

Accepted Manuscript

Fluids, Melting, Granulites and Granites: A Controversy Reply to the Commentary of J. D. Clemens, I. S. Buick and G. Stevens

L.Y. Aranovich, A.M. Makhluף, C.E. Manning, R.C. Newton, J.L.R. Touret

PII: S0301-9268(16)30042-0

DOI: <http://dx.doi.org/10.1016/j.precamres.2016.03.020>

Reference: PRECAM 4480

To appear in: *Precambrian Research*



Please cite this article as: L.Y. Aranovich, A.M. Makhluף, C.E. Manning, R.C. Newton, J.L.R. Touret, Fluids, Melting, Granulites and Granites: A Controversy Reply to the Commentary of J. D. Clemens, I. S. Buick and G. Stevens, *Precambrian Research* (2016), doi: <http://dx.doi.org/10.1016/j.precamres.2016.03.020>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Fluids, Melting, Granulites and Granites: A Controversy**Reply to the Commentary of J. D. Clemens, I. S. Buick and G. Stevens**

L. Y. Aranovich^{a,b}, A. M. Makhlu^c, C. E. Manning^c, R. C. Newton^{c,*}, J. L. R. Touret^d

^a Inst. of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry, Russian Academy of Sciences, Moscow, Russia

^b Dept. of Geology, Univ. of Johannesburg, Johannesburg, South Africa

^c Dept. of Earth, Planetary and Space Sciences, University of California at Los Angeles, Los Angeles CA, USA

^d Inst. de Mineralogie, de Physique des Materiaux, et de Cosmochemie (IMPMC) Sorbonne Univs., UPMC Univ. Paris 06, UMR-CNRS 7590, Museum National D'Histoire Naturelle, IRD UMR 206, 4 Place Jussieu, F-75005 Paris, France

*Corresponding author, Tel.: +1 3102062917 E-mail: rnewton@g.ucla.edu

The commentary of Clemens, Buick and Stevens on our papers Aranovich et al (“Dehydration Melting and the Relation Between Granites and Granulites”, *Precambrian Research* 253, 26-37, 2014) and Newton et al (“Fluids and H₂O Activity at the Onset of Granulite Facies Metamorphism”, *Precambrian Research* 253, 17-25, 2014) contains many interesting arguments and is a useful contribution in helping to formulate the framework of what we believe to be an important on-going controversy. In question is whether volatile components, especially H₂O, have been commonly infiltrated into sites of deep-seated metamorphism and granitic magma genesis, or whether granitic magmas, and their supposed residues, the granulites, more commonly resulted from fluid-absent

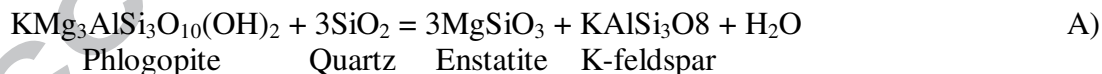
(closed system) melting processes. This is an old debate in petrology, coined by N. L. Bowen nearly a century ago as the “Pontiffs versus the Soaks”, i.e. those who adhere religiously to established dogma (in Bowen’s time restricted to simple low-pressure experimental melting diagrams) versus those who indiscriminately invoke the action of exotic fluids, or “ichors”, for any and all petrogenetic purposes, free from the embarrassing restrictions of any hard data of physical chemistry.

The authors of “Commentary” are quite frank in espousing their fluid-absent point of view. In their “Preamble” they state: “The authors (of our two papers) attempt to show that the view of these processes as dominantly fluid-absent should be re-appraised. We disagree—“. Throughout their paper Clemens et al (2016) reiterate their belief that the bulk of analytical and experimental evidence favors the fluid-absent hypothesis of deep-crustal melting and that granulite facies metamorphism takes place, for the most part, in the absence of active fluids.

