A systematic nomenclature for metamorphic rocks:

5. VERY LOW- TO LOW-GRADE METAMORPHIC ROCKS

Recommendations by the IUGS Subcommission on the Systematics of Metamorphic Rocks**.** Web version of 1/3/2004

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INTRODUCTION

The Subcommission for the Systematics of Metamorphic Rocks (SCMR), aims to publish international recommendations on how metamorphic rocks and processes are to be defined and named, as was previously done for igneous rocks by the Subcommission on the Systematics of Igneous Rocks (Le Maitre et al., 1989).
The principles used by the SCMR for defining and classifying metamorphic rocks are outlined in Schmid et al. (2002).
A Study Group was set up in 1987 under the leadership of Péter Árkai to study the nomenclature and systematics of rocks and processes related to the so-called very low- to low-grade metamorphism, that is, from the diagenetic field to the greenschist facies or epizone. The Study Group consists of 30 scientists from 5 continents who are specialists in this area and who agreed to cooperate. This paper presents the definitions that were agreed, by repeated iterations, considering on one hand the various opinions within the Study Group (largely gathered through questionnaires), and by discussing these results within the SCMR, on the other. Being the result of multiple discussions and compromises, the definitions presented here are recommended for international use.

I. VERY LOW- AND LOW-GRADE METAMORPHISM

The SCMR agreed that for the purposes of its discussions and definitions the grade of metamorphism would be taken as equivalent to the temperature of metamorphism. The whole temperature/grade range of metamorphism has been divided into five parts, namely: very low, low, medium, high and very high (Smulikowski et al., 2004) The present paper deals with the nomenclature of the very low- and low-grade rocks. It also covers the transition from diagenesis to metamorphism and from very low-grade to low grade (the greenschist facies or epizone).

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II. FROM DIAGENESIS TO METAMORPHISM

1.*Diagenesis*

According to the SCMR (Smulikowski et al., 2004.), metamorphism is: '*a process involving changes in the mineral content/composition and/or microstructure of a rock, dominantly in the solid state. This process is mainly due to an adjustment of the rock to physical conditions that differ from those under which the rock originally formed and which also differ from the physical conditions normally occurring at the surface of the Earth and in zone of diagenesis. This process may coexist with partial melting and may also involve changes in the bulk chemical composition of the rock'.* Consistent with this definition, the term diagenesis covers the lowest temperature part of the changes in the outer part of the Earth's crust, excluding weathering.

Diagenesis (*sensu lato*): *All the chemical, mineralogical, physical and biological changes undergone by a sediment after its initial deposition, and during and after its lithification, exclusive of superficial alteration (weathering) and metamorphism.* The changes involved in diagenesis are the result of such processes as compaction, cementation, reworking, authigenesis, replacement, crystallization, leaching, hydration, dehydration, bacterial action, and formation of concretions. [Authigenesis is "the process by which new minerals form in place within an enclosing sediment or sedimentary rock during or after deposition" (from Bates and Jackson, 1987).] These processes occur under conditions of pressure and temperature that are normal at the Earth's surface and in the outer part of the Earth's crust.

Diagenesis (*sensu lato*) may be subdivided into:

- shallow diagenesis (=diagenesis *sensu stricto*): *the chemical, mineralogical, physical and biological changes that take place in a sediment under physical conditions that do not differ significantly from those under which the sediment originated. It is characterized by the absence of alteration of detrital minerals*.
- deep diagenesis: changes *that are characterized by clay mineral reactions (such as the transformation of smectite to illite, kaolinite to dickite, etc., and the increase of the proportion of illite layers in interstratified clay minerals).*

Instead of shallow and deep diagenesis the adjectives 'early' and 'late' are also used in the literature. However, in order to avoid the time connotation implied by these adjectives, the SCMR prefers the terms 'shallow' and 'deep'.

Deep diagenesis is the term recommended by the SCMR, as the equivalent to the three terms epigenesis, katagenesis and catagenesis of Russian authors, and middle + late or deep burial stage diagenesis of Müller (1967) and Dunoyer de Segonzac (1970).

