2. TYPES, GRADE AND FACIES OF METAMORPHISM

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Types of metamorphism

Metamorphism: *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 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, that is, regional metamorphism (m.) and 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, for example, impact m., hydrothermal m., combustion m., lightning m.; some of the terms listed under (2) also fall into this category for example, contact m., 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 from the viewpoints of extent, setting and cause is shown in Figure 2.1. 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. are not used here because they overlap with the terms used in Figure 2.1 or have ambiguous usage.

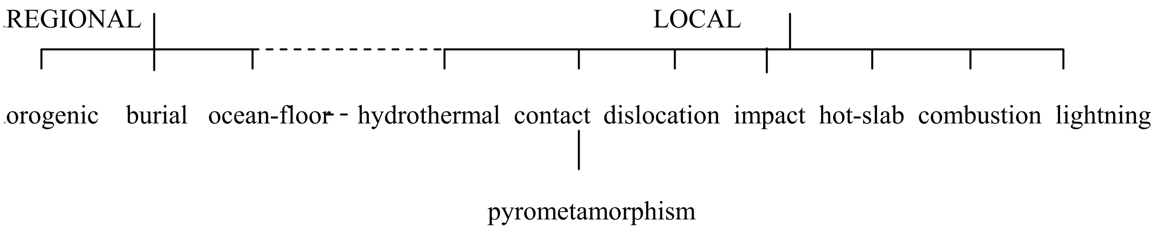

Fig. 2.1. Main types of metamorphism

Regional metamorphism is *a type of metamorphism which occurs over an area of wide extent, that is, 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 recrystallised 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 recrystallisation, 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 commonly referred to as mylonites and cataclasites is formed.

Impact metamorphism is *a type of metamorphism of local extent caused by the passage of a shock wave due to the impact of a planetary body (projectile or impactor) on a planetary surface (target).* It includes melting and vaporisation of the target rock(s).

Contact metamorphism is *a type of metamorphism of local extent that affects the country rocks* *around magma bodies emplaced in a variety of of environments from volcanic to upper mantle depths, in both continental and oceanic settings.* 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 or may not be accompanied by significant deformation depending upon 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 (to form, for example, fritted rocks, buchites).

Hydrothermal metamorphism is *a type of metamorphism of local extent caused by hot H_2O-rich fluids.* It is typically of local extent in that it may be related to a specific setting or cause (e.g. where an igneous intrusion mobilises H_2O in the surrounding rocks). However, in a setting where igneous intrusion is repetitive (e.g. in ocean-floor spreading centres) the repetitive operation of circulating hot H_2O fluids may give rise to regional effects as in some cases of ocean-floor metamorphism. 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 that is due to a strike of lightning.* The resulting rock is commonly 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. 2.2a and 2.2b).

Polymetamorphism is *a metamorphism resulting from more than one metamorphic event* (Fig. 2.2c and 2.2d). In these definitions a **metamorphic event** refers to a coherent 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 2.2 the continuous lines in 2.2a and 2.2b 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. 2.2a) or **polyphase** (with two or more climaxes, Fig. 2.2b). Polymetamorphism illustrated in Figure 2.2 shows two monophase metamorphic events (2.2c) and two polyphase events (2.2d), 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. 2.2a) or anticlockwise (Fig. 2.2b) according to whether thermal climaxes are reached under conditions of decreasing or increasing pressure respectively. In practice it may be a difficult matter to differentiate polyphase metamorphism from polymetamorphism.

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

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 but without precise designation of the temperatures and pressures involved. 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 & Smulikowski, this vol.). In a P-T grid the above divisions are represented by five isothermal and five isobaric bands respectively (Fig. 2.3). 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 three fields (radial sectors in a P-T diagram) to give: **low, medium, high, P/T metamorphism** (Fig. 2.3), broadly reflecting the main divisions of facies series (see below), in addition terms such as **very low and very high P/T metamorphism** may also be used.

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 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 should refer 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 (as in Fig. 2.3), 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+H_2O.* Isograds represent mineral reactions not rock chemical composition. Hence, although the expressions like 'isoreactiongrad' (Winkler 1974) and 'reaction isograd' (Bucher & Frey 1994) may convey this meaning more accurately they are unnecessary.

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 & 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 characterised 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 . 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 recognised 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* (Árkai et al., this vol.). These facies or subfacies, involving prehnite and pumpellyite, may be collectively referred to as the **subgreenschist facies** (e.g. Bucher & Frey 1994, Merriman & Frey 1999) and this term has accordingly been provisionally accepted by the SCMR as a general term covering a range of very low-grade metamorphism (Árkai et al., this vol., Fig. 5.1).

