Flow strength of wet quartzite in steady-state dislocation creep regimes

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Key points:

- Best-fit flow laws derived from high-quality creep experiments of wet quartzite with consideration of pressure and slip-system dependence
- Micromechanics-based homogenization method developed for the creep of wet quartzite by simultaneous basal <a> and prism <a> slips
- Results reconciling discrepancies among flow laws derived from experiments and consistent with observations and theoretical considerations

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Abstract

We quantitatively investigated the flow laws of wet quartzite in steady-state dislocation creep regimes by considering both the dependence of the activation enthalpy on pressure and dependence of the stress exponent on slip systems. From a critically-selected set of creep experiments of wet quartzite with microstructures and c-axis fabrics suggesting steady-state dislocation creeps, we obtained two endmember flow laws corresponding respectively to dominant prism <a> slip and dominant basal <a> slip systems. To characterize the dislocation creep of wet quartzite by a continuous combination of prism <a> and basal <a> slips commonly observed in nature and experiments, we developed a self-consistent micromechanics-based homogenization approach. Our results reconciled the large discrepancies in flow law parameters for wet quartzite determined from different creep experiments and are broadly consistent with microstructures and c-axis fabrics from nature and experiments as well as theoretical considerations.

Plain Language Summary

Understanding the rheology of continental crust is a fundamental problem related to the physics of Earth and geodynamics. Our current understanding of the rheology of continental crust is based on the high-temperature and high-pressure creep experiments on wet quartzite in recognition that quartz is a common and strength-controlling mineral in the crust. These experimental data are commonly fitted into a power-law flow law, which is incorporated in many geodynamic models. Unfortunately, past creep experiments on wet quartzite yield very different quartz flow law parameters. We critically select 19 high-quality creep experiments on wet quartzite and demonstrate that the current dataset is consistent with two endmember flow laws,

corresponding to dominant basal <a> and dominant prism <a> slip systems. In both experiments and nature, the creep behavior of wet quartzite is a continuous spectrum from dominant basal <a> to a mixture of basal <a> and prism <a> slip and dominant prism <a> slip. We propose a self-consistent micromechanics-based approach to determine the creep behavior in such situations and plot the results in a 3D strength profile. In nature, the temperature, pressure, and the relative contribution of dominant slip systems profoundly affect the strength of wet quartzite.

1. Introduction

An accurate expression for the creep of quartzite is of paramount importance in geodynamics (e.g., Kohlstedt et al., 1995; Ranalli, 1987; Beaumont et al., 2001; Lavier et al., 2013; Chowdhury et al., 2017). Despite many decades of effort, our knowledge on this subject is still incomplete. The dislocation creep of wet quartzite has been described by a flow law of the form $\dot{\varepsilon} = Af_w^m \exp\left(-\frac{Q}{RT}\right)\sigma^n$, where $\dot{\varepsilon}$ is the strain rate, A the pre-exponential parameter, f_w the water fugacity, m the water fugacity exponent, Q the activation energy, R the universal gas constant, T the absolute temperature, σ the differential stress, and n the stress exponent. A major problem has been that past experiments have yielded very different values of Q, n, m, and A (*flow law parameters*, hereafter), with n varying between 2 and 4, Q between $130\ \mathrm{kJ/mol}$ and $240\ \mathrm{kJ/mol}$, and m between 0.372 and 2.8 (Kronenberg and Tullis, 1984; Koch et al., 1989; Gleason and Tullis, 1995; Luan and Paterson, 1992; Post et al., 1996; Rutter and Brodie, 2004; Chernak et al., 2009; Holyoke and Kronenberg, 2013). Such a large range of flow law parameters translates to very large uncertainties in the predicted strength of the continental crust and may have profoundly affected the outcome of many geodynamic models where a quartz flow law is used.

