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Focus paper

High-temperature granulites and supercontinents

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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

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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).

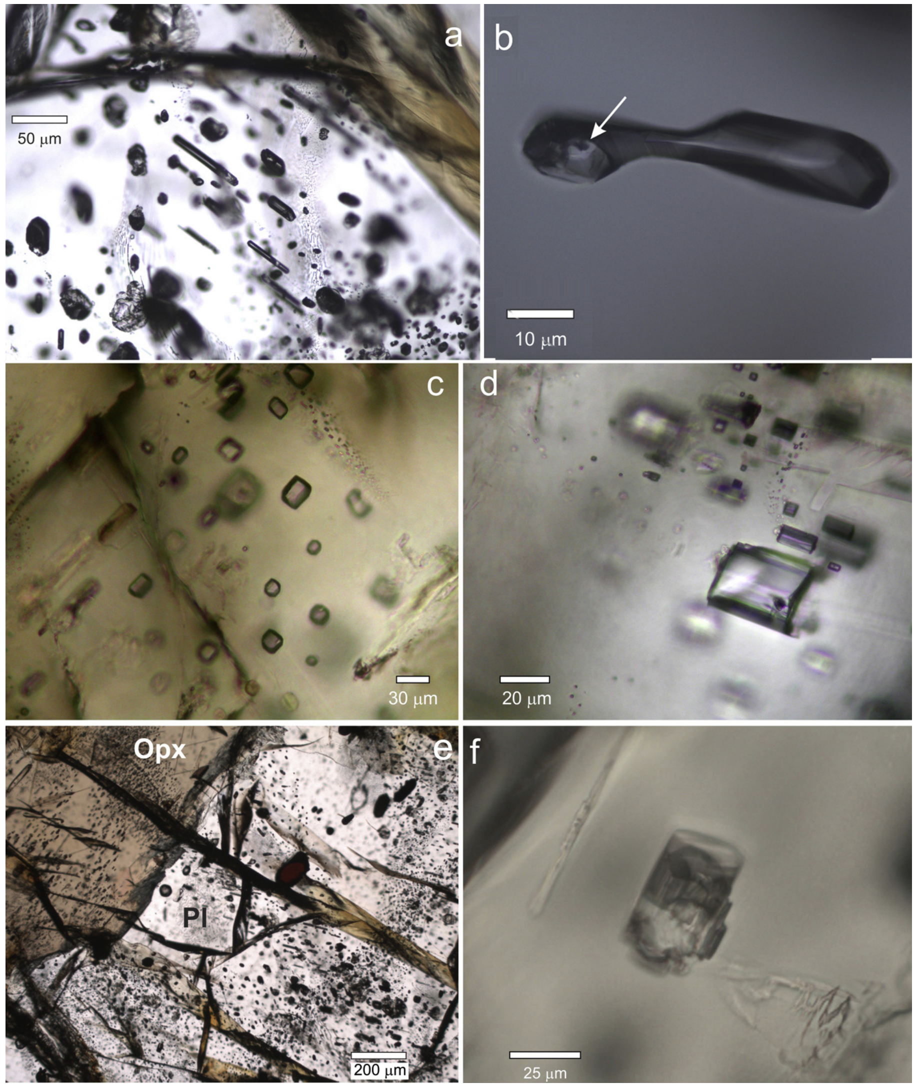

Figure 1. (a) Primary, moderate-density ($\sim$0.9 g/cm^3) magnesite-bearing CO_2 inclusions in garnet from sapphirine-bearing granulites, Harukutale, Sri-Lanka Central Highlands (Bolder-Schrijver et al., 2000). (b) Example of a magnesite-bearing CO_2 inclusion in the Central Highlands granulites in Sri Lanka. (c) Pure CO_2, high-density ($\sim$1.1 g/cm^3) fluid inclusions in plagioclase in late Archean garnet-granulite (Kondalpattimedu near Salem, southern India, see Santosh and Tsunogae, 2003). (d) Moderate-density ($\sim$1.0 g/cm^3), pure CO_2 fluid inclusions in perthitic K-feldspar in ultrahigh-temperature late Pan African granulites from charnockites from the Anchankovil shear zone area in southern India (Santosh, 1987; Ishii et al., 2006). (e) Primary CO_2 fluid inclusions in orthopyroxene and plagioclase in sapphirine-bearing granulites from Sri Lanka (Bolder-Schrijver et al., 2000) (cf. a). Note that each dark spot represents an inclusion that comprises high-density CO_2, illustrating the large amount of CO_2 fluid present in this rock. (f) Detail of an inclusion in orthopyroxene (same sample as in e). The inclusion comprises a monophase CO_2 fluid phase (dark phase in the middle of the inclusion) and numerous identified (carbonates) and unidentified isotropic solid phases (including probably halite). The anisotropic solid phases occurring as white masses are most likely alkali carbonates. Note that this inclusion shows a conspicuously close resemblance with carbonate melt inclusions in volcanic rocks from the East African Rift in Tanzania (Figs. 1 and 2 in Káldos et al., 2015).

Most UHT granulites are characterised by an anticlockwise *P-T* path (Harley, 1989; Santosh et al., 2012). High-temperature and even UHT granulite metamorphic conditions can also be reached through clockwise *P-T* paths; they show a temperature increase during uplift and equilibrate at HT/UHT metamorphic conditions (e.g., Harley, 2008). In all cases, the middle crust comprises abundant granite intrusions, most of which are coeval with granulite metamorphism in the lower crust. For instance, in the French Massif Central mid-crustal Carboniferous granites were emplaced $\sim$300 Ma ago (Ledru et al., 2001). This event occurred simultaneously with the granulite metamorphism as evidenced by radiometric dating of granulite xenoliths in Quaternary volcanoes (e.g., Pin and Vielzeuf, 1983).

The systematic relation between granites in the middle crust and LILE-depleted granulites in the underlying lower crust has led to the idea that granulites are *restites*. Restites are assemblages of refractory anhydrous minerals from which granitic melts have been extracted, i.e., the granite-granulite connection (Clemens, 1990, 1992). This is, for example, the case for granulites in Scotland (Pride and Muecke, 1980), a region where the idea of restite granulites has taken its roots, and in northern Quebec (Morfin et al., 2013), where the lower crust has actually been enriched in melts. However, in southern Norway the granulite domain does not at all show an increase in the degree of melting. Former supracrustals can still be identified, sometimes with extremely delicate structures such as flysch-type banding or cross-bedding (Touret, 1965). These HT granulites are definitely not restites and were able to withstand high metamorphic temperatures without melting. This phenomenon can only be understood by including low H_2O-activity fluids as an essential element of granulite facies metamorphism, as we have argued for many years (Touret and Huizenga, 2011, 2012a and references therein).

3. Fluids in granulites

The importance of fluids during granulite metamorphism was initiated by the discovery of CO_2 inclusions in granulites from southern Norway (Touret, 1971). Soon afterwards, similar fluid inclusions were also found in numerous other granulite terrains worldwide (e.g., Santosh, 1986, 1987). The major exception is for granulites that suffered solid state recrystallisation (roughly equant mineral size with equilibrated triple junction boundaries), which is the type of texture precisely called granulitic in the British literature (Harker, 1932). This recrystallisation process wipes out any inclusion in the former mineral. But even in these rocks, fluid inclusions can still be found in resistant minerals (notably garnet) or non-recrystallised quartz domains. Figs. 1 and 2 show some typical examples of fluid inclusions found in granulites.

In addition to CO_2, NaCl-saturated aqueous (brines) fluid inclusions have also been found in many granulites (Touret, 1985; Newton et al., 1998). The occurrence of brine and CO_2 fluid inclusions as part of a single fluid inclusion assemblage is clear evidence of fluid-fluid immiscibility at peak metamorphic conditions (Fig. 2) (Touret, 1985, 1986, 1995; Newton et al., 1998). This observation is supported by experimental evidence (Johnson, 1991). A number of scientists did not believe that fluid inclusions formed in the deep crust could survive the way up to the Earth's surface, claiming that these inclusions were late and thus not related to granulite metamorphism (e.g., Lamb et al., 1987). But a better understanding of the fluid inclusion behaviour in relation to the metamorphic *P-T* paths (e.g., Touret, 2001; Touret and Huizenga, 2011), as well as the determination of a precise chronology of inclusion formation with respect to their host minerals (concept of fluid inclusion assemblage as introduced by Goldstein and Reynolds, 1994; see also Touret, 2001) have established beyond any reasonable doubt that these fluids were indeed present at peak metamorphic conditions (Touret and Hartel, 1990). Both fluid types (CO_2 and brines) have a low H_2O-activity, the prime condition to stabilise the granulite water-deficient mineral assemblages at high *P* and *T* (e.g., Newton et al., 2014). Fig. 1 shows a variety of fluid inclusions found in granulites from type localities in South India and Sri Lanka.