We do not agree that our point of view is a re-appraisal of a near-consensus opinion. Over the past two decades many workers have judged that field evidence in various terranes where partial melting is inferred to have taken place, including granulite facies terranes, favors the view that infiltration of exotic volatiles, including H₂O, was active (summarized by Aranovich et al, 2013). Moreover, many workers have amassed evidence that fluids of low H₂O activity were influential in granulite facies metamorphism of the deep crust (summarized by Touret and Nijland, 2013). In succeeding paragraphs we discuss issues raised by Clemens et al (2016) concerning (1) the temperature ranges, H₂O contents, H₂O activities and possible melt yields in deep-crust source regions of granitic magmas, (2) characteristic H₂O activity in granulite facies

metamorphism and partial melting, (3) the reputed possibility of efficient melt extraction, (4) geochemical differentiation of the crust and (5) the significance of fluid inclusions in granulites. Since the separate critiques of our two papers by Clemens et al (2016) have considerable overlap, we deal with their issues jointly.

The recent paper of Collins et al (2016) showed, using large data sets of Ti-in-zircon thermometry of granites and experimental data of zircon saturation temperatures in granitic magmas, that the temperature scale of magma genesis of subduction zone, or I-type, granites should be shifted downward from previous estimates, with necessarily greater H₂O contents of the granitic liquids. Sufficient experimental data are available to address this problem; that is, to estimate the temperatures, H₂O contents and H₂O activities of granitic melts which could coexist with intermediate gneisses at deep-crustal conditions, either by fluid-absent dehydration melting or with additional input of externally-derived H₂O. Figure 1 shows the H₂O activity at liquidus temperatures of an alkali-feldspar-quartz melt from dry melt to saturation with an aqueous fluid at 1.0 GPa, according to Aranovich et al (2013) and Clemens and Vielzeuf (1987). Shown also are the H₂O activity values defined by the model granulite facies assemblage phlogopite-quartz-K-feldspar-enstatite, in equilibrium according to the reaction:



These model granulite facies H₂O activity values are reversed data (Aranovich and Newton, 1998) and should be considered more definitive than the thermodynamic extrapolations from much lower-pressure experimental data of previous studies. Detailed defense of this assertion is given in Aranovich and Newton (1998, p. 195) and Berman et al (2007, p. 146). The two H₂O activity versus temperature trends intersect at 830 °C.

This is the temperature at which a simple granitic liquid could coexist with a model biotite-orthopyroxene (granulite facies) intermediate gneiss. The corresponding H_2O activity is 0.36, corresponding to a H_2O content of the magma of 5.2 wt. %, according to the reversed haplogranite liquidus composition measurements of Makhluf et al (2014), shown in Fig. 2.

Shown also is the temperature range (860-890 °C) over which orthopyroxene and biotite coexist in experimental dehydration melting at 1.0 GPa of a natural tonalite of H_2O content 0.8 wt. % (Rutter and Wyllie, 1988). The corresponding H_2O activities range from 0.22 to 0.32 (Fig. 1) and the H_2O contents range from 4 to 4.8 wt. % (Fig. 2). The difference between the H_2O activity indications in natural and synthetic systems presumably results from neglect of the Fe in natural biotite and orthopyroxene, the Al and Ti in natural granulite facies biotite, and the Na content of alkali feldspar. It is probable that synthetic phlogopite is somewhat less thermally stable than the natural biotite.

The foregoing temperatures, H_2O contents and H_2O activities seem quite plausible for generation of granitic liquids in the deep crust by dehydration melting. Experimental studies on homogenization temperatures of melt inclusions of the Transbaikal (Siberia) anorogenic granites give liquidus temperatures around 875 °C (Litvinovskii et al, 1994). This temperature range is consistent with the estimates of Collins et al (2016) for within-plate (anorogenic) granites and with the H_2O contents of melt inclusions in quartz of granites compiled by Scaillet et al (1996). Most of these values are greater than 4 wt. % H_2O and range as high as 7.5 wt. %. The overall negative correlation of the H_2O contents of Scaillet et al's (1996) melt inclusions with apparent entrapment temperatures was

considered by Clemens and Watkins (2001) to be strong evidence for closed-system melting, but may have other plausible interpretations (Weinberg and Hasalova, 2015a,b).

