Comment on "Pressure-to-Depth Conversion Models for Metamorphic Rocks: Derivation and Applications"

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Abstract

Bauville and Yamato (2021, G-cubed, https://doi.org/10.1029/2020GC009280) propose model-based methods to convert metamorphic pressures to depths based on the claim that pressure data from global (ultra)high-pressure rocks challenge the lithostatic assumption and support their model which invokes excessive overpressures. It is argued here that the opposite is true: Natural pressure data are fully consistent with the lithostatic assumption. They reflect selection of (ultra)high-pressure rocks by accessibility and preservation. The data are however inconsistent with the model predictions of Yamato and Brun (2017, Nature Geoscience 10, 46-50) and Bauville and Yamato (2021). Furthermore, their model requires critical assumptions that are not justified by the principles of rock mechanics and unsupported by microstructures from (U)HP rocks.

Comment on "Pressure-to-Depth Conversion Models for Metamorphic Rocks: Derivation and Applications"

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Abstract: Bauville and Yamato (2021, G-cubed, https://doi.org/10.1029/2020GC009280) propose model-based methods to convert metamorphic pressures to depths based on the claim that pressure data from global (ultra)high-pressure rocks challenge the lithostatic assumption and support their model which invokes excessive overpressures. It is argued here that the opposite is true: Natural pressure data are fully consistent with the lithostatic assumption. They reflect selection of (ultra)high-pressure rocks by accessibility and preservation. The data are however inconsistent with the model predictions of Yamato and Brun (2017, Nature Geoscience 10, 46-50) and Bauville and Yamato (2021). Furthermore, their model requires critical assumptions that are not justified by the principles of rock mechanics and unsupported by microstructures from (U)HP rocks.

Keywords: tectonic overpressure; UHP metamorphism; lithostatic pressure; Mohr-Coulomb plasticity; rheology; finite strain

Key Points:

- Pressure data from (ultra)high pressure rocks are compatible with lithostatic assumption but are inconsistent with excessive overpressures.

- Model invoking excessive overpressures requires assumptions not justifiable and is unsupported by rock microstructures.

- Tectonic fabrics cannot represent stress states and Mohr-Coulomb plasticity is independent of stress rotation.

1. Introduction

Yamato and Brun (2017) and Bauville and Yamato (2021) claim that metamorphic pressures from global (ultra)high-pressure ((U)HP) rocks challenge the lithostatic pressure assumption but support their model that invokes excessive overpressures. Bauville and Yamato (2021) propose methods to convert metamorphic pressure data to depth on the basis of the Yamato and Brun model and its development. The purpose of this comment is threefold. First, I contest their interpretation of the natural pressure data and argue that the data are fully consistent with and better explained by common interpretations based on the lithostatic assumption. Second, I point out that their model requires critical assumptions that are not justified by the principles of rock mechanics and are unsupported by microstructures of (U)HP rocks. Finally, I question some concepts and derivation in Bauville and Yamato (2021) related to finite strain deformation, stress rotations, and the Mohr-Coulomb rheology.

2. Do Pressure Data from (U)HP Rocks Challenge the Lithostatic Assumption and Support a Mechanic Model Invoking Excessive Overpressures?

The mineral assemblages of (U)HP rocks commonly record a 'peak' pressure (P_p), which is commonly interpreted by researchers to represent the maximum depth of rock burial (Chopin 1984; Smith 1984), and a lower 'retrograde' pressure (P_r) interpreted to represent the depth of the initial isothermal decompression (Ernst et al., 2007; Hacker and Gerya 2013; Powell and Holland, 2010). The pressure drop, $\Delta P = P_p - P_r$, thus corresponds to the amount of exhumation attained by the isothermal decompression. This interpretation assumes that P_p and P_r are approximately lithostatic (lithostatic assumption, hereafter). In reality, both P_p and P_r may deviate from the lithostatic values, but the magnitude of deviation is limited by the rock strength, which is likely less than hundreds of MPa for the time scale relevant for (U)HP metamorphism and far below the GPa level lithostatic pressure (e.g., Jiang and Bhandari 2018).

The pressure data from global (U)HP rocks as compiled in Bauville and Yamato (2021) are replotted in the P_p vs ΔP space (Fig.1A) and in the P_p vs P_r space (Fig.1C). Yamato and Brun (2017, p.47) claim that the linear relation between P_p and ΔP "…puts in question the classical interpretation [based on the lithostatic assumption] of P-T-t paths …" but supports their model that invokes excessive overpressures. They propose that ΔP may be due to a switch in stress regime, from compression to extension, at the same depth without actual ascent of the rocks. Bauville and Yamato (2021) argue that there is a linear dependence of P_r on P_p that requires their model to explain.

