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Fluid regime during the formation of continental crust

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Many studies have been devoted to the study of oceanic crust, much less on its continental equivalent. It has been known for a long time that the average composition of the continents is approximately granitic, with however a marked difference between a granitic Upper/Middle crust, also including metamorphic rocks of low-to medium grade (up to amphibolite facies), and a granulite Lower crust, which tends to be more basic (metagabbros) at the crust-mantle interface. Both units are separated by a weak geophysical discontinuity (Conrad), less continuous and obvious than the Moho at the lower limit of the crust. Granite formation in the Upper/Middle crust is believed to occur mainly by dehydration melting, breakdown of H2O-bearing minerals (mainly muscovite and other micas) and melting under the influence of liberated H2O. Since the Archean, this process is initiated by subduction: « Hydrous mantle-derived basaltic magmas intrude the base of the crust where they remelt underplated rocks and evolve in granitic magmas » (Arndt, 2013). At the scale of the Earth, metamorphic/magmatic ages in cratons (about 80% of the exposed Earth surface) cluster around few values which correspond to the amalgamation and rapid disruption of supercontinents (approximate ages in Ga) : Pangea (0.3), Gondwana (0.6), Rodinia(1), Columbia (1.5), Neoarchean supercontinent at the limit Archean/Proterozoic, etc. Even if it is clear that subduction processes have played a role in the formation of these supercontinents, their size and disposal at the scale of the Earth is hardly compatible with subduction alone. Alternative is intraplate metamorphism/melting under the influence of a series of rising plumes, generated by accelerated mantle convection. Crustal melting is only possible in presence of an adequate, H2O-rich fluid phase. This can happen in the Upper/Middle crust by dehydration melting, but then the produced water is subtracted from the environment, dissolved in the granite magma, and brought back to the surface in rising granite intrusions. Such a mechanism cannot be operative in the lower crust, which lacks the H2O-bearing mineral phases able to initiate dehydration melting. Hence comes the

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idea of a « restitic » lower crust, a residual left after the loss of granitic component. But this idea is not compatible with a number of observed features, such as the preservation of almost intact metasediments or, above all, the widespread occurrence in the lower crust of « dry » granitoids (charnockites), besides the scarcity of H2O-bearing minerals (orthopyroxene or garnet instead of biotite) strict equivalents of mid-crustal granites. (See e.g. discussion in Touret, J.L.R., Huizenga, J.M. , 2020). I would argue in this note that the study of fluid remnants preserved in mineral inclusions (fluid inclusions) supports an alternative model, namely lower crustal melting under the influence of mantle-derived fluids of low water activity (Newton et al., 2019). Such a model raises two major questions : 1)The composition and origin of these fluids and 2) What is their mode of action.

Composition and origin of « deep » fluids

The fluid distribution in the continent and underlying mantle above a rising plume is illustrated in this figure, based on fluid inclusion studies. This mode of formation of the continental crust may be intra-cratonic, in most cases related to the disruption and amalgamation of supercontinents (Touret et al., 2016). The orther way to create continental crust is by lateral accretion above subduction zones. The major difference is then that UHT-temperature are not reached, but otherwise major results remain comparable to those of the present model.

Upper Mantle :

Deepest mineral samples reaching the Earth's surface are diamonds, most of them produced at a depth between 150 and 250 km. The plume itself may carry reduced gazes (CH4, e.g. Simakov, 2003). When it meets the trace of a former subduction zone, melting of the former sediments generate fluids ultimately inherited from the surface, first of all N2 (major gaz found in diamond) and brines (Förster et al., 2019). Other fluids are complicated hydrocarbons (Sobolev et al., 2019) generated during the partial oxydation of CH4 to form diamond. Low salinity aqueous fluids provoke mantle metasomatism and melting, leaving a residual of garnet harzburgite. The result of mantle melting is hydrous melts (kimberlite), which can carry large quantity of NaCl (Kamenetsky et al., 2007), but of debated origin (possible contamination during eruption, Grishina et al., 2014). Other rock samples at this depth are asthenospheric eclogites buried during collision orogen, containing diamond and carbonate in garnet inclusions (Frezzotti , 2019).

Carbonatites result from mantle melting in the graphite field, at a depth of 100-150 km. Inclusions are mainly melts, complicated by extensive phenomena of magmatic immiscibility.