The main difficulty with the dehydration melting model is the small yields of granitic liquid which could be obtained. Several authors, including ourselves, have expressed doubt that the amount of H₂O resident in biotite and amphibole of intermediate gneisses would be sufficient to produce large amounts of granitic magmas by fluid-absent melting (Rutter and Wyllie, 1988; Johannes and Holtz, 1991; Weinberg and Hasalova, 2015a) unless melting temperatures were generally greater than about 950 °C. The paper by Collins et al (2016) indicates that this condition was not met for the cordilleran batholiths, and rarely for the within-plate alkaline granites. Moreover, most workers would assume that the lower continental crust at the time of generation of the Mesozoic and Tertiary batholiths was already in the granulite facies, so that only about 2/3 of the potential hydrous minerals (the mafic components) were actually in the form of biotite and amphibole, the remainder being pyroxenes and garnet. If so, the maximum yield of granitic liquid having 5 wt. % H₂O would be only around 10 % of the country rock by dehydration melting, even assuming complete dehydration and perfectly efficient extraction, both of which seem dubious. If accumulation of granitic liquid is dominantly vertical, it would seem impossible to explain the great thicknesses of some batholiths such as the Transbaikalian granites, which may be generally 15 km thick, based on seismic soundings (Litvinovskii et al, 1994). If, on the other hand, there is the possibility of influx of externally derived H₂O, there is no theoretical limit on the amount of granitic liquid which could be generated, short of melting of the entire crust. According to Figs. 1 and 2, the lower crust could remain in the granulite facies, with the generation of liquids

of 4-5 wt. % H₂O, in the temperature range 850-900 °C. If there were high rates of H₂O influx, the lower crust might actually rehydrate, with the possibility of generation of liquids at lower temperatures and higher H₂O contents, as suggested for the origin of the cordilleran batholiths by Collins et al (2016).

Most previous workers have made use of the equilibrium of biotite-quartz-K-feldspar-orthopyroxene to define H₂O activity at the beginning of granulite facies metamorphism, since the appearance of orthopyroxene in felsic gneisses is a definitive isograd of progressive metamorphism. The lower P-T limits of the granulite facies are thought to be around 0.5 GPa and 750 °C. Newton et al (2014) showed that earlier estimates of H₂O activity of 0.15-0.30 under these conditions should be revised upward to as high as 0.5, in agreement with the thermodynamic analysis of Perchuk et al (2000) on orthopyroxene-bearing migmatites in Sri Lanka. If SiO₂ activity is lowered, as in anatectic melt, inferred by Perchuk et al (2000) for the Udadigana, Sri Lanka incipient charnockite occurrence, a(H₂O) could be as high as 0.6.

Clemens et al (2016) indicate that this revision of the H₂O activity scale is not novel, but makes use of outmoded data. They cite experiments on the H₂O contents of synthetic cordierite grown at granulite facies conditions (T>700 °C; P 0.4-0.6 GPa; Harley et al, 2002) to indicate that granulite facies a(H₂O) may range anywhere between 0.18 and 0.63. This conclusion seems quite at odds with the conclusion of Clemens and Watkins (2001) that the H₂O content of granitic melts produced by fluid-absent melting in the granulite facies over a small pressure range is narrowly constrained. We do not believe that the cordierite H₂O barometer scale is calibrated well enough to be a definitive

indicator for granulites. The large range of inferred H₂O activities in cordierite granulites found by Harley et al (2002) would seem to point in that direction.

The accusation of Clemens et al (2016) that Newton et al's (2014) revised H₂O activity scale controverts the experimental work of Vielzeuf and Clemens (1992) on the melting of phlogopite plus quartz is unjustified. Newton et al (2014) showed that their revised H₂O activity scale of the assemblage phlogopite-quartz-orthopyroxene-K-feldspar actually satisfies the Vielzeuf and Clemens (1992) experimental points better than does the fit to their experiments preferred by Vielzeuf and Clemens (1992).

Another key aspect of the fluid or no-fluid controversy is whether small amounts of granitic melt, limited to less than 20 % for ordinary biotite-amphibole gneiss source rocks, can be efficiently separated from the host rock and collected at upper crustal levels to form granite batholiths. The paper of Sawyer (1994) was gratefully hailed as a solution to the extraction problems posed by the high viscosity and low relative buoyancy of partial melts of quartzofeldspathic rocks of low H₂O content (Wickham, 1987). Qualitative arguments were given by Sawyer (1994) to support the concept that shear deformation during partial melting could aid liberation of small melt fractions, even less than 5%. Sawyer (1999) bolstered his case for separation of low melt fractions citing the common occurrence of interconnected microscopic grain boundary veinlets of feldspars and quartz in granulites, which veinlets he interpreted as frozen grain boundary melts.

