



Reply to Comment by D. Jiang on "Pressure-to-depth conversion models for metamorphic rocks: derivation and applications"

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REPLY

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This article is a reply to comment by Jiang (2021), <https://doi.org/10.1029/2021GC009737>.

Key Points:

- Pressure data are consistent with a model assuming lithostatic pressure or a model assuming constant depth and non-zero deviatoric stress
- Metamorphic rocks can experience and record large deviatoric stress in <1,000 years. Thus, alternative pressure-to-depth models are required
- Jiang's hypothesis does not falsify the proposed pressure-to-depth conversion models. Models cannot be distinguished from pressure data only

Supporting Information:

Supporting Information may be found in the online version of this article.

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Reply to Comment by D. Jiang on "Pressure-to-Depth Conversion Models for Metamorphic Rocks: Derivation and Applications"

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Abstract In our study (Bauville & Yamato, 2021, <https://doi.org/10.1029/2020gc009280>), we derived simple formulas for pressure-to-depth conversion that allow (or not) to take into account deviatoric stresses. We then tested them against a data set of pressure from high-pressure (HP) metamorphic rocks. In his comment, Jiang argues that the classical pressure-to-depth conversion, which assumes negligible deviatoric stresses (i.e., lithostatic pressure assumption) (a) provides a better explanation of the data and (b) is the only acceptable pressure-to-depth conversion method from the point of view of rock mechanics. We disagree with both arguments because (a) although Jiang's explanation is plausible, it does not falsify alternative models. As we concluded in Bauville and Yamato, several models explain equally well the data, and pressure data alone is not enough to validate or falsify any of these models. (b) There is a growing corpus of evidence that even HP metamorphic rocks undergo large deviatoric stress and can record even transient events in their mineralogical assemblage. Finally, Jiang criticizes that we used terms related to deformation loosely to illustrate stress concepts, and that our proposed method of falsification based on markers of deformation may be infeasible for HP metamorphic rocks. We take here the opportunity to clarify all these aspects.

1. Introduction

In our study (Bauville & Yamato, 2021), we derived simple formulas for pressure-to-depth conversion that allow (or not) to take into account deviatoric stresses. We applied these models to a data set of peak pressure (P_p) and retrograde pressure (P_r) of high-pressure metamorphic rocks. Because the equations have many free parameters, we presented end-member models to illustrate the influence of individual parameters on the estimation of depth. For clarity, we summarize the main results of our study (see Table 1 and Figure 1).

First, we presented models where we estimated the peak and retrograde depth independently, assuming varying magnitude of deviatoric stress, from zero (i.e., lithostatic) to maximum shear stress (see *Introductory model* and *L-model* in Table 1). We noticed that the range of depth estimated for P_p and P_r overlapped. Therefore, we tested the hypothesis that P_p and P_r were recorded at the same depth. At constant depth, a change in stress state may lead to the transition from P_p and P_r . We calculated the combinations of stress states consistent with this hypothesis assuming either stress rotation or a change in horizontal stress magnitude (see *S-model1*, *S-model2*, and *YB-model* in Table 1). Figure 1a summarizes the depth estimate at which P_p was recorded for the various models. We also presented the results of the models that assume constant-depth with scatter plots of pressure data on top of theoretical model results (Figures 1b–1e). The stress states are limited by the Mohr-Coulomb equation, where we assumed a coefficient of friction of 0.65 and a cohesion of 0. After this initial choice of parameter we did not fit the model to the data (data and models are independent in our study).

We concluded that all data points could be equally well explained by models where (a) P_p and P_r are independent (L-model), or (b) P_p and P_r are recorded at constant depth (S-model, that is, all points fit in the model domain in Figure 1d). The model proposed by Yamato and Brun is a more constrained version of the S-model and can explain all data points except the ones we termed "outliers" (Figure 1e). The maximum depth for the P_p event is ~160 km according to the L-model and ~80 km for the S-model. Thus, the depth predictions of the two models imply very different geodynamic scenarios. These models are only end-members, and exhumation and stress change are likely to co-occur.

