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Perspective

Ultrahigh-temperature granitoids in southern India: fuelling the fluid debate about the lower continental crust

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The discovery of CO_2-rich inclusions in granulites has led to the notion of 'carbonic metamorphism', incidentally published for the first time in the *Comptes rendus de l'Académie des sciences* in 1970 [7]. It has initiated a debate about the fluid regime in the lower crust, 'fluid-absent' versus 'CO_2-flooded', which, after 35 years, is still very active among metamorphic petrologists. Fluid inclusions in rock-forming minerals are many, but small, few microns in size, and extrapolating their data involves evidently a number of problems and uncertainties. Granulites worldwide, provided that they have escaped solid-state recrystallisation ('granulitic textures'), contain a great amount of CO_2-rich inclusions, found also in lower crustal and mantle-derived ultrabasic xenoliths in basalts from recent volcanoes [4]. In both cases, the fluid density of synmetamorphic inclusions matches precisely the P–T conditions of mineral equilibration, demonstrating that a free CO_2-bearing fluid phase has been present at the base of the continental column during peak granulite metamorphic conditions.

But how many fluids? The first model, directly based on fluid inclusion data, led to the idea of a 'carbonic wave' [2], namely that hydrous fluids have been flushed upwards by mantle-derived carbonic fluids. It could not stand the weight of physical evaluation and experimental evidence. CO_2-density in granulite inclusions is relatively high, equalling or even exceeding the density of liquid water (up to about 1.17 $g\,cm^{-3}$), but it remains much too low to migrate spontaneously through the crust. Only magmatic transfer is possible, fluids being firstly dissolved or transported in the melt, secondly released into the surrounding rocks during magma crystallization. A number of arguments supports then a model of discrete stratified fluid-present horizons in the continental crust and the upper mantle [8]: H_2O dominates from the surface until migmatite middle crust, where it dissolves in granitic melts. Then, below this aqueous barrier, CO_2 becomes dominant, transferred from underlying continental mantle into the granulite lower crust by synmetamorphic intrusions, also responsible for the temperature increase that triggers granulite metamorphism. The more recent discovery of highly concentrated aqueous solutions (brines) as another major granulite fluid [9] complicates somewhat the picture, but does not alter its major lines.

Now it must be recognized that the fluid amount involved in this process is by no mean easy to quantify. There is much evidence that the amount of water absorbed by granitic melts is huge, as shown notably by the widespread hydrothermal activity around most granite batholiths. But the amount of CO_2 delivered in the lower crust during granulite metamorphism is much more difficult to estimate. Fluids in inclusions record the intensive properties of the fluid system (composition, density); stable isotopes indicate mainly the fluid source, but none gives an unambiguous answer about fluid quantities present at peak metamorphic conditions.

Important evidence, curiously underestimated in most current textbooks, can directly be seen in the field: many places in southern India or Sri-Lanka show occurrences of 'incipient charnockites' [5], in which

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gneisses of various origin, metatonalites as well as metapelites, have been transformed into massive, igneous charnockites under the influence of fluid streaming. In Madagascar, E. Pili and co-workers [3] have described kilometre-size shear zones, which also have been the site of extensive fluid circulation. The fact that these fluids are able to induce large-scale metasomatic transformations, prior to charnockite melting, or homogenize regional C-isotopes to mantle values shows that the fluid quantities involved must be very large indeed. The spectacular CO_2 inclusions found in southern India granitoids by Santosh and co-workers [6], confirming earlier findings from the northern part of the South-Indian granulite domain (Doddabetta charnockite complex [11]), bring new arguments to the debate. Some plutons still contain about 1% wt CO_2, which because of fluid loss and partial recrystallisation can only represent a fraction of the fluids initially contained in the pluton at the magmatic stage. These granites are so close from regional granulites that there is little doubt that they did originate by granulite melting, illustrating the 'granite–granulite' connection advocated by Clemens [1]. Granulite-facies protoliths were already water-deficient, carbonate-poor or absent, a fact which makes very unlikely that the CO_2-loaded granites were generated by 'vapour-absent' processes. Vapour-absent melting is well seen in migmatites from metapelites, for instance in southern Norway [10]. CO_2 then is either absent (as in most mid-crustal granites), or present in very small amount, only when the original metapelite did contain some organic material in the form of graphite. In this case, only a very small amount of CO_2 is found, always subordinate to H_2O. Moreover, CO_2 is not pure, but mixed with hydrocarbons [10]. A very different situation from southern India, which in this case can only be explained by a massive influx of externally derived CO_2 at the time of granulite melting. Note finally that it is not a coincidence that all these apparently rather exotic occurrences, CO_2-loaded granitoids, incipient charnockites, CO_2-streaming along regional shear zones, occur in neighbouring regions, all belonging to the former Gondwanaland. All these domains did follow similar P–T paths during regional post-metamorphic cooling, corresponding roughly to high-density CO_2 isochores. A happy coincidence, essential for the preservation of synmetamorphic inclusions, but not related to peak conditions. These rocks are indeed exceptional, but only because of their preservation, not formation. In this respect, they can be taken as representatives for the lower continental crust in general, at the time when it has acquired its definitive structure. Many arguments (geophysical measurements, xenoliths in recent volcanoes) support the hypothesis of a granulite lower crust at the base of all continents, a fact that authorizes to extrapolate the conclusions derived from these remarkable Gondwana rocks to the scale of the entire Earth.

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