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A systematic nomenclature for metamorphic rocks:

2. TYPES, GRADE AND FACIES OF METAMORPHISM

Recommendations by the IUGS Subcommission on the Systematics of Metamorphic Rocks: Web version 1.1.2004

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INTRODUCTION

The Subcommission for the nomenclature of Metamorphic Rocks (SCMR), a branch of the IUGS Commission on the Systematics in Petrology, 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, 2002).
The principles used by the SCMR for defining and classifying metamorphic rocks are outlined in Schmid et al (2004).
This paper presents the recommended definitions for the main terms concerning types, grade and facies of metamorphism and related topics prepared by the Subcommission. In many cases the reasoning behind them is given.

I. TYPES OF METAMORPHISM

Metamorphism: *a process involving changes in the mineral content/composition and /or microstructure of a rock, dominantly in the solid state. The process is mainly due to an adjustment of the rock to physical conditions that differ from those under which the rock originally formed and that also differ from the physical conditions normally occurring at the surface of the Earth and in the zone of diagenesis. The process may coexist with partial melting and may also involve changes in the bulk chemical composition of the rock.*

Metamorphism can be variably classified on the basis of different criteria such as:

1) the extent over which metamorphism took place, for example, regional metamorphism (m.), local m.;

2) its geological setting, for example, orogenic m., burial m., ocean floor m., dislocation m., contact m. and hot-slab m.;

3) the particular cause of a specific metamorphism, e.g., impact m., hydrothermal m., burning

m., lightning m.; to this category may also be attributed contact m., pyrometamorphism and hot-slab m.;

4) whether it resulted from a single or multiple event(s), that is, monometamorphism and polymetamorphism;

5) whether it is accompanied by increasing or decreasing temperatures, that is, prograde m., and retrograde m.

The main classification of metamorphism is shown in Figure 1. It does not include all terms known from the literature. Many terms such as thermal metamorphism, dynamic metamorphism, dynamothermal metamorphism, deformation metamorphism, up-side-down metamorphism, cataclastic metamorphism etc. have not been considered here because they do not represent the major distinctions of metamorphism, are ambiguous or unnecessary.

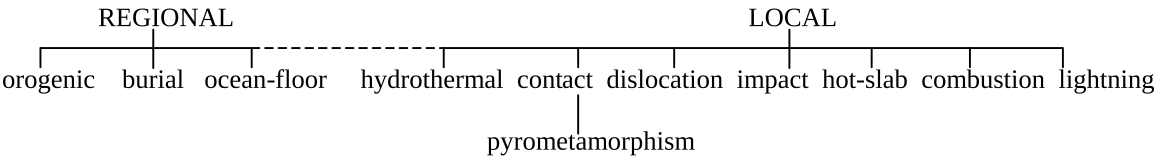

Figure 1. Main types of metamorphism

Regional metamorphism is *a type of metamorphism which occurs over an area of wide extent, i.e. affecting a large rock volume, and is associated with large-scale tectonic processes, such as ocean-floor spreading, crustal thickening related to plate collision, deep basin subsidence, etc.*
Local metamorphism is *a type of metamorphism of limited areal (volume) extent in which the metamorphism may be directly attributed to a localised cause, such as a magmatic intrusion, faulting or meteorite impact.*

If the metamorphism, even of a very wide extent, can be related to a particular source, for example, heat of an intrusion, or is restricted to a certain zone, for example, dislocation, it is considered as local.

Orogenic metamorphism is *a type of metamorphism of regional extent related to the development of orogenic belts.* The metamorphism may be associated with various phases of orogenic development and involve both compressional and extensional regimes. Dynamic and thermal effects are combined in varying proportions and timescales and a wide range of P-T conditions may occur.

Burial metamorphism is *a type of metamorphism, mostly of regional extent, which affects rocks deeply buried under a sedimentary-volcanic pile and is typically not associated with deformation or magmatism.* The resultant rocks are partially or completely recrystallized and generally lack schistosity. It commonly involves from very low to medium metamorphic temperatures and low to medium P/T ratios.