Recently, Lu and Jiang (2019) have shown that the large difference in Q among experiments may be explained by the pressure dependence of the activation enthalpy. Using the following flow law (e.g., Karato and Jung, 2003):

$$\dot{\varepsilon} = Af_w^m \exp\left(-\frac{Q+PV}{RT}\right)\sigma^n = Af_w^m \exp\left(-\frac{H}{RT}\right)\sigma^n \qquad (1)$$

where P is the pressure, V the activation volume, and H $(=Q+PV)$ the activation enthalpy, they applied an iterative method to the experiment data of Gleason and Tullis (1995), Luan and Paterson (1992), and a set of pressure stepping experiments of Kronenberg and Tullis (1984) to obtain the following set of flow law parameters: n = 4, m = 2.7, V = 35.3 cm^3/mol, and Q = 132 kJ/mol. Furthermore, there is growing evidence that in the dislocation creep regime n may depend on the active dominant slip system (Goldsby and Kohlstedt, 2001; Hirth and Kohlstedt, 2003) and the reported variation of n between 2 and 4 for quartzite may reflect a switch of the dominant slip systems (Tokle et al., 2019).

In this contribution, we re-examine the existing high-quality quartz creep experiments data by considering *both* the activation enthalpy dependence on pressure and the stress exponent dependence on dominant slip systems. We select 19 creep experiments on quartz samples with grainsize of 20-200 μm, deformed from 700 °C to 1200 °C and interpreted to represent steady-state regimes 2 and 3 dislocation creeps (Hirth and Tullis, 1992), to determine the flow law parameters using Eq.1. A detailed description of the selection criteria of previous creep experiments for our analysis is given in supplementary information and Lu and Jiang (2019). We found that current experimental dataset is consistent with two endmember dislocation creep flow laws, corresponding respectively to a dominant prism <a> slip and a dominant basal <a> slip. Furthermore, both experiments and natural quartz-bearing mylonites suggest that both basal <a> and prism <a> slips can be significant. We develop a self-consistent micromechanics-based method to numerically determine the flow behavior of wet quartzite in such situation.

2. Dislocation creep flow laws determined from experiments

The flow law expressed in Eq.1 implies that *n*, *m*, and *V* cannot be determined in isolation, because they are related by (Lu and Jiang, 2019):

$$m = -n\left(\frac{\partial \ln \sigma}{\partial \ln f_w}\right)_{T,\dot{\varepsilon}} + \frac{V}{RT}\left(\frac{\partial P}{\partial \ln f_w}\right)_{T,\dot{\varepsilon}} \tag{2}$$

In addition, to determine *n* through the relation $n = \left(\frac{\partial \ln \dot{\varepsilon}}{\partial \ln \sigma}\right)_{T,P,f}$ requires experiment runs under constant *T*, *P*, and f_w conditions. As experiments (Dataset S1) were carried out under different *P-T* conditions, one needs to normalize the data to a common reference *P-T* condition. The following iterative approach, which is a refined one from that in Lu and Jiang (2019), is used to determine all the parameters in Eq.1: First, starting with an initial input of *n*, the values of *m* and *V* are solved using Eq.2, based on a minimum of three sets of *P* and f_w stepping experimental data at constant $\dot{\varepsilon}$ and *T* (Lu and Jiang, 2019). Second, with the values of *n*, *m* and *V*, the activation energy *Q* is determined from *T* stepping experimental data (see supplementary information for details). Third, the values of *m*, *V*, and *Q* allow for normalization of all data in Dataset S1 to a reference *P-T* condition. With the normalized strain rates and normalized stresses, an updated value of *n* is obtained by linear regression. A new round of iteration is initiated with the updated n. The iteration continues until the output and input n values are within a specific tolerance of ($\left|n_{output} - n_{input}\right| \le 0.1$). The pre-exponential term A is a final fitting parameter, which can be obtained once n, m, V, Q are determined. The final set of n, m, V, Q, and A are the best-fit flow law parameters for the data.