Table 1
Summary of Model Parameters and Assumptions

Model	Assumptions					Related figure in Bauville and Yamato (2021)
	Driving mechanism of the P_p to P_r transition	Depth at P_p and P_r	Deviatoric stress magnitude	Orientation of the first principal stress	Data points consistent with the model	
Introductory model	Change in depth or stress magnitude/orientation	Independent	From zero to yield stress	Horizontal or vertical (i.e., Andersonian)	All	2, 3, 4, 5
L-model	Exhumation	Independent	Zero	NA	All	4, 5, 9
S-model1	Change in magnitude of horizontal stress	Constant	From zero to yield stress	Horizontal at P_p , horizontal or vertical at P_r	All	6, 9
S-model2	Stress rotation	Constant	From zero to yield stress	Horizontal at P_p , from 0° (horizontal) to 90° (vertical)	All	7, 9
YB-model (after Yamato and Brun [2017])	The first principal stress switches from horizontal to vertical	Constant	Yield stress	Horizontal at P_p , horizontal or vertical at P_r	All but outliers	8, 9

Notes. All models were presented assuming a friction angle of 0.65, and zero cohesion. Results can easily be recomputed with arbitrary friction angle and cohesion using the python notebooks in the original article's supplement. In all models we assumed that the total vertical normal stress is constant and equal to the weight of the column of rock (i.e., lithostatic pressure).

2. About a “Best” Model

The premise of Jiang's comment is that “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”. This description is in stark contrast with our actual conclusion which stated that “the validity of either of these models cannot be assessed based only on pressure and temperature data”. As we clearly stated in our conclusion, we also agree that the pressure data are consistent with a model based on the lithostatic assumption (see L-model in Table 1 and Figure 1), but alternative models where larger deviatoric stresses are considered explain the data equally well (Figure 1).

Jiang assumes that the pressure data distribution is limited by two factors: (a) the accessibility and preservation of rocks and (b) the amount of exhumation. There are several issues with Jiang's proposition and criticism. First, Jiang states that “the maximum amount of stage 1 exhumation is always limited by the duration of the exhumation multiplied by the rate of exhumation” but does not explain what limits both duration and exhumation rate. Thus, it remains unclear where the limit is between a “reasonable” and “unreasonable amount of exhumation.” His proposed purple domains are only an arbitrary outline of the data distribution and are inconsistent between Figures 1a (linear boundary) and 1c (non-linear boundary).

Second, Jiang does not show a confidence interval for his regression line. In addition, a fundamental assumption behind linear regression is that the data are homoscedastic (i.e., the standard deviation is constant), which is not the case here. Therefore, the values of slope and intercept presented by Jiang must be interpreted with caution. Third, Jiang's representation of the model by Yamato and Brun (2017) in his Figure 1 is misleading since it shows only the line that corresponds to [$\sigma_2 = \sigma_1$ at P_p , $\sigma_2 = \sigma_3$ at P_r], which passes through the center of the data but not the line corresponding to [$\sigma_2 = \sigma_3$ at P_p], and [$\sigma_2 = \sigma_1$ at P_r] which would outline the limits of the data distribution. By not plotting these three lines that cover the extent of Yamato and Brun's model in his Figure 1a, Jiang makes the model appear worse than it is. These three lines are represented in this reply's Figure 1d.

Finally, Jiang states that “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.” Actually, the term $\rho g z$ simply represents the weight of the overlying column of rocks. That remains true even if additional shear stresses are applied,