Ocean floor metamorphism is *a type of metamorphism of regional or local extent related to the steep geothermal gradient occurring near spreading centres in oceanic environments.* The recrystallization, which is mostly incomplete, encompasses a wide range of temperatures. The metamorphism is associated with circulating hot aqueous fluids (with related metasomatism) and typically shows an increasing temperature of metamorphism with depth.

Dislocation metamorphism is *a type of metamorphism of local extent, associated with fault zones or shear zones.* Grain size reduction typically occurs in the rocks, and a range of rocks

largely referred to mylonites and cataclasites forms.
Impact metamorphism is *a type of metamorphism of local extent caused by the impact of a planetary body (projectile or impactor) on a planetary surface (target). It includes melting and vaporisation of the target rocks.*
Contact metamorphism is *a type of metamorphism of local extent that affects the country rocks around a magma body.* It is essentially caused by the heat transfer from the intruded magma body into the country rocks. The range of metamorphic temperatures may be very wide. It may be accompanied by deviatoric stress related to the dynamics of the intrusion.
Pyrometamorphism is *a type of contact metamorphism characterised by very high temperatures, at very low pressures, generated by a volcanic or subvolcanic body.* It is most typically developed in xenoliths enclosed in such bodies. Pyrometamorphism may be accompanied by various degrees of partial melting (fritted rocks, buchites).
Hydrothermal metamorphism is *a type of metamorphism of local extent caused by hot H_2O-rich fluids.* Metasomatism is commonly associated with this type of metamorphism.
Hot-slab metamorphism is *a type of metamorphism of local extent occurring beneath an emplaced hot tectonic body.* The thermal gradient is inverted and usually steep.
Combustion metamorphism is *a type of metamorphism of local extent produced by the spontaneous combustion of naturally occurring substances such as bituminous rocks, coal or oil.*
Lightning metamorphism is *a type of metamorphism of local extent, which is due to a strike of lightning.* The resulting rock is a fulgurite, an almost entirely glassy rock.

A rock or a rock complex may bear the effects of more than one metamorphic event (e.g. contact metamorphism following regional metamorphism), and thus the following types of metamorphism can be distinguished.
Monometamorphism is *a metamorphism resulting from one metamorphic event* (Fig. 2a and 2b).
Polymetamorphism is *a metamorphism resulting from more than one metamorphic event* (Fig. 2c and 2d). In these definitions a **metamorphic event** refers to a continuous sequence of metamorphic conditions (temperature, pressure, deformation) under which metamorphic reconstitution commences and continues until it eventually ceases. Typically a metamorphic event will involve a cycle of heating and cooling, which in orogenic metamorphism will be accompanied by pressure and deformation variations.

The series of metamorphic conditions in the metamorphic event may be represented on the pressure-temperature (P-T) diagram by a **P-T-t path**, where '**t**' refers to time. Thus in Figure 2 the continuous lines in 2a and 2b represent the sequence of P-T conditions which occurred in a given rock body over a period of time of a particular metamorphic event.

It is accepted that the changes in P-T conditions during a metamorphic event do not necessarily involve only one phase of heating and then cooling and/or one phase of increasing then decreasing pressure. Thus a metamorphic event may be **monophase** (e.g. with one thermal climax, see Fig. 2a) or **polyphase** (with two or more climaxes, Fig. 2b). Polymetamorphism illustrated in Figure 2 shows two monophase metamorphic events (2c) and two polyphase events (2d), which have left their imprints on a rock body. Note that points on a P-T-t path may be labelled with specific ages and that, even in a monophase event, stages of metamorphism corresponding to restricted sections of the P-T-t path may be distinguished. The path may be clockwise (Fig. 2a) or anticlockwise (Fig. 2b) according to whether thermal climaxes are reached under conditions of decreasing or increasing pressure respectively. In practice it is often a delicate matter to differentiate polyphase metamorphism from polymetamorphism.

The term "plurifacial metamorphism", as defined by de Roever and Nijhuis (1963) and de Roever (1972), may correspond to either polyphase metamorphism or polymetamorphism and is not recommended for general use by SCMR.

