

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

Dazhi Jiang^a

Yamato and Brun¹ 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 exhumed²⁻⁴. 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 pressure⁵.

Yamato and Brun¹ proposed that the drop in pressure from P_{peak} to P_{reto} 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_{reto} was due to a tectonic underpressure r when the stress regime switched to extension ($P_{\text{reto}} = P_l - r$) (Fig.1a). Thus, the pressure drop, $\Delta P = P_{\text{peak}} - P_{\text{reto}} = R + r$, 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 ($< 0.05 \text{ GPa}$) compared to P_{peak} and ΔP , this relation simplifies to:

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

^a 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 $P_{\text{peak}} = 1.5 \Delta P$.

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 events⁸,⁹ 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 0.56 GPa. 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 (>2.5 GPa) and high pressures (<2.5 GPa) separately, 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 $0.75 \sim 1.0 \pm 0.5$ 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.

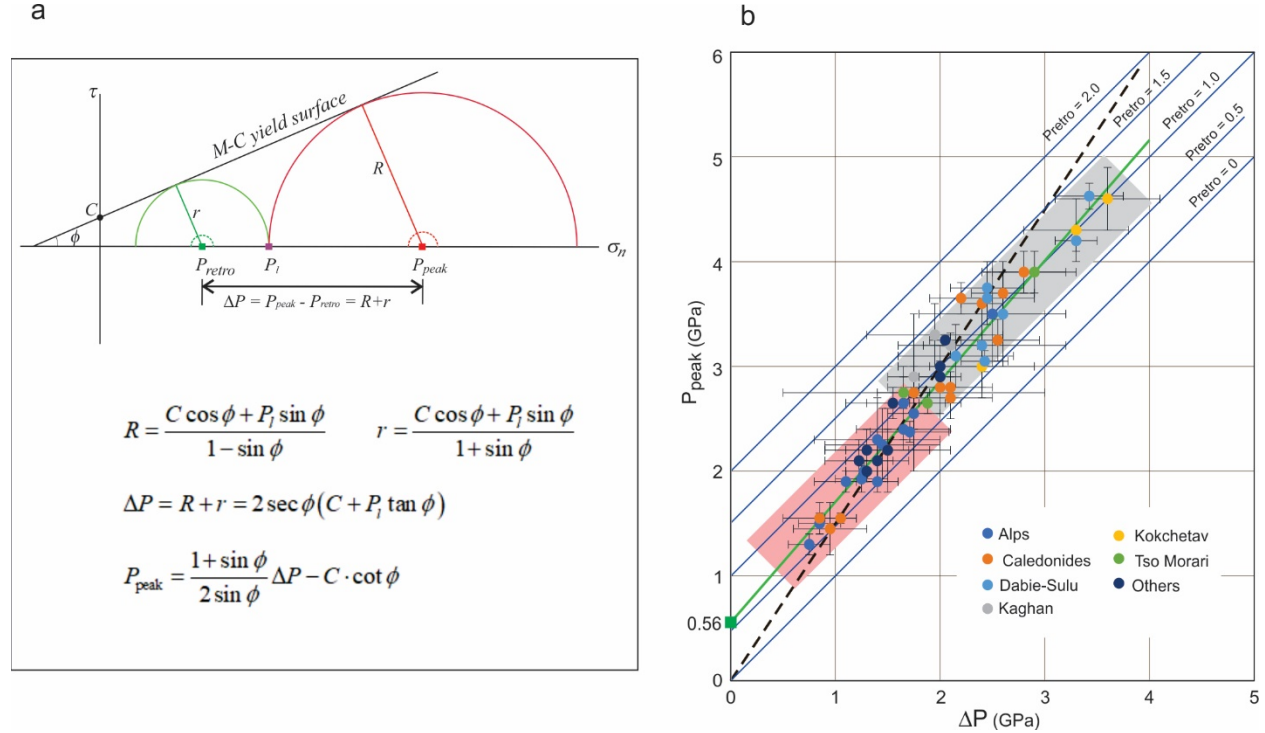


Figure 1: Mohr circle presentation of Yamato and Brun's model and plot of pressure data from global (U)HP rocks. **a**, Mohr circle presentation (shear stress τ versus normal stress σ_n) of the state of stress in (U)HP rocks. C is cohesion and ϕ is internal friction angle. In Yamato and Brun's model, (U)HP rocks were at the same depth corresponding to lithostatic pressure (P_i). 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 (>2.5 GPa) and shaded pink region HP data (<2.5 GPa).

References

1. Yamato, P. & Brun, J.P. Metamorphic record of catastrophic pressure drops in subduction zones. *Nature Geosci.* **10**, 46-50 (2017).
2. Ernest, W.G., Hacker, B. R. & Liou, J. G. Petrotectonics of ultrahigh-pressure crustal and upper-mantle rocks – Implications for Phanerozoic collisional orogens. *Geol. Soc. Am.* **433**, 21-49 (2007).
3. Powell, R. P. & Holland, T. Using equilibrium thermodynamics to understand metamorphism and metamorphic rocks. *Elements* **6**, 309-314 (2010).
