FREY (1967), LISZKAY (1965), and HAN-

SEN (1972). Only a summary is given here. Detailed results will be published elsewhere.

The traverse chosen for the Lower Liassic is essentially identical with that of the Upper Triassic (Fig. 1). This allows direct comparison of the progressive metamorphism of the two formations with different original material. Some additional samples from the western end of the Gotthard Massif were studied from the collections of LISZKAY (1965) and HANSEN (1972). The Lower Liassic is a black-shale formation made up originally of clays, marls, sandstones and arenaceous limestones. The mean thickness varies considerably from 20 to 200 m. The lithology of these marine, near-shore deposits is very similar in all areas studied. Concerning the question whether the formation can be regarded as isochemical, composite analyses from sections at different metamorphic grade were made. It can be said that the mean rock composition is similar in all areas although the variation in a single outcrop may be large.

A summary of the distribution of some important minerals is presented in Fig. 3. Assemblages in pelitic and marly rocks are treated separately. The data are based on 34 unmetamorphic samples from the Tabular Jura and three boreholes below the Molasse Basin; 120 anchimetamorphic shales and slates from the Glarus Alps; 85 epimetamorphic phyllites from the eastern Urseren Zone; and 115 epi- and mesometamorphic samples from the southern border of the Gotthard Massif.

Pelitic Liassic (Fig. 3a)

The unmetamorphosed Liassic differs from the unmetamorphosed Keuper in the following respects: kaolinite is a typical clay mineral, organic material is always present but hematite is missing. The latter phenomena allows one to distinguish in the field easily between the Liassic black-shales and the Keuper red-beds.

In the anchimetamorphic Liassic kaolinite is absent but pyrophyllite is present in almost 50% of the samples studied. Evidentally pyrophyllite was formed by the well-known reaction: 1 kaolinite + 2 quartz = 1 pyrophyllite + 1 H_2O. No irregular mixed-layer illite/montmorillonite could be found in the Glarus Alps; however, traces of rectorite (= regular mixed-layer paragonite/montmorillonite) are present at the beginning of the anchizone. A second, non-expandable mixed-layer phase paragonite/muscovite (FREY, 1969b) is very abundant in the anchimetamorphic shales and slates; it occurs in about 90% of the samples studied. These two mixed-layer phases may be regarded as precursors of paragonite, which is present in almost 50% of the anchimetamorphic samples studied. In addition, all samples contain illite to muscovite and chlorite. According to the (060) d-spacing, the illite to muscovite must be almost free of Fe and Mg. Since illite and irregular mixed-layer

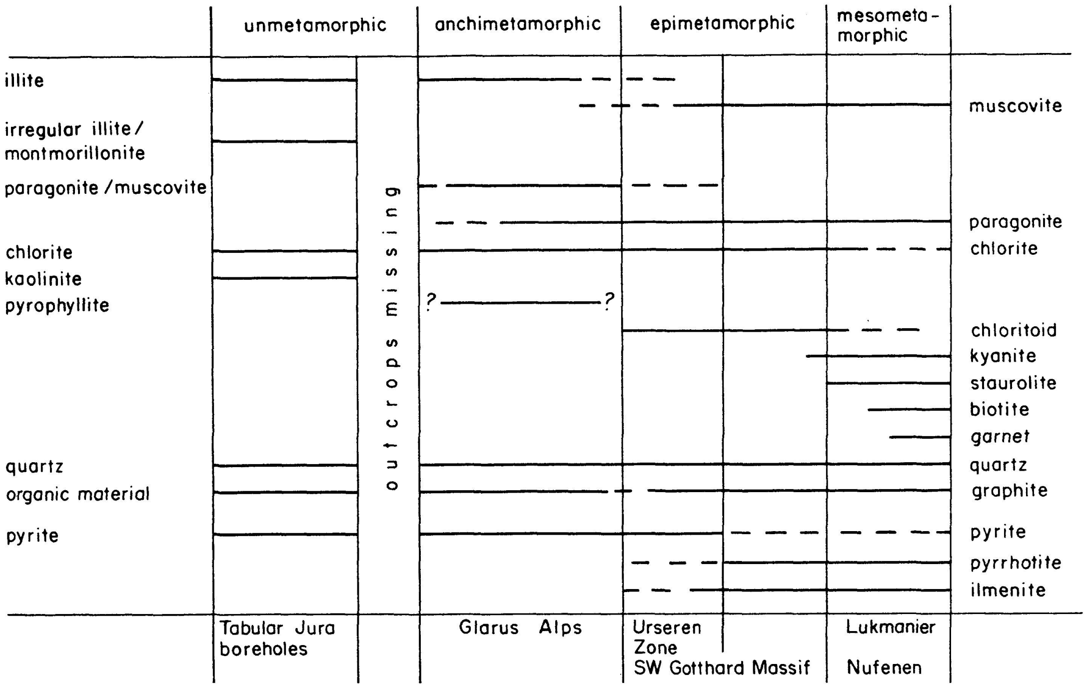

Fig. 3a. Distribution of some important minerals of the *pelitic* Lower Liassic black-shale formation. Solid line = mineral is a major phase; dashed line = mineral is a minor phase; ? = distribution not clearly defined due to insufficient data.

illite/montmorillonite in the unmetamorphosed clays contain appreciable amounts of Fe and Mg, most of these elements must now be incorporated in chlorite, the only major Fe- and Mg-bearing phase in the anchizone.

