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New parametric implementation of metamorphic reactions limited by water content, impact on exhumation along detachment faults

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ABSTRACT

Metamorphic phase changes have a strong impact on the physical and mechanical properties of rocks including buoyancy (body forces) and rheology (interface forces). As such, they exert important dynamic control on tectonic processes. It is generally assumed that phase changes are mainly controlled by pressure (P) and temperature (T) conditions. Yet, in reality, whatever the PT conditions are, phase changes cannot take place without an adequate amount of the main reactant — water. In present day geodynamic models, the influence of water content is neglected. It is generally assumed that water is always available in quantities sufficient for thermodynamic reactions to take place at minimal Gibbs energy for given P and T conditions and a constant chemical composition. If this assumption was correct, no high-grade metamorphic rocks could to be found on the Earth's surface, since they would be retro-morphed to low-grade state during their exhumation. Indeed, petrologic studies point out that water, as a limiting reactant, is responsible for the lack of retrograde metamorphic reactions observed in the rocks exhumed in typical MCC contexts. In order to study the impact of fluid content on the structure of metamorphic core complexes, we have coupled a geodynamic thermo-mechanical code Flamar with a fluid-transport and water-limited thermodynamic phase transition algorithm. We have introduced a new parameterization of Darcy flow that is able to capture source/sink and transport aspects of fluid transport at the scale of the whole crust with a minimum of complexity. Within this model, phase transitions are controlled by pressure temperature and the local amount of free fluid that comes from both external (meteoric) and local (dehydration) sources. The numerical experiments suggest a strong positive feedback between the asymmetry of the tectonic structures and the depth of penetration of meteoric fluids. In particular, bending-stress distribution in asymmetric detachment zones drives the penetration of meteoric fluids to greater depths. However, thermal weakening and/or slow re-equilibration of the protolith rocks at depth tend to decrease the asymmetry of structure, changing the orientation of the bending stresses and reduce the activity of asymmetric detachments in favor of spreading structures, which results in the formation of double-domes.

1. Introduction

Thermo-mechanical models of long term tectonic process all solve conjointly for conservation of momentum and advection diffusion of heat with different numerical schemes and rheological models. Simplifying to a viscous incompressible rheological model, conservation of momentum can be written as

$$\nabla \cdot (\eta_{\mathrm{eff}}\ \dot{\varepsilon}) + \rho_{\mathrm{eff}} g = 0, \quad (1)$$

where η_{eff} is the effective viscosity, $\dot{\varepsilon}$ is the strain-rate tensor, ρ_{eff} is the effective density and g is the gravitational acceleration.

The coefficients ρ_{eff} and η_{eff} depend on the prescribed rheological model (temperature/pressure dependant and visco-plastic behavior) but also and mainly on the minerals that compose the rocks. In an attempt to make these models more self-consistent, thermo-dynamic coupling has been introduced in the thermo-mechanical codes (e.g., Gerya et al., 2004; Rüpke et al., 2004; Warren et al., 2008; Yamato et al., 2008; Burov and Yamato, 2008). It is performed using tabulated mineral assemblages in pressure–temperature (P–T) space for a given constant chemical composition. The tabulated dataset is obtained by minimizing free Gibbs energy under the assumption of water saturation at any given P–T condition. The coupling is obtained under the rather strong assumption that all rocks in the models are at thermodynamic equilibrium for the P–T conditions computed within the thermo-mechanical part of the model. This default assumption of fluid abundance in metamorphic environments is not universally applicable. In many situations, the local water content can be insufficient to allow metamorphic reactions to occur. Yet, the role of the water content distribution and its impact on the metamorphic (= mechanical softening) reactions during the localization of deformation has never been explicitly introduced in fully coupled numerical models of continental extension.

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Geologically, the classical implementation of thermodynamic coupling implies that the metamorphic grade of rock always reflects its current P–T conditions. As a result, all exhuming rocks in these models are fully retromorphosed on their way up to the surface. This modeling assumption contradicts field observations of, for example, exhumed eclogites that safely make their way back to the surface without noticeable retrograde modifications (e.g. Behr and Platt, 2011). Comparing nature to the typical permanent equilibrium behavior implemented in thermo-dynamically coupled models (e.g., Gerya et al., 2002;Hebert et al., 2009; Rüpke et al., 2004; Yamato et al., 2008), it is clear that models of rock exhumation misestimate the buoyancy term in the force balance equation (Eq. (1)). Accounting for the fact that retrograde metamorphic changes do not affect the bulk of the exhumed material but only the shear zone accommodating their exhumation, some authors (e.g., Huet et al., 2011a) have proposed not to account for thermo-dynamic reactions when modeling the exhumation of high-grade metamorphic rocks. While minimizing the error on buoyancy, this approach tends to misestimate the viscous strength of the retromorphosed shear zones (Gueydan et al., 2003; Huet et al., 2014).

In nature, one of the main limitations to retrograde phase transitions is the lack of water in the system (e.g. Oliot et al., 2010). Observations show that rocks, which do not retrieve a sufficient amount of water, to achieve their retrograde transformation, have preserved a large part of high-grade paragenesis and hence are characterized by density and strength acquired at their last thermodynamic equilibrium state. Retrograde metamorphic facies are usually rich in phyllosilicates. Their soft localizing rheology results in localization of deformation and affects, by proxy, the overall dynamic of exhumation (e.g. Etheridge, 1986; Marquer and Burkhard, 1992; Oliot et al., 2010, 2014; Yardley et al., 2010; Gueydan et al., 2003). Capturing these meta-stable states of rocks is extremely important from a dynamic point of view as it affects both the rheology and buoyancy forces.

