ULTRAMETAMORPHISM AND CRUSTAL ANATEXIS

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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 H_2O-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}.

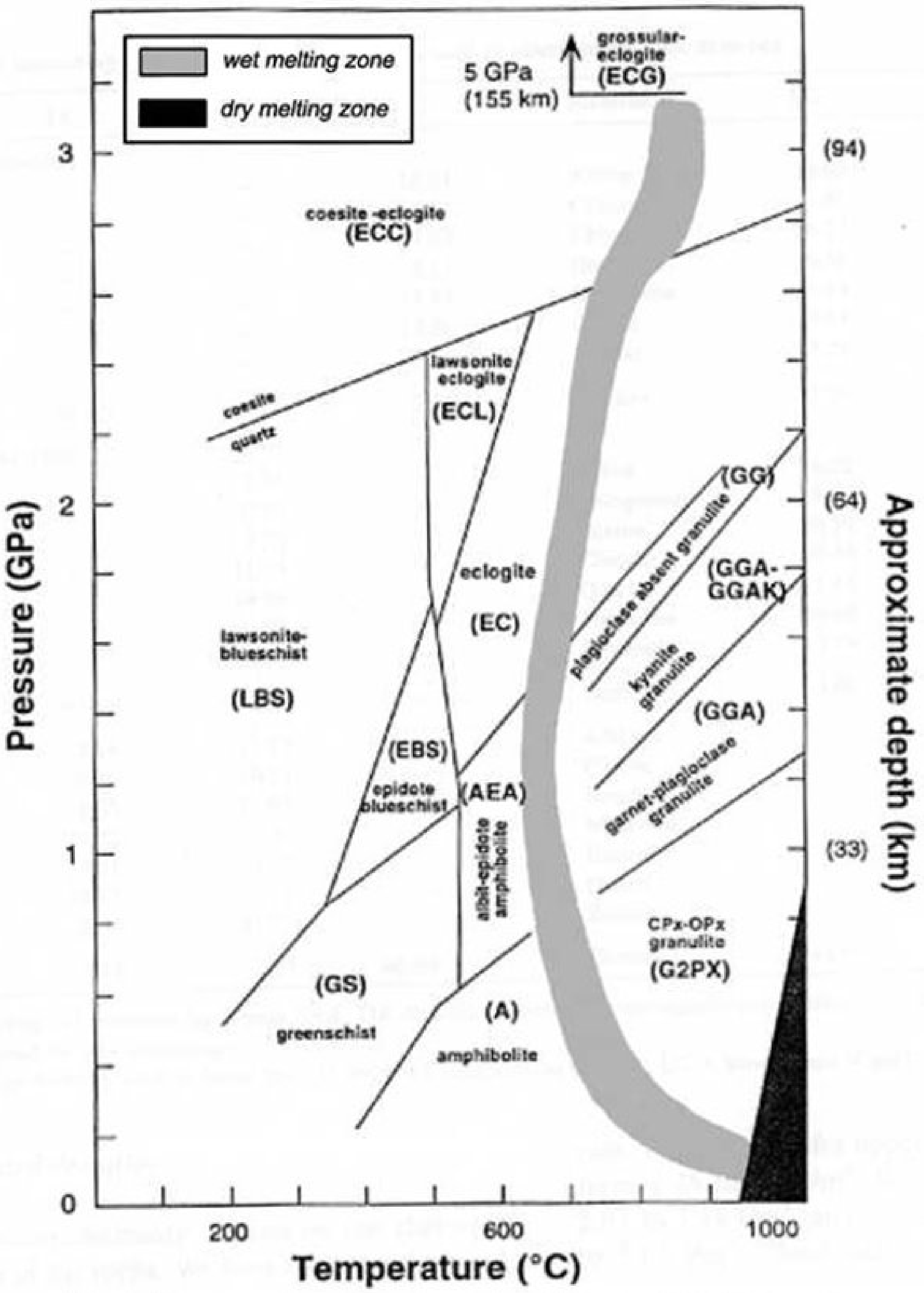

Figure 1. The pressure–temperature petrogenetic grid delineating fields of metamorphic facies, and zones for wet and dry crustal melting. Source: after Bousquet et al., 1997.

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.

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Bibliography

Barbarin B. (1990). Granitoids: main petrogenetic classifications in relation to origin and tectonic settings. *Geological Journal* **25**, 227–238. [The most fully achieved attempt to classify the different granite types in the world.]

Bates R.L. and Jackson J.A. (1980). *Glossary of Geology*, 751 pp. Falls Church, VA: American Geological Institute. [The most comprehensive glossary in English to understand the meaning of the words used by geoscientists today.]

Bonin B., Dubois R., and Gohau G. (1997). *Le Métamorphisme et la Formation des Granites: Evolution des Idées et Concepts Actuels*, 317 pp. Paris: Editions Nathan, Faculty of Sciences, Nathan-Université. [In French, a review of the history of the ideas concerning metamorphism and granite generation.]