In the epimetamorphic phyllites triclinic chloritoid appears by the reaction pyrophyllite + chlorite = chloritoid + quartz + H_2O. Although chloritoid forms within the stability field of pyrophyllite, this latter phase does not occur in the epizone here. This must be due to the relatively low Al-content of the host-rocks, since the assemblage chloritoid-pyrophyllite is common in high-alumina rocks of Devonian age studied by Sagon (1970).

The higher-grade pelitic rocks were studied in great detail in the Lukmanier region by Fox (work in progress, personal communications 1972–1973). Kyanite appears already in the epizone in assemblages containing chlorite-monoclinic chloritoid (here and in the following muscovite and quartz are always additional phases; paragonite and even margarite may also be present). At slightly higher grade staurolite enters the assemblage mentioned above, then biotite, and finally garnet. Four- and five-phase assemblages on a AFM-plot (Thompson, 1957) are common. Two of such assemblages in the Liassic were described earlier as belonging to the Quartenschiefer formation (Frey, 1969a, samples MF 160 and 161). Such low-variance assemblages could be explained either by buffering of the fluid phase (e. g. Guidotti, 1970) or by mosaic equilibrium (e. g. Osberg, 1971). In the light of detailed microprobe work carried out by Fox the latter seems more likely.

Marly Liassic (Fig. 3b)

All phases from the unmetamorphosed and anchimetamorphosed pelitic Liassic are also present in marly assemblages containing either dolomite and/or calcite. In this respect particularly interesting are the coexistence of pyrophyllite and paragonite with both calcite and, less commonly, dolomite. These assemblages were believed to be incompatible by Chatterjee (1971); see also discussion in Chiesa et al. (1972).

In the epimetamorphic phyllites margarite appears as an additional phase in marly assemblages. Comparison with assemblages from the anchizone mentioned above seems to indicate that the first margarite was formed by the following simplified reaction: 2 pyrophyllite + 1 calcite = 1 margarite + 6 quartz + 1 H_2O + 1 CO_2. However, since margarite shows considerable solid solution with paragonite already at low-grade (Jones, 1971; Ackermand and Morteani, 1973; Höck, 1974), paragonite may be present on the left hand side of this reaction. In addition, the coexistence of pyrophyllite with dolomite in the anchizone would suggest that some margarite was also formed by a reaction involving pyrophyllite and dolomite. Both margarite and chloritoid