Fluid inclusions, stable isotope studies, and field relationships have led to some general conclusions regarding the fluid characteristics of HT/UHT and HP granulites. Firstly, the major fluid types include CO_2 (of variable density) and brines, which are identical for both HT/UHT and HP granulites. However, they appear different in their relative amounts; brines are generally more dominant in HP granulites whereas CO_2 prevails in HT and especially UHT granulites. In HT/UHT granulites, CO_2 inclusions are particularly abundant in or near syntectonic basic intrusions. This and the mantle signature of isotope geochemical tracers ($\delta^{13}C$, noble gas isotope ratios) (Dunai et al., 1992; Dunai and Touret, 1993) indicates a dominantly external (mantle) origin for CO_2. This implies that CO_2 is introduced into the lower crust by the mantle-derived intrusions, which have also provided the heat responsible for HT/UHT granulite metamorphism. This is confirmed by the fact that similar fluid inclusions also exist in mantle-derived xenoliths in volcanic rocks, which are

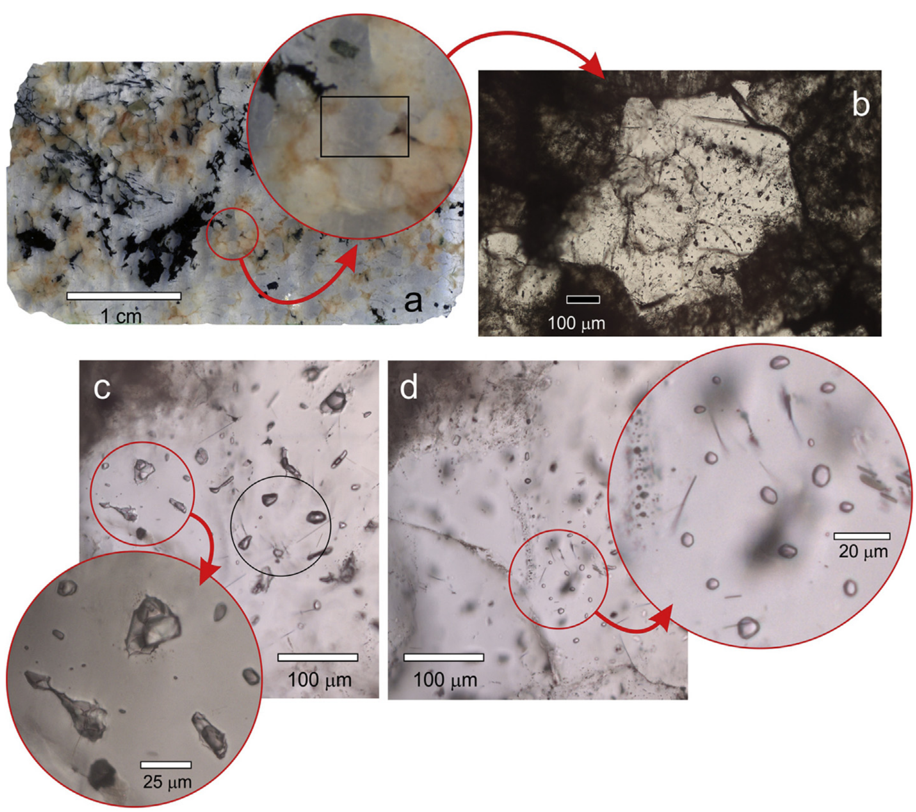

Figure 2. Brine and pure CO_2 fluid inclusions quartz-feldspar gneisses from the Bakhuis ~2.1 Ga ultrahigh-temperature granulite belt in Suriname (De Roever et al., 2003; Klaver et al., 2014), which are currently being researched by De Roever and Huizenga. (a) Doubly polished thick section of a quartz-feldspar gneiss that comprises brines and ultrahigh-density CO_2 fluid inclusions. The fluid inclusions occur in quartz shielded by feldspar shown in b. (b) Quartz showing isolated and clustered brine and ultrahigh-density CO_2 fluid inclusions. (c) Primary brine inclusions with numerous unidentified solid phases (red circle) occurring together with high-density monophase CO_2 inclusions. (d) Evidence of fluid-fluid immiscibility. Cluster of small (generally <10 μm) ultrahigh dense CO_2 fluid inclusions. The inclusions homogenise into the liquid phase at temperatures ranging between −55 and −60 °C (Huizenga, unpublished data), corresponding to a maximum density of ~1.16 g/cm^3.

far more abundant than in granulite xenoliths. It has been hypothesised that these CO_2 fluids are derived from the breakdown of magmatic carbonates at depth, which are thus considered to be the ultimate source of most lower crustal CO_2 (Frezzotti and Touret, 2014). This suggestion is supported by the fact that some inclusions in granulites appear to be very similar to fluid/melt inclusions found in carbonatites, notably from Tanzania (cf. Fig. 1f and Figs. 1 and 2 in Káldos et al., 2015).

The dominant mantle source of fluids in HT/UHT granulites indicates an external origin. On the other hand, both CO_2 and brine fluids in HP granulites appear to be internally generated. The brines do most likely represent remnants of former pore fluids already present in the protolith. Field relations and carbon stable isotope data suggest also a dominantly local derivation for CO_2, which in many cases appears to be generated by the reaction between graphite (former organic matter in detrital sediments) and H_2O liberated by the subsolidus breakdown of hydrous minerals (micas of amphiboles). This is followed by preferential dissolution of H_2O, initially mixed with CO_2, in partial melts of granitic composition (see e.g., Touret and Dietvorst, 1983). Obviously, this process occurs also in HT/UHT granulites, but in these rocks this process is not that significant compared to the influx of externally-derived CO_2.

Interestingly, metacarbonates cannot be a significant source for lower crustal CO_2. Many granulite terranes (e.g., the Grenville Province in Canada and the USA) contain regional-size occurrences of marbles in the stratigraphic sequence. This indicates that sedimentary carbonates were preserved throughout progressive metamorphism at oxidising conditions (see discussion in Nijland et al., 2014). If redox conditions were more reducing, carbonates would have been (partially) transformed into graphite (Nokleberg, 1973), with no possibility for carbon to enter the fluid phase. The marbles horizons show δ^{13}C-compositions reflecting their pre-metamorphic values (Broekmans et al., 1994). This remarkable feature has been taken as an argument to negate the possibility of CO_2 streaming. However, it actually only indicates that there was no significant infiltration of CO_2 derived from decarbonation reactions. It does not exclude CO_2 streaming from another source such as mantle-derived magmas. In fact, it is quite possible that this externally-derived CO_2 has protected the metacarbonates against decarbonation reactions, helping them to withstand the extreme temperatures reached during HT/UHT granulite metamorphism.

Second, in some HT/UHT granulites, high-density CO_2 inclusions can be extremely abundant and well preserved (e.g., Santosh and Tsunogae, 2003), occurring in many rock-forming minerals including garnet, feldspar, and quartz (Fig. 1). Remarkably, fluid inclusions in quartz in HT/UHT granulites are less abundant, in contrast to what is observed in most other rock types. Formed at peak metamorphic conditions (i.e., at a depth of 15–20 km and at temperatures between 800 and 1000 °C), these primary inclusions have not been seriously affected by post-metamorphic cooling and uplift. They do not show any sign of decrepitation or transposition; in many cases they exhibit a beautiful negative crystal shape (Fig. 1c,d for instance; Fig. 13-7 on p. 377 in Roedder, 1984; or Fig. 2 in Van den Kerkhof et al., 2014). The fluid density matches approximately the peak *P-T* conditions, as evidenced by the intersection of the fluid isochore (line of constant density that a fluid trapped in an inclusion must follow in *P-T* space if no leakage or volume change has occurred) and the *P-T* conditions defined by the mineral assemblage (Touret, 2001). The only discrepancy in most cases studied so far is a slight pressure difference at peak metamorphic temperature, about 1 kbar for a regional pressure of 7–8 kbar and a temperature of ~800 °C (e.g., Coolen, 1981). As discussed in Touret (2001), this can be explained either by a thin film invisible water on the wall of the fluid inclusion cavity or, more likely, by selective water leakage. Brine and CO_2 inclusions occur normally together in the same mineral grain, but their relative amount may be quite different (generally there are many more CO_2 than brine inclusions). The subsequent retrograde *P-T* evolution, however, results in distinct differences in shape and content of both fluid inclusion types. In contrast to CO_2 inclusions, brine inclusions have not survived the post-metamorphic uplift. They show systematically signs of *transposition* (partial decrepitation or implosion, Touret, 2001), corresponding to the loss of some liquid relative to the solid mineral phases included in the cavity (daughter minerals). Brine inclusions contain systematically one or several of these solids (Fig. 3b,c,e,f), first of all halite and other halides and frequently also Fe-Ti oxides. The cavity is commonly squeezed around these solids (referred to as *collapsed inclusions* in Touret, 2001). These collapsed inclusions eventually end up as isolated NaCl cubes (Fig. 3b,c) or as irregular crystal aggregates masses within the mineral host, without any trace of remaining liquid left (Fig. 3e,f). This remarkable difference with CO_2 inclusions is easily explained by the striking difference between the CO_2 and the much steeper aqueous isochores in *P-T* space.

For most granulites (especially HT and UHT granulites) the post-metamorphic *P-T* path starts with sub-isobaric cooling until a temperature of 600–500 °C is reached followed by rapid decompression towards the surface. The initial near-isobaric *P-T* path is virtually parallel to that of the high-density CO_2 isochores (i.e., a pseudo-isochoric *P-T* path, Touret, 2001). Consequently, only minor differences between the lithostatic and fluid pressure (i.e., pressure of the fluid trapped in the inclusion) exist. The strength of the host mineral is not relevant; even open cavities would remain unaffected if fluid and lithostatic pressure are equal. On the other hand, brine inclusions would be grossly underpressurised during isobaric cooling due to the steep slope of H_2O-NaCl isochores in *P-T* space. This will result in fluid leakage and collapse of the cavity around halite daughter crystals, if present. The fact that halite did exist at high temperature shows that the solution was already saturated, imposing a composition close to molten salts at peak UHT granulite conditions (at least 70–80 wt.% eq. NaCl for $T > 800$ °C). Brine fluids are extremely mobile and able to move along grain boundaries. They have a great capacity of element dissolution and transport, especially alkalies (Na and K), resulting in a great variety of microstructures (e.g., K-feldspar microveins and myrmekites) (Fig. 4). These types of microstructures have been ignored for a long time but are clearly present in granulites (e.g., Franz and Harlov, 1998) and in particular in their magmatic equivalents (charnockites) (Hansen et al., 1984; Perchuk and Gerya, 1995; Touret and Huizenga, 2012b).