Bousquet R., Goffé B., Henry P., Le Pichon X., and Chopin C. (1997). Kinematic, thermal and petrological model of the Central Alps: Lepontine metamorphism in the upper crust and eclogitisation of the lower crust. *Tectonophysics* **273**, 105–127. [An attempt to relate geological, petrological and geophysical evidences in the well-known mountain belt of the Central Alps.]

Brown M. (1994). The generation, segregation, ascent and emplacement of granite magma: the migmatite-to-crustally-derived granite connection in thickened orogens. *Earth-Science Reviews* **36**, 83–130. [A comprehensive review on crustally derived granite magmas.]

Brown M., Friend C.R.L., McGregor V.R., and Perkins W.T. (1981). The Late Archaean Qôrqut granite complex of southern west Greenland. *Journal of Geophysical Research* **86**, 10617–10632. [A description of one of the oldest crustally derived granites.]

Brown M.A., Brown M., Carlson W.D., and Denison C. (1999). Topology of syntectonic melt-flow networks in the deep crust: inference from three-dimensional images of leucosome geometry in migmatites. *American Mineralogist* **84**, 1793–1818. [A three-dimensional image of how liquids droplets can connect and segregate in a porous medium.]

Bucher K. and Frey M. (1994). *Petrogenesis of Metamorphic Rocks*, 318 pp. (sixth edition: complete revision of Winkler's textbook) Berlin, Heidelberg: Springer-Verlag. [A complete textbook on metamorphism by the best specialists today.]

Clemens J.D. and Vielzeuf D. (1987). Constraints on melting and magma production in the crust. *Earth and Planetary Science Letters* **86**, 287–306. [This paper deals with the relationships between the mineral assemblages subjected to partial melting and their fertility in terms of volumes of liquids produced.]

Coleman R.G. and Wang X. (1995). *Ultrahigh Pressure Metamorphism*, 528 pp. Cambridge, UK: Cambridge Topics in Petrology, Cambridge University Press [The state of the art of a new topic in metamorphic petrology, that is, metamorphism of the crust at depths below 80–100 km.]

Davidson C., Schmid S.M., and Hollister L.S. (1994). Role of melt during deformation of the deep crust. *Terra Nova* **6**, 133–142. [How crustal liquids can promote and channel deformation within the deep crust.]

Dietrich R.V. and Mehnert K.R. (1961). *Proposal for the Nomenclature of Migmatites and Associated Rocks* (Twenty-first International Geological Congress, Copenhagen, Denmark, 1960) Report, part 26, section 14, pp. 56–67. [An essay to clarify the nomenclature of migmatites.]

Gilluly J. (Chairman) (1948). Origin of granite. *Geological Society of America Memoir* **28**, 139 pp. [The proceedings of a symposium held at Ottawa, an echo of the hot debates with the best specialists of the moment.]

Harris N.B.W. and Massey J. (1994). Decompression and anatexis of the Himalayan metapelites. *Tectonics* **13**, 1537–1546. [An attempt to relate geochemical data to the physical process of partial melting.]

Holtz F., Johannes W., Tamic N., and Behrens H. (2001). Maximum and minimum water contents of granitic melts generated in the crust: a reevaluation and implications. *Lithos* **56**, 1–14. [Using experimental evidence, how much crustal liquids can incorporate water and how water solubility can influence magma mobility.]

Huang W.L. and Wyllie P.J. (1975). Melting reactions in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2 to 35 kilobars, dry and with excess water. *Journal of Geology* **83**, 737–748. [After Tuttle and Bowen, an experimental study of melting of a synthetic granite at very high pressures.]

———. (1981). Phase relationships of S-type granite with H_2O to 35 kbar: muscovite granite from Harney Peak, South Dakota. *Journal of Geophysical Research* **86**, 10515–10529. [An experimental study of melting of crustally derived granite.]

Johannes W. and Gupta N.L. (1982). Origin and evolution of a migmatite. *Contrib. Mineral Petrology* **79**, 14–23. [An interpretation of the heterogeneity of migmatites.]

Le Fort P. (1981). Manaslu leucogranite: a collision signature of the Himalaya. A model for its genesis and emplacement. *Journal of Geophysical Research* **86**, 10545–10568. [A comprehensive study of the Manaslu leucogranite in High Himalaya—the most famous crustally derived granite in the world.]

Miller C.F., Watson E.B., and Harrison T.M. (1988). Perspectives on the source, segregation, and transport of granitoid magmas: transactions of the Royal Society of Edinburgh. *Earth Sciences* **79**, 135–156. [A discussion on the hot topics in granite geology today.]

