Reply to: "Global data of (ultra)high-pressure metamorphism do not call for excessive overpressures"

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Jiang criticizes the model we proposed with J.P Brun[1] on two aspects: (1) He argues against the assumptions on which our model is based, which he presents as "*not justified by the principles of rock mechanics in the context of realistic geologic setting*". (2) He attempts to demonstrate that the natural data we used do not support our model. He claims that these data can be better explained by considering a P_{peak} (from 1 to 4 GPa) independent of P_{retro} (see definitions in Fig.1a), P_{retro} being roughly constant (~0.75-1.0 ± 0.5 GPa) and corresponding to deep crustal levels. I here show that Jiang does not "*demonstrate*" that our model is wrong and that the arguments used to invalidate it are not relevant.

Natural *P* data and model. Figure 1 summarises different ways to plot the pressure data and two possibilities to interpret them: the one presented in Jiang's comment and the one from Yamato and Brun[1]. We note that other possibilities of interpreting these data exist[2]. In our study[1], we propose a mechanical model where a switch in the state of stress sustained by the rocks between compression and extension (i.e., a switch between σ_1 and σ_3) can lead to a pressure variation (*ΔP*) that we quantify and then compare with natural data (Fig.1a and b). This mechanical model is indeed based on assumptions (as every model; see below), but presents a good fit with the data when the state of stress is close to the frictional yield. The "best-fit line" proposed by Jiang (Fig. 1b) corresponds to the simple linear regression of the data and is not based on any mechanical model.

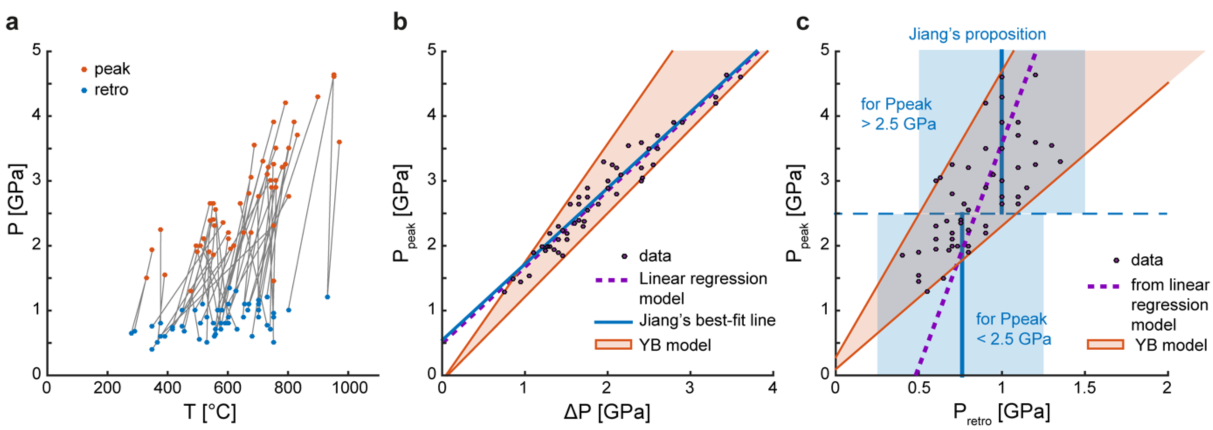

Figure 1| a, P-T data corresponding to the dataset used in Yamato and Brun[1]. Peaks of pressure (P_{peak}) corresponds to pressure estimates of the red dots. P_{retro} values correspond to pressure estimates of the blue dots. ΔP corresponds to the difference between P_{peak} and P_{retro} values ($\Delta P = P_{peak} - P_{retro}$). **b**, Graphic presenting linear distribution of P_{peak} as a function of ΔP. Blue line ("best-fit line" in Jiang's comment) corresponds to the result of the linear regression model of the data (purple dashed line). Red area corresponds to the range of possibilities obtained from our model[1] (YB model). **c**, Graphic presenting the distribution of P_{peak} as a function of P_{retro}. Blue vertical lines/areas correspond to Jiang's proposition. The purple dashed line corresponds to the linear regression obtained from b. Red area is the range of possible values obtained using our model[1].

Figure 1c displays the relation between P_{peak} and P_{retro}. It shows the difference between the interpretation of Jiang and our model. Jiang proposes that P_{retro} corresponds to lithostatic pressure at lower crustal depths, and he concludes that P_{peak} is independent of P_{retro}, over a wide range, from 1 to over 4 GPa (Fig. 1c). His proposition, not consistent with his "best-fit line" (dashed purple line in Fig. 1c), could be convincing if the P_{peak} data were aligned vertically independently of P_{retro}, which is not the case. Jiang's proposition also requires an explanation to separate the dataset at 2.5 GPa. Moreover, the ranges of values Jiang selected for P_{retro} are so large (between 0.25 and 1.5 GPa with a mean at 0.56 GPa selecting all data, between 0.5 and 1.5 GPa for UHP rocks, and between 0.25 and 1.25 GPa for HP rocks, Fig. 1c) that every data necessarily fits. On the contrary, the model we propose can explain the data distribution.