2. Very low-grade metamorphism: the transition zone

The transition zone between diagenesis (*sensu lato*) and metamorphism, effectively the field of very low-grade metamorphism, is characterized by the gradual change of various features, which affect the rocks through this zone up to their partial or complete alteration into metamorphic rocks.

However, in the context of rock nomenclature, the main problem is that the most critical changes, marking this transition, are not visible with the naked eye because they commonly occur only on the microscopic or submicroscopic scale. Thus, the related nomenclature requires an important exception to the SCMR principle (Schmid et al., 2002), which states that, wherever possible, definitions are based on features that can be seen with the naked eye.

Indeed, on a mesoscopic scale these transitional rocks commonly display characteristics identical with, or very similar to, those of their non-metamorphic equivalents. Therefore, these very low-grade rocks can, in some cases, only be recognized by means of microscopic investigations and in most cases using other instrumental techniques. These include measurements of the illite Kübler index (formerly often called as ‘crystallinity’) and coalified organic matter order-disorder by means of X-ray powder diffraction, measurements of vitrinite reflectance by means of optical microscopy, fluid inclusion thermobarometry, etc.

Different criteria have been used for the characterization and subdivision of the transitional field between diagenesis and low-grade metamorphism in various rock types. Consequently, various systems and nomenclatures have been established (for example, specific mineral associations, illite Kübler index zones, microstructural zones, coal rank scales, etc.). See Figure 1 for a schematic comparison of these systems. Details and comprehensive interpretations can be found in the textbooks edited by Frey (1987a) and Frey and Robinson (1999), including the studies of Frey (1987b); Liou et al. (1987); Teichmüller (1987); Mullis (1987); Merriman and Peacor (1999); Merriman and Frey (1999), Robinson and Bevins (1999) and Alt (1999).

The temperature (and pressure) boundaries related to the sequence of stages or zones of each nomenclature scheme are not defined exactly, and in most cases they do not coincide with those of the other schemes. The correlation between the nomenclature schemes and absolute temperature is full of uncertainties, mostly because of the greatly differing nature of the disequilibrium processes considered, the transitional open- semi-closed systems, and in consequence, the great variations in the chemical effects of the fluids present.

Because the transition between diagenesis and metamorphism is gradual, any boundary between these two fields can only be arbitrarily defined. In practice, it is not possible to establish an isothermal boundary that can be applied to all, or even to the majority, of the rock types. Furthermore, rocks having different bulk composition, different grain-size, different amount of strain, different porosity and permeability, etc., may react at relatively higher or lower temperatures, so that, at a given depth or temperature a given rock may react whilst others may remain unchanged. Thus, the temperature of the beginning of metamorphism may vary considerably between rock types.

3. The problem of mixed sequences

The problem of different rock types, as discussed above, raises a related and important question. If the very-low grade character of a rock in a lithologically mixed sequence can be determined (for example, as the prehnite-pumpellyite facies (see below) in basic volcanic rocks): can that classification be extrapolated to other rock types in the sequence even though they do not display any measurable alteration in hand specimen (and, often, not even at the microscopic scale)? Alternatively, should different grade terms be used for the different rock types?

To put the question another way. Within the same rock pile, depending on the chemical, mineralogical and physical properties of the different rocks, some (for example, carbonate rocks) may show hardly any signs of alteration, whereas others that underwent the same T-P_l-P_f [1]conditions, are clearly recrystallized, and therefore must be classified as metamorphic rocks, and thus receive metamorphic rock names. In these cases, should the metamorphic name/grade be extrapolated to the unaltered rocks, or should they be given the most appropriate, non-metamorphic name, disregarding that of their surroundings?

