Dislocation creep of olivine: Backstress evolution controls transient creep at high temperatures

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Abstract

Transient creep occurs during geodynamic processes that impose stress changes on rocks at high temperatures. The transient is manifested as evolution in the viscosity of the rocks until steady-state flow is achieved. Although several phenomenological models of transient creep in rocks have been proposed, the dominant microphysical processes that control such behavior remain poorly constrained. To identify the intragranular processes that contribute to transient creep of olivine, we performed stress-reduction

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tests on single crystals of olivine at temperatures of 1250–1300°C. In these experiments, samples undergo time-dependent reverse strain after the stress reduction. The magnitude of reverse strain is $\sim10^{-3}$ and increases with increasing magnitude of the stress reduction. High-angular resolution electron backscatter diffraction analyses of deformed material reveal lattice curvature and heterogeneous stresses associated with the dominant slip system. The mechanical and microstructural data are consistent with transient creep of the single crystals arising from accumulation and release of backstresses among dislocations. These results allow the dislocation-glide component of creep at high temperatures to be isolated, and we use these data to calibrate a flow law for olivine to describe the glide component of creep over a wide temperature range. We argue that this flow law can be used to estimate both transient creep and steady-state viscosities of olivine, with the transient evolution controlled by the evolution of the backstress. This model is able to predict variability in the style of transient (normal versus inverse) and the load-relaxation response observed in previous work.

1 Introduction

The evolution of viscosity during flow of mantle rocks at high temperatures is fundamental to a variety of geodynamic processes. For example, transient creep of the upper mantle has been identified as a major contributor to geodetically observed surface deformations during post-seismic creep (Pollitz 2005; Freed, Hirth, and Behn 2012; Masuti et al. 2016; Qiu et al. 2018), for which the strains are typically $<10^{-3}$, and inferred viscosities are one to two orders of magnitude lower than the long-term, steady-state viscosity. Because transient viscosities also continue to evolve during postseismic deformation, they likely cause a time-dependent transfer of stresses to neighbouring faults, rather than the instantaneous transfer assumed by popular calculations of Coloumb stress changes (e.g., Freed 2005). Although sophisticated earthquake forecast models do incorporate time-dependent loading according to average plate motion rates (e.g., Field et al. 2015, 2017), they still do not incorporate variable loading rates that would occur due to

42   transient creep of the lithosphere. In addition, transient viscosities are expected to be important, although

43   they have not yet been thoroughly considered, in other small-strain processes including flexure of the

44   lithosphere near volcanic loads (Zhong and Watts 2013) or in subducting slabs near trenches (Hunter and

45   Watts 2016), during which the strains rarely exceed 10^{-2}.

46   Although by far the bulk of investigations into the rheological behavior of the upper mantle have focused

47   on measuring and predicting steady-state viscosities in olivine attained under constant applied stress (e.g.,

48   Hirth and Kohlstedt 2003), some experiments have been conducted to investigate transient creep in

49   olivine. These experimental data confirm that the initial viscosities at the onset of creep or just after other

50   abrupt changes in stress are typically several orders of magnitude lower than the eventual steady-state

51   viscosities (Post 1977; Smith and Carpenter 1987; Hanson and Spetzler 1994; Chopra 1997). These rapid

52   changes in viscosity occur over the initial strain increments of $<10^{-2}$, and the most likely microstructural

53   changes responsible for this evolution are changes in the distribution and arrangement of dislocations

54   (Hanson and Spetzler 1994; S. Karato and Spetzler 1990; Durham, Goetze, and Blake 1977). However,

55   there are certain cases in which the initial viscosity is higher at the onset of creep and decreases with

56   progressive deformation, which is referred to as an "inverse" transient. Hanson and Spetzler (1994)

57   observed that single crystals of olivine can exhibit either a normal or an inverse transient, depending on

58   the orientation of loading. In addition, Cooper et al. (2016) observed that the type of transient can change

59   in a single experiment as the applied stress is gradually increased. This variability in observations

60   highlights that the specifics of the microstructural evolution and its link to both transient creep and

61   steady-state creep remain poorly constrained.