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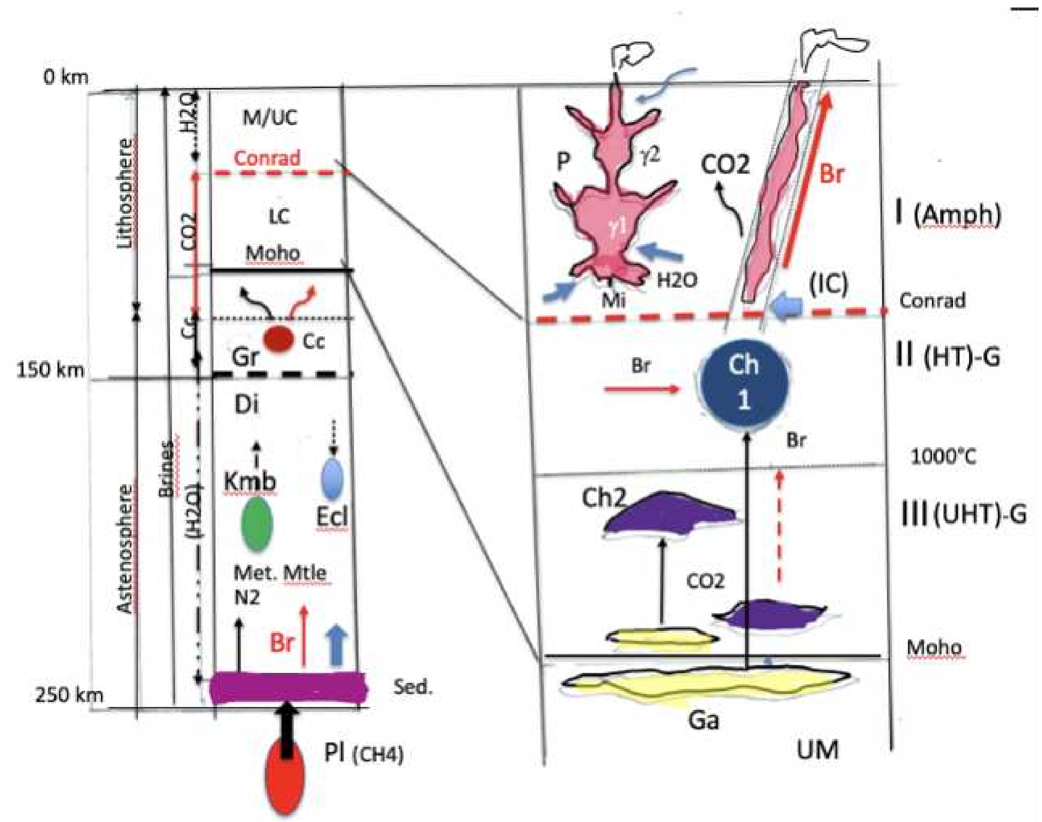

Formation of the continental crust (based on fluid inclusion studies). Left : Section mantle-crust. Pl = Plume, Br= Brines, Met. Mtle = Metasomatic mantle, Kmb= Kimberlite, Ecl= Eclogite, Di= Diamond, Gr= Graphite, Cc= Carbonatite, LC = Lower Crust, M/UC= Middle/Upper crust Right : Detail of the continental crust, divided in 3 layers. From top to bottom, I (Amph)(Upper/Middle crust, Greenschist to Amphibolite metamorphic facies) : II and III : Granulite Lower crust, II (HT) = High temperature , III (UHT) : Ultrahigh temperature, T> 1000°C. Ga = Gabbros, Ch 1 and 2 : HT- and UHT- massive charnockites, respectively, IC = Incipient charnockites. Granite intrusions in the Upper/Middle crust. Left : granites formed by dehydration melting : 1 = Mid crustal batholiths, P = Pegmatites, Mi = Migmatites, Shallow intrusieves (Cu-porphyries). Right : Granites generated by brine streaming (Closepet type) (*) In complement with this diagram, a short, but representative selection of fluid inclusions in various rock settings can be found on my homepage : (http://www.annales.org/archives/x/touret-.html).

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A great variety of inclusions include carbonate and brine components (Guzmics et al. 2011), together with hydrous alumino-silicate glasses, intermediate between a melt and hydrous solution (Hurai et al, 2011). Aqueous silicic melts are also found in lithospheric eclogites (Ferrando et al., 2005), possibly another cause of broad mantle metasomatism.