Patiño Douce A.E. and Beard J.S. (1995). Dehydration-melting of biotite gneiss and quartz amphibolite from 3 to 15 kbar. *Journal of Petrology* **36**, 707–738. [An experimental approach to anatexis, with analysis of the liquid products.]

Patiño Douce A.E. and McCarthy T.C. (1998). Melting of crustal rocks during continental collision and subduction. *When Continents Collide: Geodynamics and Geochemistry of Ultra-High Pressure Rocks* (eds. B.R. Hacker and J.G. Liou), pp. 27–55. Dordrecht: Kluwer Academic Publishers. [A review of the experimental evidence—with emphasis on the compositions of liquids and residues during partial melting.]

Rapp R.P. (1995). The amphibole-out phase boundary in partially melted metabasalt, its control over melt fraction and composition, and source permeability. *Journal of Geophysical Research* **100**, 15601–15610. [An experimental approach to the debated problem of the conditions of the partial melting of the oceanic crust.]

Read H.H. (1957). *The Granite Controversy: Geological Addresses Illustrating the Evolution of a Disputant*, 430 pp. London: Thomas Murby and New York: Interscience Publishers. [The evolving ideas concerning the origin of granite of a world-renowned field geologist throughout his lifetime.]

Robertson J.K. and Wyllie P.J. (1971). Rock–water systems: with special reference to the water deficient regions. *American Journal of Science* **271**, 252–277. [An attempt to classify the different kind of magmatic environments with respect to fluids.]

Robinson D. and Bevins R.E. (1989). Diastathermal (extensional) metamorphism at very low grades and possible high-grade analogues. *Earth and Planetary Science Letters* **92**, 81–88. [The definition of metamorphism outside orogenic belts.]

Sawyer E.W. (1994). Melt segregation in the continental crust. *Geology* **22**, 1019–1022. [A very thorough examination, by a field geologist, of the pathways followed by crustal liquids in the deep crust.]

Scaillet B., Pichavant M., and Roux J. (1995). Experimental crystallization of leucogranite magmas. *Journal of Petrology* **36,** 663–705. [An experimental study of partial melting of the crustally derived Manaslu leucogranite.]

Searle M.P. (1999). Extensional and compressional faults in the Everest–Lhotse massif, Khumbu Himalaya, Nepal. *Journal of the Geological Society* **156**, 227–240. (London). [A demonstration of the roles played by coeval thrust and detachment planes in the emplacement of crustally derived granites.]

Sederholm J.J. (1907). *Om Granit och Gneiss,* 110 pp. Helsinki, Finland: Bulletin de la Commission Géologique de Finlande No. 23. [The seminal work of Sederholm: introducing the concept of anatexis.]

Thompson A.B. (2001). Clockwise P–T paths for crustal melting and H_2O recycling in granite source regions and migmatite terrains. *Lithos* **56**, 33–45. [A thermodynamic discussion on the generation and fates of metapelitic liquids, within evolving orogenic belts.]

Turner F.J. (1968). *Metamorphic Petrology: Mineralogical and Field Aspects*, 403 pp. New York: McGraw-Hill, International Series in the Earth and Planetary Sciences. [A classical textbook on metamorphism, with emphasis on mineral assemblages and field evidence.]

Tuttle O.F. and Bowen N.L. (1958). *Origin of Granite in the Light of Experimental Studies in the System* SiO_2–$NaAlSi_3O_8$–$KAlSi_3O_8$–H_2O, 153 pp. Geological society of America Memoir 74. [The definitive experimental evidence for the magmatic origin of granite.]

Vigneresse J.L., Barbey P., and Cuney M. (1996). Rheological transitions during partial melting and crystallization with application to felsic magma segregation and transfer. *Journal of Petrology* **37**, 1579–1600. [An examination of the roles played by porosity and liquid volumes in the rheology of natural systems.]

Vigneresse J.L. and Tikoff B. (1999). Strain partitioning during partial melting and crystallizing felsic magmas. *Tectonophysics* **312**, 117–132. [How crystal-laden liquids can promote and channel deformation within the deep crust.]

Yoder, Jr. H.S. (1993). Timetable of petrology. *Journal of Geological Education* **41**, 447–489. [A calendar of the major advances in petrology through time; as seen by a prominent US experimental petrologist.]

Biographical Sketch

Bernard Bonin was born in 1948, at Algiers (Algeria). A past student of the École Normale Supérieure, Paris (1967–1971), he graduated in Earth Sciences up to the Doctorat d'État ès-Sciences (D.Sc. Thesis) at Université Pierre-et-Marie Curie, Paris, in 1980. A laureate of the Viquesnel Prize, awarded by the Société Géologique de France in 1986, since 1981 he has been Professor pf Mineralogy-Petrology at the Université de Paris-Sud, Orsay, where he was elected twice as the Chair of the Department of Earth Sciences (1984–1988 and 1995–1999).

He was until 2001the 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).