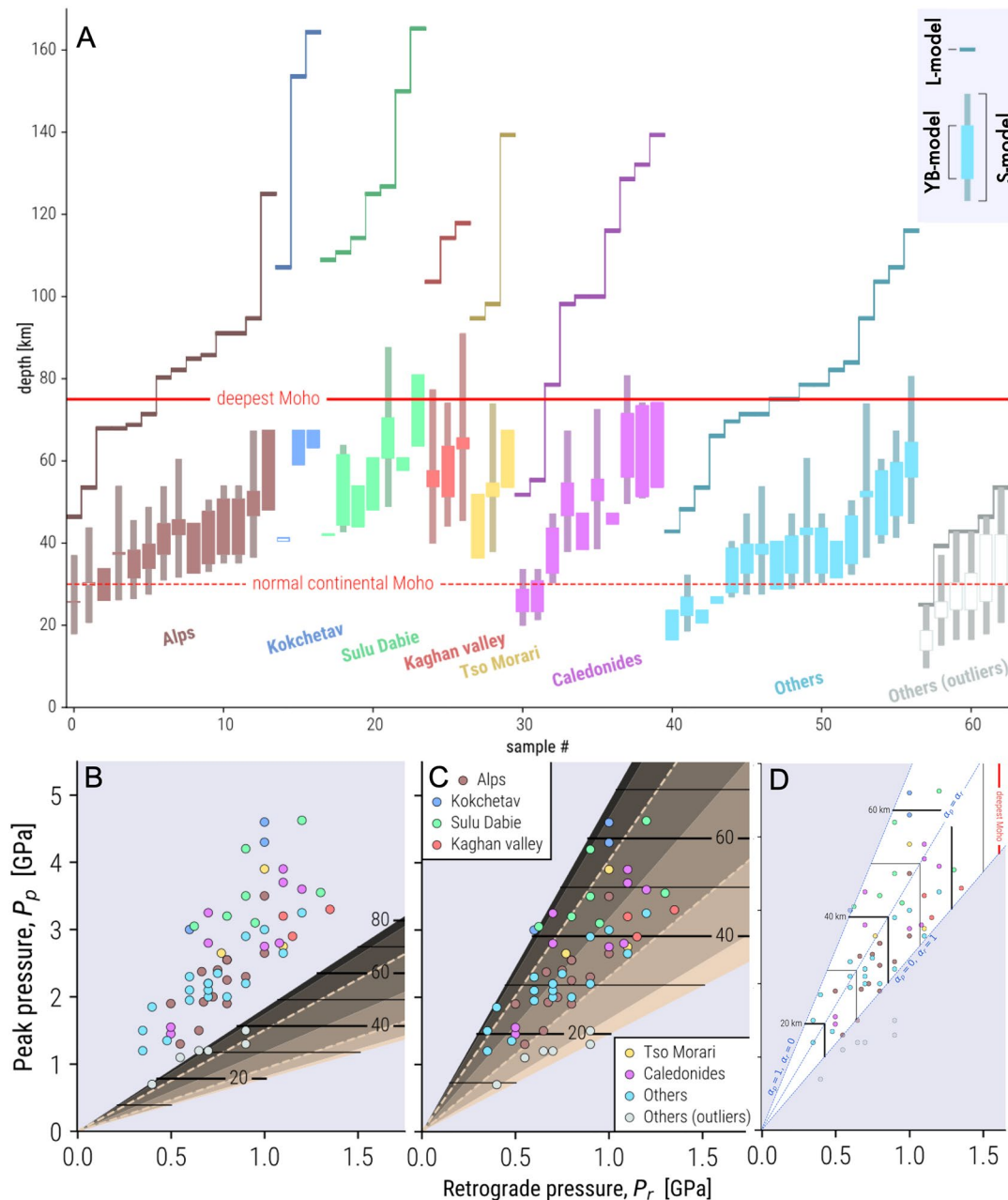


Figure 1. Summary of Bauville and Yamato's main results. (a) Depth estimated from pressure data using various models; (b and c) predictions of the S-model with different parameters (originally Figures 7d and 7g); (d) prediction of the YB-model. See Table 1 for model details.

which would lead to the rotation of the stress state. The assumption that only ρgz applies in the vertical direction is commonly used in the literature, for example in the critical taper theory whose theoretical predictions have been validated by physical experiments (e.g., Dahlen, 1984; Lehner, 1986). However, it is true that σ_z may deviate significantly from ρgz where topography is none zero or in heterogeneous material because of additional dynamic stresses (Moulas, Burg, & Podladchikov, 2014; Schmalholz et al., 2019). We clearly stated and discussed the assumptions of homogeneity and zero topography, and their limitations in Bauville and Yamato (2021).

3. Clarification on Stress and Strain

We accept the criticism of Jiang that, indeed the strain ellipsoid and its relation to stress is difficult to measure, and in this sense, it does not constitute the best tool to estimate the ratio of principal stresses. More elaborate paleostress inversion methods such as fault slip analysis (Kaven et al., 2011) or grain boundary piezometer (Shimizu, 2008; Stipp & Tullis, 2003) are independent on strain and would be probably more appropriate. Since it is not a point of debate, we provide the requested derivation of Equations 18–20 as Supporting Information.

