



Invited review article

Grain-scale pressure variations in metamorphic rocks: implications for the interpretation of petrographic observations



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ABSTRACT

Recent work on mineral reactions and microstructures in metamorphic rocks has focused on forward modelling of phase equilibria and on their description through chemical potential relationships which control mass transfer in rocks. The available thermodynamic databases and computer programs for phase equilibria modelling have significantly improved the quantification and understanding of geodynamic processes. Therefore, our current methodological framework seems to be satisfactory. However, the quantification approaches in petrology focus on chemical processes with oversimplified mechanics. A review of the recent literature shows that mechanical effects in rocks may result in the development of pressure variations even on a hand specimen or grain scale. Such variations are critical for interpreting microstructural and mineral composition observations in rocks. Mechanical effects may influence element transport and mineral assemblage in rocks. Considering the interplay of mechanical properties and metamorphic reactions is therefore crucial for a correct interpretation of microstructural observations in metamorphic rocks as well as for quantification of processes. In this contribution, arguments against pressure variations are inspected and disproved. The published quantification procedure for systems with grain-scale pressure variations is reviewed. We demonstrate the equivalence of using Gibbs and Helmholtz energy in an isobaric system and go on to suggest that Gibbs free energy is more convenient for systems with pressure variations. Furthermore, we outline the implications of the new quantification approach for phase equilibria modelling as well as diffusion modelling. The appropriate modification of a macroscopic flux for a system with a pressure variation is derived and a consequence of using mass or molar units in diffusional fluxes is discussed. The impact of ignoring grain-scale pressure variations on geodynamic modelling and our understanding of the processes in the Earth's interior is assessed. We show that if a pressure variation is overlooked, the error in depth estimates from crustal metamorphic rocks could be as large as the thickness of the crust.

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1. Introduction

Many phenomena in the Earth's interior can be explained by mineral reactions and phase transformations. Mineral reactions greatly affect the physical properties of Earth materials and impose first order controls on geodynamic processes. Differences in mechanical properties due to reaction, such as relative differences in viscosity between magma and the rock from which it melts, may reach over ten orders of magnitude (e.g. Cruden, 1990; Dimanov et al., 2000; Rosenberg and Handy, 2005). High mechanical strength may suppress reaction associated with large volumetric changes, thus preserving rock history and properties (Liu et al., 1998; Morris, 2002, 2014; Mosenfelder et al., 2000; Schmid et al., 2009; Zhang, 1998). Recent observations show that mechanically maintained pressure variations can be significant even on a micro-scale. Current analytical and imaging techniques allow direct investigation of minerals under residual pressure (Fig. 1a,b; Howell, 2012; Howell et al., 2010; Nasdala et al., 2005). High residual pressures (GPa level) are still present in rocks at ambient conditions, for example the ultrahigh pressure mineral, coesite, is preserved as inclusions in garnet at the Earth's surface (Parkinson, 2000), as well as residual pressure in quartz inclusions in garnet (e.g. Enami et al., 2007; see also Moulas et al., 2013, and references therein). Furthermore, few studies document that ultrahigh-pressure (UHP) phases can be preserved even within a polycrystalline matrix (Fig. 1c; Ji and Wang, 2011; Liou and Zhang, 1996; Yang et al., 2014). Experimental studies also suggest a development of grain-scale heterogeneous pressure as revealed, for example, by the coexistence of low and high pressure SiO₂ polymorphs in quartzite deformation experiments (Hirth and Tullis, 1994). Given that the magnitude of metamorphic pressure provides the key constraint (via depth of burial) for geodynamic reconstructions of orogens, ignoring such pressure variations in petrological analysis is likely to significantly influence the quality and general results of these reconstructions.