In response to this very difficult question the SCMR recommends the following:

- those rocks which display at least one observable or measurable sign of very low-grade metamorphism (i.e. diagnostic minerals or mineral assemblages, appropriate values of illite Kübler index, appropriate values of vitrinite reflectance, etc.) should be given metamorphic rock names;

- those rocks which do not show any sign of very low-grade metamorphism should be given the appropriate non-metamorphic rock name, regardless of their close spatial and genetic relationship to the 'metamorphic' rocks.

This implies that metamorphic rock names may alternate with sedimentary or magmatic ones in a geologic profile or map. This might give rise to cartographic boundaries that would require specific explanations.

III. THE VARIOUS NOMENCLATURE SYSTEMS OF VERY LOW- AND LOW-GRADE METAMORPHISM

The possibilities for discrimination between diagenesis, very low- and low-grade metamorphism are schematically shown in Figure 1.

1. ***Rocks with diagnostic minerals and mineral assemblages (mainly basic rocks)***

a) Zeolite and subgreenschist facies

In rocks of basic to intermediate compositions, the occurrence of zeolites is attributed to alterations at low temperatures in the presence of CO_2-poor or -absent aqueous fluids. The SCMR defines the zeolite facies as follows:

Zeolite facies: *a facies* (in the sense of Eskola, 1920) *which embraces all mineral assemblages which include various zeolites plus quartz, irrespective of the mode of origin, whether metamorphic, or hydrothermal or diagenetic* (Coombs et al., 1959; Coombs, 1971; Boles and Coombs, 1977).

In silicate rocks (see Bucher and Frey, 1994), the first appearance of one or some of the following minerals: Fe-Mg-carpholite, glaucophane, lawsonite, laumontite, paragonite,

[1] P_l – lithostatic pressure; P_f – fluid pressure

prehnite, pumpellyite or stilpnomelane, is often regarded as the beginning of metamorphism (although the status of laumontite is questionable[2]).
The SCMR recommends that only a few metamorphic facies should be used as a general rule (Smulikowski et al., 2004), but leaves open the possibility to use other facies or subfacies if required to describe a specific region, provided that these additional facies or subfacies are clearly defined. Although the very low- and low-grade P-T field covers quite a small part of the whole metamorphic field, various authors have suggested that it should be subdivided into several facies or subfacies to cover the situation with particular lithologies. They also suggest different methods for defining the additional facies or subfacies.
The following are a few of these suggestions and the recommended SCMR definitions. As grade is taken as equivalent to temperature (Smulikowski et al., 2004) it follows that metamorphic rocks formed at temperatures lower than the low-temperature limit of the greenschist facies belong to the very low-grade field. The high P/T and high-P part of this field includes a small part of the glaucophane-schist (blueschist) facies (Smulikowski et al., 2004).
The part of the field of very low-grade metamorphism characterized by pressures lower than those of the glaucophane-schist facies has been called the ***subgreenschist facies*** (see, for example, Bucher and Frey, 1994; Merriman and Frey, 1999). The subgreenschist facies embraces various metabasite facies/subfacies (Fig. 1) characterized by the diagnostic mineral assemblages of prehnite+pumpellyite, prehnite+actinolite, pumpellyite+actinolite, and also, according to certain authors, laumontite.
The SCMR defines these facies/subfacies as follows.

The ***prehnite-pumpellyite facies*** *is characterized in metasandstones and metavolcanic rocks of appropriate composition by the presence of prehnite and/or pumpellyite in the absence of zeolites, lawsonite, or jadeite. Quartz-albite-chlorite-prehnite and/or pumpellyite can coexist stably* (Coombs, 1960).

The ***pumpellyite-actinolite facies*** *is characterized by the mineral association of pumpellyite-actinolite-quartz (± chlorite, albite and epidote) and by the lack of prehnite* (Hashimoto, 1966).