Third and lastly, in addition to the fact that fluid inclusion studies indicate that two immiscible low H_2O-activity fluids, high-density CO_2 and concentrated saline solutions (brines) were present at peak metamorphic conditions, they can also give some information on the overall proportion or minimum amount of the fluids present in the rock. Quantities of CO_2 fluids preserved in fluid inclusions in minerals that have escaped recrystallisation can be up to few weight percent for some charnockites or related rocks in southern India (Touret and Hansteen, 1988) and Sri Lanka (e.g., Bolder-Schrijver et al., 2000) (Fig. 1e). Additional evidence supporting the large amount of fluids involved is given by the extensive metasomatic effects caused by CO_2 fluids and brines that occur during retrogression of granulite terrains. These include albitisation and scapolitisation (recently described in some detail by Touret and Nijland, 2013), regional-scale quartz-graphite vein occurrences in, for example, Sri-Lanka, India and Madagascar (e.g., Luque et al., 2014), and quartz-carbonate

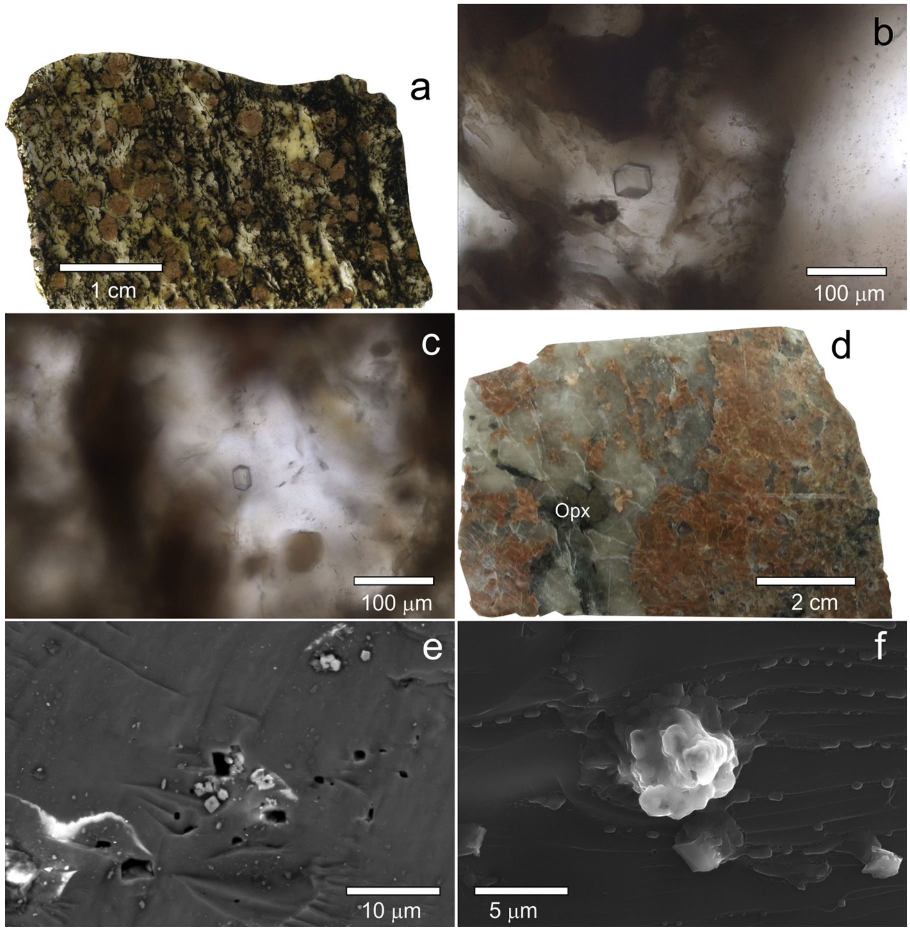

Figure 3. Halite occurrences in granulites. (a–c) Isolated single halite crystals (probably hosted in quartz) in a garnet gneiss from the Bakhuis ultrahigh-temperature granulite belt (De Roever et al., 2003), currently researched by De Roever and Huizenga. (a) Doubly polished thick section of garnet granulite. (b) Isolated halite cube (plane polarised light). (c) Isolated rectangular-shaped halite in the vicinity of halite cube shown in (b) (plane polarised light). (d–e) Halite in a quartz-orthopyroxene vein from Satnur locality near Kabbal in Southern India (Newton et al., 2014). (d) Quartz-orthopyroxene vein. (e) Backscatter SEM image of open cavities (black) surrounded by swarms of small NaCl crystals (white) deposited on the broken surface. (f) Backscatter SEM image of irregular mass of NaCl (white) still present in a quartz cavity. SEM analyses on broken quartz surfaces were done by D. Deldicque in the Laboratoire de Géologie, Ecole Normale Supérieure Paris. This inclusion is strikingly similar to the halite inclusions found by Káldos et al. (2015) in Kerimasi jacupirangite (Fig. 2 in Káldos et al., 2015).

megashear zones (Newton, 1990). Quartz-carbonate megashear zones are linear domains of regional size, typically over 100 km by 10 km, in which up to 30% of the country rocks (Newton, 1990; Newton and Manning, 2002) are replaced by carbonates in the form of fine-grained massive calcite or, more commonly, dolomite (Fig. 5) (Dahlgren et al., 1993) like in the Bamble area in southern Norway. Here, carbonate formation occurred at a temperature of 500–700 °C. The carbonate mineral phases show a uniform $\delta^{13}C_{PDB}$ signature between −6 and −9‰ (Dahlgren et al., 1993), which clearly indicates a primary mantle origin. Retrograde hydrothermal quartz-graphite veins found in the HT/UHT granulites of Sri-Lanka Central Highlands, by far the largest world reserves of highly crystalline graphite (e.g., Luque et al., 2014), are also an indication of the large amount of CO_2 fluids that have migrated through the crust.

Both, field and geochemical data suggest an ultimate granulite fluid source but also indicate significant differences in the behaviour of the two major fluid types. Deep brines frequently contain sulphate, hence they have a strong oxidising effect (Newton and Manning, 2005; Hansen and Harlov, 2007). Most of the carbon in the fluid phase will finally end up in carbonates. Obviously, CO_2 and brines can still be present in the form of fluid inclusions which form the dominant inclusion type found in large shear zones. But when minerals like sulfides are present in the host rock, the oxygen fugacity may be low enough to provoke the reduction of infiltrating CO_2 into graphite (e.g., Huizenga and Touret, 2012). We hypothesise that this is what might have happened in Sri-Lanka (Touret, unpublished data). These retrograde effects lead to significant ore concentrations including uranium and/or rutile during albitisation (e.g., Engvik et al., 2014), graphite (Sri Lanka, e.g., Luque et al., 2014), and gold (e.g., Cameron, 1988; Newton, 1990) in quartz-carbonate mega-shear zones (Newton, 1990; Newton and Manning, 2002; Fu and Touret, 2014). Their extent shows that the amount of granulite fluids in the lower crust at peak conditions must have been indeed very high, orders of magnitude more than the remnants preserved in fluid inclusions. In the example described by Dahlgren et al. (1993) in southern Norway (Kamerfoss near Risör), dolomite veins occur in localised (few metre size) breccias (Fig. 5), showing a relatively small displacement of the host rock fragments. This occurrence indicates explosive breccias, caused by a sudden release of high-velocity, overpressurised fluids in a small vent. Many other examples of explosive volcanism are well known in Southern Norway, including the famous carbonatite occurrences in the Fen area (Brøgger, 1921). Their age is quite variable, with two major periods of activity during the late Precambrian and Carboniferous, respectively (Verschure et al., 1983). On the other

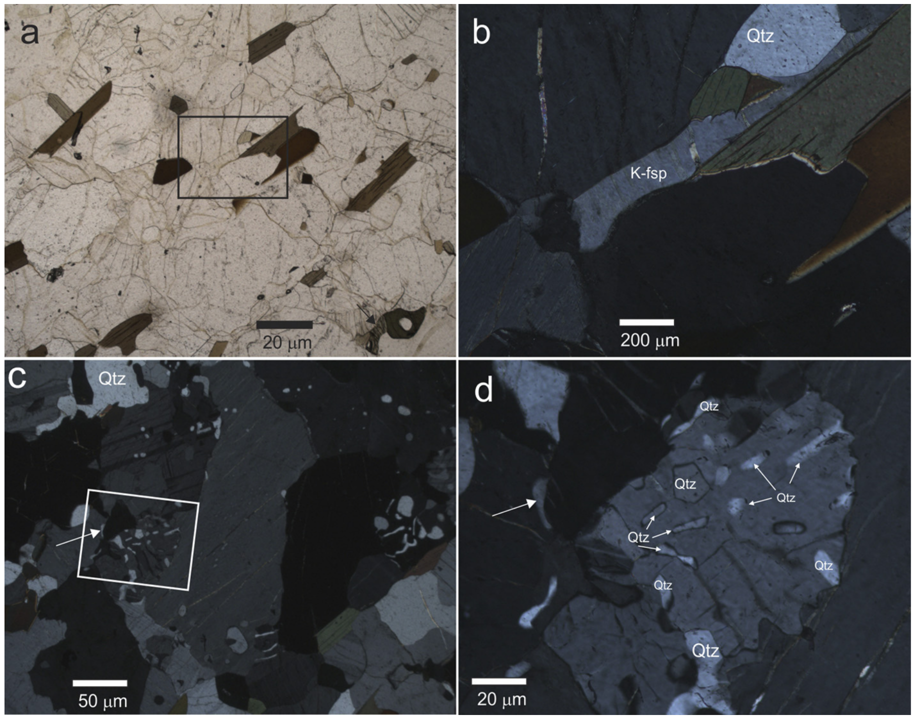

Figure 4. Brine-induced metasomatic features in incipient charnockites from Kurunegala in Sri Lanka (Perchuk et al., 2000; Touret and Huizenga, 2012a). (a) Charnockite (plane polarised light) comprising quartz, feldspar (mesoperthite), biotite and orthopyroxene (arrow in the bottom right corner). Black rectangle: field of view of shown in (b). (b) K-feldspar microvein developed along the boundaries of mesoperthite, biotite, and quartz (crossed polars). (c) Myrmekite and K-feldspar microvein (arrow) around large mesoperthite crystals (crossed polars). Note that white spots in the upper part of the photograph are quartz blebs with an identical optical orientation that are formed from the myrmekite reaction (Touret and Nijland, 2013). White rectangle: field of view shown in (c). (d) Detail of the myrmekite (crossed polars). Large arrow: K-feldspar microvein along the boundary of two mesoperthite crystals.

hand, dolomite veins in Kamerfoss occur within actinolite-rich domains (Touret and Nijland, 2013) and are related to the scapolitisation-albitisation event which has occurred at the onset of granulite retrogression about 1000 Ma ago. It seems that CO_2-rich deep fluids (lower crustal source for the Kamerfoss carbonate breccia, a mantle source for the Fen carbonatite) were able to penetrate repeatedly within the Precambrian basement in more recent times.