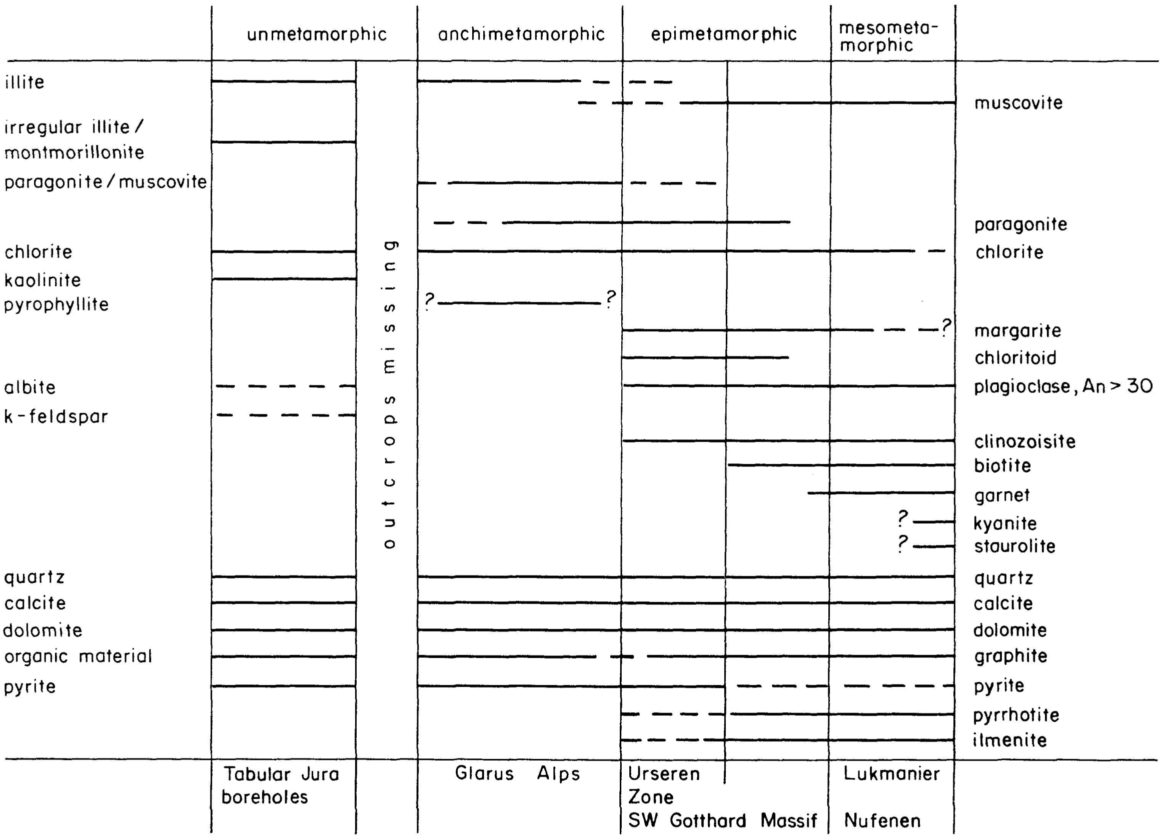

Fig. 3b. Distribution of some important minerals of the *marly* Lower Liassic black-shale formation. Solid line = mineral is a major phase; dashed line = mineral is a minor phase; ? = distribution not clearly defined due to insufficient data.

are found in assemblages together with dolomite and/or calcite. Outcrops are not continuous enough to work out the exact position of both the margarite and the chloritoid isograd. Clinozoisite and plagioclase are absent in the marly Liassic of the eastern Urseren Zone, which is probably due to chemical control. On the other hand these phases appear already at the beginning of the epizone at the southwestern end of the Gotthard Massif. The reactions producing clinozoisite are not yet known; chemographic analyses suggest that clinozoisite may appear by reactions involving margarite and carbonate minerals (at relatively high X_{CO_2}) and paragonite and carbonate minerals (at relatively low X_{CO_2}), see FREY and ORVILLE, 1974, Fig. 6. The appearance of plagioclase in the marly Liassic deserves special attention. So far, only plagioclase in margarite-bearing assemblages were studied (FREY and ORVILLE, 1974). The first-appearing plagioclase in the lower-grade epizone is not albite as expected but oligoclase-andesine. It was probably formed by reactions between paragonite and margarite on one hand and calcite and dolomite on the other hand. Depending on which other minerals are present in the rock (that is the *complete* mineral assemblage), the An-content of the plagioclase may remain constant or increase with increasing grade.

The next phase entering in the progressive sequence is biotite. Note that biotite appears much earlier in the marly Liassic than in the pelitic assemblages of the same formation. The same holds true for garnet, which is relatively rich in grossularite component ($^1/_3$ grossularite, $^2/_3$ almandine)[5]).

In the highest-grade epizone both paragonite and chloritoid seem to be no longer stable in marly rocks (Fig. 3b). Their breakdown reactions, however, are not yet understood. Margarite, on the other hand, is stable up to the highest grade reached in this progressive sequence (that is lower-grade mesozone). Margarite seems to coexist there with both staurolite and kyanite.

BÜNDNERSCHIEFER

Although the Bündnerschiefer represent volumetrically the most important metasediment of the Central Alps, their mineralogical composition is not as well known as those of the Quartenschiefer and Lower Liassic; this is particularly true for the low-grade (anchi- and epimetamorphic) Bündnerschiefer. The metamorphism of the higher-grade (meso- and ? katametamorphic) Bündnerschiefer have been become well-known through the regional study of the coexisting mineral pair calcite-plagioclase of WENK (1962). Furthermore TROMMSDORFF (1966) reported on the regional distribution of scapolite and

[5]) It may be mentioned that garnet with the composition $^1/_3$ spessartine, $^1/_3$ grossularite, $^1/_3$ almandine appears at much lower grade in rocks of granitic composition (STECK, 1966; STECK and BURRI, 1971).

Orville (1970, personal communications 1970–1973) and Orville and Johannes (1972) are presently undertaking a survey study on the marly Bündnerschiefer of the Central Alps (see discussion below). In addition, a great number of local studies report on the mineralogical composition of the Bündnerschiefer (for references see p. 501). However, complete assemblages are only rarely listed and mineral reactions going on are almost completely unknown.

The location of the traverse discussed in this study was mainly dictated by the scarce information available on low-grade Bündnerschiefer (Thum and Nabholz, 1972; Kupferschmid, 1971 and personal communications 1972 to 1973).