The ***prehnite-actinolite facies*** *is characterized by the mineral association of prehnite-actinolite-epidote (± chlorite, albite, quartz and titanite) and by the absence of pumpellyite in rocks of appropriate bulk composition (mostly metabasic rocks and their clastic derivates)* (Liou et al., 1985).

b) The transition to the greenschist facies

In the case of rocks of suitable composition (mostly of basic to intermediate composition), the first appearance of the diagnostic mineral assemblage actinolite + epidote + chlorite + albite + quartz in the absence of pumpellyite and/or prehnite

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[1] COOMBS et al. (1959) and BOLES and COOMBS (1977) argue that the zeolite facies should be regarded as a *mineral facies*, irrespective of the origin of the mineral assemblage. They regarded it as unrealistic to arbitrarily interpret laumontite as metamorphic and heulandite or analcime (plus quartz) as diagenetic.

indicates the onset of low-grade metamorphism, that is, the transition from very low- to low-grade metamorphism, i.e. from subgreenschist to greenschist facies.
The first appearance of the lawsonite + chlorite + albite association or of sodic amphibole lies within the very low-grade field, indicating high P/T.
Although very fine-grained chloritoid may appear already in very low-grade (anchizonal) metapelites (often hard to be detected by optical microscopy), chloritoid typically occurs in low-grade (greenschist facies) rocks.

2. Rocks devoid of diagnostic minerals and mineral assemblages

In many common rocks, such as ‘normal’ marine pelites, carbonate rocks, etc., no diagnostic minerals and mineral assemblages form in the very low-grade field. In these rocks, the transitions from non-metamorphic to very low-grade and from very low-grade to low-grade metamorphic domains take place through the diagenetic zone, the anchizone and the epizone (Fig. 1), each zone being characterized by specific values of the illite Kübler index (KI), which is measured on the <2 µm fraction of clay-rich clastic rocks following the recommendations on sample preparation, X-ray diffraction settings and inter-laboratory standardization summarized by Kisch (1991). For comparing the various sample preparation techniques, the procedure and standards suggested by Warr and Rice (1994) are useful. Concerning the proper nomenclature of indices (formerly called ‘crystallinity’) expressing the reaction progress of illite-muscovite and chlorite in diagenetic and low-temperature metamorphic conditions, the authors refer to the recommendations of Guggenheim et al. (2002).

Diagenetic zone [or more precisely, *diagenetic illite Kübler index zone*]: *zone characterized by illite Kübler index (KI) values greater than 0.42 $\Delta°2\theta$ CuK_{α} (after Kübler, 1967, 1968, 1984)*.

Anchizone: *transitional zone between the diagenetic zone and the epizone characterized by illite Kübler index (KI) mean values between 0.42 and 0.25 $\Delta°2\theta$ CuK_{α} (after Kübler, 1967, 1968, 1984).* Metamorphism in this zone is consistently called ***anchimetamorphism***, which roughly corresponds to very low-grade metamorphism. [The term 'anchimetamorphism' was originally introduced by Harrasowitz (1927) to indicate changes in mineral content of rocks under pressure and temperature conditions prevailing between the Earth’s surface and the zone of metamorphism.]

Epizone: *zone of low-grade metamorphic rocks characterized by illite Kübler index (KI) mean values less than 0.25 $\Delta°2\theta$ CuK_{α} (after Kübler, 1967, 1968, 1984)*. Note: the term epizone was originally proposed by Grubenmann (1904) to indicate shallow depth of metamorphism. At present, however, this term is mainly used in the context of illite Kübler index investigations.

In addition to the illite Kübler-index, some other characteristics such as vitrinite reflectance (Fig. 1), chlorite Árkai index (see Gugenheim et al., 2002), Conodont Colour Alteration Index (CAI), etc. can be also used for determining diagenetic and metamorphic zones. Note, however, that only approximate correlations can be established between these parameters. Examples and explanations of common deviations from the generalized scheme are given by Kisch (1987) and Merriman and Frey (1999).

IV. PROTOLITH NAMES, DEFINITIONS OF SPECIFIC ROCK NAMES

Very few specific rock terms exist in the realm of very low-grade metamorphism. This can be explained by the fact that, with the exception of the structure of slates, mesoscopic features characteristic of this metamorphic grade do not exist.