Alternative interpretation is, however, possible, as discussed below.

An unresolved problem with small melt extraction is the large amount of quartzofeldspathic leucosome (presumably former melt) shown in some well-documented granulite terranes (Timmermann et al, 2002; Percival, 1991; Morfin et al (2013). These

rocks are all strongly deformed yet managed to hold onto large amounts of melt until temperatures fell below the freezing point. Another point is the non-granitic mineral compositions of supposed thin melt lamellae in some granulites: quartz + K-feldspar in some (Hansen et al, 1995), quartz + plagioclase or quartz only in some (Hartel and Pattison (1996) and two feldspars + quartz in others (Harlov et al (1998)). The suggestion by some authors that these mineralogic variations may be explained by crystallization-fractionation processes operating at the grain boundary level seems dubious. More probable is the interpretation that the (nearly ubiquitous) grain boundary quartz-feldspar veins in granulites are deposits of very penetrative saline solutions of low H₂O activity, as first postulated by Perchuk and Gerya (1992). Yet another problem is that some mobilizates in granulites have the same (tonalitic-trondhjemetic) compositions as the host rock, the presumed residuum. It appears that the physics and chemistry of partial melting in the granulite regime is still too imperfectly understood to appeal to this mechanism as the principal granite (and granulite) forming process.

Another major issue in the granulite debate is whether melt extraction can deplete the large ion lithophile elements (LILE) like Rb and Th, which elements are characteristically low in some, but not all granulites. Clemens et al (2016) argue that these elements must be depleted by extraction of a granitic melt, since these elements will be partitioned at least to some extent into departing liquids. This does not really address the concern voiced by Aranovich et al (2014). They note that biotite in the highest-grade, LILE-depleted granulites of the South India Archean granulite facies terrane is itself depleted in Rb relative to lower-facies biotites. Since biotite strongly prefers Rb relative to a granitic melt, Hansen et al (2002) show that the granulite residuum would not be

markedly depleted in Rb unless very large melt fractions (>40%) were removed. This is very unlikely to have been realized in the South India high grade tonalitic gneisses, whose bulk chemistry is not much different than lower grade gneisses in the same terrane (Hansen and Harlov, 2007). In view of the low melt solubilities of the U and Th carrier minerals monazite and zircon, Clemens et al (2016) appeal to selective entrainment of accessory minerals in rising magmas as a means of depleting the radioactive elements.

Clemens et al (2016) express the opinion that the CO₂-rich fluids characteristically found included in minerals of granulite facies rocks merely represent the residues of ambient pore fluids from which most of the H₂O has been dissolved into departing partial melts. This trivial interpretation of the often high CO₂ contents in granulite minerals, notably garnet (up to one wt %: Srikantappa et al, 1992; Touret and Hansteen, 1988) is disputed by several studies showing that carbon isotopes in granulite facies minerals have a pronounced mantle-origin signature (fluid inclusions in quartz: Jackson et al, 1988; cordierite: Armbruster et al, 1982; scapolite: Blattner, 1976). Dunai and Touret (1993) found that He isotopes from synmetamorphic CO₂-rich fluid inclusions in deep-crustal garnet granulites from southern India contain He isotopes that can only be explained if the fluids are mantle-derived. The concentrated brine fluid inclusions found also in some granulites and migmatite leucosomes (e.g. Fig. 1 in Manning and Aranovich, 2014) are similarly dismissed by Clemens et al (2016) as only residual pore fluids. This interpretation ignores the many reports of elevated Cl (up to 0.8 wt. %) in melt inclusions in minerals of granites (Dolejs and Baker, 2004 and references therein) and the presence of halogen-rich biotite and amphibole in some granulite facies assemblages. Calculations by Zhu et al (1994) and Newton et al (1998) have shown that Cl/(Cl+H₂O) ratios in a

magnesian biotite as low as 0.015 imply a Cl-rich fluid in equilibrium with the granulite facies assemblages.