4. Hacker, B.R. & Gerya, T.V. Paradigms, new and old, for ultrahigh-pressure tectonism. *Tectonophysics* **603**, 79–88(2013).
5. Jiang, D. & Bhandari, A. Pressure variations among rheologically heterogeneous elements in Earth's lithosphere: A micromechanics investigation. *Earth Planet. Sci. Lett.* **498**, 397-407 (2018).
6. Kohlstedt, D. L., Evans, B., & Mackwell, S. J. Strength of the lithosphere: Constraints imposed by laboratory experiments. *J. Geophys. Res. (Solid Earth)*. **100** (B9), 17587–17602 (1995).
7. Jin, Z.-M., Zhang, J. Green, H.W., Jin, S. Eclogite rheology: implications for subducted lithosphere. *Geology* **29**, 667–670 (2001).
8. Andersen, T.B., Mair, K., Austrheim, H., Podladchikov, Y.Y., Vrijmoed, J.C. Stress release in exhumed intermediate and deep earthquakes determined from ultra-mafic pseudotachylite. *Geology* **36**, 995–998 (2008).
9. Stöckhert, B. Stress and deformation in subduction zone: insight from the record of exhumed metamorphic rocks. *Geol. Soc. Lond. Spec. Publ.* **200**, 255-274 (2002).
10. Lu, L. X. & Jiang, D. Quartz flow law revisited: the significance of pressure dependence of the activation enthalpy. *J. Geophys. Res.: Solid Earth* **124**(1), 241-256 (2019).
11. Eshelby, J.D. The determination of the elastic field of an ellipsoidal inclusion, and related problems. *Proc. R. Soc. Lond. Ser. A, Math. Phys. Sci.* **241**, 376–396 (1957)
12. Jiang, D. Viscous inclusions in anisotropic materials: theoretical development and perspective applications. *Tectonophysics* **693**, 116–142 (2016).
13. Yin, A., Manning, C. E., Lovera, O., Menold, C. A., Chen, X., & Gehrels, G. E.. Early Paleozoic tectonic and thermomechanical evolution of ultrahigh-pressure (UHP) metamorphic rocks in the northern Tibetan Plateau, northwest China. *Int. Geol. Rev.* **49**(8), 681-716 (2007).
14. Chopin, C. Coesite and pure pyrope in high-grade blueschists of western alps: a first record and some consequences. *Contrib. Mineral. Petrol.* **96**, 253-274 (1984).
15. Smith, D. Coesite in clinopyroxene in the Caledonides and its implications for geodynamics. *Nature* **310**, 64-644 (1984).

Acknowledgements

I thank A. Yin for a discussion on buoyancy and advice on style.