Journal of Structural Geology xxx (2013) 1–13

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

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

Fabric development as the key for forming ductile shear zones and enabling plate tectonics

Laurent G.J. Montési*

Department of Geology, University of Maryland, 237 Regents Drive, College Park, MD 20742, USA

ARTICLE INFO

Article history:
Received 15 December 2011
Received in revised form
21 December 2012
Accepted 23 December 2012
Available online xxx

Keywords:
Ductile shear zone
Localization
Foliation
Phyllosilicates

ABSTRACT

Lithospheric deformation on Earth is localized under both brittle and ductile deformation conditions. As high-temperature ductile rheologies are fundamentally strain-rate hardening, the formation of localized ductile shear zones must involve a structural or rheological change or a change in deformation conditions such as an increase in temperature. In this contribution, I develop a localization potential that quantifies the weakening associated with these changes. The localization potential corresponds to the increase in strain rate resulting from that change under constant stress conditions. I provide analytical expressions for the localization potential associated with a temperature increase, grain size reduction, an increase in water fugacity, melt content, or the abundance of a weak mineral phase. I show that these processes cannot localize deformation from a mantle convection scale (10^3 km) to a ductile shear zone scale (1 km). To achieve this, is it necessary to invoke a structural transition whereby the weak phase in a rock forms interconnected layers. This process is efficient only if one phase is much weaker than the others or if the weakest phase has a highly non-linear rheology. Micas, melt, and fine-grained aggregates – unless dry rheologies are used – have the necessary characteristics. As none of these phases is expected to be present in the dry lithosphere of Venus, this concept can explain why Venus, unlike the Earth, does not display a global network of plate boundaries. The diffuse plate boundary in the Central Indian Ocean may be as yet non-localized because serpentinization has not reached the ductile levels of the lithosphere.

1. Introduction

The formation of ductile shear zones remains an enigma of geology. The structure, geometry, and kinematics of shear zones, or mylonites (e.g., Ramsay, 1980; Passchier and Trouw, 2005) have been well documented but there has been little advance as to their mechanics. The difficulty in understanding shear zone mechanics arises from the fundamentally strain-rate hardening characteristics of rocks that deform in the plastic regime, as repeatedly demonstrated by laboratory experiments (e.g. Evans and Kohlstedt, 1995). Therefore, deformation over wide deformation zones, at a low strain rate, should be favored in the middle to lower crust. Instead of this distributed deformation style, localized shear zones are a common occurrence over a variety of scales including kilometric structures that form major tectonic boundaries (Bak et al., 1975; Hamner, 1988; Vauchez and Tommasi, 2003; Gumiaux et al., 2004).

To compensate for strain-rate hardening, shear zones must be weaker than their surroundings thanks to a different value of some state or structural variable that facilitates continued deformation in previously deformed rocks (Poirier, 1980; White et al., 1980; Montési and Zuber, 2002; Regenauer-Lieb and Yuen, 2004). In the brittle field, localization is often associated with a state variable associated with the failure envelope in elastoplastic materials (Rudnicki and Rice, 1975; Rice, 1976; Needleman and Tvegaard, 1992), the microstructure of a slip surface (Dieterich, 1978, 1979; Ruina, 1983; Dieterich and Kilgore, 1994), or a continuum description of damage (Kachanov, 1986; Lyakhovsky et al., 1997, 2011). In a high temperature plastic regime, the nature of the state variable remains a topic of debate, with most studies focusing on grain size evolution or shear heating (Schmid et al., 1977; Etheridge and Welkie, 1979; Brun and Cobbold, 1980; Fleitout and Froideveau, 1980; Hobbs et al., 1986; Fliervoet et al., 1997; Regenauer-Lieb and Yuen, 1998; Braun et al., 1999; Kaus and Podladchikov, 2006; Crameri and Kaus, 2010; Platt and Behr, 2011a, b). However, I will show that even stronger localization may be expected from the development of a layered fabric.

Ductile shear zones are not only a fundamental feature of terrestrial geology. They may also help to explain the different tectonic regime of various terrestrial planets, especially the lack of plate tectonics on Venus. In the next section, I compare the tectonics of

---

* Tel.: +1 301 405 7534; fax: +1 301 314 7970.
E-mail address: montesi@umd.edu.

0191-8141/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jsg.2012.12.011

Please cite this article in press as: Montési, L.G.J., Fabric development as the key for forming ductile shear zones and enabling plate tectonics, Journal of Structural Geology (2013), http://dx.doi.org/10.1016/j.jsg.2012.12.011

Earth and Venus to argue that ductile shear zones play a fundamental role in generating plate boundaries on Earth. Then, I develop a technique to estimate how much localization may be expected from a change in state variable in a ductile material. By applying this concept to shear heating, grain size diminution, and fabric evolution, I show that the development of a layered structure has the highest potential to localize deformation. Returning to geodynamic applications, I show that the localization potential is much reduced under the dry conditions of Venus compared to Earth. It is also possible to better understand the presence of a diffuse plate boundary in the Central Indian Ocean if localization by fabric development is taken into account.

2. Plate tectonics and ductile shear zones

The cold and strong outer layer of our planet, the lithosphere, is organized in essentially rigid plates separated by plate boundaries, narrow deformation zones (Isacks et al., 1968; Kreemer et al., 2003). Heat loss is modulated by plate tectonics as cold plates converge and sink into Earth's warmer interior at subduction zones (Korenaga, 2008). To be sustained, this motion must be accompanied by plate creation, which occurs at divergent plate boundaries. The narrow width of plate boundaries implies a reduced resistance to deformation, which is also needed to generate strike-slip plate boundaries (Bercovici et al., 2000). Thus, all three kinds of motion – convergence, divergence, and strike-slip motion – are necessary to form a global plate boundary network and sustain plate tectonics. Plate tectonics require not only sufficient vigorous mantle convection, but also a strong lithosphere with weak, localized, deformation zones (Bercovici et al., 2000; Bercovici, 2003; O'Neill et al., 2007).