Clemens et al (2016) state unjustly that the experimental and theoretical physical chemistry of immiscible CO₂ and brines at high temperatures and pressures cited by Newton et al (2014) is not à propos of the granulite problem. We showed that some rocks from the transitional granulite terrane of South India have fluid inclusions in quartz that have compositions, densities and H₂O activities expected of immiscible fluids at the metamorphic P-T conditions, and that the two types of fluids co-occur in the same generations of fluid inclusion trails, showing that they were coevally emplaced. The structural position of these incipient charnockites, on the upper-level fringes of the massive granulites, requires that the fluids must have passed through the radiometrically co-eval granulites below them. Of course, the ultimate origin of the fluids, particularly the brine suite, remains uncertain, but this fact does not justify their dismissal as irrelevant. The more common preservation of the CO₂-rich suite is explainable by the equation of state of CO₂: its isochores are more nearly parallel to the return P-T paths of the granulites from depth than are the isochores of H₂O-rich fluids (Touret, 2001).

The subject of metasomatism by fluid action is relegated by Clemens et al (2016) to a role of “local”, but not regional importance in deep-crustal processes. This point of view is certainly not a currently prevalent one. There are many recent descriptions of regional metasomatic alteration, including in granulite facies terranes (for instance the classical terrane of Russian Lapland : Korikovsky and Aranovich, 2010; 2015). Summaries of regional high grade metasomatism are given by Touret and Huizenga (2011) and Touret and Nijland (2013).

In view of the difficulties and contradictions encountered by the dehydration (closed system) melting hypothesis for the origin of granite batholiths and granulite facies terranes, it seems preferable to suppose, with Collins et al (2016), that H₂O, in amounts larger than could have been present in hydrous minerals of high grade tonalitic gneisses, can be supplied by invading basalts, now thought to contain commonly around four wt. % H₂O for the subduction zone basalts (Plank et al, 2013). Clemens et al (2016) agree that invasion of basaltic magmas into the lower crust is the most probable origin of the high temperatures for partial melting and granulite facies recrystallization. However, Bowen (1928) showed that, to melt significant quantities of country rock, a heat-equivalent amount of basaltic liquid must crystallize to supply the latent heat of melting. The H₂O content of a crystallizing basaltic liquid must re-emerge somewhere and, since the hydrous melting temperatures of intermediate rocks are lower than those of mafic rocks, melting of the lower crust must ensue. This scenario is, in principle, the same as that advocated by Litvinovsky and Podladchikov (1993). These authors argue that there might be attendant metasomatic alteration of crustal rocks, with modification of the partial melts. A high-H₂O-activity fluid phase would not be produced, though some H₂O could be partitioned into fluid phases dominated by anhydrous volatile components from the basalt, as discussed by Manning and Aranovich (2014), or from sedimentary packets in the thermally activated zone. Alternatively, the anhydrous volatiles might be derivatives of sea water and surficial sediments which could migrate downward as deep as 15 km into the crust (Connolly and Podladchikov, 2004).

Clemens et al (2016) seem not to take seriously the current active discussion of the importance of metasomatism in deep-crust/upper mantle processes. We believe, on the

contrary, that this new avenue of investigation will prove to be more fruitful than the older simplistic view of closed-system crustal evolution.

Acknowledgements

The two papers under discussion were an outgrowth of the Limpopo Field Workshop and Symposium organized by Professor Dirk Van Reenen and hosted by the Department of Geology of Johannesburg University in June-July of 2013. We acknowledge many helpful and stimulating discussions with participants of that meeting.

We thank John Clemens, Ian Buick and Gary Stevens for instigating what we hope will be a useful discussion of an important topic in geochemistry.

Figure Captions

Fig. 1 Liquidus (melt-quartz-alkali feldspar) equilibrium H_2O activity at 1.0 GPa. **Open squares:** H_2O activity determined by equilibration of simple granitic melt with (K, Na)Cl solutions of known H_2O activity (Aranovich et al 2013; Aranovich and Newton, 1997). **X-symbols:** Liquidus H_2O concentrations of simple granitic melts measured by Ebadi and Johannes (1991) in CO_2 - H_2O fluids, converted to activity-temperature points by activity-concentration data of Aranovich and Newton (1999). **Dashed Line:** Liquidus H_2O activity-concentration function of a simple granitic liquid shown by Clemens and Vielzeuf (1987), attributed to calculations by H. Nekvasil. The agreement of the latter estimate with the other data is remarkably good, except that we adhere to the revised temperature scale of melting of a dry simple granite of Holtz et al (2001). Shown also are reversed data for the model granulite-forming dehydration reaction of phlogopite + quartz to enstatite + K-feldspar, Expression A, text. The intersection of this trend with the