62   Due to the complexity of, and uncertainty regarding, potential micromechanical processes involved,

63   experimental observations of transient creep have generally been fit by empirical models in which the

64   underlying physics is not investigated. The Burgers model is often employed (Smith and Carpenter 1987;

65   Chopra 1997), amongst several others (Post 1977; Hanson and Spetzler 1994). However, the lack of a

66   rigorous microphysical basis to these models limits confidence in extrapolating them to predict

67   deformation at natural conditions under which the key processes potentially differ from those in

68   experiments. Moreover, as these processes and associated microstructural changes are poorly constrained,

69   model predictions cannot easily be tested against the microstructures of natural rocks. Thus, there remains

70   a need to establish the fundamental microphysics of transient creep.

71   Distinguishing among different models of transient creep is difficult. In general, the experimentalist is

72   tasked with fitting models to strain-time curves or strain rate-time curves, for which differences among

73   models are subtle (Post 1977; Hanson and Spetzler 1994). Additional constraints can potentially be

74   gleaned from the microstructures of deformed materials (Hanson and Spetzler 1994). However, the small

75   strains involved can result in microstructural changes beyond the resolution of some common

76   observational techniques, such as standard electron backscatter diffraction (EBSD) (Thieme et al. 2018).

77   We alleviate these problems by using stress-reduction experiments. These tests involve applying a rapid

78   reduction in stress to a sample undergoing steady-state creep and have been applied extensively to the

79   study of engineering materials (Blum and Weckert 1987; Biberger and Gibeling 1995; Poirier 1977).

80   Stress reductions typically induce an ensuing period of transient creep. As each test requires only a small

81   strain interval and causes only limited modification of the microstructure, multiple tests can be performed

82   on a sample within one experiment (e.g., with different magnitudes of stress reduction). Unlike increases

83   in stress magnitude, which are always followed by ongoing creep in the original direction, reductions in

84   stress can also result in a period of anelastic reverse strain (Blum and Weckert 1987; Biberger and

85   Gibeling 1995; Poirier 1977). As such, stress-reduction tests provide a wide variety of characteristics

86   against which to test models of transient creep.

87 Despite their potential, stress-reduction tests have been underutilized for geological minerals. Stress-

88 reduction tests have been applied to ice (Meyssonnier and Goubert 1994; Caswell, Cooper, and Goldsby

89 2015) and garnet (Z. Wang, Karato, and Fujino 1996). Applications to olivine have been limited primarily

90 to torsional microcreep experiments on fine-grained aggregates by Gribb and Cooper (1998) and Jackson

91 et al. (2002; 2014). Chopra (1997) reported two experiments on natural dunites, and Cooper et al. (2016)

92 reported one experiment on a single crystal. However, the microphysical controls on the behaviour

93 exhibited in such tests have not been systematically investigated.

94 Here we report stress-reduction experiments on single crystals of olivine to isolate and investigate

95 transient creep arising from intragranular processes. We analyse the microstructures of the deformed

96 samples using high-angular resolution electron backscatter diffraction (HR-EBSD) (Wilkinson, Meaden,

97 and Dingley 2006; D. Wallis et al. 2019), which is ideally suited to detecting subtle microstructural

98 changes, including lattice rotations and stress heterogeneities associated with geometrically necessary

99 dislocations (GNDs). We combine the results with previous rheological data to constrain the

100 microphysical processes that control the transient viscosity of rocks after rapid stress changes and make

101 predictions about the variability in rheological behavior that may be observed during transient creep in

102 Earth.

103 ## 2 Methods

104 ### *2.1 Sample preparation*

105 Four samples were prepared from gem-quality single crystals of San Carlos olivine. Rough crystals were

106 oriented using EBSD. The crystals were cut into rectangular parallelepipeds, with lengths in the range of

107 2 to 5 mm and aspect ratios in the range of 2:1 to 3:1, that were free from visible cracks and inclusions.

