Tectonophysics 608 (2013) 812–831

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Major role of shear heating in intracontinental inverted metamorphism: Inference from a thermo-kinematic parametric study

S. Duprat-Oualid [a,*], P. Yamato [a,b], P. Pitra [a]

[a] Géosciences Rennes, UMR6118, Université de Rennes 1 & CNRS, 35042 Rennes, France
[b] ETH-Zurich, Sonneggstrasse 5, CH-8092 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 3 May 2013
Received in revised form 16 July 2013
Accepted 30 July 2013
Available online 13 August 2013

Keywords:
Inverted metamorphism
Shear heating
Numerical modelling
Thermal properties of the lithosphere

ABSTRACT

Inverted metamorphism corresponds to the stacking of high-temperature metamorphic units structurally on top of lower-temperature units and is commonly observed along main thrusts in major orogens. Yet, in spite of many existing models, the origin and preservation of the metamorphic inversion in intracontinental collision belts are still debated. In this study, we use a crustal-scale 2D thermo-kinematic model in order to investigate the key parameters controlling the inversion of the geothermal gradient at crustal scale. Our results confirm that the kinematic framework strongly impacts the thermal evolution around the thrust. Erosion velocity and thermal conductivity of rocks are two parameters that control the spatial location of the thermal perturbation and the intensity of inversion, respectively. However, even in extreme kinematic configurations, i.e., convergence velocities >3 cm·yr^{-1} and relatively high thrust dip angles ~30°, the thermal inversion is fleeting and thrust temperatures cannot reach the high temperature peak values characteristic of natural occurrences (>600 °C) if shear heating is not taken into account. Conversion of mechanical energy into heat represents a main contribution to the thermal budget along main crustal shear zones. It leads to high temperature conditions in the thrust zone and our results attest that it is the only process that allows the preservation through time of an intense thermal inversion. Our quantification shows that shear heating is much more efficient than other processes such as accretion and surface denudation and is compatible with the observations of inverted metamorphism in the Himalayan or Variscan belts, for example. This comparison with natural occurrences suggests that the formation and preservation of intracontinental inverted metamorphism require shear zone viscosity values of the order of 10^{20}–10^{21} Pa·s for convergence velocities between 1 and 3 cm·yr^{-1}.

1. Introduction and state of the art

An inverted metamorphic sequence is characterised by an upward intensification of metamorphism, typically an increase of the metamorphic peak temperature. Inverted metamorphism is mostly related to major thrusts, where convergence velocities are high. The major occurrences can be ascribed to one of three distinct geological contexts: (i) metamorphic soles beneath ophiolites (e.g., Abd El-Naby et al., 2000; Hacker, 1991; Jamieson, 1986; Williams and Smyth, 1973); (ii) oceanic subduction zones (e.g., Platt, 1975; Toksöz et al., 1971); and (iii) major thrusts in continental collision (e.g., Kohn, 2008; LeFort, 1975).

The present study is focused on the third geological setting. The best documented example is the inverted metamorphic sequence associated with the Main Central Thrust (MCT) zone in the southern Himalayas (e.g., Arita, 1983; Caddick et al., 2007; Frank et al., 1973; Harrison et al., 1997, 1998, 1999; Henry et al., 1997; Hubbard, 1989; Jain and Manickavasagam, 1993; Kohn, 2008; LeFort, 1975; Sinha-Roy, 1982), but other examples were described in the Variscan belt (Arenas et al., 1995; Ballèvre et al., 2009; Burg et al., 1984; Pitra et al., 2010; Štípská and Schulmann, 1995), in the Caledonian belt (Andreasson and Lagerblad, 1980; Johnson and Strachan, 2006; Mason, 1984; Watkins, 1985) or in the Appalachian belt (Camiré, 1995). The pressure and temperature conditions within such thrust zones attest to a medium pressure, medium-high temperature metamorphism. As an example, inverted metamorphic sequences in both the Himalayas and the Variscan belt have recorded peak temperatures between 500 and 700 °C and peak pressures between 8 and 11 kbar (e.g., Burg et al., 1984; Corrie and Kohn, 2011; Guillot, 1999; Kohn, 2008; Macfarlane, 1995; Pitra et al., 2010). Natural intracontinental metamorphic inversions are thus characterised by inverted thermal gradients between 10 and 50 °C·km^{-1} (e.g., Kohn, 2008; Pitra et al., 2010). Such intense thermal perturbations over a thickness of several kilometres necessarily imply geodynamic processes at crustal or even lithospheric scale. Several numerical models have been developed, most of them constrained by or aiming to fit data from the Himalayan belt (e.g., Bollinger et al., 2006; Henry et al., 1997; Jamieson et al., 1996, 2004; Kohn, 2008). They suggest two alternative hypotheses to explain the metamorphic inversion.