4. Evidence for High Differential Stresses and Fast Kinetics of HP Metamorphic Reactions

Jiang claims that there is no evidence that GPa level differential stresses can be sustained for the Ma time scale in the P - T condition of (U)HP metamorphism. However, many studies challenge this claim and demonstrate that high differential stress occurs at several scales (Jackson et al., 2004; Jamtveit, Austrheim, & Putnis, 2016; Putnis et al., 2017; Tajčmanova et al., 2015). At the lithospheric scale, non-negligible differential stresses are required to maintain and support mountain belts and their roots (Jackson et al., 2004; Moulas, Podladchikov, et al., 2013; Schmalholz et al., 2019). At the crustal-scale, in-situ stress measurements reveal that the continental crust can be in a state of stress near the failure threshold, with differential stress >100 MPa at depth >5 km (Townend & Zoback, 2000). At the outcrop scale, rheological heterogeneities can lead to local overpressure that results in parageneses of different grades (Corvò et al., 2021; Jamtveit, Moulas, et al., 2018; Luisier et al., 2019). Finally, at the grain scale, characteristic microstructures and chemical zonation of minerals in (U)HP rocks indicate that HP paragenesis can be associated with significant overpressure (Tajčmanova et al., 2015) and brittle behavior (Lund et al., 2004; Scambelluri et al., 2017). Hence, although there is no consensus yet, there are growing theoretical arguments and observational evidence that rocks can indeed sustain high differential stresses, and this, over long enough time to be recorded by metamorphic rocks (Fossen 2016; Moulas, Schmalholz, et al., 2019).

Depending on the pressure, temperature, fluids, grain size, and strain rate conditions, rocks may deform elastically, viscously or in a brittle manner (e.g., Yamato et al., 2019). The dominant deformation depends on the intrinsic rheological properties of the rock and the properties of the newly formed material when it reacts (e.g., Burov, 2011; Bürgmann & Dresen, 2008; Fossen, 2016). Viscous deformation can be associated with large overpressure due to large deviatoric stresses either in the rock considered or in the surrounding rock. Thus, even viscous rocks that record low differential stress, such as mylonite (e.g., Behr & Platt, 2014), may record a significant overpressure if they are embedded within a stronger lithosphere (e.g., Moulas, Burg, & Podladchikov, 2014). In his comment, Jiang concedes that frictional behaviors can occur at (U)HP conditions but argues that they are too transient to be recorded by rocks in their mineralogy/paragenesis. However, it was demonstrated (Chu et al., 2017; Malvoisin et al., 2020) that eclogite can form in less than 500 years, which is in the same order of magnitude as the recurrence of large earthquakes. Moreover, there is growing evidence showing that (U)HP metamorphism can be closely associated, in both space and time, with brief frictional events such as earthquakes (Angiboust et al., 2012; Austrheim & Boundy, 1994; Herten et al., 2017; Jamtveit, Petley-Ragan, et al., 2019; John & Schenk 2006; Lund et al., 2004; Scambelluri et al., 2017; Yang et al., 2014). This evidence suggests that metamorphic rocks can keep the imprints of short tectonic events. Thus, the stress states associated with these events must be considered when interpreting the pressure of metamorphic rocks.

5. Conclusion and Perspective on the Need of Alternative Models

Jiang proposed the hypothesis that the pressure data corresponds to the lithostatic pressure (L-model) and that data distribution is limited by rock availability and the amount of exhumation. He argues that this hypothesis "better explains" data distribution than the constant depth hypothesis (S-model, YB-model). This hypothesis is plausible even though Jiang does not test it quantitatively. However, pressure data are consistent with both the L-model and S-model, and neither Jiang nor Bauville and Yamato (2021) falsified any of these models. Therefore, both end-member models and their combinations remain valid options.

Having a range of options to interpret pressure data is essential because the “classical interpretation,” based on lithostatic pressure (L-model), is not always satisfactory (e.g., Ford et al., 2006; Jamtveit, Petley-Ragan, et al., 2019; Luisier et al., 2019; Palin et al., 2017; Pleuger & Podladchikov, 2014; Schenker et al., 2015; Zuza et al., 2020). For example, the L-model suggests extremely fast subduction/exhumation velocities (Little et al., 2011; Parrish et al., 2006; Rubatto & Hermann, 2001), but the exhumation mechanism remains debated. Also, rocks of the same age within a coherent tectonic unit may record significantly different peak pressure, P_p (Jamtveit, Petley-Ragan, et al., 2019; Luisier et al., 2019). Finally, the depth of the metamorphic sole formation obtained by converting pressure estimates (~ 1.0 GPa, e.g., Agard et al., 2016) using the lithostatic assumption is also puzzling as there is no evidence of ophiolite presenting such a thickness (e.g., Garber et al., 2020; Moulas, Podladchikov, et al., 2013). These examples show that a unique pressure-to-depth conversion model cannot reconcile all observations. Thus, physically sound and falsifiable alternatives to the lithostatic model deserve to be considered because they may bring a new light on the geological history of orogens.

Data Availability Statement

The database is available at <https://doi.org/10.5281/zenodo.4126862>.

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