Bündnerschiefer is the usual Mesozoic rock of the eugeosynclinal trough of the north-Penninic realm in the Swiss Alps. Main rock types comprised originally calcareous shales, silty limestones and sandstones. That is lithology is similar as in the Lower Liassic formation but generally Bündnerschiefer are richer in carbonates and poorer in organic material or graphite. The stratigraphy of the Bündnerschiefer is ill defined, working in Bündnerschiefer is "like trying to solve one equation with two variables, stratigraphy and structure" (W. Leupold, orally; in Trümpy, 1960, p. 860). Primary thickness of the Bündnerschiefer may have reached several kilometres. In the upper part, flysch characteristics appear (Pre-Flysch of Trümpy, 1960). Sedimentary age may range from Liassic to Eocene.

A provisional summary of the distribution of some important minerals is presented in Fig. 4. The data are based on the following publications. Anchi-

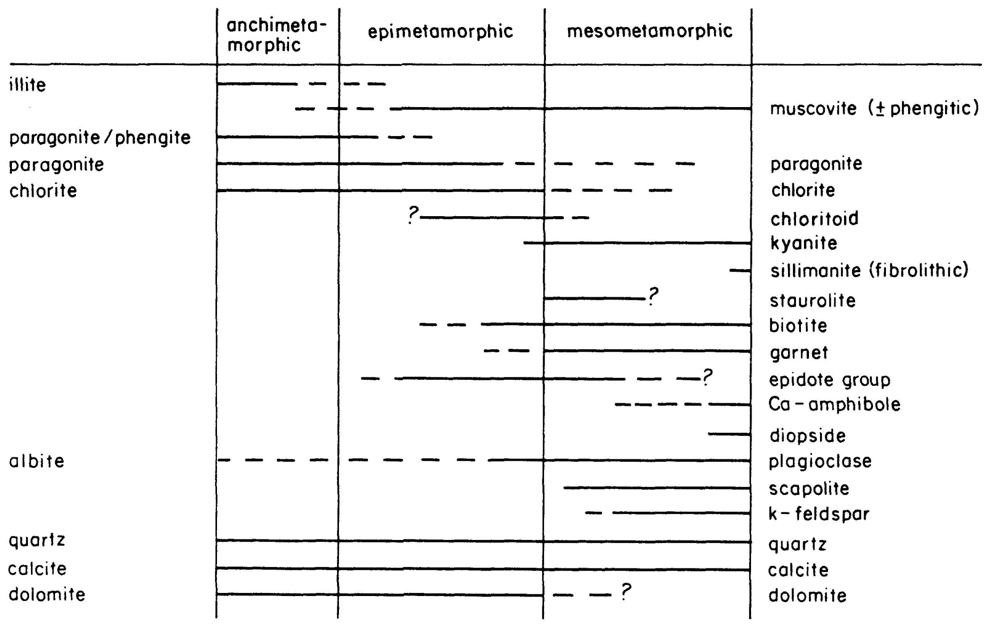

Fig. 4. Distribution of some important minerals of the Bündnerschiefer. Solid line = mineral is a major phase; dashed line = mineral is a minor phase; ? = distribution not clearly defined due to insufficient data.

zone: THUM and NABHOLZ (1972); epizone: GANSSER (1937), VAN DER PLAS (1959), LÜTHI (1965), KUPFERSCHMID (1971, and personal communication 1973); epi- to mesozone: BADER (1934), CHATTERJEE (1961), EGLI (1966); mesozone: BOSSARD (1929), GRÜTTER (1929), MITTELHOLZER (1936), NIGGLI et al. (1936), BURCKHARDT (1942), HASLER (1949), BUCHMANN (1953), GÜNTHERT (1954), BRUGGMANN (1965), HUNZIKER (1966), WIELAND (1966), ORVILLE (1970), BIANCONI (1971), HANSEN (1972). It must be pointed out that although the progressive sequence presented in Fig. 4 is exclusively based on Bündnerschiefer-type metasediments, these rocks enclose a great time span and were laid down in different basins. Heterogeneity, therefore, is even more pronounced than in the Quartenschiefer or the Lower Liassic formation.

Some lowest-grade Bündnerschiefer were recently investigated by THUM and NABHOLZ (1972). These anchi- to epimetamorphic slates show the unique sheet silicate assemblage of illite, chlorite, mixed-layer paragonite/phengite and paragonite; albite is rare. Since the same sheet silicates were also found in similar anchimetamorphic rocks in the above-lying Prättigau Flysch and are known to be stable from almost the beginning of the anchizone (Fig. 2 and 3), the stability ranges of the above mentioned minerals were extended down in Fig. 4 to the anchizone.