Venus is likely active today (Smrekar et al., 2010) but its tectonic style is markedly different from Earth's (Solomon et al., 1992). Only rifts, which accommodate limited plate divergence, resemble terrestrial rifts (Schaber, 1982; Campbell et al., 1984; Stofan et al., 1989; Senske et al., 1991; Foster and Nimmo, 1996). The East African Rift, on Earth, (Fig. 1A) and Devana Chasma, on Venus, (Fig. 1B) are both characterized by ~50 km wide, fault-bounded rift valleys with volcanic edifices. By contrast, strike-slip motion is rare on Venus and accommodates only limited offsets (Koenig and Aydin, 1998; Tuckwell and Ghail, 2003), unlike terrestrial large-offset strike-slip boundaries. Lithospheric shortening on Venus is distributed over vast regions of ridged plains (Fig. 1D) or broad fold belts (Squyres et al., 1992; McGill, 1993; Banerdt et al., 1997), whereas Earth features mainly narrow mountain belts. On Earth, even where shortening is spread over a wide area, like in the Sierra

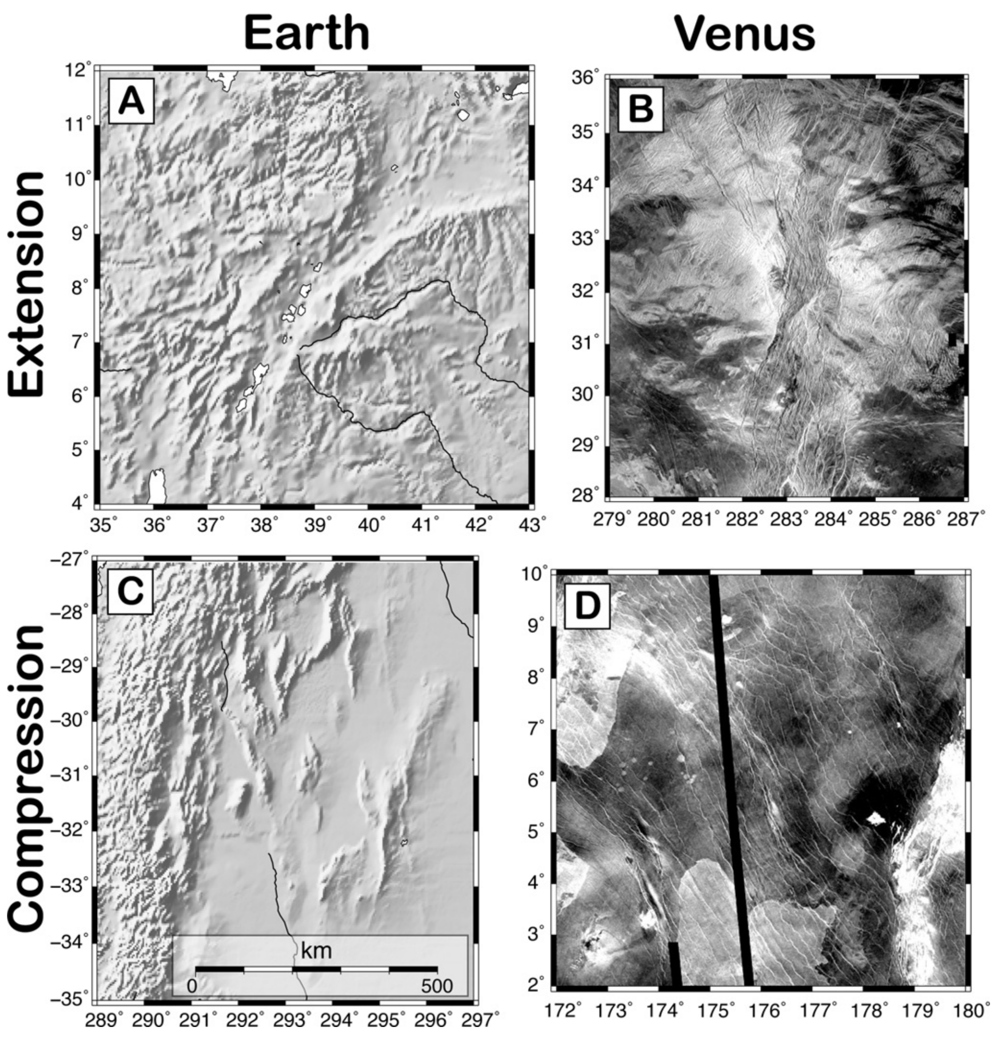

Fig. 1. Comparison of tectonic features on Earth and Venus: A) East African Rift (Ethiopia, Earth); B) Devana Chasma (Beta Regio, Venus); C) Sierra Pampeanas (Argentina, Earth); D) Yalyane Dorsa (Rusalka Planitia, Venus). Earth images are shaded relief from Etopo5 digital elevation model (resolution 5 arc-minutes per pixel) while Venus images are radar mosaics from Magellan data, constructed using the map-a-planet application. Each image covers an 8° × 8° region, displayed at the same scale (panel C).

Please cite this article in press as: Montési, L.G.J., Fabric development as the key for forming ductile shear zones and enabling plate tectonics, Journal of Structural Geology (2013), http://dx.doi.org/10.1016/j.jsg.2012.12.011