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

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Abstract

D. Jiang submitted a comment entitled ≪ Metamorphic data from global subduction zones do not call for excessive overpressures ≫ to Nature Geoscience. His comment on our paper entitled ≪ Metamorphic record of catastrophic pressure drops in subduction zones ≫ (Nature Geoscience 10, 46-50, 2017) will not be published. However, because his comment remains available on the web via ESSOAR (https://www.essoar.org/doi/abs/10.1002/essoar.10504134.3), I here propose to share my reply.

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.

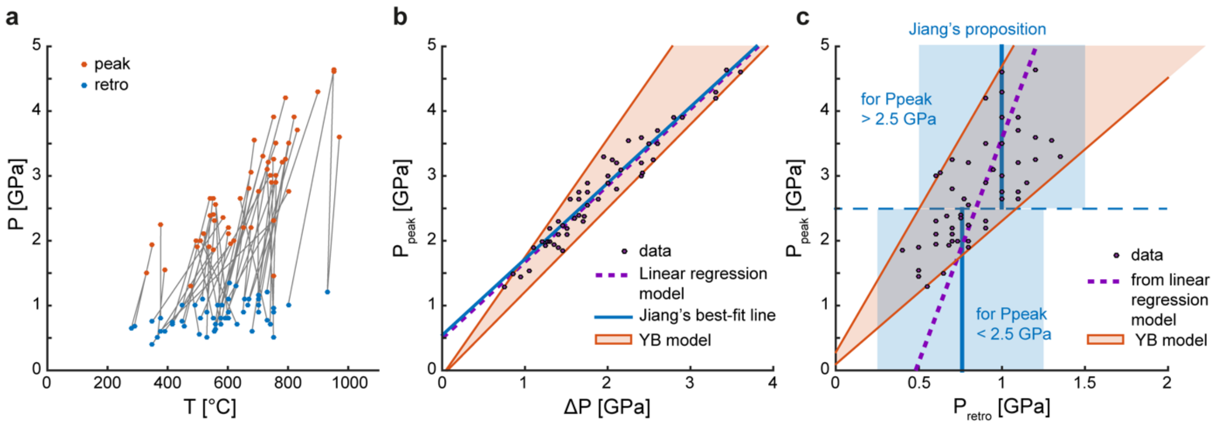

Figure 1| a, *P-T* data corresponding to the dataset used in Yamato and Brun[1]. Peaks of pressure (P_{peak}) corresponds to pressure estimates of the red dots. P_{retro} values correspond to pressure estimates of the blue dots. ΔP corresponds to the difference between P_{peak} and P_{retro} values ($\Delta P = P_{peak} - P_{retro}$). **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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My thoughts are with Jean-Pierre, who left us one year ago. I'm sure he would have appreciated defending our ideas together. I also warmly thank A. Bauville, M. Baïsset, C. Luisier and T. Duretz for the fruitful exchanges which allowed me to clarify this reply.

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

Dazhi Jiang[a]

Yamato and Brun[1] claimed that metamorphic data from global (ultra)high-pressure ((U)HP) rocks display an unusual linear relation, between peak pressure and pressure drop, that challenges current interpretation of *P-T-t* paths but supports their model invoking excessive overpressures. Here, I demonstrate that their model requires critical assumptions that are not justified by the principles of rock mechanics in the context of realistic geologic settings and unsupported by microstructures of (U)HP rocks. More importantly, contrary to their claim, the global (U)HP data are compatible with the current framework of metamorphic petrology but at odds with their model prediction.

The mineral assemblages of (U)HP rocks commonly record a 'peak' pressure (P_{peak}), which is interpreted by researchers to represent the maximum depth of rock burial, and a lower 'retrograde' pressure (P_{reto}) interpreted to represent the depth to which the rocks were exhumed[2-4]. This interpretation assumes that the metamorphic pressures are approximately lithostatic. In reality, the metamorphic pressure may deviate from the lithostatic value, but the magnitude of deviation is limited by the rock strength, which is likely less than hundreds of MPa for the Ma time scale relevant for (U)HP metamorphism and far below the GPa level lithostatic pressure[5].

