Journal of Structural Geology 50 (2013) 91–118

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

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

Strain accumulation and fluid–rock interaction in a naturally deformed diamictite, Willard thrust system, Utah (USA): Implications for crustal rheology and strain softening

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ARTICLE INFO

Article history:
Received 3 January 2012
Received in revised form
22 October 2012
Accepted 30 October 2012
Available online 15 November 2012

Keywords:
Strain
Diamictite
Willard thrust fault
Fluids
Fault
Deformation
Rheology

ABSTRACT

Structural and geochemical patterns of heterogeneously deformed diamictite in northern Utah (USA) record interrelations between strain accumulation, fluid–rock interaction, and softening processes across a major fault (Willard thrust). Different clast types in the diamictite have varying shape fabrics related to competence contrasts with estimated effective viscosity ratios relative to micaceous matrix of: ~6 and 8 for large quartzite clasts respectively in the Willard hanging wall and footwall; ~5 and 2 for less altered and more altered granitic clasts respectively in the hanging wall and footwall; and ~1 for micaceous clasts that approximate matrix strain. Within the footwall, matrix X–Z strain ratios increase from ~2 to 8 westward along a distinct deformation gradient. Microstructures record widespread mass transfer, alteration of feldspar to mica, and dislocation creep of quartz within matrix and clasts. Fluid influx along microcracks and mesoscopic vein networks increased westward and led to reaction softening and hydrolytic weakening, in conjunction with textural softening from alignment of muscovite aggregates. Consistent Si, Al, and Ti concentrations between matrix, granitic clasts, and protoliths indicate limited volume change. Mg gain and Na loss reflect alteration of feldspar to phengitic muscovite. Within the hanging wall, strain is overall lower with matrix X–Z strain ratios of ~2 to 4. Microstructures record mass transfer and dislocation creep concentrated in the matrix. Greater Al and Ti concentrations and lower Si concentrations in matrix indicate volume loss by quartz dissolution. Na gain in granitic clasts reflects albitization. Large granitic clasts have less mica alteration and greater competence compared to smaller clasts. Differences in strain and alteration patterns across the Willard thrust fault suggest overall downward (up-temperature) fluid flow in the hanging wall and upward (down-temperature) fluid flow in the footwall.

1. Introduction

Deformation of rocks is typically heterogeneous as a consequence of multiple factors, including variations in material properties, from micron-scale differences in grain mineralogy to km-scale layering in the crust (e.g. Turner and Weiss, 1963; Goodwin and Tikoff, 2002; Park et al., 2006; Horsman et al., 2008). Heterogeneity may also result from fluid–rock interaction and strain softening processes during progressive deformation, leading to development of faults and ductile shear zones (e.g. Carter et al., 1990; Stewart et al., 2000; Selverstone and Hyatt, 2003; Yonkee et al., 2003; O'Hara, 2007). Our understanding of deformation processes has been greatly influenced by laboratory rock deformation experiments that provide quantitative information on rheology under controlled conditions (e.g. Kirby, 1985; Paterson and Luan, 1990; Hirth and Tullis, 1992; Gleason and Tullis, 1995; Kohlstedt et al., 1995; Holyoke and Tullis, 2006). However, experiments are necessarily conducted at fast strain rates on small samples, typically with simple mineralogy and limited finite strain, requiring extrapolation to realistic geologic conditions. For example, idealized rheologic models of crustal strength have been developed based on experimental deformation of granite and

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http://dx.doi.org/10.1016/j.jsg.2012.10.012

quartzite conducted at fast strain rates and high temperatures (e.g. Brace and Kohlstedt, 1980; Sibson, 1983; Kirby, 1985; Kirby and Kronenberg, 1987; Scholz, 1988; Kohlstedt et al., 1995). Such extrapolation, however, has limitations that are difficult to evaluate without additional information on microstructures, strain, and alteration patterns within naturally deformed rocks (e.g. Stöckhert et al., 1999; Imber et al., 2001; Rutter et al., 2001). Thus, detailed structural and petrologic studies of tectonites play a complimentary role to laboratory experiments, providing data from a variety of geologic settings to test idealized rheologic models.

Fluids play a key role during deformation, and their influence has been extensively studied experimentally (e.g. Jaoul et al., 1984; Tullis and Yund, 1989; Kronenberg and Wolf, 1990; Tullis et al., 1996) and in naturally deformed rocks (e.g. Kronenberg et al., 1990; Selverstone et al., 1991; Newman and Mitra, 1993; Wawrzyniec et al., 1999; Selverstone and Hyatt, 2003; Vernon, 2004; O'Kane et al., 2007; Bhattacharyya and Mitra, 2011). Multiple factors, including evolution of fracture networks and microtextures during progressive deformation, mineral reaction rates, and transient changes in fluid pressure, control fluid–rock interaction over a range of scales with complex feedbacks (e.g. Streit and Cox, 1998; Yonkee et al., 2003; Wibberley, 2005; Ault and Selverstone, 2008; Gleason and DeSisto, 2008). Varying spatial-temporal distributions of fluids and contrasting styles of fluid–rock interaction can result in localization of deformation related to reaction softening, hydrolytic weakening, increased diffusion rates, and enhanced fracturing.