II. METAMORPHIC TEMPERATURE, PRESSURE, GRADE, ISOGRAD

Relative terms such as high-temperature or low-pressure are often used to refer to the physical conditions of metamorphism. In order to maintain similarity of meaning it is proposed that the whole spectrum of temperature conditions encountered in metamorphism be divided into five parts, and the corresponding metamorphism may be designated as: **very-low-, low-, medium-, high-, very-high-temperature metamorphism**. Likewise the broad range of pressure conditions may be divided into five to give: **very-low-, low-, medium-, high-, very-high-pressure metamorphism**. In the highest part of the very high pressure **ultra-high-pressure metamorphism** may be distinguished (Desmons et al., 2004). In a P-T grid the above divisions are represented by five isothermal and five isobaric bands respectively (Fig. 3). Circumstances of temperature and pressure may be combined together, for example, medium-pressure/low-temperature metamorphism.

Related terms may be used to describe the ratio of pressure to temperature during metamorphism. The whole range of P/T ratios encountered may be divided into five fields (radial sectors in a P-T diagram) to give: **very-low, low, medium, high, very-high P/T metamorphism** (Fig. 3).

The term **metamorphic grade** is widely used to indicate relative conditions of metamorphism, but it is used variably. Within a given metamorphic area, the terms lower and higher grade have been used to indicate the relative intensity of metamorphism, as related to either increasing temperature or increasing pressure conditions of metamorphism or most often both. Unfortunately this may give rise to ambiguity, about whether grade refers to relative temperature or pressure, or some combination of temperature and pressure. To avoid this it is recommended that **metamorphic grade refers only to temperature of metamorphism**, following Turner and Verhoogen (1951), Miyashiro (1973) and Winkler (1974). If the whole range of temperature conditions is again divided into five, then we may refer to **very low, low, medium, high, very high grade of metamorphism** in the same way as for "very low, low, ..." etc. temperature of metamorphism and with the same meaning.

Depending on whether metamorphism is accompanied by increasing or decreasing temperature two types can be distinguished.

Prograde (= progressive) metamorphism is *a metamorphism giving rise to the formation of minerals which are typical of a higher grade (i.e. higher temperature) than the former phase assemblage.*

Retrograde (= retrogressive) metamorphism is *a metamorphism giving rise to the formation of minerals which are typical of a lower grade (i.e. lower temperature) than the former phase assemblage.*

Isograd is *a surface across the rock sequence, represented by a line on a map, defined by the appearance or disappearance of a mineral, a specific mineral composition or a mineral association, produced as a result of a specific reaction, for example, the ‘staurolite-in’ isograd defined by the reaction:*

garnet+chlorite+muscovite=staurolite+biotite+quartz+H2O.
Isograds actually indicate mineral reactions, hence the expressions like 'isoreaction-grad' (Winkler 1974) and 'reaction isograd' (Bucher and Frey 1994) are more accurate but unnecessary.

III. METAMORPHIC FACIES AND FACIES SERIES

Metamorphic facies is a fundamental notion in metamorphic petrology. The concept of metamorphic facies replaced that of depth zones, that is, epi-, meso- and catazone (Grubenmann and Niggli 1924), when it became obvious that metamorphic grade is not necessarily correlated with depth.

The concept of metamorphic facies was first proposed by Eskola (1915) who later (Eskola, 1920) gave the following definition: A *metamorphic facies* is "a group of rocks characterized by a definite set of minerals which, under the conditions obtaining during their formation, were at perfect equilibrium with each other. The quantitative and qualitative mineral composition in the rocks of a given facies varies gradually in correspondence with variation in the chemical bulk composition of the rocks". In the same paper he defined also mineral facies as a more general term applicable to both igneous and metamorphic rocks. A *mineral facies* "comprises all the rocks that have originated under temperature and pressure conditions so similar that a definite chemical composition has resulted in the same set of minerals ...". Subsequently Eskola (1939) wrote (translated from German by Fyfe et al. 1958) "in a definite facies are united rocks which for identical bulk composition exhibit an identical mineral composition, but whose mineral composition for varying bulk composition varies according to definite laws".

The Subcommission proposes the following definition of facies, which follows Eskola's writings and the commentaries of other workers (in particular Turner 1981).