Fig. 6 shows general section of the continental crust (including fluid compositional domains) representing the time where the crust has acquired its structure during peak metamorphism (Fig. 6a), and after cooling and isostatic re-equilibration (Fig. 6b). At the climax of the orogenic cycle, the lower crust is a major reservoir of low-H_2O activity fluids (CO_2 and highly saline brines). These fluids are expelled towards the outer envelopes when the metamorphic episode has come to an end, which is evidenced by extensive retrograde alteration at higher crustal levels. Fig. 6b illustrates schematically the three major ways for the release of the vast amount of lower crustal fluids, namely through quartz-carbonate megashear zones (oxidising conditions), quartz-graphite veins (reducing conditions) or carbonate-rich explosive breccias.

4. How continents are formed

One way (and for many workers the only way) by which continents grow is laterally, through volcanism along active margins (continent-ocean collision). Metamorphism in this

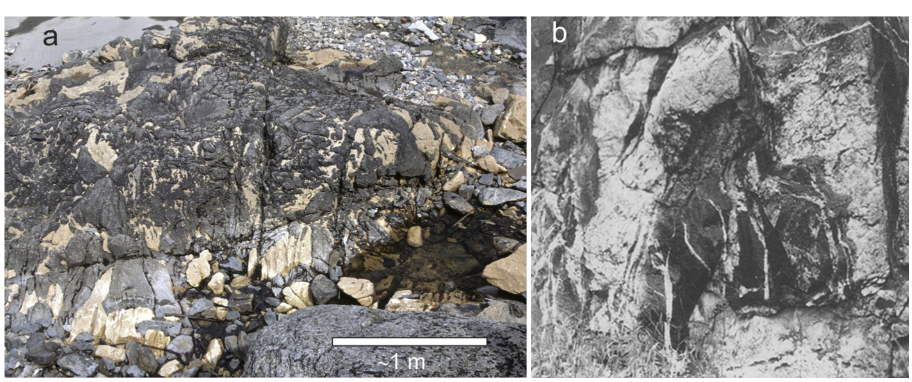

Figure 5. (a) Hydrothermal dolomite (light brown) in meta-gabbro (dark), emplaced at the end of Sveconorvegian metamorphic event (Kamerfoss, Bamble Province, Norway) (Dahlgren et al., 1993; Touret and Huizenga, 2012a). (b) Part of the original photo by Dahlgren et al. (1993) of dolomite veins at the Knipen locality (Fig. 3b in Dahlgren et al., 1993, published by permission from Springer). Situated along a fresh road-cut, this exposure, which lasted only for few years before weathering, illustrates well the brecciated character of the carbonate veins. Width of photo: ~2 m.

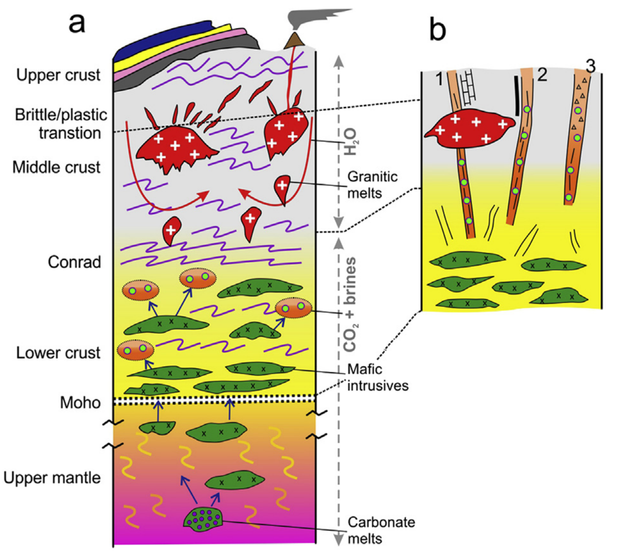

Figure 6. Fluid distribution in the crust at (a) peak HT granulite and (b) retrograde conditions in the lower crust. (a) Peak metamorphic conditions; the middle crust is characterised by granite intrusions with hydrothermal veins systems (indicated in red) around them. The granite batholiths (indicated in red with white crosses) have their roots in wet (H_2O-dominated) migmatites. All free H_2O dissolves in the granite melts (red arrows), i.e., the middle crust acts as a H_2O barrier, preventing H_2O from moving into the lower crust. H_2O-saturated melts crystallise near their source under amphibolite facies metamorphic conditions. The Conrad boundary represents the boundary between the middle and lower crust. The top of the lower crust is characterised by dehydrated migmatites. Despite the temperature increase, partial melting tends to decrease with increasing depth due to limited H_2O availability. The granite melts are thus relatively dry (H_2O-unsaturated), able to rise in the upper crust or even reaching the surface (not represented on the diagram). In the lower crust, mantle-derived syn-metamorphic intrusives (green) provide heat and deep fluids (CO_2, possibly brines where most brines are locally derived). The mafic intrusions become more abundant while approaching the Moho. (b) Post-metamorphic release of deep crustal fluids. The upper part of the eroded section corresponds in most cases to the upper limit of granite intrusions. Fluids move along large- and small-scale shear zones. The nature of the fluids and associated mineralisation is controlled by the local environment (e.g., oxygen fugacity) and the fluid composition at the source. The three basic mechanisms (1, 2, 3) by which fluids escape from the lower crust during post-metamorphic uplift include: (1) quartz-carbonate megashear zones (Newton, 1990), (2) quartz + graphite veins (e.g., Luque et al., 2014), and (3) explosive breccia with carbonate infill (cf. Bamble, Dahlgren et al. 1993, see Fig. 5).

setting typically generates eclogites and/or HP granulites. The model of formation of the HT/UHT granulite lower crust that we have discussed above implies that there is also a possibility of vertical growth, through stacking of mantle-derived magmas at the base of the crust. These provide the heat which explains the HT/UHT metamorphic regime, together with the fluids which invade the lower crust at peak metamorphic conditions. Both HT/UHT and HP metamorphic regimes occur during the formation of a mountain chain (orogen) are ultimately eroded when incorporated in the mass of the continent. In the early sixties, Japanese geologist A. Miyashiro (Miyashiro, 1961), together with independent work by E. den Tex and H. Zwart in Holland (Den Tex, 1965; Zwart, 1967) introduced the notion of paired belts, based on the example of circum-Pacific accretionary orogens (Ryoke and Sanbagawa Belts, respectively). The initial concept, first based on the hypothesis of two parallel HP and HT mountain chains of the same age, has recently been extended, to include "*penecontemporaneous belts of contrasting type of metamorphism that record different apparent thermal gradients, one warmer and the other colder, juxtaposed by plate tectonics processes*" (Brown, 2010). One reason for this modification is that the apparent contemporaneity of both belts in Japan, due in part to their relative young ages (Cretaceous), is more an exception than the rule. In the Variscan orogen of Middle Europe, now exposed in a series of fragmented thrust slices (known in the French Massif Central as *Groupe Leptyno-amphibolique*, GLA, e.g., Lardeaux, 2014) has been metamorphosed at HP conditions in early Ordovician (~400 Ma ago), about 100 million years before the Carboniferous HT granulite event, during which the unexposed HT granulite lower crust has been formed. This Carboniferous age (~300 Ma ago) also corresponds to the emplacement of voluminous granites in the middle crust as we discussed earlier in section two.

