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Research paper

From granulite fluids to quartz-carbonate megashear zones: The gold rush

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ABSTRACT

At peak granulite-facies metamorphic conditions, lower continental crust is arguably fluxed by large amounts of two key low water activity fluids: (i) high-density CO_2 and/or (ii) concentrated saline solutions. These fluids are either internally-derived, generated by mineral reactions or dehydration melting or, notably for CO_2, externally-derived, issued from the underlying mantle. Postmetamorphic evolution results in complete disappearance of these fluids, except for minute remnants preserved in minerals as fluid inclusions. Two major processes are involved: (i) at peak conditions, granitoid magmas form, migrate upward, and crystallize as shallow intrusions in the upper crust (mineralized porphyry types or reduced intrusions); (ii) during the rapid decompression which almost systematically follows a period of post-peak isobaric cooling, especially for ultrahigh-temperature granulites (anticlockwise *P-T* paths), quartz-carbonate megashear zones are formed by repeated periods of seismic activity. Seismic activity may continue until all free fluids have disappeared, resulting in the ultramylonites and pseudotachylites that are found in many granulite domes. A great majority of vein-type Au deposits worldwide occur in the above-mentioned settings or nearby. We suggest that the Au has been scavenged by the granulite fluids, then redistributed and concentrated during the formation of veins and related phenomena.

1. Introduction

After years of discussion, it has been gradually accepted that low water activity fluids could be present in the lower continental crust during peak granulite-facies metamorphic conditions, in sufficiently large enough amounts to account for the various dehydration reactions occurring at this metamorphic grade (e.g., Newton, 1986; Harlov, 2012). When granulites are uplifted towards the Earth's surface, these fluids leave the rock systems, except for minute remnants preserved in rock-forming minerals as fluid inclusions. Although very high temperatures can be reached during granulite-facies metamorphism, about 1000 °C or higher in the case of ultrahigh-temperature (or UHT) granulites, minerals such as zircon and coesite are not completely re-equilibrated (e.g., Möller et al., 2003; Ruiz-Cruz and de Galdeano, 2012). This permits an accurate reconstruction of the pressure-temperature-time (*P-T-t*) trajectory of the rocks en route to the Earth's surface. It is known that *P-T* estimates are particularly complicated when minerals such as mica or amphibole are involved (Spear, 1993), as is the case for most metamorphic rocks that have not experienced dehydration. In this respect, the scarcity of hydroxyl-bearing mineral phases, as well as the extreme range of *P* and *T* conditions, make granulites almost ideal rocks for mineral thermobarometry, as evidenced by the continuous flow of publications (e.g., Harley, 1989; Kelsey, 2008). These works have confirmed the hypothesis, first proposed by Beloussov (1960), that granulites constitute the lower continental crust and are equilibrated when granitoid magma intrudes at upper crustal levels (i.e., granulite-granite connexion: Clemens, 1990). The average Au content of granulites worldwide is low, ca. 0.2–1.5 ppb (e.g., Sighinolfi and Santos, 1976; Cameron, 1993), but many vein-type Au deposits are located in or in close proximity to granulite complexes. Examples include: (i) Griffin's Find, Yilgarn,

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Western Australia (<0.1 Moz Au; Phillips and Powell, 2009; Tomkins and Grundy, 2009); (ii) Challenger, South Australia (2 Moz Au; Tomkins and Mavrogenes, 2002; Phillips and Powell, 2009); and (iii) Renco, southern Zimbabwe (1 Moz Au; Kisters et al., 1998; Phillips and Powell, 2009). The idea that Au mineralization occurs in granulite terranes is not new, it enjoyed even some popularity in the early 90's (e.g., Kyser and Kerrich, 1990; Barnicoat et al., 1991). But it was then not widely accepted, mainly because of the supposedly "dry" (fluid-absent) character of granulite-facies metamorphism (p. 206 in Kyser and Kerrich, 1990). The situation is now different, and the potential role of fluids during and after granulite-facies metamorphism much better understood (e.g., Harlov, 2012). The object of the present paper is to discuss in some detail the way by which granulite-facies metamorphism in general, and granulite fluids in particular, have contributed to the formation of these deposits.

