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## Reply

## Reply to comment by J.D. Clemens and G. Stevens on ‘Water-fluxed melting of the continental crust: A review’

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Airport halls and kitchen benches everywhere attest to the importance of water-fluxed melting. They commonly show migmatites lacking anhydrous peritectic minerals, as is expected from the reactions listed in Table 2 in Weinberg and Hasalová (2015), W&H henceforth. The question we should ask is not whether it is a significant process but how and when it happens. We start this response by clarifying that in W&H, we never meant to imply that water-fluxed melting is the dominant melting process, but that it is widespread and relevant to understanding the evolution of the continental crust. The aim of our paper was to review the many reported cases in which water-fluxed melting has been inferred, to draw attention to its common occurrence, to suggest how this may take place and discuss its possible role in crustal evolution. In order to avoid confusion, in this reply we refer consistently to their Fig. 1, referring to Fig. 1 in Clemens and Stevens (2015), or to our Fig. 1 shown here.

There is no doubt dehydration melting reaction is a key process in the origin of granitoids, as emphatically stated by Clemens and Stevens (2015, C&S henceforth). Magmas derived from such reactions are able to rise far in the crust before solidifying because they are initially hot and have low H<sub>2</sub>O content, placing them far from their water-saturated solidus curve in PT space. This, however, does not exclude water-fluxed melting from also playing an important role and contributing to the complexity of granitic belts, particularly because this process too can give rise to hot melts with low initial H<sub>2</sub>O contents (by initial H<sub>2</sub>O content we mean the value with which melt is generated, the value that stabilizes

melt at a given PT when the system is rock buffered; see Johannes and Holtz, 1996). A lack of interest in water-fluxed melting over the last 20 years has meant a bias in the way we interpret migmatites and think about granitoids. This bias has not helped us understand and deal with the many terranes dominated by water-fluxed melting (e.g., the anatectic granites of the Opatica Subprovince, Sawyer, 2010; the Karakoram shear zone, Reichardt and Weinberg, 2012).

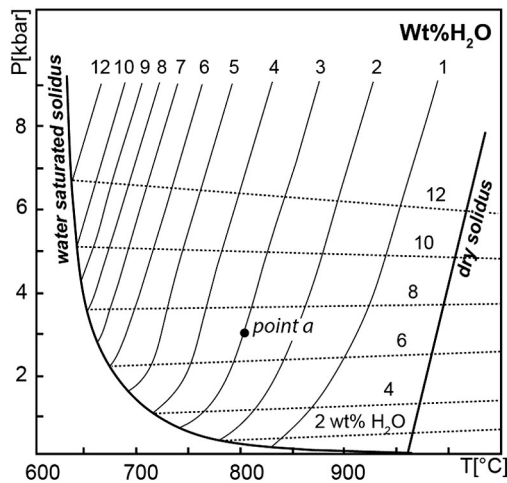
The underlying reason for C&S's comment is their misplaced expectation that water-fluxed melting gives rise to H<sub>2</sub>O-saturated melts. In our review, we argued that this is the exception rather than the rule: in most cases these melts, like those generated by dehydration melting reactions, will be undersaturated in H<sub>2</sub>O. C&S are unhappy that we have “ignored” the main point raised by Clemens and Watkins (2001) when in fact W&H demonstrated its shortcomings while avoiding being explicit. The issue is that neither the absolute H<sub>2</sub>O content inferred for granitic melts at the source, nor their negative trend with increasing T (their Fig. 1, or Fig. 3 in Clemens and Watkins, 2001) can be used to differentiate between water-fluxed and dehydration melting reactions. We explain this further.

The steep solid lines in our Fig. 1 mark the minimum H<sub>2</sub>O content necessary to stabilize melt in equilibrium with an haplogranite. These are equilibrium values in an environment that is rock buffered, i.e., where H<sub>2</sub>O is the limiting reactant. As long as there is quartz and feldspars in excess, addition of H<sub>2</sub>O at any particular PT raises the melt fraction, while maintaining the melt H<sub>2</sub>O content (see Johannes and Holtz, 1996). The significant point of these curves, and missed by C&S, is that they show the H<sub>2</sub>O content of melt formed by water-fluxed melting in rock-buffered systems. In contrast, the flat dotted lines in our Fig. 1 show the solubility or the maximum H<sub>2</sub>O content in the melts. Such values only arise when the system is no longer rock buffered such as will happen when relatively large volumes of H<sub>2</sub>O are injected into a limited volume of rocks. In fluid-buffered systems, melts will be saturated in H<sub>2</sub>O.

