The metamorphic facies concept

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Summary. Present-day facies schemes are reviewed in relation to their definitions and applicability: a simplification is proposed based on assemblages in basaltic rocks, with secondary facies defined subsequently on pelitic assemblages.

Introduction and the definition of facies

THE metamorphic facies concept, introduced by Eskola (1915), has proved to be such a powerful agent in the study of metamorphism that the commonly accepted terms for the principal metamorphic facies are in general use amongst geologists, whereas specialists in the study of metamorphic rocks find themselves able to apply and extend the facies system wherever necessary. It is therefore fitting that Tilley (1924) was among the first to welcome and critically consider the concept and is also joint-author of the latest proposal for a new facies (Yoder and Tilley, 1962, pp. 513–514, the 'pyroxenite facies'). The development of detailed schemes, has, however, been to a large extent in the hands of Turner (most recently expressed in Turner and Verhoogen, 1960) following on the work of Eskola (1939, especially). The evolution of ideas can be studied in the comprehensive review in Fyfe, Turner, and Verhoogen (1958) and in the most interesting early discussion by Turner (1948, pp. 45–59).

The earliest definition of metamorphic facies which is now quoted, apart from the general formulation of Eskola in 1915, is that of Eskola (1920): '. . . the term metamorphic facies to designate a group of rocks characterised by a definite set of minerals . . . at perfect equilibrium. . . .'

Criticism of this definition has been almost entirely directed at the equilibrium requirement, which is manifestly not found in most regionally metamorphosed rocks, especially in the low and middle grades of metamorphism. It is usually possible, though, to ignore the evidence of disequilibrium and find the probable original equilibrium assemblage. Apart from minor criticisms of terminology and of individual facies, the most substantial direct criticism has been that of Ramberg (1952, p. 136), who found that if too literal [? logical] an application is made of Eskola's ideas, there will be an infinite number of facies. Like Turner (1948),

Ramberg proposed a definition involving physical conditions, thereby introducing a subjective, or interpretative element into the definition.

Although the original definition has broadly withstood the tests of time, the application of Eskola's ideas has revealed weaknesses which have not yet been fully discussed or resolved, weaknesses which stem chiefly from the almost infinite variety of rock types involved and the ever-increasing complexity of the external factors (P, T, P_{H_2O}, P_{CO_2}, etc.) invoked to explain particular assemblages. Examination of Eskola's definition (or, indeed, any of the definitions subsequently discussed) shows that any particular facies, defined by a set (or sets) of characteristic mineral assemblages, must eventually have its boundaries defined by reactions which take place within any one rock-type without change of bulk composition. Conventionally, expulsion of mobile components (most commonly H_2O and CO_2) is disregarded, but this convention must eventually lead to difficulties in situations in which normally inert components become mobile, as probably happens, for instance, in the production of cordierite–anthophyllite rocks. Once a particular rock-type (composition) is chosen to define any one boundary, it is logically desirable that all the boundaries of that facies, and therefore of all facies, be defined by the same rock-type. It appears that this consideration was a powerful factor in leading Eskola to choose the common basalt type of rock to define most of his eight facies (1939). Nevertheless it was not possible to obtain a satisfactory definition of the various facies in terms of the assemblages developed in basaltic rocks alone, so that auxiliary assemblages had to be used in order to make unique diagnosis possible, such as orthoclase–andalusite, which occurs in the pyroxene hornfels facies and is absent from all others.

As a consequence of the non-ideal situation arising from the complexity of natural rocks and the factors which control the mineral assemblage, and in particular because no single rock-type exists which shows sufficient, definable variation, the definition of a metamorphic facies has evolved into a series of statements concerning the nature of a facies (Fyfe, Turner, and Verhoogen, 1958, pp. 10 and 18). Of particular interest are the statements: '. . . a metamorphic facies is here defined as a series of mineral assemblages . . .' (p. 18), and 'A facies or subfacies therefore is defined and recognised on the basis of a complete association (in time and place) of mutually gradational assemblages, rather than on one critical assemblage' (p. 10). The latter statement is based on the argument that most common assemblages belong to two or more facies.

