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Mantle to lower-crust fluid/melt transfer through granulite metamorphism

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Abstract

The "unexpected" (the word is from H.G.F. Winkler, 1974) discovery of CO_2-rich inclusions in granulites has initiated a debate which, after more than 35 years, is still an important issue in metamorphic petrology. Experimental and stable isotope data have led to the conception of a "fluid-absent" model, opposed to the "fluid-assisted" hypothesis, derived from fluid inclusion evidence. Besides CO_2, other fluids have been found to be of importance in these rocks, notably concentrated aqueous solutions (brines), also able to coexist with granulite mineral assemblages at high *P* and *T*. Brines also occur in inclusions or, more impressively, have left their trace in large scale metasomatic effects, typical of a number of high-grade areas: e.g., intergranular K-feldspar veining and quartz exsolution (myrmekites), carbonate metasomatism along km-scale shear zones (Norway, India), "incipient charnockites" (India, Sri Lanka, Scandinavia), highly oxidized Archean granulites. All together, this impressive amount of evidence suggests that the amount of fluids in the lower crust, under peak metamorphic conditions, was very large indeed, far too important to be only locally derived. Then, except for remnants contained in inclusions, these fluids have left the rock system during postmetamorphic uplift.

Fluid remnants identical to those occurring in deep crustal granulites are also found in mantle minerals, including diamonds. Major mantle fluid source is related to the final stages of melting processes: late magmatic emanations from alkalic basaltic melts, carbonate-metasomatizing aqueous fluids issued from igneous carbonatites. Even if a local derivation of some fluids by crustal melting cannot be excluded, most lower-crustal granulite fluids have the same origin. They are transferred from the mantle into the crust by synmetamorphic intrusives, also responsible for the high thermal gradient typical of granulites, notably HT- or UHT-types. These are mostly found in Precambrian times, generated during a small number of time intervals: e.g., around 500, 1000, 1800, 2500 Ma. HT-granulites forming events occur at world-scale in supercontinents or supercratons, either at the end of amalgamation, or shortly before breaking-off. They provide a mechanism for a vertical accretion of the continental slab, which complement the more classical way of lateral accretion above subduction zones at convergent boundaries.

Keywords: granulites; CO_2 and brine inclusions; continental crust

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Introduction

Most geology textbooks of today speak of a "revolution of the sixties", referring to the advent of plate tectonics, which indeed brought major changes in many branches of Earth sciences. Plate tectonics is directly related to a better understanding of the way in which oceans are created at mid-oceanic ridges, then disappear by subduction during oceanic and continental subduction. The structure of the oceanic crust is relatively simple, composed of a small number of horizontal layers above the underlying mantle. Much less known is the fact that, at approximately the same time, another "revolution" also happened for the understanding of the structure of the continental crust, largely under the influence of Russian scientists (notably V.S. Sobolev at Novosibirsk and V.V. Belousov at Moscow). It was then realized that, under a thin sedimentary cover, continents were no longer a homogeneous mass of granites, as first proposed by Edward Suess under the name of Sal (Suess, 1883–1909), later transformed into SiAl by Alfred Wegener (Wegener, 1929). Like crustal domains under the oceans, they are also stratified, composed of three zones of roughly equal thickness, all dominantly metamorphic: low- to medium-grade upper crust, granitic migmatite middle crust, and granulite lower crust, separated from the mantle by a major geophysical discontinuity, the Moho. Magmatic rocks constitute indeed a significant part of the two lower zones, but they do not form continuous layers. They occur as discrete bodies, either generated by partial melting of the premetamor-

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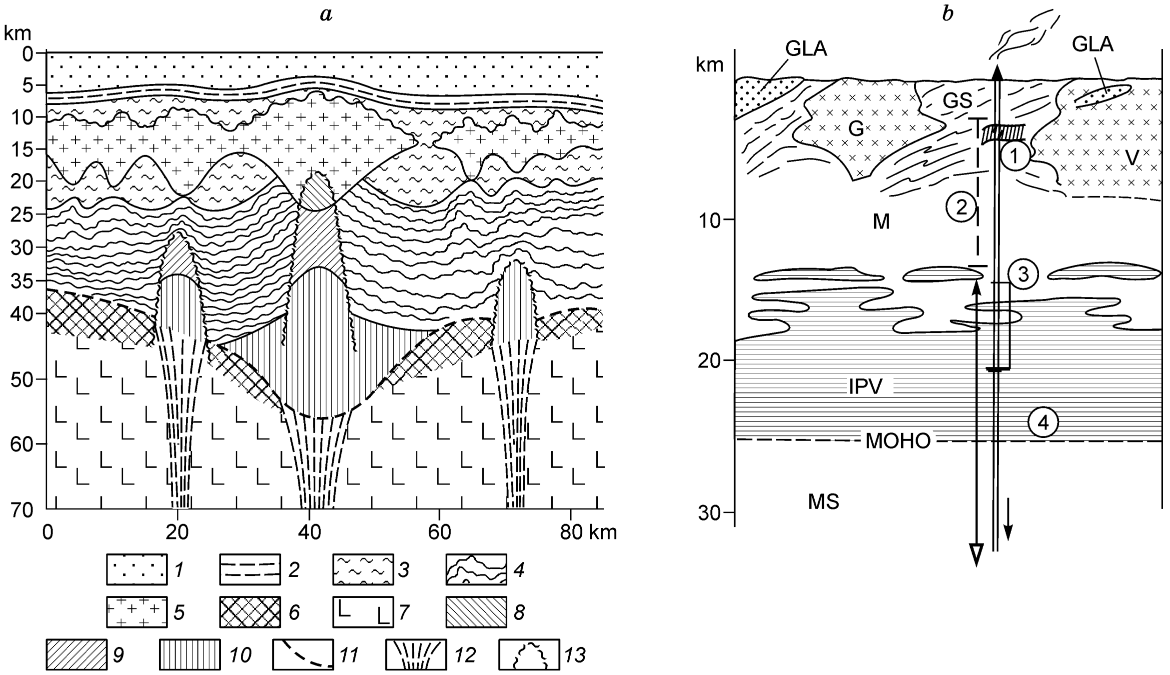

