Metamorphic data from subduction zones do not call for significant overpressures

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The work of Yamato and Brun[1] has profound implications for the geodynamics of subduction zones. If their model holds, most research on (ultra)high-pressure rocks since their discovery[2-4] would require serious reconsideration. Here, I point out that their model requires critical assumptions that are hard to justify for subduction zones. More importantly, the natural data that they considered to support their model can be better explained without invoking their model.

The mineral assemblages of (ultra)high-pressure-low temperature ((U)HP-LT) rocks worldwide commonly record two distinct pressures: a higher 'peak' pressure (P_{peak}), which is interpreted by most geologists to represent the maximum depth the rocks reached where they underwent (U)HP metamorphism, and a lower 'retrograde' pressure (P_{reto}) that is commonly taken to reflect the depth the rocks were exhumed to, following peak metamorphism[4-6]. This interpretation is based on the general assumption that the pressures derived from metamorphic rocks are essentially lithostatic. Although it is generally agreed that pressure in Earth's lithosphere is expected to deviate from the lithostatic value, the magnitude of this deviation is always limited by the strength of rocks which on the Ma time scale relevant for metamorphism is likely below hundreds of MPa[7], far below the GPa level lithostatic pressure.

Yamato and Brun[1] claimed that pressure data from worldwide (U)HP rocks could be explained by a tectonic stress switch from burial related compression to extension at the onset of exhumation. They proposed that both the peak and retrograde metamorphism took place at the same depth corresponding to the lithostatic pressure P_l (Fig.1a). P_{peak} was due to an excess tectonic overpressure (R, Fig.1a) related to the compressive stress regime ($P_{\text{peak}} = P_l + R$) whereas P_{retro} was due to a tectonic underpressure (r, Fig.1a) when the stress regime switched to extension (i.e., $P_{\text{retro}} = P_l - r$) (Fig.1a). Thus, the pressure drop, $\Delta P = P_{\text{peak}} - P_{\text{retro}} = R + r$, does not require any actual ascent of the rocks. This extraordinary claim is based on the following assumptions: 1) The rheology of rocks is Mohr-Coulomb frictional. 2) The stress state must remain on the yield surface so that Mohr circles touch the Mohr-Coulomb yield envelop. 3) The stress state is Andersonian with the vertical stress being a principal stress with magnitude equal to the lithostatic pressure.

None of these assumptions are justifiable for (U)HP metamorphism. First, the transformation of mineral phases during (U)HP-LT metamorphism takes place on the Ma time scale[8] for which the more relevant rheology is viscous[9]. Frictional behaviors in (U)HP rocks are associated with transient events like the formation pseudotachylyte[10] quite unrelated to the Ma time scale blueschist and eclogite facies metamorphism. Second, there is no evidence that differential stresses of many GPas can be sustained for the Ma time scale of (U)HP metamorphism

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as required if the stress state reaches the Mohr-Coulomb yielding envelop. In the compression regime for instance, the differential stress ($2R$ in Fig.1a) for $\phi = 30^\circ$ is $2P_l$. Many (U)HP eclogites did not even develop ductile fabrics[11] which suggest that the differential stress was below the ~100MPa level required to activate the dislocation creep at a viscous strain rate around $10^{-12}s^{-1}$ [12]. Third, (U)HP rocks are tabular bodies constrained at great depth in the subduction zone. The stress orientations and magnitudes in (U)HP rocks at the time of peak and retrograde metamorphism were determined by their mechanical interactions with the surrounding lithosphere[13-15], which makes it unlikely for the stress state to be Andersonian.

If one accepts the above three assumptions, then simple relations among the pressure parameters can be derived (see Fig.1a) based on the geometry of the Mohr circle representation. A major result is the following linear relation between P_{peak} and ΔP:

$$P_{\mathrm{peak}} = \frac{1+\sin\phi}{2\sin\phi}\Delta P - C\cdot\cot\phi \qquad (1)$$

Taking $\phi = 30^\circ$ and C=0, this relation becomes $P_{\mathrm{peak}} = \frac{3}{2}\Delta P$. Yamato and Brun claimed that this relation explained the linear dependence between P_{peak} and ΔP (their fig.1b) which they considered to be "extremely difficult to reconcile with" variations in subduction zone characteristics and the wide variety of tectonic settings where (U)HP rocks are found.

I challenge this claim. The same data are replotted here in Fig.1b. The best-fit line (solid green line) is $P_{\mathrm{peak}} = 1.17\Delta P + 0.56$ which has a slope significantly below their predicted $\frac{3}{2}$ (red dashed line in Fig.1b). In addition, the line does not pass the origin but has a positive intercept of 0.56GPa (green square dot in Fig.1b) on the P_{peak} axis. An alternative and more reasonable interpretation of the data is that they show nothing more than the trivial relation of $P_{\mathrm{peak}} = \Delta P + P_{\mathrm{retro}}$. While (U)HP rocks have formed over a large range of P_{peak} (from 1 to over 4 GPa), they were exhumed to a narrow range of P_{retro} between 0.5 GPa and 1.5 GPa after peak metamorphism. The deviation of the best-fit line from 1 is caused by the spread of P_{retro} around 1.0 ± 0.5 GPa. As the relation $P_{\mathrm{peak}} = \Delta P + P_{\mathrm{retro}}$ is a definition, it certainly is independent of any mechanisms of subduction zones or variations in their characteristics.