A **metamorphic facies** is *a set of metamorphic mineral assemblages, repeatedly associated in time and space and showing a regular relationship between mineral composition and bulk chemical composition, such that different metamorphic facies (sets of mineral assemblages) appear to be related to different metamorphic conditions, in particular temperature and pressure, although other variables, such as* P_{H2O} *may also be important.*

It is one of the strengths of the metamorphic facies classification that it identifies the regularities and consistencies in mineral assemblage development; which may be related to P-T conditions, but does not attempt to define actual pressures and temperatures.

In the broad sense, considering the exceptionally wide range of chemical compositions of rocks, and narrow ranges of P-T conditions over which mineral assemblages may change, it is theoretically possible to define a very large number of facies. In practice it has been found most convenient to define a reasonably small number of facies, which cover the broad range of crustal P-T conditions (including those found in ultra thickened crust). These have been based principally on major changes in the mineral assemblages of rocks of basaltic composition, because such rock types are widespread and they show changes in mineral assemblages that are both distinct and reasonably limited in number, as realised by Eskola himself.

Within such major and broad facies, subunits or **subfacies** have been defined showing, for example, more detailed changes in pelitic assemblages. However no widely used scheme of subfacies exists, and we make no attempt to define such here, since they may be defined for specific circumstances when necessary.

Eskola (1920, 1939) distinguished eight facies, namely: **greenschist facies (f.), epidote-amphibolite f., amphibolite f., pyroxene-hornfels f., sanidinite f., granulite f.,**

glaucophane-schist f. and eclogite facies. Coombs et al. (1959), building on a suggestion of Eskola's, added a **zeolite facies** and a *prehnite-pumpellyite zone*, which Turner (1968) called *prehnite-pumpellyite metagraywacke facies*. Miyashiro (1973) used the above ten facies renaming the last one as the *prehnite-pumpellyite facies*. More recently various authors have recognized distinctions in the assemblages containing prehnite and pumpellyite, and erected three facies or subfacies based on the assemblages *prehnite-pumpellyite, prehnite-actinolite and pumpellyite-actinolite* (Arkai et al 2004). These facies or subfacies may be collectively referred to as the **subgreenschist facies** (see, for example, Bucher and Frey 1994, Merriman and Frey 1999). This term has accordingly been provisionally accepted by the SCMR as a general term covering the range of very-low-grade metamorphism (Arkai et al 2004, Fig. 1).

The merits of recognising such a group of facies are evident from their extensive use over many years, and **the SCMR recommends that these ten facies be adopted as the major facies for general use**. Note, however that **blueschist facies** is commonly used as a synonym for the glaucophane-schist facies and that the epidote-amphibolite facies is sometimes considered as part of the greenschist facies (on the basis of the coexistence of epidote with sodic plagioclase i.e.<An17).

Table 1. Metamorphic facies and their characteristic minerals and mineral parageneses in metamorphosed rocks of basaltic chemical composition.

FACIES	MINERALS AND MINERAL PARAGENESES
Zeolite facies	Zeolites such as laumontite and heulandite etc.(in place of other Ca-Al silicates such as prehnite, pumpellyite and epidote)
Subgreenschist facies	Prehnite-pumpellyite, pumpellyite-actinolite, prehnite-actinolite (prehnite and pumpellyite are the diagnostic Ca-Al silicates rather than minerals of the epidote or zeolite groups)
Greenschist facies	Actinolite-albite-epidote-chlorite (an epidote group mineral is the diagnostic Ca-Al silicate rather than prehnite or pumpellyite)
Epidote-amphibolite facies	Hornblende-albite-epidote(-chlorite)
Amphibolite facies	Hornblende-plagioclase (plagioclase more calcic than An17)
Pyroxene hornfels facies	Clinopyroxene-orthopyroxene-plagioclase (olivine stable with plagioclase)
Sanidinite facies	Distinguished from the pyroxene hornfels facies by the occurrence of especially high-temperature varieties and polymorphs of minerals (e.g. pigeonite, K-rich labradorite)
Glaucophane-schist or Blueschist facies	Glaucophane-epidote-(garnet), glaucophane-lawsonite, glaucophane-lawsonite-jadeite
Eclogite facies	Omphacite-garnet-quartz (no plagioclase, olivine stable with garnet)
Granulite facies	Clinopyroxene-orthopyroxene-plagioclase (olivine not stable with plagioclase or with garnet)

The diagnostic minerals and mineral parageneses of the facies in metamorphosed basaltic rocks are given in Table 1. It must be emphasised that diagnostic mineral assemblages for these facies may also be listed for other rock compositions. In the case of pelitic rocks there would be several assemblages in each of these facies because the phase assemblages of pelitic rocks are more sensitive to changes in the P-T conditions than those of metabasaltic rocks. Mineral assemblages for other rock compositions in these facies are given in many textbooks such as Turner (1968, 1981), Miyashiro (1973, 1994), Bucher and Frey (1994), and Kretz (1994).