Fig. 1. Structure of the continental crust, according to V.V. Belousov (1966) (*a*). *1*, sediment rocks; *2–4*, metamorphic rocks: *2*, green schist facies; *3*, amphibolite facies; *4*, granulite facies; *5*, granites; *6*, eclogites; *7*, granulite peridotites of upper mantle; *8–10*, crystalline rocks: *8*, acid; *9*, moderate; *10*, basic; *11*, Moho; *12*, asthenosphere upwelling; *13*, boundaries of fusion penetration. Variscan crust under the French Massif Central (Touret and Huizenga, 1999) (*b*). GLA, granulitic amphibole group (400 Ma HP-granulites/eclogites); GS, upper crust; G, V, Variscan (carboniferous) granites; M, granitic migmatites; IPV, Variscan lower crust (HT-granulites); MS, upper mantle. Encircled figures stand for: 1, Last magma chamber of Cenozoic volcanoes; 2, granitic migmatites; 3, upper level of granulite xenoliths; 4, main range (origin) of granulitic/ultrabasic volcanic xenoliths.

phic, supracrustal component (case for most granites in the middle crust), or injected from the mantle, in the form of dominantly gabbroic intrusions. These become more and more abundant when approaching the underlying mantle. This model, to my knowledge firstly clearly expressed by V.V. Belousov in 1966 (Fig. 1, *a*), was later confirmed by many studies, both petrographical and geophysical (e.g., Ramberg and Smithson, 1975). Figure 1, *b* shows an interesting example of the Variscan crust under the French Massif Central, which contains two types of granulites or granulite-related rocks: occurring at the surface, subduction-related high-pressure granulites and eclogites, dated at about 400 Ma (Eohercynian phase) and exhumed through a complicated system of near horizontal thrust planes and nappes. At depth, in the present-day lower crust, high-temperature granulites, formed at about 300 Ma, when large masses of granites were emplaced in the middle crust. These Hercynian granulites are not known in surface outcrops, but they are brought to the surface as xenoliths in recent volcanoes, together with a greater number of underlying, mantle-derived ultrabasic samples.

Large domains (continental size) of granulite lower crust occur in the core of most Precambrian shield areas, whereas others are brought to the surface as xenoliths in lavas from recent volcanoes, together with a greater number of ultrabasic mantle samples. All contain water-deficient mineral assemblages, such as pyroxenes or garnet, in sharp contrast with the hydrated mineral phases (micas, amphiboles) which are typical of the middle- and upper crust.

Experimental data: fluid-absent regime

Experimental metamorphic petrology made great progress during the second half of the 20th century. For the first time, it was then possible to estimate *P-T* conditions at which most metamorphic reactions take place. Largely through the work of the group led by H.G.F. Winkler at Göttingen, in friendly but fierce competition with other experimentalists in the USA and other countries (notably the Geophysical Lab in Washington DC, USA), it was found that, in "normal" metamorphic conditions prevailing in the middle crust, partial melting could affect many supracrustal lithotypes, generating granitic melts which will then collect and rise to various levels of the upper crust in the form of plutonic or subvolcanic intrusions. Crustal melting temperatures are significantly lower than those occurring in the mantle (about 700 °C against more than 1000 °C), but they require the presence of water. The role of other fluids, notably CO_2-bearing, is very minor: CO_2 does not affect melting temperatures significantly, and carbonates, the most important CO_2-bearing mineral phases during prograde metamorphism, are progressively dissolved by acid solutions at the very beginning of the burial, so that the fluid phase remains dominantly aqueous.

Crustal melting is preceded, then accompanied by a great number of metamorphic reactions, during which hydrous minerals are progressively destroyed in the order: zeolites, chlorites, and micas, first muscovite and then biotite. The number of water molecules in each mineral composition steadily decreases, resulting in relatively dryer conditions at increasing depth. As soon as melting occurs, interstitial free aqueous fluids tend to be dissolved in the granitic melts, with a marked influence on the slope of the melting curve, i.e., the level at which the magma will crystallize: saturated melts (negative slope) freeze almost immediately, whereas undersaturated melts may rise for many kilometers, eventually reaching the surface in the form of volcanic extrusions. Most granitic magmas produced in the middle crust are water-saturated, directly rooted in the underlying migmatites. Granites produced in the lower crust (or in the mantle by magmatic differentiation), on the other hand, are systematically water-undersaturated, typically emplaced in the upper crust or generating huge rhyolitic provinces. These considerations, together with a great number of data on the stability of the most various mineral phases in the *P-T* range of geological interest, have led lo the popular model of fluid-absent regime (Thompson, 1983), supposed to prevail at the base of the continents: all free fluids (in this respect supposed to be only water) are either bound in mineral structures or dissolved in melts. As far as granulites are concerned, this model has two important consequences:

1. Typical granulite minerals (first of all, pyroxenes and garnets, besides many other Fe/Mg-bearing mineral phases) are multicomponent solid solutions. This results in extreme complexity in the field appearance of progressive metamorphic isograds. But, in the perspective of the vapour-absent model, the critical parameter is temperature, higher in granulites than in the surrounding rocks: isograds at the amphibolite/granulite boundary are strictly temperature-dependent.

2. As temperature increases with depth, to reach in some cases extreme magmatic range (more than 1000 °C in UHT-granulites (Kelsey, 2008)), granulites should be restites left after the removal of the granite component. This idea fits well with the overall depleted character of the lower continental crust in heat-producing elements (K, Rb, etc.), known since the early days of geochemistry.

Fluid inclusion data: the two granulite fluids

The notion of “dry” granulite lower crust, generated by fluid-absent processes, was challenged by the “unexpected discovery” (the word is from H.G.F. Winkler, 1974) of a great number of fluid inclusions in granulite rock-forming minerals, first in Southern Norway (Touret, 1971) and then in virtually all other granulite terranes, regardless of the location, geodynamic setting or age. Inclusions contain mainly pure CO_2 of variable density (Fig. 2), reaching extreme values (more than 1.1 g/cm^3) in the case of the “superdense” inclusions, significantly heavier than liquid water. Then, but in much smaller amounts, highly saline aqueous solutions (brines) can be found, whose composition in some cases approaches molten salts. Especially for them, similar inclusions can be observed in other environments: evaporites, boiling fluids in subvolcanic intrusions, metamorphic carbonate-bearing rocks, and so on. Besides more specific characters discussed below, notably the adequacy between inclusion data and metamorphic *P-T* conditions, granulite inclusions are however very typical, from a number of features.