On the basis of Tokle et al. (2019, their Fig.1), the high-temperature and low-temperature data point to two different values of n. We thus consider the high-temperature and low-temperature data in Dataset S1 separately. For experimental data associated with samples deformed at higher temperatures (900-1200°C) and lower stresses (Luan and Paterson, 1992; Gleason and Tullis, 1995; Stipp and Tullis, 2003; Heilbronner and Tullis, 2006; Nachlas and Hirth, 2015; Kidder et al., 2016; Richter et al., 2018), we used an initial value of $n = 4$, three sets of P and f_w stepping experimental data from 820 MPa to 1590 MPa (Kronenberg and Tullis, 1984), and the T stepping experimental data from 827 °C to 1050 °C (Luan and Paterson, 1992; Gleason and Tullis, 1995) in the above described iterative method. We obtained a final set of $n = 3.9 \pm 0.2$, $m = 2.6$, $V = 35.8\ \mathrm{cm^3/mol}$, $Q = 132 \pm 19\ \mathrm{kJ/mol}$, and $A = 2.5 \times 10^{-(14 \pm 0.4)}\ \mathrm{MPa^{-n-m}s^{-1}}$. For data associated with samples deformed at lower temperatures (700-900 °C) and higher stresses (Kronenberg and Tullis, 1984; Koch et al., 1989; Post et al., 1996; Chernak et al., 2009; Tokle et al., 2013; Richter et al., 2016; Richter et al., 2018), we used an initial value of $n = 2$, the three sets of P and f_w stepping experimental data from Kronenberg and Tullis (1984) performed between 820 to 1590 MPa, and the T stepping experimental data from 750 °C to 900 °C (Koch et al., 1989) in the iteration. We got a final set of $n = 2.5 \pm 0.1$, $m = 1.7$, $V = 23.1\ \mathrm{cm^3/mol}$, $Q = 126 \pm 16\ \mathrm{kJ/mol}$, and $A = 6.3 \times 10^{-(12 \pm 0.4)}\ \mathrm{MPa^{-n-m}s^{-1}}$. Therefore, the best-fit flow laws are respectively:

$$\dot{\varepsilon} = 2.5\times10^{-14} f_w^{2.6} \exp\left(-\frac{132000+35.8P}{RT}\right)\sigma^4$$ dominant prism <a> slip (3a)

$$\dot{\varepsilon} = 6.3\times10^{-12} f_w^{1.7} \exp\left(-\frac{126000+23.1P}{RT}\right)\sigma^{2.5}$$ dominant basal <a> slip (3b)

with f_w, P, and σ all in MPa.

Eq.3a differs from the flow law obtained in Lu and Jiang (2019) slightly in m and V ($m = 2.7$, $V = 35.3\ \mathrm{cm^3/mol}$ in Lu and Jiang, 2019) and more in A ($A = 6.0\times10^{-15}$ in Lu and Jiang 2019) because Lu and Jiang (2019) applied the stress calibration of Holyoke and Kronenberg (2010) for the experimental data. Such calibration is not applied here for reasons given in supplementary information.

Using the two flow laws of Eqs.3, the strain rate versus differential stress plots for all data in Dataset S1 at a reference *P*-*T* condition of $T = 900\ °\mathrm{C}$ and $P = 1500\ \mathrm{MPa}$ are shown in Fig.1. Clearly, the two distinct flow laws are consistent with the current dataset: Eq.3a is the best-fit flow law for wet quartzite deforming predominantly by prism <a> slip and producing characteristic Y-max c-axis fabrics (Fig.2), whereas Eq.3b is the best-fit flow law for wet quartzite deforming predominantly by basal <a> slip with characteristic cluster of c-axes in the periphery (Fig.2).

3. Self-consistent determination of creep behavior of wet quartzite in the transitional regime

A steady-state dislocation creep is always associated with the activation of multiple slip systems (von Mises, 1928). Quartz c-axis fabrics from both experimental samples (Fig.2) and natural mylonites (e.g., Stipp et al., 2002; Law et al., 2010; Toy et al., 2010; Behr and Platt, 2011; Whitney et al., 2014) also suggest that common slip systems in quartz are basal <a>, prism <a>, and rhomb <a>. Quartz c-axis fabrics suggest that rhomb <a> cannot be a dominant slip system and prism <c> is not important unless at very high-temperature conditions (Lister and Dornsiepen, 1982) and is rare in mylonites. In most natural quartz-bearing mylonites, one may assume that at least one of basal <a> and prism <a> must be dominant to achieve a steady-state dislocation creep. In such a case, we must consider the creep due to simultaneous operation of both basal <a> and prism <a> systems that cannot be described by either Eq.3a or Eq.3b.