The relative position of the ten facies in P-T space is shown in Fig. 4.

Metamorphic facies are commonly found in different regular sequences. This led to the concept of metamorphic facies series (Miyashiro 1961).

Metamorphic facies series is *a sequence of metamorphic facies developed under the same range of P/T ratios, thus represented by a radial sector in the P-T diagram*.

Miyashiro (1961) distinguished five facies series. Later (Miyashiro 1973) he related them to **baric types of metamorphism**: low-pressure I, low-pressure II (intermediate), medium-pressure (Barrovian), high-pressure I (intermediate) and high-pressure II. In Fig. 3c they correspond to the 5 radial sectors of the P/T ratios.

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REFERENCES

ARKAI P., SASSI F.P. and DESMONS J., 2004. 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. SCMR website (www.bgs.ac.uk/SCMR).

BUCHER K. and FREY M. 1994. Petrogenesis of metamorphic rocks. Springer, Berlin, 318 pp.

COOMBS D.S., ELLIS A.J., FYFE W.S.and TAYLOR A.M., 1959. The zeolite facies, with comments on the interpretation of hydrothermal syntheses. Geochim. Cosmochim. Acta, **17**, 53-107.

de ROEVER W.P., 1972. Application of the facies principle to rocks metamorphosed in more than one metamorphic facies, with special reference to plurifacial metamorphism in southeastern Spain. Proc. Koninkl. Neder. Akad. van Wetenschappen, Series B, **75**, 253-260.

de ROEVERW.P.and NIJHUIS H.J.,1963. Plurifacial alpine metamorphism in the eastern Betic Cordilleras (SE Spain), with special reference to the genesis of the glaucophane. Geol. Rundschau, **53**, 324-336.

DESMONS J. and SMULIKOWSKI W., 2003. High P/T metamorphic rocks. Recommendations by the IUGS Subcommission on the systematics of metamorphic rocks. SCMR website (www.bgs.ac.uk/SCMR).

ESKOLA P., 1915. On the relations between the chemical and mineralogical composition in the metamorphic rocks of the Orijarvi region. Comm. geol. Finlande Bull., **44**, 1-107 (in Finnish), 109-145 (in English).

ESKOLA P., 1920. The mineral facies of rocks. Norsk. Geol. Tidsskr. **6** (1922), 143-194.

ESKOLA P., 1939. Die metamorphen Gesteine. *In*: Barth T.F.W., Correns C.W., Eskola P. Die Entstehung der Gesteine. Springer, Berlin, 422 pp.

FYFE W.S., TURNER F.S. and VERHOOGEN J., 1958. Metamorphic reactions and metamorphic

