ULTRAMETAMORPHISM AND CRUSTAL ANATEXIS

Bernard Bonin
Université de Paris-Sud, Orsay, France

Keywords: anatexis, melting, solidus, liquidus, water-saturated, water-deficient, dehydration, migmatite, paleosome, neosome, leucosome, melanosome, mesosome, agmatite, metatexite, diatexite, ductile, embrittlement, granite, granodiorite, tonalite, trondhjemite, restite, peraluminous, crust, clockwise P–T path, anti-clockwise P–T path, decompression, extension, orogenesis, subduction, collision, within-plate

Contents

1. Introduction
2. Ultrametamorphic Facies: a Brief Summary
   2.1. High to Ultra-High Pressure Metamorphism
   2.2. High-Temperature Metamorphism
3. Anatexis and Migmatites: Where and When?
   3.1. Migmatites and Migmatitic Terrains
   3.2. Geometric Relationships with Granitic Bodies
4. Geometry of Partial Melting: Mobility and Fate of Crustal Liquids
   4.1. Water-Saturated and Water-Deficient Melting Processes
   4.2. Mobility of Anatectic Liquids
   4.3. Liquid Compositions According to Their Protoliths
5. Geodynamic Settings: Anatexis Under Compressional and Extensional Regimes
   5.1. Orogenic Episodes: Clockwise P–T Paths
   5.2. Within-Plate Settings: Paucity of Anatectic Processes
6. Conclusion. What About Elsewhere?
   Glossary
   Bibliography
   Biographical Sketch

Summary

Crustal melting, also named “anatexis,” can occur at various depths if suitable values of thermodynamic parameters are reached. In the presence of a free H2O-bearing vapor phase, quartzofeldspathic and metapelitic rocks at the amphibolite–granulite boundary or in the high-temperature zone of the eclogite facies are easily melted because of the dP/dT negative slope at crustal depths of the “wet” solidus curve in the pressure–temperature space. In the more frequent cases where vapor phase is lacking, the anatexis isograd is reached at more extreme temperatures that are not attained in normal steady geotherms in the crust. Thus, anatexis can occur only if the middle to lower crust is subjected to either water influx, increasing heat flow, or both. Such perturbations of the steady state of the continental crust are likely to develop extensively during collision and post-collision episodes of a major orogenic event. They are less developed in within-plate settings. It is expected that anatexis is a distinctive feature of Earth’s continental crust and could be lacking in the other terrestrial planets.
1. Introduction

Extreme values of pressure and temperature can be reached by continental and oceanic crustal formations in certain circumstances because of either deep burial, or anomalous heat flow, or both. These conditions correspond to ultrametamorphism, a term originated by Holmquist in 1909. During ultrametamorphic episodes, some types of rocks can be subjected to partial melting, which can result in the generation, ascent, and emplacement of magmatic bodies and volcanic formations. Current geophysical (mainly seismological) studies show that crust, like mantle, is usually at the solid state, implying that, though not uncommon, partial melting is never a protracted process. In 1907, the Finnish geologist Sederholm was the first to coin the term anatexis for melting of a pre-existing rock. In the literature, anatexis applies generally to melting of crustal formations only, though this restricted meaning is not postulated by the term itself. The thermodynamical parameters, such as lithostatic pressure, temperature, fluid pressure and activity, oxygen fugacity, bulk compositions of rocks that are melted, and so on, constitute critical factors that vary strongly according to geodynamic settings. Their values and their variations promote or hinder anatectic processes.

2. Ultrametamorphic Facies: A Brief Summary

In this section, “ultrametamorphism” is defined as metamorphism occurring under extreme thermodynamic conditions. As such, it constitutes a part of the higher-grade regional metamorphism. Extreme pressures refer to depths greater than normal (about 40 km) crustal ones and have values higher than 1.2 GPa. “Ultra-high pressure metamorphism” (UHPM) occurs at pressures higher than 2.8 GPa, the minimum pressure required for formation of coesite at ~700 °C, and is characterized by low thermal gradients of less than ~15°C km⁻¹. Pressures ranging from 1.2 to 2.8 GPa define “high-pressure metamorphism” (HPM). Extreme temperatures refer to thermal gradients higher than ~15 °C km⁻¹ up to more than 100 °C km⁻¹ and define “high-temperature metamorphism” (HTM).

2.1. High to Ultra-High Pressure Metamorphism

The discovery within upper crustal metamorphic formations of Earth of coesite, the high-pressure polymorph of silica replacing quartz at depths of more than 85 km, and of diamond, the high-pressure polymorph of carbon replacing graphite at depths higher than 100 km, has drastically changed scientists’ ideas concerning the limits of crustal metamorphism. All the currently described HPM and UHPM areas consist predominantly of supracrustal rocks of continental, and more rarely of oceanic, affinities.

In the P–T petrogenetic grid (Figure 1), the HPM space comprises two major facies, namely:

- *Blueschist*, subdivided into low-temperature *lawsonite blueschist* LBS and medium-temperature *epidote blueschist* EBS. Temperature is constantly lower than 500 °C, while pressure conditions are bracketed between 0.6 and 2.3 GPa. Related thermal gradients are very low and less than 7°C km⁻¹.
Eclogite, further subdivided into two subfacies, namely: eclogite sensu stricto EC and lawsonite eclogite ECL, both in the quartz stability field. These high-pressure subfacies yield a range of temperatures between 500 and 1000 °C, while pressures vary from 1.2 to 2.8 GPa, corresponding to thermal gradients of ~7.5 up to 12.5 °C km⁻¹.

