PRESSURE, TEMPERATURE, FLUID PRESSURE CONDITIONS OF METAMORPHISM

Marco Scambelluri
University of Genoa, Italy

Keywords: metamorphism, temperature, pressure, fluid

Contents

Summary

This article presents an insight into the main aspects of the metamorphism of rocks. Metamorphism is a process of mineralogical and compositional change that has affected considerable volumes of rocks that are presently exposed on Earth’s surface, and that constitute large parts of old cratonic areas, mountain buildings, and oceanic basins. These rocks still preserve at surface environments relict, metastable associations of metamorphic minerals and/or metamorphic mineral inclusions that indicate their past crystallization at geological environments such as the base of the continental crust, the boundaries between colliding plates, and the deep mantle.

The study and analysis of these rocks has thus given important answers on the modes of accretion and consumption of Earth’s crust, on the evolution of mountain chains and continents, and on a number of processes that have driven the evolution our planet through geological timescales. Metamorphic transformations in rocks normally occur in the solidus state and in absence of significant production of partial melts and magmas. They are driven by changes that normally result from tectonic processes in some of the

following variables: the pressure and temperature conditions of a given rock body, its bulk chemical composition, the availability and access of C–O–H bearing fluid phases, the presence and/or absence of rock deformation.

Pressure, temperature, bulk rock and fluid compositions are the principal factors controlling the type of the metamorphic mineral assemblages produced, which are indicative of the dominant thermal regime during the transformation and of the geodynamic environment.

An increasing amount of research work and evidence has emerged in the last decade recognizing the fundamental role played in metamorphic processes by the fluid phases, particularly in the kinetics and enhancement of metamorphic reactions, in the diffusion and transport of elements at variable scales in metamorphic environments, and in the development of large-scale phenomena such as partial melting of the crust and mantle.

1. Introduction

“Metamorphism” of a given rock body occurs in response to significant changes of intensive variables, such as pressure, temperature, and composition, which disturb the pre-existing equilibrium conditions and force the rock to reach a new state of more stable equilibrium.

The IUGS subcommission on the systematics of metamorphic rocks has defined metamorphism as the process causing substantial changes in the mineralogy, structure and/or bulk chemical composition of a given rock volume. Changes are attributable to physico-chemical conditions different from the ones attained in sedimentary and diagenetic environments, and may include partial melting as long as most of the rock volume remains in a solid state. If significant change in the bulk rock composition is the dominant process because of the open system behavior of a given rock body, the term “metasomatism” is applied.

In metamorphic terrains, the preservation of large volumes of rocks recording various events of recrystallization and of reconstitutive phase changes provides evidence on the evolution of the Earth’s system through time. Metamorphism is generally associated with large-scale tectonic processes that cyclically occurred during Earth’s history. On a global scale, metamorphic rocks are dominant terrestrial materials and are among the oldest rock dated so far at 3.7 billion years: their study is therefore a key to deciphering the main events and large-scale mass movements that dominated Earth’s history from infancy to the present.

This article aims at reviewing the main driving forces of metamorphism, grossly individuated with temperature, pressure and role of the fluid phases involved. It will not consider the important effects of deformation on rock recrystallization, on the catalysis of mineral reactions and on reaction kinetics. This article is based on several textbooks on the petrography and petrology of metamorphic rocks (Powell, Best, Yardley, Bucher and Frey, and Spear–see Bibliography for details); these texts represent the most relevant sources of basic information on the process of metamorphism.