To the author, it seems more than a little curious that the state of affairs has ever come about whereby common assemblages do in fact belong to more than one facies. Taken out of its context this statement would appear to be absolutely reasonable, as a mineral assemblage developed in, say, a pelite will in general not coincide in range of stability with an assemblage developed in an amphibolite. But it must be remembered that, as a consequence of the original definition of a facies, every change in assemblage in a definitive rock-type of fixed composition will constitute a new facies. To make assemblages of assemblages, the criterion of a facies, as Fyfe, Turner, and Verhoogen have done, means that the boundaries between 'facies' will be blurred, as not every rock-type will choose simultaneously to develop a new assemblage under a critical combination of external conditions. To overcome this defect, a compromise solution seems to have been adopted, whereby assemblages of assemblages are used to diagnose a facies, while particular reactions are chosen to define its boundaries. This appears to be a return to Goldschmidt's notion of 'facies groups' (Goldschmidt, 1921) and to represent a major departure from any application of the simple idea of 'one assemblage equals one facies'.

Subfacies

A further complication in the facies system of nomenclature was introduced by Eskola (1939) in the form of 'subfacies'. This idea was adopted by Turner and developed until four of the major facies of Fyfe, Turner, and Verhoogen have subfacies. The assemblages used to define the subfacies are in calcsilicate systems in the sanidinite facies, in pelitic systems in the greenschist and almandine–amphibolite facies, and in basaltic systems in the granulite facies. No suggestion has been made that any subfacies can be recognized outside of its own (major) facies, because assemblages of assemblages are used in each case to define facies. Each subfacies is therefore confined to a particular facies, but it is evident that the assemblages used to define the subfacies may actually be stable within another facies. Thus we have (Turner and Verhoogen, 1960) as examples of stable assemblages:

(a) almandine–amphibolite facies, sillimanite–almandine–orthoclase subfacies:
   (i) in basaltic systems, almandine– or epidote–plagioclase–hornblende;
   (ii) in pelitic systems, sillimanite–almandine–orthoclase;

(b) granulite facies, hornblende granulite subfacies:
  (i) in basaltic systems, plagioclase–hornblende–diopside–hypersthene;
  (ii) in pelitic systems, sillimanite–almandine–orthoclase.

It would appear that the distinction between facies and subfacies is arbitrary, because, whereas the boundary between the facies quoted above is based on reactions within a basaltic system, the boundary between the pyroxene hornfels and the granulite facies is defined by a reaction (inversion) within a pelitic system. The arbitrariness of this distinction may in part be due to the fact that no one has considered the true meaning of a subfacies in detail. The prefix 'sub' is ambiguous: we have not been informed whether it is intended to designate a 'subordinate' or a 'subdivisory' character (or both). It appears that the term is at present primarily used in the latter sense, but the subdivisions so far defined have grown up in a non-systematic manner, being chosen as a result of historical factors, such as the availability of discussions of particular rock-types in particular grades of metamorphism.

The definition of particular facies

Having briefly considered the definition of facies and subfacies, it is appropriate to study next the facies system proposed by Fyfe, Turner, and Verhoogen (1958) and modified in Turner and Verhoogen (1960). As a whole book could be written on the general subject of the problems of individual facies, only a few salient points can be noted here. The general division of facies into regional and contact types tends to imply that there are two (entirely) separate types of metamorphism, high- and low-pressure. Although it is stated (Turner and Verhoogen, 1960, p. 509) that 'transitional facies will ultimately be established', the possibility of this seems remote, as pressure-sensitive reactions or inversions, not yet known, must be found. It seems fairly clear that, among the common rock-types, there is little likelihood of achieving such an aim unless unusually detailed analysis shows pressure-sensitive changes in minerals which are members of solid-solution series. In hydrous rock-systems it is probable that vapour pressure effects will over-rule such changes, but there is perhaps more likelihood of success in anhydrous systems containing such minerals as cordierite and garnet. It is therefore considered that this division of facies into two groups is a retrogressive step, which simplifies the presentation and makes life easier for students, but which nevertheless gives a false impression of a fundamental division.

Amongst the individual facies, attention may be drawn to difficulties arising in the application of three examples. The essential means for identifying the albite–epidote hornfels facies is 'the difference in field occurrence' (Turner and Verhoogen, 1960, p. 510): it contains assemblages identical with those in the greenschist facies. Objection may be taken to its name—do any rocks describable as 'albite–epidote hornfels' exist ?—while there must be some doubt whether the assemblage albite–epidote is in fact an equilibrium assemblage under the range of conditions which is specified for this facies.

