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Review

Composition and evolution of the continental crust: Retrospect and prospect

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

[a] *Institut de Minéralogie, Physique des Matériaux, Cosmochimie, Sorbonne Universités, 4 Place Jussieu, F-75005 Paris, France*
[b] *121 Rue de la Réunion, 75020 Paris, France*
[c] *School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China*
[d] *Department of Earth Science, University of Adelaide, Adelaide, SA 5005, Australia*
[e] *Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, NO-1432 Ås, Norway*
[f] *EGRU (Economic Geology Research Centre), James Cook University, Townsville, Queensland 4811, Australia*
[g] *Department of Geology, University of Johannesburg, PO Box 524, Auckland Park 2006, South Africa*

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ABSTRACT

Until the middle of the 20th century, the continental crust was considered to be dominantly granitic. This hypothesis was revised after the Second World War when several new studies led to the realization that the continental crust is dominantly made of metamorphic rocks. Magmatic rocks were emplaced at peak metamorphic conditions in domains, which can be defined by geophysical discontinuities. Low to medium-grade metamorphic rocks constitute the upper crust, granitic migmatites and intrusive granites occur in the middle crust, and the lower crust, situated between the Conrad and Moho discontinuities, comprises charnockites and granulites. The continental crust acquired its final structure during metamorphic episodes associated with mantle upwelling, which mostly occurred in supercontinents prior to their disruption, during which the base of the crust experienced ultrahigh temperatures (>1000 °C, ultrahigh temperature granulite-facies metamorphism). Heat is provided by underplating of mantle-derived mafic magmas, as well as by a massive influx of low H_2O activity mantle fluids, i.e. high-density CO_2 and high-salinity brines. These fluids are initially stored in ultrahigh temperature domains, and subsequently infiltrate the lower crust, where they generate anhydrous granulite mineral assemblages. The brines can reach upper crustal levels, possibly even the surface, along major shear zones, where granitoids are generated through brine streaming in addition to those formed by dehydration melting in upper crustal levels.

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* Corresponding author at: Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, NO-1432 Ås, Norway.

E-mail address: jan.marten.huizenga@nmbu.no (J.M. Huizenga).

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1. Introduction

Continents are unique features of the planet Earth within the solar system. Since the discovery of plate tectonics, it is known that the continental crust differs significantly from the oceanic crust. Oceanic crust has a limited time of existence, is created by basaltic volcanism at mid-ocean ridges, and subsequently disappears by subduction after ~200 million years. A considerable number of studies have been devoted to the oceanic crust, thanks notably to large-scale international drilling programs (IODP). Less studies have dealt with the formation of the continental crust as a whole, resulting in the paradox that the oceanic crust, covered by the oceans, is better known than the base of exposed continents.

Elaborating on a model proposed by us in 2016 (Touret and Huizenga, 2012; Touret et al., 2016; Touret and Huizenga, 2012), this contribution presents some thoughts on the formation and evolution of the continental crust, following three major lines of evidence: (i) At a global scale, the continental crust is dominated by metamorphic rocks, evolving at its time of formation from (ultra)high temperature metamorphic rocks at the base, to low-grade (greenschist-facies) metamorphic rocks at shallow crustal levels. (ii) Metamorphic events occurred within supercontinents during their final stage of amalgamation and/or disruption. (iii) The metamorphic evolution was controlled by mantle-derived high-salinity brine and CO_2 fluids, resulting in markedly different fluid regimes between the lower and middle-upper crust. Here we will review how our knowledge about the composition of the continental crust has evolved historically (sections 2–4), followed by our view on the formation of the continental crust (section 5 onwards).

2. Geophysical boundaries: The Moho and Conrad discontinuities

In 1909, following an earthquake in the region of Zagreb (Croatia), the local director of the Meteorological Institute, Andrija Mohorovičić (1857–1936) identified two sets of waves. One wave is following the surface whereas the other wave is refracting at depth at a higher velocity medium. He called this discontinuity the Moho, which was subsequently traced around the globe. Andrija Mohorovičić interpreted this discontinuity to be the crust-mantle boundary. It is anecdotic that Andrija Mohorovičić was a self-taught seismologist, having just received some good-quality seismometers. Like Alfred Wegener (1880–1930) a few years later, he was primarily a meteorologist and responsible for the meteorological measurements in Croatia and Slovenia. Hence, two of the most important discoveries in modern Earth Sciences, namely the crust-mantle boundary and the concept of continent drift, were made by meteorologists, and not geologists. The Moho discontinuity lies at a depth of 5–10 km below the oceanic crust but occurs at a greater depth under the continents: ~35 km under the old, stabilized Precambrian cratons (covering ~60% of the Earth's surface, even more if the cratons covered by a thin layer of sedimentary rocks, e.g. in Siberia, are included), and 70–90 km under active orogens (Braile and Chiangl, 1986).

In 1923, the Austrian-American Victor Conrad (1876–1962) (this time a geophysicist) found within the continents, approximately half way between the Moho discontinuity and the surface, sub-horizontal domains at which the seismic wave velocity increases in a discontinuous manner. Much weaker than the Moho discontinuity, this discontinuity is not found everywhere, and its existence has long been questioned. However, it was assumed by the middle of the 20th century that the Conrad discontinuity marks the boundary between a granitic upper crust, referred to as SiAl by Eduard Suess (1831–1914) and a more basic, basaltic lower crust (referred to as SiMa). This idea was discredited in the mid-sixties, when it was realized that the SiMa corresponded to the composition of the oceanic crust, which is strikingly different from the continental crust. By then the name of Conrad was almost forgotten. But more recent views reinitiated the notion of a Conrad discontinuity, regarding it as a metamorphic boundary between amphibolite-facies middle crust and a granulite-facies lower crust (Wever, 1989).

An additional distinct geophysical discontinuity includes high electrical conductivity zones, which were found at the base of numerous continents (e.g., Haak and Hutton, 1986). These were interpreted by some as indication of the existence of conductive fluids at depth (Touret and Marquis, 1994). However, with reference to the Kola Superdeep Borehole, free fluids in stabilized cratonic crust can only exist at depths of 5–7 km (Zhamaletdinov, 2019). For that reason, a high conductivity at depths greater than 5–7 km can be best explained by conductive minerals including graphite or sulphide. The temperature at the base of the Kola Superdeep Borehole (~12.2 km) is as low as 212 °C (Lobanov et al., 2021), indicating an extremely cold craton in Kola. In most cratonic areas, based on an average thermal gradient of ~30 °C/km, the temperature at the Moho discontinuity should be ~440 °C. However, the situation is very different in mobile belts or mantle upwelling/plume-related metamorphic environments, in which the temperature at the Moho discontinuity, which is much deeper in collisional orogens, can be as high as 800 °C (Schutt et al., 2018) or even >1000 °C, as will be discussed below. The Conrad and Moho discontinuities are obviously of great importance for determining the composition of the continental crust, which will be discussed in the next section.

3. Composition of the continental crust: A historical perspective

Since the middle of the 19th century, it was thought that the Earth's outer layer was made of granite, under a relatively thin cover of sedimentary rocks. The main person responsible for introducing this idea was Henry Benedict de Saussure (1740–1789), who had observed that in the Alps successive rock layers were disposed on each other in such a way that older rocks occur at a higher altitudes. Consequently, the Mont-Blanc, which at this time was thought to be the highest mountain in the world, should expose the oldest and deepest rock. This idea was the main reason for De Saussure to climb to the Mont-Blanc summit in August 1787. De Saussure died two years later (1789), just having the time to be world famous through his expedition (abundantly illustrated by nice paintings) and the publication of the first tome of the "Voyages dans les Alpes" (De Saussure, 1787). Volumes 2 and 3 were published in 1794 and 1796, respectively, after his death.

Fig. 1. Claude Sébastien Hugard de la Tour, *Vue du Mont-Blanc depuis le Gramont*, 1852–1853, Ecole des mines de Paris – MINES Paris-Tech. The painting shows a view of the Mont-Blanc from the Crammont mountain in Italy. Photo by Stéphane Asseline, Région Île-de-France.

The painting by Claude Sébastien Hugard de la Tour (1818–1886) (Fig. 1) adorns the honour staircase in the Ecole des Mines (Paris, France). Ordered in 1852, it was presented at the Salon in 1853 and then placed in the Hôtel de Vendôme, and subsequently moved to its current location in the headquarters of the Ecole des Mines. The painting represents the Italian side of the Mont-Blanc, seen from the Cramont (or Grammont), a small mountain near Courmayeur. According to De Saussure in the Voyage dans les Alpes (Tome 2, Chapter 34), Cramont is the best place to have a full view of the famous mountain. The Italian side of the Mont-Blanc is indeed much steeper than the French side near Chamonix. It gives an impression of a vertical extrusion, the mechanism by which the great man at the Ecole des Mines, Léonce Elie de Beaumont (1798–1814), thought that all mountains were formed. Together with other famous landscapes, the view was selected by the director of the Ecole des Mines (long time co-worker of Elie de Beaumont) Ours Pierre Armand Petit-Dufrénoy (1793–1857) for the education of young mining engineers: "combining artistic quality and geological evidence" (quote from a letter of Dufrénoy to the ministry, January 1855). Other paintings are allegories, made by Alexandre Denis Abel de Pujol (1785–1861) (Bouvier and Dessens, 2020).

The granitic rock at the top of Mont-Blanc was named "protogine" by a medical doctor from Genève, Louis Jurine (1751–1819), who continued the work of De Saussure. Jurine explains why he coined this name in a letter to the director of the Conseil des Mines in Paris (Jurine, 1806), sent together with a collection of alpine rocks and minerals: "this name derives from the Greek, protoginos (first, mother of the rocks), it seemed to me that the summits of the Mont-Blanc and its satellites could claim this priority of creation" (translated from the Lettre à Monsieur Gillet-Laumont, 1806).