At least for the CO_2-bearing ones, they can be quite large (30 to 50 μm in size) and abundant, provided that no postmetamorphic recrystallization (annealling) has occurred. It is true that such recrystallization (or annealling), which tends to wipe out all mineral inclusions (fluid and solid), is widespread in many granulites, having even given a typical

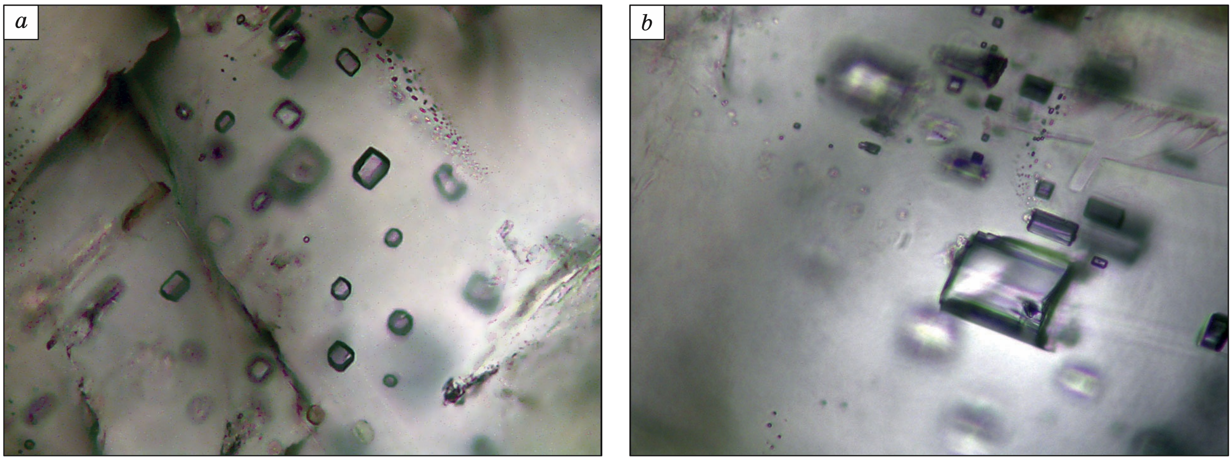

Fig. 2. Examples of CO_2 inclusions in feldspars from Southern India granulites (courtesy M. Santosh) (inclusion size: 30–40 μm). *a*, Very high density (1.07–1.095 g/cm^2) CO_2-inc. in plagioclase from a late Archean (2.4–2.7 Ga) garnet granulite near Salem (Kondallpatimeddu) (Santosh and Tsunogae, 2003); *b*, moderate density (0.96–0.99 g/cm^3) CO_2-inc. in perthitic K-feldspar from late Pan-African (540 Ma) UHT-granulite (Achankovil Shear Zone, Punnalathupadi) (Shunsuke et al., 2006 and/or Santosh, 1987).

name (the granulite texture of English authors). But experience shows that, by carefull observation, it is possible to find domains having escaped this postmetamorphic recrystallization. These may then contain a much greater number of relatively large inclusions than the neighboring wet granitic rocks.

Unlike what is commonly observed in other rock types, inclusions do not occur only in quartz, but also in a great number of other mineral phases: e.g., garnet, pyroxenes, feldspars. In fact, as granulite quartz is most affected by the annealling process, inclusions in this mineral are either absent, or late, not related to granulite metamorphism. Small brine inclusions have however been observed in the "platy" quartz of Saxonian granulites, one of the best example of mineral annealling.

First of all, low salinity aqueous fluids or mixed H_2O-CO_2 fluids, so common in mid-crustal veins and around granitic batholiths, are very rare to absent. Understandable exceptions are retrogressed granulites, which may contain many of these inclusions. But then it is clear that they are late, related to the secondary hydrated mineral phases.

From a number of investigations made in many granulite terranes all over the world, we can derive a consistent picture of the dominant fluid types occurring in lower crustal rocks now occurring at the Earth's surface (Newton, 1989; Touret, 1987).

In HT- and UHT-temperature granulites (pressure between 5 to 10 kbar, i.e., depth 15 to 30 km), CO_2 inclusions strongly dominate in size and abundance. Brine inclusions also occur, notably in metasedimentary protoliths (quartzites, former evaporites) (e.g., Touret, 1972). But they are much smaller, difficult to see, containing only a very small amount of liquid at room temperature. The cavity is squeezed around a number of solid minerals, most commonly carbonates and/or salts ("collapsed" (or squeezed) inclusions, Touret and Huizenga, 1999, see also Fig. 3). It is important to note that identical inclusions (notably pure CO_2, Roedder, 1965) are also found in ultrabasic massifs or in mantle xenoliths brought to the surface by alkali basalts. In high-pressure granulites and eclogites (above 10–15 kbar pressure), the amount of CO_2 progressively decreases, then tends to disappear from the free fluid phase when carbonates become stable. This trend is especially noticeable in HP- and UHP-eclogites, in which CO_2 is replaced by N_2 as the dominant gas species. Typical fluids are carbonate and/or chlorine-rich aqueous solutions, repeatedly found in all high-pressure minerals, including diamonds (Izraeli et al., 2001). These solutions can be progressively enriched in silicates, to grade into hydrous silicate melts in some eclogites (Ferrando et al., 2005).

The discovery of these inclusions has led to the proposal of another model for the formation of granulites. Regional dehydration is not caused by partial melting, but by the occurrence of low H_2O-activity fluids, which dilutes water in the insterstitial free fluid phase. I had first coined the name "carbonic metamorphism" (Touret, 1970), later transformed into "carbonic wave" (Newton et al., 1980). Both names are unsatisfactory: CO_2 is not the only fluid involved and, even if the model requires some gaseous transport, we know now that distances are much shorter than implicitly suggested by the concept of "wave". I prefer to speak of "fluid-assisted dehydration" (or metamorphism), in order to keep a strict parallel with the fluid-absent model.