simple granitic liquid H₂O activity-temperature trend gives the temperature at 1.0 GPa (830 °C) at which a simple granitic melt could form by dehydration melting of phlogopite + quartz, either fluid-absent or by input of additional H₂O of external origin. The **shaded box** is the temperature interval over which biotite and orthopyroxene coexist in the presence of a granitic partial melt of a natural tonalite found by Rutter and Wyllie (1988). The apices of the box give the associated H₂O activity range. The higher temperatures and lower activities indicated for the natural system probably results from greater stability of the Al, Ti biotite than phlogopite.

Fig. 2: Reversed liquidus H₂O contents of simple granitic liquids at 1.0 GPa (Makhluf et al (2014) compared with extrapolation estimates from lower pressures. Our H₂O contents at a given temperature are generally higher than given by other authors, which fact indicates that the yield of granitic liquids by partial melting of an intermediate biotite-amphibole gneiss would be lower than possible with the other liquidus H₂O values shown.

References

Aranovich, L.Y., Makhluf, A.R., Manning, C.E., Newton, R.C., 2014. Dehydration melting and the relationship between granites and granulites. *Precambrian Research* 253, 26-37.

Aranovich, L.Y., Newton, R.C., Manning, C.E., 2013. Brine-assisted anatexis: experimental melting in the system haplogranite–H₂O–NaCl–KCl at deep-crustal conditions. *Earth and Planetary Science Letters* 374, 111-120.

Aranovich, L.Y., Newton, R.C., 1998. Reversed determination of the reaction: Phlogopite + quartz = enstatite + potassium feldspar + H₂O in the ranges 750–875°C and 2–12 kbar at low H₂O activity with concentrated KCl solutions. *American Mineralogist* 83, 193-204.

Aranovich, L. Y., Newton, R. C., 1997. H₂O activity in concentrated KCl and KCl–NaCl solutions at high temperatures and pressures measured by the brucite–periclase equilibrium. *Contributions to Mineralogy and Petrology* 127, 261-271.

Aranovich, L. Y., Newton, R. C., 1999. Experimental determination of CO₂–H₂O activity-concentration relations at 600–1000 °C and 6–14 kbar by decarbonation and dehydration reactions. *American Mineralogist* 84, 1319-1332.

Armbruster, T., Schreyer, W., Hoefs, J., 1982. Very high CO₂ cordierite from Norwegian Lapland: Mineralogy, petrology, and carbon isotopes. *Contributions to Mineralogy and Petrology* 81, 262-267.

Berman, R.G., Aranovich, L.Y., Rancourt, D.G., Mercier, P.H.J., 2007. Reversed phase equilibrium constraints on the stability of Mg-Fe-Al biotite. *American Mineralogist* 92, 139-150.

Blattner, P., 1976. Replacement of hornblende by garnet in granulite facies assemblages near Milford Sound, New Zealand. *Contributions to Mineralogy and Petrology* 55, 181-190.

Bowen, N.L., 1928. *The Evolution of Igneous Rocks*. Princeton University Press
Princeton NJ., 251 pp.

Clemens, J.D., Buick, I.S., Stevens, G., 2016. Fluids, melting, granulites and granites: A commentary. *Precambrian Research* (in press).

Clemens, J.D., Vielzeuf, D., 1987. Constraints on melting and magma production in the crust. *Earth and Planetary Science Letters* 86, 287-306.

Clemens, J.D., Watkins, J.M., 2001. The fluid regime of high-temperature metamorphism during granitoid magma genesis. *Contributions to Mineralogy and Petrology*, 140, 600-606.

Collins, W.J., Huang, H.Q. Jiang, X., 2016. Water-fluxed crustal melting produces Cordilleran batholiths. *Geology* 44, 143-146.

Connolly, J.A.D., Podladchikov, Y.Y., 2004. Fluid flow in compressive tectonic settings: Implications for midcrustal seismic reflectors and downward fluid migration. *Journal of Geophysical Research: Solid Earth* 109, 1-12.