2. General Features of Metamorphism

2.1. Pressure–Temperature Conditions of Metamorphism

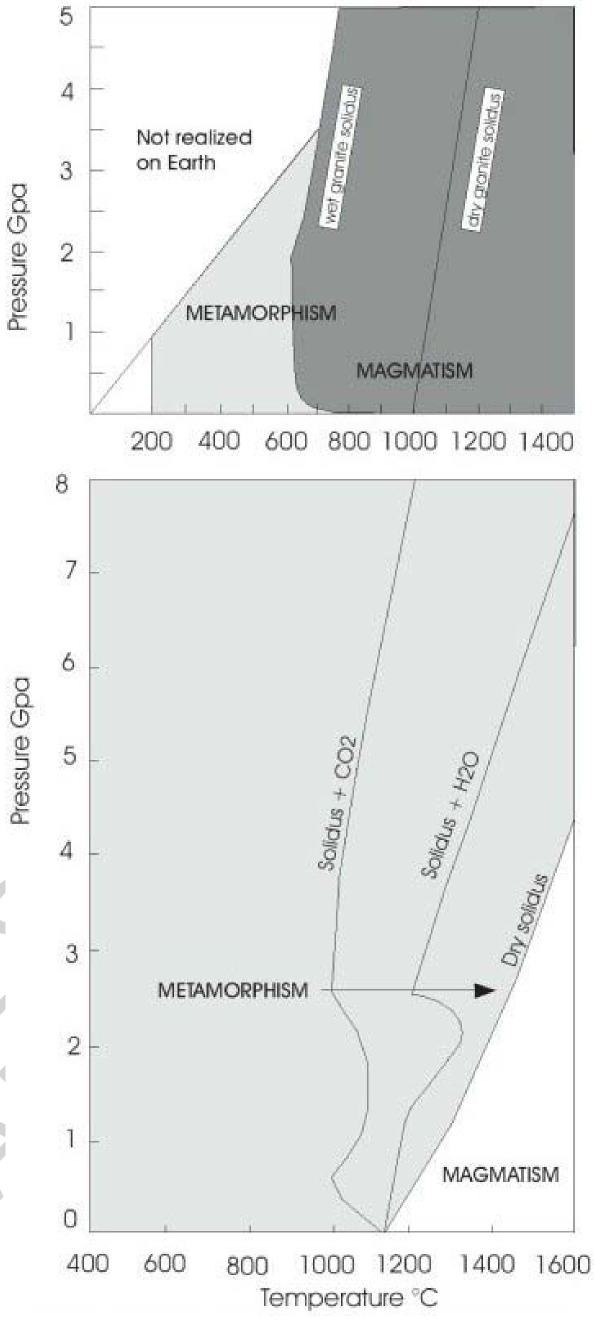

Figure 1. A: pressure versus temperature diagram showing the main domain of metamorphism in crustal rocks, between the field of diagenesis at low temperature and pressure and the wet solidus of granites and of basaltic systems. Source: drawn after Bucher and Frey, 1994. B: pressure–temperature diagram showing the field of metamorphism in mantle peridotites, delimitated at high temperatures by the dry peridotite solidus, and at lower temperatures by the peridotite solidus in the presence of water and of CO_2.

The physico-chemical conditions at which metamorphic transformations begin depend on the type, texture, and composition of the rock material involved. Organic matter, for instance, records metamorphic changes at significantly lower temperatures than silicate and carbonate rocks. In many rock systems, the boundary between diagenesis and metamorphism is faint and arbitrary, and metamorphic phase transitions appear to develop at temperatures as low as 200 °C (Figure 1A).

Key minerals such as carpholite, stilpnomelane, paragonite, and zeolites are indicators for the beginning of metamorphism. The high temperature limit of metamorphism corresponds to the onset of partial melting of a given rock system: metamorphic rocks recording high-temperature recrystallization associated with partial melting display granitic melt layers and/or pockets closely associated with restitic rock volumes. The latter appear depleted in fusible components that were uptaken by the melt phase. The partial melting temperatures of rocks depend on pressure and rock composition, as well as on the amount and composition of fluid present. At a constant pressure and in the presence of water-rich fluids, the partial melting of granitic rocks starts at a lower temperature (about 650 °C) than the melting of basaltic rocks (about 700 °C). In the absence of fluid, partial melting temperatures are as high as 1000 °C for granitic systems and 1100 °C for basaltic ones (Figure 1A).