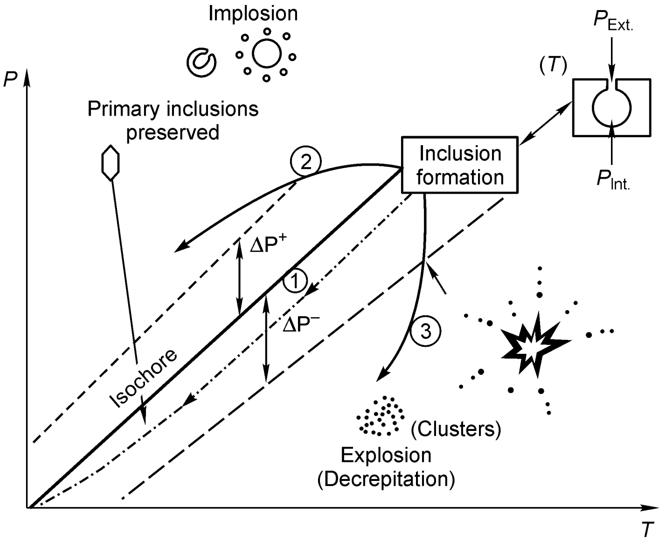

Fig. 3. Relation between metamorphic *P-T* path and inclusion isochores. *1*, pseudo-isochoric (inclusion preservation); *2*, isobaric cooling (inclusion transposition by implosion, leading to squeezed inclusions); *3*, decompression (inclusion transposition by explosion, leading to decrepitation) (e.g., Touret, 1981).

The granulite controversy

Though the occurrence of remarkable fluid inclusions in granulites became rapidly known among the geological community, the idea of fluid-assisted metamorphism at this deep level was not readily accepted, generating a controversy which, after some 40 years, is far from over. Only a short summary can be given here; interested readers can find more detail in the books issued from a series of NATO Advanced Study Institutes, held between 1984 and 1990, which contain an invaluable source of information on the "granulite problem" (NATO ASI, 1985 to 1990). Critics, mainly expressed by experimental petrologists or stable isotope specialists, centered around a few major issues.

Deep inclusions cannot survive the transport up to the surface. At a depth of 30 to 50 km, commonly reached during granulite metamorphism, pressures attain 10–20 kbar, an order of magnitude more than few kbar at which most inclusions explode during experimental runs (Naumov and Malinin, 1968). But these experiments were done on aqueous inclusions in quartz, whereas anhydrous inclusions, for instance CO_2 in olivine from volcanic xenoliths, can stand up to more than 10 kbar pressure when brought to the surface in hot lavas. Moreover, the idea of nonpreservation of deep inclusions, widespread among nonspecialists (even among some specialists!), ignores the fact that, neglecting the secondary effects of volume changes in the mineral host, inclusions are isochoric (constant density) systems: at any temperature, the pressure of interest is not the absolute fluid pressure, but the difference with the external pressure, defined along the postmetamorphic *P-T* path (Touret, 1981) (Fig. 3). Fluid inclusion techniques, supported by a number of experiments, enable us to follow the different possibilities in detail: decrepitation for fluid overpressure, shrinkage of the cavity for fluid underpressure, or preservation when the metamorphic *P-T* path is roughly parallel to the fluid isochore. This scenario is realized for dense CO_2 inclusions in many granulites, notably those belonging to the HT- and UHT-types (Touret and Huizenga, 1999). Alternatively, aqueous saline inclusions, which have much steeper isochores, will automatically be strongly underpressed and either disappear or subsist only in the form of minute, "squeezed" inclusions. But the missing fluid leaves impressive traces in the rock, provided that these are observed carefully: Na-feldspar grain boundaries, lining many metamorphic phenocrysts, abundant myrmekites, metasomatic replacement of some minerals by Na-rich feldspar (albitization). Despite the fact that they had been ignored for many years, all these features point to extensive action of alkali-rich fluids at intergranular boundaries during and after the peak of high-grade metamorphism (Perchuk et al., 1994).

Inclusions are trapped after (and independently of) granulite metamorphism. Some workers have claimed that inclusions (in that case CO_2-bearing) were late, trapped well after granulite peak metamorphic conditions (Lamb et al., 1987). It is true that many inclusions are re-equilibrated during postmetamorphic uplift, occurring along secondary trails which, at first glance, may look quite late. However, when addressing the right samples (notably, like those in Southern Finland, HT-granulites showing a pseudo-isochoric retrograde *P-T* path) and the appropriate technique of investigation, the existence of synmetamorphic inclusions can be proven beyond any doubt (Touret and Hartel, 1990; Tsunogae et al., 2002): occurrence of primary inclusions in metamorphic minerals, notably garnet; concordance between fluid and solid mineral *P-T* data; fluid composition in agreement with external fugacity parameters, etc. In domains which have escaped postmetamorphic recrystallization, the fluid amount contained in inclusions may still be surprisingly high, up to some per cent by weight in some garnet cores of Southern India enderbites (Touret and Hansteen, 1988). Similar results have been found more recently in a number of other occurrences, many of them in Southern India or Sri Lanka (e.g., Santosh and Tsunogae, 2003).

Carbon isotope profiles indicate the absence of significant fluid/mineral interaction during granulite metamorphism. Many regional granulite terranes, e.g., in the Grenville province of North America and Southern Scandinavia, contain km-size occurrences of former limestones, sometimes partly reduced in graphite, more commonly perfectly preserved in the form of calcite or dolomite-bearing marbles. Stable carbon isotope profiles at the boundary of the carbonate layers indicate that the sedimentary signature of the carbon is still preserved, and that it has very little or no effect on the surrounding rocks (Valley et al., 1983). Alternatively, it has been shown in other cases that limited zones of dehydration may occur on the edge of former sedimentary carbonates, but only at a scale not exceeding a few decimeters (Knudsen and Lidwin, 1996). When carbonates are transformed into garnet-pyroxene skarns, such as in the Arendal region of Southern Norway, it could be seen that inclusions are not CO_2-rich, but that they contain aqueous brines, a fact which suggests that the carbonate alteration is less due to metamorphism than to hydrothermal, sea-floor type alteration at the time of or slightly after the sedimentation. These data show only that premetamorphic carbonates cannot be a major source of granulitic CO_2-fluids. This hypothesis is further supported by the average mantle signature of the inclusion fluid (Hoefs and Touret, 1974, unpublished data), as well as by the fact that CO_2 inclusions are especially abundant in and near synmetamorphic, mantle-derived intrusives, indispensable for providing the additional heat required for HT- and especially UHT-granulites (Kelsey, 2008). Much more than providing CO_2, former sedimentary carbonates are protected by an external CO_2-fluid pressure during high-grade metamorphism, the only way to stabilize fragile minerals at the extreme granulite temperatures.

