Earth and Planetary Science Letters 278 (2009) 13–25

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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

Short communication

Mechanical decoupling of high-pressure crustal units during continental subduction

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ARTICLE INFO

Article history:
Received 15 June 2007
Received in revised form 18 September 2008
Accepted 16 November 2008
Available online 8 January 2009

Editor: C.P. Jaupart

Keywords:
numerical modeling
lithosphere strength
HP–LT metamorphism

ABSTRACT

The mechanics of the transition from continental subduction toward upper crustal nappe stacking is still poorly understood and is studied here through a 2D thermal and strength numerical modeling of a subducted passive margin. Geological observations in the core of most mountain belts show the piling up of several HP–LT upper crustal units that are most likely related to the detachment of upper crustal units from the subducted continental margin and to the subsequent stacking of the detached units at depths. The Adula unit (Lepontine Dome, Central Alps, Switzerland) is a long and thin upper crustal unit and is used here as a natural case-study as it provides a well-documented example of these units. 2D thermal modeling shows that two steps, successive in time, characterized the burial history of the passive margin undergoing continental subduction: 1—an increase in the margin strength due to an increase in the confining pressure during the first million years of the margin subduction and 2—the progressive heating of the subducted margin from the overlying lithosphere leads to a decrease in the margin strength due to thermal weakening, which progressively counter-balances the increase in confining pressure. Two strength gradients develop within the subducted lithosphere: 1—along the slab, the strength decreases with increasing burial depth and 2—perpendicular to the slab, the strength increases with depth due to an inverse temperature distribution. The detachment of HP–LT continental units from the subducted margin could occur when the slab strength becomes lower than the applied net stress. This allows the detachment of ductile weakened thin and long upper-crustal units. The thickness and length of the detached crustal units are controlled by the following parameters, in order of their importance: subduction dip angle, crustal rheology, mantle heat flux and subduction velocity. The comparison of our model results with the geometry and PT conditions of the Adula unit yields an estimate of the Alpine subduction dip angle at the time of deformation and metamorphism.

1. Introduction

Mountain building is the result of three successive steps ((Beaumont et al., 1996; Schmid et al., 2004) — Fig. 1). The first stage is oceanic subduction, which induces the formation of oceanic accretionary wedges. Second, the subduction of continental margin induces the stacking of long and thin upper crustal units at great depths (Burchfiel, 1980; Gillet et al., 1986; Mattauer, 1986), and leads to the piling-up of high-pressure, low-temperature (HP–LT) units. At this stage, the convergence between the two plates is mostly accommodated within the subduction zone, where the stacking of HP–LT metamorphic units occurs (Hacker et al., 2003a,b; Guillot et al., 2003; Jolivet et al., 2005). Third, the ongoing convergence induces a more penetrative shortening, which leads to a pronounced thickening on a lithosphere scale. This induces the widening of the orogen, marked by the migration of orogenic fronts (Malavieille, 1984; Beaumont et al., 1996) and defines the collision *sensu-stricto* (Fig. 1). These three stages are well defined in the Alps, and therefore, we have chosen this area as our field case-study in this paper. Oceanic closure and the beginning of oceanic subduction in the Liguro–Piemontais Ocean started during Cretaceous time (Albo-aptien, 100 Ma (Nairn et al., 1988; Stampfli et al., 1998; Dercourt et al., 2000; Rosenbaum and Lister, 2004). The age of the continental subduction is established by HP–LT and UHP metamorphism ages, which range from the Eocene to the Early Oligocene (50–35 Ma — (Stampfli et al., 1998; Challandes et al., 2003; Bousquet et al., 2004; Engi et al., 2004; Goffe et al., 2004; Rosenbaum and Lister, 2004; Schmid et al., 2004; Maxelon and Mancktelow, 2005). Finally, continental collision *sensu-stricto* occurred during the late Oligocene and the Miocene (30–15 Ma) as evidenced by the ages of the successive frontal thrusts in the northern and southern parts of the Alpine collision belt (Burkhard, 1988; Leloup et al., 2005; Challandes et al., 2008; Ciancaleoni and Marquer, 2008).

Most of the numerical models of orogenic processes analyze the evolution from subduction to collision on a lithosphere scale, with an emphasis on exhumation processes and surface-tectonic interactions (Beaumont et al., 1996; Escher and Beaumont, 1997; Gerya et al., 2006). The three successive steps of orogenic formation have been modeled with a particular focus on the role of crustal rheology (a weak

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0012-821X/$ – see front matter
doi:10.1016/j.epsl.2008.11.019