Where deformation mechanisms differ from one grain to another, the stress (and strain rate) field varies among grains accordingly. On a suitable Representative Volume Element (RVE) containing a large number of grains such that the average strain rate and average stress over the RVE represent the macroscale fields, the macroscale (or average) fields can be expressed as:

$$\bar{\dot{\varepsilon}} = \sum r_i \dot{\varepsilon}_i \,, \ \bar{\sigma} = \sum r_i \sigma_i \tag{4}$$

where $\dot{\varepsilon}_i$, σ_i, and r_i are the strain rate, stress, and volume fraction of the *i*th grain, respectively; $\bar{\dot{\varepsilon}}$ and $\bar{\sigma}$ are, respectively, the macroscale (or average) strain rate and stress on the RVE. The macroscale creep behavior of the sample is then a relation of the form $\bar{\dot{\varepsilon}} = f(\bar{\sigma}, \lambda)$ where λ is a parameter describing the current *fabric state* of the aggregates. In the simplistic Voigt situation where all grains are assumed to have a uniform stain rate ($\dot{\varepsilon}_1 = \dot{\varepsilon}_2 = \bar{\dot{\varepsilon}}$, Voigt, 1887), the grains with prism <a> slip as the dominant deformation mechanism will have a uniform stress σ_1 after Eq.3a, and those grains with dominant basal <a> slip will have another uniform stress σ_2 after

Eq.3b. Denoting the volume fractions for two grain types by α and $1-\alpha$, the macroscale (average) stress on the RVE is:

$$\bar{\sigma} = \alpha A_1^{-\frac{1}{n_1}} f_w^{-\frac{m_1}{n_1}} \exp\left(\frac{Q_1+PV_1}{n_1RT}\right)\bar{\dot{\varepsilon}}^{-\frac{1}{n_1}} + \left(1-\alpha\right) A_2^{-\frac{1}{n_2}} f_w^{-\frac{m_2}{n_2}} \exp\left(\frac{Q_2+PV_2}{n_2RT}\right)\bar{\dot{\varepsilon}}^{-\frac{1}{n_2}} \tag{5}$$

where subscripts “1” and “2” stand for the flow laws for dominant prism <a> slip and dominant basal <a> slip. Similarly, if the stresses in all grains are assumed uniform – the Reuss situation (Reuss, 1929), the macroscale (average) strain rate on the RVE is expressed as:

$$\bar{\dot{\varepsilon}} = \alpha A_1 f_w^{m_1} \exp\left(-\frac{Q_1+PV_1}{RT}\right)\bar{\sigma}^{n_1} + \left(1-\alpha\right) A_2 f_w^{m_2} \exp\left(-\frac{Q_2+PV_2}{RT}\right)\bar{\sigma}^{n_2} \tag{6}$$

Fig.3 shows the deformation mechanism maps based on the Voigt and Reuss situations. One can see that in the Reuss case, the two strain rates ($\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$) are on a comparable order. Similarly, in the Voigt case, the two stresses (σ_1 and σ_2) are also comparable in magnitude. Therefore, in the *P-T* range where natural mylonites form, the simultaneous operation of both slips must be considered for the macroscale strain rate and stress relationship.

The Voigt and Reuss averages only provide the upper and lower bounds for the macroscale flow behavior where both basal <a> and prism <a> are significant because the assumption of either uniform stress or uniform strain in all grains is unrealistic. Even in a single-phase polycrystal aggregate like quartzite, $\dot{\varepsilon}_i$ and σ_i are distinct in each grain due to its unique shape, orientation, and rheology (here determined by the dominant slip system) (Mura, 1987; Nemat-Nasser & Hori, 1999). A self-consistent micromechanics approach based on the Eshelby formalism (Jiang, 2014, 2016, Qu et al., 2016) is utilized to quantitatively describe such interactions between a grain and the polycrystal aggregate. Briefly, the $\dot{\varepsilon}_i$ and σ_i in any individual grain is related to the macroscale fields and macroscale rheology by a set of *partitioning equations*. The macroscale rheology is expressed in terms of the constituent grains rheology by a set of *homogenization equations*. The partitioning and homogenization equations are then solved simultaneously so that a self-consistent solution for the macroscale rheology (here the macroscale flow law) is obtained. A more detailed description of the specific approach is in supplementary information. As an example, we consider an RVE of 500 quartz grains subjected to a macroscale strain rate of $10^{-12}s^{-1}$. A geothermal gradient of 20℃/km is considered so that *P* is not an independent variable. The water partial pressure is assumed to equal to the lithostatic pressure, and the water fugacity is calculated based on Pitzer and Sterner (1994). We assume that the quartz grains are rheologically isotropic (following either of the two flow laws of Eq.3), randomly mixed, and have ellipsoidal shapes with a maximum axial ratio of 2. Although our homogenization method allows tracking of grain shapes and orientations and hence macroscale rheological anisotropy due to preferred shape fabric development, we limit the calculation here to the initial state of the quartzite where the grains are randomly oriented in space, and the macroscale rheology is isotropic. This is because quartz flow laws (Eq.3) do not consider any anisotropy.

