Metamorphism today: new science, old problems

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Abstract: A concise history of the discipline of metamorphic petrology is presented, from the eighteenth-century concepts of Werner and Hutton to the end of the twentieth century.

At the beginning of the twenty-first century, can we speak of a crisis in metamorphic petrology? Only a few years ago, it was still considered to be one of the most 'scientific' branches of the Earth sciences, flourishing in all major universities. It was a time when, in a few places, metamorphic petrologists were given official positions in chemistry or physics departments, as the best possible specialists for a discipline like equilibrium thermodynamics, traditionally considered an integral part of chemistry. Currently, the situation is completely different. The irruption of 'exact' sciences in the traditionally 'descriptive' biological and terrestrial disciplines, has been marked by a profusion of new terms such as biogeochemistry and associated 'new' disciplines, all claiming to be drastically different from their predecessors and seeking recognition and independence. Added to a pronounced change in scientific priorities, caused by a growing awareness of the fragility of our environment and the uncertain fate of future generations, the result is an obvious decline in some topic areas, among which is metamorphic petrology. The large population of metamorphic petrologists that was hired during the golden years of university expansion after World War II is now slowly disappearing without being replaced, and public and private funding is redirected to apparently more urgent problems, mostly dealing with the environment.

However, among the three rock types occurring at the Earth's surface or accessible to direct observation in the outer layers of our planet (sedimentary, magmatic, metamorphic), metamorphic rocks are by far the most abundant. Sediments only make up a thin, discontinuous layer at the Earth's surface. Magmas are (partly) formed at depth by partial melting of former metamorphic rocks, but this melting is local, limited in time and space. After crystallization, most volcanic and plutonic rocks are reworked and transformed into metamorphic rocks. The Earth is in constant evolution, characterized by permanent continental masses and temporary oceans, created and collapsing at a timescale of few hundred million years. The oceanic crust, created by magmatic eruptions at mid-ocean ridges, is to a large extent – at least 80% in volume – transformed into metamorphic rocks by sea-floor hydrothermal alteration. So, all together, it is not an exaggeration to claim that most rocks that we can observe are metamorphic. Yet, if the present trend continues, metamorphic petrology will soon join other 'ancient' disciplines, like mineralogy and palaeontology, on the list of endangered species in today's competitive university world.

It is true that metamorphic petrology has always had problems in finding its right place between its neighbours, magmatic and sedimentary petrology, with which it partly overlaps. This is probably one of the reasons why, a century apart, two prominent petrologists have felt the need to make an extensive review of the historical development of their discipline: Gabriel Auguste Daubrée (1857, 1859) and Akiho Miyashiro (1973, 1994), and many others essays can be found (e.g. Hunt 1884; Williams 1890; Yoder 1993). Metamorphic petrologists ourselves, we have drawn on the work of these illustrious predecessors, without attempting to go into the detail of their investigations. To cover everything would require more than one book. We have, however, tried to identify the most important lines of research and thinking, showing that despite considerable developments in methodology, instrumentation and interpretation, some basic questions keep recurring, and probably will do so for years to come.

Metamorphism and magmatism: from the beginning, not easy to define limits and relations

Even now, it is not easy to define metamorphic rocks so as to distinguish them unambiguously

from sedimentary or magmatic rocks. Metamorphic rocks derive from 'protoliths' (sedimentary, magmatic or metamorphic) formerly exposed at the surface, buried at lesser and greater depths during the subsiding of sedimentary basins or the formation of mountain chains, then brought back to the surface by erosion. Changing pressure and temperature conditions lead to the formation of new minerals, typically formed through (fluid-assisted) solid-state recrystallization. In the early stages, most newly formed minerals are platy (chlorites, micas), and they define a new rock structure/texture: schistosity for low-grade metamorphic rocks (transition from pelite (sediment) to slate, and then to schist); foliation for high-grade rocks (gneiss). But any petrologist knows that structural elements alone cannot give a precise definition, which relies essentially on the presence of characteristic minerals: zeolites at the beginning of metamorphism; and, at highest temperatures, minerals like pyroxene or garnet, which result in rocks devoid of oriented structures. This is the domain of granulites, where metamorphic temperatures can reach 1000°C or more, overlapping the magmatic domain. For these rocks, the distinction between magmatic and metamorphic rocks is by no means clear-cut. Metamorphic rocks, in principle, should not have passed through a melting stage. But partial (or total) melting is common at these high temperatures, resulting in an intricate mixture of both types (migmatites). Moreover, magmatic rocks, once crystallized at depth, may have subsequently been deformed and recrystallized, becoming a new category of metamorphites (orthoderivates). In such cases, the precise characterization of the different rock types requires an advanced knowledge of the conditions of their formation, notably the timing at which the different events have occurred. Is the magmatic rock, with granite as the typical example, the cause of metamorphism, provoking mineral recrystallization at its contact? Or is it its result, the ultimate product of metamorphic transformation? In this respect, metamorphism is closely related to the 'granite problem', a major source of discussion among petrologists for nearly two centuries.

Metamorphism in the period of Neptunism and Plutonism

The Neptunist scheme, proposed by Abraham Gottlob Werner (1774) and developed in the writings of his students such as Jean François d'Aubuisson des Voisins (1819), had little place for what we would call metamorphism. Every rock type was deposited in a stratified form at a given time. Even 'hard rocks' like schist and granite were supposedly deposited from a hypothetical 'primitive' ocean, hotter and more concentrated than the present-day, 'post-Flood' ocean. As observed by Gabriel Gohau (in Bonin et al. 1997), this scheme was linear overall, each epoch being characterized by a specific rock type (though Werner did envisage rises and falls of his ocean, and different conditions of storm and calm, to allow for divergences from his general 'directionalist' scheme). The oldest rock was thought to be granite, and the evolution was essentially irreversible: there was only one epoch for the formation of granite, as well as all non-fossiliferous rocks (gneiss, schists), all regarded as 'primitive rocks'.

At the turn of the nineteenth century, Werner's prestige and influence were such that most of continental Europe had accepted his views, despite the fact that students of the French Massif Central, notably Faujas de Saint Fond and Desmarest, had recognized the igneous origin of basalts. But the Scotsman James Hutton went much further. According to his thinking, not only basalt, but even granite, the fundament of the Wernerian system, was an igneous rock, a kind of lava that might be younger than the surrounding rocks. Hutton's *Theory of the Earth*, first published in 1788 and then elaborated in a book of the same title in 1795, corresponded, at least from an early twentieth-century perspective, to the only true 'revolution' that Earth sciences have known (Von Zittel 1899; Geikie 1905). Not only lavas, but also 'plutonic' rocks, notably granite, were supposedly made by fire, at any epoch of the Earth's history, provided that adequate physical conditions (notably temperature) were attained. Note that Hutton remained rather vague about the location and cause of this fire. He simply referred to subterraneous fire or heat and argued that, as the reality of heat was demonstrable by its effects, it was unnecessary to search for its cause. In fact, in this respect Hutton was not a great distance from Werner, who had explained present-day basalt, the only volcanic rock that he recognized, by the underground combustion of coal deposits. For instance, Hutton stated that combustible rocks, issued from the vegetal remnants in sediments, constituted an inexhaustible heat source (Gohau, in Bonin et al. 1997).

Yet Hutton's ideas led to the notion of metamorphism. In the Isle of Skye, he had observed that lignite at the contact of basalt was transformed into shiny coal, from which he inferred the igneous origin of basalt. However, he did not

use the word 'metamorphism', at least in the sense that it has today (The term 'metamorphosed' is to be found in the *Theory of the Earth* (Hutton 1795, vol. 1, p. 504), but in the context of a long citation (in French) from Jean Philipe Carosi, about the supposed formation of flint ('silex') from a 'calcareous body' under the influence of running water, a notion which Hutton rejected.)

Hutton's ideas were not immediately accepted by the whole scientific community. Several of Werner's students, notably Leopold von Buch, were convinced of the igneous origin of basalt after having seen the active volcanoes in Italy. However, as late as 1863, most popular geology books in France (e.g. Figuier (1863), which was soon translated in neighbouring countries (Beima 1867)), were still much influenced by the Wernerian system. Hutton himself, who had initially studied medicine and then agronomy, before turning to geology, was considered to be an amateur by much of the European establishment. A 'Wernerian Society' was even created in Edinburgh not long after Hutton's death (1803), with the goal of expounding and defending the ideas of the old master of Freiberg. But Hutton found two dedicated disciples, John Playfair and, after his death, Charles Lyell, who proved to be lucid and prolific writers and finally achieved a wide acceptance of his views.

It is remarkable to see how much the dispute relied on theoretical arguments, with only a few people taking a more empirical approach, resorting to the examination of field exposures to decide between both systems. George Bellas Greenough, first president of the Geological Society of London, who travelled through Scotland equipped with Playfair's (1802) exposition of Hutton's work and the Wernerian-inspired *Mineralogy of the Scottish Isles* by Robert Jameson (1800), was a notable exception, but he found the evidence inconclusive (Rudwick 1962). Hutton's friend Sir James Hall (1805, 1812, 1826) sought to carry out experiments to test Hutton's ideas, but without total success.

In the last volume of the first edition of his *Principles of Geology* (Lyell 1833, pp. 374–375), Lyell claimed the paternity of the term 'metamorphism'. Daubrée (1857) gave the year 1825 as the first introduction of the term by Lyell, but despite careful search, Gohau (in Bonin *et al.* 1997) was unable to find the original reference.

A difference of a few years is not really of great importance: the idea was already 'in the air'. Before 1833, the name (often in a slightly different form, '*métamorphose*'), had already been used by a number of other authors, including Ami Boué (1820, 1824) and Léonce Elie de Beaumont (1831) in France. In fact, it seems that the contribution of Ami Boué to the birth of the concept of metamorphism from Hutton's theory is far more important than those of Lyell and Elie de Beaumont, but his writings, still rather difficult to find today, remained relatively 'confidential' (G. Godard pers. comm.). This was not the case with Elie de Beaumont, a powerful and authoritative figure at a time of French economic prosperity, who had been a good field geologist in his younger days, responsible with Dufrénoy for the first edition of the *Carte géologique de la France*. His great idea, developed from the theory of 'central fire' of Fournier (1820, 1837) and Cordier (1828), who themselves developed earlier concepts adumbrated by Descartes, Leibniz and Buffon (Green 1992), was that the Earth had cooled progressively, leading to a thickening of the crust and shrinkage of the outer envelope 'to stay in contact with the molten core' (Elie de Beaumont 1831). In 1833, in his lectures at the Collège de France, he introduced the notion of 'ordinary metamorphism' ('*métamorphisme normal*') 'for the transformations occurring at the bottom of the oceans under the influence of the incandescent core' and 'extraordinary metamorphism' ('*métamorphisme anormal*'), produced by temperature changes at contacts with igneous masses. *Métamorphisme normal* still relied on a vague notion of a Wernerian '*Urozean*', whereas *métamorphisme anormal* was much closer to contact metamorphism as we know it today. The terminology introduced by Elie de Beaumont was soon modified by two French colleagues, leading to the names still used today. Daubrée (1857), who developed the experimental approach initiated by Hall at the time of Hutton, called ordinary metamorphism '*régional*', as opposed to *métamorphisme de juxtaposition* (the *métamorphisme anormal* of Elie de Beaumont) caused by the proximity of eruptive rocks. Daubrée recognized that the latter, soon called 'contact metamorphism' in the international literature, resulted in a loss of pre-existing structure, whereas regional metamorphism led to foliation (*feuilletage*). This regional metamorphism might occur at different times. Thus, in this respect, Daubrée (1857) was close to some views defended by Lyell. However, for pre-Silurian rocks, he still invoked a 'primitive' metamorphism, which was different from any Lyellian or modern concept. In all cases, temperature (only approximately estimated at that time) was not considered to be a dominant factor. Daubrée, with Elie de Beaumont at the Paris Ecole des Mines, then the major geological centre in

France, was impressed by minerals deposited from thermal spas, notably at Plombières in the Vosges (Daubrée 1857). Thus, together with most of his colleagues, he thought that most recrystallizations at depth were induced by circulating solutions. Even granite was thought to be produced by 'aqueous plasticity', not igneous melting (Breislak 1822). Daubrée's ideas were not that different from Werner's conceptions, except that the '*Urozean*' was not thought to be at the Earth's surface, but hidden at depth.