At high *P-T* conditions, rock permeability is too low to account for significant fluid movements. Permeability experiments done at low-crustal conditions indicate very low permeability, apparently incompatible with large fluid movements through the rock masses. These results are at odds with the observation of the secondary trails of fluid inclusions, abundant in any high-grade metamorphites, which witness the occurrence of many fluid flow episodes through the rocks, for a wide range of *P-T* conditions. The question, still open, deserves to be more carefully investigated by dedicated experiments (evolution of a constant volume fluid + solid system at variable *P* and *T*). It can however be observed that, in this respect, both granulite fluids, namely CO_2 and brine, should behave very differently. Because of its large wetting angle (Watson and Brenan, 1987), CO_2 is easily trapped in inclusions, then continuously evolving along pseudo-secondary or secondary trails. Rock permeability is essentially governed by transient and successive networks of microfissures, not interacting directly with the mineral host. Brines, on the other hand, are much more mobile along grain boundaries. They play a major role in mineral crystallization and evolution. Added to the fact that they are much more easily transposed because of the steeper slope of their isochore, this means that they are much more important for the adaptation of the rock mineral composition to changing *P-T* conditions, despite the fact that only few remnants will be preserved in inclusions.

CO_2 influx should result in the deposition of graphite. The composition of Ti-Fe oxides in many granulites record f_{O_2} conditions within the graphite stability field. In consequence, it has been said that large-scale influx of externally derived CO_2 should result in the deposition of large quantities of graphite (Lamb and Valley, 1984). This mechanism is indeed operative in some cases, being the way by which the large graphite occurrences in Sri Lanka or Madagascar are explained (Katz, 1987). But this case remains exceptional: in general, no trace of graphite is found in granulites, neither in the rocks nor within the CO_2-inclusions. In fact, many granulites are highly oxidized (Harlov et al., 1997), suggesting that, in many cases, the Ti-Fe mineral assemblages has suffered late re-equilibration. Moreover, we can consider the fO_2/T curves of graphite stability and Fe-Ti oxides, respectively, which intersect in the P-range of interest at a temperature of about 600 °C (Lamb and Valley, 1984). If CO_2 is introduced in the rock system at a higher temperature, it will be outside of the graphite stability field. Once trapped in inclusions, it will escape the oxide mineral control, being further able to persist at lower temperatures because of the well-known difficulty of graphite to nucleate.

Additional arguments supporting a fluid-assisted dehydration

Discussing (briefly!) the arguments which have been proposed against the fluid-assisted model has certainly some bearing on the granulite controversy. But the final interest of this discussion remains not essential: the fluid-assisted model is directly supported by a number of observations, some of them obvious, which can be found in virtually all granulite terranes.

Prograde granulite metamorphic isograds are not strictly temperature-dependent. Because of the mutivariant character of most metamorphic reactions, the exact position of the different isograds is not easy to delineate precisely in the field. Furthermore, a systematic investigation is an immense task, especially when (as usual!) the regional structure is very complex. In this respect, few regions have been as well investigated as Southern Norway, which has served as a field training school for generations of students from Dutch (notably Utrecht), Danish, and British universities. A summary of regional mineral P-T estimates, based on hundreds of analyses, is given in Fig. 4 (Nijland and Maijer, 1993). It is clear that regional metamorphic isograds, notably the pyroxene isograds which settle the boundary of the granulite domains, do not follow the isotherms precisely. Alternatively, isolated granulite "islands" have been observed well outside the granulite core, which from inclusion studies were found to be related to the local action of highly saline brines (Nijland et al., 1998). Such a local increase in the metamorphic grade, less related to temperature than to the action of local fluids, is probably far more widespread than generally realized.

All granulites are not restites. As already indicated for the metacarbonates, many regional granulites contain premetamorphic supracrustal remnants, still well recognizable despite the extent of metamorphic crystallization. For some rock types, notably quartz-rich, it can be accepted that they have escaped partial melting because of inappropriate composition. But, still in the case of Southern Norway, we have found examples of metagraywackes, in principle an ideal rock for granite melting, still perfectly preserved, with even traces of premetamorphic structures (e.g., conglomerate, cross or graded bedding, Touret, 1974). Partial melting has occurred, but it does not affect more than 10 or 20% of the rock. Fluid inclusion studies have demonstrated that the fluid phase trapped in the molten part of the rock is dominantly carbonic (CO_2 + more reduced gaseous species, notably methane), produced by the reaction between water and premetamorphic graphite (Touret and Dietvorst, 1983). In other words, partial melting exists, but to a limited extent. It is a way to produce low water-fugacity free fluids, either by preferential water dissolution in the granitic melts, or by reaction between H_2O and organic graphite, notably in metapelites. Fluid-absent and fluid-assisted models are rather complementary than mutually exclusive, both playing a role for the control of the fluid regime in the lower crust.

Even poorly preserved in inclusions, brine fluids have left many traces in the granulite mineral assemblage. Discussing the experimental evidence which had led the Norman L. Bowen to propose the concept of magmatic reaction series, some petrologists once believed that plutonic rocks, notably granites, were not issued from molten magmas, but created by solid-state diffusions of ions or atoms within the mineral structure. These contrasting views led to the famous controversy between "magmatists" and "solidists", which was one of the major issues in Earth Sciences during the first half of the twentieth century. The battle is now fully over, with an apparent complete victory of the first group: nobody today would deny the magmatic origin of granites (more details in Touret and Nijland, 2002). But this does not negate the fact that metasomatic features can be observed in many granitic rocks, notably mineral dissolution (feldspar in greisen, quartz in "episyenites", mother rocks of many uranium deposits, e.g., Leroy, 1984) or replacement (albitization). But this metasomatism is not dry, caused by spontaneous atom or ion diffusion in the mineral lattice. We know now that it relates to the action of intergranular fluids, released from the magma during its crystallization. Similar features are widespread in granulites, actually far more than in granitic rocks. Perchuk and his group in Moscow were the first to identify K-feldspar microveins at the boundary between quartz and feldspar in some Russian granulites (e.g., Perchuk and Gerya, 1993), and later found a number of other minerals there and in many other world occurrences (Franz and Harlov, 1998; Harlov and Förster, 2002; Harlov et al., 1998). It is interesting to note that, despite their ubiquitous character, these intergranular microveins had remained completely unnoticed, until fluid inclusion studies indicated the possible occurrence of intergranular fluids at these deep levels.