Carbonatite melts destabilise at a depth of approximately 75 km, in the domain of spinel (eventually plagioclase) lherzolite. Then all rock-types produced at this level, either undisturbed mantle (lherzolite), melting products (gabbros) or restites (spinel harzburgites) contain abundant CO2 inclusions. CO2 density at this level is more than 1.1 g/cm3, higher than liquid water. Brine inclusions as a rule do not survive uplift, but their possible occurrence is indicated by the Cl-content of some minerals (e.g. amphibole or apatite).

Continental Crust

Mantle fluids (high density CO2 and highly saline brines) accumulate as immiscible fluids at the base of the crust in UHT (UltraHigh Temperature, T > 1000°C) domains (Touret & Huizenga, 2020) (III, Fig.). Then each fluid can eventually mix with locally-derived equivalent (especially brines, which can be derived from former sediment pore fluids or evaporites) and migrate according to its physical properties (wetting angle). Relatively immobile CO2 remains in the upper part of the lower crust, where it cares for the stability of H2O-absent mineral assemblages (pyroxene and/or garnet) (II, Fig.). Much more mobile brines circulate easily along intergrain boundaries. They are concentrated along shear zones, able to reach the Middle/Upper crust and, eventually, the surface of the Earth. They are found in granites occurring along these shear zones (g in I, Fig.). These contain the same type of brine inclusions than those found in charnockites, with however an important difference : because of the lower pressure, CO2 is expelled out of the magma at the onset of crystallization, to concentrate in lateral veins or segregations.

Other granites are formed in the Middle /Upper crust by dehydration melting, either large-size batholiths (g1, Fig.) or, closer to the surface, shallow intrusives (Cu-porphyries = g2, Fig.). Inclusions in these rocks are dominantly aqueous, rare CO2 inclusions can eventually be due to local incoming of lower crustal fluids. High salinity brines are extremely common, especially during the late stage of magma crystallization (pegmatites). In shallow intrusives, brine inclusions are also formed by fluid immiscibility (boiling), when magmatic fluids mix with surface water infiltrating from the surface.

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Mode of action of CO2 and brine fluids

The mode of action of both fluids, CO2 and brines is well illustrated by the « incipient charnockites » which, in the typical section of Southern India, occur precisely at the limit between massive charnockites and crustal granite (Closepet) (Touret et al., 2019). Some incipient charnockites occur along a network of fractures (clearly indicating a metasomatic transformation of the gneiss), other in patches which suggest local melting (Perchuk et al., 2000). Brine and CO2 inclusions are present in both cases, but their mode of action is clearly different : CO2 fluids have a very limited capacity of transport element. They do not take any part in metasomatic processes, but they are instrumental for the stability of granulite and charnockite. Anhydrous mineral assemblage (especially orthopyroxene). Element transport capacity of brines on the other hand, is extremely high. They are able to promote extensive feldspathisation phenomena in the lower crust, change overall rock composition and, when minimum melting composition have been reached, induce melting. Brines increase significantly minimum melting temperature, by at least 100-150°C compared to low salinity aqueous fluids (Newton, 2020). These high temperatures, in line with the extreme temperatures found in UHT-rocks, are a strong argument for estimating that the initial cause of crustal heating is a raising plume.In the granites of the middle crust, brine fluids occur only at the final stage of crystallization, they do not influence crustal melting. They are the transport media of rare elements (mainly ores), present in the whole intrusion (ore-bearing granites, Cu-porphyries) as well as in the late crystallization products (pegmatites, hydrothermal ore-bearing veins).

Conclusion

The present model of charnockite-granite forming by streaming of mantle-derived fluids (Newton et al., 2019) is an alternative to the classical view that granites result from fluid-absent partial melrting in the lower crust. This model is clearly based on the crustal profile in Southern India, which has some unique characteristics in the course of the Earth's history, e.g. oldest K-feldspar granite (Closepet) and coincidence in time (ca 2.5 Ga) with the Great Oxydation Event in the atmosphere (apparition of free oxygen). It is not clear if both event are interrelated, but in any case later conditions of superficial alteration and initiation of metamorphic cycles have drastically changed. This might be the reason why granulite facies metamorphism has decreased in scale since the late Archean, but many of its definitive features have persisted (Newton, 2020). It must also be noted that the model defended in this short paper is based on fluid inclusion data, which for some reason have been questioned by some petrologists since the beginning of microscope studies in the middle of the 19th century. But a lot of work has

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been done, these times are now over. Fluids did exist in deep rocks when they were subjected to extreme temperatures, a major condition to create new continental crust.

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