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Melt organisation and strain partitioning in the lower crust

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ABSTRACT

Partial melts can form as a result of crustal thickening due to orogenesis. Even small melt fractions weaken the crust, so that partially molten volumes should accumulate significant amounts of strain. However, relatively little is known of how strain partitions in partial melts, and how effective the melt expulsion processes from the partially molten crust are. Using examples from the Western Gneiss Region (WGR), Norway, we consider a case of co-existing migmatites and shear zones. Field, image analysis, and microanalytical methods allow (semi) quantification of melt volume, rock mineralogy and mineral chemistry, and microstructures. Integration of these analyses implies effective syn-melt strain partitioning and subsequent freezing of both the shear zone and migmatite texture. We propose a mechanism that allows i) syn-melt strain localisation at an outcrop scale through stress-driven melt organisation, resulting in significant relative competence differences in a partially molten rock volume; and ii) formation of fine-grained rocks at outcrop that is entirely or mostly syn-melt, without subsequent mylonitic shearing in the solid-state. Syn-melt shear zones that have not acted as effective melt transport channels and/or that have not accumulated post-melt deformation may be more common than conventionally assumed.

1. Introduction

In-situ partial melting is known to cause potentially dramatic strength decreases in the crust, even for small melt volumes, constraining styles of orogenic deformation and exhumation (e.g. Beaumont et al., 2001; Rosenberg and Handy, 2005; Jamieson and Beaumont, 2013; Levine et al., 2013). Such partial melting adds to the already heterogeneous nature of most rocks (e.g. based on grain size, mineralogy, microstructure, etc.). Lithological heterogeneities are significant factors in controlling strain partitioning on all scales (Fossen and Cavalcante, 2017). However, relatively little is known about how strain partitions in partially molten rock volumes. For example, the co-existence of partially molten rock together with regions of high strain (i.e. shear zones) is a common feature of many orogenic belts (e.g. the Himalaya) but the mechanism(s) and relative timing(s) of their formation remain poorly understood.

There are known theoretical feedback relationships between melting, rheological weakening (depending on melt fraction and melt connectivity), shear zone nucleation, and melt transport so that syn-melt shear zones are expected to function as effective transport channels for crustal partial melts (e.g. Brown and Solar, 1998; Rosenberg and Handy, 2005; Brown, 2007, and references therein). Mid- and lower crustal partial melts are indeed seen to infiltrate many shear zones and source many large intrusive bodies, with some areas even showing possible direct evidence of melt removal (e.g. Brown, 1994; Johannes et al., 2003; Stuart et al., 2016).

Despite the basic relationships being known, the behaviour of partially molten crust as observed at outcrop is not always easily explained by the models and experiments (Lee et al., 2017; Rosenberg and Handy, 2005), meaning that many aspects of how partially molten crust actually deforms remain unknown. For example, it is unclear why very large volumes of melts are seen to remain approximately in-situ within the crust in the form of migmatites, despite their sometimes immediate proximity to one or several shear zones (e.g. Labrousse et al., 2004). Conversely, it remains unclear in many cases what caused the strain partitioning into a shear zone within the partially molten volume in the first place. Non-expulsion of melts might be explained by the shear zones forming post-crystallisation (post-melt), but this contradicts with the theoretical predictions of inevitable formation of syn-melt shear zones (e.g. Holtzman et al., 2003; Walte et al., 2005). Another option is that the shear zones formed syn-melt but did not act as effective melt transport channels. If this is true, there may be significant implications to how partially molten crust deforms at a large scale.

In order to begin investigating the possibility of non-expulsion of partial melts through shear zones, we first need to demonstrate that such shear zones may exist. In this paper, we address this using representative rock samples from an extensively migmatized crust of the Western Gneiss Region (WGR), Norway. We use image analysis, optical

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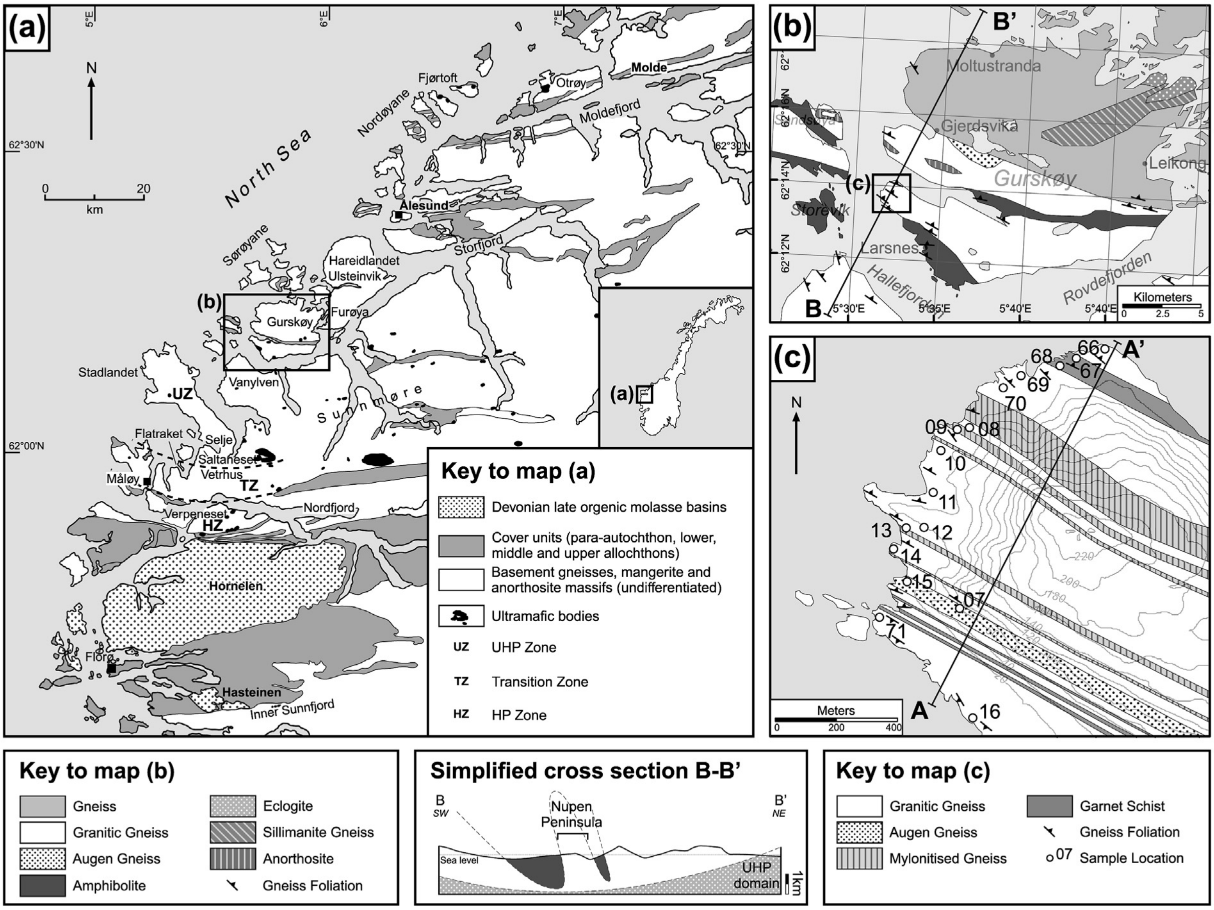