The Mont-Blanc granite became the symbol of the "Terrain Primitif" (Primitive Terrane), the basement on which all other rock layers were deposited (Fig. 2). "*La science géologique considère (que) ce terrain primitif se compose de trois couches, schistes, gneiss, micaschistes, reposant sur cette roche inébranlable qu'on appelle le granit*" *Jules Verne, Voyage au centre de la Terre* » (Geological science considers that this "terrain primitive" is made of three layers, schists, gneiss, mica-schists, lying on this unshakeable rock which is called the granite) wrote Jules Verne in 1864 in one of his most famous books, Le voyage au centre de la Terre (A journey to the center of the Earth). A quick survey would probably show that these ideas have not fully disappeared in today's "Grand public"!

A major step forward occurred at the end of the 19th century when Eduard Suess (1831–1914) introduced the concept of SiAl (silicon-aluminium) and SiMa (silicon-magnesium). Being the major constituents of felsic rocks, SiAl represents the crust above the Moho discontinuity, whereas SiMa represents the underlying mantle comprising basic rocks approximately basaltic in composition. However, the discovery of radioactivity showed that the continental crust cannot be entirely granitic. SiAl (granite) comprises most of the heat-producing elements, e.g., ^{40}K in K-feldspar. Granites in the upper part of the sialic crust, situated above the Conrad discontinuity, are sufficient to explain the heat flow measured at the Earth's surface. Taking that in consideration, the lower part between the Conrad and Moho discontinuities must be more basic, assumed to be roughly basaltic according to estimated densities and seismic wave velocity. For a while, this basaltic part of the crust was considered to be SiMa as proposed by Suess. But increased knowledge on the composition of the oceanic crust obtained after the Second World War (mainly as a result of instrumentation developed for submarine tracking) showed that the real SiMa could not be the basaltic part of the crust. These results culminated into the almost universally adopted view after the Second World War that the outer envelopes of the Earth comprise magmatic rocks, i.e. a granite upper crust, a basaltic lower crust, and

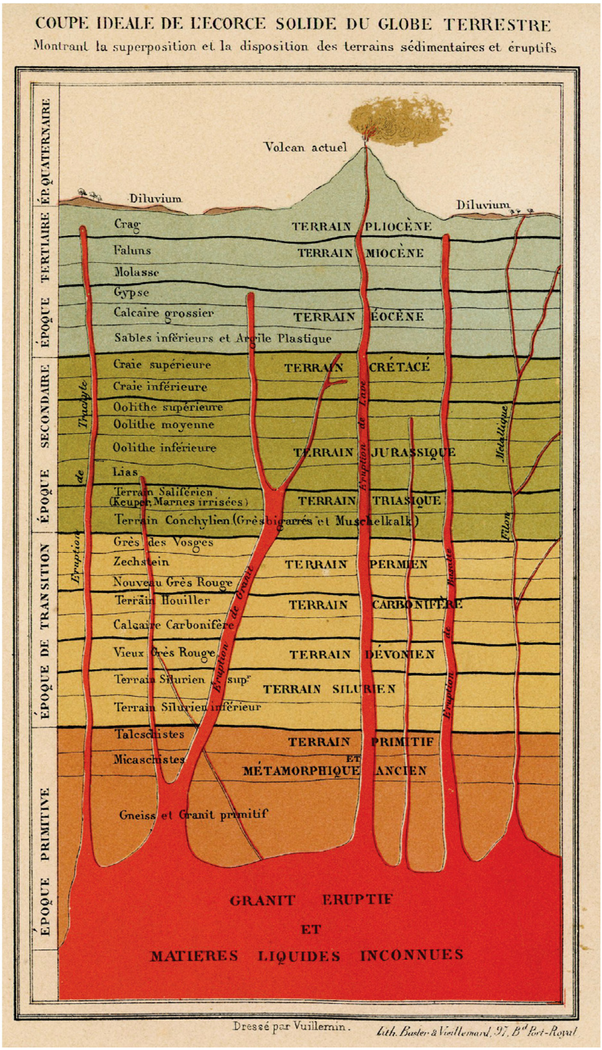

Fig. 2. Ideal section of the solid crust of the terrestrial globe by Louis Figuier (1863). In red "Eruptive granite and unknown liquid matter" (private collection J.L.R. Touret). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

an ultrabasic upper mantle. This interpretation marked the victory of the magmatists over the solidists, who supported the theory that all igneous rocks (except basalt) were formed by solid state processes.

As far as the composition of the crust is concerned, the victory of the "pontiffs" (as they were dubbed by C.E. Wegman) (Touret, 1998) did not last for long. In the 1960s, a series of papers published in French and Russian proposed a different hypothesis, namely that the continental crust is not magmatic but metamorphic. Evidently, a number of magmatic rocks can occur in the metamorphic column but most of them, notably the majority of granites, are S-type granites in the sense of Chappell and White (2001) meaning that they are formed by partial melting of metamorphic rocks (mainly detrital metasedimentary rocks). Moreover, when these rocks occur in the lower crust, pressure and temperature conditions are so high that they are completely recrystallized and transformed into typical metamorphic rocks (e.g., two-pyroxene granulites, which is the most common crustal rocks within volcanic xenoliths). The French and Russian papers that reported these ideas were published outside of the mainstream of scientific literature and did not attract an immediate wide international interest. To our knowledge, one of the first publications was written by the Belgian petrologist Paul Michot (Michot, 1956), who devoted all his life to the study of high-grade metamorphic rocks and intrusive anorthosite-charnockite complexes in Rogaland (southwestern Norway). Michot (1956) noted that the Conrad discontinuity under northern Germany and the Baltic Sea was progressively rising towards the north and cropping out in southern Norway. Hence, high-grade granulites along the southern Norwegian coast (Bamble and Rogaland areas) should represent the rocks underneath the Conrad discontinuity. Only a few people were aware of the work of Paul Michot at the time of these publications. But, thanks to the work of some prominent Norwegian geologists (in particular Tom F.W. Barth, the first president of IUGS), southern Norway became a kind of natural laboratory, attracting geoscientists from all over the world. It is there that most of the ideas presented in this paper slowly developed between 1960 and the end of the 20th century.

The Russian research, illustrated by a cross section published by Vladimir V. Beloussov in 1960 (Fig. 3a), was well known, but did not convince most petrologists that the lower crust was made of granulites. Beloussov, like most Russian authorities at this time, was better known to be a stubborn opponent of plate tectonics, a fact which prohibited most western petrologists to adhere to his views in other geoscience disciplines. At that time, many petrologists considered granulites as petrological curiosities, i.e., relics (restites) after the extraction of a granitic melt, occurring mainly in remote Precambrian cratonic areas. For example, for French petrologists, the ideal granulite locality was Madagascar, where exotic petrology was more or less considered as a counterpart of the unique flora and fauna. Also, it is not easy to exhume rocks

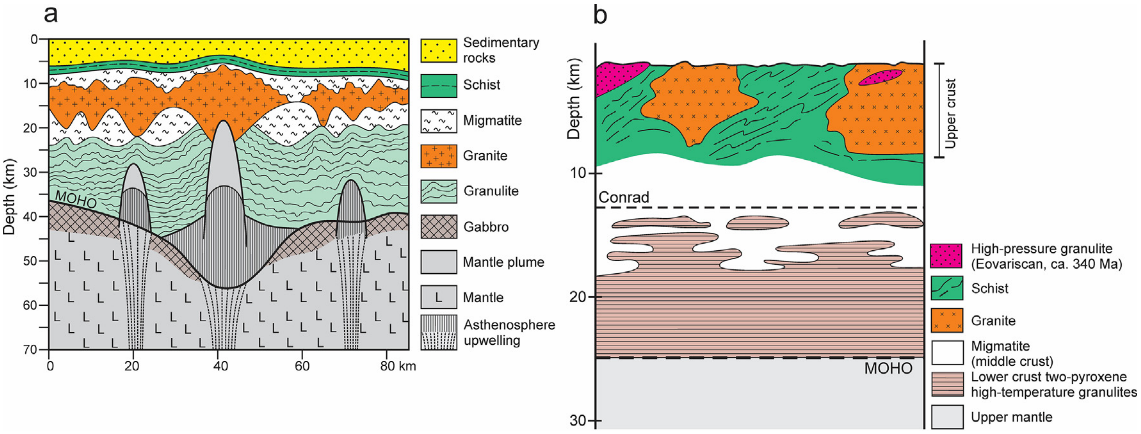

Fig. 3. Sections of the continental crust according to (a) Beloussov (1966) and (b) Dupuy et al. (1979) and Touret (2009). In (b), crustal levels were identified by xenoliths in recent volcanoes from the Massif Central in France.