Miyashiro (1961) suggested that paired belts were formed during a single collisional event, the HT belt being further away from the collision front and approximately of the same size (or even smaller) than the HP one. However, HP rocks occur almost exclusively in relatively young (post Cambrian) orogens, in narrow, elongated belts following the limit of the ocean-continent. High-temperature granulites, on the other hand, constitute the lower part of most cratons and are dominant, if not exclusive, Precambrian in age (Brown, 2008). It is not easy to understand how a pure compressional regime can provide at depth the room necessary to accommodate the intrusions of voluminous mantle-derived magmas. Moreover, a number of examples show that the relations between HP and HT rocks can be far more complicated than a simple, progressive collision. The Sveconorwegian in Southern Scandinavia, for instance, does not show a single, but a succession of compressional and extensional orogenic phases between 1.14 and 0.96 Ga (Andersson et al., 2008). The time difference between the HP- and subsequent HT-metamorphic event is also quite variable, possibly related to the slope of the subduction plane: about 100 Ma for the Paleozoic Hercynian orogeny whereas it is less than 10–20 Ma in the western Alps (Bousquet et al., 2008). Keeping these complexities in mind, we suggest that the model as shown in Fig. 7 has been operative for building the architecture of most

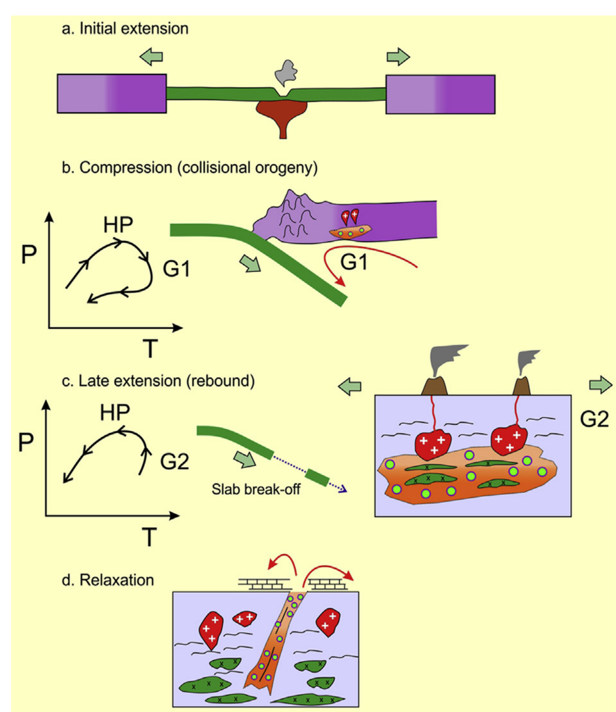

Figure 7. A model of how continents are formed. a. Preparation: formation of oceanic crust; b: lateral accretion above ocean subduction (G1: clockwise *P-T* path); c: extensional rebound after slab break-off; vertical accretion by magma stacking at the base of the crust (G2: anticlockwise *P-T* path); d: release of lower crustal fluids at peak metamorphic conditions during uplift.

continental areas since the advent of modern-type plate tectonics, at least 2 Ga ago: a major collisional event, interrupted by extensional rebounds, most likely induced by the detachment of the subducted slab.

5. From continents to supercontinents

In his controversial, yet epoch-making book entitled *Die Entstehung der Kontinente*, Alfred Wegener postulated that all continents were once united in a single mass, that he referred to as *Urkontinent* (Wegener, 1912), which later came to be known as Pangea (Van Waterschoot van der Gracht, 1926). Ironically, this name was then used by most established geologists of the time to demonstrate that such a supercontinent could not have existed! (Frankel, 2012). Only after World War II major achievements in Earth Sciences (probably less due to plate tectonic theories than the extraordinary analytical possibilities of modern instrumentation) established beyond any doubt that not only Pangea had existed, but also that it has not been a unique landmass. Supercontinents did exist as long as plate tectonics processes were operative, presumably since the early Archean (e.g., Cawood et al., 2006). Understandably, older supercontinents are the most difficult ones to be identified and the names and even existence of some of them (Vaalbara, Superia, Sclavia, Kenorland) remain a matter of discussion. However, most scientists now accept the history of supercontinents (Neoarchean to present) as reviewed in Nance et al. (2014): Columbia (Nuna) (1.9–1.7 Ga), Rodinia (1.3–1.0 Ga), Pannotia (or Gondwana, the reason being that Pannotia consists of two supercontinents, Gondwana and Laurentia, respectively) (0.8–0.5 Ga), and finally Pangea (~0.3 Ga). The amalgamation of each supercontinent corresponds to a series of discrete collisional events, each lasting for a few 100 Ma, separated by longer periods during which only a few metamorphic episodes have occurred. A careful review of metamorphic gradients during all these events by Brown (2010) showed a steady decrease of metamorphic gradients with time, with at least two successive plate tectonic regimes: a Precambrian one (2.7–0.7 Ga), with only hot orogens (UT/UHT metamorphism), and a modern one, involving cold subduction and the widespread occurrence of HP/UHP metamorphic rocks (Fig. 4 in Brown, 2010). Gondwana plays a critical role for the transition between both regimes as it includes both metamorphic types: probably the most typical being UHT Pan-African metamorphic rocks (Kelsey, 2008) and eclogites, and HP metamorphic terranes (e.g., Möller et al., 2000) (Fig. 4 in Brown, 2010). The details of the processes of amalgamation-disruption of these supercontinents have been discussed in recent works (e.g., Meert, 2014; Nance et al., 2014). Here we emphasise the point that at least for the last supercontinents (Gondwana and Rodinia and to a lesser extent Pangea), the final amalgamation involved the formation of linear belts of UHT metamorphic rocks. Examples include the Rogaland osumilite-bearing aureoles around anorthosites in Rodinia, and UHT occurrences in central and eastern Africa, Antarctica, Madagascar, Sri-Lanka and southern India in Gondwana. The UHT occurrences in Gondwana are by far the most abundant and typical occurrences of UHT granulites described so far (Kelsey, 2008; Kelsey and Hand, 2015) (Fig. 8). More generally, it has been shown that the final amalgamation of a supercontinent is sealed by a UHT orogen (Santosh and Omori, 2008; Santosh et al., 2012) (Fig. 9).

In addition to the above, it has also been observed that supercontinent disruption is frequently followed by cold climates, notably periods during which ice caps can cover virtually the entire Earth, referred to as *Snowball Earth* (Hoffman et al., 1998; see also Fig. 5 in Nance et al., 2014). Marked by the widespread deposition of glacial sediments (tillites), the cold periods lasted millions of years (Hoffman, 1999) ending abruptly with the deposition of *cap rocks*; continuous layers of carbonates (calcite and dolomites) which sharply overlie glacial deposits (http://www.snowballearth.org). Such a situation suggests rapid fluctuations of atmospheric CO_2 concentrations characterised by an initial decrease to explain the widespread cold climate followed by a sudden increase at the time of the deposition of the cap rock. Cap carbonates have a number of

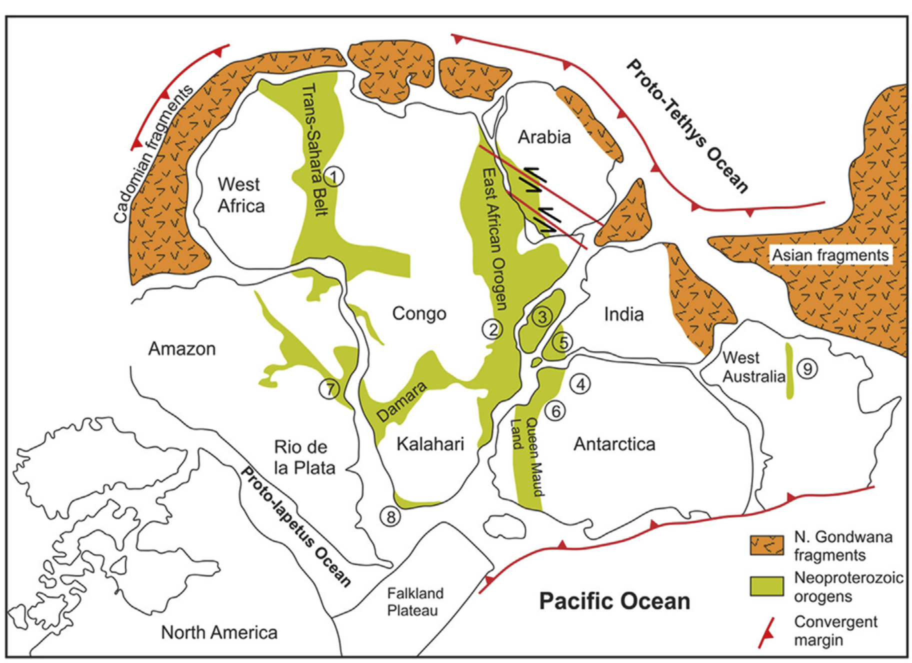

Figure 8. Pan-African UHT granulite occurrences in Neoproterozoic terranes using data supplied by Kelsey (2008) (Gondwana reconstruction after Kröner and Stern, 2004). 1: In-Ouzzal, Hogar, Algeria (e.g., Kienast and Ouzegane, 1987); 2: Furua, Tanzania (Coolen et al., 1982); 3: Madagascar (Paquette et al., 2004); 4: Highland Complex, Sri Lanka (Osanai et al., 2006); 5: Southern India (Tsunogae and Santosh, 2006); 6: Napier Complex, Antarctica (Ellis, 1980); 7: Bahia region, Brazil (Ackerman et al., 1987); 8: Namaqualand, South Africa (Waters, 1986); 9:Warumpi Province, Australia (Scrimgeour et al., 2005). Figure modified after Touret and Huizenga (2012a).