Another facies which presents acute problems in recognition and definition is the hornblende–hornfels facies. There is no general problem here, as there are numerous mineral assemblages which differ from those normally developed in the well-established amphibolite and pyroxene–hornfels facies, and which clearly develop as the result of physical conditions differing from these facies, as indicated by experimental data and field relations. The difficulties stem from the unusually large range of minerals which are said to be present in, or absent from, this facies, particularly in relation to the almandine–amphibolite facies. As almost all of the reactions involved are highly temperature-sensitive, it is exceptionally difficult to define an assemblage of assemblages, the stability limit of which will constitute an effective boundary with the almandine–amphibolite facies, which must in general be a higher-pressure facies. The gross zone of overlap suggests that a more rigorous analysis of the nature and occurrence of the assemblages said to be diagnostic of the two facies in question is indicated.

The third example concerns the boundary between the greenschist and almandine–amphibolite facies, which has always presented a problem, as any survey of the history of the facies concept will show. The very well-defined assemblage albite–epidote–hornblende, rightly said by Ramberg (1952, pp. 148–149) to comprise rather great areas of rocks, has been placed by Turner in the greenschist facies (Fyfe, Turner, and Verhoogen, 1958) on the basis of the subassemblage albite–epidote, used to define that facies. Thus amphibolites are members of the greenschist facies, a historically confusing nomenclatorial problem. Finally, it may be remarked that the albite–epidote–plagioclase reaction, though entirely permissible for defining a facies, is one which appears to be subject to so many possibly decisive independent variables, that its use will preclude (in nearly all cases) any attempt at close assignments of P, T conditions for its occurrence in nature. Complexity is introduced by the fact that epidote is one of the rare hydrates more dense than its nearest

anhydrous equivalent; the reaction will be influenced by variations in the activities of H_2O, CO_2, and O_2 as well as the presence or absence of excess Na_2O, CaO, Al_2O_3, SiO_2, or Fe_2O_3 in the system, besides control by external P and T.

Concerning classifications

As a means of classifying metamorphic rocks, the suitability of facies is beyond doubt. The scheme is simple to apply, yet comprehensive, is elastic and is also capable of being interpreted genetically. Nevertheless, difficulties will always arise in the application of facies because of the varied nature of the uses to which the classification is put. Two principal classes of people exist: the professional student of metamorphic rocks, for whom the classification is ever-adjustable and flexible, and the more general 'geologist' who is interested only in correct summaries of the facts concerning metamorphic rocks. The former group will contain creators and modifiers of the classification, as well as acceptors and appliers of proposed schemes: they may in general be assumed to be sufficiently proficient in the niceties of the problem that the problematic aspects of any classification may be instantly recognized. The second group, however, will generally assume that the 'experts' have produced not only the most satisfactory scheme available, but also the one in which error is effectively absent. This places an onus upon the creators of classifications to ensure that their schemes are incapable of incorrect application and genetic interpretation.

Such a requirement will generally create a conflict between any ideal classification and the most practical equivalent version, manifested usually in the nomenclature. Too many pigeon-holes or names will usually render a classification unworkable (how many is too many is open to doubt, but twenty is probably of the right order), but too few will engender error and confusion. The metamorphic facies classification is particularly subject to this difficulty, with the result that almost any scheme will have drawbacks on one side or the other, on account of the limitations imposed by the natural rock systems observed. If it is accepted that no better scheme exists, as is surely the case, then the question is only whether one compromise system or another is chosen.

Suggestions for the further development of the metamorphic facies concept

The general criticisms levied above on the scheme set out in Turner and Verhoogen (1960) have caused the author to think from time to time in terms of revisions of the scheme, but the complexity of natural

rock systems and the inadequacy of our information about them (a matter of considerable concern) have, in combination with other factors, caused hesitation and even reversals of trends of thought.