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 2.1. 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 occurring in metamorphosed basaltic rocks for each of the facies are given in Table 2.1. 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 basaltic rocks. Mineral parageneses for other rock compositions in these facies are given in many textbooks such as Turner (1968, 1981), Miyashiro (1973, 1994), Bucher & Frey (1994), and Kretz (1994).

The relative positions of the ten facies in P-T space are shown in Fig. 2.4.

In many areas of regional metamorphism and contact metamorphism, sequences of mineral assemblages may be mapped that reflect increasing temperatures and increasing pressures of metamorphism. Such sequences typically reflect a variety of P/T values (Fig. 2.3) and show a sequence of isograds where mineral reactions define changes in the stability of mineral parageneses. In order to relate such prograde sequences of mineral parageneses to the broadly recognised metamorphic facies (Fig. 2.4), Miyashiro (1961) developed the concept of the ***metamorphic facies series.***

Metamorphic facies series *is a sequence of metamorphic facies developed under a particular range of P/T.*

For regional metamorphism Miyashiro (1961) suggested three principal facies series and the existence of some intermediate facies series. Later (Miyashiro, 1973a), he referred to them as **baric types of metamorphism** because they broadly indicate different radial sectors in a P-T diagram such as Figure 2.3 (e.g. Miyashiro, 1994, Fig.8.1; Spear, 1993, Fig.2-3) and are distinguished by their range of P/T rather than their range of pressures or temperatures. The three principal baric types are:

1. a ***low-P/T type*** (also referred to as the *andalusite-sillimanite series* or *Abukuma type*) characterised by andalusite at lower grades and sillimanite at higher grades and typified by the sequence greenschist f.→amphibolite f.→granulite f.;

2. ***medium-P/T type*** (also referred to as the *kyanite-sillimanite series* or *Barrovian type*) characterised by kyanite at lower grades and sillimanite at higher grade and typified by the sequence greenschist f.→epidote-amphibolite f.→amphibolite f.→granulite f.;

3. ***high-P/T type*** (also referred to as *glaucophanic metamorphism*) characterised by the presence of glaucophane and typified by the sequence subgreenschist f. (prehnite-pumpellyite)→glaucophane-schist/blueschist f.

The three principal metamorphic facies series of Miyashiro have been generally adopted (e.g. Yardley, 1989; Spear 1993; Kornprobst, 2002) although, it is accepted that subdivisions, intermediates and variants exist (e.g. Harte & Hudson, 1979; Miyashiro, 1994).

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FIGURE CAPTION

Fig. 2.2. 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. 2.3. Schematic representation in P-T space of the five isothermal, five isobaric bands and three P/T radial sectors.

Fig. 2.4. 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 & Frey (1994). The SCMR has not discussed the various presentations and makes no recommendation on the absolute P and T values, the precise fields of the facies or the nature of the areas of uncertainty between the fields.