This paper presents a new implementation of thermodynamic coupling in thermo-mechanical code. The new formulation includes exchange of water during metamorphic reactions within a simplified fluid circulation model. In order to get better insights on how this new complex coupling affects the dynamics of exhumation from the onset of localization at depth to the final stage, we have chosen the simplest exhumation problem: the dynamics of detachment zone in a purely granitic metamorphic core complex.

2. Geological evidence for fluid-limited phase transitions: in the case of MCCs

Metamorphic-core complexes (MCCs) are the result of continental extension in context of a weak ductile lower crust (Buck, 1991). MCCs are characterized by distributed deformation in their core and localized deformation on a detachment fault located at their rim, as summarized by Brun and Van Den Driessche (1994) (Fig. 1-a). Detachment faults commonly include a ductile shear zone that evolves into a brittle-cataclastic fault zone during progressive exhumation and cooling (Gueydan et al., 2003, 2004; Lacombe et al., 2013; Lecomte et al., 2010; Lister and Davis, 1989). The localized simple shear deformation along the detachment contrasts with the co-axial strain distribution within the core of MCCs and gives them their asymmetry (Brun and Van Den Driessche, 1994; Davis et al., 1986; Huet et al., 2011a; Tirel et al., 2004, 2008). This asymmetry is found to emerge from rapid strain localization inherited from asymmetric boundary conditions (Tirel et al., 2008; Huet et al., 2011a; Wu et al., 2015), from lateral change in thickness of the lower crustal ductile channel (Huet et al., 2011b) or basal heat flow (Le Pourhiet et al., 2003; Rey et al., 2009) or simply from fast mechanical softening both in the brittle and in the ductile fields (Huismans and Beaumont, 2003; Lavier et al., 2000; Chéry, 2001; Le Pourhiet et al., 2013; Schenker et al., 2012). It is characteristic from exhumation process and its sole existence is sufficient to explain both contrasting cooling paths and degree of retrogradation of mineral assemblages (Huet et al., 2011b; Jolivet and Goffé, 2000; Whitney et al., 2004; Whitney et al., 2013).

Yet, these detachments are not only localized shear zones where metamorphosed rocks are exhumed in the footwall from lower to upper crustal levels (Fig. 1-b) (e.g. Coney and Harms, 1984; Gans, 1997; Gans and Miller, 1985; Perchuk and Gerya, 2011; Reynolds and Lister, 1987). Fluid flow and metamorphic reactions also concentrate along them (Gottardi et al., 2011; Holk and Taylor, 2000; Morrison and Anderson, 1998; Mulch et al., 2006). As a result, detachments are also reaction fronts where thermodynamic re-equilibration of metastable assemblages is catalyzed by the infiltration of fluids in the high strain

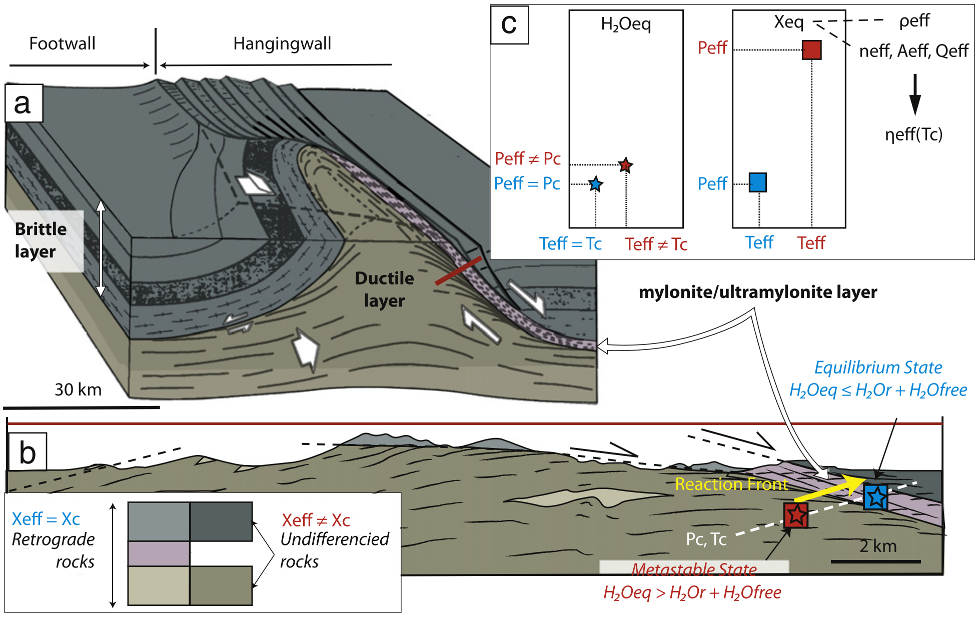

Fig. 1. a — A schematic representation of a metamorphic core complex. b — Interpretation of a detachment fault zone. c — Plot representing the implementation of the fluid-limited re-metamorphic changes in the model in terms of equilibrium water content and effective chemical composition of the rocks.
a — Modified after Brun and Van Den Driessche (1994). b — Modified after Jolivet and Goffé (2000).