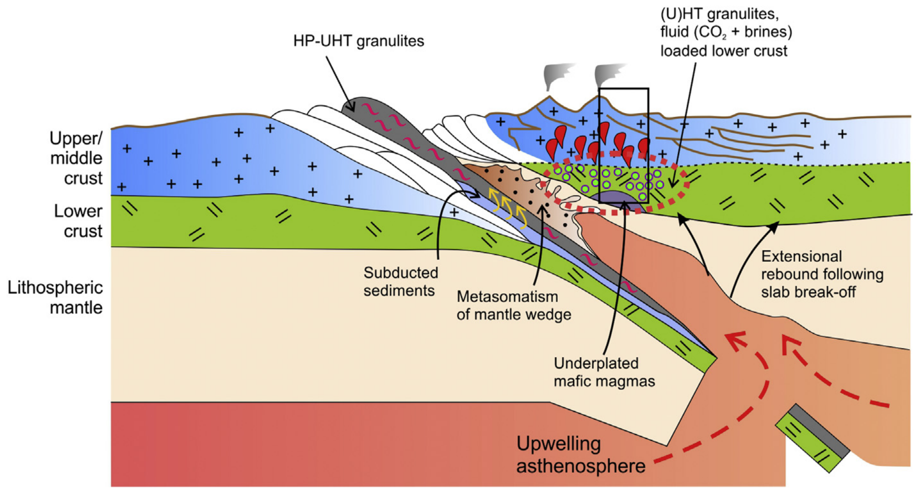

Figure 9. Supercontinents sealed by UHT orogens (modified after Santosh et al., 2012). The model proposes that asthenospheric upwelling during slab break-off following the collisional assembly of continents leads to UHT metamorphism and ponding of low H_2O-activity fluids (brines and CO_2) into the lower crust sourced from underplated mafic magma's. For HP granulites, fluids are internally sourced (yellow arrows). The inset corresponds to Fig. 6a.

features which distinguish them from standard carbonates, e.g., world-wide occurrence on platforms, shelves and slopes (even in region otherwise lacking carbonate strata), thick sea-floor cement, microbial mounts with vertical tubular structure, primary and early diagenetic sulphate (barite) (http://www.snowballearth.org). Most important is the negative $\delta^{13}C$ isotopic signature, which is in sharp contrast to the positive values recorded in sedimentary carbonates (e.g., Kennedy, 1996). The frequent occurrence of giant wave ripples indicate that carbonate deposition has been accompanied by violent seismic activity, like the explosive breccias found in Southern Norway. The similarities between both rock types, i.e., the mode of deposition as well as in the isotopic signature, lead us to propose that former granulite fluids, first of all CO_2, could well have reached the atmosphere after supercontinent disruption and thus played a role in the sudden end of the glacial periods (Touret and Huizenga, 2012a).

Fluids that pond beneath the lower crust during the amalgamation of continents into supercontinents through subduction-accretion-collision process are likely to cause instability. The formation of supercontinents leads to a *thermal blanket* effect whereby a large region of the mantle is covered by the supercontinent, thus inhibiting heat loss. We propose that the coupled effect of heating from the mantle and fluids accumulated in the lower crust leads to the breakup of supercontinents. Studies focussing on the involvement of fluids on earthquakes have shown that mantle CO_2 does play an active role in the mechanical weakening of the middle and lower crust (e.g., Miller et al., 2004; Collettini et al., 2008). For example, Miller et al. (2004) proposed that earthquakes can instigate a fluid connection between the lower and upper crust resulting in a sudden, fast upward flow of overpressurised CO_2 fluids along fault zones. It is possible to create an overpressurised carbon-saturated CO_2 fluid ($P_{fluid} \approx P_{CO_2} > P_{lithostatic}$) of several kbars if the fugacities for both oxygen and hydrogen fugacities are buffered by the fayalite-magnetite-quartz and the biotite-magnetite-K-feldspar, respectively in the lower crust (Skippen and Marshall, 1991; Touret, 1992). Obviously, it is not likely that such high fluid overpressure can exist in the lower crust; it will result in instantaneous fluid-induced fracturing and fast upward migration of the CO_2 fluid. Such a process can explain why mantle $\delta^{13}C$ values have been observed in surface fluids (e.g., Collettini et al., 2008); the fast moving CO_2 simply did not allow chemical equilibration between the fluid phase and host rock along the fluid pathway.

6. Conclusion

Despite continuous destruction by collision and subduction, it is remarkable that the total mass of the continental crust has remained relatively constant during most of the Earth's history. This shows that crustal growth, either laterally or vertically, must approximately compensate its destruction. The most obvious way by which a continent grows, namely through volcanic accretion above subduction zone, is only the beginning of a long evolution, leading finally to the formation of a single supercontinent. A large part of the structure of continents is acquired through widespread granulite metamorphic episodes in the lower crust and coeval emplacement of granites in the middle crust. At peak metamorphic conditions, the lower crust is invaded by mantle-derived low H_2O-activity fluids: high-density CO_2 and brines. These fluids, in particular CO_2, lead to tectonic instability and fragmentation of the supercontinent. In other words, supercontinent disruption is already programmed at the time of its amalgamation.

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References

Ackerman, D., Herd, R.K., Reinhardt, M., Windley, B.F., 1987. Sapphirine parageneses from the Caraiba complex, Bahia, Brazil: the influence of Fe^{2+}-Fe^{3+} distribution on the stability of sapphirine in natural assemblages. Journal of Metamorphic Geology 5, 323–339.

Andersson, J., Bingen, B., Cornell, D., Johansson, L., Söderlund, U., Möller, Ch., 2008. The Sveconorwegian Orogen of Southern Scandinavia: Setting, Petrology and Geochronology of Polymetamorphic High-grade Terranes. Guidebook, 33 IGC excursion No 51, August 2-5, 83 pp.

Belousov, V.V., 1966. Modern concepts of the structure and development of the Earth's crust and the upper mantle of continents. Quarterly Journal of the Geological Society 122, 293–314.

Bohlen, S.R., Mezger, K., 1989. Origin of granulite terranes and the formation of the lowermost continental crust. Science 244, 326–329.

Bolder-Schrijver, L.J.A., Kriegsmann, L.M., Touret, J.L.R., 2000. Primary carbonate/CO_2 inclusions in sapphirine-bearing granulites from central Sri-Lanka. Journal of Metamorphic Geology 18, 259–269.

Bousquet, R., Oberhänsli, R., Goffé, B., Wiederkehr, M., Koller, F., Schmid, S.M., Schuster, R., Engi, M., Berger, A., Martinotti, G., 2008. Metamorphism of metasediments in the scale of an orogen: a key to the Tertiary geodynamic evolution of the Alps. In: Siegesmund, S., Fügenschuh, B., Froitzheim, N. (Eds.), Tectonic Aspects of the Alpine-Dinaride-Carpathian System, Geological Society Special Publication 298, pp. 393–412.

Broekmans, M.A.T.M., Nijland, T.G., Jansen, J.B.H., 1994. Are stable isotopic trends in amphibolite to granulite facies transitions metamorphic or diagenetic? - An answer for the Arendal area (Bamble sector, SE Norway) from Mid-Proterozoic carbon-bearing rocks. American Journal of Science 294, 1135–1165.

Brøgger, W.C., 1921. Die Eruptivgesteine des Kristianagebietes, IV. Das Fen-Gebiet in Telemark, Norwegen. Norske Vidensk Selsk Skifter I, Math Naturwiss K1 (1920) 9, 1–408.

Brown, M., 2007. Metamorphic conditions in orogenic belts: a record of secular change. International Geology Review 49, 193–234.

Brown, M., 2008. Geodynamics regimes and tectonic settings for metamorphism: relationship to the supercontinent cycle. Indian Journal of Geology 80, 3–21.

Brown, M., 2010. Paired metamorphic belts revisited. Gondwana Research 18, 46–59.

Cameron, E.M., 1988. Archean gold: relation to granulite formation and redox zoning in the crust. Geology 16, 109–112.

Cawood, P.A., Kröner, A., Pisarevski, S., 2006. Precambrian plate tectonics: criteria and evidence. GSA Today 16 (no. 7), 4–11.

Clark, C., Healy, D., Johnson, T., Collins, A.S., Taylor, R.J., Santosh, M., Timms, N.E., 2015. Hot orogens and supercontinent amalgamation: a Gondwanan example from southern India. Gondwana Research 28 (4), 1310–1328.

Clemens, J., 1990. The granulite-granite connection. In: Vidal, Ph, Vielzeuf, D. (Eds.), Granulites and Crustal Evolution, NATO ASI Series. Kluwer, Dordrecht, pp. 25–36.

Clemens, J., 1992. Partial melting and granulite genesis. A partisan overview. Precambrian Research 55, 297–301.

Collettini, C., Cardellini, C., Chiodini, G., De Paoloa, N., 2008. Fault weakening due to CO_2 degassing in the Northern Apennines: short- and long-term processes. In: Wibberley, C.A., Kurz, W., Imber, J., Holdsworth, R.E., Collettini, C. (Eds.), The Internal Structure of Fault Zones: Implications for Mechanical and Fluid-flow Properties, Geological Society of London Special Publication 299, pp. 175–194.

Conrad, V., 1925. Laufzeitkurven des Tauernbebens vom 28 November 1923. Mitteilungen der Erdbeben - Kommission, Akademie der Wissenschaften in Wien, Neue Folge 59.

Coolen, J.J.M.M.M., 1981. Carbonic fluid inclusions in granulites from Tanzania - a comparison of geobarometric methods based on fluid density and mineral chemistry. Chemical Geology 37, 59–77.

Coolen, J.J.M.M.M., Priem, H.N.A., Verdurmen, E.A.Th., Verschure, R.H., 1982. Possible zircon U-Pb evidence for Pan-African granulite facies metamorphism in the Mozambique belt of southern Tanzania. Precambrian Research 17, 31–40.

Dahlgren, S., Bogoch, R., Magaritz, M., Michard, A., 1993. Hydrothermal dolomite marbles associated to charnockitic magmatism in the Proterozoic Bamble Shear Belt, Southern Norway. Contributions to Mineralogy and Petrology 113, 394–408.

De Roever, E.W.F., Lafon, J.-M., Delor, C., Cocherie, A., Rossi, P., Guerrrot, C., Potrel, A., 2003. The Bakhuis ultrahigh-temperature granulite belt (Suriname): I. Petrological and geochronological evidence for a counterclockwise P–T path at 2.07–2.05 Ga. Géologie de la France 2-3-4 175–205.

Den Tex, E., 1965. Metamorphic lineages of orogenic plutonism. Geologie en Mijnbouw 44, 105–132.