Other scientists were following Hutton more closely regarding the major role of fire and, above all, the uniformity of physical conditions since the beginning of Earth's history. These contrasting views led to controversy, well illustrated by an exchange of notes between Joseph Durocher (1845) with Joseph Fournet (1848), the major defendant of magmatic theories, and Theodor Scheerer (1847), who had joined the Ecole des Mines group from Scandinavia. It would take too long here to report the details of this debate, but essentially it dealt (already!) with the question of the metamorphic or magmatic nature of granite, a recurrent debate which was to rekindle in the twentieth century (see summary by Gohau in Bonin *et al.* (1997, pp. 37–45)). Here, we may only mention that the most extreme 'hydrothermalist' was Achille Delesse, also related to the Ecole des Mines group. His book on metamorphism (Delesse 1857), first printed as a series of papers in the *Annales des Mines*, was later taken as their original reference source by the 'transformist' school. Delesse preferred the name 'general' rather than the normal or regional metamorphism of Daubrée and Elie de Beaumont, and 'special' for contact metamorphism. The first type was characterized by its regional scale, and a usually unseen cause. The second occurred at contacts with volcanic or plutonic rocks. But, in all cases, temperature was not considered to be an important factor. Delesse thought that only effusive lavas were true igneous rocks. But, in most cases, these had little influence on the surrounding rocks. Consequently, igneous rocks were not regarded as a cause of metamorphism; they were not igneous, but, like the surrounding gneiss, were the ultimate product of metamorphism. They could supposedly be formed almost at room temperature under the action of appropriate circulating solutions.

For his demonstration, besides observations which were, indeed, not irrelevant (e.g. the absence of indications of mutual influence between granite and gneiss), Delesse used arguments that may sound surprising today. For instance, granite must soften at the sea shore, as it is easily penetrated by sea-weed! Together with water, under great pressure but at moderate temperature, all rocks which are not clearly volcanic lavas could form from 'a very fluid muddy-paste' ('*une pâte boueuse trés fluide*'), analogous to a cement. Metamorphism occurred during the consolidation of this 'paste' and affected both the surrounding rocks ('*métamorphisme éverse*' or '*exomorphisme*') as well as the plutonic rock itself ('*métamorphisme inverse*' or '*endomorphisme*').

The golden (German) era of descriptive petrography

France was defeated by Prussia in 1870, and French scientists were soon to lose their pre-eminence on the international scene. Strasbourg, now at the western border of the German nation, became a major university, with a mineralogy chair occupied by Harry Rosenbusch, who together with Ferdinand Zirkel from Leipzig and some others created modern descriptive petrography. The polarizing microscope and techniques of sample preparation (thin sections), elaborated by a small group of British scientists (Davy, Brewster, Nicol and Sorby) during the first half of the century, were by then of high quality, and were to remain largely unchanged for many years. For more than fifty years – the first edition of the *Mikroskopische Physiographie der Mineralien und Gesteine* was published in 1873 and the last in 1929, well after his death – Rosenbusch compiled a descriptive catalogue of all magmatic and metamorphic rock types, worldwide. Discussion of magmatic rocks occupied by far the most important place: more than four-fifths of the *Physiographie*. But he also showed a keen interest in metamorphic rocks, and one of his major Strasbourg achievements was to study the contact aureole of the Andlau granite, in the Vosges (Rosenbusch 1877) (see Fig. 1). Rosenbusch identified several successive zones, based on the rock structure (schists, knotted schists, hornfelses). Contact metamorphism could be clearly related to heating by the intrusive granite. The same process could occur on a larger scale, if caused by a continuous, hidden layer of granite at the base of the continents. This was so evident for Rosenbusch that he did not consider any type other than contact metamorphism for the clay-rich sediments (pelites), which show the most obvious changes during progressive metamorphism. He observed that rocks in the contact aureoles around the Andlau massif did not contain feldspar, and he regarded this an
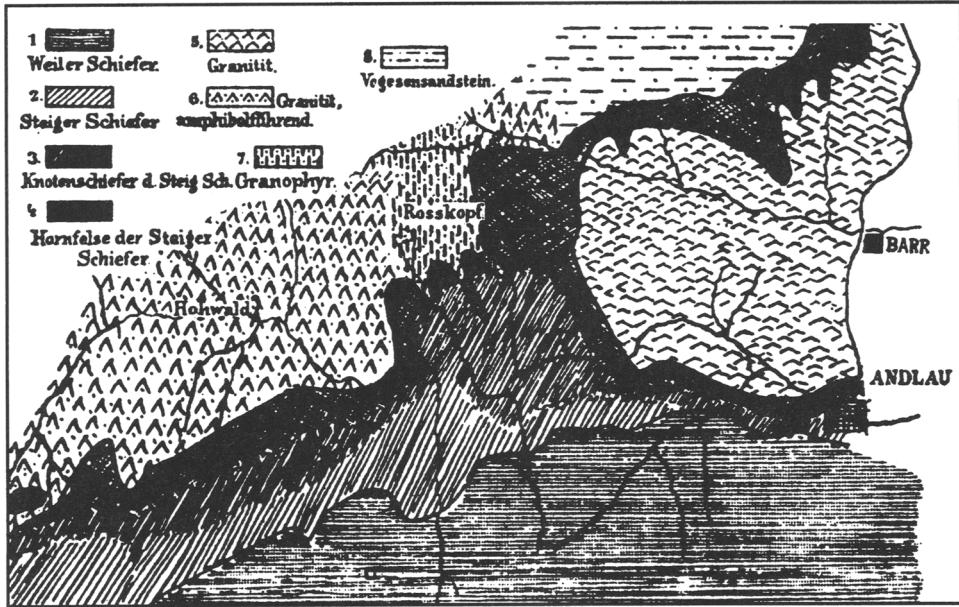
Fig. 1. Contact metamorphism of the Barr-Andlau granite, Vosges (Rosenbusch 1877).

essential feature of contact metamorphism. However, feldspars are major constituents of most rocks occurring in areas of regional metamorphism, which therefore had to be fundamentally different. Rosenbusch ascribed the acquisition of gneissose structure to deformation, mostly of former igneous rocks, and defined the new concept of 'dynamometamorphism'. Both types could be independent, but in general they occurred successively, dynamometamorphism being superimposed on former contact metamorphism to give the typically foliated texture.

It is interesting to note that Rosenbusch's ideas on dynamometamorphism derived directly from some experiments by Daubrée, who showed that deformation could generate heat. However, despite the prominent position of Daubrée in his country's academic system, dynamometamorphism did not become popular in France. The ideas of Rosenbusch were vigorously discussed in France by the followers of Delesse and Elie de Beaumont, notably Alfred Michel-Lévy. Together with Ferdinand Fouqué, who was trained by Rosenbusch himself, Michel-Lévy brought a major contribution to the theory of polarization microscopy. Both authors wrote a book on the determination of the rock-forming minerals – the French equivalent of the *Mikroskopische Physiographie* –

which, although it had not the encyclopedic character of the treatise of the master of Heidelberg, attached much greater importance to the determination of feldspars (Fouqué & Michel-Lévy 1878; Michel-Lévy 1888). This had major consequences, not only for igneous rock classification (for the French based on feldspar composition; for the Germans on the colour index), but also for the conception of metamorphism. Michel-Lévy (1887) found feldspar in the contact aureole of the Flamanville granite in Normandy. In consequence, there was, in his view, no fundamental difference between contact and regional metamorphism. He eliminated the old notion of '*terrains primitifs*', a relic from Werner's belief that metamorphism (as we would call it) depended on age and occurred under conditions essentially different from today. Feldspathization could occur at any time, mostly under the influence of '*émanations*' issued from a mysterious source at depth. Deformation was unimportant: '*les actions mécaniques déforment, mais ne transforment pas*' (De Lapparent 1906, p. 1945). This citation is almost literally taken from Pierre Termier (1903: '*les actions dynamiques déforment, mais elles ne transforment point*'), who reached international celebrity with his concept of '*colonnes filtrantes*'. This idea was derived from the observation that, in the Alps, synclinal structures are more

strongly metamorphosed and 'feldspathized' than anticlines, supposedly because they were closer to 'vapours emanating from an underlying eruptive centre'.

The first attempts at global interpretation: stress/anti-stress minerals, and depth zones

At the beginning of the twentieth century, descriptive petrography was sufficiently developed to attempt some kind of general interpretation. Rosenbusch had identified successive zones in contact metamorphism, but mainly on structural/textural grounds. The more important observation that regular mineral changes might also occur in regional metamorphism soon followed, albeit hampered by lack of communication between the different schools.

First observations were made by George Barrow (1893) in the Scottish Highlands (Fig. 2). Barrow was a self-taught field geologist employed by the Geological Survey, who had, however, studied science at King's College London and learnt much from George P. Scrope, for whom he acted as an amanuensis. Barrow found a regular sequence of changes in the mineralogy of metamorphic rocks close to a granite intrusion. He defined 'successive areas', based on the occurrence of different aluminium silicates: sillimanite, kyanite, staurolite. This work was politely discussed during its oral presentation at a meeting of the Geological Society – notably by the young Alfred Harker, who was to revisit the issue some years later (Harker 1918) – but it remained more or less unnoticed in the published literature of the time. (Barrow was in dispute with his Survey colleagues about a number of issues, which may account for his ideas being disregarded or discounted for several years.) In 1915, a similar approach was taken by Victor Moritz Goldschmidt in the Trondheim area, Norway (see Fritscher 2002), but without being aware of Barrow's work. So Barrow's ideas were forgotten or ignored for a couple of decades, being eventually resuscitated by Cecil Tilley (1925) and subsequently by Harker himself (Harker 1932). At this time, Barrow's zones were 'completed', with the addition of chlorite, biotite, staurolite and garnet to the index minerals.

It is important to note that the relation to contact metamorphism, which was obvious in the original discovery ('silicates of alumina which are connected to the intrusion'), was then replaced by the notion of regional metamorphism. Harker (1918, 1932), who was extremely influential until the 1930s and 1940s, with his

brilliant style and excellent illustrations (Fig. 3), developed the concept of 'stress' versus 'anti-stress' minerals, which to some extent was an elaboration of Rosenbusch's ideas on dynamometamorphism. This was done in response to the ideas of Friedrich Becke (1903) and Ulrich Grubenmann (1904–1906), which he thought too static. According to Harker, stress minerals, characteristic of regional metamorphism, were formed under a strong non-hydrostatic stress regime. The Barrovian region of the Scottish Highlands was taken as the type example of this ('normal') metamorphism. In contact metamorphism, on the other hand, only anti-stress minerals (cordierite, andalusite), stable under a hydrostatic stress regime, were present. By relating the occurrence of metamorphic minerals to deformation, Harker anticipated one of the great developments of structural metamorphic petrology which were to occur after World War II (see below). But his views also had a negative influence. By providing a 'short-cut explanation' (Miyashiro 1973) for the occurrence of metamorphic minerals by an unquantifiable mechanism, they diverted many petrologists' interests towards explanations based on changing physical (pressure or temperature) or chemical (rock and mineral composition) parameters.

Given that the German school had dominated the early stage of descriptive petrography, it should not be a surprise that many followers of Zirkel and Rosenbusch also came from German-speaking countries: Austria and Switzerland. Independently of Barrow, they discovered a regular scheme of mineral evolution during progressive metamorphism, essentially at a regional scale, which they attributed to the depth at which rocks had been transported during orogenic evolution.