108 Samples were cut with long axes corresponding to the $[110]_c$, $[101]_c$, and $[011]_c$ orientations, following

109 the notation of Durham and Goetze (1977), with the intention of maximizing the resolved shear stress on

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110   the (010)[100], (001)[100] and (100)[001], and (010)[001] slip systems, respectively. The end faces of

111   samples were ground flat and parallel using 1500 grit SiC paper.

2.2 Deformation experiments

113   Deformation experiments were conducted in a 1-atm uniaxial creep apparatus in the Rock Rheology

114   Laboratory at the University of Oxford. Details of the apparatus design are provided by Cao et al. (2020).

115   Samples were placed in direct contact with alumina platens, which were in direct contact with SiC

116   pistons. Although San Carlos olivine and alumina are not in chemical equilibrium, reaction products were

117   not visible after experiments, indicating that any reaction was limited in extent. The loading column is

118   housed inside a vertical tube furnace. The hot zone of the furnace is >5 cm, and temperature was

119   controlled with a thermocouple placed within 1 cm of the sample. The temperature difference across the

120   samples was <1°C. The oxygen fugacity was controlled with a mixture of CO and CO_2, and the ratio of

121   gas flow rates was maintained constant to set the oxygen fugacity at a value of 10^{-8} to $10^{-7.5}$ atm, near the

122   Ni:NiO buffer at the temperatures of the experiments. A gas-tight seal was maintained on the moving SiC

123   piston by means of frictionless oil bellows. An axial load was applied to the loading column with a

124   piezoelectric actuator using a closed-loop servo-control system, and the load was measured and controlled

125   with a precision of ~1 N. Changes in sample length were assessed by measuring displacements of the SiC

126   piston relative to the loading frame. Displacements were measured with a linear encoder with resolution

127   of 10 nm and corrected for distortion of the apparatus using the complex compliance of the apparatus

128   calibrated by Cao et al. (2020).

129   Samples were initially subjected to a small compressive load (~10 N) using the piezoelectric actuator to

130   ensure that contact was maintained with pistons and the sample remained upright and aligned throughout

131   the heating procedure. Samples were heated to temperatures of either 1250 or 1300°C over the course of

132   approximately 3 hours. Deformation was not initiated until the measured temperature reached and

133   maintained a steady value within 1°C of the set point.

134   Once the temperature stabilized, the load was gradually increased at a constant rate to the desired value,

135   corresponding to stresses of 77 to 189 MPa, over the course of ~120 s. An example of the stress and strain

136   evolution for experiment OxR0009 is illustrated in Figure 1. The load was maintained at the desired

137   value, and the displacement was monitored until an approximately steady-state displacement rate was

138   achieved, which typically required 2 to 5% strain. At this point, the load was reduced to a new set point at

139   the maximum rate achievable by the apparatus, which was on the order of ~10 ms for the largest stress

140   reductions. In order to record this deformation with sufficient resolution, the data sampling rate was

141   increased from 0.1 Hz to 100 kHz just prior to the load reduction and then returned to 0.1 Hz just after the

142   load reduction. This new load was maintained and the displacement monitored until a positive

143   displacement rate was clearly observed. The load was then gradually increased back to the original value

144   at a similar loading rate as in the initial loading increment. The load was then held constant until a steady-

145   state displacement rate was again achieved, which was typically within a factor of two of the steady-state

146   rate achieved in the first loading step. This cycle of load reduction followed by a return to the original

147   load was carried out multiple times in each experiment. In each cycle, the load was reduced a greater

148   amount than in the previous cycle, but after each load reduction, the load was always returned to the

149   original control value. For several experiments, this progression of load reductions was repeated to test

150   the reproducibility of the sample response. An overview of the experimental conditions are provided in

