Metamorphic data from global subduction zones do not call for excessive overpressures

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Yamato and Brun[1] claimed that metamorphic data from global (ultra)high-pressure ((U)HP) rocks exhibit an unusual linear relation, between peak pressure and pressure drop, which challenges current interpretation of *P-T-t* paths but supports their model invoking excessive overpressures. If their model holds, most research on (U)HP rocks since their discovery[2-4] would require serious reconsideration. Here, I demonstrate that their model requires critical assumptions that are neither justified by the principles of rock mechanics in the context of realistic geologic settings nor consistent with microstructures of (U)HP rocks. Furthermore, the global data are inconsistent with their model prediction but can be readily explained in the current framework.

The mineral assemblages of (U)HP rocks commonly record a 'peak' pressure (P_{peak}), which is interpreted by most 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[4,5]. This interpretation assumes that the metamorphic pressures are approximately lithostatic. In reality, the metamorphic pressure is expected to 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 [6].

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 tectonic stress regime switch from compression to extension 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) in 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 from the geometry of the Mohr circle presentation (Fig.1a). A major result is the linear relation $P_{\text{peak}} = \dfrac{1+\sin\phi}{2\sin\phi}\Delta P - C\cdot\cot\phi$. As C is small (<0.05GPa) compared to P_{peak} and ΔP, this relation simplifies to:

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

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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[7] for which the rocks deform predominantly by viscous flow as required by the *P-T* conditions[8,9]. Frictional behaviors in (U)HP rocks could have been associated with local and/or transient events[10,11] 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 of (U)HP metamorphism. Such high differential stresses would have caused fast strain rates ($\sim 10^{-10}s^{-1}$), many orders of magnitude higher than those expected of crustal mylonites, based on available flow laws [9,12] for quartzofeldspathic and eclogite rocks under (U)HP conditions. There is no microstructural evidence in (U)HP rocks for this. Third, because (U)HP rocks are rheologically distinct bodies constrained at great depth in a subduction zone, the stress orientations and magnitudes in the rocks were determined by their mechanical interaction with the surrounding lithosphere[6,13,14], which makes the stress state unlikely Andersonian.

A big claim of Yamato and Brun is that natural data from global (U)HP rocks (Fig.1b) exhibit an unusual linear relation between P_{peak} and ΔP (their fig.1b) that challenges 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 [4,15]. As the HP rocks were formed near the Moho of thickened continental crusts, buoyancy driving might have not been as significant in their exhumation, leading to a different mean of P_{retro}. As the relation $P_{\text{peak}} = \Delta P + P_{\text{retro}}$ is a definition, it applies to all (U)HP rocks, regardless of any possible difference in their burial and exhumation processes or tectonic settings in which they are found.

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). The fact that natural pressure data from global (U)HP rocks conform to the truism relation $\Delta P = P_{\text{peak}} - P_{\text{retro}}$ supports the current interpretation that P_{peak} and P_{retro} recorded two events at different depths. It is unnecessary to invoke mechanisms with excessive overpressures.

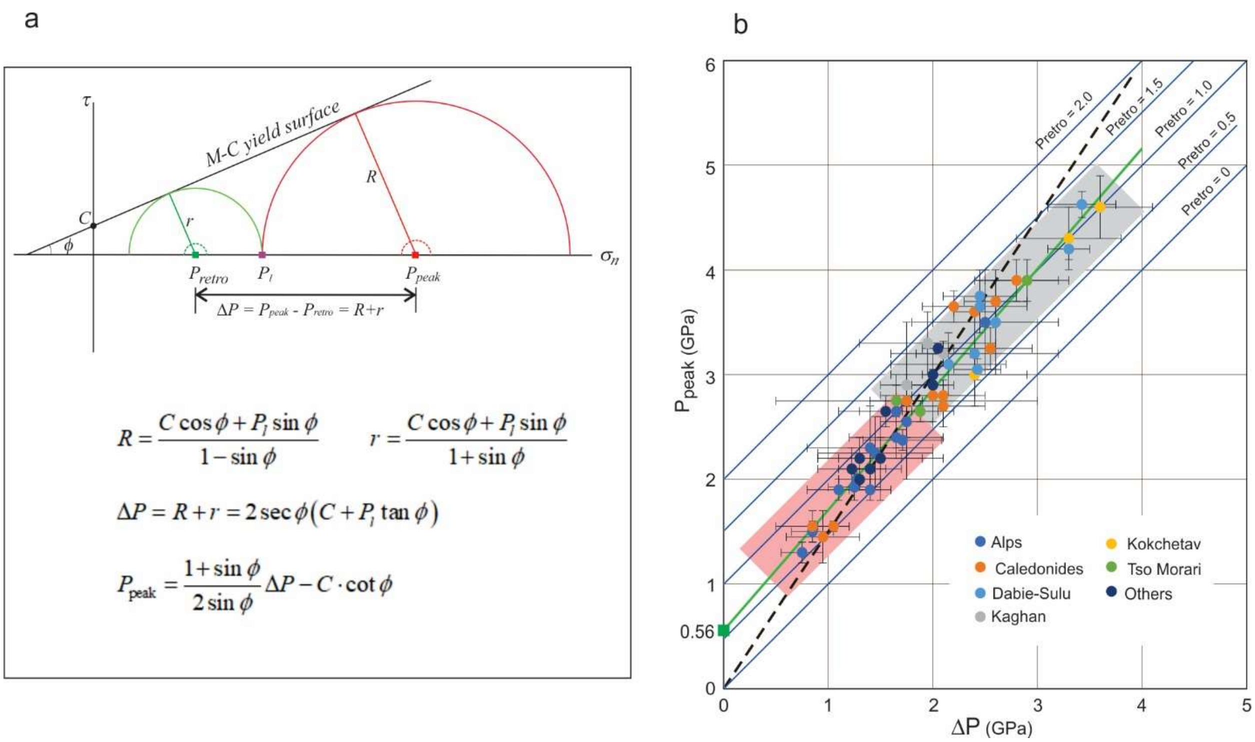

Figure 1: Mohr circle presentation of Yamato and Brun's model and plot of natural pressure data from global (U)HP rocks. **a**, Mohr circle representation (shear stress τ versus normal stress σ_n) of the state of stress in (U)HP rocks. C is cohesion and ϕ is internal friction angle. In Yamato and Brun's model, (U)HP rocks were at the same depth corresponding to lithostatic pressure (P_l). The stress states in compression and 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 (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 black dashed line is for $P_{\text{peak}} = 1.5\Delta P$. Shaded grey region covers UHP data (>2.5GPa) and shaded pink region HP data (<2.5GPa).

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