The above temperature ranges therefore represent the upper temperature limits for crustal metamorphism. At mantle conditions the temperature limit of metamorphism rises significantly, solid-state changes in this environment being attained at much higher temperatures. Figure 1B shows the solidus curves of peridotites in the absence of fluid (dry solidus) and in the presence of carbonic (solidus + CO_2) and aqueous solutions (solidus + H_2O): it appears that in the absence of fluid phases, subsolidus (metamorphic) phase transitions in mantle rocks can be attained at temperatures as high as 1500 to1600 °C and at relevant depths for a range of geothermal gradients. A large proportion of upper mantle peridotites thus record subsolidus changes and thereby behave as metamorphic rocks. Concerning the pressure limits of metamorphism; low-pressure transformations occur in most contact aureoles formed during magma ascent and emplacement at shallow levels in Earth's crust. The high-pressure limit of metamorphism is as yet unknown. In the recent past, it was thought that the maximum pressures attained by metamorphic rocks buried at convergent plate margins and recrystallized under high-pressure conditions (eclogite-facies rocks) did not exceed 10 kilobar pressure, roughly corresponding to 30 kilometers depth. The more recent discovery that coesite is the stable SiO_2 form in eclogite-facies rocks of several orogenic belts (as for instance the Italian Alps, the Caledonides of Norway, and the Dabie-Shan mountains of China) has set the high pressure limit of metamorphism above 30 kilobars (90–100 km; ultra-high pressure metamorphism) The finding of diamonds in some ultra-high pressure rocks has set the possible limit at much deeper levels An extraordinary record of ultra-deep provenance of mantle rocks has been recently proposed for the metamorphic garnet lherzolites of Alpe Arami in the Swiss Alps and of Western Norway. Although a debate is going on to assess the exact origin and depth of provenance of these rocks, particularly the Arami garnet peridotite, they are thought to retain phase transformations of deep mantle olivine (wadsleyte) and of majoritic garnet (forming at depths close to the transition zone in the upper mantle) into mineral assemblages stable at shallower depths of about 80 to 100 km in the upper mantle.

These recent discoveries derive from the application of advanced techniques to the current analysis of metamorphic rocks, and shift the pressure boundary of metamorphism recorded by rocks presently exposed on the surface to extreme depths in the upper mantle, thereby enabling us to considerably deepen our knowledge of the behavior of Earth's interior.

2.2. Types of Metamorphism

Metamorphism can be manifest over large regions such as orogenic chains at convergent plate margins, cratonic areas, oceanic basins, and extensional environments where deep crustal and/or mantle rocks are slowly exhumed to the surface. On the other hand, metamorphism can be the result of local-scale processes such as development of kilometer-large contact aureoles around plutons intruded at high crustal levels in cool country rocks, or frictional heating along major faults.

Orogenic metamorphism dominates in mountain-building, where considerable volumes of rocks with different paleogeographic and lithospheric provenances are tectonically stacked together as the result of large-scale movements during plate convergence and collision. These orogenic cycles bring surficial crustal rocks to mantle depths and then return them to Earth's surface, thus causing the superposition of several metamorphic events coupled with permanent ductile deformations. The main features of metamorphic rocks exposed in orogenic belts are their strongly deformed structures, developed as the result of stress, and deformations developed at variable temperatures and pressures during their orogenic pathways. However, metamorphism and deformation are extremely heterogeneous in these rocks, and the records of the starting materials are systematically preserved in several undeformed rock domains, enabling the reconstruction of the whole history of rock materials involved in the orogenic cycle.

Oceanic basins are diffusely floored by mafic and ultramafic rocks metamorphosed at variable temperatures and moderate pressures in the presence of seawater-derived solutions. A great amount of petrographic, petrologic, and geochemical work has been performed on oceanic metamorphic rocks in the course of ocean drilling projects aimed at defining the dynamics of present-day oceans. Diffuse features of oceanic gabbros, basalts, and peridotites are hydration reactions at variable conditions that affect these rocks in the vicinity of oceanic ridges and during lateral spreading of the oceanic centers. Close to midoceanic ridges, the lithosphere is cut by hydrothermal systems where deep seawater penetration occurs (down to about 3 km and more) accompanied by complex fluid/rock interactions that determine an exchange of components with the surrounding rocks. These processes locally bring about the metasomatism of rocks, consisting of Mg-, Ca-, Na-enrichments and diffuse Si-depletion. The above features significantly control the element and volatile budgets of oceans, and enrich the oceanic lithosphere in exogenic and crustal components, which become recycled into the mantle once the oceanic lithosphere is deeply buried along subduction zones.