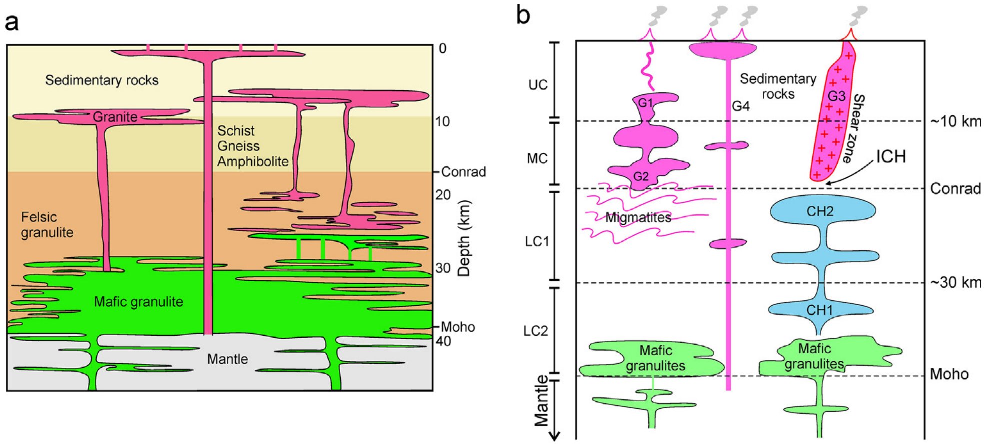

Fig. 4. Ideal composition of the continental crust. (a) Modified after Hawkesworth and Kemp (2006b) and Hawkesworth et al. (2020). (b) Present paper. UC = upper crust, MC = middle crust, LC1: upper part of the lower crust (high-temperature granulites), LC2: bottom part of the lower crust (ultrahigh-temperature mafic granulites). The migmatites extend to the base of the upper part of the lower crust (LC1). G1 and G2 represent shallow- and mid-crustal granites, respectively, produced by dehydration melting. G3 represents granite produced by brine streaming (e.g., Closepet granite, India). G4 represents granite melts directly issued from the mantle. ICH = incipient charnockites, CH1: ultrahigh-temperature charnockites, CH2: high-temperature charnockites.

formed at a depth of a few tens of km. Most granulites are dislocated by tectonic movements, subjected to retrograde morphism and (near) surface alteration. In this respect, the geology of Scandinavia played a very important role. Scrapped by Quaternary glaciers and mostly devoid from any vegetation, outcropping conditions are ideal for detailed observations and mapping. Education and research are of high quality, with a strong desire for international cooperation. It is in this region that some of the most important discoveries were made, notably the fact that granites do not form a continuous layer but a series of batholiths with a diameter of a few kilometres, with a root of mixed migmatites, in which granitic melts are formed by partial melting of the host gneiss.

Crustal and mantle xenoliths that are carried to the surface by recent volcanoes (Fig. 3b) confirm the model of Beloussov (Fig. 3a) and, sixty years later, it still forms the basis of the current idea on the structure of continental crust in cratonic areas (Fig. 4). Interesting is the fact that the composition of the lower crustal granulite xenoliths does not significantly change with time. Most of the granulite xenoliths are Precambrian in age, but Miocene (Pamir Mountains, Gordon et al., 2012) or even younger (Central Mexico, Hajob et al., 1989) have also been found and show a strikingly similar compositions. Lower crustal granulites worldwide have shown to belong to two categories: high-temperature granulites (800–850 °C), and ultrahigh-temperature granulites (>900 °C, sometimes >1000 °C).

Above the Moho discontinuity, which marks the separation between crust and mantle ($\sim$35 km deep), the Conrad discontinuity separates the crust not into two, but in three entities. These include: (i) The upper crust (down to a depth of 5–7 km) situated above the Conrad discontinuity ($\sim$15 km deep), which comprises greenschist facies metamorphic rocks cut by shallow intrusives (Cu-porphyries), subjected to intense hydrothermal alteration. These intrusions can reach the surface as expressed by widespread volcanic activity. (ii) The amphibolite-facies middle crust (from 5–7 km depth to the Conrad discontinuity), which includes homogeneous granite batholiths in the upper part that are rooted in granitic migmatites. (iii) Between the Conrad and Moho discontinuities, a continuous granulite lower crust forms the base of the continents (Rudnick et al., 2003). Most regional granulites are true migmatites, which are only different from mid-crustal granitic migmatites by the fact that H_2O-bearing minerals (e.g., micas) are replaced by anhydrous mineral assemblages including orthopyroxene and/or garnet. Granite equivalents are orthopyroxene-bearing charnockites, which were first defined in southern India (region of Madras, now Chennai; Holland, 1900) and were recently identified to be subduction-related arc magmas that subsequently underwent granite facies metamorphism, and precisely dated as Neoarchean (Yang et al., 2021). Charnockites were later identified to be major component in numerous granulites terranes. Charnockites contain, like granites, heat-producing elements, indicating that the overall depletion of the lower crust relative to the middle crust cannot be due to selective element migration, but is related to a change in rock composition, with the volume of metagabbros increases near the Moho discontinuity. This hypothesis is further supported by gravity measurements and the systematic compositional changes between deep volcanic granulite xenoliths and shallower supracrustal granulites exposed at the Earth's surface (Rudnick et al., 2003).

In summary, the present ideas on the composition of the continental crust are represented in the sections shown in Fig. 4. The on average $\sim$40 km thick continental crust is divided into two parts: (i) Above the Conrad discontinuity, the upper and middle crust comprise low-to medium grade metamorphic rocks under a thin sedimentary cover (MC-UC in Fig. 4b). (ii) In between the Conrad and Moho discontinuities, the granulite lower crust is divided into two parts: the upper part (LC1 in Fig. 4b), mostly containing felsic granulites and situated above the bottom part of the lower crust (LC2 in Fig. 4b), which extends to the upper mantle.

Granite intrusions (G1–G4 in Fig. 4b) occur in the upper and middle crust, which near its base is entirely composed of granitic migmatites. The granite equivalent in the lower crust is charnockite, whereas intrusions in upper part of the lower crust (LC1) are dominantly mantle-derived metagabbros. There are, however, marked differences in opinion on the crustal levels at which granite magmas are generated. Fig. 4a (after Hawkesworth et al., 2020) illustrates the most widely accepted view, namely that granulites are restites, remaining in place after expulsion of granitic melts (Fyfe, 1973). It implies that the main granite source would be in the lower crust, with granitic melts rising over large distances (several 10′s of km) through the continental crust.

The discovery of CO_2 and high-salinity brine fluid inclusions in high-grade metamorphic rocks has led to an alternative model involving these fluids, namely fluid-assisted melting. This started a debate which, after more than 50 years, still has not come to an end. It is not possible here to summarize an enormous amount of literature (aptly done on the research site of Dave Waters, Oxford University, https://www.earth.ox.ac.uk/~davewa/index.html). We will only point out two critical issues indicating that the dehydration melting model can only be of limited importance in the lower crust.

First, granite melts produced by the breakdown of H_2O-bearing minerals are water-saturated. If the regional temperature remains constant, they will crystallize when the pressure decreases. For granitic migmatites in the middle crust, the distance between the homogeneous granites and their migmatite roots rarely exceeds 1–2 km. Conversely, dry granitic magma produced in the mantle (I-type granites) can rise through the entire crust, eventually reaching the surface in the form of rhyolites.

Second, and most importantly, H_2O-bearing minerals are rare or absent in the granulite lower crust, compared to the middle or upper crust. Those which may occur have chemical compositions (e.g., relatively high Ti content in biotite) which increase their stability to relatively higher (granulite-facies) temperatures.

Supported by observations in the amphibolite/granulite transition zone, i.e. "incipient charnockites", it is for these reasons that we proposed that granite melting in the lower crust relates to another mechanism, namely streaming of mantle-fluids (high-density CO_2 and brines) into the crust (Newton et al., 2019) (Fig. 4b). Typical pressure–temperature conditions are between 7 kbar and 10 kbar and 800 °C to >1000 °C, respectively (at a depth of 20–30 km) (high to ultrahigh temperature granulite metamorphism). As in the mantle, melts produced under these pressure–temperature conditions are CO_2-saturated. At lower crustal pressures, the magma contains the CO_2 until the final stage of crystallization and it becomes a charnockite, which, except for the occurrence of orthopyroxene instead of biotite, is identical to a granite (Rajesh and Santosh, 2004; Rajesh, 2007). As in the middle crust, most granitic melts produced this way do not move over great distances, unless they are situated in domains of tectonic deformation. But brines and CO_2 can be focused along shear zones to reach upper crustal levels. There they may initiate further granite melting at a relatively lower pressure (Aranovich et al., 2013), allowing CO_2 to leave the magma at the onset of crystallization (Bhattacharya et al., 2014). The best example of such a scenario is the Closepet granite of southern India, which will be discussed in more detail in section 7.

In summary, the continental crust acquires its final structure during a major episode of high-temperature and relatively low-pressure metamorphism, resulting in a combination of metamorphic (amphibolite to granulite) and melting (granites and charnockites) processes in the middle and lower crust. Both processes are strictly dependent on the nature and abundance of fluids, which were present in the rock system when they occurred (e.g., Newton, 2020). Before proposing a comprehensive model, it is necessary to review the knowledge that we have about these fluids, based on remnants preserved in minerals.

4. Role and composition of magmatic and metamorphic fluids: Fluid inclusion data

When the continental crust was thought to be magmatic, there was no need to consider the influence of fluids. Only one fluid was thought to be of importance, water, evidently a major feature of the Earth's surface, but not able to reach a depth exceeding a few kilometres. Fluids were considered to be exclusively hot magmas, related to some kind of volcanic activity or to a mysterious "feu central", inherited from the creation of the Earth. High-quality petrographic microscopes became available in the middle of the 19th century and revealed the common existence of fluid remnants (fluid inclusions) hosted in minerals from igneous rocks (e.g., quartz in granites, Sorby, 1858), but these were generally considered to be insignificant. They were considered to be too small and it was believed that they were possibly formed during superficial alteration, and, therefore, only interesting in a few ore deposits. During the long magmatic/metasomatic granite controversy, tenants of metasomatism denied the existence of any fluid during the formation of granite (solid state reactions), despite the fact (as was discovered later), that fluid-rock interaction would have been the best way to interpret their observations.