Figure 1. The pressure–temperature petrogenetic grid delineating fields of metamorphic facies, and zones for wet and dry crustal melting. Source: after Bousquet et al., 1997.
The UHPM space is composed of the other eclogite subfacies, namely: *coesite eclogite* ECC and *grossularite eclogite* ECG, both in the coesite stability field. These ultra-high-pressure facies yield a very large range of temperatures up to 1000 °C and are essentially defined by pressures higher than the quartz–coesite transition, that is, 2.2 to 2.8 GPa for this range of temperatures. ECG has recorded pressures of the order of magnitude of 5 GPa. Variable thermal gradients range again from 7 up to ~12 °C km⁻¹.

The most striking feature of HPM to UHPM rocks is that their density increases dramatically from normal upper crustal values of 2.75 (granite) to 2.94 (gabbro) to values as high as 3.1 to 3.63, respectively. Thus, for any given depths greater than 100 km, the mafic oceanic crust is constantly heavier than the upper mantle, while the silicic continental crust remains less dense than the upper mantle. So different densities, depending on their bulk compositions, result in contrasting vertical mobilities of metamorphic rocks.

Water contents in rocks have been computed from water bound in hydrous minerals and rock porosities. In the quartz stability field, bulk-rock water amounts remain high in blueschists, of the same order of magnitude as in low-grade greenschists, but decrease considerably in eclogites, because of the scarcity of hydrous minerals. In the coesite stability field, stable hydrous minerals are rare, so that rocks are distinctively water-deficient. Extreme variability of water contents coupled with temperature will play a significant role in the ability of rocks to melt.

### 2.2. High-Temperature Metamorphism

Lower crustal formations exposed in old cratons are usually characterized by high-temperature dry parageneses. HTM is basically defined by temperatures higher than the “wet” granite solidus, that is, more than 650 °C, and, accordingly, by high thermal gradients.

In the P–T petrogenetic grid (Figure 1), the HTM space is occupied by the large area of the granulite facies and, along the temperature axis, by the sanidinite facies (not shown in the Figure 1). The rare sanidinite facies is found mostly in crustal xenoliths trapped into basaltic lava flows, while the granulite facies is regionally expanded. Different granulite subfacies have been defined:

- **Two-pyroxene granulite** G2PX, characterized by simultaneous crystallization of clinopyroxene and orthopyroxene. This subfacies yields the lowest pressures, less than 1.2 GPa at 1000 °C. Thermal gradients are typically higher than ~50 °C km⁻¹. Dehydration reactions promote dry rocks. Because pressure is relatively low, compression is less important than thermal expansion which, coupled with dehydration effects, results in rock densities of the same order of magnitude as in greenschists.

- **Garnet-plagioclase** granulite GGA, characterized by plagioclase replacing clinopyroxene. Pressures are bracketed between 1.2 and 1.8 GPa at 1000 °C. Thermal gradients range from ~20 to ~50 °C km⁻¹. Higher pressures result in slightly higher densities, while rocks are still rather dry.
• **Kyanite granulite** GGAK, characterized by kyanite replacing sillimanite. This subfacies yields the highest pressures recorded in granulites, up to 2.2 GPa at 1000 °C. Accordingly, thermal gradients are the lowest observed, but still higher than ~15 °C km⁻¹. The granulite to eclogite transition is marked by the *no-plagioclase garnet granulite* GG. Because of increasing pressure and mineralogical changes, dry rock densities increase sharply at the granulite to eclogite transition.

3. Anatexis and Migmatites: Where and When?

The fact that, deep in the crust, some rocks could become partly liquid is not obvious. Indeed, the occurrence of liquids in some active orogens has been inferred by conductivity modeling, based on laboratory experiments to calibrate the models and assuming that silicate liquid is the cause of the anomalies recorded in the data. Field observation of rocks likely to have undergone partial melting can be made only after a long time has elapsed since the end of the event itself. Evidence for crustal melting is represented by *migmatites*, which constitute a large part of the lower to middle crust of eroded orogens.

### Bibliography


©Encyclopedia of Life Support Systems (EOLSS)


**Biographical Sketch**


He was until 2001 the Secretary of the Commission on Granites of IAVCEI (IUGG), and since 1981 has been Coordinator of the European network EUROGRANITES. In 2002 he took the office of chair of the Subcommission of Systematics of Igneous Rocks (IUGS); Acting as a member of the editorial boards of the *Journal of African Earth Sciences* (Pergamon-Elsevier, Oxford), *Periodico di Mineralogia* (Roma, Italy), and *Schweizerische mineralogisch-petrographische Mitteilungen* (Zürich, Switzerland), he is frequently asked to review manuscripts submitted to international journals.

He has published five textbooks, and his other publications include 17 research books, memoirs and geological maps, 20 articles, 68 reports and book reviews, 184 communications to national and international conferences, and 99 papers published in peer-reviewed journals. His current research topics cover i) the magmatism of telluric planets (Mars, Venus), ii) Earth’s magmatism and geodynamics, with emphasis on the orogenic — anorogenic transition, and iii) the granitoids–volcanism relationships (evolution of plutonic and volcanic alkaline magmatic suites, mineralogy of peralkaline granites and associated rocks).