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3D Thermo-mechanical modelling of a stretched continental lithosphere containing localized low-viscosity anomalies (the soft-point theory of plate break-up)

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ABSTRACT

We present numerical models of extensional visco-elasto-plastic 3D continental lithosphere containing weaker areas within its mantle section. We aim at understanding the 3D crustal structure of volcanic passive margins that is characterized by both across-strike and along-strike finite strain gradients, with maxima around central igneous complex or their feeding magma reservoirs. It is suggested that localized hot melting zones within the lithosphere act as mechanical soft points and result in the local focusing of extension. To test this hypothesis 3D thermo-mechanical models of extensional continental lithosphere containing thermally induced soft points are implemented. Results show that crustal extension initiates and is focused over soft points in the mantle, reproducing the tectonic segmentation and zig-zag pattern of VPMs (volcanic passive margins).

1. Introduction

At volcanic passive margins (VPMs), the extension of the continental lithosphere focuses in a narrow rifting zone, usually 30–50 km wide, marked by a strong necking of the lithosphere coeval with the accretion, before and during continental break-up of a transitional mafic magmatic crust (e.g. Roberts et al., 1979; White et al., 1987; Mjelde et al., 2001; Geoffroy, 2005). This transitional crust is composed of intruded continental crust overlain by seaward-dipping basaltic wedges indicated by seaward-dipping reflectors (SDRs) (Hinz and Weber, 1976; Barton and White, 1997; Planke et al., 2000) and underlain by high-velocity (V_p ~7.2 to 7.7 km s^{-1}) seismic zones (HVZ) usually interpreted as thick bodies of high Mg underplated mafic magmas (=LCB: lower-crustal body; Kelemen and Holbrook, 1995).

Tectonic, geophysical and petrological observations show that VPMs are segmented along-strike. Potential field data point out that the U.S. East Coast VPM exhibits along-strike variations in the amplitude of gravity and magnetic signals with a dominant 50–100 km wavelength (Holbrook et al., 1994a,b; Behn and Lin, 2001). Geological observations on some exposed VPMs show that this segmentation is also both magmatic and tectonic (Karson and Brooks, 1999; Geoffroy et al., 2001). These VPMs are punctuated every 50–150 km by long-lived igneous centers active before, during, and in some cases after break-up. The internal structure of one of these igneous centers has been investigated on the Namibian VPM (Bauer et al., 2000). These igneous centers have been recently proposed to be the upper crustal feeders of sub-aerial volcanism (e.g. early traps and consecutive seaward-dipping reflector sequences) (Callot and Geoffroy, 2004; Geoffroy et al., 2007). In addition, finite extension significantly increases towards these magma centers (Fig. 1; Geoffroy et al., 2001). This is clearly expressed by the along-strike increase in both horizontal magma dilatation and tectonic-controlled crustal flexuring towards the igneous centers (e.g. Myers, 1980; Nielsen and Brooks, 1981; Geoffroy, 1998; Geoffroy et al., 2001; Callot et al., 2002, Klausen and Larsen, 2002). Another striking point is the non-linearity of volcanic margins. Volcanic margins display an along-strike zig-zag pattern; the break-up zone connects non-aligned igneous centers with a clear curvature and an increase in finite extension towards these latter. This is documented both along the SE Baffin (Geoffroy et al., 2001) and along the E-Greenland volcanic margins (Fig. 1; Nielsen and Brooks, 1981; Callot et al., 2002). Along-strike finite strain increase towards crustal igneous centers is also suggested by the few along-strike seismic profiles of SDRs (White et al., 1987; Barton and White, 1997; Gernigon et al., 2004). Geoffroy (2001) followed by Callot et al. (2002) proposed a conceptual model able to explain this magmatic and tectonic segmentation (Fig. 2). According to this model, the segmentation would be the consequence of local upwellings of the asthenosphere associated with

