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

Dazhi Jiang[1]

The work of Yamato and Brun[1] has profound implications for the geodynamic conditions responsible for (ultra)high-pressure metamorphism. If their model holds, most research on (ultra)high-pressure rocks since their discovery[2-4] would require serious reconsideration. Here, I demonstrate that their model requires critical assumptions that cannot be justified by the principles of rock mechanics in the context of realistic geologic settings. More importantly, the global data that they considered to support their model can be better explained in the current framework without invoking their model with excessive overpressures.

The mineral assemblages of (ultra)high-pressure ((U)HP) rocks commonly record a 'peak' pressure (P_{peak}), which is interpreted by most geologists 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[4-6]. 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[7] for the Ma time scale relevant for (U)HP metamorphism and far below the GPa level lithostatic pressure.

Yamato and Brun[1] claimed 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, Fig.1a) in compression ($P_{\text{peak}} = P_l + R$) 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, $\Delta P = P_{\text{peak}} - P_{\text{retro}} = R + r$, 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 representation (Fig.1a). 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 compared to P_{peak} and ΔP, this relation simplifies to:

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

[1] Department of Earth Sciences, Western University, London, ON, Canada N6A 5B7. Email: djiang3@uwo.ca

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 $P_{\mathrm{peak}}=\frac{3}{2}\Delta P$.

However, none of the above assumptions are justifiable for (U)HP metamorphism. First, the transformation of mineral phases during (U)HP metamorphism occurs at a Ma time scale[8] for which the rocks deform viscously as required by the P-T conditions[9]. Frictional behaviors in (U)HP rocks could have been associated with transient high-strain-rate events such as the formation of pseudotachylyte[10]. Second, there is no evidence that GPa-level differential stresses can be sustained for the Ma time scale of (U)HP metamorphism, which is implied in their model (the differential stress in compression for $\phi=30^{\circ}$ is $2P_l$). The lack of ductile-flow fabrics in many (U)HP rocks[11] suggests that differential stresses were probably below 100 MPa to activate dislocation creep[12]. Third, as tabular bodies constrained at great depth in a subduction zone, the stress orientations and magnitudes in (U)HP rocks were determined by their mechanical interaction with the surrounding lithosphere[7, 13, 14], which makes Andersonian stress state unlikely.

Yamato and Brun claimed that natural data of P_{peak} and ΔP (Fig.1b) from global (U)HP rocks from a wide variety of tectonic settings support their model-predicted relation in Eq.1. However, the best-fit line (solid green line in Fig.1b) of the data is $P_{\mathrm{peak}}=1.17\Delta P+0.56$. It has a slope significantly below the predicted 1.5 (dashed red line in Fig.1b) as well as a positive intercept at 0.56 GPa that is inconsistent with Eq.1. An alternative and more straightforward interpretation of the data is through the trivial relation of $P_{\mathrm{peak}}=\Delta P+P_{\mathrm{retro}}$. 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 narrow range of P_{retro} between 0 and 1.5 GPa, with a mean P_{retro} at 0.56GPa. The spread of P_{retro} around 1.0 ± 0.5 GPa can explain the small deviation of the slope of the best-fit line from 1. The spread of P_{retro} corresponds to depths of 20-50 km, which is consistent with the fact that (U)HP rocks are found in the lowermost crust settings[4]. As the relation $P_{\mathrm{peak}}=\Delta P+P_{\mathrm{retro}}$ is a definition, it is valid in all (U)HP rocks, regardless of any possible difference in their burial and exhumation histories.

If one does not make the assumptions as Yamato and Brun, then the two Mohr circles for the stress states at P_{peak} and P_{retro} are not required to meet on the horizontal axis. The differential stresses are also much lower than the yielding stresses as well (dashed Mohr circles in Fig.1a). 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. The fact that natural pressure data from global (U)HP rocks conforms to the truism relation $\Delta P=P_{\mathrm{peak}}-P_{\mathrm{retro}}$ supports the current interpretation that P_{peak} and P_{retro} recorded two independent events at different depths. It is unnecessary to invoke the mechanisms proposed by Yamato and Brun.

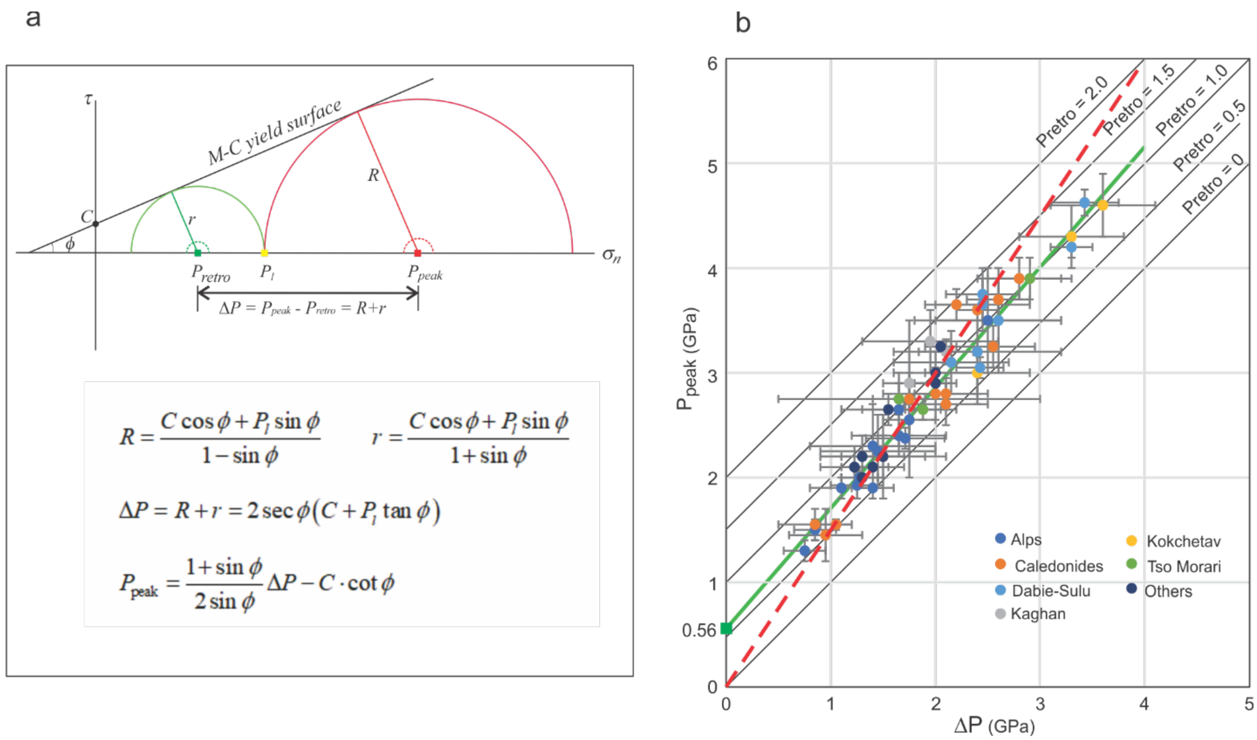

Figure 1: Mohr circle representation of Yamato and Brun's model and plot of natural pressure data from subduction zones. **a**, Mohr circle representation (shear stress τ versus normal stress σ_n) of the state of stress in (U)HP rocks. *C* is cohesion and ϕ is internal friction angle. In Yamato and Brun's 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 $P_{peak} = \frac{3}{2}\Delta P$.

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