Metamorphic petrologists as well as structural geologists bring important observational constraints for geodynamic models. If properly quantified and interpreted, fabrics and microstructures in rocks provide fundamental constraints on lithospheric evolution. However, in the context of complex rock fabrics and microstructures, application of inappropriate quantification approaches may lead to flawed interpretations. The classical view of metamorphic microstructures assumes fast relaxation of stresses (therefore constant pressure) as well as constant temperature. In this case, chemical diffusion is the only limiting factor in the thermodynamic equilibration of the microstructure (Ashworth and Birdi, 1990; Fisher, 1973; Joesten, 1977). The presence of zoned porphyroblasts, coronal structures and spatially organized reaction zones thus points to the preservation of an apparent disequilibrium in the microstructures (e.g. Carlson, 2002 and references therein). This classical view is limited because it precludes the possibility that metamorphic microstructures involve mechanically maintained pressure variations. Several quantitative studies have considered mechanical effects on mineral reactions (Ferguson and Harvey, 1980; Fletcher, 1982; Fletcher and Merino, 2001; Milke et al., 2009; Rutter, 1976; Schmid et al., 2009; Wheeler, 1987). None of these studies focused on a mechanical consequence for diffusion and the resulting chemical redistribution between and in minerals. Recently, Tajčmanová et al. (2014) focused on a complementary scenario to the classical diffusion controlled view, where fast diffusion is accompanied by slow stress relaxation. They point out that chemical zoning in grains (e.g. of plagioclase) surrounding a high-pressure phase (e.g. kyanite), associated with decompression at high temperature (>700 °C), may reflect pressure variations on that scale. Such a microstructure then need not be interpreted as a preserved chemical disequilibrium (i.e. by sluggish chemical diffusion) but can be fully quantified via appropriately modified equilibrium thermodynamics. The importance of mechanical effects on metamorphic reactions has also been suggested

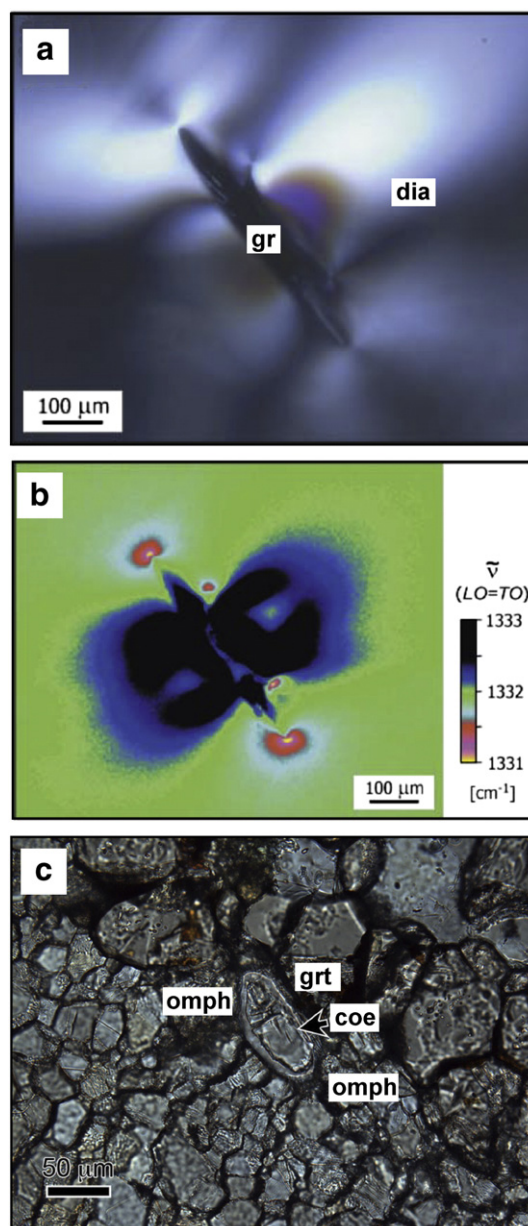


Fig. 1. a) Crossed-polarized light photomicrograph of graphite inclusion in diamond and b) Raman map of the same area portraying the distribution of remnant internal pressure - the blue-black region based on the frequency of the LO-TO phonon (modified from and see Nasdala et al., 2005 for details). c) Intergranular coesite with thin rim of quartz (modified from Yang et al., 2014). Abbreviations: gr = graphite; dia = diamond; omph = omphacite; grt = garnet; coe = coesite.

recently in the context of nonhydrostatic thermodynamics (Wheeler, 2014). Wheeler (2014) endeavours to show that the effect of differential stress on the inferred pressure conditions, under which a metamorphic reaction takes place, can be as dramatic as several GPa. However, this theory contradicts the available experimental data and its feasibility is discussed below.

Whereas observational and theoretical results obtained so far have provided insights into the interplay between deformation and mineral reaction, recent developments in conceptual models have opened new horizons in understanding mineral reaction mechanisms in the Earth's lithosphere. It is timely that these latest breakthroughs in considering metamorphic microstructures, in particular involving grain-scale pressure variations, are reviewed here.

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