Earth and Planetary Science Letters 269 (2008) 436–447

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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

Thinning of continental backarc lithosphere by flow-induced gravitational instability

Claire A. Currie [a,b,*], Ritske S. Huismans [a,c], Christopher Beaumont [a]

[a] Department of Oceanography, Dalhousie University, Halifax, NS, Canada B3H 4J1
[b] Department of Physics, University of Alberta, Edmonton, AB, Canada T6G 2G7
[c] Department of Earth Science, Bergen University,Allegaten 41, N-5007, Bergen, Norway

ARTICLE INFO

Article history:
Received 1 February 2007
Received in revised form 19 January 2008
Accepted 24 February 2008
Available online 7 March 2008

Editor: C.P. Jaupart

Keywords:
subduction zone
mantle lithosphere
gravitational instability
thermal–mechanical model
Cascadia subduction zone
Canadian Cordillera

ABSTRACT

Many continental backarcs have thin (~60 km) lithosphere for 100s of km behind the volcanic arc, even where there has been no significant extension. One mechanism to produce thin backarc lithosphere is through gravitational thinning of normal thickness lithosphere by subduction-related mantle flow. The stability of backarc mantle lithosphere is examined using thermal–mechanical models of subduction of an oceanic plate beneath continental lithosphere with an initial thickness of 120 km and a thermal structure similar to average Phanerozoic continental lithosphere. Subduction-induced mantle flow shears the base of the backarc lithosphere, producing lateral density perturbations. Owing to the non-Newtonian lithosphere rheology, shearing also reduces the effective viscosity of the lowermost lithosphere, enabling the density perturbations to become gravitationally unstable. The perturbations develop into rapidly-growing downwellings which result in removal of lower backarc lithosphere on timescales of 5–10 Ma. Conductive heating and shearing of the remaining lithosphere results in a second, more muted, phase of gravitational instability and thinning. Lower lithosphere instability is enhanced by higher subduction rates, weaker intrinsic rheology, higher compositional density, and hotter initial thermal structure. The numerical model results are in good agreement with a buoyancy stability analysis, which includes the vertical gradients in temperature and strain rate through the lithosphere. As both rheology and density depend on lithosphere composition, significant thinning may be restricted to continental mantle lithosphere that is fertile and contains a small amount of water. To produce a final thickness comparable to that observed without lithospheric contraction or extension, it is necessary to have a weak lithosphere rheology, an initial thermal structure hotter than average Phanerozoic continental geotherms, or a combination of the two. The region of thin lithosphere at the northern Cascadia backarc coincides with terranes that were accreted to the North American craton. The known fertile composition of the backarc lithosphere may allow it to be thinned, while the drier, more refractory craton lithosphere is resistant to thinning.

1. Introduction

Some of the thinnest continental lithosphere is found in the backarc of subduction zones. Currie and Hyndman (2006) compiled observational constraints on lithosphere thermal structure for circum-Pacific continental backarcs that have not experienced significant recent extension. In most cases, high temperatures in the crust and shallow mantle are found for several hundred kilometers behind the volcanic arc and indicate a 60–70 km lithosphere thickness, approximately half the average thickness of Phanerozoic continental lithosphere (e.g. Poudjom et al., 2001). As an example, Fig. 1 shows thermal constraints for the northern Cascadia backarc. Indicators of high backarc temperatures include: 1) surface heat flow of 75 mW/m^2 (Fig. 1a), 2) low mantle seismic velocities (Fig. 1b), 3) estimates of high temperatures from peridotite xenolith thermobarometry, 4) present-day widespread sporadic basaltic volcanism, 5) high elevations (1.5–2 km) for a ~35 km backarc crustal thickness, and 6) an effective elastic thickness less than 30 km (Currie and Hyndman, 2006 and references therein). Together, the observations are consistent with a temperature of 1200 °C at ~60 km depth and a lithosphere thickness only slightly larger (Currie and Hyndman, 2006). The eastern limit of high temperatures and thin lithosphere coincides with the Rocky Mountain Trench, 500 km east of the volcanic arc, based on rapid changes in lithosphere properties and deformation style (Lowe and Ranalli, 1993; Hyndman and Lewis, 1999).