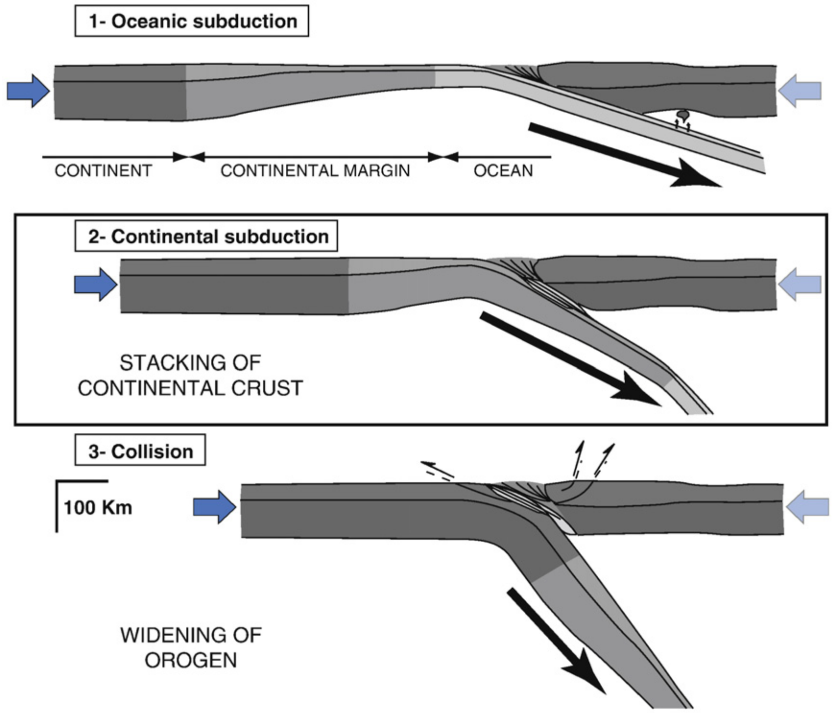

Fig. 1. Schematic drawing of a three-step evolution in a convergence zone at a lithosphere scale. 1—Oceanic subduction, 2—Continental subduction, 3—Collision. This study focused on the continental subduction and subsequent detachment of the HP–LT crustal unit, as indicated by the black box.

upper crust versus a strong lower crust) and the crust–mantle coupling in defining the crustal thickening style. In these types of models, the depths at which the upper crustal material is detached from the down going subducted plate is indirectly imposed by a velocity discontinuity (called point S, Beaumont et al., 1996; Escher and Beaumont, 1997; Pfiffner et al., 2000; Braun, 2003). This velocity discontinuity is often defined at the crust–mantle boundary and avoids detachment of continental unit at depths greater than 60 km (van den Beukel, 1992; Beaumont et al., 1996; Escher and Beaumont, 1997; Pfiffner et al., 2000). The aim of the present paper is to analyze the processes that control the detachment of a crustal unit during continental subduction. This topic is crucial to quantify the parameters that control the maximum depth reached by a crustal unit in a continental subduction and subsequently to better understand the parameters that define the peak pressure of metamorphic rocks. This topic is also a first step toward understanding the piling-up of HP–LT units, which is typical of the core of mountain belts.

Van den Beukel (1992) was the first to attempt to describe stacking during the subduction of a continental margin. Assuming a relatively hot subduction thermal gradient, Van den Beukel (1992) qualitatively discussed the conditions for stacking occurrence by comparing the margin strength, inferred from the 2D thermal states of continental subduction, and the applied net stress. The margin strength is shown to increase during the first 20–40 km of the burial history and then decreases at greater burial depths. The applied net stress along the subduction plate, which was assumed to be the sum of the buoyancy plus the resisting stress, increases with burial depth. At burial depths greater than 30–40 km, the margin strength becomes lower than the applied net stress, leading to a possible thrust sheet detachment. However, the detachment is dictated by a prescribed rheological discontinuity at the base of the weak upper crust. The depth at which stacking occurs is seen to decrease with an increasing subduction thermal gradient and increases with increasing convergence velocity. Therefore, thermal heating, and hence strength weakening, during continental subduction seems to control unit stacking at depths. The role of subduction velocity, subduction dip angle and crustal rheology in defining the stacking depth needs to be more systematically investigated. Moreover, the relationship between continental unit thickness/length and stacking processes remains poorly constrained. These are the two main objectives of the present paper.

Using a 2D thermal and strength model of the continental subduction, we will show that thin crustal units could detach from the subducted lithosphere due to a thermal weakening of the continental margin during burial and without prescribed rheological heterogeneities. The comparison of the applied net stress along the subduction plane and the 2D margin strength allows us to quantitatively predict stacking areas (e.g. unit length and thickness) within the margin crust. The role of subduction dip angle, subduction velocity, rheological and thermal parameters is investigated. Finally, our model predictions are tentatively compared with the Adula unit (Lepontine Dome, Swiss Alps).

2. Model

Following Van den Beukel (1992), this study is based on a 2D comparison of the applied net stress along the subduction plane and of the margin strength that evolves with burial history. The applied net stress is estimated by a simple force balance analysis, that is slightly different to that proposed by Van den Beukel. The margin strength is calculated from the 2D temperature distribution within the subducted lithosphere, which evolves with burial history (Fig. 2).

2.1. 2D thermal modeling

The 2D transient heat conduction is solved using the finite element method and the numerical code SARPP (see detailed description in Gueydan et al. (2004) and Leroy et al. (2008)):

$$\rho \cdot C \cdot \frac{\partial T}{\partial t} - k \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) = r \quad (1)$$

where ρ, C, k and r are the density, capacity, thermal conductivity and radiogenic heat production, respectively. The values of these parameters for the crust and the lithosphere mantle are given in Table 1. The heat