The situation changed significantly when it was realized that the continental crust was not entirely magmatic, but dominantly metamorphic, with granitic rocks locally created by partial melting of the surrounding metamorphic rocks. In both cases, the role of fluids is essential: progressive metamorphic mineral reactions are essentially dehydration and decarbonation reactions, liberating H_2O-rich and carbon-bearing fluids (CO_2, CH_4, or heavier hydrocarbons,). More exceptional are other atmospheric volatiles, e.g. N_2 transported at depth as NH_4 ions in feldspar of micas. Other fluid species like O_2 (mostly related to natural irradiation) or H_2 (under very reducing conditions) are very rare. Sulphur-bearing fluid species (i.e., H_2S, SO_2), which are abundant in the atmosphere near volcanic eruptions, are rare or absent in the crust as sulphur is stored in sulphide mineral phases.

Fluid-related research was accompanied by an significant improvement of instrumentation (fluid inclusion microthermometry, Raman microspectrometry) and interpretation, thanks notably to the pioneering work of a few individuals, first of all Edwin Roedder in the USA. At present, fluid inclusion research is a domain of full activity, with hundreds of publications per year, producing spectacular results, possibly considered by some petrologists with some distance (eager to accept them if they confirm their views, but even faster to consider them as irrelevant if they do not). Summarizing all these results, as was done by Edwin Roedder (Roedder, 1984), is beyond the scope of this paper. However, some consistent trends regarding the type of fluid found in the crust irrespective of their age, are given below.

In upper crustal granites (Cu-porphyries, shallow intrusives), high-temperature, magmatic fluids are strongly influenced by mixing with surface descending fluids, leading to extensive boiling phenomena. This is exemplified by fluid inclusion assemblages including liquid-rich high-salinity and vapour-rich fluid inclusions (Fig. 5). Both the vapour and the high-salinity liquid-rich fluids have the ability to transport metals (e.g., Heinrich et al., 1999).

Typically, fluid inclusions in mid-crustal, dehydration-melting granites are aqueous with variable salinities, from NaCl rich fluids

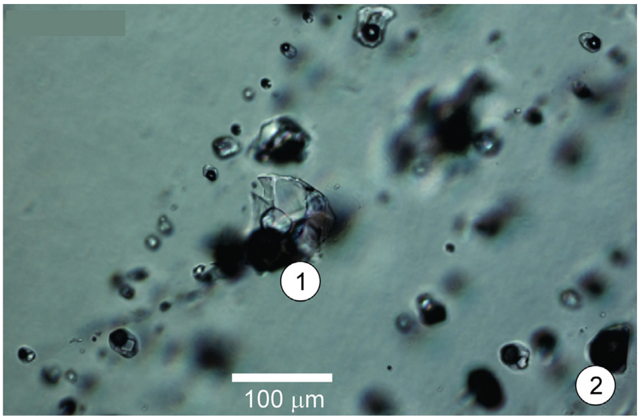

Fig. 5. Fluid inclusions in quartz from a shallow intrusive, the Cu-porphyry Rosia Poienni, Rumania (Damman et al., 1996) (boiling fluid system). 1: Multiphase aqueous fluid inclusion, 2: Vapour-dominated fluid inclusion.

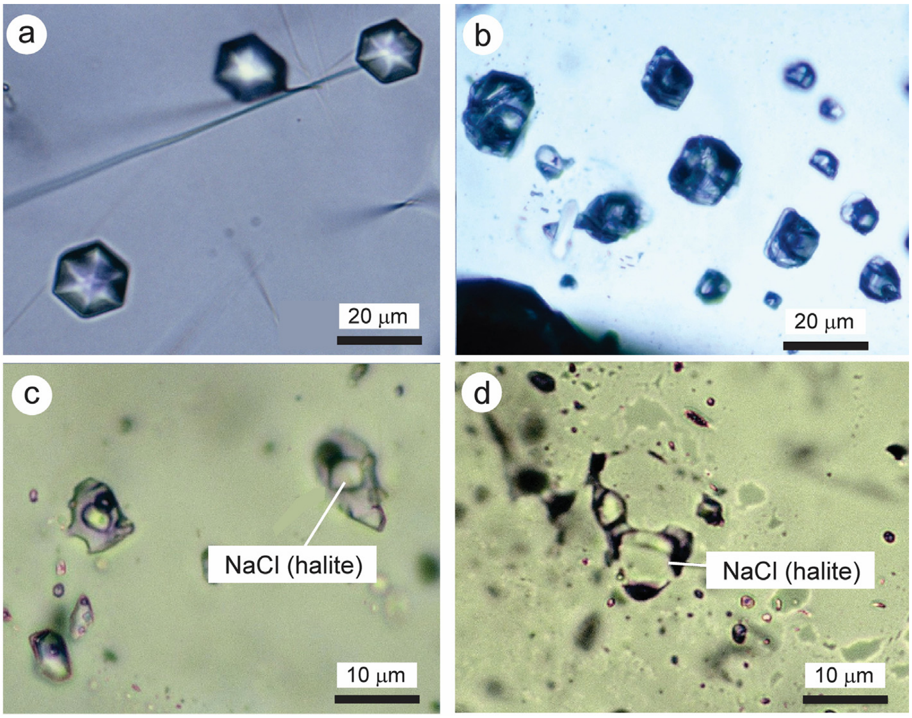

Fig. 6. Fluid inclusions in granulites. (a,b) CO_2 fluid inclusions in the Furua granulites from Tanzania (after Coolen, 1982). (c,d) Brine fluid inclusions in granulite skarn from Arendal (Banble Provicne, Norway; after Touret, 1985).

to almost pure water. As the water solubility in granite magmas exceeds that of other components (i.e., CO_2) by about one order of magnitude, the magma separates the different fluids in which CO_2 are mainly found in pegmatites or hydrothermal dykes at the periphery of the granite batholiths whereas H_2O remains in the granite.

Up to the apparition of migmatites (second sillimanite isograd) in the metamorphic column, fluid inclusions are not found in the rock itself (except for few fluid inclusions inherited from the sedimentary protolith) but in monomineralic segregations (quartz or calcite veins). The main types of fluid inclusions are well illustrated by the metamorphic veins occurring in the Western Alps (Mullis et al., 1994), which are also found in other collisional orogens. In order of progressive metamorphism, fluid inclusions in idiomorphic quartz contain H_2O and oil (heavy hydrocarbons), H_2O and CH_4 (Fenster quartz), pure H_2O of variable (mostly low) salinity (Dauphiné habitus), and finally homogeneous CO_2-H_2O fluids hosted in Tessiner quartz (well-known and spectacular three-phase fluid inclusions comprising H_2O liquid, CO_2 liquid, and CO_2 vapour). This sequence corresponds to the progressive oxidation of carbon in the COH system (e.g., Huizenga, 2001), indicating that, at regional scale, the main fluid is associated with the progressive evolution of organic matter initially contained in sedimentary rocks.

5. Fluids in the lower crust: nature, abundance and origin

If fluids in the middle to upper crust are only restricted to magmatic intrusions or metamorphic segregations, the situation becomes drastically different in the granulite lower crust. When granulites were thought to be restites, the question of fluids was non-existent: granulites are markedly depleted in H_2O-bearing minerals and free a fluid phase (considered to be exclusively H_2O) could not be present. Numerous fluid inclusion studies revealed a completely different picture, i.e. most granulites contain a remarkable amount of fluid inclusions, as reported from various granulites worldwide (Fig. 6). The only exception is when the rock is completely recrystallized (annealed), a process during which all inclusions (fluid and solid) are wiped out. These fluid inclusion data have already been reviewed and discussed elsewhere (e.g., Santosh et al., 1992; Newton and Manning, 2005; Touret and Huizenga, 2011; Newton et al., 2014), and their plate tectonic significance on a global scale have also been evaluated (Santosh and Omori, 2008), so we will only recall the main results here. Pro-, peak- and retrograde metamorphic fluid remnants have been found in granulites. Prograde fluid inclusions are rare, exclusively high-salinity brines, and restricted to detrital protoliths (e.g., quartzites) and meta-evaporites. At peak metamorphic conditions, most fluid inclusions that are formed contain pure CO_2 of variable densities. The highest densities correspond well with peak metamorphic pressure–temperature conditions, with a small pressure deficit due to a limited amount of H_2O in the fluid, not exceeding 10–20 vol%. At low temperature, H_2O and CO_2 are separate fluid phases in which H_2O forms an invisible thin film along the fluid inclusion cavity wall. Alternatively, it may have left the fluid inclusion by diffusion into the host mineral (Bakker and Jansen, 1990). These CO_2 fluid inclusions are systematically observed in orthopyroxene-bearing rocks, formed during peak (800–1000 °C) and retrograde metamorphic conditions (to ~500 °C) (Touret and Hartel, 1990).

