Geoscience Frontiers 7 (2016) 101–113

HOSTED BY

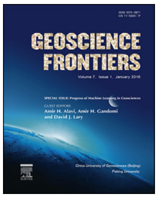
ELSEVIER

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf



Focus paper

# High-temperature granulites and supercontinents

J.L.R. Touret[a], M. Santosh[b], J.M. Huizenga[c,d,*]

[a] *Institut de Minéralogie, Physique des Matériaux, Cosmochimie (IMPMC), Sorbonne Universités et UPMC Univ Paris 06, UMR CNRS 7590, Muséum National d'Histoire Naturelle, IRD UMR 206, 4 Place Jussieu, F-75005 Paris, France*

[b] *School of the Earth Sciences and Resources, China University of Geosciences (Beijing), 29 Xueyuan Road, Beijing 100083, China*

[c] *Economic Geology Research Institute (EGRU), College of Science, Technology and Engineering, James Cook University, Townsville, Queensland, 4811, Australia*

[d] *Unit for Environmental Sciences and Management, North-West University, Private Bag X6001, 2520, South Africa*

ARTICLE INFO

*Article history:*
Received 28 April 2015
Received in revised form
20 August 2015
Accepted 4 September 2015
Available online 21 September 2015

*Keywords:*
Continents
Supercontinents
Magmatism and metamorphism
Fluids
Tectonics

## ABSTRACT

The formation of continents involves a combination of magmatic and metamorphic processes. These processes become indistinguishable at the crust-mantle interface, where the pressure-temperature (*P-T*) conditions of (ultra) high-temperature granulites and magmatic rocks are similar. Continents grow laterally, by magmatic activity above oceanic subduction zones (high-pressure metamorphic setting), and vertically by accumulation of mantle-derived magmas at the base of the crust (high-temperature metamorphic setting). Both events are separated from each other in time; the vertical accretion post-dating lateral growth by several tens of millions of years. Fluid inclusion data indicate that during the high-temperature metamorphic episode the granulite lower crust is invaded by large amounts of low $H_2O$-activity fluids including high-density $CO_2$ and concentrated saline solutions (brines). These fluids are expelled from the lower crust to higher crustal levels at the end of the high-grade metamorphic event. The final amalgamation of supercontinents corresponds to episodes of ultra-high temperature metamorphism involving large-scale accumulation of these low-water activity fluids in the lower crust. This accumulation causes tectonic instability, which together with the heat input from the sub-continental lithospheric mantle, leads to the disruption of supercontinents. Thus, the fragmentation of a supercontinent is already programmed at the time of its amalgamation.

## 1. Introduction

Continents are present since the very beginning of the Earth history, at least since ~3.5 Ga. Controversy surrounds the question of how and when continents reached their present size, but the general consensus is that continents grew rapidly during the Archean and attained an approximate near steady-state growth from the Proterozoic (~2.7 Ga) onwards (e.g., Taylor and McLennan, 1995). While continental crust is added laterally at subduction zones along active margins (e.g., the western margin of the American continents), a substantial volume of the continental crust disappears into the mantle during continental collision (Stern, 2011; Kawai et al., 2013). Despite the steady-state growth since ~2.7 Ga, the geographical distribution of continental masses never ceased to show remarkable changes. Major episodes of continental growth occurred during discrete pulses of intense magmatic-metamorphic activity that lasted a few hundred million years. These events of continental growth are separated from each other by roughly equal time periods (Brown, 2007, 2008). Continental destruction and continental growth were approximately coeval (e.g., Stern, 2011), displaying a never-ending ballet at the Earth's surface. These processes impose a relative displacement of the continental masses as compared to oceans. Salient advancement of modern trace element and isotope geochemistry has gained insight into the *supercontinent cycle* (e.g., Murphy et al., 2009), a process which involves continents progressively amalgamating to constitute a single unit, surrounded by a single ocean, followed by separation into moving fragments until the next amalgamation occurs. Several studies have addressed this subject, which is considered to be one of the focal themes of

---

[*] Corresponding author. Economic Geology Research Institute (EGRU), College of Science, Technology and Engineering, James Cook University, Townsville, Queensland, 4811, Australia.
*E-mail address:* jan.huizenga@jcu.edu.au (J.M. Huizenga).
Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2015.09.001
1674-9871/

current research in geology (e.g., Nance et al., 2014; Clark et al., 2015).

In this work, we focus on the role of deep fluids during continent formation and evolution, an aspect that is underestimated in recent studies. One reason for this may be that there has not been a general agreement on the nature of the lower continental crust, with conflicting magmatic versus metamorphic models. We will, therefore, first discuss the arguments that favour the second hypothesis (granulite lower crust), followed by reviewing the role of fluids in granulites, and the formation and breakup of continents. We will argue that episodes of granulite metamorphism, leading to supercontinent amalgamation, immediately prepare for their disruption. In other words, the demise of supercontinents is already programmed at the time of their birth.

## 2. A granulite lower continental crust

A review of the current literature reveals that there is no general agreement on the composition or, above all, on the structure of the continental crust. In 1925, the Austrian geophysicist V. Conrad found that seismic velocities in the lower part of the continental crust were progressively changing, and are intermediate between those of the upper crust and the mantle (Conrad, 1925). This observation led to the idea of a widespread *Conrad discontinuity*, once almost more popular than the Moho, which marks a transition at the base of the continent between a dominantly granitic and a more basic crust. Further studies have questioned the nature and even the existence of the Conrad discontinuity, which is not found everywhere (Litak and Brown, 1989). Despite these reservations, the idea of progressive *basification* of the continental crust at depth remained and, as a consequence, various names such as gabbroic or even basaltic crust are found in the literature, notably among geophysicists (e.g., Smithson and Brown, 1977). We believe that this terminology should be discarded.