Van Hise (1904) proposed four 'depth zones' of metamorphism, against only two for Becke (1903), characterized by the occurrence of a certain number of given minerals, which he called 'typomorphic'. Finally Grubenmann wrote, first alone (1904–1906), then with his successor at Zürich, Paul Niggli (1924), a series of books which remained the basic references in continental Europe in the inter-war period. He defined three depth zones, with names which are still used in some of the geological literature (epizone, mesozone and catazone, in order of increasing depth). Contact metamorphism was assumed to be a local, relatively unimportant phenomenon, which differed only from regional metamorphism by producing different structures. Regional metamorphism was the 'real thing', and all observed metamorphic types were
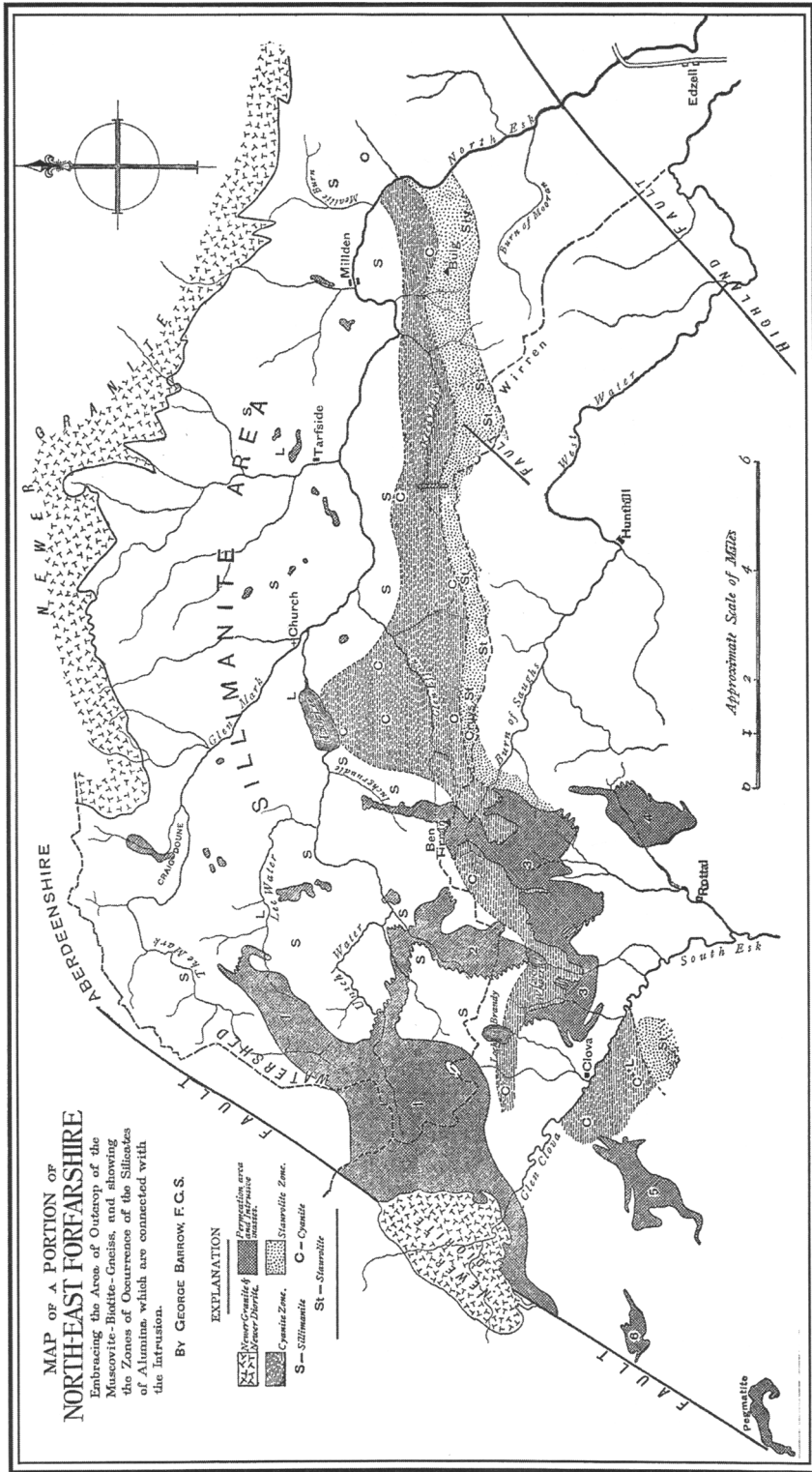
Fig. 2. Original map by George Barrow of progressive metamorphic zones in the Scottish Highlands (later called Barrovian metamorphism). From Barrow 1893, *Quarterly Journal of the Geological Society.*
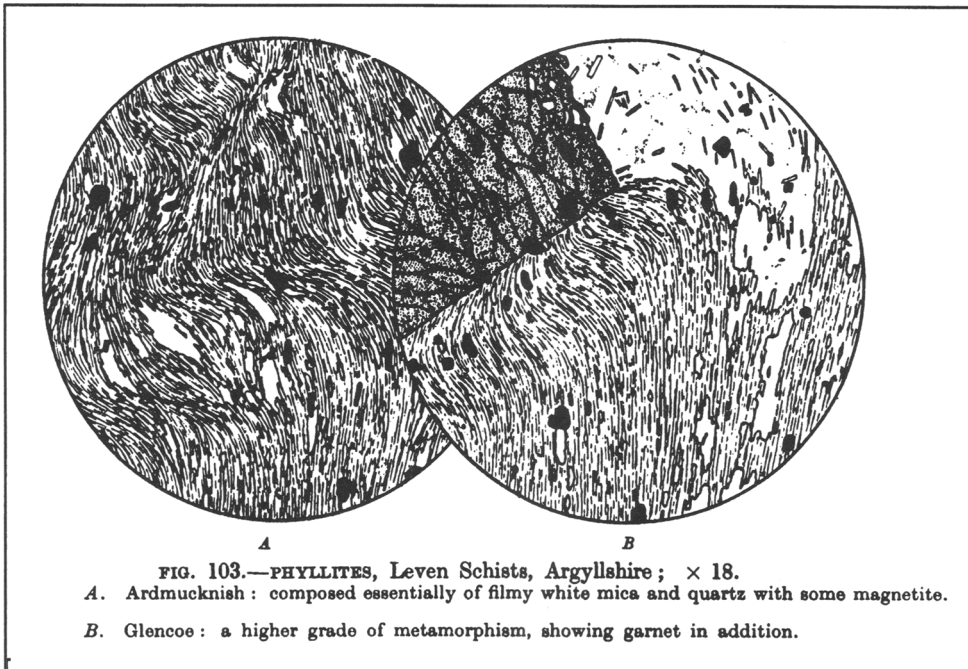
FIG. 103.—PHYLLITES, Leven Schists, Argyllshire; × 18.

A. Ardmucknish : composed essentially of filmy white mica and quartz with some magnetite.

B. Glencoe : a higher grade of metamorphism, showing garnet in addition.

Fig. 3. Illustrations by Alfred Harker (1932) of metamorphic textures (phyllites from Barrovian metamorphism).

assigned to a given zone on the basis of general impressions of grain sizes (increasing with depth) and mineral compositions. For instance, phyllites, chlorite schists and glaucophane schists were assigned to the epizone; biotite and muscovite-bearing schists and amphibolites to the mesozone; and muscovite-free gneisses, eclogites and granulites to the catazone. Under the influence of Niggli, the cause of metamorphism was regarded as exclusively magmatic: an intrusion at depth, typically a granite, provided the heat source. Mixed rocks (i.e. gneiss and granite), soon to be described from Nordic countries (migmatites), were explained in terms of granite injection, eventually supplemented by later deformation.

The depth-zone system was easily accommodated by the notion of '*métamorphisme géosynclinal*', formulated contemporaneously by the French school, notably Emile Haug (1907–1911). Depth zones correspond to successive layers in geosynclines, closer and closer to the granitic basement (Fig. 4). But contrasting views on the role of granite remained, yielding ongoing discussions between Rosenbusch and Michel-Lévy. Was the magmatic/metamorphic distinction clear-cut, as claimed by Niggli and the upholders of magmatic differentiation, notably Norman Bowen (1928)? Alternatively, were there intermediate rocks, 'feldspathized' gneiss, caused by 'emanations' issued from underlying granite? This view was a kind of tradition in the French school, and was soon to be boosted by a revolution from Scandinavia. The importance of this revolution took a long time to be fully appreciated, but finally it created modern metamorphic petrology.

New light from Scandinavia: migmatites and mineral facies

Petrology (magmatic and metamorphic) has been developed as a real science at a few major European universities (in Germany, Britain and France). At a time when travelling was less easy than today, many interesting field areas were relatively close to the research centres, in a few typical orogenic belts (Caledonian, Variscan, Alpine). But many of these exposures are strongly altered, partly covered by superficial material, or, in the case of the Alps, difficult to reach. Scandinavia provided a very different picture: rocks there have been polished by the
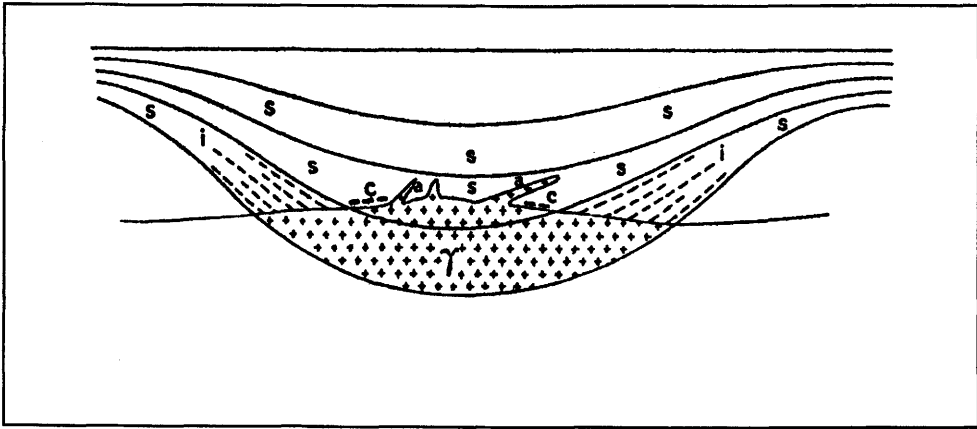
Fig. 4. '*Métamorphisme géosynclinal*', as seen by Haug (1907–1911, fig. 48). Translation of the French caption: 'Schematic section explaining the transformation of a geosyncline bottom, made of schists (s), into granite (γ), with 'lateral impregnation' (i), formation of contact aureoles (c) and apophyses (a) at lower depth'.

recent glaciations, providing excellent exposures. The Norwegian Waldemar Christofer Brøgger, who after his studies of geology in Kristiania went to Germany to study optical mineralogy and microscopic petrography, first with Heinrich Mühl in Kassel, and subsequently under Rosenbusch and Paul von Groth in Strasbourg, brought back these skills, as well as useful contacts, to major universities in Scandinavia (Hestmark 1999). Brøgger became professor, first at Stockholm's Högskole and later at the University of Kristiania (Oslo). Several of his students proved to be notable researchers, able to transpose field observations into an elaborate interpretative system. Notable among these men were Jakob Johannes Sederholm in Finland, and Johan Herman Vogt and Victor Moritz Goldschmidt in Norway. Vogt was to become professor of metallurgy at the Kristiania University and had a profound influence on experimental petrology (Vogt 1903–1904).

Goldschmidt was more a theoretician, who made the breakthrough, essentially by himself, at a very early age (see Fritscher 2002). Sederholm, who started his work earlier (before the end of the nineteenth century), was more field-orientated, also more of a '*chef de file*', who managed to have near him two great scientists, César Eugène Wegmann of Switzerland and Pentti Eskola of Finland, who may be regarded as the real founders of modern metamorphic petrology.

Sederholm and his co-workers on the one hand, and Goldschmidt on the other, operated roughly contemporaneously (during the period 1910–1930). However, they addressed different problems: the transition between gneiss and granite for Sederholm; the relations between rock chemistry and mineral assemblage for Goldschmidt and Eskola. Only after World War II were these approaches more or less integrated.