Contact metamorphism is the most diffuse type of local metamorphism affecting rocks at their point of contact with intrusive and extrusive igneous bodies. Metamorphic and metasomatic changes in these country rocks are determined by heat flow and by the infiltration of late-stage igneous fluids emanating from the magma chamber. As a consequence, aureoles of contact metamorphic rocks generally develop around plutons. The extension and width of aureoles depend on factors such as the volume and composition of intruded magmas, and the depth of emplacement, as well as the properties of country rocks. The volume of an intrusive body is important because large plutons bring more heat than smaller ones. The composition of the dominant intrusive rock type is another parameter controlling the overall temperature, since granitic melts form at much lower temperatures than basaltic ones. The intrusion depth determines the thermal gradient and heat flow between hot plutons and country rocks. The highest temperature differences are attained at surface crustal levels, since in deep crustal environments the temperature differences between country rocks and magmas are much lower.

2.3. Kinetics of Metamorphic Reactions

The process of metamorphism does not affect a given rock body homogeneously; from kilometric to microscopic scales the records of earlier evolutionary stages can survive a metamorphic event. Metamorphic terrains therefore contain rock domains that equilibrate at certain (dominant) metamorphic conditions; these domains are spatially associated with minor volumes of rocks that still record previous geologic events, manifest as relict minerals and as preserved rock textures. The basement rocks of Western Norway represent a well-known example of such an association of rock volumes, recording metamorphic imprints acquired at different geologic ages. Here mafic rocks with Precambrian granulite–facies metamorphism outcrop as relict bodies inside major volumes of mafic rocks re-equilibrated at eclogite–facies conditions during the Caledonian orogenesis. Granulitic and eclogitic domains were never separated during the whole time span from Precambrian to Caledonian, and their spatial association has been shown to result from unfavorable reaction kinetics during the transformation of granulites into eclogites. Detailed structural and petrologic studies demonstrated that this transition mainly took place in the rock volumes more intensely affected by plastic deformation and by the infiltration of aqueous fluid solutions.

Similarly, the widespread exposure of rocks formed in the deep crust and mantle indicates unfavorable reaction kinetics during their exhumation pathways to Earth’s surface. Deep metamorphic mineral assemblages survive outside their stability field because of a combined effect of exhumation rates faster than the ones of metamorphic mineral reactions, and lack of fluid infiltration. The presence of fluids would cause hydration reactions and re-equilibration of high-grade minerals into hydrous mineral assemblages stable at shallow crustal environments. Despite the fact that mineral reactions are expected on the base of thermodynamic predictions, high activation energies can be required for the transformation to develop. Until these energy barriers are trespassed, metamorphic reactions and, most importantly, nucleation and growth of new metamorphic minerals do not occur. Activation energies are lowered by plastic rock deformation, by significant temperature overstepping of a mineral reaction boundary, and by the presence of fluids and deformation controlling the diffusions of cations. Field and petrographic experience indicate that rock volumes less affected by fluid and deformation activity are the ones less intensely transformed and better preserving pre-metamorphic features.

The general preservation of deep rocks at Earth's surface, as well as diffuse survival in metamorphic terrains of pre-metamorphic features, indicate that slow reaction kinetics occurred systematically, thereby preventing the full recrystallization of a given rock volume during a certain metamorphic event. When catalytic factors do not assist mineral reactions, rocks do not transform during a given metamorphic event, and the nature of pre-metamorphic materials metastably survives the transformation.

-
-
-

Bibliography

Andersen T., Frezzotti M.L., Burke E.A.J. (2001*)*. Fluid inclusions: phase relationships, methods, and applications. *Lithos* **55**, 320 pp. [This is a special volume that presents all the essential aspects of fluid–phase petrology through the analysis of fluid inclusions in rocks.]

Ahrens T.J. and Schubert G. (1975). Gabbro–eclogite transition and its geophysical significance. *Reviews in Geophysics and Space Physics* **13**(2), 383–400.

Austrheim H. (1987). Eclogitization of lower crustal granulites by fluid migration through shear zones. *Earth and Planetary Science Letters* **82**, 221–232. [This is a scientific article showing the interdependence of fluid infiltration and metamorphic reactions in deep crustal rocks that underwent continental collision.]

Bard J. P. (1980). *Microtextures of Igneous and Metamorphic Rocks*, 264 pp. Dordrecht, Boston, Lancaster: D. Riedel. [This book presents all the essential aspects of microstructures in rocks.]