This spread of P_{retro} corresponds to the depth range around 20-50 km, if the general lithostatic pressure assumption is made, which is consistent with the fact that (U)HP rocks are found in the lowermost crust settings[4]. There may be unrecognized geodynamic mechanisms for P_{retro} to cluster in this range. But it is possible that (U)HP-LT rocks exhumed to a level deeper than 1.5 GPa might still be buried or their (U)HP record had been subsequently reset and (U)HP rocks exhumed to depths shallower than 0.5 GPa are more susceptible to erosional removal.

The fact that natural data call for nothing more than the trivial definition relation $\Delta P = P_{\text{peak}} - P_{\text{retro}}$ to explain supports the current interpretation that P_{peak} and P_{retro} recorded two independent events at different depths. The differential stresses associated with P_{peak} and P_{retro} were likely an order of magnitude or more below the yielding stresses (dashed Mohr circles in Fig.1a). It is important to emphasize that if one gives up the assumption that ΔP must arise from a stress regime change at the same depth or the assumption that the stress states must be Andersonian, then the two dashed Mohr circles are not required to meet on the horizontal axis. The argument of Yamato and Brun that pressure drop in ductile rheology must be always smaller than that in frictional rheology (their fig.3) is no longer valid.

In conclusion, current pressure and pressure drop data from (U)HP rocks worldwide can be well understood within the current framework of metamorphic geology. It is unnecessary to invoke the mechanisms proposed by Yamato and Brun.

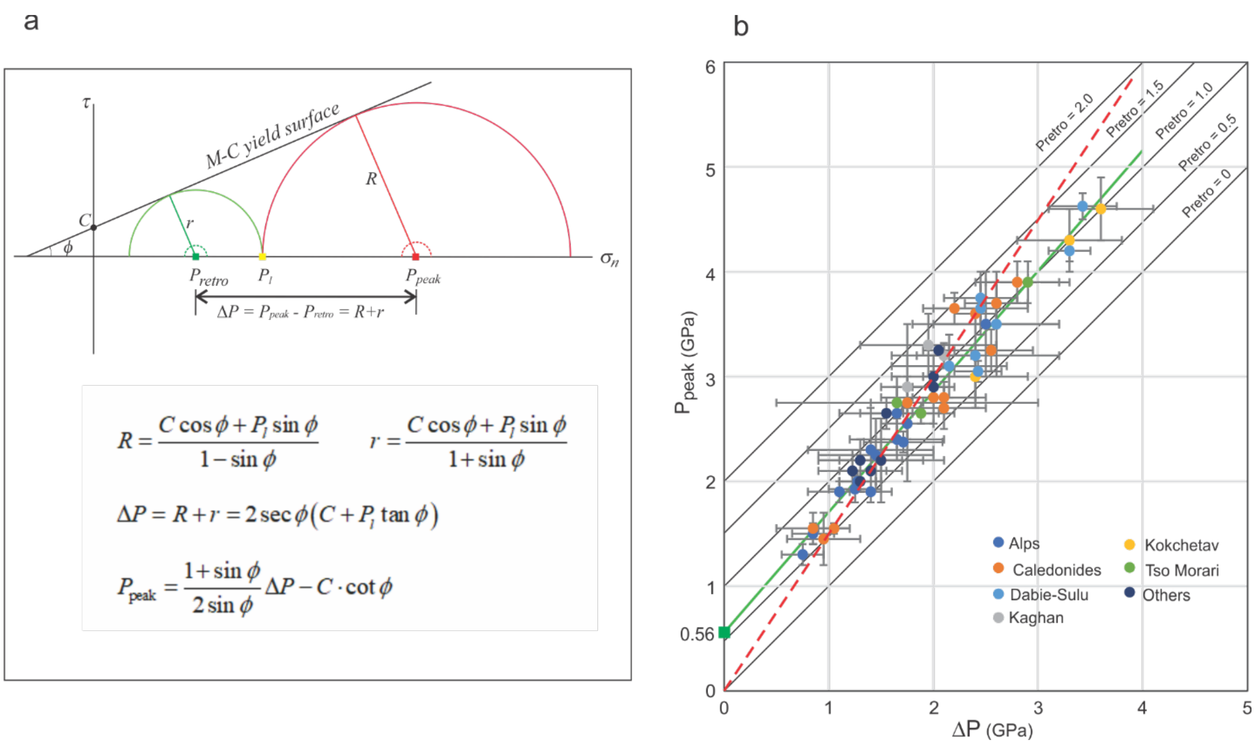

Figure 1: Mohr circle representation of Yamato and Brun's model and plot of natural pressure data from subduction zones. **a**, Mohr circle representation (shear stress τ versus normal stress σ_n) of the state of stress in (U)HP rocks. C is cohesion and ϕ is internal friction angle. In Yamato and Brun's model, (U)HP rocks were at the same depth corresponding to lithostatic pressure (P_l). The stress states in compression and in extension are represented by the solid red and solid green circles respectively, both reaching the Mohr-Coulomb yield surface. The two Mohr circles meet at P_l on the horizontal axis. If viscous rheology is considered, the differential stresses associated with P_{peak} and P_{retro} are at least an order of magnitude below the yield surface (represented schematically by the 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 natural data with error bars. The solid green line is the best-fit for the data and the red dashed line is for $P_{\text{peak}} = \frac{3}{2}\Delta P$.

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