Let us examine the plots in Figs.1A and C carefully and see if the assumption that P_p and P_r are lithostatic will lead to great difficulty.

As P_p, P_r, and ΔP are related by $P_p = \Delta P + P_r$, for each data point in Fig.1A, one can draw a line of unit slope passing the data point and the intercept of the line on the vertical axis is the corresponding P_r (Fig.1B). Considering this for all data points in the set, one realizes that all

P_r are clustered within a narrow strip (δP_r, purple-shaded in Fig.1A) between ~0.3 and 1.3GPa. The overall trend for all the data, having a slope near unity, as indicated by the linear regression fit of $P_p = 1.17\Delta P + 0.52$, is clearly because of the limited range in P_r. With the lithostatic assumption, δP_r corresponds to depths between ~12 and 50km. Thus, Fig.1A suggests that although (U)HP rocks in the current dataset were formed over a great pressure range (from below 1 GPa to over 4 GPa), corresponding to 35km and >140 km depth difference, they were exhumed during the isothermal decompression stage to the limited depth range of ~12 and 50 km. This depth range may simply represent the interval where (U)HP rocks are preserved after formation at deeper levels *and* are accessible to our observations. Ultra-high pressure assemblages with P_r>~1.3GPa may have not been preserved and, if preserved, may still be buried and not accessible for observation yet. Thus, the linear trend of the data may simply reflect natural selection of (U)HP rocks by accessibility and preservation, independent of exhumation mechanisms.

A big claim of Yamato and Brun (2017, p.47) is that the linear relation as shown in Fig.1A challenges the lithostatic assumption but supports their analysis which yielded a model prediction of $P_p = \frac{1+\sin\phi}{2\sin\phi}\Delta P - C\cdot\cot\phi$, where ϕ and C are the friction angle and cohesion respectively. The dashed blue line in Fig.1A, $P_p = 1.5\Delta P$, is for $\phi = 30^\circ$ and C=0. However, the data trend has a much shallower slope near unity and a significant positive intercept of 0.52 that are inconsistent with the model prediction.

Perhaps noticing the above discrepancy between data and prediction, Bauville and Yamato (2021) used the P_p vs P_r plot instead. In the plot of the same data here (Fig.1C), I have used an equal scale for P_r and P_p to avoid distortion of line slopes. Fig.1C is also fully compatible with the lithostatic assumption. One should note that although in the lithostatic interpretation P_p and P_r represent two events at different depths, the distribution of P_p vs P_r *cannot* be totally random in space because of the following constraints. First, by definition all data must plot above the grey-shaded area whose upper bound is given by the $P_p = P_r$ line (Fig.1C). Second, as (U)HP rocks are formed in low-temperature and high-pressure settings, they must be exhumed, shortly after formation (Ernst et al., 2007), to shallower depths (corresponding to δP_r in Fig.1A and C) so that the (U)HP assemblages are preserved. Direct geological observations are also constrained by the accessibility of rock exposures. The δP_r interval is consistent with accessible depth range for direct observations. Thus, a greater P_p must in general be associated with a greater ΔP, as supported by Fig.1A, for the rocks to reach the δP_r interval. Although the exhumation rate for (U)HP rocks varies and may be as fast as the subduction rate (e.g., Rubatto and Hermann, 2001; Parrish et al., 2006), the maximum amount of stage 1 exhumation is always limited by the duration of the exhumation multiplied by the rate of exhumation. This means that an extremely low P_r (like 0.5GPa) associated with a very high P_p

(like 4.0 GPa) is unlikely, as such a P_p and P_r pair requires an unreasonable amount of exhumation in stage 1 (Fig.1C). The current dataset suggests that 12km (~0.3 GPa) might be the shallowest depth to which (U)HP rocks can be exhumed by stage 1 exhumation. With the above constraints considered, the distribution of P_p and P_r in Fig.1C is fully consistent with P_r being independent of P_p.