Sederholm (1907) tried to elucidate the complicated relations between the most common type of high-grade 'crystalline schists', namely gneiss and granite, already an important topic in Nordic geology since the work of Baltazar Keilhau in the early nineteenth century. Both rock types have basically the same mineralogical composition, differing only in structure, a fact that had led Rosenbusch to propose the concept of 'dynamometamorphism'. Sederholm could see that most of the Precambrian Baltic Shield is made of an intricate mixture of granite and gneiss, at all scales, which he named migmatites (see Fig. 5). To explain their formation, he called for a mysterious 'ichor' (literally, the 'blood of a nymph'), which could permeate the rocks, partly dissolving and 'granitizing' them. Migmatites were found to dominate the core of all Precambrian terranes, and were also identified by Sederholm in the Vosges, on the occasion of an excursion to classical 'Rosenbusch' exposures. (In fact, we know now that they constitute the bulk of continental masses, the so-called 'granitic layer' of geophysicists.)

Migmatites have complex textures, for which a profusion of terms was created, mostly by Sederholm himself. He was an excellent linguist, who could write papers in Swedish, Finnish,
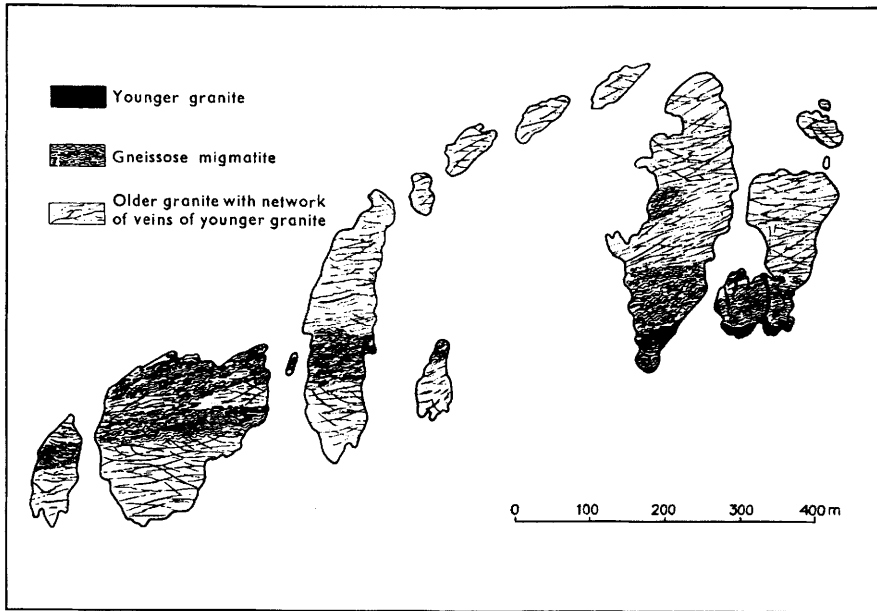
Fig. 5. Map by Sederholm (1907) of granite/gneiss contacts, using the term 'migmatite' for the first time.

German, English and French; he definitely had a flair for terminology. Besides 'migmatites' and 'ichor', he coined names like 'agmatite', 'anatexis', 'deuteric', 'dictyonite', 'homophanous', 'katarchean', 'myrmekite', 'palingenesis', 'palympsest', 'ptygmatic': most terms are derived from Greek and are still found in the petrologic vocabulary. These names did not provide *explanation*, but at least they showed that a simple magmatic explanation, namely the injection of granite dykes into pre-existing gneiss, faced serious difficulties. The 'geometrical' approach received a decisive impulse from the young Wegmann (1929, 1935), who transposed structural techniques elaborated in the Alps to Precambrian areas (see Fig. 6). Development of these techniques would ultimately lead to structural metamorphic petrology, now almost an independent discipline.

The work of Goldschmidt was completely different, but it also started from field observations, this time on metamorphic aureoles around intrusive granite in the Oslo region (Goldschmidt 1911). Having a much broader physicochemical background than most of his contemporaries – except possibly Paul Niggli, who was also an excellent chemist – Goldschmidt discovered systematic relations between rock composition and metamorphic mineral assemblage in hornfels, the highest-grade metamorphic rocks of the contact aure-

oles. Although it had been vaguely noted, in particular by Barrow, that some minerals preferentially occur in certain rock types, it was more or less tacitly assumed that the role of rock chemistry was not important. The formation of new minerals depended either on changing external conditions (pressure and temperature) or on external introduction of new elements. Goldschmidt demonstrated that rocks are chemical systems, which can be treated according to the laws of physicochemical equilibria, notably the 'phase rule' (see Fritscher 2002). The importance and pioneering aspect of his work are fully recognized today. Other geologists had, however, already attempted to apply chemical thermodynamics to the study of rocks, notably Becke (1903) who, from the well-known Clausius–Clapeyron equation, had understood that pressure increase should lead to the formation of higher density materials. He applied this 'volume law' to eclogites and, simply by comparing the molar volumes of gabbroic and eclogite mineral assemblages, he concluded that eclogites were high-pressure equivalents of gabbro (Godard 2001).

The work of Goldschmidt on contact aureoles had attracted the attention of Eskola, a student of Sederholm in Helsinki, who had investigated some comparable rocks in the Orijärvi region in southern Finland (Eskola 1915). Eskola came to Oslo, and in 1920, the first comprehensive paper
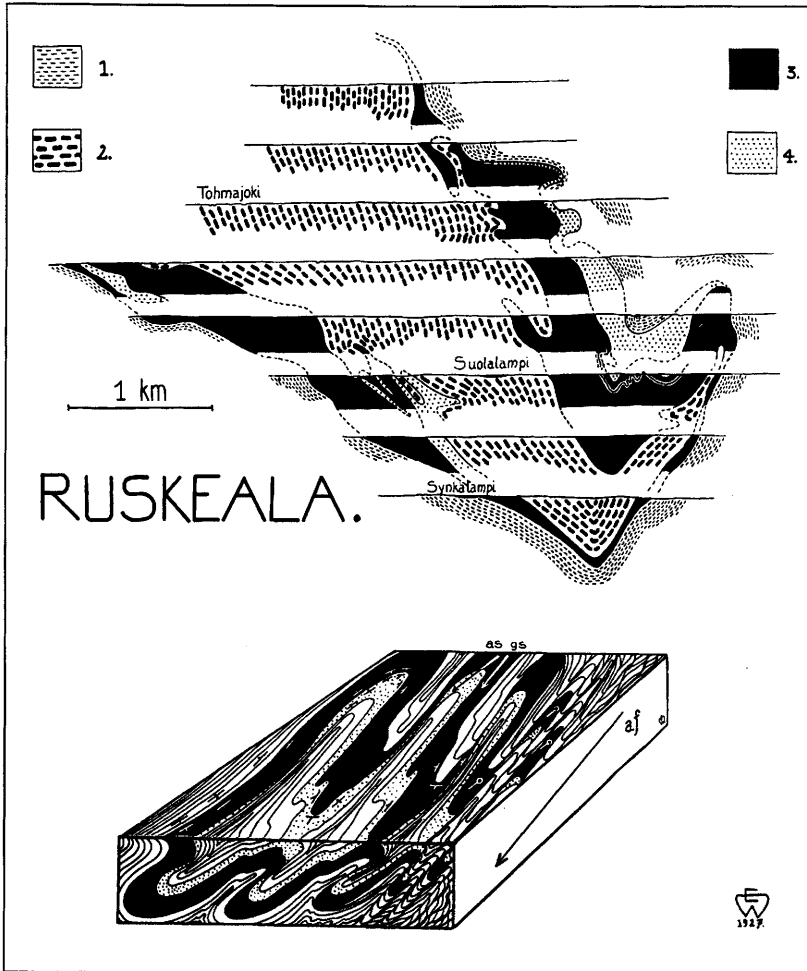
Fig. 6. Examples of the structural contribution brought by Wegmann (1929) to the study of Precambrian metamorphic complexes. Above: serial profiles, allowing the representation of three-dimensional structures on a plane. Below: block diagram, showing the relation between true (af) and apparent fold axes. The correct axial direction can only be measured along vertical layers.

on the notion of mineral facies was published (see Fig. 7). It is interesting to note that Eskola considered magmatic as well as metamorphic rock types (Eskola 1920):

A mineral facies comprises all the rocks that have originated under pressure and temperature conditions so similar that a definite chemical composition has resulted in the same set of minerals, quite regardless of their mode of crystallization, whether from magma or aqueous solution or gas, and whether by direct crystallization from solution (primary crystallization) or by gradual change of earlier minerals (metamorphic recrystallization).

But, as the conclusion was rather obvious for magmas, the initial notion of 'igneous facies' was soon replaced by that of high-temperature metamorphic facies (granulite), and only the different metamorphic facies have remained, with the names and broad pressure–temperature (P–T) interpretation that they still have today.

An epoch-making controversy: 'soaks' *contra* 'pontiffs'

Even if the name 'facies' was immediately endorsed by Becke (1921), it was not easy for the Scandinavian newcomers to be recognized by
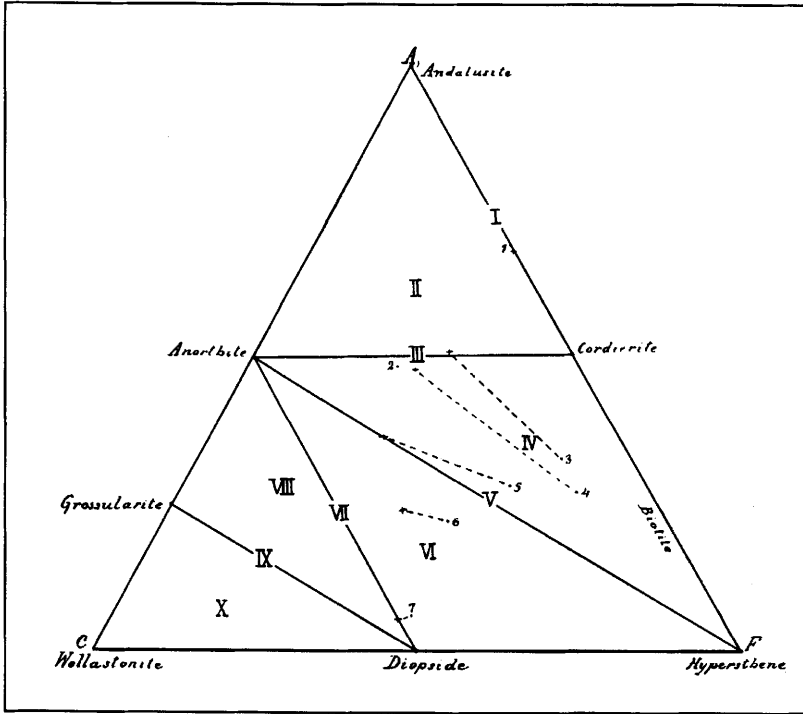
Fig. 7. ACF diagram by Eskola (1920), used for the definition of metamorphic facies. ACF metamorphic parameters: A = aluminium, C = calcium, F = iron + magnesium. I to X: the ten classes of hornfelses observed by V. M. Golsdchmidt (1911), corresponding to bi- or triphase diagnostic metamorphic assemblages. 1 to 7: whole-rock compositions. Dashed lines ending in a cross: correction made by subtracting potassium component, since K-bearing minerals (notably biotite) cannot be adequately represented in the diagram. The corrected compositions give a much better correspondence between chemistry and mineralogy (e.g. 3/III, 5/V, 7/VII).

the international scientific establishment. Mineral facies superficially resembled depth zones, to the point that a number of authors had proposed an equivalence of terminology (e.g. greenschist facies and epizone). At a time when it was not easy to have precise information on the chemistry of mineral and rocks, many petrologists did not see the need to deploy complicated thermodynamic equations. They also failed to see the real novelty of the concept, namely that pressure and temperature do not always show the same relation ('geothermal gradient'), and thus that they could be treated as independent variables. Eskola made repeated attempts to demonstrate the superiority of his facies concept to that of depth zones, but mostly in regional Nordic journals (e.g. *Bulletin de la Commission géologique de Finlande*, 1915; *Norsk Geologisk Tidsskrift*, 1920; *Geologiska Förening i Stockholm Förhandlingar*, 1929), too often considered as subordinate literature. Harker, who saw little room for his stress and

anti-stress minerals in chemical thermodynamics, reviewed Goldschmidt's classification of Oslo hornfelses in a rather negative manner, and he almost completely ignored Eskola's work (even though it was clear that the concept of mineral facies would have been the easiest way to explain Barrow's zones). It was significant that when, just before World War II, Eskola finally published the most elaborate version of his work, together with Tom F. W. Barth for the magmatic and Carl W. Correns for the sedimentary rocks (Eskola 1939), he mentioned in his extensive historical introduction all names that counted in the preceding generations, *except* Harker.