In 1960s, it was shown that the lower continental crust is composed of rocks metamorphosed under granulite-facies *P-T* conditions. This idea was proposed in the former USSR (Belousov, 1966), and supported thereafter by a wealth of data including seismic velocities, heat budget and field evidence from rocks that we can study at the Earth's surface, either exposed by tectonic movements (regional granulites) or transported as xenoliths in lavas from recent volcanoes. For the structure of a continent, the model proposed in 1995 by R.L. Rudnik and D.M. Fountain is in our view the most realistic one (Rudnick and Fountain, 1995). On the basis of seismic refraction data, they divided the crust into type sections associated with different tectonic provinces. Each shows a three-layer crust consisting of upper, middle, and lower crust, in which P-wave velocities increase progressively with depth. There is large variation in average P-wave velocity of the lower crust between different type sections, but in general, lower crustal velocities are high (>6.9 km/s) and average middle crustal velocities range between ~6.3 and ~6.7 km/s (Rudnick and Fountain, 1995).

The average composition of the continental crust is intermediate and contains a significant proportion of the bulk silicate Earth's incompatible trace element budget (35–55 wt.% of Rb, Ba, K, Pb, Th, and U) (Rudnick, 1995). However, this generalised picture should not hide the overall stratified character of the continental crust. Heat producing elements decrease with depth indicating an overall increase of mafic rocks. This change is markedly progressive and the variation is a function of geodynamic setting (active or passive margins, extensive or compressive regime), explaining the elusive character of the Conrad discontinuity (Lowrie, 2007). Using average P-wave velocities derived from crustal type sections, the estimated area extent of each type of crust and the compositions of different types of granulites, average lower and middle crust compositions can be estimated. The middle crust is composed of rocks at amphibolite-facies *P-T* conditions and is granodioritic in bulk composition, containing significant amounts of K, Th, and U. The lower crust is composed of granulite-facies metamorphic rocks and is lithologically heterogeneous. Its average composition is mafic, approaching that of primitive mantle-derived basalt, but it may have intermediate bulk compositions in some regions. A comparison of the exposed granulites to volcanic xenoliths shows that the basification is progressive, from dominantly metamorphosed supracrustals in the upper crust to former magmas in the lower crust, related to melts invading from the underlying mantle and emplaced at peak granulite metamorphic conditions (syn-metamorphic intrusions, e.g., Bohlen and Mezger, 1989; Touret and Huizenga, 2012a). This process leads to crustal thickening (vertical accretion) through accumulation at the mantle-crust interface of mantle-derived melts of dominantly basaltic composition (magmatic underplating, Bohlen and Mezger, 1989) as documented, for example, in southern and central Queensland in Australia (Ewart et al., 1980).

In summary, if the term *granulite lower crust* should be the only one to be retained, it must be recognised that it does not waive all ambiguity or misunderstanding. The name *granulite* seems to have been especially attractive to petrologists, who attributed different meanings (German, English or French sense, see discussion in Touret and Nijland, 2013). However, if only the metamorphic interpretation is considered to be valid (i.e., rocks metamorphosed at granulite-facies *P-T* conditions), a major issue needs clarification. The temperatures of granulite-facies metamorphism are close or even equal to magmatic temperatures (ultrahigh-temperature granulites, see below). Therefore, the distinction between magmatic and metamorphic rocks in the lower crust is by no means easy. For instance, two-pyroxene granulites found in many volcanic ejecta (Kay and Kay, 1983) can be considered to be either magmatic, if one considers the origin (basalt melt), or metamorphic, based on their mineral assemblage. As metamorphism postdates the magmatic process, we believe that lower crustal rocks are essentially metamorphic in nature. Of critical importance is to know the type of metamorphic evolution. This can either be high-pressure (HP, $P > \sim 10$ kbar, Brown, 2007) metamorphism, characterised by a clockwise *P-T* path (e.g., O'Brien and Rötzler, 2003), or high/ultrahigh-temperature (HT/UHT, $T > 800/900$ °C, Brown, 2007) metamorphism characterised by an anticlockwise *P-T* path (Harley, 1989). As will be discussed below, these contrasting *P-T* paths are of major importance to understand how the continental crust has been formed and from where the fluids have been sourced.

In most cases, fragments of the lower crust exposed at the surface do not show the upper boundary (transition middle-lower crust). There are, however, a number of cases where this boundary is exposed, amenable to direct observation. One of the best example, despite being limited in size, is the Lherz area in the French Pyrenees, where the Conrad (amphibolite to granulite) and Moho (crustal to mantle) discontinuities can be seen within a distance of less than 2 km (Vielzeuf and Kornprobst, 1984). The Proterozoic metamorphic terrane of southern Norway (Bamble sector and Rogaland) shows a less complete section (i.e., no mantle rocks are exposed), but is much larger in size and better documented. Here, the amphibolite-granulite transition is marked by a series of metamorphic isograds which have been mapped in great detail in the eastern Bamble sector (Nijland et al., 2014) and in Rogaland in the west (Westphal et al., 2003). The transition between the middle and lower crust corresponds to several isograds (mainly orthopyroxene), defining a temperature up to ~1000 °C in osumilite-bearing rocks of Rogaland. This temperature is well above the minimum granite melting temperature (700 to 850 °C), i.e., these rocks represent a typical example of UHT granulite metamorphism (Maijer et al., 1977).