As the original (sedimentary or magmatic) features of the protoliths can usually be easily recognized in this realm, the general use of the sedimentary or magmatic name of the protolith prefixed with '*meta*' or *meta-*' is highly recommended (for example, meta-andesite, metasandstone), excluding the very few cases when *specific rock terms* are available (for example, slate). As stated in Schmid et al. (2004) the SCMR recommends the use of the *prefix meta or meta-* in combination with a protolith-based name only when the protolith is easily identifiable or obvious. It must never be used for former metamorphic rocks (for example, 'meta-phyllite' is not an acceptable term) (Schmid et al., 2004).

The *specific rock terms* are defined below.

Slate: *An ultrafine- or very fine-grained rock displaying a slaty cleavage*. Slate is usually of very low metamorphic grade, although it may also occur in low-grade conditions. The definition of *slaty cleavage* is given by Brodie *et al*. (2004.) as; '*A well developed schistosity in a rock in which the individual grains are too small to be seen by the unaided eye'*. The definition of *schistosity* is given by Brodie *et al*. (2004) as *'A preferred orientation of inequant mineral grains or grain aggregates produced by metamorphic processes'.*

Phyllite: A *fine- to medium-grained rock characterized by a lustrous sheen and a well-developed schistosity resulting from the parallel arrangement of phyllosilicates. Phyllite is usually of low metamorphic grade*.

Paleovolcanite rock terms*:* the *SCMR recommends following the definitions for volcanic rock terms given by Le Maitre et al. (1989, 2002) and that the recommendations given in the present paper are used for rocks which underwent any kind of very low-grade metamorphic alteration.*

Spilite: *An altered basic to intermediate, volcanic or subvolcanic rock in which the feldspar is partially or completely composed of albite and is typically accompanied by chlorite, calcite, quartz, epidote, prehnite, or other low-temperature hydrous crystallization products.* Preservation of eruptive (volcanic and subvolcanic) features is an important characteristic of spilites. The term spilite may be classified as metabasalt or meta-andesite, as appropriate, regardless of its origin.

The 'spilite problem', debated in the geological literature for many decades, is of special interest for researchers working in the field of very low- and low-grade metamorphism. This is the reason why the term 'spilite' has been considered by the SCMR, despite the fact that the Subcommission on the Systematics of Igneous Rocks include this term in their glossary[3] (Le Maitre et al., 1989, 2002). The SCMR recommends that the definition given by Le Maitre et al. should be expanded to include

[2] Note: the term 'spilite' is not a root or recommended name in the IUGS classification of Igneous Rocks, although it is included in the glossary (Le Maitre, 2002)

rocks of intermediate composition, because many spilites have an andesitic rather than a basic composition.

Greenschist: *SCHIST whose greenish colour is due to the presence of minerals such as actinolite, chlorite and epidote.* More precise terms should be used whenever possible (for example, epidote bearing actinolite-chlorite schist).

Greenstone: *A granofels whose greenish colour is due to the presence of minerals such as actinolite, chlorite and epidote*. More precise terms should be used whenever possible (for example, chlorite-epidote granofels).

V. TERMS NOT RECOMMENDED FOR GENERAL USE

In addition to the terms listed above, the Study Group also discussed some other terms, which, however, are not recommended for international use. They are listed below, with the corresponding explanations.

Brownstone facies*: a low-temperature facies encompassing ocean floor weathering and low-temperature hydrothermal alteration on the ocean floor.* The most widespread secondary minerals present under oxidizing conditions include a K-rich dioctahedral iron illite resembling celadonite. This replaces olivine, occupies vesicles, replaces interstitial glass, and eventually, augite. Under reducing conditions its place is taken by saponite, and pyrite is also characteristic. Plagioclase may be replaced by clay minerals or potassium feldspar. Glassy rinds of basaltic pillow lava alter to palagonite in association with phillipsite and other low-temperature zeolites and calcite.