In proposing any system of facies, various facts of metamorphic life must be considered:

(a) that the only rock types which are sufficiently universal, and also contain minerals with small enough ranges of stability, for use to be made of them as a basis of a general classification, are basalts and pelites;

(b) of these, the pelitic systems show the most variation, but the basaltic group is present over the widest range of conditions—pelites could not be used to define the eclogite facies and would be unsuitable for use in defining a glaucophane-schist facies or granulite facies, on account of rarity and/or chemical differentiation;

(c) the difficulties caused by the presence of CO_2 must eliminate all carbonate-hydroxyl-bearing rocks from use as a principal class in any scheme intelligible to the layman;

(d) there are not enough solid–solid reactions in which only anhydrous phases participate to define any system of facies;

(e) there are no minerals which are not members of solid-solution series which possess sufficient polymorphs to be of use by themselves in any system of facies (the alumino-silicates provide the closest approach).

The limitations thus imposed must mean that any simple facies system must be incapable of precise interpretation in terms of physical conditions, while as greater degrees of precision of interpretation are sought, so must there be a corresponding increase in the precision of the described system(s), with a corresponding reduction in its applicability to other regions or sets of rocks.

Bearing in mind the limitations and criticisms already mentioned, certain tentative suggestions may be made, the development of which must await a later article. Adhering to Eskola's definition of 1920 (given above) and taking literally the requirement that once a 'definite set of minerals' changes into another set of minerals, by reaction and *not* by continuous change of bulk composition, then another facies is defined, a set of (primary) facies may be set up based on rocks of basaltic composition. The vagueness of this composition should not be sufficiently great to undermine the definition: it can be considered in more detail later.

A minimum set of such (primary) facies would include Turner's (1948)

greenschist, albite–epidote–amphibolite, amphibolite, and eclogite facies;
Turner and Verhoogen's (1960) glaucophane-schist facies and zeolite
facies(?); and a hornblende-two-pyroxene facies and a pyroxene facies
(though the status and definition of the latter pair must be considered
in more detail than is possible here), together with Yoder and Tilley's
'pyroxenite' facies. Notable absences from this group include the
pyroxene–hornfels facies and all other contact metamorphic facies,
whose assemblages within basaltic systems do not differ from those of
the facies already mentioned. In this brief statement not all possible
facies have been mentioned; there are, notably within the greenschist
group of rocks, probable variations in assemblage in rocks of defined
bulk composition, but the complexity within this facies is so great that
any subdivisions must be withheld for the time being.

In order to extend the series of facies so defined, which is insufficiently
numerous to contain the natural divisions of metamorphic rocks
generally recognized, a series of 'secondary facies' (i.e. true facies, but
of a subordinate nature) must be established, preferably using rocks of
pelitic composition. This composition, albeit not so well defined, may
be (again for the time being) defined as those rocks which lie within the
triangle A-anorthite-almandine in the conventional ACF diagram (this
is a wider definition than Fyfe, Turner, and Verhoogen give (1958,
p. 200)). This immediately introduces a vast number of possible facies,
so many indeed, that the system is weakened as far as communication
with the layman is concerned. Hence a compromise seems desirable, and
it is suggested that the secondary facies be grouped into five facies-
groups or macro-facies, characterized by the presence of

> (a) hydrous aluminium silicates,
> or (b) kyanite (+ vapour),
> or (c) andalusite (+ vapour),
> or (d) sillimanite (+ vapour),
> or (e) mullite + quartz (+ vapour).

The advantages and disadvantages of using these minerals as facies
indicators must also be deferred to later, but it must be noted that under
the literal interpretation of facies followed herein, each alternative (a)
to (e) above must define a new facies. Considerations of metastable
crystallization and complexities in the interpretation of the presence of
any particular alumino-silicate phase are matters to be decided locally;
the hard fact remains that, broadly, the geological distribution of the
phases mentioned fits with the relative fields of stability so far defined.

The scheme presented possesses about seventeen combinations of (primary) basaltic facies and (secondary) pelitic (macro-) facies, and is capable of considerable subdivision within the existing framework. Further (?micro-) facies may be added where circumstances warrant it, using rocks of different bulk composition.

It may be objected that this scheme also uses the criticized idea of assemblages of assemblages, but differences exist between this and previous schemes, notably that that idea does not appear in the definition, while every different assemblage is in fact used to define a facies. The system of nomenclature indicates this; the amphibolite facies includes all rocks metamorphosed under conditions giving rise to amphibolites from basaltic rocks, the kyanite facies similarly, while a more limited range of conditions give rise to rocks metamorphosed in the amphibolite and kyanite facies. The use of this dual nomenclature will unfortunately preclude the adoption of Tilley's recommendation (1924) that mineral assemblages be used as names for the different facies.

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