The other fluid that occurs in granulites are high-salinity brines (Newton and Manning, 2010; Touret and Huizenga, 2011). In contrast to CO_2 fluids, brines do not move in the rocks along networks of healed microfractures (trails of secondary fluid inclusions), but they circulate easily along mineral intergrain boundaries. They have a great capacity of element transport, in particular alkalis. In contrast to CO_2, the presence of saline fluids are commonly not indicated by the occurrence of fluid inclusions (systematically strongly deformed or imploded) but by the characteristic metasomatic microtextures (K- or Na-feldspar microveins, e.g. Franz and Harlov, 1998; Safonov et al., 2019). These textures were first iden-

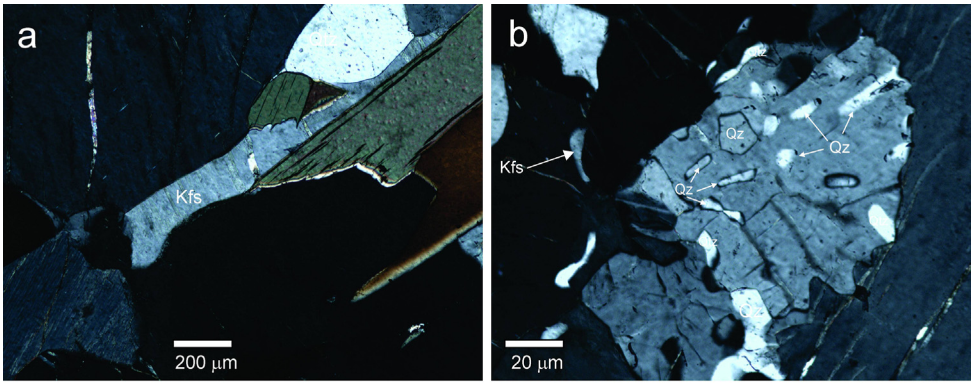

Fig. 7. Intergranular feldspar microvein and myrmekite texture caused by circulating brines in granulites (after Touret and Huizenga, 2011; Touret et al., 2016). (a) K-feldspar microvein developed along the boundaries of mesoperthite, biotite, and quartz (crossed polars). (b) Myrmekite texture (crossed polars). Large arrow: K-feldspar microvein along the boundary of two mesoperthite crystals.

tified in "incipient charnockites" (local transformation of amphibolite-facies gneiss in granulites), and subsequently in many other granulites and charnockites globally (Fig. 7). In ultrahigh temperature granulites, highly saline brines (well above 50 wt.% NaCl equivalent) and high-density CO_2 fluid inclusions occur as contemporaneous, but independent fluid inclusions (immiscible fluid mixture, e.g. Fig. 2 in Touret et al., 2016). Such a fluid inclusion assemblage is the result of unmixing of a homogeneous CO_2 and brine fluid and also occurs in some mantle-derived ultramafic rocks, notably the platinum-bearing deposits of the Stillwater complex in Montana (Hanley et al., 2008). At lower temperature, some CO_2 can be liberated from disrupted fluid inclusions and react with the brine fluid. This explains the late carbonate microcrystals systematically found in many granulites. A number of these brines contain sulphate (anhydrite), in line with the high degree of oxidation that characterizes a number of regional granulites (e.g., Ivrea Zone and southern India) (Harlov et al., 1997).

It has recently been found that another fluid, referred to as an "acidic fluid", is responsible for the formation of Cl-bearing apatite (Samuel et al., 2021). Such a fluid may have important capacities of metasomatic reactions, at least comparable to those of brines. More work is required to further identify this fluid, but the fact that fluid inclusions in apatite contain exclusively CO_2 may suggest that this fluid is derived from a CO_2-H_2O fluid and forms at high pressure and temperature carbonic acid (H_2CO_3), which is able to transport halogens (Cl and F) in the form of complexes (Pirajno, 2018). Other examples of acidic fluids occur in "chambered" pegmatites (e.g., Volyn-Volodarsk, Ukraine), where they are related to spectacular dissolution effects of beryl or topaz, as well as leaching out of quartz in a graphic assemblage in a wide zone below the pegmatite chamber. Fluid inclusions in quartz from the Volyn-Volodarsk pegmatite have been studied in great detail by the Russian researchers (e.g., Zakharchenko, 1971). The earliest fluid inclusions contain a great number of daughter minerals, which make a very mobile melt at ~800 °C. Quartz leaching and beryl dissolution occurs at a temperature of 400–500 °C, when the fluid phase comprised low salinity H_2O and increasing CO_2 content. It would also support the idea of acidic fluids made of a combination of H_2O and CO_2, with F as a ligand, as shown by late-stage fluorite crystallization. It seems well established that these acidic fluids have the capacity to dissolve resistant minerals including zircon (Samuel et al., 2021). As they are also able to dissolve and transport large quantities of silica, which might be responsible for the large amount of quartz found in the quartz-carbonate megashear zones that surround regional granulite areas (Newton and Manning, 2005).

5.1. Fluid volume

Fluid inclusions may indicate the composition of the fluids which did exist at the time of their formation, but they give a limited information on the volume of fluid. Only when they are especially abundant, such as in the core of garnet or other minerals in ultrahigh-temperature granulites, fluid inclusions alone may indicate a lower limit of the fluid amount (still a few wt.% in the Doddabetta charnockite from India or in the sapphirine-bearing granulites from Sri-Lanka, e.g. Touret and Hansteen, 1988). The simple fact that granulite fluids had regional effects shows that their amount must not have been trivial. But the confirmation that it must have been very large amounts indeed is given by the extent of late phenomena, caused by these fluids when they have left the rock system at the end of the granulite metamorphic episode, including regional albitization and metasomatic transformation of granitoids as in southern Sweden and Norway extending over 1000's km^2 (Engvik et al., 2014), or mega-shear zones 100's km in length and a few km's wide, characterized by quartz-carbonate (oxidised environment) or graphite (reduced environment) veins. Both types of shear zones may be closely related with their nature depending on the dominant lithology of the host rock, i.e. detrital sedimentary rocks for quartz-carbonate veins and sulphide-bearing host rocks for graphite veins. Both have a great potential for ore deposits, notably gold (Klein et al., 2006; Fu and Touret, 2014). There is ample evidence that these megashear zones are related to granulite fluids. The brines, found systematically in quartz-hosted fluid inclusions in the quartz-carbonate shear zones, have a great oxidation potential, especially when they contain $CaSO_4$ (observed in many granulite brines, especially when they are derived from former sedimentary rocks). For graphite veins, the relation with granulite areas was noted by Katz (1987) and confirmed by more recent studies (e.g., Luque et al., 2014; Touret et al., 2019a; Touret et al., 2019b). Graphite is formed by reduction of the CO_2 fluid in regional metamorphic rocks (e.g., Luque et al., 2014). It is interesting to note that the timing of these late effects can be variable relative to the peak of metamorphism. They are almost simultaneous in southern Norway but delayed by hundreds of million years in Sri-Lanka (Touret et al., 2019a; Touret et al., 2019b). It indicates that fluids may remain at depth when temperature decreases until the end of the metamorphic episode, provided that the pressure (depth) remains more of less constant. Fluids leave the rock system only at the beginning of regional uplift, when lower crustal rocks start their final journey towards the Earth's surface. The regional extent of these metasomatic features is definitive proof that fluid quantities stored in the lower crust at peak metamorphic conditions must have been very large indeed.

5.2. Fluid origin

The origin of the lower crustal fluids is a complicated problem, especially considering the large volume of fluids that must have existed at peak metamorphic conditions. For CO_2, it is interesting to note that remnants of former carbonate-bearing sedimentary rocks are relatively rare. Limestone, especially if it contains silicate minerals, is destroyed during prograde metamorphism. In the few samples which persist in granulites (e.g. Arendal "skarns", southern Norway), fluid inclusions do not comprise CO_2, but a brine fluid (Touret, 1985) (Fig. 6c). Geochemical tracers ($\delta^{13}C$, $^3He/^4He$) show without ambiguity that free CO_2 in the lower crust is mainly derived, if not exclusively, from the mantle (Hoefs and Touret, 1975; Matthews et al., 1987; Dunai and Touret, 1993). The problem is more complicated for aqueous fluid inclusions which, at granulite-facies metamorphic conditions, can only be low H_2O-activity high-saline brines as any low-salinity aqueous fluid will provoke melting after which the aqueous fluid will be dissolved in the melt.

Some brine inclusions are found in detrital metasedimentary rocks or in altered former oceanic crust (southern Norway, southern Africa) (Touret, 1985). Hypersaline fluids may be generated by high-grade metamorphism of evaporites, which are not uncommon in post-Archean granulite terranes (Touret, 1979; Eglinger et al., 2014). These fluids are inherited from surface fluids, preserved during prograde metamorphism in mineral microcavities or along mineral intergrain boundaries. They can, however, hardly explain the large amount of fluids present at peak metamorphic conditions that is necessary to explain effects at a regional scale. Moreover, saline fluids derived from meta-evaporites are Ca-rich (Eglinger et al., 2014) whereas Na is the dominant dissolved ion in brine inclusions found in granulites. Brines in granulites are not restricted to specific lithologies. We, therefore, believe that neither CO_2 nor hypersaline brines can be entirely generated within the lower crust. Virtually all mantle rocks or minerals found in xenoliths, the best source of information of the deepest samples found at the Earth's surface, contain high-density CO_2 inclusions and have been affected by brines (Frezzotti and Touret, 2014). The same fluids (immiscible mixture of high salinity brines and $CO_2 \pm CH_4$ carbonic fluid) are also found in mantle-derived ultramafic complexes of, for example, Stillwater (USA), rapidly brought at the Earth's surface by meteorite impact (Hanley et al., 2008), and the Bushveld Complex (South Africa) (Ballhaus and Stumpfl, 1986). As detailed below, it seems obvious that the majority of brines and CO_2 found in granulites are ultimately derived from the mantle.