In epimetamorphic Bündnerschiefer, chloritoid occurs both in pelitic and marly rocks (GANSSER, 1937; KUPFERSCHMID, 1971), but it seems not to be a common mineral (CHATTERJEE, 1961; LÜTHI, 1965). The assemblage chloritoid-garnet reported from calciferous micaschists (VAN DER PLAS, 1959, p. 519; GANSSER, 1937, p. 387) may belong to the early Alpine metamorphic event. Although albite (some of which may be of detrital origin) is widespread in the lower-grade epizone, the main Na-bearing phase seems to be paragonite. The assemblage paragonite-calcite is common, but also paragonite-dolomite seems to be a stable assemblage (KUPFERSCHMID, 1971; LIBORIO et al., 1971; CHIESA et al., 1972). The breakdown of these assemblages has not yet been studied in the Bündnerschiefer, but it will probably take place in the higher-grade epizone in analogy with the Lower Liassic formation (Fig. 3b). This means that a lot of the plagioclase at this grade was formed through a reaction involving paragonite. Whether or not margarite plays a significant role in the Bündnerschiefer cannot be determined in view of the scarce X-ray data available at present. It should be mentioned that margarite has been found so far at only three localities (Simplon, Val Formazza, Valle Mesolcina).

WENK (1962) and SCHWANDER and WENK (1967) studied the assemblage plagioclase-calcite in the mesometamorphic Bündnerschiefer of the Central Alps in great detail. "The anorthite content of plagioclase associated with calcite is almost uniform in a given region but varies from area to area depending on the grade of metamorphism. In general, the higher the anorthite-content in this paragenesis, the higher the temperature attained within the same rock series during alpine metamorphism" (Wenk, 1962, p. 139). Although this picture may be statistically true, there are many exceptions as even mentioned by Wenk (1962, p. 149). A critical evaluation of Wenk's plate 1 (1962) shows, that in general the number of exceptions increase with increasing anorthite content. In the area of highest anorthite content, An 70–An 100, 37 out of 69 or 54% of the samples show an anorthite content less than An 70 and are therefore exceptions. For this reason it does not seem justified to use the term isograd for these at best metamorphic zone boundaries, and students should be warned of an oversimplificated representation of these boundaries by thick lines termed "isograds" in a modern textbook (Turner, 1968, Fig. 7–29). However, in the light of the work done by Crawford (1966) and Cooper (1972) there is definite hope that the peristerite gap in margarite-free Bündnerschiefer may serve as an isograd (see also Bearth, 1958; Wenk and Streckeisen, in press) in the highest-grade epizone.

Orville (1970, and personal communications 1970–1973) and Orville and Johannes (1972) have taken up again the work on plagioclases in carbonate-bearing mesometamorphic Bündnerschiefer. They approximated the complicated metasediments by a seven-component system (K_2O-Na_2O-CaO-Al_2O_3-SiO_2-H_2O-CO_2) including the seven phases plagioclase, calcite, quartz, muscovite, K-feldspar, zoisite, and vapor. This seems to be a reasonable approximation although clinozoisite is present instead of zoisite and F and Cl may also have been present in the fluid phase. Newly formed K-feldspar may be present in marly Bündnerschiefer beyond the tremolite isograd and is an important phase beyond the diopside isograd. (These isograds are based on mineral assemblages in Triassic marbles associated with Bündnerschiefer (Trommsdorff, 1966).) All possible plagioclase-producing reactions in the above mentioned system are not only dependent on temperature and pressure, but also sensitive to the composition of the fluid phase (X_{CO_2} in a H_2O-CO_2 fluid). It can be shown then that theoretically the composition of plagioclase can only be used as an indicator of temperature and pressure in the "divariant" assemblage containing all the seven phases mentioned earlier. This is another example which shows the importance of considering the *complete* assemblage of metamorphic rocks (see also p. 499). The "divariant" assemblage mentioned above is common in mesometamorphic Bündnerschiefer. However, preliminary microprobe work carried out by the author on plagioclases from this divariant assemblage coming from a single outcrop at Lago Tremorgio show a very complicated picture. The An-content of plagioclase shows irregular variation from oligoclase to almost pure anorthite not only within a single thin section, but also within a single plagioclase grain. Whether this observation means that equilibrium was not attained, or that gradients in the fluid composition occurred or that no fluid was present remains to be answered.

Conclusion

Pelitic and marly metasediments represent complicated rock systems. Most so-called isograds in these rocks from the Central Alps represent at best metamorphic mineral zone boundaries. Much more detailed petrographic work is needed to decide whether these zone boundaries are isograds or not. The next step would be to work out the three dimensional course of these isograds. The Alps with its high relief seem to be a favourable place for this attempt. It might then be possible to decide how the regional metamorphism in the Central Alps was generated.

Acknowledgements

I would like to express my sincere thanks to J. S. Fox, C. Kupferschmid, and P. M. Orville for making available their unpublished results. The writer is grateful to Peter H. Thompson for stimulating discussions and correcting the English. This paper benefited from the following reviewers: N. D. Chatterjee, J. S. Fox, E. Niggli, P. M. Orville, P. H. Thompson, and V. Trommsdorff. To all these friends my sincere thanks. This work was partly supported by a grant from the "Schweizerischer Nationalfonds" (No. 5358.2).