facies. Mem. Geol. Soc. Amer. **73**, 259 pp
GRUBENMANN U. and NIGGLI P., 1924. Die Gesteinsmetamorphose, vol. 1. Borntraeger, Berlin, 539 pp.
KRETZ R. 1994. Metamorphic crystallization. Willey & Sons, Chichester, 507 pp.
LE MAITRE R. W. (Ed) et al., 1989. A classification of igneous rocks and glossary of terms. Blackwell Scientific Publ., Oxford, 193pp.
LE MAITRE R. W. (Ed) et al., 2002. A classification of igneous rocks and glossary of terms. Cambridge University Press, Cambridge, 236pp.
MERRIMAN R. J. and FREY M., 1999. Patterns of very low-grade metamorphism in metapelitic rocks. In, *Low-grade metamorphism*, FREY M. and ROBINSON D. (eds.). Blackwell Scientific Publ., Oxford, 10-60.
MIYASHIRO A., 1961. Evolution of metamorphic belts. J. Petrol**.** **2**, 277-311.
MIYASHIRO A., 1973. Metamorphism and metamorphic belts. Allen & Unwin, London, 492 pp.
MIYASHIRO A., 1994. Metamorphic Petrology. UCL Press, London, 404 pp.
SCHMID R., FETTES D., HARTE B., DAVIS E., DESMONS J., MEYER-MARSILIUS H-J. and SIIVOLA J., 2004. A systematic nomenclature for metamorphic rocks. 1. How to name a metamorphic rock. Recommendations by the IUGS Subcommission on the systematics of metamorphic rocks. SCMR website (www.bgs.ac.uk/SCMR).
TURNER F.J., 1968. Metamorphic petrology, mineralogical and field aspects. McGraw-Hill, New York, 403 pp.
TURNER F.J., 1981. Metamorphic Petrology, 2nd ed. McGraw-Hill, New York, 524 p.
TURNER F.J., VERHOOGEN J., 1951. Igneous and metamorphic petrology. McGraw-Hill, New York, 602 pp.
WINKLER H.G.F., 1974. Petrogenesis of metamorphic rocks, 3rd ed. Springer, Berlin, 320 pp.
YARDLEY B.W.D., 1989. An introduction to metamorphic petrology. Longman Earth Science Series, Singapore, 248 pp.