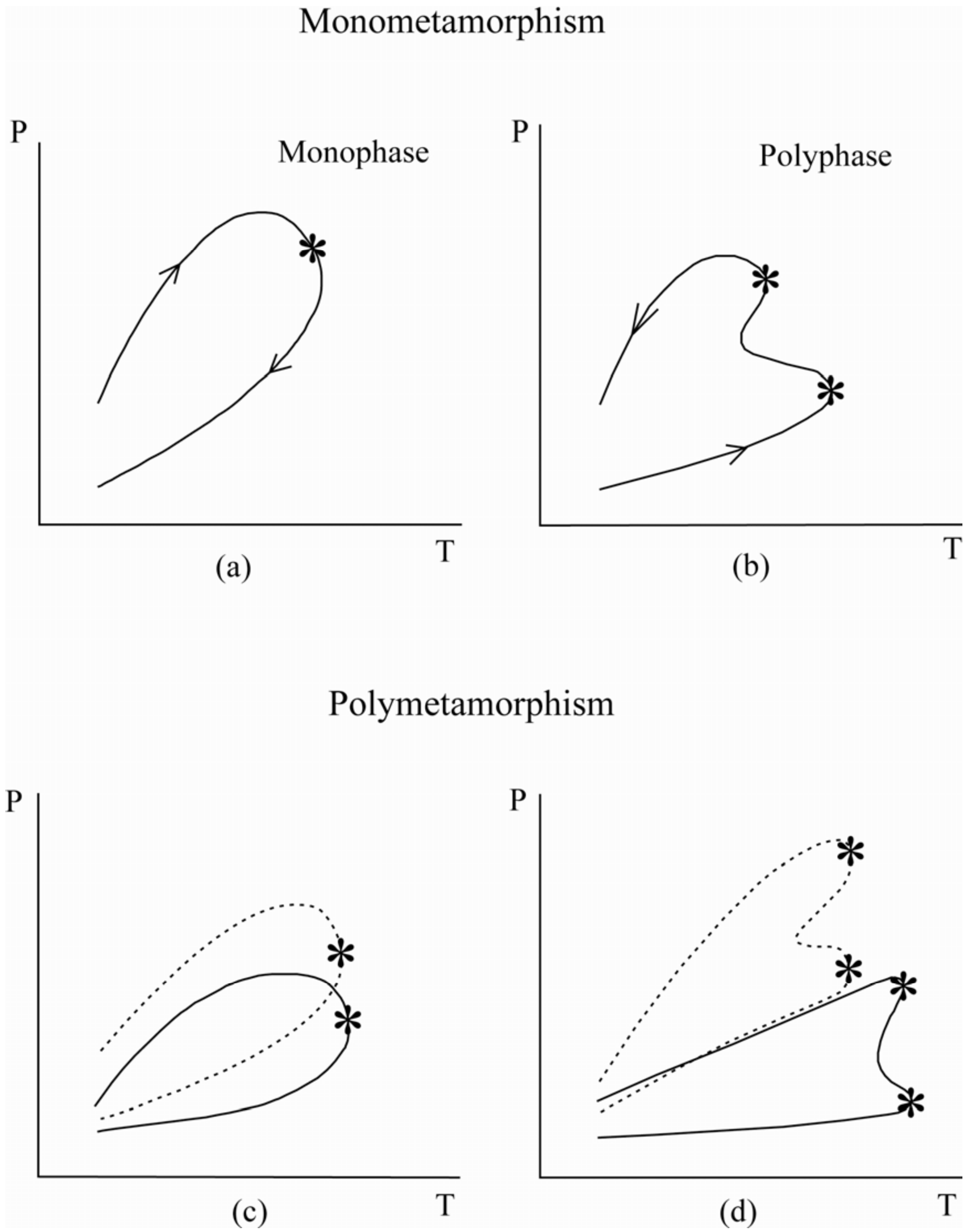
Monometamorphism
P
Monophase
T
(a)
P
Polyphase
T
(b)
Polymetamorphism
P
T
(c)
P
T
(d)

Fig 2.2

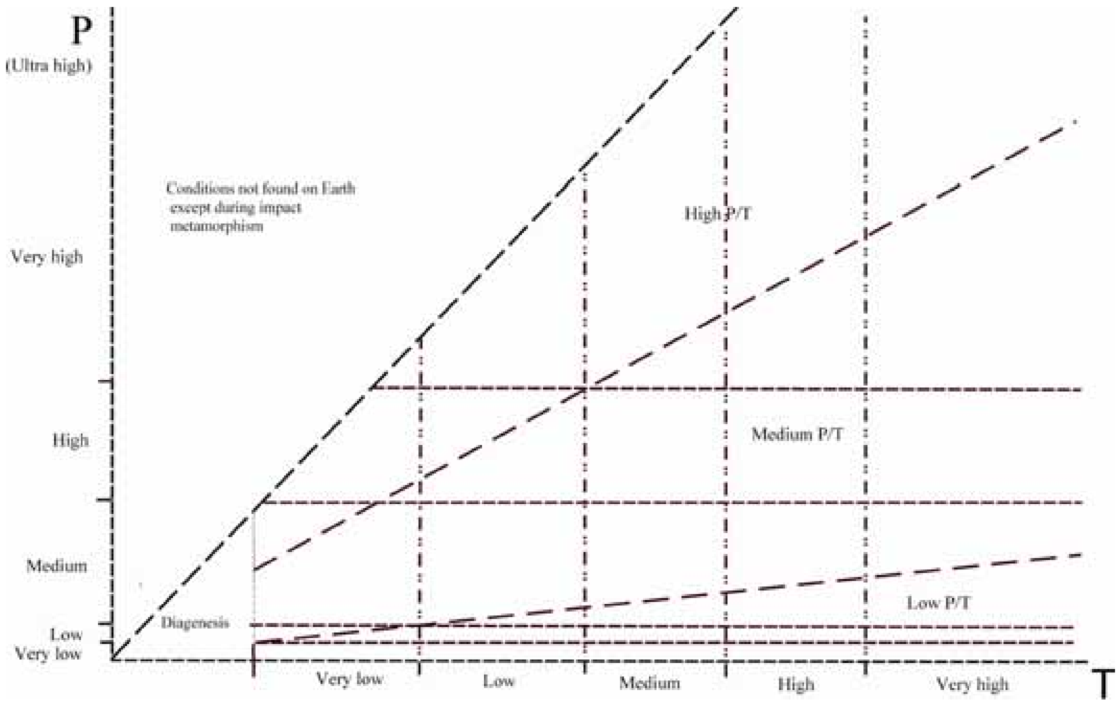
P
(Ultra high)
Very high
High
Medium
Low
Very low
Conditions not found on Earth except during impact metamorphism
High P/T
Medium P/T
Low P/T
Diagenesis
Very low
Low
Medium
High
Very high
T