However, it is clear that, for thirty years after the introduction of the depth zones or mineral facies concepts, the big question was not the relative merits of the two systems, but the relationships between gneiss and granite (e.g. Raguin 1957): is the granite the cause or the result of metamorphism? Migmatites are at the

core of this problem. Sederholm's 'ichor' was supposedly able to transform some pre-existing sediments into homogeneous granite. Wegmann provided a geometrical framework, by defining a 'migmatite front' separating isochemically recrystallized from 'granitized' rocks. These views were enthusiastically endorsed by extreme 'transformists' – Herbert Read and Doris Reynolds in Britain, René Perrin and Marcel Roubault in France – who did not call for fluid media to transport the elements. Granitization supposedly occurred by 'solid-state reaction', by element diffusion through the crystalline structure. This hypothesis was, of course, denied by the magmatists, who relied on experimental evidence. Both camps found vigorous and able defenders, and *The Granite Controversy* by H. H. Read (1957; see Fig. 8) can still be read with pleasure, at least for the quality of the expression (see also Read 1943–1944). Personal attacks were not lacking. Because of the supposedly authoritarian character of the magmatist *'chef de file'*, Niggli, they were called 'pontiffs' by the transformists. Bowen replied with the nickname 'soaks', as well as with the devastating appellation of 'Maxwell's Demon' to volatiles in general, which (at the time) could not be demonstrated experimentally. Some authors, notably Jean Jung and Maurice Roques in France, attempted to incorporate the notion of migmatites within the framework of depth zones. Using the example of the French Massif Central, they separated 'ectinites', isochemically recrystallized rocks, from metasomatically transformed migmatites (Jung & Roques 1952). The cause of metamorphism was still believed to be geosynclinal burial (see Fig. 4).The successive ectinite zones, more or less horizontal, apparently corresponded to increasing depth in a geosyncline. Microstructural studies, which had received a great impulse from Bruno Sander in Austria (Sander 1948–1950), soon showed that Jung and Roques' 'zoneography', with its 'migmatite front' cutting obliquely the horizontal ectinite boundaries, could not be reconciled with detailed field observations, even in the supposed type locality (the French Massif Central; Demay 1942; Collomb 1998). However, the apparent simplicity of the system made it attractive to many geologists, who could map rapidly wide areas of poorly exposed, unknown terranes, e.g. in Africa. The problem was that some field geologists, notably in French-speaking countries, failed to represent also the lithologies of the rocks. For instance, limestones, metavolcanics and quartzites could be collectively described as *'micaschistes supérieurs'* or *'gneiss inférieurs'*. Unfortunately, this made their maps almost useless when the concept of mineral facies replaced that of zoneography.

As far as the migmatite problem was concerned, the quarrel between soaks and pontiffs ended in the 1960s with apparent victory for the pontiffs. Experimental petrology showed that solid-state diffusion is very limited, even at high temperatures, and that a rock like a granite can only be formed by crystallization from a melt. Granite magmas can be formed by different processes at different levels, notably in the lower part of the continental crust. This is the domain of the granulites where, as we will see, some of the old questions were to reappear.

The revolution of the 1960s

It is customary in the Earth sciences to envisage a 'revolution' in the 1960s, with the development of plate-tectonic concepts. Plate tectonics, however, was less a drastic change in geological thinking than a consequence of technological progress: the ability, with equipment directly resulting from World War II, to measure remanent magnetism in the lavas emitted at mid-oceanic ridges and ocean-floor mapping (see Barton 2002). The symmetrical magnetic 'zebra' pattern on both sides of the ridges immediately suggested how oceanic crust was created, to disappear by subduction under the continents. But marine geophysics was not the only discipline to be transformed by modern technology. For metamorphic petrology, a number of instruments fundamentally changed the nature and even the scope of the discipline.

Firstly, the electron microprobe (first patented by J. Hillier in the USA in 1947, with the first working instrument being developed by R. Castaing and R. Guinier in 1949, though the instrument did not come into widespread use until the 1960s), allows in situ spot analysis of any mineral phase. Analyses are almost instantaneous, compared to the tedious, time-consuming wet-chemical analysis, especially for silicates. Chemical petrology was reborn, and the importance of this new instrument, now standard in any laboratory, can only be compared to the proliferation of microscope studies during the second half of the nineteenth century.

Modern technology also opened a new field of research for trace-element and isotope geochemistry. Mass spectrometers and other techniques of 'nuclear' mineralogy, at the edge of scientific research before the War, became standard instruments in many geoscience research laboratories. It was now possible to measure, on smaller and smaller samples, the relative proportions of both stable and radioactive isotopes
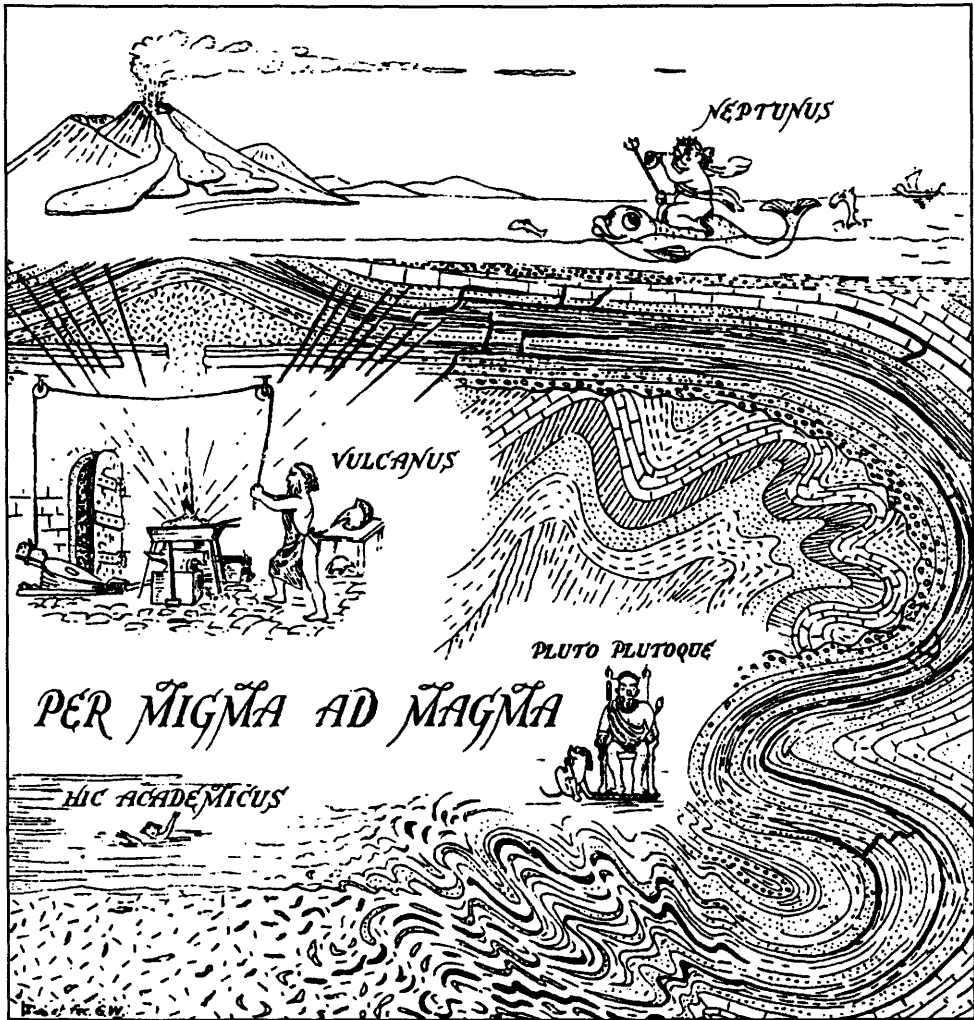
Fig. 8. Frontispiece of *The Granite Controversy* by H. H. Read (1957) (drawn by D. A. Walton).

in a given rock or mineral. Knowing the decay constants of radioisotopes, the time at which the nuclear reaction started could be calculated. After chemical age determinations, pioneered well before World War II (see Lewis 2002), a new discipline was thus created, geochronology, which in due course went well beyond simple age determination. Radiometric dating is in practice the only way to establish the age of a relatively old rock which does not contain

remnants of living organisms (fossils). Since early work by Holmes *et al.* (1957) on the Pre-cambrian of southern Norway and Canada, radiometric investigations have had a major impact on our understanding of the Precam-brian, which cannot be dated by fossils, but covers more than four-fifths of Earth history. Not only radiogenic, but also stable isotopes can be used as tracers, for the investigation of most varied processes: mineral crystallization or recrystallization, origin of various rock com-ponents, interactions between rocks and fluids, etc. These techniques were developed within the framework of a new discipline, geochemistry, from a name/discipline created by Vernadsky (1924). (The name was first suggested in 1838 by Christian Friedrich Schoenbein, but in a differ-ent sense from that which it has today.)

High pressure and temperature experiments have also become an essential part of metamor-phic petrology. After the pioneering efforts of Hall, Daubrée and Vogt, a decisive impulse came from the Geophysical Laboratory of the Carnegie Institution, Washington DC, in the United States (Young 1998, 2002) which, through to the present, remains the standard reference for experimental studies. During the first half of the century, most experiments were done on magmatic rocks, which could be treated as dry, fluid-absent systems. Many metamorphic minerals contain volatiles (e.g. CO_2 or H_2O) in their structure, and serious experimentation could only start when volatile-bearing, hydrothermal syntheses could be undertaken at sufficiently high pressures and temperatures. This was achieved around 1950, notably through the work of Hatten Yoder and others (Yoder & Eugster 1954). From this time onwards, a flow of data emerged, not only from the Geophysical Laboratory, but from many places in the world (e.g. Göttingen and Bochum in Germany; Toronto and Ottawa in Canada; the former Soviet Union). The results of this immense research effort drastically changed the percep-tion of the physical conditions (temperature and pressure) at which metamorphic changes occur. In the granite debate, a key argument of the transformist school for the solid-state origin of granite was the supposedly low metamorphic temperatures, well below the melting-point of the water-saturated granite system (about 700°C). Harker (1932, p. 209) thought that mus-covite recrystallization could take place in cata-clastic (dynamic) metamorphism 'at ordinary temperature' (meaning surface temperature), and that the lowest temperature at which meta-morphism could appear (the chlorite zone in Barrovian metamorphism) was also close to this

temperature. The decisive factor for the development of metamorphic minerals was not temperature but time and, above all, defor-mation (or state of stress). Maximum tempera-tures, corresponding to amphibolite facies, should not exceed 600°C, well below the melting-point of granite.

With regard to pressure, uncertainties were even greater. There was no precise idea about the absolute value of pressure; it could only be roughly estimated from depth of burial (1 km corresponds to roughly 0.3 kbar). The lithostatic pressure was not thought to exceed a maximum of about 3 kbar, corresponding to a depth of 10 km, the supposed thickness of the 'metamorphic layer' in the upper part of the continental crust. In any case, this absolute value was not import-ant, as it was (again) not a controlling factor, in contrast to (in Harkerian thinking) the state of stress (isotropic or anisotropic).