2. High-pressure granulites versus high-temperature granulites

Granulites are rocks metamorphosed above minimum granite melting temperature, that is, approximately between 700 and 1000 °C. It has been known from simple diagnostic minerals (e.g., aluminium silicate and cordierite) that the pressure was slightly more variable than the temperature: occurring between two extremes, the "classical" intermediate granulites cluster around pressures of about 7 kbar (i.e., depth of about 20 km). High-pressure (HP) granulites, transitional to eclogites cluster around 10–12 kbar. Lastly high-temperature (HT) granulites, sometimes equilibrate at pressures as low as 5 kbar (e.g., Newton et al., 1980). Harley (1989) was the first to show that there is a striking difference in the *P-T* trajectory between HP-granulites and HT-granulites, i.e., clockwise for the former (like eclogites) and anticlockwise for the latter, with a correlative increase in both temperature and pressure at peak metamorphic conditions (Fig. 1). This can only be accounted for by the accumulation of mantle-derived intrusions at the crust-mantle interface. The heat is provided for by the intrusion, and the pressure increase is provided for by a vertical thickening of the crust during the metamorphic episode (Touret, 2009). Such a model is corroborated by the fact that the granulite-facies lower crust becomes increasingly igneous at depths, as shown by the marked opposition between granulite complexes occurring at the Earth's surface (mainly supracrustal origin) and the almost exclusively igneous origin of granulite xenoliths in lavas from recent volcanoes (Bohlen and Mezger, 1989). Many UHT-granulites are low-pressure types "par excellence", but it must also be noted that the UHT field can also be reached by HP-granulites through a significant temperature increase during decompression clockwise *P-T* path, e.g., the Limpopo Belt (Tsunogae and van Reenen, 2011) or Dabie Shan, China (Tong et al., 2011). Both types may occur in a single orogen, conforming to the concept of "paired belts" as proposed by Miyashiro (1961) from the example of the Sanbagawa and Ryoke orogens in northeastern Japan. Both orogens are relatively young in age (Cretaceous) and approximately contemporaneous, but this has later proven to be more the exception than the rule. In the Hercynian (or Variscan) orogen of central Europe, for instance, Eo-Hercynian high pressure metamorphism, occurring notably in the Moldanubikum unit, predates by about 100 Myr the widespread Carboniferous low-pressure Hercynian metamorphism, during which the European crust has acquired its present structure. This includes the granitic migmatite and voluminous granites emplaced in the middle crust (now outcropping at the surface in the basement complexes which defines the whole Variscan chain) and the granulite lower crust, known from xenoliths in recent volcanoes. The French Massif Central is a good regional example (Fig. 2), which could be repeated in virtually all other Hercynian massifs such as Central Spain, Brittany, Vosges, and Bohemia (e.g., Matte, 1991). Known locally as the "Complexe leptyno-amphibolique", the Eo-Hercynian HP metamorphic rocks, dated at about 400 Ma, are thrusted across lower-grade basement in nappes

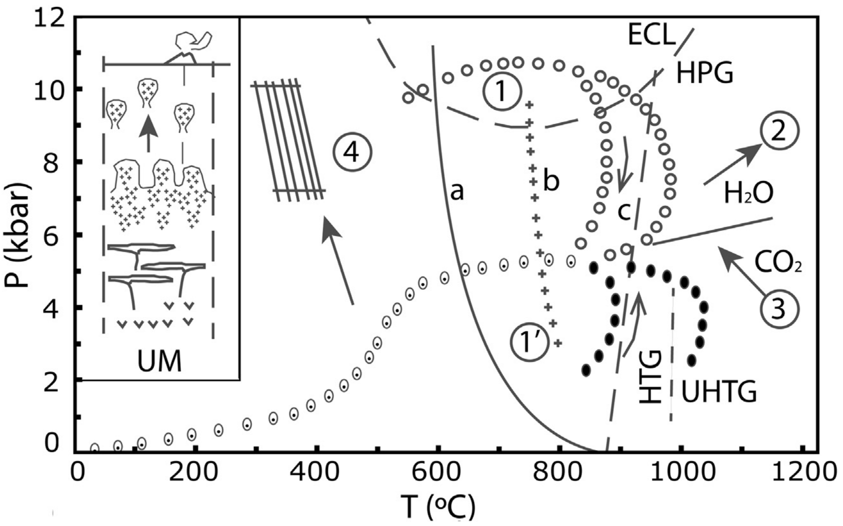

Figure 1. Fluid control during clockwise high-pressure (HP, open circles) and anticlockwise high-temperature (HT, solid circles) *P-T* paths and retrogression (circles with dots) (adapted from Fig. 6, Touret and Huizenga, 2012). HP-paths: ECL (eclogite), grading into high-pressure granulite (HPG). Rocks contain a limited amount of internally-generated fluids, either inherited from the surface or progressively released during dehydration/decarbonation reactions ①. HT-paths: high- or ultrahigh-temperature granulite (HTG/UHTG), also involving internally-generated fluids during the prograde part of the path ①′. For all paths, crustal melting occurs via anatexis, for HP-paths through decompression melting along the curve b, anywhere between a (wet granite melting) and c (dry granite melting), depending on the local H_2O activity. Free water is then dissolved in the melt, transported to upper levels in ascending magmas (crosses in sketch to the right), then released during magma crystallization ②. For HT/UHT paths, the anticlockwise trajectory, corresponding to a simultaneous increase of pressure and temperature, is caused by the stacking of mantle-derived intrusions at the base of the crust (see inset for sketch, UM = Upper Mantle). These intrusions introduce into the rock system large quantities of externally-generated, mantle-derived CO_2 ③, possibly also other types of low-H_2O activity fluids (brines). These fluids remain in the lower crust during isobaric cooling at the end of the metamorphic episode, eliminated along megashear zones during a rapid decompression (regional uplift) which occurs typically at lower temperatures ④.