Further evidence of metasomatism is found in myrmekites, vermicular quartz blebs in plagioclase, typically occurring near or at the margins of large K-feldspar grains. Many hypotheses have been put forward to explain this spectacular texture, but the most commonly accepted one corresponds to the replacement of feldspar assemblages by Na- and Ca-rich aqueous fluids. Myrmekites are common in granites, especially when deformation has facilitated the incoming of external fluids. But they may reach a much greater size and abundance in some granulites, to the point that they deserve the qualification of "giant " (e.g., Limpopo belt, South Africa, Touret and

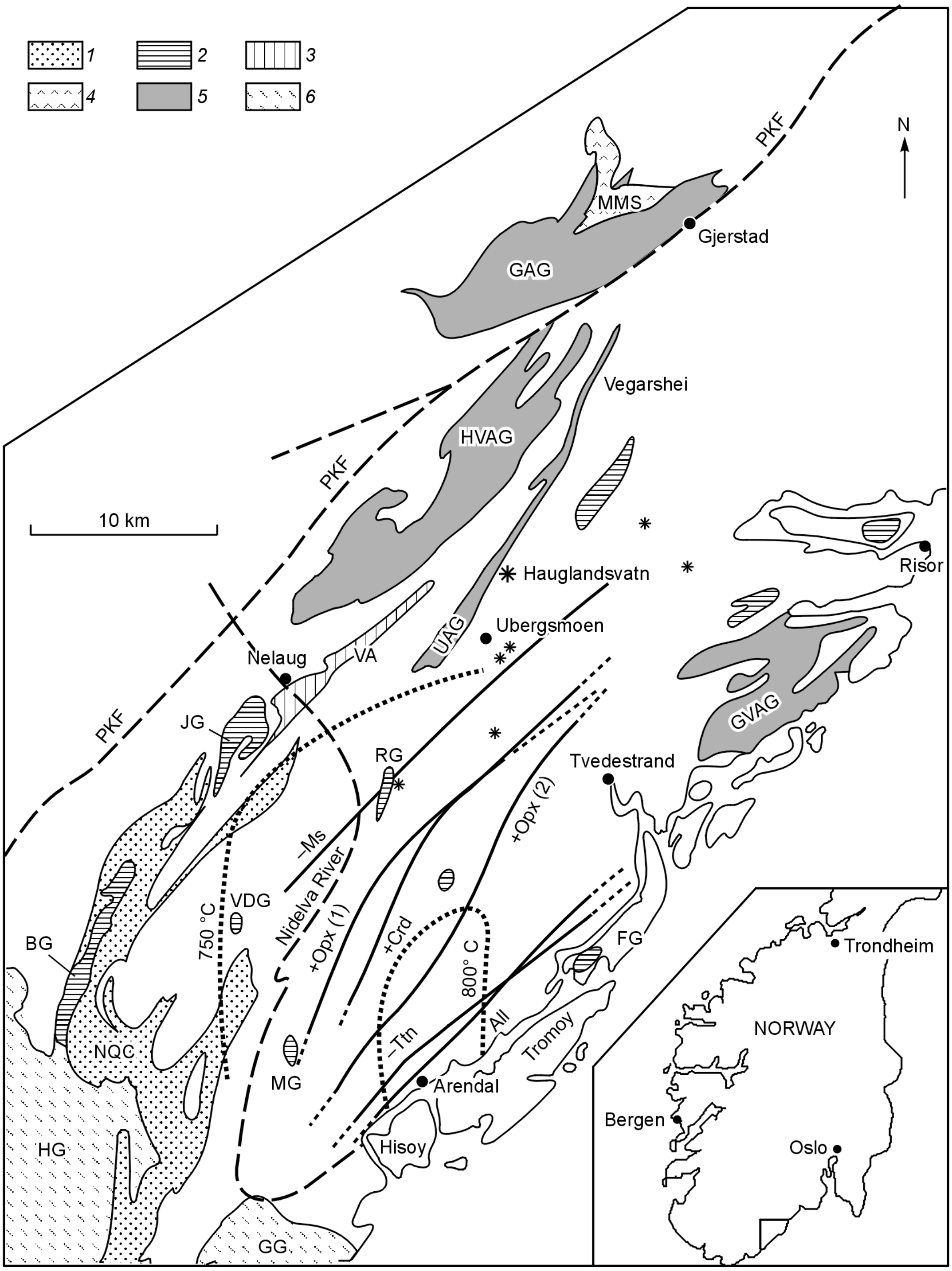

Fig. 4. Regional isograds in the Bamble province of Southern Norway (Nijland and Maijer, 1993). *1*, Quartzites of Nidelva complex; *2*, metagabbro; *3*, K-amphibolites; *4*, monzonites; *5*, charnockite-granite gneisses; *6*, posttectonic granites. Opx 1 and 2, Orthopyroxene (granulite) isograds in metabasites and metapelites, respectively. Solid lines: metamorphic isograds, with indication of the critical mineral appearance (+) or disappearance (–) (Ms, primary muscovite; Opx (1), orthopyroxene in metabasites; Opx (2), in metapelites; Crd, cordierite; Ttn, titanite). Dashed thin lines: isotherms (750 and 800 °C). Stars: granulite islands, outside the main coastal high-grade core, related to the local action of saline fluids (Nijland et al., 1998). Most important regional units: GAG, HVAG, UAG, GVAG, Gjerstad-, Hovdefjell-Vegarshei-, Ubergsmoen-, Gjeving Augen Gneiss, respectively; HG, GG, Herefoss and Grimstad granites; PKF, Porsgrunn-Kristiansand fault line (Great Breccia of Norvegian authors, e.g., Ramberg and Smithson, 1975 and Oftedahl, 1980, separating Bamble and Telemark provinces).

