Tectonophysics 603 (2013) 136–154

Contents lists available at ScienceDirect

Tectonophysics

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

Leucosome distribution in migmatitic paragneisses and orthogneisses: A record of self-organized melt migration and entrapment in a heterogeneous partially-molten crust

C. Yakymchuk [a],*, M. Brown [a], T.J. Ivanic [b], F.J. Korhonen [b]

[a] Laboratory For Crustal Petrology, Department of Geology, University of Maryland, College Park, MD 20742, USA
[b] Geological Survey of Western Australia, East Perth, WA 6004, Australia

ARTICLE INFO

Article history:
Received 12 January 2013
Received in revised form 10 May 2013
Accepted 21 May 2013
Available online 4 June 2013

Keywords:
Migmatite
Fractal
Scale invariance
Self-organized criticality
Leucosome

ABSTRACT

The thickness and spatial distribution of foliation-parallel leucosomes in metric to decametric scale interlayered units of migmatitic paragneiss and orthogneiss from the Fosdick migmatite–granite complex in West Antarctica are quantified along one-dimensional transects. This study demonstrates that leucosomes in stromatic metatexite migmatites have thickness and spacing distributions consistent with being sampled from a power-law (scale-invariant) distribution. However, leucosome distribution in the paragneisses and orthogneisses yields different scaling exponents and the largest leucosomes in orthogneiss are thicker than those in the paragneiss by approximately half an order of magnitude. The difference in the spatial distribution and maximum thickness of leucosomes between the two rock types is attributed to the decimetric scale of inherited compositional layering in migmatitic paragneiss that restricted the development of larger leucosomes compared with an absence of such heterogeneity in migmatitic orthogneiss that allowed thicker leucosomes to form. Phase equilibria modeling of the protoliths of the paragneisses and orthogneisses shows that at Cretaceous peak metamorphic conditions the spectrum of metasedimentary protolith compositions could have produced 8–48 vol.% melt and the range of igneous protolith compositions could have produced 3–17 vol.% melt at the crustal depth exposed, which is generally less than the volume of leucosome at outcrop (43–72 and 39–67 vol.%, respectively, in the paragneiss and orthogneiss). This discrepancy indicates that the Fosdick complex acted as both a source of melt production and a zone of melt entrapment, whereby some of the melt derived from deeper in the crust has partially crystallized during migration to shallower levels in the crust. The observed power-law behavior of leucosomes is consistent with the hypothesis that intracrustal differentiation by anatexis and granite magmatism is scale-invariant and represents a self-organized critical system. The interaction of this critical system with the compositional layering in the paragneisses and the interlayering between paragneiss and orthogneiss accounts for the three-dimensional distribution of leucosome in stromatic metatexite migmatites.

1. Introduction

The partial melting of crustal rocks and the redistribution of the melt are the principal processes that differentiate the continental crust to produce a refractory lower portion and a complementary enriched upper portion (e.g. Brown, 2010a,b; Brown and Rushmer, 2006; Sawyer et al., 2011; Vielzeuf et al., 1990). The variable extent of partial melting according to lithology and/or the intrusion of granite magma creates domains with different rheologies that play a key role in focusing strain during the build up and collapse of orogens (Davidson et al., 1994; Hollister and Crawford, 1986; Jamieson et al., 2011; Vanderhaeghe and Teyssier, 2001).

For the process of crustal differentiation to be effective, an interconnected melt-flow network must be activated in the deeper suprasolidus crust to enable the extraction and ascent of anatectic melt to shallower subsolidus crust where it may accumulate in plutons (Brown, 1994, 2010a; Hobbs and Ord, 2010; Solar and Brown, 2001; Vanderhaeghe, 1999; Wickham, 1987). Formerly suprasolidus crust is represented by migmatites and granulites exposed at the surface. In such rocks, leucosome provides evidence of former melt-flow networks that existed at multiple scales from grain boundary films to centrimetric- and metric-scale veins. Ultimately these networks link to metric- and decametric-scale tabular and cylindrical bodies of granite that represent former transport conduits for melt.