Dolejš, D., Baker, D.R., 2004. Thermodynamic analysis of the system $\text{Na}_2\text{O}-\text{K}_2\text{O}-\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}-\text{F}_2\text{O}$ – 1: Stability of fluorine-bearing minerals in felsic igneous suites. *Contributions to Mineralogy and Petrology* 146, 762-778.

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

Ebadi, A., Johannes, W., 1991. Beginning of melting and composition of first melts in the system $\text{Qz}-\text{Ab}-\text{Or}-\text{H}_2\text{O}-\text{CO}_2$. *Contributions to Mineralogy and Petrology* 106, 286-295.

Hansen, E., Ahmed, K., Harlov, D.E., 2002. Rb depletion in biotites and whole rocks across an amphibolite to granulite facies transition zone, Tamil Nadu, South India. *Lithos* 64, 29-47.

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

Hansen, E.C., Newton, R.C., Janardhan, A.S., Lindenberg, S., 1995. Differentiation of late Archean crust in the eastern Dharwar craton, Krishnagiri-Salem area, south India. *The Journal of Geology*, 629-651.

Harlov, D.E., Hansen, E.C., Bigler, C., 1998. Petrologic evidence for K-feldspar metasomatism in granulite facies rocks. *Chemical Geology* 151, 373-386.

Harley, S.L., Thompson, P., Hensen, B.J., Buick, I.S., 2002. Cordierite as a sensor of fluid conditions in high-grade metamorphism and crustal anatexis. *Journal of Metamorphic Geology*, 20, 71-86.

Hartel, T.H.D., Pattison, D.R.M., 1996. Genesis of the Kapuskasing (Ontario) migmatitic mafic granulites by dehydration melting of amphibolite: the importance of quartz to reaction progress. *Journal of Metamorphic Geology* 14, 591-611.

Holtz, F., Johannes, W., Tamic, N., Behrens, H., 2001. Maximum and minimum water contents of granitic melts generated in the crust: a reevaluation and implications. *Lithos* 56, 1-14.

Jackson, D.H., Matthey, D.P., Santosh, M., Harris, N.B.W., 1988. Carbon stable isotope analysis of fluid inclusions by stepped heating. *Mem. Geol. Soc. India* 11, 149-158.

Johannes, W., 1985. The significance of experimental studies for the formation of migmatites, in: Ashworth, J.R. (Ed.), *Migmatites*. Springer, US pp. 36-85.

Johannes, W., Holtz, F., 1991. Formation and ascent of granitic magmas. *Geologische Rundschau*, 80, 225-231.

Korikovsky, S.P., Aranovich, L.Y., 2010. Charnockitization and enderbitization of mafic granulites in the Porya Bay area, Lapland Granulite Belt, Southern Kola Peninsula: I. Petrology and geothermobarometry. *Petrology* 18, 320-349.

Korikovsky, S.P., Aranovich, L.Y., 2015. Charnockitization of feldspar-free orthopyroxene-clinopyroxene-phlogopite metaultramafite in the Lapland granulite belt, southern Kola Peninsula: Compositional trends of rocks and minerals, PT parameters, and fluid regime. *Petrology* 23, 189-226.

Litvinovsky, B.A., Podladchikov, Y.Y., 1993. Crustal anatexis during the influx of mantle volatiles. *Lithos* 30, 93-107.

Litvinovskii, B.A., Zanzilevich, A.N., Wickham, S.M., 1994. Angara–Vitim batholith, Transbaikalia: structure, petrology, and petrogenesis. *Russian Geology and Geophysics* 35, 190-203.

Makhluf, A.R., Newton, R.C., Manning, C.E., 2014. Experimental determination of liquidus H₂O contents of simple granites at deep crustal conditions. AGU Fall Meeting Abstracts, V51C-4778.

Manning, C.E., Aranovich, L.Y., 2014. Brines at high pressure and temperature: Thermodynamic, petrologic and geochemical effects. *Precambrian Research* 253, 6-16.

Morfin, S., Sawyer, E.W., Bandyayera, D., 2013. Large volumes of anatectic melt retained in granulite facies migmatites: An injection complex in northern Quebec. *Lithos* 168, 200-218.