Huizenga, 1999). The example shown in Fig. 5, in a rock sample from the Bamble Province of Southern Norway, is very typical in this respect. The myrmekite is not located on the edge of K-feldspar, as this mineral is conspicuously absent from a rock which contains only large crystals of quartz, cordierite and antophyllite (protolith: hydrothermally altered submarine basaltic lava). Large myrmekites occur at the contact between quartz and cordierite (Fig. 5, *a*). Small brine

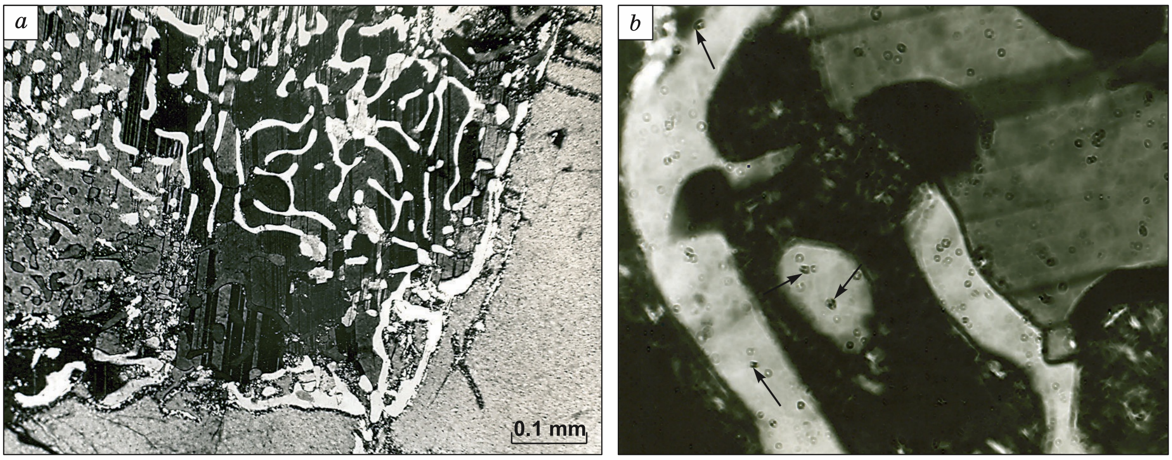

Fig. 5. "Giant" myrmekite at the contact between quartz and cordierite in a quartz-cordierite-antophyllite rocks, Akland by Sondeled, Bamble Province of Southern Norway. *a*, General view of the myrmekite (cordierite to the right); *b*, detail of the quartz-plagioclase assemblage. Arrows, brine inclusions (liquid + vapor H_2O, halite cube with the cavity ≈15 μm in size).

inclusions, probably remnants of the hydrothermal fluid, are clearly visible in some quartz blebs (Fig. 5, *b*). There is little doubt in this case that former K-feldspar grains have been transformed into the quartz-plagioclase assemblage of the myrmekite under the influence of saline fluids.

Granulite fluids, but how much?

If, from all arguments mentioned above, it can be safely assumed that some anhydrous (CO_2 and brine) free-fluid phase did exist at peak granulite conditions, fluid inclusions alone are unable to provide reliable information on the total fluid amount involved. The only tentative indication can be given by the remarkable amount of CO_2 still preserved in the core of some minerals, as in the Indian charnockites and enderbites (see above), but even these contain an unknown, presumably minor sample of the free fluid phase occurring at depth. It must also be observed that, especially for brines, the overall quantity of free fluids does not need to be very large. Because of their extreme mobility and ability to percolate along the mineral grain boundaries, small fluid/rock ratios may account for all observed phenomena, notably biotite dehydration and widespread oxydation (Newton and Manning, 2006).

However, a quantity of field evidence, all situated on the edges of granulite domains, testifies to the trace of fluids leaving or entering the granulite core, suggesting that the fluid amount at peak conditions may have been very large indeed, much too large to have been only locally derived. When the lower crustal segment was subjected to metamorphism, with a temperature at its base approaching or in excess of 1000 °C, it acted as a large fluid reservoir, able to store huge quantities of the typical granulite fluids: first of all, dense CO_2, but also brines (Touret, 1992). Interestingly, most of these field observations had remained unnoticed for many years, even if the different occurrences had been thoroughly studied by experienced petrologists. They were only discovered when it was obvious that fluid movements could have played a role

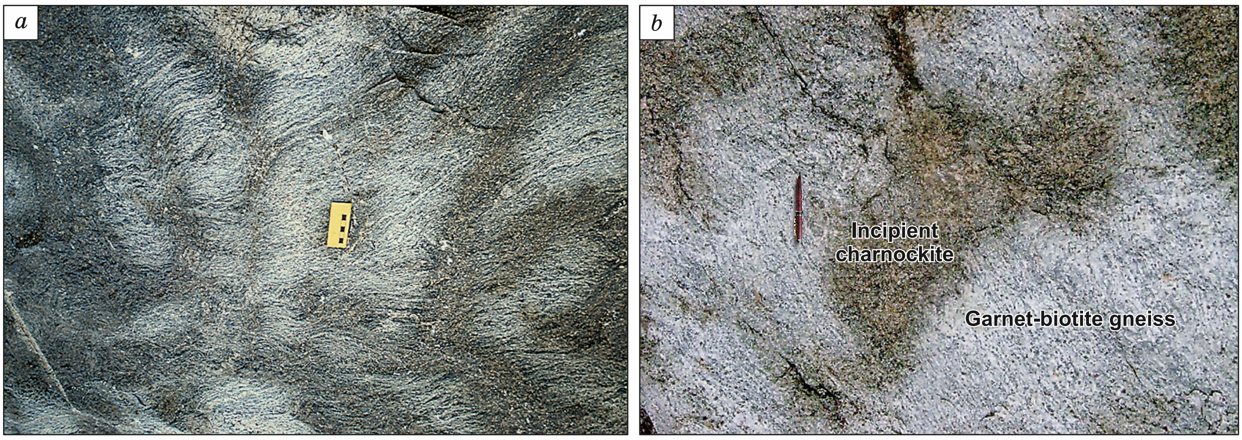

Fig. 6. Incipient charnockite in Kurunegala, Sri Lanka, on this example at the expense of garnet-bearing metapelites. *a*, Outcrop scale (metric): dark charnockite layers intersecting the gneiss foliation (light gray) (Photo courtesy A. Kroner). The contact is not intrusive, but the result of transformation and in situ melting of the gneiss under the influence of incoming fluids. *b*, Detail of the contact: courtesy M. Santosh).

during and after the formation of the granulite mineral assemblages. Two of them deserve to be commented on in some detail.

Fluid-assisted dehydrated zones (incipient charnockites). As early as 1961, C.S. Pichamuthu had reported the local transformation of biotite-amphibole gneisses into charnockite in Mysore state, Southern India. His observation raised no marked interest until the 1980s, when it was realized that some of these "incipient" charnockites, in most cases irregular patches of decimetric to metric size (Fig. 6), could not only affect a variety of protoliths, from meta-igneous volcanites to sedimentary metapelites, but also occurred sometimes along a regular fracture network, suggesting fluid pathways. These incipient charnockites were found in many places in Southern India and Sri Lanka, as well as, more recently, Norway (Knudsen and Lidwin, 1996) and Sweden (Harlov et al., 2006). In a very detailed study, Perchuk et al. (2000) concluded that gneisses had been metasomatically altered by brine streaming under minimum melting for the postmetasomatic composition. Magmatic charnockites could then be produced in situ, without showing any sign of restitic material on the edge of the molten zone. CO_2 is present in minor amounts in inclusions, but it does not seem to have played a major role in the transformation process. It seems to be injected from the neighboring granulite core or, possibly, locally produced by the breakdown of some carbonate minerals initially contained in brines.