6. Continental crust: where and when?

The occurrence of zircons older than 4 Ga (Compston and Pidgeon, 1986; Iizuka et al., 2006) implies the existence of some kind of granitic crust since the early days of our planet. It did most probably occur as isolated spots in an early solidified basaltic crust in a magma ocean. The crustal growth rate, which has been debated for many years (e.g., Hawkesworth et al., 2019), depends on numerous factors, including, amongst others, the nature and physical state of the crust, which was less rigid in the early Earth, and the rate and mechanisms by which the crust is destroyed (subduction in the upper crust, delamination in the lower crust). Hawkesworth and Kemp (2006a) estimated that the residence time of the lower crust is up to six times shorter than that of the upper crust. A recent study (Hawkesworth et al., 2020) indicates a relatively rapid growth in the Archean of a more mafic, less rigid and thinner crust than today, covering ~60% of the surface of present-day crust at ca. 3 Ga. At this time, the crust was rigid enough to initiate plate tectonics including crust formation and destruction very similar to the current plate tectonic processes, i.e. juvenile continental crust is created above ocean-continent subduction zones and subsequently destroyed during continent collision (Palin and Santosh, 2021). The result is a formation of a supercontinent, which is subsequently disrupted in fragments thereby initiating a new cycle of ocean/continent subduction (Cawood and Buchan, 2007). The granulite lower crust is only fully exposed in completely eroded supercontinents (older than ca. 0.5 Ga). The youngest supercontinent (Pangea) shows only mid-crustal granites, together with recycled fragments of former cratons. However, the structure of the Pangea crust can be inferred from xenoliths in recent volcanic rocks (Fig. 3b). Fig. 8 shows that the majority of zircons ages between ca. 3 Ga and ca. 0.5 Ga correspond with the time of formation of the successive supercontinents. In all these supercontinents, the metamorphic structure of the continental crust is identical, i.e. ultrahigh-temperature granulites at the crust-mantle boundary and greenschist facies metamorphic rocks below the thin sedimentary cover. This leads to the conclusion that the formation of the continental crust, or at least the completion of its structure, was accompanied by significant metamorphic events in the core of the successive supercontinents (Brown and Johnson, 2019).

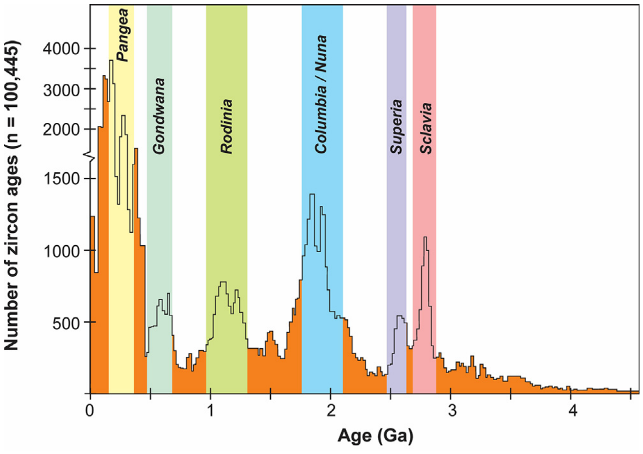

Fig. 8. Distribution of zircon ages in Precambrian supercontinents between 0.5 Ga and 3 Ga (modified after Hawkesworth et al., 2020).

7. Formation of the continental crust: An integrated model

On the basis of the discussion in the previous sections, we propose an integrated model of the formation of the continental crust. An important piece of information could be given by exposed profiles, but continuous crust-mantle sections are exceedingly rare. In order to be brought to the surface, deep rocks undergo extensive alteration and deformation. Major dislocations occur often at the boundary between the mantle and lower crust or between the lower and middle crust. Few profiles reaching the mantle are known in recent orogens, e.g. the Alps (Ivrea Zone) or the Pyrenees (Lherz), but these are of relatively small size and strongly deformed. Transitions between the lower and middle crust are more common, i.e. they occur at a regional scale in a number of Precambrian areas. Southern Norway, which was part of the Rodinia supercontinent, is in this respect a classical area, but so is the Precambrian of southern India. The southern part of India has the advantage that it was part of both Archean and Neoproterozoic supercontinents, i.e. the Archean (ca. 2.6 Ga) Eastern Dharwar

Craton (Fig. 9) in the north, which is intersected in the south by crustal blocks of the much younger (ca. 0.55 Ga) high-grade metamorphic rocks belonging to the Gondwana supercontinent.

In the Eastern Dharwar Craton, south of the "Fermor line" (boundary between granulites to the south and amphibolites to the north as defined by the orthopyroxene isograd, Fig. 9), rocks are dominantly massive charnockites (type locality St. Thomas Mt. Madras, now Chennai; Holland, 1900; Yang et al., 2021). Incipient charnockites (i.e., the local transformation of gneiss into charnockite, e.g., Newton and Tsunogae, 2014) occur at the northern boundary of the massive charnockite, providing much information on the role and mode of the activity of dehydrating fluids (Touret et al., 2019a; Touret et al., 2019b). North of the Fermor line occur amphibolite facies gneisses and associated granites, including the remarkable Closepet granite, a series of intrusions with a length of ~200 km long and few 10's km wide, situated along a major shear zone starting in the granulite domain (Fig. 9). Massive charnockites are dated at ca. 2.5 Ga (Rajesh and Santosh, 2004), the same age as the Closepet granite (concordant zircon age of 2513 ± 5 Ma, Friend and Nutman, 1991).

The geological map of southern India (Fig. 9, modified after Chardon et al., 2008) is in line with the crustal profile shown in Fig. 4b. The Dharwar craton has a complex history (Li et al., 2018), starting in the Early Archean (~3.4 Ga) by a series of microcontinents, comprising the common tonalite-trondjhemite-granite suite in Archean terranes (e.g., Kröner, 1985). These were successively accreted by horizontal subduction, associated to local thickening and high-pressure metamorphism. Final metamorphism, during which the crust-mantle interface was brought to ultrahigh-temperature granulite temperature (>1000 °C) occurred in the completely accreted supercontinent, when the crust was restored to its normal thickness (35–40 km). Continental collision is a relatively cold process, causing much lower metamorphic gradients than those of ultrahigh-temperature granulites. The ultrahigh temperature is, therefore, best explained by the stacking of mantle-derived magmas at the crust-mantle interface, as observed in most examples of mafic granulite lower crust (Fig. 4).

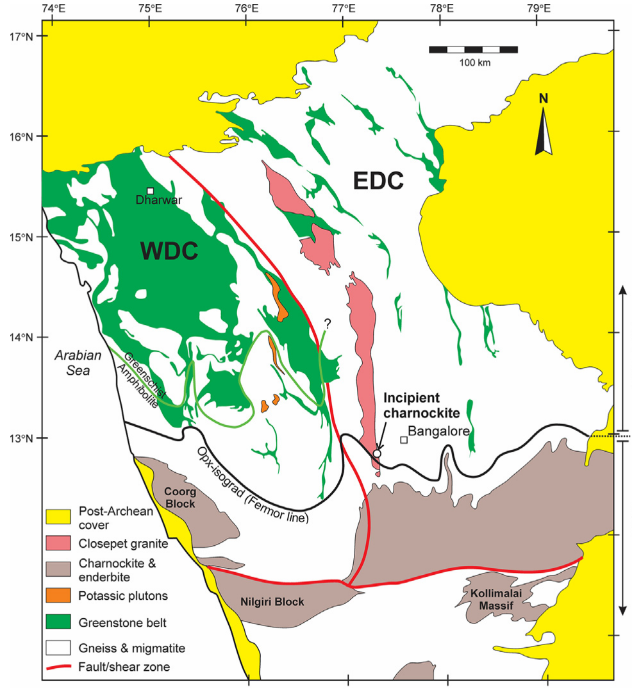

Fig. 9. Geological map of the Dharwar craton (modified after Chardon et al., 2008). MC-UC: middle crust-upper crust; LC1: upper part of the lower crust (see also Fig. 4b); EDC: Eastern Dharwar craton; WDC: Western Dharwar craton; Opx: orthopyroxene. See text for further discussion.

For reasons discussed above, the scarcity of H_2O-bearing minerals prohibits the formation of massive charnockite by dehydration melting. However, some granites can be formed by dehydration melting of biotite and, especially, muscovite-bearing schists in the middle crust, at the onset of the formation of granitic migmatites (Fig. 4b). This is especially true in younger cratons, observed notably in southern Indian Gondwana terranes. The change in atmospheric composition after the apparition of free oxygen (2.3–2.0 Ga, Lyons et al., 2014) led to drastic changes in alteration-sedimentation and the formation of sedimentary rocks with much higher mica content than the igneous tonalite-trondjhemite-granite derivates. But in Eastern Dharwar Craton, fluid inclusion data led us to propose another mechanism, namely melting induced by the streaming of mantle-derived fluids (high-density CO_2 and brines). The different evolutionary steps include the following (Fig. 10, Touret and Huizenga, 2020): (i) Accretion of the supercontinent by a mobile belt connecting two colliding cratonic fragments. (ii) Charnockite and granite melting by fluid streaming. Lower crustal fluids are focused along shear zones to reach the middle and upper crust, to induce the formation of granites (e.g., Closepet type). Melting is initiated by brines and the final mineral assemblage is determined by the availability of CO_2. In the lower crust, CO_2 remains in the magma until final crystallization (i.e., charnockite). In the upper crust, the pressure is lower and CO_2 is expelled at the onset of crystallization and subsequently concentrated in lateral veins or segregation. The final product is a granite. (iii) Elimination of lower crustal fluids at the end of the metamorphic episodes along shear zones, either in a reduced (graphite veins) or oxidised (quartz-carbonate) environment. (iv) Melts, which were instrumental to produce the mantle fluids, may remain at great depth for millions of years. They may produce alkaline intrusions or carbonatites in a stabilized craton.

8. Fluid regime during the final equilibration of the continental crust: A synthesis

In all cases of the granite formation, either by dehydration melting (I in Fig. 11) or by brine streaming (II in Fig. 11), the role of fluids is of utmost importance. In the case of dehydration melting, fluids are internally generated. The breakdown of volatile-bearing minerals (mainly micas for H_2O, carbonates for CO_2), liberates H_2O and CO_2, which are incorporated into the magma. The solubility of H_2O in granite magmas exceeds that of CO_2 by an order of magnitude. CO_2 is released from the saturated melt, whereas H_2O remains in the melt until the final stage of magma crystallization (G2 in Fig. 11). It may incorporate the elements, which have not entered any mineral structure, being mostly expelled as concentrated solutions (brines) in the end product of granite crystallization (pegmatites). Large volumes of water are transported towards the surface in shallow intrusives. Near the surface, magmatic fluids are mixed with surface fluids (mainly sea water), with extensive circulation and unmixing (boiling). Most typical in this respect are Cu-porphyry intrusions, (G1 in Fig. 11), which are major hosts of ore deposits (Cu, Au).

