

## Metamorphism under stress: The problem of relating minerals to depth

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**STRESS AND METAMORPHISM—THE DEPTH PROBLEM**

Metamorphism and rock deformation often occur together. In a paper in this issue of *Geology*, Wheeler (2014, p. 647) presents theoretical results that show that a differential stress driving the deformation could have a dramatic effect on metamorphic reactions. If this is true, then Wheeler's result has considerable consequences for geological applications, because it is commonly assumed that the metamorphic reactions are controlled by the lithostatic pressure (the weight of the overlying rock) which can be directly related to depth. According to this common practice, metamorphic minerals are used to estimate the burial depth of the tectonic unit in which the minerals have been found (e.g., Jolivet et al., 2003). If such depth estimates could indeed be considerably inaccurate, then this inaccuracy could help to answer some open geodynamic questions. For example, the depth of the metamorphic sole beneath ophiolites, which is constrained by the thickness of the observed overlying rock (<~15 km), is usually much less than the depth estimated from the metamorphic minerals of the sole (>~30 km; Moulas et al., 2013, and references therein). However, the potential inaccuracy of depth estimates based on minerals would question current paradigms in geology.

**PARADIGMS UNDER THREAT**

The discovery of micrometer-scale ultrahigh-pressure (UHP) minerals, such as coesite and diamond, in exhumed crustal rocks has revolutionized both metamorphic petrology and geodynamics (Chopin, 1984, 2003; Smith, 1984). The plate tectonics paradigm, with an old (not recycled into the mantle) continental crust floating horizontally on a denser mantle, had to be refined because the UHP (>28 kbar) minerals indicate the subduction of continental crust deep into the mantle (>100 km), and also their subsequent exhumation to the surface. Moreover, chronological studies show that the vertical motions during exhumation have the same velocities as the horizontal motion of continental plates, that is, several centimeters per year (e.g., Rubatto and Hermann, 2001). UHP metamorphism became an exciting research field because careful microscopic observation alone could have enormous consequences for the geodynamic history of the corresponding region. The formation at large mantle depth became widely accepted as the unique cause for UHP metamorphism in crustal rocks, and has been proposed as a new paradigm (Hacker and Gerya, 2013). The fundamental assumption of this UHP paradigm is that the pressure indicated by UHP minerals must be converted to depth by applying the lithostatic formula for pressure.

**NON-HYDROSTATIC THERMODYNAMICS**

The relationship between stress, pressure, and metamorphic reactions can be quantified with thermodynamic calculations. In these calculations, borrowed from gases and fluids and applied to solids without any modification (e.g., Connolly, 2009), it is commonly assumed that the stress state at every point is isotropic, and is fully represented by a single scalar "thermodynamic pressure" that controls the metamorphic reactions. This fluid-like version of thermodynamic theory is often referred to as hydrostatic thermodynamics. However, the relation between a single thermodynamic pressure and the stress in a solid is not so simple. For example, rock deformation experiments have shown that

quartz was partially converted to coesite at a confining pressure of only 12.5 kbar although a thermodynamic pressure of 28 kbar is required (Hirth and Tullis, 1994). Hirth and Tullis (1994) suggested that it was the magnitude of the largest stress (28 kbar) in the loading direction that controlled the reaction from quartz to coesite, and neither the confining pressure nor the mean stress (18 kbar). Also, the observation of coesite in both garnet and omphacite in exhumed rock (Chopin, 1984; Smith, 1984) indicates pressure variations >10 kbar on the mineral scale according to the well-accepted "pressure vessel" model that explains the preservation of coesite during the exhumation (Gillet et al., 1984; Perrillat et al., 2003; O'Brien and Ziemann, 2008). Furthermore, a differential stress of up to 17 kbar on the mineral scale has been indicated by observed coherent mineral lamellae (e.g., Pryer and Robin, 1996). However, the influence of pressure variations and differential stress on metamorphic reactions is commonly neglected in hydrostatic thermodynamic calculations.

Different approaches exist to account for non-hydrostatic effects in thermodynamic relationships between solids under stress (Grinfeld, 1991, see p. 125–132). A more microscopic approach concerning grain-scale stress variation considers partial Gibbs energy (chemical potentials) of the solid phases as functions of the normal stresses that act locally on mineral interfaces (Gibbs, 1906; McLellan, 1980; Wheeler, 2014). The more macroscopic approach of Dahlen (1992) starts from the same local relationships ("closely following" McLellan, 1980) but ends with approximate partial Gibbs energies as a function of fluid pressure for a fluid-saturated rock, even if the reaction between solid phases does not involve fluids. Dahlen's approach is similar to considering the "pore fluid" pathway in the sense of Wheeler (2014). Consequently, Dahlen predicts zero sensitivity to differential stress, while Wheeler shows that if other pathways are active then the sensitivity may be dramatic.