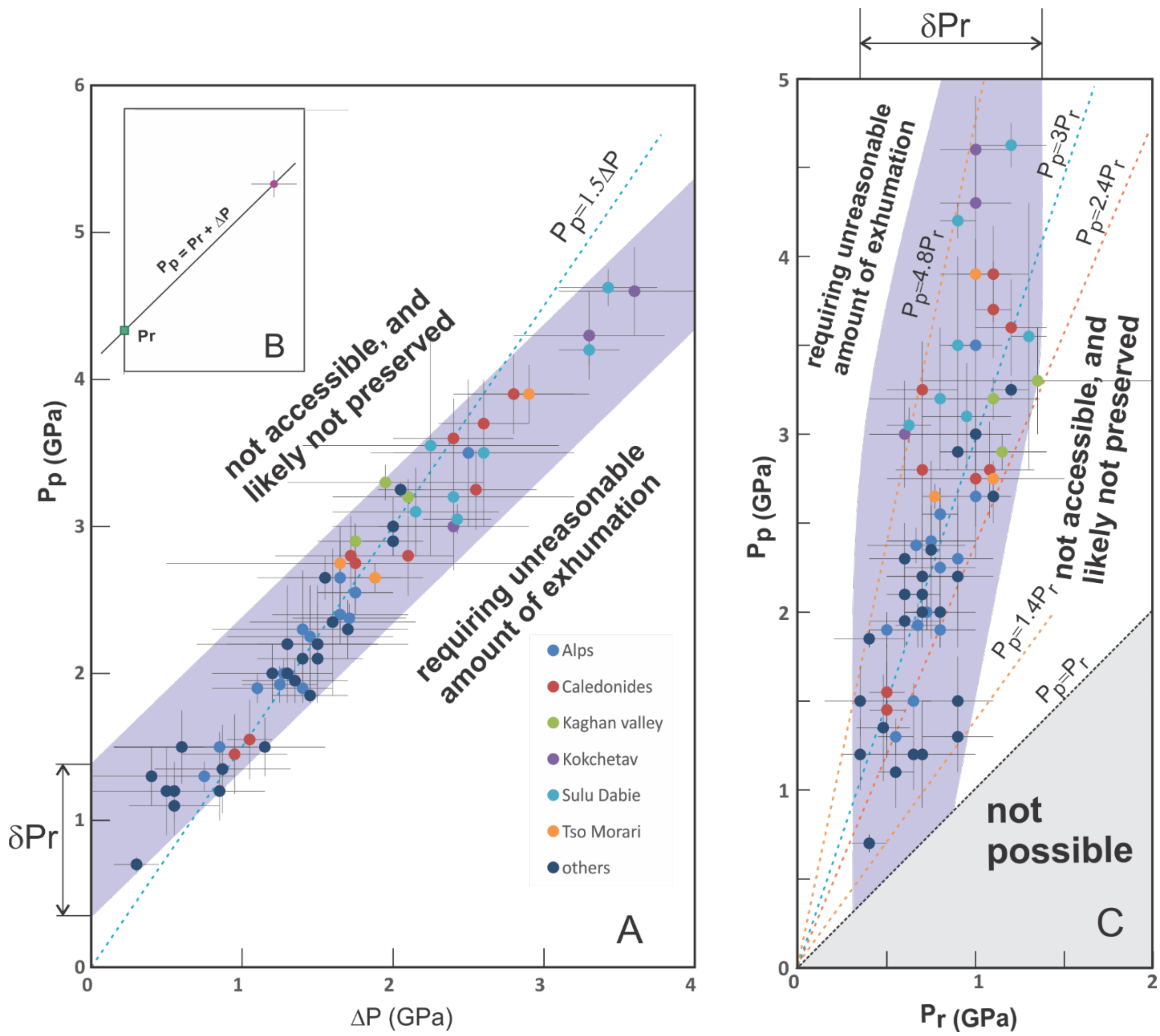

Figure 1: Metamorphic pressure data from global (U)HP rocks. (A): Plot of P_p vs ΔP of data with error bars. The trend for all the data has a slope close to unity. Purple shaded region represents the narrow strip of δP_r between 0.3 and 1.3 GPa. The blue dashed line is the model-predicted relation ($P_p = 1.5\Delta P$) of Yamato and Brun (2017). (B) Each data point corresponds to a P_r through the definition relation $P_p = \Delta P + P_r$. (C): The same data with error bars plotted in the P_p vs P_r space. The upper bound of the grey-shaded area is given by $P_p = P_r$. No data may

plot in this area. δP_r corresponds to the range shown in (A). The blue dashed line ($P_\mathrm{p} = 3P_r$) corresponds to that of $P_\mathrm{p} = 1.5\Delta P$ in (A). By changing the horizontal stress magnitude or varying the principal stress orientation, varying slopes for the P_p vs P_r relation (orange dashed lines) are predicted by Yamato and Brun (2017) and Bauville and Yamato (2021). Purple shaded region outlines the domain (U)HP rocks are preserved *and* accessible. The data are compiled in Bauville and Yamato (2021). See text for more detail.