Assumptions in models. All models require assumptions. Even if ours were already discussed in the original paper[1], I here take the opportunity to clarify some points and to set Jiang's claims in the context of recent literature.

(1) Metamorphism, time and deformation mode. Depending on the pressure, temperature, fluids, grain size, and strain rate conditions, rocks may deform elastically, viscously (which does not necessarily mean without significant differential stress, see below) or in a brittle manner[3]. The dominant deformation depends on the intrinsic rheological properties of the rock and the properties of the newly formed material when it reacts[4-6]. In his comment, Jiang concedes that frictional behaviours can occur at (U)HP conditions but argues that they are too transient to be recorded by rocks in their mineralogy/paragenesis. However, it was demonstrated[7,8] that eclogite can form in less than 500 years, which is on the same order of magnitude as the recurrence of large earthquakes. Moreover, there is growing evidence showing that (U)HP metamorphism can be closely associated, in both space and time, with brief frictional events such as earthquakes[9-16]. This evidence suggests that metamorphic rocks can keep the imprints of short tectonic events. Thus, the stress states associated with these events must be taken into consideration when interpreting the pressure of metamorphic rocks.

(2) Evidence for high differential stresses. Jiang claims that there is no evidence that GPa level differential stress can be sustained for the Ma time scale in the *P-T* condition of (U)HP metamorphism. However, many studies challenge this claim and demonstrate the occurrence of high differential stress at several scales[17-20]. At the lithospheric scale, non-negligible differential stresses are required to maintain and support mountain belts and their roots[17,21,22]. At the crustal scale, in-situ stress measurements reveal that the continental crust can be in a state of stress near the failure threshold, with differential stress >100 MPa at depth >5 km[23]. At the outcrop scale, important rheological differences can lead to local overpressure that results in parageneses of different grades[24,25]. Finally, and contrary to what is mentioned in Jiang's comment, at the grain scale, characteristic microstructures and mineral zonation in (U)HP rocks indicate that HP paragenesis can be associated with significant overpressure[19] and brittle behaviour[10,15]. Hence, although there is no consensus yet, there are growing theoretical arguments and observational evidence that rocks can indeed sustain high differential stresses, and this, over long enough time to be recorded by metamorphic rocks[4,26].

(3) Stress orientations and magnitudes. Finally, the third criticism relates to the fact that, in our study, we only considered Andersonian cases, with σ_1 and σ_3 vertical in extension and compression, respectively. This is a point that indeed matters as soon as we consider deviatoric stress and distinct bodies of different strengths. We agree that our simple model is applicable strictly only for homogeneous material. However, even in the case of an inclusion/matrix system, the local pressure is related to the far-field state of stresses (being at most equal to the far field σ_1[27,28]). Moreover, it is possible to expand the Yamato and Brun derivation for any stress magnitude and any stress orientation (see Fig 6 and 7 in Bauville and Yamato[2]). Results then show that the assumptions that the stress state is (i) Andersonian and (ii) close to the brittle limit are not absolute requirements. Much data can indeed also be explained by models where the magnitude of differential stress is only a fraction of its maximum value and/or the stress state rotates between peak and retrograde conditions.

In summary, the model proposed by Yamato and Brun[1] constitutes a possible mechanical explanation for *P-T* estimates recorded in rocks. This mechanical model is based on mathematical equations relating P_{peak} and P_{retro} and it is in principle possible to falsify this model. Jiang's proposition is not based on a mechanical model for the relation between P_{peak}

and P_{retro} and is, therefore, not scientifically sound. It also involves a large error range and requires an explanation for the artificial separation of the data at 2.5 GPa. It is, of course, possible that P_{peak} data are not all due to large overpressure and that some rocks are exhumed by buoyancy. However, such *"classical interpretation"*, based on lithostatic pressure, is not always satisfactory (e.g.[16,25,29-33]). There are many problems related to lithostatic pressure-to-depth conversion such as the depth of metamorphic sole formation[34], a geodynamic explanation for extremely fast subduction/exhumation velocities[35-37], or the observation of different P_{peak}, which exist within coherent tectonic units that have essentially the same age[16,25]. All these unsolved problems, related to the lithostatic pressure assumption, are the primary motivation to propose alternative pressure models like ours.

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