Barrow G. (1893). On an intrusion of muscovite biotite gneiss in the S.E. Highlands of Scotland and its accompanying metamorphism. *Quarterly Journal of the Geological Society of London* **49**, 330–358. [This is the first description and mapping of metamorphic zones in metamorphic basement rocks.]

Best M. G. (1982). *Igneous and Metamorphic Petrology*, 630 pp. New York, San Francisco: W.H. Freeman. [This book discusses many basic aspects of petrology and presents a very good link between field observations and theoretical systems.]

Bozhilov K., Green H.W., and Dobrzhinetskaya L.F. (1999). Clinoenstatite in Alpe Arami peridotite: additional evidence of very high pressure. *Science* **284**, 128–132.

Brown W.H., Fyfe W.S., Turner F.J. (1962). Aragonite in California glaucophane schist and the kinetics of aragonite-clacite transformation. *Journal of Petrology* **3**, 556–582.

Bucher K. and Frey M. (1994). *Petrogenesis of Metamorphic Rocks*, 318 pp. Berlin, Heidelberg, New York: Springer-Verlag. [This book presents the essential aspects of metamorphism in all rock systems.]

Chopin C. (1984). Coesite and pure pyrope in high-grade pelitic blueschists of the Western Alps: a first record and some consequences. *Contribus to Mineralalogy and Petrology* **86**, 107–118. [This is a first and very well-known example of coesite in rocks of crustal origin, demonstrating their subduction down to about 100 km depth.]

Clemens J.D. and Droop G.T.R. (1998). Fluids, P–T paths and the fates of melts in the Earth's crust. *Lithos* **44**, 21–36.

Dobrzhinetskaya L.F, Eide E.A., Larsen R.B., Sturt B.A., Tronnes R.G., Smith D.C., Taylor W.R., and Posukhova T. (1995). Microdiamond in high-grade metamorphic rocks of the Western Gneis region, Norway. *Geology* **23**, 597–600.

Dobrzhinetskaya L.F, Green H.W., and Wang S. (1996). Alpe Arami: A peridotite massif from depths more than 300 km. *Science* **271**, 1841–1845. [This is a scientific article providing evidence for the possible origin of Swiss Alpine ultramafic rocks at extraordinary depths in the upper mantle.]

Eskola P. (1915) On the relations between the chemical and mineralogical composition in the metamorphic rocks of the Orijarvi region. *Bulletin de la Commission Gelogique de Finlande* **44.**

Green H.W., Dobrzhinetskaya L.F, and Bozhilov K. (1997). Determining the origin of ultrahigh-pressure lherzolites (reply). *Science* **27**, 704–707.

Gregory R.T. and Taylor H.P.J. (1981). An oxygen isotope profile in a section of oceanic crust, Samail ophiolite, Oman: evidence of d^{18}O buffering of the oceans by deep (> 5 km) seawater hydrothermal circulation at mid ocean ridges. *Journal of Geophysical Research* **86**, 2737–2755. [This research paper provides a comprehensive picture of the stable isotope composition of rocks in a section of oceanic lithosphere.]

Griffin W.L. and Carswell D.A. (1985). In situ metamorphism of Norwegian eclogites: an example. *The Caledonide Orogen: Scandinavia and Related Areas*, (eds. D.G. Gee and B.A. Sturt), pp. 813–822. London: John Wiley.

Hacker B.R., Sharp T., Zhang R.J., Liou J.G., and Hervig R.L. (1997). Determining the origin of ultrahigh-pressure lherzolites. *Science* **278**, 702–704.

Mottl M.J. (1983) Metabasalts, axial hot springs, and the structure of hydrothermal systems at mid-ocean ridges. *Geological Society of America Bulletin* **94**, 161–180.

Miyashiro A. (1973). *Metamorphism and Metamorphic Belts*, 492 pp. London: Allen and Unwin.

Norris R.J and Henley R.W. (1976). Dewatering of a metamorphic pile. *Geology* **4**, 333–336.

Powell R. (1978). *Equilibrium Thermodynamics in Petrology* 284 pp. London: Harper and Row. [This book presents the basic aspects of thermodynamic modeling of rock systems.]