* Corresponding author. Tel.: +33 223236783.
E-mail address: sylvia.duprat-oualid@univ-rennes1.fr (S. Duprat-Oualid).

0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.07.037

On the one hand, the inverted zonation is the result of a post-metamorphic deformation of a preexisting "normal" metamorphic sequence. This may result from late thrusts cutting through the initial metamorphic sequence (e.g., Brunel and Kienast, 1986), passive deformation of metamorphic isograds within a ductile shear zone (e.g., Gibson et al., 1999; Grujic et al., 1996; Jain and Manickavasagam, 1993) or crustal-scale folding (e.g., Searle and Rex, 1989; Stephenson et al., 2000).

On the other hand, the inverted zonation may result from a temporary spatial perturbation of crustal isotherms (Burg and Schmalholz, 2008; Jamieson et al., 1996, 2004; LeFort, 1975; Peacock, 1987a). In this hypothesis, metamorphism is synchronous with the deformation event. Some authors propose that inverted metamorphism occurs due to a diffusive heat transfer across the major thrust from the hotter upper unit to the colder subjacent unit (e.g., England and Molnar, 1993; LeFort, 1975; Shi and Wang, 1987). Particularly, the thermal inversion may be due to a "channel flow", i.e., the extrusion of deep hot crustal rocks above a colder plate (e.g., Grujic et al., 1996; Jamieson et al., 1996, 2004). This model presents the advantage of reproducing the ranges of metamorphic pressures and temperatures characterising the outcroping sections of the MCT (Beaumont et al., 2001). However, it requires strong erosion localised on the thrust front and specific internal physical properties in terms of viscosity and angle of friction. Furthermore, it fails to reproduce some important metamorphic and geochronological records on both sides of the MCT (Kohn, 2008).

Beyond the first-order role of the kinematic framework and thermal diffusion, several studies have specifically focused on the contribution of radiogenic heat, including the accretion of radioactive material across the active thrust, and on the role of erosion (Bollinger et al., 2006; Huerta et al., 1996, 1998, 1999; Royden, 1993; Ruppel and Hodges, 1994). Accretion models allowing the accumulation of highly radioactive material over a duration longer than 30 Myr can lead to a significant increase of temperature within the hanging wall (e.g., Huerta et al., 1996, 1998). However, such studies involve disputable initial assumptions. As an example, the orogenic accretionary wedges of these models (e.g., Huerta et al., 1998) are deeply rooted at 30 to 60 km depths. Reasonable accretion velocities associated with lower, realistic erosion velocities lead to wedges several hundreds of kilometres wide at the surface. Outcrouping rocks across such wide zones should consequently be characterised by a continuous intense deformation and none of the known frontal thrusts displays such a configuration. Moreover, in most cases, strong accretion alone cannot reproduce the high temperatures observed in natural inverted metamorphic sequences. On the contrary, accretion leads to progressive cooling of the active thrust plane to steady temperatures lower than 400 °C at 30 km depth with no significant thermal inversion (Royden, 1993). Concomitant surface denudation characterised by an erosion velocity greater than the accretion velocity is necessary to raise the temperatures in the thrust zones (e.g., Bollinger et al., 2006; Royden, 1993).