Dunai, T.J., Touret, J.L.R., 1993. A noble-gas study of a granulite sample from the Nilgiri Hills, Southern India: implications for granulite formation. Earth and Planetary Science Letters 119, 271–281.

Dunai, T.J., Touret, J.L.R., Villa, I.M., 1992. Mantle-derived helium in fluid inclusions of a 2.5 Ga-old granulite, Nilgiri Hills, Southern India. In: Kharaka, Y.K., Maest, A.S. (Eds.), Water-rock Interaction. Balkema, Rotterdam, pp. 919–922.

Ellis, D.J., 1980. Osumilite–sapphirine–quartz granulites from Enderby Land, Antarctica – P-T conditions of metamorphism, implications for garnet-cordierite equilibria and the evolution of the deep crust. Contributions to Mineralogy and Petrology 74, 201–210.

Engvik, A.K., Ihlen, P.M., Austrheim, H., 2014. Characterisation of Na-metasomatism in the Sveconorwegian Bamble sector of south Norway. Geoscience Frontiers 5, 659–672.

Ewart, A., Baxter, K., Ross, J.A., 1980. The petrology and petrogenesis of the Tertiary anorogenic mafic lavas of Southern and Central Queensland, Australia - possible implications for crustal thickening. Contributions to Mineralogy and Petrology 73, 129–152.

Frankel, H.R., 2012. The Continental Drift Controversy: Paleomagnetism and Confirmation of Drift, vol. 2. Cambridge University Press, 525 pp.

Franz, L., Harlov, D.E., 1998. High grade K-feldspar veining in granulites from the Ivrea-Verbano zone, Northern Italy: fluid flow in the lower crust and implications for granulite facies genesis. Journal of Geology 106, 455–472.

Frezzotti, M.L., Touret, J.L.R., 2014. CO_2, carbonate-rich melts, and brines in the mantle. Geoscience Frontiers 5, 697–710.

Fu, B., Touret, J.L.R., 2014. From granulite fluids to quartz-carbonate megashear zones: the gold rush. Geoscience Frontiers 5, 747–758.

Goldstein, R.H., Reynolds, T.J., 1994. Systematics of Fluid Inclusion Studies in Diagenetic Minerals. Society for Sedimentary Geology (SEPM) Short Course 31, Tulsa, 199 pp.

Hansen, E.C., Harlov, D., 2007. Whole-rock, phosphate, and silicate compositional trends across an amphibolite- to granulite-facies transition, Tamil Nadu, India. Journal of Petrology 48, 1641–1680.

Hansen, E.C., Newton, R.C., Janardhan, A.S., 1984. Fluid inclusions in rocks from amphibolite-facies gneiss to charnockite progression in Southern Karnatak, India: direct evidence concerning the fluids of granulite metamorphism. Journal of Metamorphic Geology 2, 249–264.

Harker, A., 1932. Metamorphism: a Study of the Transformation of Rock Masses. Methuen & Company, 360 pp.

Harley, S., 1989. The origin of granulites: a metamorphic perspective. Geological Magazine 126, 215–247.

Harley, S., 2008. Refining the P-T records of UHT crustal metamorphism. Journal of Metamorphic Geology 26, 125–154.

Hoffman, P.F., 1999. The break-up of Rodinia, birth of Gondwana, true polar wander and the snowball Earth. Journal of African Earth Sciences 28, 17–33.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P., Schrag, D.P., 1998. A Neoproterozoic Snowball Earth. Science 281, 1342–1346.

Huizenga, J.M., Touret, J.L.R., 2012. Granulites, CO_2 and graphite. Gondwana Research 22, 799–809.

Ishii, S., Tsunogae, T., Santosh, M., 2006. Ultrahigh-temperature metamorphism in the Anchankovil Zone: implications for the correlation of crustal blocks in southern India. Gondwana Research 10, 99–114.

Johnson, E.L., 1991. Experimentally determined limits for H_2O–CO_2–NaCl immiscibility in granulites. Geology 19, 925–928.

Káldos, R., Guzmics, T., Váczi, T., Baris, A., Berkesi, M., Havancsák, K., Dankházi, Z., Szabó, C., 2015. Analytical Advances in Studying Melt Inclusions: a HR-Raman and FIB-SEM Case Study of Carbonate Melt Inclusions in Jacupirangite from Kerimasi (Tanzania). European Current Research On Fluid Inclusions (ECROFI-XXIII), Leeds, UK, pp. 80–81. Extended Abstracts' Volume.

Kawai, K., Yamamoto, S., Tsuchiya, T., Maruyama, S., 2013. The second continent: existence of granitic continental materials around the bottom of the mantle transition zone. Geoscience Frontiers 4, 1–6.

Kay, S.G., Kay, R.W., 1983. Thermal history of the deep crust inferred from granulite xenoliths. American Journal of Science 283-A, 486–513.

Kelsey, D.E., 2008. On ultrahigh-temperature crustal metamorphism. Gondwana Research 13, 1–29.

Kelsey, D.E., Hand, M., 2015. On ultrahigh temperature crustal metamorphism: phase equilibria, trace element thermometry, bulk composition, heat sources, timescales and tectonic settings. Geoscience Frontiers 6, 311–356.

Kennedy, M.J., 1996. Stratigraphy, sedimentology, and isotopic geochemistry of Australian Neoproterozoic postglacial cap dolostones: deglaciation, $\delta^{13}C$ excursions, and carbonate precipitation. Journal of Sedimentary Research 66, 1050–1064.

Kienast, J.R., Ouzegane, K., 1987. Polymetamorphic Al, Mg-rich granulites with orthopyroxene–sillimanite and sapphirine parageneses in Archaean rocks from the Hoggar, Algeria. In: Bowden, P., Kinnaird, J. (Eds.), African Geology Reviews, Geological Journal Thematic Issue. John Wiley & Sons, Chichester, pp. 57–79.

Klaver, M., De Roever, E.W.F., Nanne, J.E.M., Mason, P.R.D., Davies, G.R., 2014. Charnockites and UHT metamorphism in the Bakhuis Granulite Belt, western Suriname: evidence for two separate UHT events. Precambrian Research 262, 1–19.

Kröner, A., Stern, R.J., 2004. Pan-African orogeny. Encyclopedia of Geology, vol. 1. Elsevier, Amsterdam, pp. 1–12.

Lamb, W.M., Valley, J.V., Brown, P.E., 1987. Post-metamorphic CO_2-rich inclusions in granulites. Contributions to Mineralogy and Petrology 96, 485–494.

Lardeaux, J.M., 2014. Deciphering orogeny, a metamorphic perspective. Part II: Variscan orogen in the French Massif Central, a review. Bulletin de la Société Géologique de France 185, 281–310.

Ledru, P., Courrioux, G., Dallain, C., Lardeaux, J.M., Montel, J.M., Vanderhaeghe, O., Vitel, G., 2001. The Velay dome (French Massif Central): melt generation and granite emplacement during orogenic evolution. Tectonophysics 342, 207–237.

Litak, R.K., Brown, L.D., 1989. A modern perspective on the Conrad discontinuity. Eos 70 (no. 29), 713–725.

Lowrie, W., 2007. Fundamentals of Geophysics, second ed. Cambridge University Press. 390 pp.

Luque, F.J., Huizenga, J.M., Crespo-Feo, E., Wada, H., Ortega, L., Barrenechea, J.F., 2014. Vein graphite deposits: geological settings, origin, and economic significance. Mineralium Deposita 49, 261–277.

Maijer, C., Jansen, J.B.H., Wevers, J., Poorter, R.P.E., 1977. Contribution to the mineralogy of Norway, no 63. Osumilite, a new mineral to Norway. Norsk Geologisk Tidsskrift 57, 187–188.

Meert, J.G., 2014. Strange attractors, spiritual interlopers and lonely wanderers: the search for pre-Pangean supercontinents. Geoscience Frontiers 5, 155–166.

Miller, S.A., Collettini, C., Chiaraluce, L., Cocco, M., Barchi, M., Kaus, B.J.P., 2004. Aftershocks driven by a high-pressure CO_2 source at depth. Nature 427, 724–727.

Miyashiro, A., 1961. Evolution of metamorphic belts. Journal of Petrology 2, 277–311.

Möller, A., Mezger, K., Schenk, V., 2000. U-Pb dating of metamorphic minerals: Pan-African metamorphism and prolonged slow cooling of high pressure granulites in Tanzania, East Africa. Precambrian Research 104, 123–146.