The experiments of Hirth and Tullis (1994) contradict the approaches of both Wheeler (2014) and Dahlen (1992). With the impact of differential stress on metamorphic reactions suggested by the results of Wheeler (2014), Hirth and Tullis (1994) should see coesite in the quartz stability field also for a largest stress of <28 kbar, which was not the case. But according to Dahlen (1992) they should not see coesite at all. However, both approaches can be easily defended. Wheeler (2014) suggests only the possibility of forming coesite subject to the chosen reaction pathway. In the absence of such a pathway in the experiments, coesite would not form at lower stress. The approach of Dahlen (1992) could be justified because it predicts correctly the 99 vol% quartz in the experiments and only fails to predict the 1 vol% of coesite, which can be considered as error due to the approximations done by Dahlen (1992). Alarming, the current practice in petrology (fluid pressure = total pressure = lithostatic pressure) is in agreement with Dahlen (1992), meaning that small coesite inclusions in UHP rocks should not be used as a proxy for any of these pressures. In fact, the non-hydrostatic solid-solid reaction in Hirth and Tullis (1994) experiments can be explained by the classical Gibbs (1906) theory developed for the non-hydrostatic solid-fluid case. The suggestion of Moulas et al. (2013), that coesite formed under a nearly hydrostatic stress that is close to the value of the largest stress in the experiments, makes the coesite crystals thermodynamically indistinguishable from a fluid, and, hence, the solid-solid reaction between quartz and coesite reduces to the solid-fluid case considered by Gibbs (1906).

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## BACK TO THE FIELD

The reliability of depth estimates based on minerals is only under threat if the thermodynamic pressure can deviate significantly from the lithostatic pressure (for example, >20%). To quantify such deviation is difficult. One possible way is to compare the metamorphic record with the structural one. For example, Pleuger and Podladchikov (2014) performed a structural restoration for the Adula nappe (Western Alps, Switzerland), which suggests that the nappe was formed at a depth of ~60 km. However, the Adula nappe includes UHP rocks that indicate a maximum lithostatic depth of ~110 km. With regard to this “depth problem” a geologist can currently choose between two types of solutions: first, the structural record is more or less complete and metamorphic reactions occurred at a depth less than the lithostatic depth, or, second, the lithostatic depth estimate is accurate but the structural record is incomplete, that is, the structures that indicate the 50 km exhumation from mantle depth have not been identified. Most geologists seem to choose the second solution. Nevertheless, in a new textbook on Alpine geology (Pfiffner, 2014), the first solution has been proposed for the Adula nappe.

A 50 km depth difference corresponds to a lithostatic pressure of ~1400 MPa. The result of Wheeler (2014) based on non-hydrostatic thermodynamics suggests that under a differential stress of 140 MPa the UHP minerals could, in principle, form at a depth of 60 km given a suitable reaction pathway. An alternative possibility, to form the UHP minerals in 60 km depth using classical hydrostatic thermodynamics, would be that stresses deviated significantly from the lithostatic pressure at 60 km depth and that, hence, the pressure controlling the metamorphic reaction was ~1400 MPa larger than the lithostatic pressure (Schmalholz and Podladchikov, 2013; Schmalholz et al., 2014).

## POTENTIAL APPLICATIONS AND OPPORTUNITIES

If minerals might not be reliable indicators of maximum burial, then one might fear that metamorphic petrology could lose one of its main applications. However, if tectonic pressure and differential stress could indeed considerably influence metamorphic reactions, then this could also create new applications. For example, if observed variations in metamorphic facies were due to pressure variations at the same depth, then these facies variations would contain important information on pressure, stress, and strength variations in rock. Then, there would be a need for a more accurate quantification of these variations, and also for a more detailed comparison of these variations with the deformation structures. Particularly, the regions without (U)HP metamorphism would be as important for geodynamic reconstructions as the (U)HP regions. Moreover, pressure variations can actually be considered in hydrostatic thermodynamic calculations. For example, Tajčmanová et al. (2014) explained the chemical zoning preserved in reaction rims as a result of mineral-scale pressure variations, and not, as usually done, as a result of sluggish kinetics of metamorphic reactions. The kinetics of metamorphic reactions (that is, the non-equilibrium thermodynamics) is yet another unsolved problem.

## REFERENCES CITED

Chopin, C., 1984, Coesite and pure pyrope in high-grade blueschists of the Western Alps - a 1st record and some consequences: *Contributions to Mineralogy and Petrology*, v. 86, p. 107–118, doi:10.1007/BF00381838.