However, the scenario is different for charnockites and granites (G3 in Fig. 11), which are related to fluid streaming (II in Fig. 11). This model requires that large quantities of fluids (high density CO_2 and highly saline brines) are stored in the lower crust at peak metamorphic conditions, especially in domains of ultrahigh temperature granulites, which act as a fluid reservoir. Some fluids, especially brines, may be locally derived. Metasedimentary rocks are rather common in many granulite terranes and a number of minerals (Cl-scapolite, anhydrite) indicate some interaction with

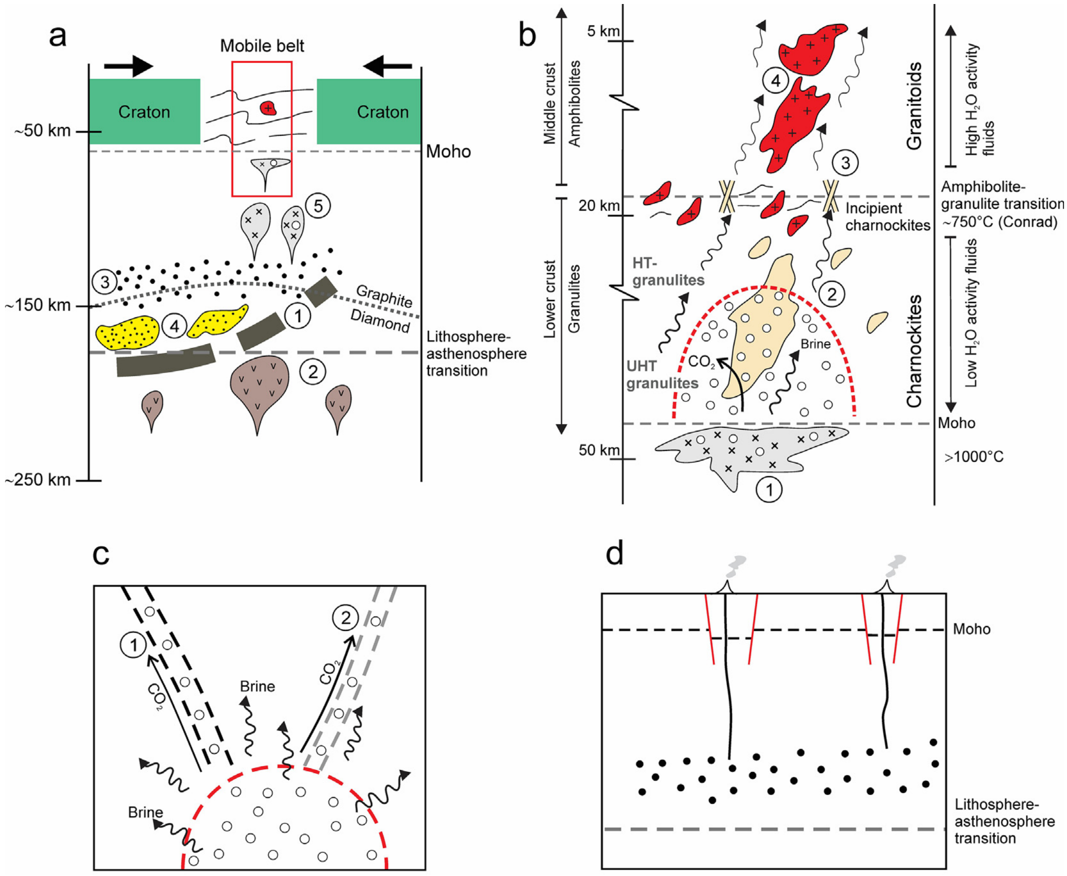

Fig. 10. Model of crust formation during amalgamation/breaking down of supercontinent (modified after Touret and Huizenga, 2020). (a) Supercontinent amalgamation by a mobile belt suturing two cratonic fragments. 1: subducted oceanic crust; 2: deep mantle plumes; 3: metasomatised mantel; 4: restite from melted subducted crust (garnet-bearing eclogites and lherzolite); 5: carbonatite and basaltic melts. (b) Fluid streaming at peak metamorphic conditions. 1: Fluid mantle source. 2: CO_2 (open circles) and brines (arrows) in the lower crust, 3: Incipient charnockites, 4: Granite formed by brine streaming in the middle crust (Closepet type). The dashed red line indicates the accumulation of CO_2 in the ultrahigh temperature granulite domain. (c) Elimination of lower crustal fluids along shear-zones from ultrahigh temperature granulites at the end of the metamorphic episode 1: Graphite veins (reduced environment), 2: Quartz-carbonate shear zones (oxidised environment). (d) Alkaline and carbonatite intrusions and extrusions into the stabilized craton. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

brines at the time of their formation. Brine fluid inclusions are very common in these rocks and have been interpreted as remnants of surface fluids which were not erased despite the substantial increase of pressure and temperature (Touret and Huizenga, 2011). However, it is very unlikely that the amount of brine generated in this way would be sufficient to explain the regional extent of brine streaming. For CO_2, the problem is less complicated: carbonate minerals are rare in Archean tonalite-trondhjemite-grano diorite rocks but more abundant in rocks in terranes belonging to more recent supercontinents (notably Gondwana). But the similarities between the evolution of the different supercontinents show that the contribution of sedimentary carbonates is minimal at best. Moreover, as mentioned earlier, geochemical tracers ($\delta^{13}C$, $^3He/^4He$) show that CO_2 in the lower crust is essentially derived from the mantle ((Hoefs and Touret, 1975; Matthews et al., 1987; Dunai and Touret, 1993).

Mantle fluids are introduced into the lower crust at peak metamorphic conditions, together with the stacking of mafic intrusions at the crust-mantle interface which was responsible for the extreme temperature reached during ultrahigh temperature granulite metamorphism (Fig. 11). Interesting in this respect is the fact that some high-density CO_2 fluid inclusions in ultrahigh temperature granulites contain primary carbonate (Bolder-Schrijver et al., 2000), suggesting that CO_2 was not introduced as a pure fluid, but as a heterogeneous mixture of CO_2 and microcarbonate crystals. Brine fluid inclusions in these ultrahigh temperature granulites are separated from CO_2 fluid inclusions but typically occur within the same quartz grain, suggesting fluid–fluid unmixing. More research is required to identify the earliest inclusions, but it is likely that the fluid was introduced as homogeneous mixture of CO_2 and salts and, possibly, traces of carbonate melts and subsequently unmixed into a high-density CO_2 and a brine fluid.

Both fluids will move according to their respective migrating properties related to their wetting angle (e.g., Watson and Brennan, 1987). The wetting angle of CO_2 is great, i.e. CO_2 does not move easily along intergrain boundaries. However, the often quoted impossibility of intergrain-boundary movement of CO_2 may not be entirely correct. For example, in a number of mafic intrusions, magmatic feldspars are characterized by a solid inclusion (oxide phases)-rich core and a solid inclusion free metamorphic feldspar rim. CO_2 fluid inclusions are found exclusively in the recrystallized feldspar rim, indicating a distinct possibility of CO_2 migration during feldspar recrystallization (Touret and Nijland, 2013). The great amount of secondary CO_2 fluid inclusion trails found in all granulites indicate that the main mechanism of CO_2 migration is through microfracturing. After the enrichment of ultrahigh temperature reservoirs at peak temperature (>1000 °C), this mechanism allows CO_2 to be present everywhere in the lower crust at decreasing temperature (to ~800 °C), controlling the crystallization of the anhydrous granulite mineral assemblages.

Conversely, the wetting angle of a brine fluid is much smaller than for CO_2, i.e. brines can easily migrate along intergrain

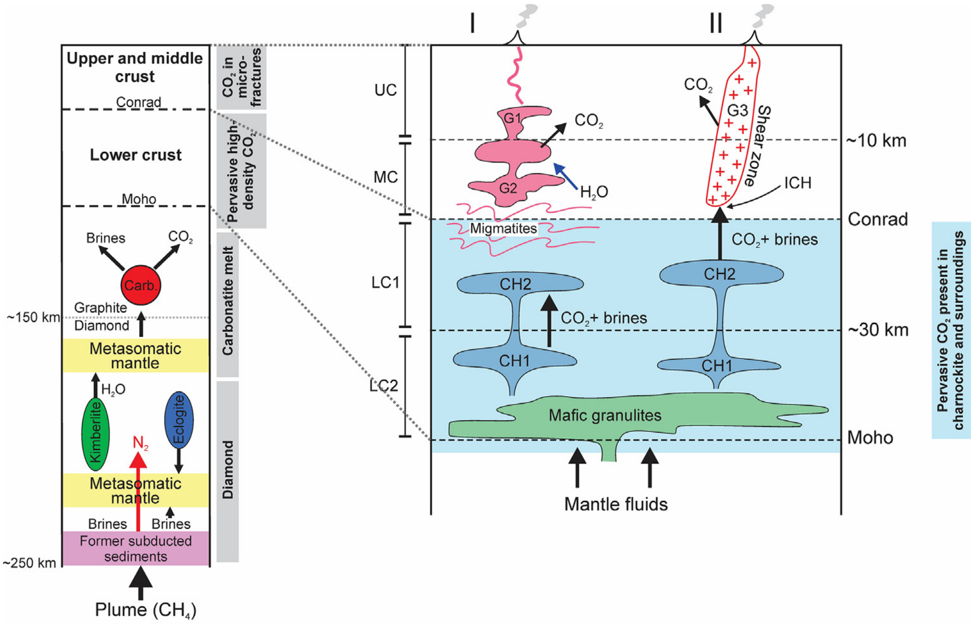

Fig. 11. Fluid/melt in the continental crust and underlying mantle during high-grade metamorphism (modified after Touret, 2021). See text for further explanation. Carb. = carbonatite, UC = upper crust, MC = middle crust, LC1: upper part of the lower crust (high-temperature granulites), LC2: bottom part of the lower crust. G1 and G2 represent shallow- and mid-crustal granites, respectively, produced by dehydration melting, G3 represents granite produced by brine streaming (e.g., Closepet granite, India), ICH = incipient charnockites, CH1: ultrahigh-temperature charnockites, CH2: high-temperature charnockites.

boundaries (Watson and Brenan, 1987), where they leave traces in the form of myrmekites or microveins. Focussed along shear zones, the brines may reach the middle crust, where they initiate granite melting after having been responsible for charnockite melting in the lower crust (Aranovich et al., 2013).