Yamato and Brun[1] proposed that the drop in pressure from P_{peak} to P_{retro} from global (U)HP rocks could be explained by a switch in stress regime, from compression during burial to extension at the onset of exhumation, at the same depth corresponding to the lithostatic pressure P_l (Fig.1a). In their model, P_{peak} arose from an excess tectonic overpressure R at compression ($P_{\text{peak}} = P_l + R$) whereas P_{retro} was due to a tectonic underpressure r when the stress regime switched to extension ($P_{\text{retro}} = P_l - r$) (Fig.1a). Thus, the pressure drop, $\Delta P = P_{\text{peak}} - P_{\text{retro}} = R + r$, required no actual ascent of the rocks. With the following three assumptions, namely, 1) the rock rheology follows a Mohr-Coulomb plasticity, 2) the stress state is at the yield state, and 3) the vertical stress is a principal stress with magnitude equal to the lithostatic value (the Andersonian stress state), their model leads to simple relations among the pressure parameters. A major result is the linear relation $P_{\text{peak}} = \frac{1+\sin\phi}{2\sin\phi}\Delta P - C\cdot\cot\phi$. As C is small (<0.05GPa) compared to P_{peak} and ΔP, this relation simplifies to:

$$P_{\text{peak}} \approx \frac{1+\sin\phi}{2\sin\phi}\Delta P \qquad (1)$$

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which is a line passing through the origin and having a slope $\left(\frac{1+\sin\phi}{2\sin\phi}\right)>1$ on the P_{peak} versus ΔP plot. For $\phi = 30^{\circ}$, it simplifies to $P_{\text{peak}} = 1.5\Delta P$.

However, none of the above assumptions can be well justified for (U)HP metamorphism. First, the transformation of mineral phases during (U)HP metamorphism occurs at a Ma time scale for which the rocks deform predominantly by viscous flow as required by the *P-T* conditions[6,7]. Frictional behaviors in (U)HP rocks could have been associated with local and/or transient events[8, 9] that do not leave their imprints in the mineral assemblages from which metamorphic pressures are obtained. Second, there is no evidence that GPa-level differential stresses (up to $2P_l$) can be sustained for the Ma time scale in the of *P-T* condition of (U)HP metamorphism. Such high differential stresses would have caused (U)HP rocks to flow at strain rates much faster than crustal mylonites, based on available flow laws [7,10] for quartzofeldspathic and eclogite rocks, for which there is no microstructural evidence. Third, because (U)HP rocks are rheologically distinct bodies constrained at great depth in the lithosphere, the stress orientations and magnitudes in them are determined by their mechanical interaction with the surrounding lithosphere[5,11,12], and are unlikely Andersonian.

A big claim of Yamato and Brun is that data from global (U)HP rocks display an unusual linear relation between P_{peak} and ΔP (their fig.1b) that challenges the current interpretation of *P-T-t* paths but supports their model-predicted relation in Eq.1. The same data are replotted in Fig.1b. The best-fit line for all the data is $P_{\text{peak}} = 1.17\Delta P + 0.56$ (solid green line) which has a slope significantly below the predicted 1.5 (dashed black line) as well as a positive intercept at 0.56 GPa (Fig.1b) that is inconsistent with Eq.1.

An alternative and more straightforward interpretation of the data is through the trivial relation of $P_{\text{peak}} = \Delta P + P_{\text{retro}}$. The data suggest that while (U)HP rocks were formed over a wide range of P_{peak}, from 1 to over 4 GPa, they were exhumed to a narrower range of P_{retro} between 0 and 1.5 GPa, with a mean P_{retro} at 0.56GPa. The spread of P_{retro} could already explain the deviation of the slope of the best-fit line from 1. If one considers ultrahigh pressures (>2.5GPa) and high pressures (<2.5GPa) seperately, the UHP data conform to a slope near 1 and $P_{\text{retro}} \approx 1.0 \pm 0.5$ GPa (grey shaded area) and the HP data also follow a slope near 1 but with $P_{\text{retro}} \approx 0.75 \pm 0.5$ GPa (pink shaded area). The intercept range $P_{\text{retro}} \approx 1.0 \pm 0.5$ GPa is equivalent to depths of 20-50 km, which may represent the neutral buoyancy depths where the UPH rocks ceased to ascent [4,13]. As the HP rocks were formed near the Moho of thickened continental crusts in the first place, buoyancy driving might have not played a significant role in their exhumation, leading to a different mean of P_{retro}. Regardless of the burial and exhumation mechanisms for (U)HP rocks, because the relation $P_{\text{peak}} = \Delta P + P_{\text{retro}}$ is a definition, it applies to all (U)HP rocks.

If one does not make the assumptions as Yamato and Brun, the differential stresses associated with P_{peak} and P_{retro} are far below the yielding stresses and the two Mohr circles (dashed in Fig.1a) are not required to meet on the horizontal axis. This invalidates Yamato and Brun's argument that pressure drop in ductile rheology must be always smaller than that in frictional rheology (their fig.3).