Carbonated megashear zones. A number of medium- to high-grade metamorphic areas, notably in China, India, or Norway (e.g., Dahlgren et al., 1993; Newton and Manning, 2002), contain shear zones of regional size (typically over 100 km by 10 km) in which up to 20% of the country rocks are replaced by massive carbonates (calcite and/or dolomite). Carbonate replacement occurred at 500–700 °C and several kilobars, and the uniform C-isotopic signature clearly point to an ultimate mantle origin (Dahlgren et al., 1993). Carbonates are issued from concentrated chloride-carbonate solutions (or hydrosaline magmas), formed as immiscible fluids in the late stage of mantle-derived alkalic magmatism. This type of magmatism, synchronous with granulite metamorphism, is widespread in granulite terranes, especially those belonging to the HT- and UHT-types. Rocks emplaced in this way occur after metamorphic recrystallization as two-pyroxene granulites, more and more abundant at deeper levels (Bohlen and Mezger, 1989). We have then a marked difference between regionally exposed granulites, mainly composed of former supracrustal rocks, and those included in volcanic xenoliths, almost exclusively igneous in origin.

Synmetamorphic intrusions appear also to be necessary to explain the extreme temperatures reached at moderate depths (30 to 50 km) during UHT-metamorphism (Kelsey, 2008). We come then to the idea of the continental crust having acquired its structure during major episodes of granulite metamorphism, resulting in a well-defined fluid distribution through the vertical column (Touret, 1987, 1992): H_2O is grossly dominant near the surface, until the "water-barrier" made by granitic migmatites. Dissolved then in melts and/or bound in mineral structures (notably micas and amphibole), it will disappear from the free fluid interstitial phase. But, at the same time, it will be replaced by low-fugacity fluids, CO_2 and concentrated saline solutions (brines), which under peak metamorphic conditions may persist within the rock masses down to the deepest levels later recorded at the Earth's surface. These fluids are carried upward by synmetamorphic intrusives, which induce crustal thickening by magma stacking and sill-type intrusions at the base of the crust. These intrusions play the most important role in the triggering of granulite metamorphism, notably the HT- and UHT-types. Not only are they responsible for extreme thermal gradients, but they also carry fluids compatible with granulite facies assemblages and limited anatexis of country rocks. Fluids are transported from the mantle not as a diffusing "wave", but dissolved in basic to intermediate alkalic melts. Then they separate from the melt during the first stages of crystallization, in a way which can be compared to the relations between carbonatites and ultrabasic melts at greater depth. Recent measurements (Webster et al., 1999) have shown that Cl is very soluble in H_2O-saturated basic magmas at elevated P and T, so that it can cause early outgassing during the ascent, liberating concentrated brines (R.C. Newton, pers. comm.). The origin of CO_2, which, as for the brines, originates mostly in the mantle, is more problematic. Either it was also dissolved in the melt, produced at low crustal level by the breakdown of some carbonates (as observed in some volcanic xenoliths, Frezzotti et al., 2002) or liberated through a second immiscibility within the carbonate-chloride solutions (Newton and Manning, 2002).

In essence, this model is not fundamentally different from the one proposed in the early 1970s, as soon as granulite inclusions were discovered (e.g., Touret, 1974). But, at this time, only CO_2 was considered to be of importance. As brilliantly predicted by D.S. Korzhinskii in the early 1960s, in more recent studies, both in the field (see above) and in the lab (notably the recent work of R.C. Newton and C. Manning at UCLA), emphasize the role of brines at these deep levels. In the lower crust as well as deep within the mantle, circulating brines are responsible for large scale metasomatic effects, which complement and/or initiate the more familiar (at least in the literature) melting processes, supposed by many to be the only way by which rocks differentiate at depth.

Granulites and crustal evolution: the time factor

Throughout the Earth's history, some granulites have been related to collisional orogens. In the Variscan chain of Middle Europe, for instance, carboniferous granulites constitute the base of present-day crust, brought to the surface, for instance in the French Massif Central, by recent volcanoes (Fig. 1, *b*). Especially in Phanerozoic time, granulites occurring at the surface (e.g., the 400 Ma GLA eclogites/granulites in the Variscan orogen, Fig. 1, *b*) belong to the HP (high-pressure)-types, formed during the compressional phase at the onset of continent collision. Lower HT (high-temperature) crustal granulites, on the other hand, are some 100 Myr younger, formed during the extensional rebound which occurred when the collisional episode has come to an end. Granulites then form a normal part of any orogen, through a large-scale clockwise evolution involving first HP and then HT metamorphic types. The picture might be significantly different for Precambrian times, which include most known HT or UHT occurrences (Kelsey, 2008). Some of them show an anticlockwise *P-T* metamorphic evolution (Harley, 1989), difficult to reconcile with large-scale compression at the beginning of the metamorphic evolution. Moreover, it had been known for a long time that granulites occur preferentially within a restricted number of time intervals: Pan-African orogeny around 500 Ma, Grenville province some 500 Myr earlier, and so on. Together with the age distribution of other metamorphic types, this question was recently refined by Mike Brown (2007); he has shown that UHT-granulites, notably, occur preferentially in four periods, all corresponding to the formation of a “supercontinent” or, in Archean times, to a “supercraton”: 500 Myr ago (Gondwana), 1000 (Rodinia), 1900 (Nuna/Columbia), 2600 (Valbara, Superia, and Sclavia) (all numbers ±100 Myr). The ages of the different metamorphic episodes are relatively regularly spread over the whole period of existence of the supercontinent, some (especially for Rodinia) relatively close to the supercontinent amalgamation, others prior to the break-off. Much work is currently being done on this problem (e.g., Santosh and Omori, 2008a), with the prospect of deep fluid transfer ultimately reaching the external envelopes (Santosh and Omori, 2008b). After years of study, granulites continue to be fascinating rocks, which are far from having uncovered all their secrets.

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