Here is where we differ from C&S. Their expectation that water-fluxed melting gives rise to H<sub>2</sub>O-saturated melts is clearly expressed in Clemens and Watkins (2001): “For wet melting, the range of melt H<sub>2</sub>O contents is simply the range of solubility of H<sub>2</sub>O in granitoid melts under the appropriate P–T conditions”. This corresponds to the flat dotted lines in our Fig. 1, that would yield melts with ~7 wt.% at point a. Saturated melts may form: a) if melting is at the water-saturated solidus (wss), where the maximum and minimum H<sub>2</sub>O content in the melt are the same (Fig. 1; Johannes and Holtz, 1996); b) in localized regions where voluminous fluid influx invades a limited volume of

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**Fig. 1.** Pressure–temperature plot showing the water-saturated solidus (wss) and two sets of curves (from Johannes and Holtz, 1996). Inclined solid lines represent the minimum water content that stabilizes melt in the presence of haplogranite. Flat dotted lines are the solubility or maximum water content of melts. Notice that the minimum and maximum water content lines meet at the water-saturated solidus.

permeable rock (fluid-buffered conditions); or c) when one of the reactants is exhausted and the melting reaction stops so that continued fluid influx raises  $H_2O$  content in the melt. Bartoli et al. (2014) showed that melt inclusions trapped in peritectic minerals during melting have variable  $H_2O$  content, reflecting compositional heterogeneities at micro-scale during melting. This could in part reflect heterogeneous distribution of fluids through the rock and variable fluid composition.

However, for the hot terranes that C&S focus on, at conditions well above the wss, we expect that the volume of quartzo-feldspathic rock will be large compared to the volume of fluids, so that melting is commonly rock buffered. If one of the solid reactant phases is exhausted during melting (point (c) above), the melt  $H_2O$  content will rise, at least temporarily, towards saturation. However, the relatively fast diffusion of hydrogen combined with melt flow, will tend to equilibrate the system by melting rocks further away, where all reactants are still available, while decreasing the  $H_2O$  content of the saturated melts. Therefore, unlike C&S, we expect water-fluxed melting at conditions above the wss to give rise to  $H_2O$ -undersaturated melts, with contents approaching the minimum content curves in our Fig. 1, or ~3 wt.% at point a rather than 7 wt.%.

In cases where equilibrium is not attained,  $H_2O$  content will be between the minimum and the maximum values. In some extreme cases, melt could be over-saturated and carry bubbles of aqueous fluids (discussed in Sections 8.2.1 and 9 in W&H). These melts with  $H_2O$  content above minimum are particularly effective agents of  $H_2O$  transport, triggering further melting as they migrate.

Given this background, we are now in a position to challenge C&S's interpretation of their Fig. 1. The absence of melts that are  $H_2O$ -saturated, rather than representing dehydration melting, could just as well be interpreted as resulting from efficient equilibration between aqueous fluids or water-rich melts and quartzo-feldspathic rocks. This equilibration would occur either during crustal melting, or during melt migration. The figure tells us nothing about the nature of the melting reaction, it simply indicates that most anatectic terranes are at least partially rock buffered at P–T conditions above the wss.

Fig. 1 in C&S has two other interesting aspects: a)  $H_2O$  content at any given temperature vary widely, with some values above the minimum  $H_2O$  content predicted for typical crustal pressures (3 to 10 kbar), b) there is a broad negative trend between  $H_2O$  content and T. With regards to (a), there are two possible interpretations for the origin of samples with high  $H_2O$  content. The first is that they were produced at high crustal pressures (significantly above 10 kbar), the second is that they were derived from water-fluxed terranes where fluid influx was sufficiently voluminous so that the melting reaction was not

entirely rock buffered (see W&H Sections 8.2.1 and 9 for discussion). With regards to (b), if we assume as C&S do, that  $H_2O$ -fluxed melting produces  $H_2O$ -saturated melts, then we should expect no trend with temperature (due to flat saturation lines in our Fig. 1). However, where water-fluxed melting is rock buffered, the trend in water content should be undistinguishable from that for melts derived from dehydration melting reactions, and decrease with increasing temperature. We note further that the samples used to estimate the water content in their Fig. 1 are granitoids far removed from their anatectic source. It is possible that a wider variation in  $H_2O$  content may be found in melts trapped in crystals while in their source (Bartoli et al., 2014).