Newton, R.C., Aranovich, L.Y., Hansen, E.C., Vandenheuvel, B.A., 1998. Hypersaline fluids in Precambrian deep-crustal metamorphism. *Precambrian Research* 91, 41-63.

Newton, R.C., Touret, J. L. R., Aranovich, L.Y., 2014. Fluids and H₂O activity at the onset of granulite facies metamorphism. *Precambrian Research* 253, 17-25.

Perchuk, L.L., Gerya, T.V., 1992. The fluid regime of metamorphism and the charnockite reaction in granulites: a review. *Geochemistry International* 34, 1-58.

Perchuk, L.L., Safonov, O.G., Gerya, T.V., Fu, B., Harlov, D.E., 2000. Mobility of components in metasomatic transformation and partial melting of gneisses: an example from Sri Lanka. *Contributions to Mineralogy and Petrology* 140, 212-232.

Percival, J.A., 1991. Granulite-facies metamorphism and crustal magmatism in the Ashuanipi Complex, Quebec - Labrador, Canada. *Journal of Petrology* 32, 1261-1297.

Plank, T., Kelley, K.A., Zimmer, M.M., Hauri, E.H., Wallace, P.J., 2013. Why do mafic arc magmas contain ~ 4wt% water on average? *Earth and Planetary Science Letters* 364, 168-179.

Rutter, M.J., Wyllie, P.J., 1988. Melting of vapour-absent tonalite at 10 kbar to simulate dehydration-melting in the deep crust. *Nature* 331, 159-160.

Sawyer, E.W., 1994. Melt segregation in the continental crust. *Geology* 22, 1019-1022.

Sawyer, E.W., 1999. Criteria for the recognition of partial melting. *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy* 24, 269-279.

Scaillet, B., François, H., Pichavant, M., Schmidt, M., 1996. Viscosity of Himalayan leucogranites: Implications for mechanisms of granitic magma ascent. *Journal of Geophysical Research Solid Earth* 101, 27-691.

Srikantappa, C., Raith, M., Touret, J. L. R., 1992. Synmetamorphic high-density carbonic fluids in the lower crust: evidence from the Nilgiri granulites, southern India. *Journal of Petrology* 33, pp.733-760.

Timmermann, H., Jamieson, R.A., Parrish, R.R., Culshaw, N.G., 2002. Coeval migmatites and granulites, Muskoka domain, southwestern Grenville Province, Ontario. *Canadian Journal of Earth Sciences* 39, 239-258.

Touret, J. L. R., 2001. Fluids in metamorphic rocks. *Lithos* 55, pp.1-25.

Touret, J. L. R., Hansteen, T.H., 1988. Geothermobarometry and fluid inclusions in a rock from the Doddabetta charnockite complex, southwest India. *Proceedings of the Italian Society of Mineralogy and Petrology* 43, pp.65-82.

Touret, J.L.R., Huizenga, J.M., 2011. Fluids in granulites. *Geological Society of America Memoirs* 207, 25-37.

Touret, J.L.R., Nijland, T.G., 2013. Prograde, peak and retrograde metamorphic fluids and associated metasomatism in upper amphibolite to granulite facies transition zones, in: Harlov, D.E., Austerheim, H. (Eds.), *Metasomatism and the Chemical Transformation of Rock*. Springer, Berlin, Heidelberg, pp. 415-469.

Vielzeuf, D., Clemens, J.D., 1992. The fluid-absent melting of phlogopite + quartz: Experiments and models. *American Mineralogist* 77, 1206-1222.

Weinberg, R.F., Hasalová, P., 2015. Reply to comment by J.D. Clemens and G. Stevens on 'Water-fluxed melting of the continental crust: A review'. *Lithos* 234, 102-103.

Weinberg, R.F., Hasalová, P., 2015. Water-fluxed melting of the continental crust: A review. *Lithos* 212, 158-188.

Wickham, S.M., 1987. The segregation and emplacement of granitic magmas. *Journal of the Geological Society*, 144, 281-297.

Zhu, C., Xu, H., Ilton, E.S., Veblen, D.R., Henry, D.J., Tivey, M.K., Thompson, G., 1994. TEM-AEM observations of Cl-rich amphibole and biotite and possible petrologic implications. *American Mineralogist* 79, 909-920.