Fig. 4 shows the numerically obtained stress-strain rate relation as a plot of $\bar{\sigma}$ verses α and *T* in 3D. The strength of wet quartzite varies significantly with temperature as well as the relative dominant slip systems (α). At lower temperatures like $T = 300^{\circ}\mathrm{C}$, the variation in strength due to α can be nearly an order of magnitude, from more than 2GPa at $\alpha = 0$ to ~300MPa at $\alpha = 1$. As higher temperatures like $T = 600^{\circ}\mathrm{C}$, the quartzite strength is significantly reduced, and the effect of dominant slip systems is subdued as well. At $T = 600^{\circ}\mathrm{C}$, the strength changes from ~10MPa at $\alpha = 0$ to ~5MPa at $\alpha = 1$.

4. Discussion

We have obtained two endmember dislocation creep flow laws (Eq.3) from well-controlled creep experiments (Dataset S1) using a flow law expression (Eq.1) that includes the pressure dependence of the activation enthalpy. Our approach differs from that of Tokle et al. (2019). They obtained two “laboratory fit” flow laws by fitting experimental data into the expression of $\dot{\varepsilon} = Af_w^m \exp\left(-\frac{Q}{RT}\right)\sigma^n$ that does not include the pressure effect on activation enthalpy. However, the effect of pressure through the activation enthalpy term and that through the f_w term are in opposite directions (Lu and Jiang, 2019). As is clear from Eq.1, a greater pressure results in a higher f_w^m that decreases σ but a reduced $\exp\left(-\frac{H}{RT}\right)$ that increases σ. Therefore, considering the pressure effect on f_w alone cannot adequately explain the great discrepancies in flow law parameters determined from creep experiments conducted under different confining pressures. Tokle et al. (2019) also used estimates of stress, strain rate, and temperature from natural samples to obtain two “extrapolated fit” flow laws for wet quartzite. We have shown that such estimates are associated with much greater uncertainties than well-controlled creep experiments and cannot allow an accurate determination of flow law parameters (Lu and Jiang, 2019).

Our numerical calculation for the creep behavior of quartzite with simultaneous basal <a> and prism <a> slip is based on micromechanics and is consistent with the common observation that quartz c-axis fabrics vary continuously from Y-max to periphery cluster patterns in both experiments and nature. Tokle et al. (2019) attributed those creep data that plot between endmembers qualitatively to the contribution of the grain boundary sliding mechanism. The grain boundary sliding mechanism may be more significant in some experiments considered by Tokle et al. (2019) as they included ultrafine-grained samples (Rutter and Brodie, 2004; Fukuda et al., 2018; Richter et al., 2018) which we did not. However, the grain boundary sliding mechanism alone is inconsistent with combined Y-max and periphery cluster c-axis fabrics from experiments and mylonite samples.