The fertility of crustal protoliths at *P*–*T* varies with the amount of H_2O-rich fluid present and the proportions of both hydrous and anhydrous minerals in the protoliths. In general, in the absence of any influx of H_2O-rich fluid, metasedimentary protoliths are more fertile

---

* Corresponding author. Tel.: +1 3019571657.
E-mail address: cyak@umd.edu (C. Yakymchuk).

0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.05.022

than metaigneous protoliths (Clemens, 2006). Most studies of melt-flow networks have concentrated on measuring the spatial distribution of leucosome in metasedimentary rocks (Bonamici and Duebendorfer, 2010; Bons et al., 2004; Hall and Kisters, 2012; Marchildon and Brown, 2003; Soesoo and Urtson, 2009; Soesoo et al., 2004; Tanner, 1999), since these lithologies are fertile, producing up to 50–60 vol.% melt at 900 °C (Clemens, 2006). However, partial melting of metaigneous rocks, such as tonalities and granodiorites, also may produce a significant quantity of melt if the temperatures are high enough or if melting is fluxed by the addition of an H_2O-rich fluid. For example, tonalites may produce up to 40 vol.% melt by hydrate-breakdown reactions (Clemens, 2006) and an estimated 10–48 vol.% melt (average 30 vol.%) was produced through H_2O-fluxed partial melting of metaigneous rocks in the Opatica subprovince of the Canadian shield (Sawyer, 1998). Additionally, the elemental compositions of granites worldwide are consistent with the input of melt derived from both metasedimentary and metaigneous sources (Clemens and Stevens, 2012). The spatial distribution of melt-transfer networks produced in suprasolidus metaigneous rocks has received less attention even though anatexis of metaigneous lower crust must play a significant role in the differentiation of the continental crust.

Primary compositional layering in rocks may represent a mechanical anisotropy that affects the development of organized networks of veins in both subsolidus and suprasolidus rocks. Several studies have quantitatively demonstrated that inherited anisotropies control the spatial distribution of veins in subsolidus rocks (Fagereng, 2011; Gillespie et al., 1999). Inherited anisotropies have also been suggested to control the spatial distribution of leucosome in suprasolidus rocks (e.g. Brown and Solar, 1998; Marchildon and Brown, 2003), although this has not been tested quantitatively.

In this contribution, the spatial distribution of leucosome in metasedimentary and metaigneous rocks is measured to test the hypothesis that leucosome networks are scale-invariant and part of a self-organized critical system, and to evaluate the effect of pre-existing heterogeneities on leucosome network development. Measurements were conducted in the Fosdick migmatite–granite complex in West Antarctica, which contains both migmatitic paragneisses and orthogneisses derived from metasedimentary and metaigneous protoliths that preserve petrographic and geochemical evidence of partial melting (Korhonen et al., 2010a,b, 2012; Siddoway et al., 2004a). The protolith of these gneisses was a turbidite sequence and a granodiorite suite, providing a contrast between heterogeneous (anisotropic) and relatively homogeneous (isotropic) source layers. The interlayering of these contrasting source layers at metric to decametric scales permits investigation of whether the heterogeneity of the metasedimentary protolith affects the thickness and spatial distribution of leucosome compared to leucosome in the homogeneous plutonic protolith.

2. Scale invariance

The scale invariance of geological structures is a ubiquitous phenomenon (Barton and La Pointe, 1995; Kruhl, 2013; Kruhl and Renftel, 1994; Turcotte, 1997). Self-similar folds, the spacing of fractures, and S–C fabrics are but a few of the examples in structural geology that are scale-invariant from the micro- to macroscale (Gillespie et al., 1993, 1999; Hippertt, 1999; Turcotte, 1997). The spatial distribution of formerly melt-bearing structures, such as the thickness and spacing of dunite layers in ophiolites (Braun and Kelemen, 2002; Kelemen et al., 2000), the thickness and spacing of leucosome layers in migmatites (Bonamici and Duebendorfer, 2010; Marchildon and Brown, 2003; Pereira et al., 2013; Tanner, 1999) and the thickness of associated granite dykes (Brown, 2005), has also been proposed to be scale-invariant, although sometimes the scale of observations is limited. If these features are scale-invariant, this will have important implications for the extrapolation of these structures from outcrop to map scale, which will enable the interpretation of spatially limited data (e.g. Gillespie et al., 1993; Kruhl, 2013). Scale invariance can be a physical (spatial or temporal) manifestation of self-organized critical behavior, a concept that has found wide applications across the physical sciences (Bak et al., 1988).