References

SMPM = Schweiz. Mineralogische und Petrographische Mitteilungen

Ackermand, D. and Morteani, G. (1973): Occurrence and Breakdown of Paragonite and Margarite in the Greiner Schiefer Series (Zillerthal Alps, Tyrol). Contr. Mineral. Petrol. 40, 293–304.

Angel, F. (1967): Über Mineralzonen, Tiefenzonen und Mineralfazies. Rückblicke und Ausblicke. Fortschr. Mineral. 44, 288–336.

Bader, H. (1934): Beitrag zur Kenntnis der Gesteine und Minerallagerstätten des Binnentals. SMPM 14, 319–441.

Bearth, P. (1958): Über einen Wechsel der Mineralfazies in der Wurzelzone des Penninikums. SMPM 38, 363–373.

— (1967): Die Ophiolithe der Zone von Zermatt-Saas Fee. Beitr. geol. Karte Schweiz, N.F. 132.

Bianconi, F. (1971): Geologia e petrografia della regione del Campolungo. Beitr. geol. Karte Schweiz, N.F. 142.

Bossard, L. (1929): Petrographie der mesozoischen Gesteine im Gebiete der Tessiner Kulmination. SMPM 9, 107–159.

Bruggmann, H. O. (1965): Geologie und Petrographie des südlichen Misox (Val Grono, Val Leggia, Val Cama). Diss. Univ. Zürich.

Buchmann, H. (1953): Geologie und Petrographie des oberen Maggia-Tales zwischen Fusio und Broglio im NW-Tessin. Diss. Univ. Basel.

Burckhardt, C. E. (1942): Geologie und Petrographie des Basodino-Gebietes (nordwestliches Tessin). SMPM 22, 99–188.

Carmichael, D. M. (1969): On the Mechanism of Pragrade Metamorphic Reactions in Quartz-Bearing Pelitic Rocks. Contr. Mineral. Petrol. 20, 244–267.

— (1970): Intersecting Isograds in the Whetstone Lake Area, Ontario. J. Petrol. 11, 147–181.

Chatterjee, N. D. (1961): The alpine metamorphism in the Simplon area, Switzerland and Italy. Geol. Rdsch. 51, 1–72.

— (1971): Phase Equilibria in the Alpine Metamorphic Rocks of the Environs of the Dora-Maira Massif, Western Italian Alps. N. Jb. Mineral., Abh. 114, 181–245.

Chiesa, S., Liborio, G., Mottana, A. e Pasquaré, G. (1972): La paragonite nei calcescisti delle Alpi: Distribuzione e interpretazione geo-petrologica. Mem. Soc. Geol. Italiana 11, 1–30.

Cooper, A. F. (1972): Progressive Metamorphism of Metabasic Rocks from the Haast Schist Group of Southern New Zealand. J. Petrol. 13, 457–492.

Crawford, M. L. (1966): Composition of Plagioclase and Associated Minerals in Some Schists from Vermont, U.S.A., and South Westland, New Zealand, with Inferences about the Peristerite Solvus. Contr. Mineral. Petrol. 13, 269–294.

Dal Piaz, G. V., Hunziker, J. C. e Martinotti, G. (1972): La zona Sesia-Lanzo e l'evoluzione tettonico-metamorfica delle Alpi nordoccidentali interne. Mem. Soc. Geol. Italiana 11, 433–460.

Egli, W. (1966): Geologisch-petrographische Untersuchungen in der NW-Aduladecke und in der Sojaschuppe (Bleniotal, Kanton Tessin). Diss. ETH Zürich.

Ernst, W. G. (1973): Interpretative Synthesis of Metamorphism in the Alps. Bull. geol. Soc. Amer. 84, 2053–2078.

Evans, B. W. and Trommsdorff, V. (1970): Regional Metamorphism of Ultramafic Rocks in the Central Alps: Parageneses in the System CaO-MgO-SiO_2-H_2O. SMPM 50, 481–492.

Frey, M. (1969a): Die Metamorphose des Keupers vom Tafeljura bis zum Lukmanier-Gebiet (Veränderungen tonig-mergeliger Gesteine vom Bereich der Diagenese bis zur Staurolith-Zone). Beitr. geol. Karte Schweiz, N.F. 137.

— (1969b): A Mixed-Layer Paragonite/Phengite of Low-Grade Metamorphic Origin. Contr. Mineral. Petrol. 24, 63–65.

— (1970): The Step from Diagenesis to Metamorphism in Pelitic Rocks during Alpine Orogenesis. Sedimentology 15, 261–279.

— (1972): Progressive low-grade metamorphism of a black-shale formation, Central Swiss Alps. Annual Meeting Geol. Soc. Amer. Minneapolis, p. 512 (Abstract).

Frey, M. and Niggli, E. (1972): Margarite, an Important Rock-forming Mineral in Regionally Metamorphosed Low-grade Rocks. Naturwiss. 59, 214–215.

Frey, M. and Orville, P. M. (1974): Plagioclase in margarite-bearing rocks. Amer. J. Sci. 274, 31–47.