- Chopin, C., 2003, Ultrahigh-pressure metamorphism: Tracing continental crust into the mantle: *Earth and Planetary Science Letters*, v. 212, p. 1–14, doi:10.1016/S0012-821X(03)00261-9.
- Connolly, J.A.D., 2009, The geodynamic equation of state: What and how: *Geochemistry Geophysics Geosystems*, v. 10, doi:10.1029/2009GC002540.
- Dahlen, F.A., 1992, Metamorphism of nonhydrostatically stressed rocks: *American Journal of Science*, v. 292, p. 184–198, doi:10.2475/ajs.292.3.184.
- Gibbs, J.W., 1906, On the equilibrium of heterogeneous substances, in *The Scientific Papers of J. Willard Gibbs*, volume 1: London, New York and Bombay, Longmans, Green and Company, p. 55–354.
- Gillet, P., Ingrin, J., and Chopin, C., 1984, Coesite in subducted continental crust—P-T history deduced from an elastic model: *Earth and Planetary Science Letters*, v. 70, p. 426–436, doi:10.1016/0012-821X(84)90026-8.
- Grinfeld, M., 1991, *Thermodynamic Methods in the Theory of Heterogeneous Systems*: Harlow, UK, Longman Scientific & Technical, 399 p.
- Hacker, B.R., and Gerya, T.V., 2013, Paradigms, new and old, for ultrahigh-pressure tectonism: *Tectonophysics*, v. 603, p. 79–88, doi:10.1016/j.tecto.2013.05.026.
- Hirth, G., and Tullis, J., 1994, The brittle-plastic transition in experimentally deformed quartz aggregates: *Journal of Geophysical Research. Solid Earth*, v. 99, B6, p. 11731–11747, doi:10.1029/93JB02873.
- Jolivet, L., Faccenna, C., Goffe, B., Burov, E., and Agard, P., 2003, Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean orogens: *American Journal of Science*, v. 303, p. 353–409, doi:10.2475/ajs.303.5.353.
- McLellan, A.G., 1980, *The Classical Thermodynamics of Deformable Materials*: Cambridge, UK, Cambridge University Press, 338 p.
- Moulas, E., Podladchikov, Y.Y., Aranovich, L.Y., and Kostopoulos, D., 2013, The problem of depth in geology: When pressure does not translate into depth: *Petrology*, v. 21, p. 527–538, doi:10.1134/S0869591113060052.
- O'Brien, P.J., and Ziemann, M.A., 2008, Preservation of coesite in exhumed eclogite: Insights from Raman mapping: *European Journal of Mineralogy*, v. 20, p. 827–834, doi:10.1127/0935-1221/2008/0020-1883.
- Perrillat, J.P., Daniel, I., Lardeaux, J.M., and Cardon, H., 2003, Kinetics of the coesite-quartz transition: Application to the exhumation of ultrahigh-pressure rocks: *Journal of Petrology*, v. 44, p. 773–788, doi:10.1093/petrology/44.4.773.
- Pfiffner, O.A., 2014, *Geology of the Alps*: Chichester, UK, Wiley Blackwell, 376 p.
- Pleuger, J., and Podladchikov, Y., 2014, A purely structural restoration of the NFP20-East cross section and potential tectonic overpressure in the Adula nappe (Central Alps): *Tectonics*, v. 33, p. 656–685, doi:10.1002/2013TC003409.
- Pryer, L.L., and Robin, P.Y.F., 1996, Differential stress control on the growth and orientation of flame perthite: A palaeostress-direction indicator: *Journal of Structural Geology*, v. 18, p. 1151, doi:10.1016/0191-8141(96)00037-5.
- Rubatto, D., and Hermann, J., 2001, Exhumation as fast as subduction?: *Geology*, v. 29, p. 3–6, doi:10.1130/0091-7613(2001)029<0003:EAFAS>2.0.CO;2.
- Schmalholz, S.M., and Podladchikov, Y.Y., 2013, Tectonic overpressure in weak crustal-scale shear zones and implications for the exhumation of high-pressure rocks: *Geophysical Research Letters*, v. 40, p. 1984–1988, doi:10.1002/grl.50417.
- Schmalholz, S.M., Duretz, T., Schenker, F.L., and Podladchikov, Y.Y., 2014, Kinematics and dynamics of tectonic nappes: 2-D numerical modelling and implications for high and ultra-high pressure tectonism in the Western Alps: *Tectonophysics*, doi:10.1016/j.tecto.2014.05.018 (in press).
- Smith, D.C., 1984, Coesite in clinopyroxene in the Caledonides and its implications for Geodynamics: *Nature*, v. 310, p. 641–644, doi:10.1038/310641a0.
- Tajčmanová, L., Podladchikov, Y., Powell, R., Moulas, E., Vrijmoed, J.C., and Connolly, J.A.D., 2014, Grain-scale pressure variations and chemical equilibrium in high-grade metamorphic rocks: *Journal of Metamorphic Geology*, v. 32, p. 195–207, doi:10.1111/jmg.12066.
- Wheeler, J., 2014, Dramatic effects of stress on metamorphic reactions: *Geology*, v. 42, p. 647–650, doi:10.1130/G35718.1.

Printed in USA