In our view, it is the magma dynamics and the tectono-thermal evolution of the crust that generate the conditions for  $H_2O$ -rich fluids to pervade hot rocks. One of the aspects we found particularly interesting in reviewing the literature was precisely the many examples of the connection between fluid migration, magmatism and tectonic evolution. C&S attempt to discredit our discussion of the connection between water-fluxed melting and other crustal processes, by saying it is tantamount to special pleading. Had C&S considered the evidence in the examples we summarized, they might have realized that magmatic processes are not isolated from other crustal processes, and that the tectono-thermal evolution of different terranes unavoidably affects the fate of fluids and the nature of magmatism. Contrary to C&S's assertions, the geological record where water-fluxed melting has been inferred is not simply explained by fluid-absent partial melting.

It is also disappointing that C&S “take issue with the idea that this is a major granite-forming mechanism and therefore significant in crustal evolution”. There are two separate issues here. Whether or not one accepts that water-fluxed melting is a major granite-forming mechanism, our survey of the literature indicates that it is a globally widespread process. This being the case, water-fluxed melting alone, even without melt extraction from the source, must influence the thermal evolution of the crust, the fate of fluids, the local fractionation of crustal rocks, as well as the structure, anisotropy and rheology of that part of the crust during and after melting. Our own studies in the Zaskar Himalayas suggest that it was the influx of  $H_2O$  that increased the melt fraction to nearly 50 vol.% causing crustal weakening, triggering the initiation of normal movement on the South Tibetan Detachment (Finch et al., 2014). Most significantly however, because melts produced by water-fluxed melting need not be  $H_2O$ -saturated, they are free to rise, impacting on crustal fractionation and the final thermal structure of continents.

In summary, we have drawn attention to an important process in continent evolution that can explain part of the rich variety of granitoids and the features of many anatectic terranes. Just how important this process is remains to be determined. More than 20 years of neglect means that it is high time to consider what happens when  $H_2O$ -rich fluids access hot rocks. Clemens and Stevens consistently attempt to minimize the importance of many magmatic processes. However, there are granites and granites precisely because there are processes and processes.

## References

- Bartoli, O., Cesare, B., Remusat, L., Acosta-Vigil, A., Poli, S., 2014. The  $H_2O$  content of granite embryos. *Earth Planet. Sci. Lett.* 395, 281–290.
- Clemens, J.D., Watkins, J.M., 2001. The fluid regime of high-temperature metamorphism during granulite magma genesis. *Contrib. Mineral. Petrol.* 140, 600–606.
- Finch, M., Hasalová, P., Weinberg, R.F., Fanning, M.C., 2014. Switch from thrusting to extension in the Zaskar Shear Zone, NW Himalaya: implications for channel flow. *Geol. Soc. Am. Bull.* 126, 892–924.
- Johannes, W., Holtz, F., 1996. *Petrogenesis and Experimental Petrology of Granitic Rocks*. Springer (335 pp.).
- Reichardt, H., Weinberg, R.F., 2012. Hornblende chemistry in meta- and diatexites and its retention in the source of leucogranites: an example from the Karakoram Shear Zone, NW India. *J. Petrol.* 53, 1287–1318.
- Sawyer, E.W., 2010. Migmatites formed by water-fluxed partial melting of a leucogranodiorite protolith: microstructures in the residual rocks and source of the fluid. *Lithos* 116, 273–286.
- Weinberg, R.F., Hasalová, P., 2015. Water-fluxed melting of the continental crust: a review. *Lithos* 212–215, 158–188. <http://dx.doi.org/10.1016/j.lithos.2014.08.021>.