Frey, J. D. (1967): Geologie des Greinagebietes (Val Camadra-Valle Cavalasca-Val di Larciolo-Passo della Greina). Beitr. geol. Karte Schweiz, N.F. 131.

Fyfe, W. S. and Turner, F. J. (1958): Correlation of Metamorphic Facies with Experimental Data; in W. S. Fyfe, F. J. Turner and J. Verhoogen: Metamorphic Reactions and Metamorphic Facies. Geol. Soc. Amer. Memoir 73, 149–185.

Gansser, A. (1937): Der Nordrand der Tambodecke. SMPM 17, 291–523.

Grubenmann, U. (1904): Die kristallinen Schiefer. Bornträger, Berlin.

Grütter, O. (1929): Petrographische und geologische Untersuchungen in der Region von Bosco (Valle Maggia), Tessin. Verh. Natf. Ges. Basel 40, 78–152.

Guidotti, C. V. (1970): The Mineralogy and Petrology of the Transition from the Lower to Upper Sillimanite Zone in the Oquossoc Area, Maine. J. Petrol. 11, 277–336.

Günthert, A. (1954): Beiträge zur Petrographie und Geologie des Maggia-Lappens (NW-Tessin). SMPM 34, 1–159.

HANSEN, J. W. (1972): Zur Geologie, Petrographie und Geochemie der Bündnerschiefer-Serien zwischen Nufenenpass (Schweiz) und Cascata Toce (Italia). SMPM 52, 109–153.

HASLER, P. (1949): Geologie und Petrographie der Sambuco-Massari-Gebirgsgruppe zwischen der oberen Valle Leventina und Valle Maggia im nordöstlichen Tessin. SMPM 29, 50–155.

HÖCK, V. (1974): Coexisting Phengite, Paragonite and Margarite in Metasediments of the Mittlere Hohe Tauern, Austria. Contr. Mineral. Petrol. 43, 261–273.

HUNZIKER, J. C. (1966): Zur Geologie und Geochemie des Gebietes zwischen Valle Antigorio (Provincia di Novara) und Valle di Campo (Kt. Tessin). SMPM 46, 473–552.

— (1973): Rb-Sr- and K-Ar-Age Determinations and the Alpine Tectonic History of the Western Alps. Habil.schrift Bern.

JÄGER, E. (1973): Die alpine Orogenese im Lichte der radiometrischen Altersbestimmung. Eclogae geol. Helv. 66, 11–21.

JONES, J. W. (1971): Zoned Margarite from the Badshot Formation (Cambrian) near Kaslo, British Columbia. Canadian J. Earth Sci. 8, 1145–1147.

JUNG, W. (1963): Die mesozoischen Sedimente am Südostrand des Gotthard-Massivs (zwischen Plaun la Greina und Versam). Eclogae geol. Helv. 56, 653–754.

KELLER, F. (1968): Mineralparagenesen und Geologie der Campo Tencia-Pizzo Forno-Gebirgsgruppe. Beitr. geol. Karte Schweiz, N.F. 135.

KRIGE, L. J. (1918): Petrographische Untersuchungen im Val Piora und Umgebung. Eclogae geol. Helv. 14, 519–654.

KUPFERSCHMID, C. (1971): Geologie auf der Lugnezer Seite der Piz Aul-Gruppe. Lizentiatsarbeit Univ. Bern (unveröffentlicht).

LEAKE, B. E. (1971): On aluminous and edenitic hornblendes. Min. Mag. 38, 389–407.

LIBORIO, G., MOTTANA, A. e PASQUARÉ, G. (1971): Distribution of Paragonite in the Mesozoic Calcschists of the Alps. Nature Phys. Sci. 231, 39–40.

LISZKAY, M. (1965): Geologie der Sedimentbedeckung des südwestlichen Gotthard-Massivs im Oberwallis. Eclogae geol. Helv. 58, 901–965.

LÜTHI, H.-J. (1965): Geologie der gotthardmassivischen Sedimentbedeckung und der penninischen Bündnerschiefer im Blinnental, Rappental und Binntal (Oberwallis). Diss. Univ. Bern.

MITTELHOLZER, A. E. (1936): Beitrag zur Kenntnis der Metamorphose in der Tessiner Wurzelzone mit besonderer Berücksichtigung des Castionezuges. SMPM 16, 19–182.

NIGGLI, E. (1960): Mineralzonen der alpinen Metamorphose in den Schweizer Alpen. Int. Geol. Congr. Copenhagen, Rept. 21st Session Norden 13, 132–138.

— (1970): Alpine Metamorphose und alpine Gebirgsbildung. Fortschr. Mineral. 47, 16–26.

— (1973): in: Stalder, H. A., de Quervain, F., Niggli, E. und Graeser, St.: Die Mineralfunde der Schweiz. Wepf, Basel.