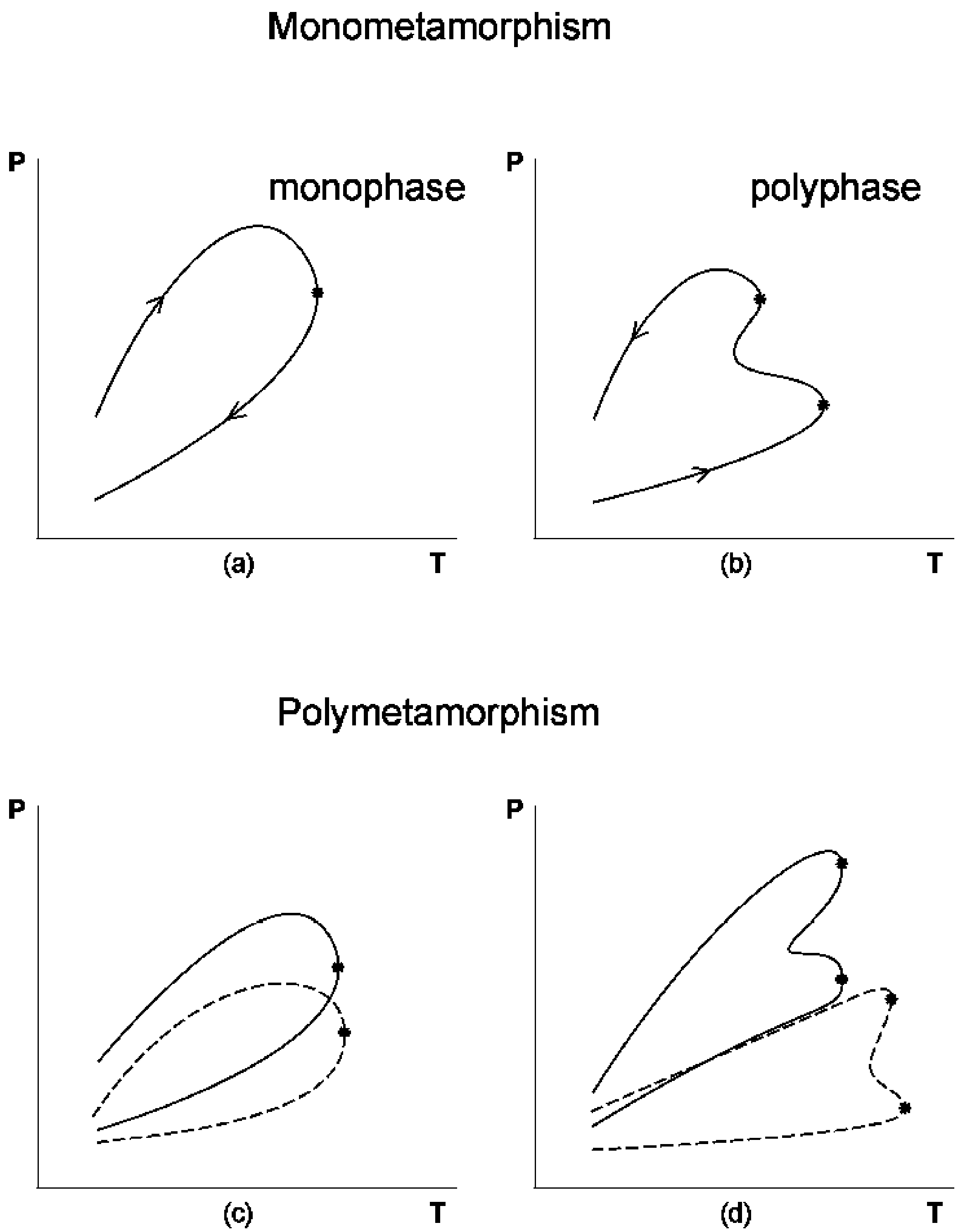

Fig. 2. Schematic P-T-t paths of monometamorphism (a and b) and polymetamorphism (c and d). Each line represents a metamorphic event: a - monophase with clockwise P-T-t path, b - polyphase with anticlockwise path, c - two monophase events, and d - two polyphase events. Asterisks represent thermal climaxes.

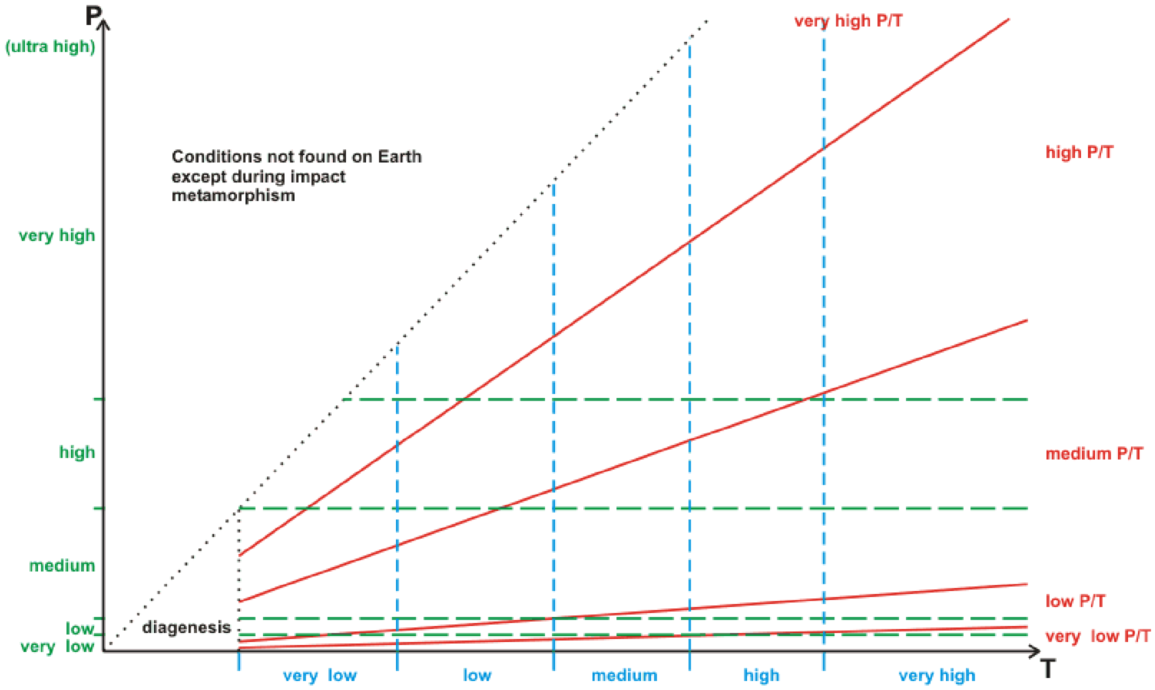

Fig. 3. Schematic representation in P-T space of the five isothermal, five isobaric bands and the five P/T radial sectors.