The origin of thin lithosphere in subduction zone backarcs is not well-understood. It is possible that the thin lithosphere is not related to subduction, for example, it is inherited from pre-subduction tectonics or due to the proximity of a mantle plume. On the other hand, subduction itself may trigger lithospheric thinning. One mechanism for producing thin lithosphere is through widespread backarc extension. The over-riding plate may also be thinned through ablative subduction, where lithosphere is mechanically removed by viscous drag from the subducting plate (Tao and O'Connell, 1992).

* Corresponding author. Department of Physics, University of Alberta, Edmonton, AB, Canada, T6L 2G7. Tel.: +1 780 492 1062; fax: +1 780 492 0714.
E-mail address: ccurrie@phys.ualberta.ca (C.A. Currie).

0012-821X/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2008.02.037

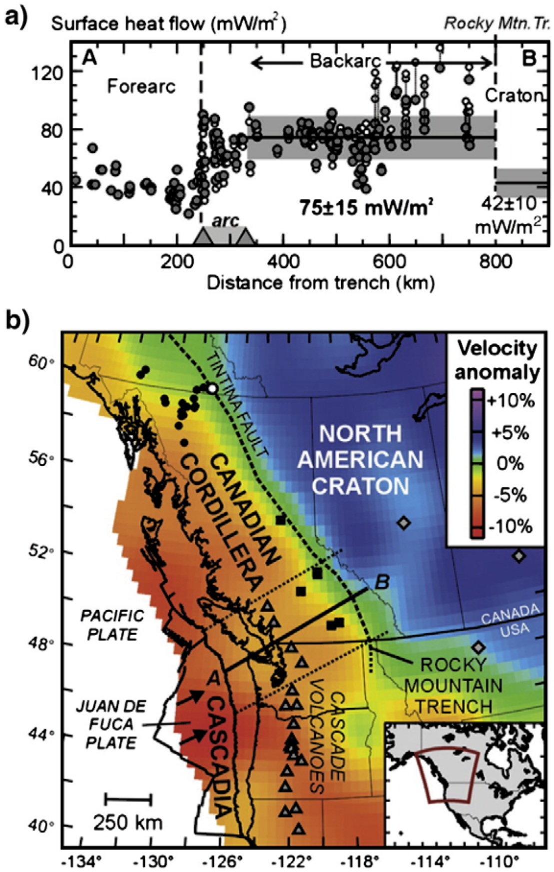

Fig. 1. a) Surface heat flow profile for the northern Cascadia subduction zone. The observed data (open circles) have been corrected for variations in upper crustal radioactive heat production (solid circles) (Currie and Hyndman, 2006). b) S-wave velocity anomalies at 100 km depth for the Cascadia subduction zone and Canadian Cordillera (van der Lee and Frederiksen, 2005). Line A–B is the heat flow profile; dotted lines denote the data swath width. Grey triangles are active arc volcanoes. Black squares are Cordilleran mantle xenolith sites (Peslier et al., 2000). Circles are locations of alkaline basalt centers; white circle is the Watson Lake site (Monger and Price, 2002). Grey diamonds are craton mantle xenolith sites (Griffin et al., 2004).

Another possibility is that fluids released from the subducting plate may infiltrate the overlying lithosphere, weakening it and making it susceptible to thinning by gravitational instability and flow in the underlying mantle. (Arcay et al., 2005, 2006) showed that hydrous weakening could lead to thinned lithosphere over a ~200 km width in the volcanic arc region, as most water is driven from the subducting plate at shallow depths. It is difficult to explain observations of thin lithosphere hundreds of kilometers behind the arc with this mechanism, unless slab-derived water can be carried far into the backarc, perhaps by transport in the convecting mantle or during earlier flat slab subduction (e.g. Dixon et al., 2004).