Melt extraction has been argued to represent a self-organized critical process (Brown, 2010b; Hall and Kisters, 2012; Hobbs and Ord, 2010). A spatial signal of self-organized criticality in the melt extraction process is the scale invariance of formerly melt-bearing structures. Although several studies have proposed that the spatial distribution of leucosome in migmatites is scale invariant (Bonamici and Duebendorfer, 2010; Bons et al., 2004, 2010; Hall and Kisters, 2012; Marchildon and Brown, 2003; Tanner, 1999), Marchildon and Brown (2003) argued that the spatial distributions of leucosome networks in Southern Brittany, France exhibited only limited scale invariance. These authors (Marchildon and Brown, 2003) proposed that pre-existing anisotropies in the rock (e.g. compositional layering and foliation) and the syn-anatectic strain regime controlled the spatial distribution of leucosome.

The limitation of these previous studies is that nearly all of the leucosome network measurements were conducted on anisotropic gneisses derived from metasedimentary protoliths (Bonamici and Duebendorfer, 2010; Bons et al., 2004, 2010; Hall and Kisters, 2012; Marchildon and Brown, 2003; Tanner, 1999). The spatial distribution of melt-transfer networks produced in formerly suprasolidus metaigneous rocks has received less attention, but such protoliths can produce significant volumes of melt during high-temperature metamorphism (Clemens, 2006; Korhonen et al., 2010a). Additionally, metaigneous protoliths tend to be homogeneous and isotropic in comparison with metasedimentary rocks. These differences are commonly carried through to the suprasolidus realm and are readily apparent by visual comparison of the migmatitic paragneisses and orthogneisses of this study (Fig. 1). The Fosdick migmatite–granite complex in West Antarctica provides an opportunity to evaluate the effect of pre-existing heterogeneities on the spatial distribution of leucosome networks in migmatite terranes because the complex comprises interlayered metasedimentary and metaigneous protoliths that have experienced the same metamorphic history (Korhonen et al., 2010a,b, 2012).

3. Geology of the Fosdick migmatite–granite complex

3.1. Regional setting

Leucosome network measurements were conducted on migmatites located in the Fosdick migmatite–granite complex exposed in the Ford Ranges of Marie Byrd Land in West Antarctica (Fig. 2). In the Ford Ranges, the early Paleozoic Swanson Formation is the oldest exposed unit (Adams, 2004; Bradshaw et al., 1983; Pankhurst et al., 1998). It is a folded and cleaved turbidite sequence (Fig. 3a) that accumulated outboard of the Cambrian Ross–Delamerian Orogen. The Devonian–Carboniferous Ford Granodiorite suite (Fig. 4a) intrudes the Swanson Formation. The emplacement of the Ford Granodiorite suite was associated with a major pulse of Paleozoic calc-alkaline magmatism along the East Gondwana continental margin (Muir et al., 1994; Mukasa and Dalziel, 2000; Pankhurst et al., 1998; Storey et al., 1999; Weaver et al., 1991, 1992, 1994), which has been variously attributed to subduction (Weaver et al., 1991) or back-arc extension (Muir et al., 1996; Tulloch et al., 2009).

Cretaceous oblique extensional deformation that preceded the final breakup of East Gondwana and formation of the West Antarctic Rift System has exposed a high-grade migmatite–granite complex in the Fosdick Mountains of West Antarctica (Richard et al., 1994; Siddoway, 2008; Siddoway et al., 2004b, 2005). The complex forms an elongate (80 x 15 km) gneiss dome composed of migmatitic orthogneisses and paragneisses, multiple generations of granite, and subordinate intrusive mafic rocks (Korhonen et al., 2010a,b, 2012; McFadden et al., 2010a,b; Richard et al., 1994; Saito et al., 2013; Siddoway et al., 2004a; Yakymchuk et al., in press). The geochemistry