Catagenesis=katagenesis*: terms used, especially by Russian authors (see above), to indicate changes occurring in (an already lithified) sedimentary rock buried by a distinct covering layer, characterized by P-T conditions that are significantly different from those of deposition and metamorphism.* This term is equivalent to ‘epigenesis’ or with the ‘middle and deep diagenesis’. It is subdivided into early catagenesis (= middle diagenesis = shallow epigenesis) and late catagenesis (= deep diagenesis = deep epigenesis).

Cryptic metamorphism*: a term for metamorphism which can be detected only by special study, for example, vitrinite reflectance, illite Kübler index, etc. and not by ordinary hand specimen or microscopic study.*

Crystalline limestone, dolomite, etc*.: carbonate rock (carbonate mineral content > 90 %) with a completely recrystallized matrix.* Foliation may be present.

Epigenesis*: a term used, especially by Russian authors, to indicate changes, transformations or processes, occurring at low temperatures and pressures that affect sedimentary rocks subsequent to their compaction, excluding superficial alteration (weathering) and metamorphism* (= catagenesis = middle and deep diagenesis). Subdivided into early and deep or late epigenesis.

Incipient regional metamorphism*: a general term for the stages of mineral modifications as characterized by the appearance of the attributes of the anchizone (anchimetamorphism).* It is approximately equivalent to the early metagenesis or with the greater part of Winkler’s (1974) ‘very low-grade metamorphism’, including the higher-T part of the ‘pumpellyite-prehnite-quartz facies’, and probably, all of the 'lawsonite-albite schist' and 'glaucophane-lawsonite schist facies' in the sense of Winkler (1974).

Metagenesis*: a term used, especially by Russian authors (see above), to indicate a more advanced stage of post-diagenetic alteration than epigenesis or catagenesis.* It is subdivided into 'early metagenesis' (which roughly corresponds to the anchizone) and 'late or deep metagenesis' (which is more or less equivalent with the epizone or the chlorite zone of the greenschist facies).

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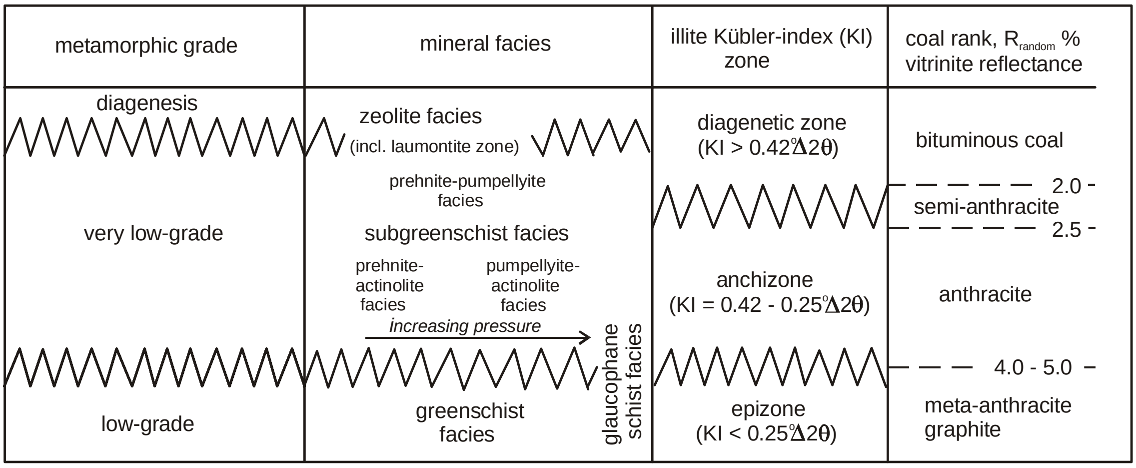

Fig. 1: Comparison of mineral facies, illite Kübler index (KI) ‘crystallinity’ zones and coal rank in the diagenetic, very low- and low-grade metamorphic realms. Zigzag lines represent uncertainties of correlation. Rough scheme simplified after FREY (1987), KISCH (1987) and MERRIMAN and FREY (1999).