The values of Q for the two endmember flow laws in Eq.3 are essentially the same within error ($Q = 132 \pm 19$ kJ/mol in Eq.3a and $Q = 126 \pm 16$ kJ/mol in Eq.3b). This is expected and consistent with the understanding that dislocation creep, regardless of slip systems, is ultimately accommodated by the same lattice diffusion of vacancy defects (Dorn 1954; Sherby and Burke 1968; Freer, 1981). The V values are reasonable both from a theoretical consideration (Lu and Jiang, 2019) and in comparison with the activation volumes of other silicates ($V = 14 \sim 24\ \mathrm{cm^3/mol}$ for olivine, Karato and Jung, 2003, and $V = 24 \sim 38\ \mathrm{cm^3/mol}$ for anorthite, Rybacki et al., 2006). The difference in V between two flow laws is poorly understood but may suggest that point defect migration associated with the two slip systems is distinct because the total activation volume is the sum of activation volume for point defect formation and that for point defect migration (Béjina et al., 2003). The values and variation of m in Eq.3 are also poorly understood. The original introduction of the f_w^m term into the flow law (Eq.1) by Kohlstedt et al. (1995) was phenomenological. There is still a great uncertainty regarding the speciation of water-related defects and exactly how they facilitate the dislocation creep (Paterson, 1989; Kronenberg, 1994; Tullis, 2002). Hobbs (1981,1985a) proposed that the charged water-related defects, acting as dopants, influence the concentrations of charged defects, such as the dislocation kinks and jogs or vacancies and interstitials, and hence the deformation rate. The value of m depends on the specific rate-controlling process and the nature of charged defects, with m being 1.5 or 1.7 if the deformation is glide-controlled, 1.5 or 2.5 if the deformation is climb-controlled, and 0.33 or 0.4 if the rate-controlling process is the diffusion of oxygen or silicon defect (Ord and Hobbs, 1986). Our values of m = 2.6 for dominant prism <a> slip and m = 1.7 for dominant prism <a> slip appear to be consistent that the dislocation creep in regimes 2 and 3 (Hirth and Tullis, 1992) is essentially climb-controlled.

It remains difficult to test quartz flow laws with natural data because the latter is limited and associated with great uncertainties related to existing quartz grainsize piezometric relations (Austin and Evans, 2007, 2009; Cross et al., 2017; Heilbronner and Kilian, 2017; Shimizu, 2008, 2012; Stipp and Tullis, 2003). We have calculated the paleostresses using the grainsize data from WMCC samples (Behr and Platt, 2011) and the piezometric relations of Heilbronner and Kilian (2017) and Shimizu (2008, 2012) which seem to be in good agreement with the flow law of Lu and Jiang (2019). Estimates of α and T are required to plot the natural data in Fig.4. The deformation temperature of WMCC samples was taken from Behr and Platt (2011). How to quantitatively estimate α for natural samples is unclear. We used the following qualitative estimates here. Samples having pure Y-max fabrics are assigned to $\alpha = 1$ and those with pure periphery cluster fabrics $\alpha = 0$. Samples with a mixture of Y-max and periphery c-axis patterns are given an α value between 0 and 1 depending on the relative strength of the two orientations. For samples with no c-axis fabrics, we assume they deform by either dominant prism <a> slip ($\alpha = 1$) or basal <a> slip ($\alpha = 0$) according to the sample descriptions. The estimations of $\bar{\sigma}$, α and T of WMCC samples, with their error bars, are plotted in the 3D strength profile (Fig.4). Because of the large uncertainties in $\bar{\sigma}$, α, T, and the choice of the macroscale strain rate and geothermal gradient, it is not fruitful to quantitatively compare natural estimates and the predictions of our flow laws. Our purpose of plotting natural estimates in Fig.4 is to present our flow laws in the context of current limited knowledge and uncertainties of continental strength in order to facilitate further investigation on the subject.

In fact, α is expected to vary with time in nature as a result of temperature change and/or finite strain buildup. Hobbs (1985b) suggests that the critical resolved shear stress (CRSS) for basal <a> slip is insensitive to temperature whereas that for prism <a> slip decreases with increasing temperature. This is supported by the observation in both experiments and nature that basal <a> slip is dominant at lower temperatures and prism <a> slip at higher temperatures. On the other hand, fabric buildup as the finite strain increases may also be responsible for slip system switch and hence α variation. Heilbronner and Tullis (2006) observed in experiments a progressive fabric transition from the periphery to Y-max with increasing strain and degree of recrystallization. Regardless of the cause of α variation in a continuous deformation, our work suggests that it affects the flow strength of wet quartzite significantly. Because of the likely variation of α, one should not expect a simple analytical expression for “the flow law” of quartzite. The flow strength of wet quartzite evolves on the curved surface, as a function of $\bar{\sigma} = f(T, P, \alpha)$ as in Fig.4. Based on the fabrics of WMCC samples (Fig.4), α decreased as the temperature dropped and led to a remarkable increase in the flow strength at shallower depths.