Changing the scope of metamorphism

The flow of experimental data which, after the 1950s, came from many places in the world, com-pletely changed the 'scope' of metamorphism. First of all, the role of pressure became better understood. In 1953, experimental petrologists, notably Lawrence Coes Jr at Norton Company, succeeded in making a pressure vessel able to sustain a pressure of a few tens of kilobars (Coes 1953). Coes synthesized a new, dense modifi-cation of silica (later named coesite), and this was followed by the discovery in the Soviet Union of an even denser form (stishovite), stable at the enormous pressure of over 50 kbar (correspond-ing to a depth of 150 km) (Stishov & Popova 1961). These species were later found near the Earth's surface, mostly at the sites of former meteorite impacts, and for coesite more recently in some terrestrial rocks (eclogites – one of the most frequently discussed metamorphic rock types since its identification by René-Just Haüy in 1822; see Godard 2001). Around 1980, dry experiments could be undertaken at much higher pressures, with the initiation of diamond-anvil techniques. Multianvil, high-pressure apparatus was first developed in Japan (Kawai & Endo 1970), and then diamond-cells by Ho-kwang Mao and Peter Bell at the Geophysical Labora-tory (Mao & Bell 1975, 1976). By simply pressing together two opposite diamond-anvils through levers, the investigator could produce extraordi-nary pressures (more than 1 megabar), corre-sponding to conditions near the Earth's core/mantle boundary. Thus, mineral-phase transitions could be predicted for depths far beyond any possibility of direct observation.

'Dry' experiments are, however, not directly relevant to metamorphic reactions, which in most cases occur in the presence of a fluid phase. With few exceptions, which incidentally turned out to be among the most difficult (e.g. all discussions with regard to the exact position of the sillimanite–andalusite–kyanite triple-point), metamorphic reactions can be studied only by hydrothermal experiments, notoriously more difficult and more dangerous than dry experiments. For safety and financial reasons, most hydrothermal experiments are limited to pressures of about 10 kbar. These were, however, sufficient to yield a wealth of new data on fluid–mineral interactions at depth and, above all, to show that crustal temperatures, commonly reached at high metamorphic grade, are sufficient to melt many former sediments. Magma, if any, did not have to be introduced from outside, but could be generated in situ by partial (or complete) melting of some metamorphic rocks. The old chicken-and-egg problem of the relationships between metamorphism and magmatism received a new powerful argument: the hen was metamorphic.

Calibrating metamorphic reactions, solving the granite controversy

Most of the hydrothermal experiments that 'flourished' after the 1960s were aimed at calibrating the zones of progressive metamorphism in terms of P and T and solving the granite problem. These types of experiments are rather different, and they were conducted differently in the two places (Washington and Göttingen) which, for many years, were to symbolize these different approaches. The Geophysical Laboratory of Washington was essentially concerned with mineral stability. Species had to be pure (mostly synthetic), in order to determine all the compositional and experimental variables. Data had to be retrieved by computational techniques, and essentially were derived from equilibrium thermodynamics, in order to construct mineral stability fields in the P–T space. At increasing P and T, successive mineral stability fields define a 'petrogenetic grid', a notion first proposed by Bowen in 1940. A number of gifted theoreticians, notably E-An Zen at the Geophysical Laboratory (Zen 1966) and James (Jim) B. Thompson at Harvard (Thompson 1955, 1957), developed this concept along the lines initiated by Goldschmidt (1912) and his student Hans Ramberg (1944, 1949, 1952). They treated metamorphic rocks, as well as mineral assemblages, as chemical multicomponent systems. This approach is now at the core of all modern studies, but its elaboration required one to go back to the literature of the end of the nineteenth or the beginning of the twentieth century (Gibbs, Backhuys Rozenboom, Schreinemakers, Van't Hoff), which had escaped the attention of most petrologists for more than fifty years.

Before coming to a quantitative interpretation of metamorphic assemblages in terms of P and T, later developing into geothermometry and geobarometry, the first results of these experiments showed that metamorphic temperatures were much higher than previously assumed. The first attempt came at the lower metamorphic grade, with the identification of metamorphic zeolites (Coombs 1954), as well as other minerals (prehnite–pumpellyite; Coombs 1960) which defined the lowest-temperature metamorphic facies, immediately following sedimentary diagenesis. These diagnostic minerals were found to occur in a systematic way in volcanic and sedimentary rocks from New Zealand and were later found at the margins of many orogenic belts, notably the western Alps. They were formed well before any platy minerals, like chlorite, capable of giving the rock a typical metamorphic texture (schistosity). Experiments on zeolites showed that the crystallization temperature must be at least 250°C. Therefore, the temperature of the first Barrovian metamorphic zone, defined by chlorite, must be significantly higher (at least 300°C by present-day estimates). At higher temperatures, an important reference would be the Al-silicates triple-point (andalusite–sillimanite–kyanite), not influenced by fluid activity. However, equilibrium conditions were notably difficult to realize. Experiments in the first half of the 1960s suggested possible temperatures as low as 300°C (Miyashiro 1949). But Robert Newton (1966) found 520°C, with even higher temperatures (600°C) obtained by Egon Althaus (1967) and Richardson *et al.* (1969). Now the commonly accepted value is around 500°C, remarkably close to the *c.* 540°C, 3.4 kbar obtained by Olaf Schuiling (1957) in his attempt to calibrate the triple-point from field occurrences. It was soon obvious that many metamorphic reactions should take place at much higher temperatures. Some regional metamorphic assemblages, characterized by the widespread occurrence of volatile-free minerals (orthopyroxene and/or garnet instead of micas or amphibole) are conspicuously similar to contact metamorphic rocks (pyroxene hornfels), obtained close to the hottest intrusions (T at least 900°C). Therefore,

the temperature of mineral equilibration must be roughly comparable. We now know that this is the case, and metamorphic minerals typical of ultra-high temperature rocks, like quartz–sapphirine, described from Enderby Land, Antarctica (Ellis *et al.* 1980) and Hoggar, Algeria (Ouzegane & Boumaza 1996), or osumilite, found in regional aureoles around massif anorthosites, e.g. Nain, Canada (Berg & Wheeler 1976) and Rogaland, Norway (Maijer *et al.* 1977), correspond to temperatures in excess of 1000°C (Ellis 1987; Harley 1989). If we remember that most mantle rocks (peridotites) show typical metamorphic textures (equilibrated and deformed in the solid state; see Den Tex 1969), the conclusion is inescapable: the field of metamorphic temperatures extends to more than 1000°C, overlapping the field of magmatic temperatures.

Experiments dealing with the origin of granite were conducted by Jean Wyart and François Sabatier (1958, 1960) in France, partly as a reaction against the most extreme views hold by some 'transformists' (Perrin & Roubault 1939, 1963). But they were developed and systematized by Helmut Winkler and his co-workers at Göttingen, resulting in a book that exerted a strong influence on European petrologists for many years (Winkler 1965). These researchers did not start from pure, synthetic materials, but from natural rocks – a tactic considered almost a crime by purists at the Geophysical Laboratory! Results, however, were spectacular, showing that some metamorphic protoliths, notably metagreywackes, easily melt at temperatures of about 700 to 800°C, well within the range of temperatures reached by many high-grade metamorphic rocks. This provides an easy explanation for the formation of migmatites, which had so puzzled Sederholm and his successors: no need for large-scale element transport or mysterious 'ichor'. Migmatites were simply partly molten rocks, formed near the source at which granite melts are produced. Discussions still continue on the mechanisms by which these partial melts are collected to form massive intrusions, able to rise and cause contact metamorphism in the upper crustal levels. It should be noted that this process is only valid for some granites (S-type granites; White & Chappel 1990), whereas others (I-type granites) have no relation to a metamorphic environment and are best explained by magmatic differentiation. Bowen, who always claimed that magmatic differentiation was the only process by which all magmatic rocks are created, was not wrong, but he had missed the metamorphic counterpart.

From mineral facies to geothermobarometry

The work of generations of experimentalists, field and structural geologists, and geochemists, has had far-reaching implications for all geosciences. We are now able to trace the origin of different rock components (trace-element geochemistry, stable isotopes), date the different stages of the rock evolution (geochronology), and estimate the pressure and temperature at which a given set of coexisting minerals has equilibrated (geothermobarometry). It would be wrong to assume that all these results have been obtained in a harmonious and linear form, without many discussions, controversies, and a number of unsuccessful attempts. Barrow-type zoneography gives only a very approximate estimate of metamorphic pressure and temperature conditions. Most index minerals (chlorite, biotite, garnet, etc.) show considerable solid solutions, resulting in multivariant mineral reactions in P–T space. Corresponding zones are not bounded by a single line, or 'isograd', but by a band, in which the compositions of coexisting minerals progressively adapt to changing pressure and temperature conditions ('sliding' reactions). The identification of these mineral reactions is an essential step in regional analysis, and can be derived relatively easily from the graphical presentation of metamorphic facies (metamorphic parameters; see Spear (1993) for technical details). On a P–T grid, major metamorphic facies appear as fields (greenschist, amphibolite, granulite, etc.) illustrating the successive steps of the metamorphic evolution in a given region (see Fig. 9).

It was soon realized that some facies are more typical for relatively high temperature facies (e.g. granulite facies), and others for high pressures (i.e. eclogite facies). In a given region, the succession of facies can be represented by a line, defining a 'metamorphic gradient'. With the progress of geothermobarometry, it became possible to quantity these gradients, with three major trends: high T–low P (typical examples being found at Buchan in the British Isles, in the Pyrenees, and on the Abukuma plateau in Japan); high P–low T (e.g. western Alps or the Franciscan Range in California); and an intermediate series, sometimes assumed to be the 'normal' type of metamorphism, represented by the Barrovian metamorphism of the Scottish Highlands. It is now clear that this evolutionary trend can be roughly understood in terms of regional pressure and temperature conditions. But attempts to go into more details, as done by
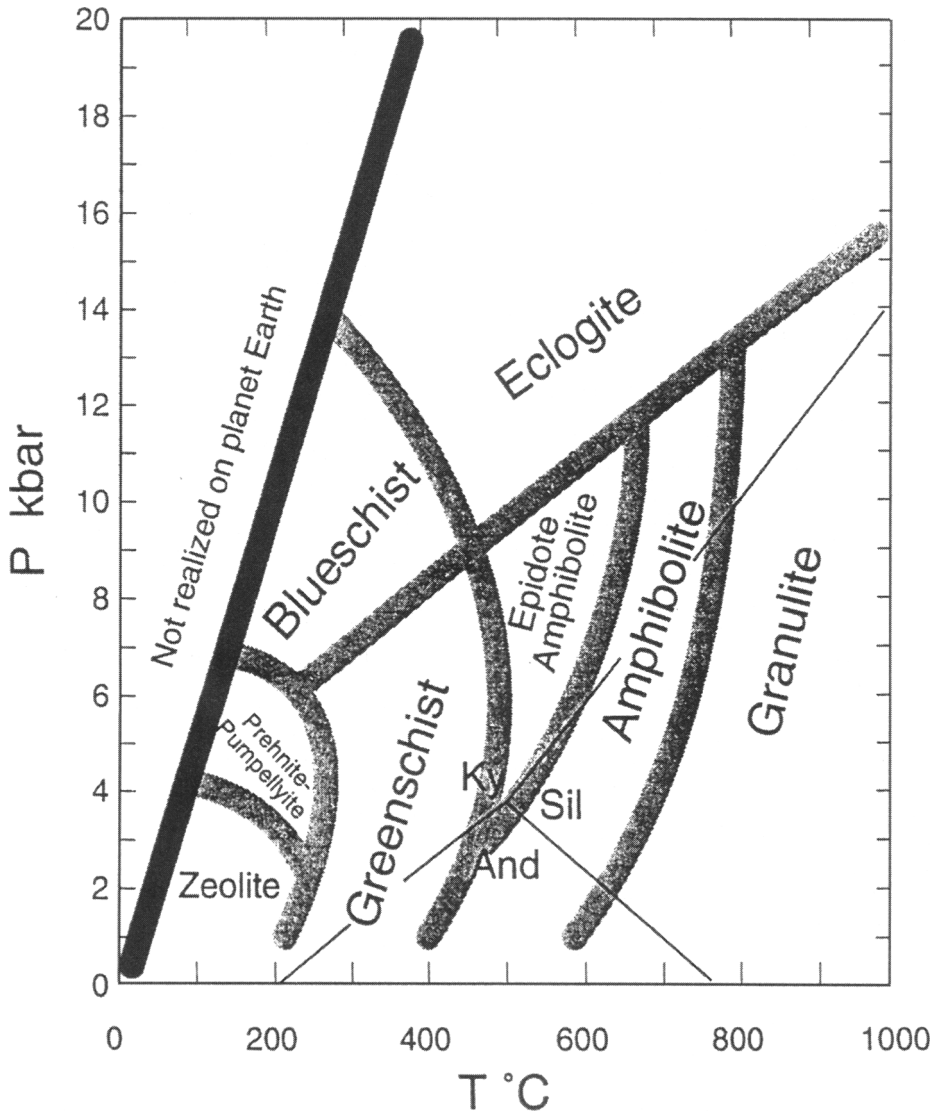
Fig. 9. Modern presentation (Spear 1993) of major metamorphic facies on a P–T diagram.