Data from global (U)HP rocks show nothing unusual than the fact that (U)HP rocks tend to be exhumed to deep crustal levels (corresponding to $0.75\sim1.0\pm0.5$ GPa) following deep burial. This supports the classical interpretation since the discovery of (U)HP rocks[14,15] that the peak and retrograde pressures represent two events at different depths. It is unnecessary to invoke mechanisms with excessive overpressures.

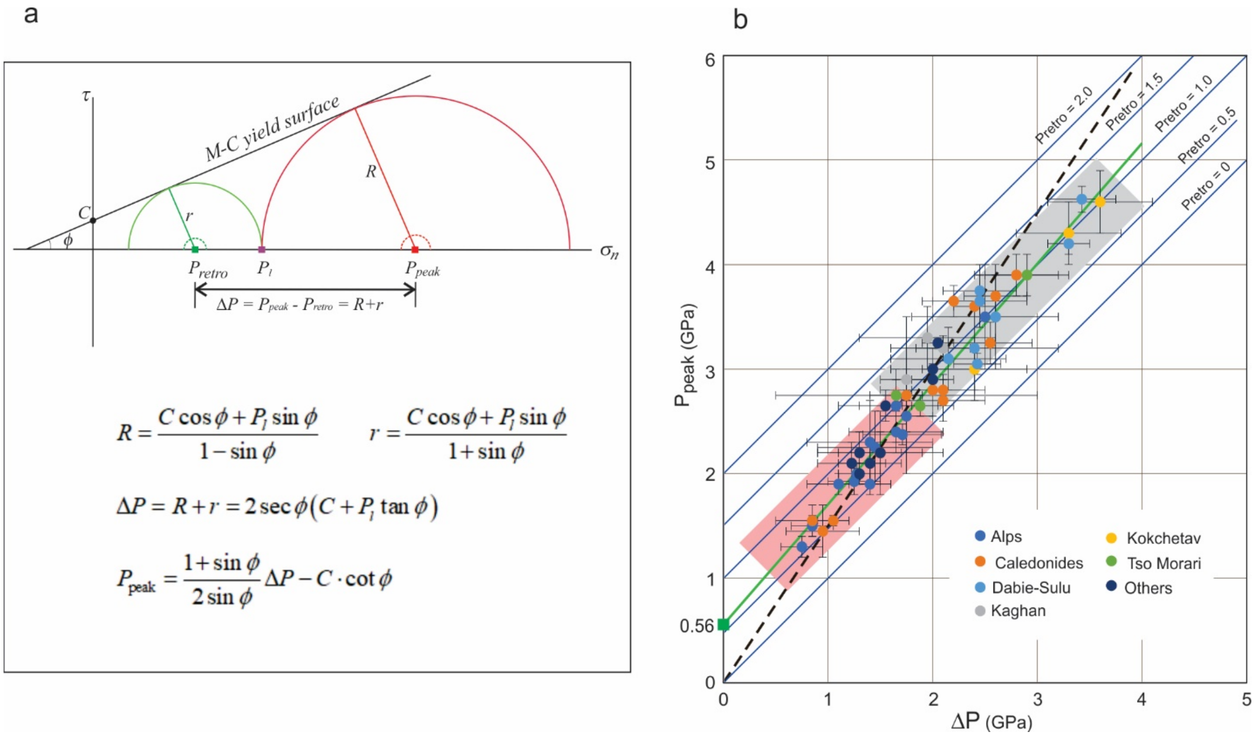

Figure 1: Mohr circle presentation of Yamato and Brun's model and plot of pressure data from global (U)HP rocks. **a**, Mohr circle presentation (shear stress τ versus normal stress σ_n) of the state of stress in (U)HP rocks. C is cohesion and ϕ is internal friction angle. In Yamato and Brun's model, (U)HP rocks were at the same depth corresponding to lithostatic pressure (P_l). Solid red and solid green circles are the stress states in compression and extension respectively, both required to reach the Mohr-Coulomb yield surface. In viscous rheology, the differential stresses associated with P_{peak} and P_{retro} are far below the yield surface (red and green dashed Mohr circles). Simple relations among parameters can be derived from the geometry of Mohr circle construction. **b**, Plot of P_{peak} versus ΔP of data with error bars. The data are compiled in their original paper. Their model-predicted relation ($P_{\text{peak}} = 1.5\Delta P$) is the dash black line. Solid green line is the best-fit for the data. Shaded grey region covers the UHP data (>2.5GPa) and shaded pink region HP data (<2.5GPa).

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