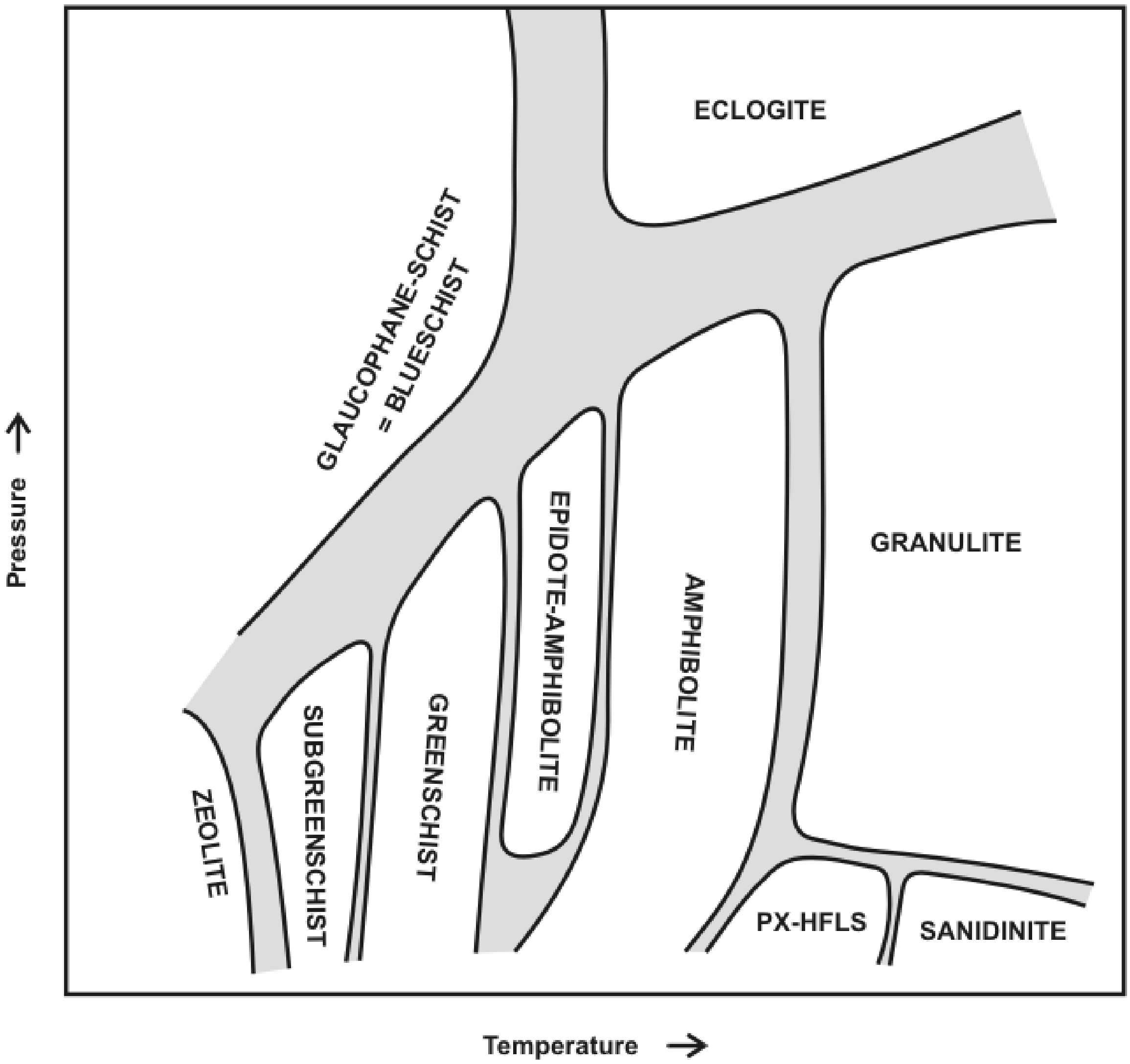

Fig 4. Diagram showing the relative position of the ten facies (Table 1) in the P-T field. Many similar diagrams exist, for example, Turner (1968, 1981), Miyashiro (1973, 1994), Winkler (1974), Yardley (1989) and Bucher and Frey (1994). The SCMR has not discussed the various presentations and makes no recommendation on the absolute P-T values, the precise fields of the facies or the nature of the areas of uncertainty between the fields.