Fig. 1. Geological map of (a) Western Gneiss Region with inset detail maps of (b) Gurskøy with section line B-B′ and (c) Nupen Peninsula with sample locations and section line A-A′ shown in Section 3.2(Geological maps modified from Kildal, 1970; Lutro et al., 1997; Lutro and Tveten, 1998; Tveten et al., 1998; Carswell et al., 2003; Root et al., 2005).

microscope, Electron Backscatter Diffraction (EBSD) and electron microprobe to i) quantify leucosome fraction, ii) semi-quantify melt fraction, iii) quantify mineral geochemistry, and iv) quantify crystallographic preferred orientation (CPO) in representative rock samples from the WGR. We demonstrate that extensive partial melting and syn-melt deformation of a geochemically relatively homogeneous granitoid protolith resulted in strong strain partitioning into a syn-melt fine-grained shear zone with no melt expulsion, and no or very little post-crystallisation plastic deformation.

2. Geological setting

The WGR is the deepest structural level of the Scandinavian Caledonides (Fig. 1a; Andreasson and Lagerblad, 1980). It is dominated by tonalites of 1686 to 1650 Ma, subsequently intruded by granite, gabbro and diabase from 1640 to 900 Ma (Tucker et al., 1990). At 950 Ma, the igneous basement underwent granulite facies metamorphism at 900°C and 1 GPa associated with extensive plutonism (Tucker et al., 1990; Krabbendam et al., 2000; Corfu and Andersen, 2002).

During the early Palaeozoic (480-430 Ma), the Caledonian Orogeny initiated, causing deformation and metamorphism of the Proterozoic basement gneiss and oceanic allochthons to 725°C and 1.2 GPa (Hacker et al., 2010). The final stage of the Caledonian Orogeny, the Scandian, resulted in the closure of the Iapetus Ocean and emplacement of oceanic allochthons onto Baltica between 430 and 410 Ma (Tucker et al., 2004; Hacker and Gans, 2005). Later collision of Baltica and Laurentia between 425 and 400 Ma resulted in the westward subduction of the Proterozoic Baltican basement and portions of the allochthon to ultrahigh-pressures (UHP) of 1.8–3.6 GPa and temperatures of 600–800°C (Fig. 2; Andersen et al., 1991; Schärer and Labrousse, 2003; Tucker et al., 2004; Hacker and Gans, 2005; Kylander-Clark et al., 2008; Hacker et al., 2010).

From 400 to 385 Ma the WGR was exhumed to shallow crustal levels (Andersen, 1998; Terry et al., 2000; Tucker et al., 2004; Hacker, 2007; Walsh et al., 2007; Hacker et al., 2010). During the exhumation event, an E-W horizontal stretching was imprinted alongside in-situ partial melting of the gneiss via post-UHP decompression-related retrograde amphibolite metamorphism as the pressure decreased from 2.8 to 0.5 GPa at temperatures of 600–800^{o}C (Fig. 2; Krogh, 1980; Chauvet et al., 1992; Andersen, 1998; Straume and Austrheim, 1999; Hacker et al., 2003; Labrousse et al., 2002; Schärer and Labrousse, 2003; Labrousse et al., 2004; Walsh and Hacker, 2004; Root et al., 2005; Engvik et al., 2007; Gordon et al., 2013, 2016). Evidence for (U)HP metamorphism was almost completely overprinted during the open-system partial melting event, as the UHP rocks were exhumed from 100 km depth to 15–20 km (Schärer and Labrousse, 2003; Root et al., 2005). Exhumation occurred from 394 to 389 Ma at a rate of 5 mm/year, followed by rapid cooling to reach 300°C by 357 Ma (Schärer and Labrousse, 2003; Root et al., 2005).

This study focuses on the Nupen peninsula in the southwest of Gurskøy (Fig. 1b and c). The primary lithology is amphibolite-facies quartzofeldspathic gneiss that has undergone partial melting. The gneisses show layers of melanosomes and leucosomes that were stretched and sheared at a later stage, indicating that the migmatization commenced early in the exhumation-related deformation history (Labrousse et al., 2002). Gurskøy was exhumed via thrusting and