Morfin, S., Sawyer, E.W., Bandyayera, D., 2013. Large volumes of anatectic melt retained in granulite facies migmatites: an injection complex in northern Quebec. Lithos 168-169, 200–218.
Murphy, J.B., Nance, R.D., Cawood, P.A., 2009. Contrasting mode of supercontinent formation and the conundrum of Pangea. Gondwana Research 15, 408–420.
Nance, R.D., Murphy, J.B., Santosh, M., 2014. The supercontinent cycle: a retrospective essay. Gondwana Research 25, 4–29.
Newton, R.C., 1990. Fluids and shear zones in the deep crust. Tectonophysics 182, 21–37.
Newton, R.C., Manning, C.E., 2002. Experimental determination of calcite solubility in NaCl–H_2O solutions at deep crust/upper mantle pressures and temperatures: implications for metasomatic processes in shear zones. American Mineralogist 87, 1401–1409.
Newton, R.C., Manning, C.E., 2005. Solubility of anhydrite, $CaSO_4$, in NaCl-H_2O solutions at high pressures and temperatures; applications to fluid-rock interaction. Journal of Petrology 46, 701–716.
Newton, R.C., Aranovich, L.Ya., Hansen, E.C., Vandenheuvel, B.A., 1998. Hyper-saline fluids in Precambrian deep-crustal metamorphism. Precambrian Research 91, 41–63.
Newton, R.C., Touret, J.L.R., Aranovitch, L.Y., 2014. Fluids and H_2O activity at the onset of granulite facies metamorphism. Precambrian Research 273, 17–25.
Nijland, T.G., Harlov, D.E., Andersen, T., 2014. The Bamble sector, South Norway: a review. Geoscience Frontiers 5, 635–658.
Nokleberg, W.J., 1973. CO_2 as a source of oxygen in the metasomatism of carbonates. American Journal of Science 273, 498–514.
O'Brien, P.J., Rötzler, J., 2003. High-pressure granulites: formation, recovery of peak conditions and implications for tectonics. Journal of Metamorphic Geology 21, 3–20.
Osanai, Y., Sajeev, K., Owada, M., Kehelpannala, K.V.W., Prame, W.K.B., Nakano, N., Jayatileke, S., 2006. Metamorphic evolution of high-pressure and ultrahigh-temperature granulites from the Highland Complex, Sri Lanka. Journal of Asian Earth Sciences 28, 20–37.
Paquette, J.L., Goncalves, P., Devouard, B., Nicollet, C., 2004. Micro-drilling ID-TIMS U–Pb dating of single monazites: a new method to unravel complex polymetamorphic evolutions. Application to the UHT granulites of Andriamena (North-Central Madagascar). Contributions to Mineralogy and Petrology 147, 110–122.
Perchuk, L.L., Gerya, T.V., 1995. Evidence for potassium mobility in the charnockitisation of gneisses. Doklady Akademii Nauk SSSR 331, 86–91.
Perchuk, L.L., Safonov, O.G., Gerya, T.V., Fu, B., Harlov, D.E., 2000. Mobility of components in metasomatic transformation and partial melting of gneisses: an example from Sri Lanka. Contributions to Mineralogy and Petrology 140, 212–232.
Pin, C., Vielzeuf, D., 1983. Granulites and related rocks in Variscan median Europe: a dualistic interpretation. Tectonophysics 93, 47–74.
Pride, C., Muecke, G.K., 1980. Rare earth element geochemistry of the Scourian complex N.W. Scotland - evidence for the granite-granulite link? Contributions to Mineralogy and Petrology 73, 403–412.
Roedder, E., 1984. Fluid inclusions. In: Reviews in Mineralogy, vol. 12. Mineralogical Society of America, 646 pp.
Rudnick, R.L., 1995. Making continental crust. Nature 378, 571–578.
Rudnick, R.L., Fountain, D.M., 1995. Nature and composition of the continental crust - a lower crustal perspective. Reviews in Geophysics 33, 267–309.
Santosh, M., 1986. Carbonic metamorphism of charnockites in the southwestern Indian Shield: a fluid inclusion study. Lithos 19, 1–10.
Santosh, M., 1987. Cordierite bearing gneisses of south Kerala, India: petrology, fluid inclusions and implications for crustal uplift history. Contributions to Mineralogy and Petrology 96, 343–356.
Santosh, M., Omori, S., 2008. CO_2 windows from mantle to atmosphere: models on ultrahigh-temperature metamorphism and speculations on the link with melting of snowball Earth. Gondwana Research 14, 82–96.
Santosh, M., Tsunogae, T., 2003. Extremely high-density pure CO_2 fluid inclusions in a garnet granulite from southern India. Journal of Geology 111, 1–16.
Santosh, M., Liu, S.J., Tsunogae, T., Li, J.H., 2012. Paleoproterozoic ultrahigh-temperature granulites in the North China Craton: implications for tectonic models on extreme crustal metamorphism. Precambrian Research 222-223, 77–106.
Scrimgeour, I.R., Kinny, P.D., Close, D.F., Edgoose, C.J., 2005. High-T granulites and polymetamorphism in the southern Arunta Region, central Australia: evidence for a 1.64 Ga accretional event. Precambrian Research 142, 1–27.
Skippen, G.B., Marshall, D.D., 1991. The metamorphism of granulites and devolatilization of the lithosphere. Canadian Mineralogist 29, 693–705.
Smithson, S.B., Brown, S.K., 1977. A model for lower continental crust. Earth and Planetary Science Letters 35-1, 134–144.
Stern, C.R., 2011. Subduction erosion: rates, mechanisms, and its role in arc magmatism and the evolution of the continental crust and mantle. Gondwana Research 20, 284–308.
Taylor, S.R., McLennan, S.M., 1995. The geochemical evolution of the continental crust. Reviews in Geophysics 33, 241–265.
Touret, J.L.R., 1965. Sur l'origine supracrustale des gneiss rubanés de Selas (Province de Bamble, Norvège Méridionale). Comptes Rendus de l'Académie des Sciences, Série D 262, 9–12.
Touret, J.L.R., 1971. Le faciès granulite en Norvège Méridionale. I: Les associations minéralogiques. Lithos 4, 239–249. II: Les inclusions fluides. Lithos, 4, 423-436.
Touret, J.L.R., 1985. Fluid regime in southern Norway: the record of fluid inclusions. In: Toby, A.C., Touret, J.L.R. (Eds.), The Deep Proterozoic Crust in the North Atlantic Provinces. Reidel, Dordrecht, pp. 517–549.
Touret, J.L.R., 1986. Fluid inclusions in rocks from the lower continental crust. In: Dawson, J.B., Carswell, D.A., Hall, J., Wedepohl, K.H. (Eds.), The Nature of the Lower Continental Crust, Geological Society Special Publication 24, pp. 161–172.
Touret, J.L.R., 1992. CO_2 transfer between the upper mantle and the atmosphere: temporary storage in the lower continental crust. Terra Nova 4, 87–98.
Touret, J.L.R., 1995. Brines in granulites: the other fluid. Boletín de la Sociedad Española de Mineralogía 18-1, 250–251.
Touret, J.L.R., 2001. Fluids in metamorphic rocks. Lithos 55, 1–25.
Touret, J.L.R., Dietvorst, P., 1983. Fluid inclusions in high grade anatectic metamorphites. Journal of the Geological Society 140, 635–649.
Touret, J.L.R., Hansteen, T.H., 1988. Geothermobarometry and fluid inclusions in a rock from the Doddabetta charnockite complex, Southwest India. Rendiconti Società Italiania Mineralogia e Petrologia 43, 65–82.
Touret, J.L.R., Hartel, T.H.D., 1990. Synmetamorphic fluid inclusions in granulites. In: Vidal, Ph, Vielzeuf, D. (Eds.), Granulites and Crustal Evolution, NATO ASI Series. Kluwer, Dordrecht, pp. 397–417.
Touret, J.L.R., Huizenga, J.M., 2011. Fluids in granulites. In: Van Reenen, D.D., Kramers, J.D., McCourt, S., Perchuk, L.L. (Eds.), Origin and Evolution of Precambrian High-Grade Gneiss Terranes, with Special Emphasis on the Limpopo Complex of Southern Africa, Geological Society of America Memoir 207, pp. 25–37.
Touret, J.L.R., Huizenga, J.M., 2012a. Fluid-assisted granulite metamorphism: a continental journey. Gondwana Research 21, 224–235.
Touret, J.L.R., Huizenga, J.M., 2012b. Charnockites microstructures: from magmatic to metamorphic. Geoscience Frontiers 3, 745–753.
Touret, J.L.R., Nijland, T.G., 2013. Prograde, peak and retrograde metamorphic fluids and associated metasomatism in upper amphibolite to granulite transition zones. In: Harlov, D.E., Austrheim, H. (Eds.), Metasomatism and the Chemical Transformation of Rock: Rock-Mineral-Fluid Interactions in Terrestrial and Extraterrestrial Environments. Lecture Notes in Earth System Sciences. Springer, pp. 415–471.
Tsunogae, T., Santosh, M., 2006. Spinel-sapphirine-quartz bearing composite inclusion within garnet from an ultrahigh-temperature pelitic granulite: implications for metamorphic history and P–T path. Lithos 92, 524–536.
Van den Kerkhof, A.M., Lronz, A., Simon, K., 2014. Deciphering fluid inclusions in high-grade rocks. Geoscience Frontiers 5, 683–695.
Van Waterschoot van der Gracht, W.A.J.M. (Ed.), 1926. Theory of Continental Drift: a Symposium of the Origin and Movements of Land-masses of Both Intercontinental and Intra-continental, as Proposed by Alfred Wegener. American Association of Petroleum Geologists, Tulsa, Oklahoma.
Verschure, R.H., Maijer, C., Andriessen, P.A.M., Boelrijk, N.A.I.M., Hebeda, E.H., Priem, H.N.A., Verdurmen, E.A.Th., 1983. Dating explosive volcanism perforating the Precambrian basement in southern Norway. Norges Geologiske Undersøkels Bulletin 380, 35–49.
Vielzeuf, D., Kornprobst, J., 1984. Crustal splitting and the emplacement of Pyrenean lherzolites and granulites. Earth and Planetary Science Letters 67, 87–96.
Waters, D., 1986. Metamorphic history of sapphirine-bearing and related magnesian gneisses from Namaqualand, South Africa. Journal of Petrology 27, 541–565.
Wegener, A., 1912. Die Entstehung der Kontinente. Geologische Rundschau 3, 276–292.
Westphal, M., Schumacher, J.C., Boschert, S., 2003. High-temperature metamorphism and the role of magmatic heat source at the Rogaland Anorthosite complex in Southwestern Norway. Journal of Petrology 44, 1145–1162.
Zwart, H.J., 1967. The duality of orogenic belts. Geologie en Mijnbouw 46, 283–309.

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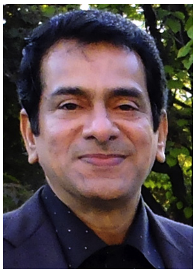

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