NIGGLI, E. und NIGGLI, C. R. (1965): Karten der Verbreitung einiger Mineralien der alpidischen Metamorphose in den Schweizer Alpen (Stilpnomelan, Alkali-Amphibol, Chloritoid, Staurolith, Disthen, Sillimanit). Eclogae geol. Helv. 58, 335–368.

NIGGLI, P. (1912): Die Chloritoidschiefer und die sedimentäre Zone am Nordostrande des Gotthardmassivs. Beitr. geol. Karte Schweiz, N.F. 36.

NIGGLI, P., PREISWERK, H., GRÜTTER, O., BOSSARD, L. und KÜNDIG, E. (1936): Geologische Beschreibung der Tessineralpen zwischen Maggia- und Bleniotal. Beitr. geol. Karte Schweiz, N.F. 71.

ORVILLE, P. M. (1970): The An-content of plagioclase as an Indicator of Metamorphic grade and of Fluid composition in the system K_2O-Na_2O-CaO-Al_2O_3-SiO_2-H_2O-CO_2. Unpublished manuscript.

ORVILLE, P. M. and JOHANNES, W. (1972): The Composition of Plagioclase as an Indicator of Metamorphic Grade and Fluid Composition in Carbonate-Bearing Pelitic Rocks. 24 th Int. Geol. Congr. Montreal, Section 2, p. 3 (Abstract).

OSBERG, P. H. (1971): An equilibrium model for Buchan-type metamorphic rocks, south-central Maine. Amer. Mineralogist 56, 570–586.

PLAS, L. VAN DER (1959): Petrology of the northern Adula Region, Switzerland. Leidse geol. Meded. 24, 415–598.

ROEVER, W. P. DE and NIJHUIS, H. J. (1964): Plurifacial alpine metamorphism in the eastern Betic Cordilleras (SE Spain), with special reference to the genesis of the glaucophane. Geol. Rdsch. 53, 324–336.

SAGON, J.-P. (1970): Minéralogie des schistes paléozoïques du Bassin de Châteaulin (Massif armoricain): distribution de quelques minéraux phylliteux de métamorphisme. C.R. Acad. Sci. Paris 270, Série D, 1853–1856.

SCHWANDER, H. und WENK, E. (1967): Studien mit der Röntgen-Mikrosonde an basischen Plagioklasen alpiner Metamorphite. SMPM 47, 225–234.

STECK, A. (1966): Petrographische und tektonische Untersuchungen am Zentralen Aaregranit und seinen altkristallinen Hüllgesteinen im westlichen Aarmassiv im Gebiet Belalp-Grisighorn. Beitr. geol. Karte Schweiz, N.F. 130.

STECK, A. und BURRI, G. (1971): Chemismus und Paragenesen von Granaten aus Granitgneisen der Grünschiefer- und Amphibolitfazies der Zentralalpen. SMPM 51, 534–538.

STRECKEISEN, A. and WENK, E. (in press): On steep isogradic surfaces in the Simplon area. Contr. Mineral. Petrol.

THOMPSON, J. B. (1957): The graphical analysis of mineral assemblages in pelitic schists. Amer. Mineralogist 42, 842–858.

THUM, I. und NABHOLZ, W. (1972): Zur Sedimentologie und Metamorphose der penninischen Flysch- und Schieferabfolgen im Gebiet Prättigau-Lenzerheide-Oberhalbstein. Beitr. geol. Karte Schweiz, N.F. 144.

TILLEY, C. E. (1924): The Facies Classification of Metamorphic Rocks. Geol. Mag. 61, 167–171.

TROMMSDORFF, V. (1966): Progressive Metamorphose kieseliger Karbonatgesteine in den Zentralalpen zwischen Bernina und Simplon. SMPM 46, 431–460.

— (1972): Change in T-X during Metamorphism of Siliceous Dolomitic Rocks of the Central Alps. SMPM 52, 567–571.

TRÜMPY, R. (1960): Paleotectonic evolution of the Central and Western Alps. Bull. geol. Soc. Amer. 71, 843–908.

— (1973): L'évolution de l'orogénèse dans les Alpes Centrales: Interprétation des données stratigraphiques et tectoniques. Eclogae geol. Helv. 66, 1–10.

TURNER, F. J. (1968): Metamorphic petrology. Mineralogical and field aspects. McGraw-Hill, New York.

WEAVER, C. E. and BECK, K. C. (1971): Clay Water Diagenesis During Burial: How Mud Becomes Gneiss. Spec. Pap. geol. Soc. Amer. 134.

WENK, E. (1962): Plagioklas als Indexmineral in den Zentralalpen. SMPM 42, 139–152.

— (1970): Zur Regionalmetamorphose und Ultrametamorphose im Lepontin. Fortschr. Mineral. 47, 34–51.

WIELAND, H. (1966): Zur Geologie und Petrographie der Valle Isorno (Novara, Italia). SMPM 46, 189–303.

Manuscript received November 12, 1973.