In the absence of accretion processes, moderate erosion velocities can lead to thrust temperatures of the order of 600 °C and to the development of inverted isotherms comparable to those observed in natural inverted metamorphic sequences (Royden, 1993). However, these conclusions require a thrust activity lasting for more than 70 Myr and exhumation of ultra-high pressure metamorphic rocks from more than 100 km depth (Royden, 1993). Such implications are not compatible with natural cases where rocks recorded metamorphic peak pressures of 8 to 11 kbar. From a mechanical approach, erosion catalyses the development of main orogenic structures (e.g., Burg and Schmalholz, 2008), and some models highlight the important influence of both the erosion and the exhumation on the thermal perturbation (e.g., Beaumont et al., 2004; Bollinger et al., 2006; Jamieson et al., 1996; Kohn, 2008).

The role of heat production by conversion of mechanical energy into thermal energy in a major shear zone (shear heating) was also considered to complete the thermal budget and the possible development of thermal inversion around a thrust (Burg and Gerya, 2005; Burg and Schmalholz, 2008; England and Molnar, 1993; England and Thompson, 1984; Graham and England, 1976; LeFort, 1975; Minear and Toksöz, 1970; Molnar and England, 1990; Pavlis, 1986; Scholz, 1980; Toksöz et al., 1971), but without real quantification. Kidder et al. (2013) specifically refute the importance of shear heating under high convergence velocity (~10 cm·yr^{-1}) and attribute the thermal inversion to accretion process.

The demonstration provided by Kidder et al. (2013) that shear heating is not a cause of inverted metamorphism in accretion domains is based on an oceanic subduction beneath an active arc (Kidder and Ducea, 2006). The very high convergence velocity (~10 cm·yr^{-1}) and the high initial geothermal gradients characterising the overriding forearc (Kidder and Ducea, 2006) and the subducting oceanic plate easily and rapidly lead to intense thermal inversion. With low shear heating (~10^{-5} W·m^{-3} implying very low viscosities of about 10^{17} Pa·s), heat advection and conduction dominate the thermal budget: both the overriding plate and the slab are rapidly cooled and the subducting material is progressively and slowly heated. Consequently, the rocks accumulated in the accretion zone are representative of the thermal state of the thrust plane. Understandingly, the thermal peaks are thus colder from the top to the base of the accretion area and such thermal inversion is compatible with the thermochronologic data from the Pelona Schist of southern California (Kidder et al., 2013). Considering a stronger shear heating along the active thrust, which is superposed on the overall cooling pattern, decreases the thermal inversion intensity recorded in the accreted sediments. Nevertheless, such shear heating assumptions are not generally applicable because very low shear stress and viscosities are involved to balance the high strain rate (10^{-12} to 10^{-11} s^{-1}).

Previous studies of syn-deformational intracontinental inverted metamorphism used various models with very different degrees of complexity (e.g., England and Molnar, 1993; Jamieson et al., 2004; Shi and Wang, 1987). However, none of the proposed models is commonly accepted to give a general explanation to the development of syn-deformation inverted metamorphism. Whereas analytical studies provide good mathematical solutions for understanding the respective influence of kinematics and heat diffusion on the thermal evolution, the other factors involved (e.g., erosion, various heat sources, variable kinematic configuration, thermo-dependence laws) are difficult to address analytically but can be solved and quantified numerically.

In the present paper, our goal is not to fit a particular natural case (e.g., the Himalayas). Rather, using a systematic approach, we aim to explore and provide a detailed synthesis of the different conditions required for the formation and preservation of crustal-scale inverted metamorphism along one intracontinental thrust. We define and compare the relative importance of each of the parameters and processes involved: kinematic setting, thrust geometry, erosion velocity, rock properties (in particular the thermal diffusivity), accretion velocity, radiogenic heat production and shear heating. The goal is to infer (i) the conditions required to locally invert the thermal field; (ii) the exact impact of each one of these parameters on the intensity, the location and the duration of the inversion and (iii) the conditions required to preserve the thermal inversion through time. Finally, we discuss how and why shear heating is crucial for the formation and preservation of inverted thermal gradients under realistic kinematic settings.

2. Numerical model

2.1. Initial setup

In order to test independently the influence of the various parameters and processes on the thermal evolution of a crustal thrust, a simple numerical model is defined in which each component can be controlled. The 2D-model setup (Fig. 1a) is focused on the first 80 km of a continental lithosphere, which includes a 30 km thick crust. In order to study the thermal evolution of a major continental thrust zone, a thrust cutting through the whole continental crust with a dip angle θ is simulated by