Helmut Winkler in the third and fourth editions of his *Petrogenesis of Metamorphic Rocks*, in which he increased the number of subfacies to more than 20, have failed (to the point that Winkler himself proposed to abolish even the concept of metamorphic facies in the last edition of his book of 1979). Metamorphic facies (or subfacies) only consider a limited part of the rock system, both for the internal (chemical component) and external (temperature, lithostatic and fluid pressures) conditions. They can only give a rough idea of pressure and temperature conditions, definitely not a quantitative esti-

mate. For this reason, the intermediate trend now tends to be abandoned, leaving only the high-T and high-P metamorphic types, which indeed correspond to well-defined orogenic belts.

Luckily, the progress of geothermobarometry, associated with precise studies of metamorphic textures, has allowed for much better calibration of metamorphic P–T conditions. Single mineral-pair geothermobarometry has benefited from the definition of internally consistent thermodynamic databases, from which reaction curves, mineral stability fields or P–T conditions of

mineral equilibration are automatically generated; examples are GEOCALC (Berman & Perkins 1987), THERMOCALC 2.7 (Holland & Powell 1998), TWQ (Berman 1991) and TPF (Fonarev *et al.* 1991). We caution against the dangers of blindly using such computer programs, with insufficient analysis and discussion of their possibilities, as well as a careful microscope study of textures and mineral assemblages. Nevertheless, the experimental thermodynamic approach has had some unexpected results, notably increasing tremendously the range of possible metamorphic conditions. We have already stated that experiments considerably increased the range of metamorphic temperatures. The case of pressure is even more spectacular. For a long time (still in many modern textbooks), the maximum pressures considered are about 10 kbar, in line with average 'high' conditions (intermediate granulites) of, roughly, 800°C and 8 kbar. Data with regard to peridotites and the Earth's mantle had already been compiled by Ringwood (1975), but mantle pressures did not occur in the metamorphic perspective of 'crustal' rocks. Although a separate blueschist facies was introduced by Eskola (1929, 1939), it took considerable time for it to be accepted. Petrologists like Francis Turner and John Verhoogen (1951) considered the formation of glaucophane to be due to solutions derived from (ultra)basic rocks. The work of Wilhelm de Roever (1950, 1955*a,b*) on Celebes, as well as discussions of the nature of Franciscan metamorphism (cf. Miyashiro 1994, p. 310), finally led to the full recognition of the role of pressure. In the 1980s, the scale of metamorphic pressure was, suddenly, multiplied by a factor of five. Coesite, which imposes a metamorphic pressure of at least 20 kbar, had been identified in the form of quartz pseudomorphs in eclogites from the southern Urals (Chesnokov & Popov 1965), but this work had been completely ignored. In 1984, Christian Chopin identified and made a correct interpretation of coesite inclusions in pyropes from the Dora Maira massif, western Alps (see also Schertl *et al.* 1991). Simultaneously, David Smith (1984) found coesite inclusions in clinopyroxene in the Norwegian Caledonides. This was soon followed, first in the Kovchetav massif, Siberia, and subsequently elsewhere, by the discovery of a mineral quite unexpected in metamorphic environments, namely diamond (Sobolev & Shatsky 1987, 1990). An astonishing sequence of completely new high-pressure minerals followed (ellenbergerite, Mg–carpholite, etc.). As for ultra-high temperatures, an ultra-high pressure (UHP) metamorphic facies had to be defined,

reaching more than 50 kbar (a depth of about 150 km). In some regions (like the Dabie-Shan Mountains, east-central China), UHP rocks cover large areas. Again, experimental petrology, especially the numerous experiments performed by Werner Schreyer and co-workers at Bochum, Germany (Schreyer 1988, 1995), facilitated petrologists' understanding.

The idea that glaucophane schists were (almost entirely) restricted to younger (i.e. Cainozoic and Mesozoic) orogenic belts (e.g. De Roever 1956, 1964; Miyashiro 1973) – a belief reminiscent of Wernerian concepts of there being different types of metamorphism for each epoch – has prevailed for a long time, but was recently shown to be incorrect (Liou *et al.* 1990). The discovery of coesite in the Precambrian of Mali (Caby 1994) has demonstrated the presence of ultra-high pressure metamorphism over large parts of the Earth's history.

The role of fluids

Hydrothermal experiments, as well as the theoretical interpretation of heterogeneous (mineral–fluid) equilibria, have underlined the importance of the fluid phase in almost all metamorphic reactions. The old adage *corpora non agunt nisi fluida*, which had been denied by the transformist school, made a triumphant comeback. If no fluid is present, element transfer is very limited, being insufficient in most cases to form new minerals. Detailed investigations on the mechanisms by which large metamorphic porphyroblasts grow underline the importance of dissolution/precipitation processes, requiring the intervention of a fluid phase. But the existence of this fluid phase is limited. As long as it is present, the composition of some minerals (e.g. garnet) will change in response to ambient P–T conditions. But if, at a certain moment, fluids disappear, then the composition will (in most cases) be fixed. It remains unchanged during subsequent metamorphic evolution, until the time when rocks finally reach the Earth's surface. For rocks recrystallizing at depth, the best way to eliminate pervasive fluids is decompression. Then, fractures will be formed in the rock mass, which drain the fluids. Mineral assemblages in the groundmass will tend to record maximum (peak) P–T conditions. During uplift, further evolution will be restricted to these veins, provided that no new fluids are introduced.

The study of this 'now missing' phase (the expression is from the late Philip Orville) has become one of the most important issues in present-day metamorphic petrology. It can be

apprehended either indirectly, from thermody-
namic calculations (Eugster 1959; French 1966),
or directly from the study of small fluid remnants
preserved in some minerals as inclusions
(Roedder 1984). Fluid inclusions have long been
known. As early as the beginning of the eight-
eenth century Johann Scheuchzer made draw-
ings of quartz crystals with fluid inclusions, and
when Sorby applied the microscope to the study
of rocks (his major paper was published in 1858,
but his observations started well before; see
Judd 1908), among the first objects he saw were
fluid (and melt) inclusions, which he investi-
gated with remarkable flair and ingenuity. Fluid
inclusions remained a significant part of descrip-
tive petrography in the times of Rosenbusch
(1873–1877), Zirkel (1866) and Vogelsang
(1867), but they largely disappeared from the
literature of petrology during the first half of the
twentieth century.

With problems of interpretation, insufficient
knowledge of the behaviour of fluid systems at
high pressure and temperature and lack of ade-
quate analytical tools, there were many reasons
for Bowen's (1928) concern about 'Maxwell's
Demon'. In fact, Bowen, who was well informed
about fluid inclusions through the thesis work of
Tuttle (1949), his most assiduous assistant,
ascribed more to fluids in general than to inclu-
sions, but the association between both was soon
made. Extreme transformists were no greater
supporters, as their motto was precisely the *lack*
of any fluid. In most places in the world, the
study of fluid inclusions was restricted to their
minor role in metallogeny. However, the former
Soviet Union was a notable exception and fluid
inclusions remained an important topic of study
there, with fundamental scientific work done
during the darkest years of World War II; and it
was from this country that a renewed inter-
national interest in fluid inclusions arose after
the war.

At the beginning of the 1960s, the situation
changed completely. We know much more about
the laws governing metasomatism (Korzhinskii
1936, 1959), as well as about the solubilities of
different minerals in various fluids (Helgeson
1964; Garrels & Christ 1965; Barnes 1967).
Notable progress has been made in the know-
ledge of fluid systems at high P and T (Kennedy
1950, 1954; Franck & Tötheide 1959) and in the
instrumentation (heating/freezing microscopic
stage: Roedder 1962–1963). Fluid inclusions are
studied not only in ore deposits but in all kinds
of sedimentary, magmatic and especially meta-
morphic rocks: alpine veins and segregation
(Poty 1969), high-grade metamorphic rocks
(Touret 1971), etc. Complementary to this type

of study are investigations on the signatures left
in the rock by the passage of fluid flows, by
means of stable isotopes or fluid–mineral inter-
actions, which have become essential in modern
metamorphic petrology. In principle, fluid inclu-
sions can provide two sets of data: P–T con-
ditions at which inclusions have been formed,
giving one point on the metamorphic P–T path;
and the chemical composition of this 'now
missing' fluid phase. Specific techniques have
evolved as a complete subdiscipline, using
advanced analytical instruments (Raman spec-
troscopes, electron and ion microprobes, laser
ablation ICP–MS, etc.). Fluid inclusion data play
a role in the vast effort now undertaken to model
fluid flow through rocks (Spear 1993). For some
petrologists, fluids in inclusions may not have
completely lost their 'Maxwell Demon' charac-
ter, but at least, the 'Demon' is now under
reasonable control.

Vapour-absent versus fluid-assisted metamorphism: resurgence of old controversies

The importance of fluid phases in medium-grade
metamorphic rocks has been demonstrated by
several petrologists, notably John Ferry (1976,
1983 1987) in Maine. In higher-grade rocks, fluid
inclusion studies have, unexpectedly, revived
old controversies. In the 1970s, high-grade meta-
morphic rocks (granulites) were found to
contain large quantities of CO_2-rich fluid inclu-
sions, also occurring in mantle xenoliths brought
to the surface by volcanic eruptions. Granulites,
like eclogites, were first thought to be relatively
rare petrological curiosities, but it was soon real-
ized that they are essential, if not exclusive, con-
stituents of the lower part of the continents.
Migmatites occur in this domain and, as temper-
atures tend to be higher, the degree of partial
melting increases: granulites are a major source
of granite magmas. Granulites are 'dry rocks',
characterized by the widespread occurrence of
anhydrous minerals like pyroxene and garnet.
Therefore, it was assumed that their formation
was only due to an increase of regional meta-
morphic temperatures. The 'unexpected dis-
covery' (the term is from Winkler) of fluid
remnants at this level has fuelled discussions,
which recall some aspects of former con-
troversies.

For the advocates of 'vapour-absent' (or fluid-
absent) metamorphism, no free-fluid phase
exists at the level of granulite formation. All
fluids are either dissolved in melts or are bound
in mineral structures. Fluid inclusions, if any, are

formed at a late stage, unrelated to 'peak' metamorphism. Proponents of this purely magmatic school, which finds strong support in experimental petrology (Thompson 1982; Clemens & Vielzeuf 1987), in equilibrium thermodynamic calculations (Lamb & Valley 1984), or in the stable isotope signature left by circulating fluids (Valley *et al.* 1990), can be seen as the direct successors of Bowen, or even Hutton. The supporters of 'fluid-assisted metamorphism', on the other hand (e.g. Newton *et al.* 1980; Perchuk & Gerya 1993; Touret & Huizenga 1999), admit the existence of a free synmetamorphic fluid phase, in some cases externally derived (i.e. produced from the underlying mantle). These fluids may play a double role: they lower the water activity by dilution, controlling the stability of water-deficient mineral assemblages and rock-melting at a lower and higher temperature, respectively, than for water-saturated systems; and they induce metasomatic transformations that may significantly change rock compositions.