8.1. Mantle plume fluids

The model presented above requires that a mantle plume contains not only melts, but also abundant and a great variety of fluids. Fortunately, the fluid regime in mantle plume (Fig. 11) is fairly well known, based on two complementary approaches: (i) the study of mantle xenoliths brought to the surface by relatively shallow (basalts) and deep (kimberlite) extrusives; and (ii) modelling carbon–oxygen-hydrogen fluid compositions at appropriate pressure, temperature, and redox conditions (Huizenga, 2001; Simakov, 2003, Stagno and Fei, 2020). The oxygen fugacity, following the trend of redox mineral buffers appropriate for the continental crust (e.g., fayalite-magnetite-quartz), shows a progressive change towards more reducing conditions. With regard to carbon-bearing fluid species, the fluid composition transitions from CO_2 under the Moho discontinuity to reduced hydrocarbons (CH_4) at greater depth (Simakov, 2003). CO_2 is stable under the Moho discontinuity in the domain where basaltic melts are generated by mantle melting (~100 km deep), to be replaced by more reduced species (CH_4) at depths >200 km (Simakov and Stegnitskyi, 2021). Between these two extremes, a most important zone between 150 km and 200 km contains aqueous fluids derived from the reaction $CO_2 + CH_4 \rightarrow 2\ H_2O + 2\ C_{solid}$ (e.g., Luth and Stachel, 2014), in which solid carbon can be either diamond (depth $> \sim150$ km) or graphite (depth $< \sim150$ km).

Deep mantle-fluids are found in diamonds, either in inclusions (Weiss et al., 2015) or as volatiles included in the mineral structure. Interestingly, these volatiles are dominated by N_2 and accompanied by various hydrocarbons (Sobolev et al., 2019). Fluids in inclusions (notably in cloudy diamonds, the cloudiness is caused by myriads of micro-inclusions) are brines, with average mass proportions of 30%–42% water, 19%–22% chlorine, 14%–17% sodium and potassium, 22%–25% Fe-Ca-Mg-carbonates and 3%–4% silica (Izraeli et al., 2001). These data, especially the association of carbon, nitrogen and salt, indicate that diamonds originate ultimately from subducted supracrustal material (ancient oceanic crust). They can stay in the mantle for millions of years, before being eventually brought to the surface by dramatic kimberlite eruptions in the stabilized crust. Diamonds are transported to the surface either in ultrabasic xenoliths or in crustal eclogites, which represent remnants of oceanic crust that was exposed to (ultra) high pressure during collisional orogenesis (Frezzotti, 2019).

The large amount of H_2O-bearing minerals in kimberlites confirms the hydrous character of kimberlite magmas (Mitchell et al., 2019). Kimberlite melts, rich in alkali chlorides and carbonates, are a potent metasomatic agent in the mantle (Kamenetsky et al., 2004). When interacting with metasomatic mantle outside of the diamond stability zone (depth <120 km), they generate carbonatite melts, which can also reach the surface in later volcanic eruptions (Guzmics et al., 2012). The carbon in the carbonatites is entirely contained in solid carbonate phases and not in a fluid phase. Fluid/melt inclusions show extensive immiscibility phenomena (Hurai et al., 2011). Walter et al. (2020) have found that in the Kaiserstuhl carbonatites, carbonatite melts exsolve primarily multicomponent high salinity fluids (Na-K-sulphate-carbonate/bicarbonate-chloride brines) of which some contain a high CO_2 content. Several Russian papers describe similar fluids, e.g. in REE-bearing siderite carbonatites from Siberia (e.g., Prokopyev et al., 2016). Melt inclusions in quartz or fluorite contain a homogeneous CO_2-high-salinity brine fluid, which is comparable to the fluids found in crustal ultrahigh temperature granulites/charnockites (e.g., Bakhuis complex in Suriname, Touret et al., 2016).

Primary carbonates in carbonatites do not survive in the mantle at the depth at which mantle melting give basalts. Primary carbonates in mantle xenoliths in basalts are rare (Ionov et al., 1996), the vast majority contain only CO_2 fluid inclusions, with the possibility of some "hidden" H_2O either leaked, or still invisibly present along the walls of the fluid inclusion cavity (Frezzotti and Touret, 2014). The possible occurrence of brines is not indicated by fluid inclusions, but by the high Cl-content of some minerals, including amphibole and apatite. Carbonatite melts decompose into CO_2 when raising slowly in the mantle at a depth lower than ~100 km, either completely, or partly, resulting in a mixture of CO_2 and fragments of carbonates. Brines, mostly hidden at mineral interfaces or included in accessory minerals (notably apatite), are also systematically present.

These fluids, especially CO_2, are present in xenoliths transported by basaltic melts, which appear to be CO_2-saturated. Their amount is not trivial and reflect an important contribution to the dynamics of the volcanic eruptions. They represent an adequate source for the voluminous quantities of fluids injected into the lower crust during granulite metamorphism. Volatile fluxes from the mantle in the granulite lower crust has occurred throughout the Earth's history, especially at the end of the Archean (Marty et al., 2019).

9. Conclusions

In the stabilized crust of Precambrian cratons, surface fluids do not infiltrate to a depth exceeding a few kilometres. But the continental crust can be traversed by mantle-derived fluids and magmas. It can also be modified and laterally accreted above oceanic subduction zones. However, the andesitic crust created by this mechanism does not reflect the average crust composition in stabilized cratons. The majority of the crust found in the Earth's continents has acquired its final structure and composition during world-scale episodes of high-temperature metamorphism which have occurred in successive supercontinents, at least between the end of the Archean (2.5 Ga) to the Late Neoproterozoic (0.55 Ga). These episodes have occurred at the end of the supercontinent amalgamation, shortly before its disruption. Basic magma stacking at the crust-mantle interface resulted in extreme temperature at the base of the crust (>1000 °C), resulting in ultrahigh temperature granulite metamorphism in the base of the crust. At this time, the lower crust was invaded by a mantle fluids, dense CO_2 and high-salinity aqueous brines, which were not only instrumental for the stability of metamorphic mineral assemblages but also induced the formation of various granitic melts, i.e. charnockites in the lower crust and granites in the middle and upper crust (Aranovich et al., 2013). It cannot be excluded that the irruption of these fluids has caused instability in the lower crust thereby initiating the disruption of the supercontinent shortly after its amalgamation (Touret and Huizenga, 2012).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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J.L.R. (Jacques) Touret received the title of Geological Engineer at the Nancy High School of Geology (ENSG, France) in 1958 and a PhD at the Nancy University in 1969. He was Professor of Petrology at the Universities of Nancy and Paris, and at the Free University Amsterdam in the Netherlands. He is member of Academia Europea and the Royal Dutch and Norwegian Academies of Science and Letters. Since his retirement, he has a guest research volunteer position at the Ecole des Mines and Sorbonne University (Paris). His main research fields include fluid-mineral interaction in high grade metamorphic and magmatic complexes, notably through the study of fluid and melt inclusions, and, in recent years, the history of geology within the framework of the national (COFRHIGEO) and international (INHIGEO) committees.

M. Santosh is Professor at the China University of Geosciences Beijing, Specially Appointed Foreign Expert of China, Professor at the University of Adelaide (Australia), and Emeritus Professor at the Faculty of Science, Kochi University (Japan). PhD (Cochin University of Science and Technology, India), D.Sc. (Osaka City University, Japan) and D.Sc. (University of Pretoria, South Africa). He is the Founding Editor of *Gondwana Research* as well as the founding Secretary General of the International Association for Gondwana Research. He is also the Editorial Advisor of *Geoscience Frontiers* and *Geosystems and Geoenvironment*. His research fields include petrology, fluid inclusions, geochemistry, geochronology, metallogeny, supercontinent tectonics, and life evolution in the Early Earth. He has published over 1300 research papers, edited several memoir volumes and journal special issues, and is co-author of the book 'Continents and Supercontinents' (Oxford University Press, 2004). He is the recipient of the National Mineral Award, Outstanding Geologist Award, Thomson Reuters 2012 Research Front Award, and the Thomson Reuters/Clarivate High Cited Researcher Award during the last eight years.

Jan Marten Huizenga is an Associate Professor at the Norwegian University of Life Sciences (since 2021). He obtained his PhD degree from the Free University in Amsterdam in 1995 under supervision of Jacques Touret. He has worked in South Africa at the University of Johannesburg and North-West University, and in Australia (James Cook University, Townsville). His research interests include, amongst others, the role of fluids in crustal rocks focussing on lower crustal granulites, fluid inclusions, hydrothermal ore deposits, and the thermodynamic modelling of carbon-oxygen-hydrogen fluid systems.