In this study, we investigate the idea that wide regions of thin backarc lithosphere may result from gravitationally-driven thinning of normal thickness lithosphere. Owing to its lower temperature, mantle lithosphere may be more dense than sublithospheric mantle and thus may be prone to gravitational instability, where the lower part of the lithosphere is removed through Rayleigh–Taylor-type downwelling. This differs from continental delamination (Bird, 1979) in that only the lowermost lithosphere participates in the instability, whereas delamination involves the peeling of the entire mantle lithosphere from the crust.

One way in which instability may be induced is through mechanical thickening of the lithosphere during horizontal shortening (Houseman et al., 1981). This process has been invoked to explain evidence of recent (<10 Ma) lithosphere thinning from seismic tomography data, volcanism, and changes in surface elevation in parts of the Central Andes backarc, which has undergone 300–350 km of shortening since the mid-Tertiary (Kay and Kay, 1993; Allmendinger et al., 1997; Garzione et al., 2006). This mechanism has also been proposed for parts of the northern Cascadia backarc (Ranalli et al., 1989). Conversely, gravitational instability may be initiated by subduction-related flow in the underlying mantle. This is the focus of the current study.

We use numerical thermal–mechanical models to investigate subduction of an oceanic plate beneath a continental plate. Through numerical experiments, we examine the conditions under which continental backarc lithosphere may undergo gravitational instability and thinning. We first study the relationship between mantle lithosphere stability and its intrinsic rheology and density structure, which are related to composition. We then investigate how subduction rate and thermal structure affect lithosphere stability.

2. Numerical model description

The initial geometry of the two-dimensional numerical models is shown in Fig. 2. The model domain has a width of 2000 km and depth of 660 km. The oceanic plate is composed of oceanic crust and mantle lithosphere, with a total thickness of 90 km. The continental plate has an initial thickness of 120 km, consisting of a 24 km upper-mid continental crust, 12 km lower crust, and 84 km mantle lithosphere. Backarc lithosphere stability is studied through numerical experiments in which material properties are varied in a ~800 km wide block of continental mantle lithosphere closest to the subduction zone (the backarc). Convergence between the two plates is kinematically imposed along the left-hand (seaward) model boundary. Within the model domain, the dynamics are driven by the far-field velocity boundary conditions and by buoyancy forces associated with thermal and compositional density variations.

2.1. Governing equations

Arbitrary Lagrangian–Eulerian (ALE) finite element techniques are used to solve for plane strain deformation of viscous-plastic materials and the associated thermal field (Fullsack, 1995). Creeping flow is governed by the quasi-static force balance and conservation of mass equations, assuming incompressibility and zero Reynolds number:

$$\frac{\partial v_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \sigma_{ij}}{\partial x_i} + \rho g = 0 \quad j = 1,2 \tag{2}$$

where $x_{i,j}$ are spatial coordinates, v_j are velocity components, ρ is density, and g is (vertical) gravitational acceleration. Repeated indices imply summation. The associated stress tensor is:

$$\sigma_{ij} = -P\delta_{ij} + \sigma'_{ij} = -P\delta_{ij} + 2\eta_{\mathrm{eff}}\dot{\varepsilon}_{ij} \tag{3}$$

where P is pressure (mean stress), σ'_{ij} is the deviatoric stress tensor, η_{eff} is the effective viscosity, δ_{ij} is the Kronecker delta (δ_{ij}=1 for i=j; 0 otherwise), and the strain rate tensor is:

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) \tag{4}$$

The two-dimensional thermal structure is governed by the energy balance equation:

$$\rho c_{\mathrm{p}}\left(\frac{\partial T_{\mathrm{K}}}{\partial t} + v_i\frac{\partial T_{\mathrm{K}}}{\partial x_i}\right) = k\frac{\partial}{\partial x_i}\frac{\partial T_{\mathrm{K}}}{\partial x_i} + A + v_z \alpha g T \rho \tag{5}$$