It is clear that the fluid-assisted school reiterates a number of arguments previously advanced by transformists, with, however, a major difference: they do not claim that mineral reactions occur in the absence of fluids but, much to the contrary, that they occur in the presence of fluids of precise composition. Also, they do not deny the possibility of melts, but merely question their ubiquitous importance. In this respect, they are less the direct successors of the extreme transformists, like Read or Roubault, than of the proponents of the 'mineralizers' or 'emanations' of the preceding generations: Termier and *'colonnes filtrantes'*, Sederholm and his 'ichor', or, even further back in time, Virlet d'Aoust or Delesse. 'Deep hydrothermalism', which may occur in the form of supercritical fluids or volatile-loaded melts at lower crustal or upper-mantle depth, appears to be a recurrent concept, especially favoured by French or Russian geologists.

The discussions about the 'granulite problem' have not come to an end, and both parties (fluid-absent versus fluid-assisted) have their supporters. A consensus is, however, in sight, with the idea that both processes are complementary, not mutually exclusive, and that they may occur at different scales and places.

Structural petrology and geodynamical interpretation

If we can reconstruct the P–T conditions of metamorphic evolution and if we can add the time factor, then we can propose P–T–t paths (or 'trajectories'), which can be interpreted in terms of plate tectonics. Metamorphic rocks are essential in this respect to model orogenic belts, a most important topic in present-day Earth sciences.

Temporal relationships between the different stages of metamorphic mineral growth may serve this purpose. But it was first necessary to reach the concept of 'plurifacial' metamorphism, namely that a single rock may preserve traces of successive metamorphic episodes. This type of investigation is essentially based on the structural relations between coexisting minerals, carefully appreciated under the microscope. Most metamorphic rocks appear then to be organized in coexisting domains, at a subcrystal size, eventually equilibrated at very different P–T conditions. This fundamental observation gives a new dimension to the concept of structural petrology, the other way of studying metamorphic rocks. A gneiss (metamorphic rock) differs from a granite (magmatic rock) by its structure, but this structure concerns not only the external, macroscopic features (foliation, schistosity), but also the internal organization of the rock-forming minerals. These can be equilibrated or not (mutual replacement), and a precise knowledge of these structural relations is evidently of prime importance for a correct estimation of P–T conditions of rock formation. Structural metamorphic petrology has taken great steps forward in modern times, and from a rather thorough survey of the literature of the 1960s, it is evident that Dutch universities have played an important role in the elaboration of a method of study that has now taken the dimensions of almost a subdiscipline. The name 'structural petrology', in its modern sense, was coined by Emile Den Tex, who took up the chair of mineralogy and petrology at the University of Leiden in 1959 after a long and profitable stay in Australia (Den Tex 1959), succeeding Wilhelm de Roever who had preferred to move to Amsterdam. In Amsterdam, De Roever and his co-workers worked mainly in the Betic cordilleras, Spain, where they identified in some rocks three consecutive stages of metamorphism, each characterized by a different metamorphic facies (glaucophane–schist, greenschist– and almandine–amphibolite facies, respectively). But their work was only published in rather obscure journals (De Roever *et al.* 1961), and remained relatively ignored abroad. This was not the case for the Leiden group, which was extremely active and became internationally known under the guidance of both Den Tex, who applied his structural petrology concepts to the study of solid-state deformation of lower crustal (granulites and eclogites)
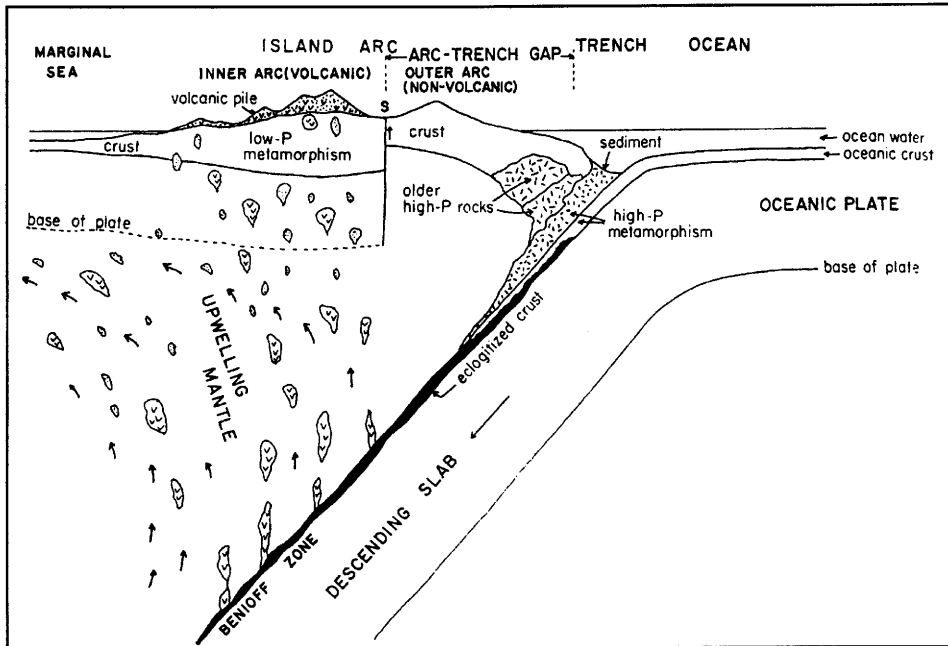
Fig. 10. The model of Miyashiro (1972) illustrating the relations between high-pressure and high-temperature metamorphic types (subduction of oceanic plate below continent).

and mantle rocks, and Henk Zwart, who worked in the Alps and French Pyrenees, notably the Bosost area in the Central Pyrenees (Zwart 1962, 1963). Structural petrology (or mineralogy) is now an extremely active field of research, using instruments or techniques (notably transmission electron microscope, high pressure and temperature experiments, interpretation of dislocations or other defects in mineral structures) that were initially developed in other disciplines, notably metallurgy, material science, or solid-state physics.

Once identified, successive metamorphic facies were found to correspond to different points on a P–T–t 'path' (or trajectory), and nowadays the determination of these is a major objective of metamorphic studies. Their elaboration relies on great instrumental sophistication (high-precision, single-grain analyses for the determination of time, and detailed discussion of a great number of analytical data for pressure and temperature), and many examples are now known with a relatively great accuracy for the most extreme conditions (notably for high-grade metamorphic rocks such as granulites or eclogites). The geodynamic interpretation is facilitated by thermal-model studies, in particular emanating from Oxford University, and culmi-

nating in a series of papers by Phil England and co-workers (England & Richardson 1977; England & Thompson 1984; Thompson & England 1984), which outlined the P–T–t paths for specific types of metamorphic rocks.

P–T–t trajectories can then be interpreted in term of plate tectonics. Even though it later proved to rely on the wrong interpretation of field evidence, the concept of paired orogenic belts, proposed by Miyashiro in 1961, played an important role in this respect. In central Japan, two metamorphic belts lie side by side, one corresponding to high-temperature metamorphic type (Abukuma-Ryoke), the other to high pressure (Sanbagawa). This last belt occupies a marginal position in respect to a subduction zone, corresponding to the collision of two oceanic plates. The interpretation by Miyashiro of the relations between the different types of metamorphism is illustrated in Figure 10. The subducted, relatively cold oceanic plate develops high-pressure metamorphism, ultimately leading to the formation of eclogite. During this evolution, it releases fluids (mostly water), which induce melting in the overlying mantle. Alternatively, the plate itself may have melted, on reaching a sufficient depth (of the order of several hundred kilometres), or sunk into the

mantle, when the density contrast between mantle rocks and high-pressure eclogites disappear ('slab detachment'). Rising magmas (or fluids, the discussion continues) supposedly induced high-temperature metamorphism in the overriding, collided plate.

In fact, it was found later that the time and space relations that Miyashiro had assumed were mistaken. The two belts are not genetically related: the Sambagawa metamorphism took place far away from the Ryoke Belt (c. 2000 km or more away), and later moved to its present position by lateral displacement. However, Miyashiro's model immediately appealed to European geologists, and it was extended to Europe (Caledonian, Variscan and Alpine orogens) by Zwart in 1967. Concurrently, it was recognized, both by Miyashiro (1961, 1967, 1972) and Zwart (1967, 1969), that the type of igneous activity varied with the type of metamorphism. The metamorphic view of orogenesis culminated in Miyashiro's great textbook *Metamorphism and Metamorphic Belts* (1973).

In all cases, however, time and space relations proved to be major problems, when the progress of geochronology and geophysics allowed better understanding of the formation of a mountain chain. Presently, neighbouring orogenic belts were either initially separated by thousands of kilometres, as in Japan, or were made at very different epochs. In central Europe, the Variscan and Caledonian orogens are separated by several hundred million years. In consequence, we have now abandoned the concept of paired belts, but we still see in most single orogens a succession of high-pressure and high-temperature metamorphic stages. For instance, in the western Alps, a Paleocene, high-pressure, eoalpine metamorphism is thought to be followed by a Miocene to Pliocene lepontine high-temperature metamorphic episode. It has also been realized that collision orogens are far more complex than oceanic subduction. Sometimes, in apparent contradiction to basic rheology laws, the oceanic plate appears to have ridden over the continental plate (obduction), leading to the formation of ophiolites, fragments of undisturbed oceanic crust preserved on the continent surface. In other cases, two continental plates may collide (continental subduction). Continent fragments may be carried down to several hundred kilometres depth, and then come back to the surface. The interrelations between the different envelopes of the solid Earth appear to be far more complicated than was formerly assumed. A proper understanding requires advanced studies, in which the three aspects of the modern science of metamorphism – structural, petrological and geochemical – are all performed at the same level of detail and sophistication.

Conclusions

Since its initiation in the first half of the nineteenth century, metamorphic petrology has evolved to a complex discipline, with at least three major trends:

1. mineralogical petrology, mainly concerned with the determination of pressure and temperature conditions at which mineral phases have equilibrated (geothermobarometry);
2. chemical (or geochemical) petrology, which adds the time factor (age determination being made by means of radioactive isotopes), but is primarily concerned with the origin of rock components and the chemical changes that may have happened during metamorphic evolution;
3. structural petrology, which is indispensable for the reconstruction of the kinematics of the rock evolution during an orogenic cycle and its interpretation in terms of global tectonics.

These three approaches are interrelated, with constant feedbacks and 'mutual support'. Thus it is useless to make a complicated solution model for estimating the pressure and temperature conditions at which two neighbouring mineral phases have equilibrated (mineralogical petrology) if these phases have not crystallized at the same time (structural and/or geochemical petrology). All three aspects of metamorphic studies have developed in different directions, to the point that contacts and mutual feedback can be completely lost. Each subdiscipline has developed its own concepts, vocabulary and equipment. Modern analytical instruments 'define' the analysed samples by an extremely narrow beam of light or particles: electrons or ions for analytical probes; lasers for some mass-spectrometric analyses. The volume of analysed material is of the order of a few cubic micrometres or less, so that a single mineral phase is the most common object of study. Field investigations, on the other hand, rely more and more on elaborate geophysical or remote-sensing techniques, which can investigate regions at a subcontinental scale. It has thus become impossible for a single individual to cover all these different aspects at the same level of sophistication. This evolution makes metamorphic petrology an ideal field for well-planned, integrated research, but at the same time it illustrates the risks mentioned at the beginning of this paper. Today, non-specialists may have the

impression that mineralogical petrology has reached its ultimate state, with computer programs that everyone can use for estimating pressure and temperature conditions of mineral equilibration. At a time of recession within the university world, it is tempting to favour other disciplines, which may give the impression of more rapid development, thus promising more success in the constant search for grants and other forms of subsidies. The dangers are obvious: science must progress in a coherent way, with consideration for all sectors.

Despite this constant progression, as well as the growing number of concerned disciplines (or subdisciplines), it is remarkable to see how some basic problems, notably the contest between fire (magma) and water (fluid), have remained at the core of research. Although transferring the debate between Werner and Hutton to present-day Earth sciences would be anachronistic, it might well be the case that if these eighteenth-century theorists could come back today, Werner and Hutton would use different instruments and speak another language, but a number of opposing viewpoints in the current debate in metamorphic petrology would still appeal to them.

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