5. Conclusions

By considering both the pressure dependence of the activation enthalpy and slip system dependence of the stress exponent, we have obtained two best-fit endmember flow laws (Eqs.3), corresponding respectively to dominant basal <a> slip and dominant prism <a> slip systems, from a dataset of carefully selected creep experiments of wet quartzite interpreted to represent steady-state regimes 2 and 3 dislocation creep.

We developed a self-consistent micromechanics-based method to numerically determine the flow strength of wet quartzite creeping by a continuous combination of basal <a> and prism <a> slips that are common in nature and experiments. The relative contribution of basal <a> slip and prism <a> slip is parameterized by α with $\alpha = 0$ and $\alpha = 1$ representing pure basal <a> slip and pure prism <a> slip respectively. The continuous mixture of the two dominant slip systems is represented by $0 < \alpha < 1$.

Our approach has reconciled the large discrepancies among flow parameters derived from different experiments, and our results are broadly consistent with c-axis fabrics from quartz-rich mylonites and experiment samples as well as theoretical considerations. The flow strength of wet quartzite over the entire range of $0 \le \alpha \le 1$ cannot be expressed in a simple analytical form but is best represented in a 3D plot as a function of temperature, pressure, and strain rate. The flow strength of wet quartzite is particularly sensitive to the dominant slip systems (α value) at lower temperatures.

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FIGURE CAPTION

Figure 1. Plots of normalized strain rate versus normalized stress for quartz creep experiments and the dislocation creep flow laws. The circles represent data collected from axial compression experiments and the diamonds from general shear experiments. All data are normalized to a reference condition of $T = 900$ °C, $P = 1500$ MPa. (a). All data are normalized using the flow law parameters $m = 2.6$, $V = 35.8$ cm^3/mol, and $Q = 132$ kJ/mol. The dashed line represents the best-fit line for the high-temperature experimental data. (b) All data are normalized using $m = 1.7$, $V = 23.1$ cm^3/mol and $Q = 126$ kJ/mol. The dashed line represents the best-fit line for the low-temperature experimental data.

Figure 2. Plots of stress and strain rate data of eight experimental runs and the corresponding quartz c-axis fabrics. All data are normalized to $T = 900$ °C and $P = 1500$ MPa using Eq.3a (for data ≥ 900 °C) and Eq.3b (for data < 900 °C). Variation in quartz c-axis fabrics suggest combined basal <a> and prism <a> slips, from Y-max pattern indicating dominant prism <a> slip at 1000 °C and 900 °C, through a mixture of basal <a>, prism <a>, and rhomb <a> c-axis fabric pattern at 915 ~ 875 °C, to a strong cluster of c-axes in the periphery reflecting dominant basal <a> slip at 800 °C and 700 °C. Grain boundary sliding mechanism cannot explain the c-axis variation.

Figure 3. Deformation mechanism maps for wet quartzite for (a) Voigt and (b) Reuss cases. (a) A plot of differential stress versus temperature, with strain-rate contour lines (10^{-10} s^{-1}, 10^{-12} s^{-1}, 10^{-14} s^{-1} and 10^{-16} s^{-1}) of prism <a> slip (solid lines) and basal <a> slip (dashed lines). (b) A plot of strain rate versus temperature, with stress contour lines (10 MPa, 100 MPa, and 1000 MPa) of prism <a> slip (solid lines) and basal <a> slip (dashed lines). The strain rates/differential stresses

of prism <a> and basal <a> slips are equal on the red lines. In the shaded areas, the difference of the strain rates/differential stress between prism <a> and basal <a> slips is less than one order of magnitude.

Figure 4. Plot of $\bar{\sigma}$ of wet quartzite versus T and α. The cross-sections of the $\bar{\sigma}-T$ plot at $\alpha=0$ and $\alpha=1$ are two endmember situations (Eqs.3). At a given T, $\bar{\sigma}$ decreases as α increases. As T increases, both the absolute strengths of prism <a> and basal <a> slips and the strength contrast decrease. Estimations of paleostress, T and α of WMCC samples (Behr and Platt, 2011) with error bars are also plotted.

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