Fig 2.3

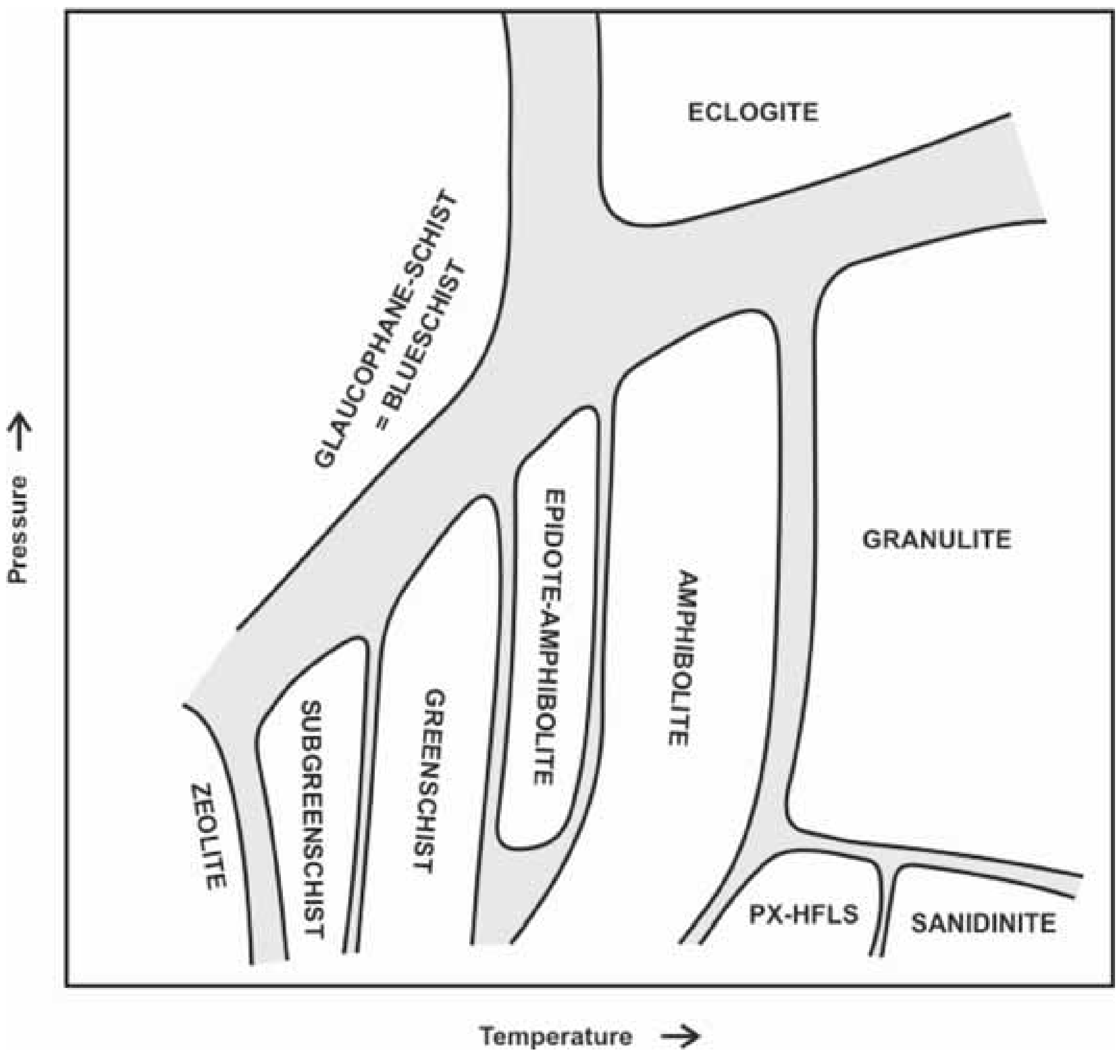
ECLOGITE
GLAUCOPHANE-SCHIST = BLUESCHIST
GRANULITE
EPIDOTE-AMPHIBOLITE
AMPHIBOLITE
ZEOLITE
SUBGREENSCHIST
GREENSCHIST
PX-HFLS
SANIDINITE
Pressure
Temperature

Fig 2.4