The argument of Bauville and Yamato (2021) that Fig.1C shows a *linear* dependence of P_r on P_p is rather far-fetched. To explain the spread of the data, the authors have to 1) invoke a wide range (from zero to several GPa) of differential stress values by a change in horizontal stress magnitude or a rotation of the stress tensor, and 2) propose that the "linear dependence" of P_r on P_p is represented by a fan area. There are two issues. First, once the stress tensor is rotated, the stress state is non-Andersonian. The assumption by Bauville and Yamato (2021) that $\sigma_z = \rho g z$ is not justified. Second, as the data are so scattered, the fan area that defines the linear dependence of P_r on P_p must cover almost the entire P_p vs P_r space except the grey-shaded area and the area that requires unreasonable amount of exhumation (Fig.1C). It is much simpler to interpret such a wide distribution of the pressure data as demonstrating that P_r and P_p are independent.

3. Model Assumptions

The model proposed by Yamato and Brun (2017) which was used and elaborated on by Bauville and Yamato (2021) requires the following assumptions: 1) the rock rheology follows a Mohr-Coulomb plasticity or a Byerlee's frictional behavior, 2) the stress state is close to or at the yield state, and 3) the stress state is Andersonian.

None of these assumptions can be well justified for (U)HP metamorphism. First, Mohr-Coulomb plasticity and Byerlee's frictional behaviors are the rheological responses for the upper brittle lithosphere (Kohlstedt, et al., 1995). Such frictional behaviors may occur at greater depth, but only associated with localized, high strain-rate events such as earthquakes (Andersen et al., 2008; Stöckhert, 2002). The pressure data compiled by Yamato and Brun (2017) and Bauville and Yamato (2021) were derived from mineral assemblages that do not represent such events. Tectonic fabrics are common in (U)HP rocks, as noticed by Bauville and Yamato (2021). They reflect large finite strains, consistent with viscous flow over the million-year time scale (Kohlstedt, et al., 1995; Jin et al., 2001). Second, stress state close to the yield state at (U)HP depths requires that GPa-level differential stresses (up to 2 times the lithostatic pressure) be sustained for the time scale and *P-T* condition of (U)HP metamorphism. Such levels of stress are more than an order of magnitude higher than stress estimates for crustal mylonites (e.g., Behr and Platt, 2014; Stipp and Tullis, 2003) and would have caused (U)HP rocks to flow at strain rates many orders of magnitude faster than crustal mylonites (Jin et al, 2001; Hirth et al., 2001;

Lu and Jiang, 2019). There is no microstructural evidence from (U)HP rocks that supports this. 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 (Jiang and Bhandari, 2018; Jiang 2016; Eshelby 1957), and are unlikely Andersonian.

4. Stress, Strain, and Mohr-Coulomb Rheology

Bauville and Yamato (2021) have used stress and strain terms interchangeably such as using “flattening deformation” for a stress state. This would have been acceptable if one deals with elastic-frictional deformation in isotropic materials because in such conditions the strain is sufficiently small and the principal axes for the stress tensor and for the strain tensor are coincident. However, the authors propose to use the shape of strain ellipsoid obtained from tectonic fabrics to determine the relative magnitudes of principal stresses. This ignores the fact that tectonic fabrics in (U)HP rocks are related to finite strains which accumulate over time in viscous flows and generally by non-coaxial deformation paths (Means et al., 1980). The strain ellipsoid from tectonic fabrics do not have any simple relation to the principal stress directions and relative magnitudes. If the analysis of Bauville and Yamato (2021) is taken to be valid for an infinitesimal deformation, then it is unclear how the analysis can be extrapolated to finite strains accumulated over millions of years of (U)HP metamorphism.

Yamato and Brun (2017) considered Andersonian stress state only. Bauville and Yamato (2021) discussed stress rotations at the P_r stage in Section 3.2 of their paper. As pointed out above, once the stress state is non-Andersonian, the vertical stress σ_z is no longer a principal stress and the assumption by the authors that $\sigma_z = \rho g z$ still holds requires justification. The derivation in Section 3.2 is difficult to follow and it is not clear how Eqs.18-20 were derived and then applied to their Fig.7. One notes that the Mohr-Coulomb plasticity, as a constitutive behavior for elastoplastic materials, is coordinate system independent. The orientation of the “yield surface” in a Mohr-circle plot is always measured with respect to the principal stresses. How a rotation of the stress tensor, which amounts to a coordinate system change, should have any effect on the Mohr circle location and size is not clear from their paper. The authors may clarify these points and give more details of how their Eqs.18-20 were obtained and applied.

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