Polymict conglomerates and diamictites provide intriguing examples of heterogeneous strain related to contrasting material properties of matrix and different clast types with variable alteration (Huber-Aleffi, 1982; Treagus and Treagus, 2002; Czeck and Hudleston, 2003; Czeck et al., 2009). Although complex, such strain patterns provide opportunities to evaluate rheologies of different materials deformed at geologic strain rates and over a range of spatial scales. Additionally, variations in alteration patterns can be used to evaluate softening processes, which are important for localization of deformation along major faults and ductile shear zones.

Various mathematical models have been developed to describe deformation of inclusions within a matrix of contrasting strength (e.g. Jeffery, 1922; Eshelby, 1957; Gay, 1968a; Bilby et al., 1975; Bilby and Kolbuszewski, 1977; Lisle et al., 1983; Freeman, 1987; Treagus et al., 1996; Treagus and Lan, 2000; Treagus and Treagus, 2001; Schmid and Podladchikov, 2003). These models make specific predictions of clast shape as a function of viscosity contrast and matrix strain, which have been applied to deformed conglomerates and other fragmental rocks to estimate relative strengths of different clast types (Gay, 1968b, 1969; Huber-Aleffi, 1982; Lisle et al., 1983; Freeman and Lisle, 1987; Treagus and Treagus, 2002; Horsman et al., 2008; Czeck et al., 2009). For the case of an isolated, initially circular, linear-viscous clast deformed by pure shear, the final clast axial ratio, R, is related to the matrix strain ratio, RS, by

$$\ln(R) = \left[5/\left(2r_{\mathrm{eff}} + 3\right)\right]*\ln(RS) \quad (1)$$

where $r_{\mathrm{eff}} = \eta_c/\eta_m$ is the ratio of clast to matrix viscosity (Fig. 1A; Treagus and Treagus, 2002).

Although progress has been made in understanding strain patterns in heterogeneously deformed conglomerates, questions remain about the nature of clast interaction, appropriate rheology, and variable deformation paths. Here, these issues are addressed by detailed analysis of deformed diamictite in which clasts have larger relative spacings, reducing clast interactions. Additionally, mathematical relations for power-law viscous behavior (Mancktelow, 2011) are applied to populations of clasts deformed in general sub-simple shear by solving systems of ordinary differential equations (Fig. 1B and C; see Appendix A in the Supplementary materials). Using the tensor mean axial ratio, $\overline{R}$, for a deformed clast population yields an approximate relationship of the form

$$\ln(\overline{R}) \approx \left[5/(2r_{\mathrm{avg}} + 3)\right]*f(R_{\mathrm{i}}, w_{\mathrm{k}})*\ln(RS) \quad (2)$$

where r_{avg} is an average viscosity ratio (in detail r_{eff} varies with clast strain rate and thus with evolving clast shape and orientation for a power law rheology) and $f(R_{\mathrm{i}}, w_{\mathrm{k}})$ is a function of initial clast axial ratio, R_{i}, and matrix kinematic vorticity, w_{k}. Effects of matrix vorticity are insignificant at low to moderate strains ($RS < 10$). Thus, the average viscosity ratio can be estimated if matrix strain and average R_{i} of clasts can be evaluated (Fig. 1D). Note $\overline{R}$ measures the shape fabric of a population of deformed clasts and includes effects of both internal strain within clasts and rotation of clasts induced by matrix flow. Viscosity ratios may change during progressive deformation due to strain softening that varies between clasts and matrix. By integrating analyses of heterogeneous strain and fluid–rock interaction, different models of rheology and softening can be tested.

Deformed diamictites exposed in the footwall and hanging wall of the Willard thrust fault, a major fault in northern Utah, display complex patterns of strain and fluid–rock interaction that vary between different clast types and matrix, providing a natural laboratory to evaluate heterogeneous deformation and softening processes. Results of detailed structural and geochemical studies on these diamictites are used to address the following questions:

1. How can clast shape fabrics best be used to estimate relative strengths of different materials in polymict clastic rocks?
2. What were the relations between strain accumulation, deformation mechanisms, and softening processes in the diamictite, and how did relations vary between different clast types and across the Willard thrust fault?
3. What were the patterns of fluid–rock interaction and fluid pathways, and how did they vary across the Willard thrust fault?
4. How do patterns of strain and fluid–rock interaction in the naturally deformed diamictite compare to idealized rheologic models based on laboratory rock deformation experiments?

2. Geologic setting

2.1. Overview

The Willard thrust sheet and its deformed footwall are well exposed in northern Utah where younger uplift and erosion have exhumed a wide range of structural levels (Fig. 2). This dominant thrust sheet comprises a 10- to 15-km-thick package of rocks that was emplaced ~60 km eastward within the Sevier fold-thrust belt (Yonkee, 2005). The thrust sheet includes an upper level of carbonate-rich Paleozoic strata, a middle level of quartzite-rich upper Neoproterozoic to lower Cambrian strata, and a lower level of micaceous Neoproterozoic strata; thin slices of Archean to Paleoproterozoic basement rocks are locally incorporated into the base of the sheet. Upper levels of the sheet exhibit relatively little deformation, but internal deformation increases downward and westward, with development of cleavage, minor folds, and vein arrays (Crittenden, 1972; Yonkee, 2005). Cleavage defines an overall asymptotic pattern, ranging from weakly developed and steeply dipping farther from the thrust, to intensely developed and subparallel to the thrust at the base of the sheet, recording components of easterly directed thrust-parallel simple shear and varying thrust-parallel shortening to extension. The footwall also displays internal deformation that varies with structural position and lithology (Evans and Neves, 1992), including development of cleavage in deeper, more western parts (Yonkee et al., 2000b).