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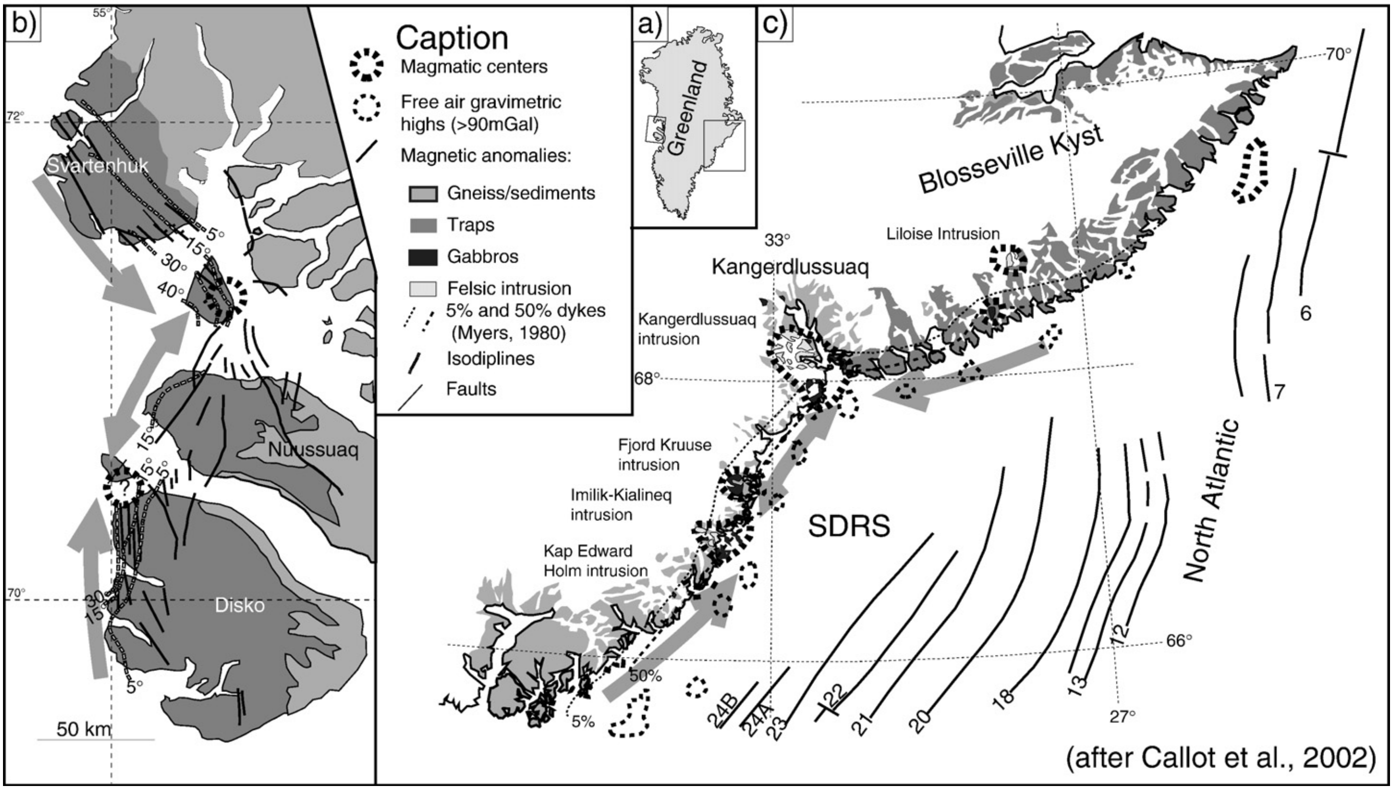

Fig. 1. Volcanic margins of Greenland. (a) Location of the studied areas; (b) simplified geological map of the West Greenland margin, with isotilt lines of the Tertiary lavas; (c) geological sketch map of the East Greenland margin. Arrow indicates strain gradient. Gravity highs above 90 mgal are likely attributable to plutonic complexes. Note the fairly regular spacing of the onshore plutonic complexes and offshore gravity highs.

small-scale convection cells in the Thermal Boundary Layer (TBL) located at the base of the lithosphere. The TBL is increasingly considered as undergoing natural small-scale convection, even in the absence of any additional heat supply (Davaille and Jaupart, 1993, 1994; Dumoulin et al., 1999; Morency et al., 2002; Korenaga and Jordan, 2002; Callot, 2002). The hot upwelling asthenosphere would cross the peridotite-solidus resulting in partial melting of the mantle. The melt product would then migrate vertically and accumulate in magma reservoirs located in the crust. These reservoirs would subsequently feed the sub-aerial volcanism (traps and SDRs, i.e. the crustal igneous centers) resulting in the along-strike segmentation of magmatism at VPMs. The second consequence of these asthenosphere upwellings is mechanical. The punctual penetration of hot asthenosphere would result in locally

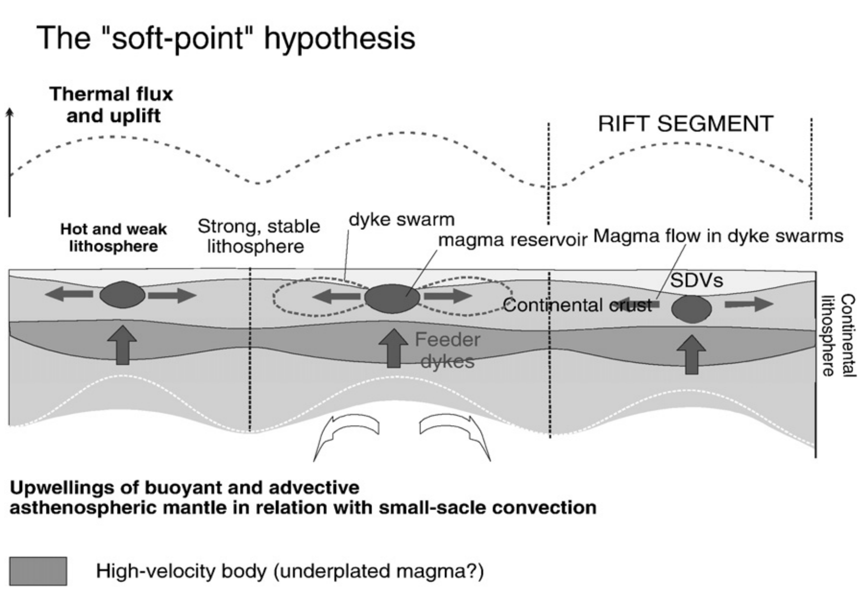

Fig. 2. Along-strike hypothetical vertical cross-section of a volcanic margin based on the hypothesis of a tectonic and magmatic segmentation controlled by asthensopheric diapiric instabilities (after Geoffroy, 2001).