Ranalli G. (1995) *Rheology of the Earth. Deformation and Flow Processes in Geophysics and Geodynamics*, 366 pp. London: Allen and Unwin.

Rubie D.C. (1986). The catalysis of mineral reactions by water and restrictions to the presence of aqueous fluid during metamorphism. *Mineralogical Magazine* **50**, 399–415.

Rubie D.C. (1990). Role of kinetics in the formation and preservation of eclogites. In *Eclogite Facies Rocks* (ed. D.A. Carswell), pp. 111–141. London: Blackie.

Smith D.C. (1984). Coesite in clinopyroxene in the Caledonides and its implications for geodynamics. *Nature* **310**, 641–644.

Sobolev N.V. and Shatsky V.S. (1990). Diamond inclusions in garnets from metamorphic rocks. *Nature* **343**, 742–746. [This research paper documents the formation of diamond in metamorphic crustally derived rocks as the result of subduction at great depths.]

Spear F.S. (1995). *Metamorphic Phase Equilibria and Pressure, Temperature, Time Paths*, 799 pp. Washington, D.C: Mineralogical Society of America, monograph. [This book thoroughly discusses many aspects of metamorphic petrology and their thermodynamic analysis.]

Tatsumi Y. 1989. Migration of fluid phases and genesis of basalt magmas in subduction zones. *Journal of Geophysical Research* **94**, 4697–4707.

Trommsdorff V., Hemann J., Muentener O., Pfiffner M., and Risold A.C. (2000). Geodynamic cycles of sub continental lithosphere in the Central Alps and the Arami enigma. *Journal of Geodynamics* **30**, 77–92.

Tullis J. and Yund R.A. (1980). Hydrolitic weakening of experimentally deformed Westerly granite and Hale albite rock. *Journal of Structural Geology* **2**, 439–451.

Tullis J., Yund R.A., and Farver J. (1996). Deformation enhanced fluid distribution in feldspar aggregates and implications for ductile shear zones. *Geology* **24**, 63–66.

Van Roermund H.L.M. and Drury M. (1998). Ultra-high pressure ($P > 6$ Gpa) garnet peridotites in Western Norway: exhumation of mantle rocks from > 185 km depth. *Terra Nova* **10**, 295–301.

Wang X., Liou J.G., and Mao H.K. (1989). Coesite-bearing eclogites in the Dabie Mountains in Central China. *Geology* **17**, 1085–1088.

Yardley B.W.D. (1989). *An Introduction to Metamorphic Petrology*, 248 pp. London: Longman, Earth Sciences Series.

Biographical Sketch

Marco Scambelluri was born in 1960 in Torino; he received his Degree in Geological Sciences at the University of Torino in 1984, and his Doctorate in Geological Sciences at the University of Genova in 1989, with a thesis on the metamorphic petrology of alpine eclogites and on the role of fluids during exhumation of these rocks. In 1990 he obtained a permanent position as researcher at the University of Genova; since 2000 he has been Associate Professor in Petrology and Petrography at the University of Genova. His research and teaching activities concern the petrology of metamorphic rocks, the composition and role of fluid phases during metamorphism, and the geology and geodynamics of crystalline basements and of orogenic belts. Much of his early research has been focused on the petrology of Alpine eclogite-facies rocks, in order to reconstruct their evolutionary histories and to define the main tectonic and geodynamic processes responsible for the subduction of ancient (Mesozoic) oceanic lithosphere and for the genesis of the Alpine collisional belt. Recent research is addressed to an understanding of the nature and compositions of fluid phases released during subduction of oceanic lithosphere and presently hosted as fluid inclusions in eclogite-facies rocks and in high to very high pressure minerals from several orogenic settings (Ligurian Alps, Western and Central Alps, Betic Cordillera). The aims of these studies are the identification of hydrous mineral phases responsible for the transport of surficial fluids and elements into Earth’s mantle at subduction zones, an understanding of the fluid phases produced during subduction, and the processes of element recycling into the mantle. Marco Scambelluri is member of the Editorial Board of *Lithos* (an international journal of petrology and geochemistry, Elsevier, Amsterdam) and of the *Periodico di Mineralogia* (Italy).