151   Table 1.

Table 1: Summary of experiment conditions and results from stress-reduction experiments.									
Sample # Experiment #	Loading direction	Temperature (°C)	Initial stress (MPa)	Total strain (%)	Steady-state strain rate (10^{-5} s^{-1})	Best-fit backstress (MPa)	Best-fit hardening coefficient, γ	Transient	Symbol in figures
OxR0002 170120c	$[101]_c$	1250	162	17%	3.76	84	14	inverse	■

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OxR0007 170323	$[110]_c$	1250	189	12%	5.81	102	28	inverse	▶
OxR0009 170616	$[110]_c$	1300	105	17%	1.95	64	12	unclear	◁
OxR0009 171018	$[110]_c$	1300	77	38%	1.31	39	5	inverse	△
OxR0010 171016	$[011]_c$	1300	116	13%	0.12	104	55	normal	○

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153   Experiments were stopped after an increment of deformation at the original load value. This final load

154   value was maintained until steady-state displacement rates were obtained so that the preserved

155   microstructure best reflects the microstructure just prior to each load reduction. At this point, the load was

156   removed entirely from the sample and the furnace was shut off. Cooling to ambient temperature required

157   several hours, but temperatures fell below 800°C in ~3 min, which is rapid enough to preserve the

158   microstructures characteristic of the highest stresses applied (Bai and Kohlstedt 1992b; Goetze and

159   Kohlstedt 1973).

2.3 Microstructural analysis

161   For one experiment (OxR0009, compressed along $[110]_c$), the microstructures within the sample were

162   characterized after two segments of deformation. The experiment was initially interrupted at 17% strain.

163   At this point, the face parallel to (001) was polished with successively finer diamond grits down to a grit

164   size of 50 nm, providing a polish suitable for EBSD. An initial EBSD map was collected in an area of

165   high surface quality near the bottom of the polished vertical face of the sample. The sample was then

166   reloaded into the apparatus and subjected to further increments of deformation. The experiment ended

167   after a total of 38% strain. Two additional EBSD maps were collected on the same sample surface parallel

168   to (001). One of these maps was located near the center of the sample and the other near a vertical edge.

169   The EBSD maps of sample OxR0009 were constructed using high-angular resolution electron backscatter

170   diffraction (HR-EBSD). Data were acquired on an FEI Quanta 650 scanning electron microscope at the

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171   University of Oxford and a Philips XL30 scanning electron microscope at Utrecht University. Both

172   instruments were equipped with an Oxford Instruments AZtec EBSD system and calibrated for HR-EBSD

173   analysis by mapping undeformed Si standards following the procedure of Wilkinson et al. (2006). A

174   routine to calibrate the chamber geometry, based on determining the pattern centre from diffraction

175   patterns collected at a range of camera insertion distances, was performed before acquisition of each

176   dataset. Conventions for reference frames in data acquisition and processing were validated using the

177   approach of Britton et al. (2016). The details of each map are presented in Table 2.

Table 2: Details of HR-EBSD maps collected from sample OxR0009. The first map was collected after experiment 170616, and the subsequent maps were collected after experiment 171018. See Table 1 for details of the experiments.

Total strain	Map location on sample surface	Step size (µm)	Number of points	Pixels in diffraction pattern
17%	Bottom edge	3.0	230 x 150	1344 x 1024
38%	Centre	0.3	300 x 250	1344 x 1024
38%	Side edge	0.5	230 x 160	1344 x 1024

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179   Maps of lattice rotation and elastic strain heterogeneity were generated following the HR-EBSD post-

180   processing method of Wilkinson et al. (2006) and Britton and Wilkinson (2011, 2012). 100 regions of

181   interest in each diffraction pattern were cross correlated with a reference pattern chosen within each map.

182   Shifts in the regions of interest were used to estimate the deformation gradient tensor, which was

183   decomposed into rotations and strains (assumed to be entirely elastic) of the diffraction pattern, at each

184   point in the map. The pattern remapping approach of Britton and Wilkinson (2012) allows residual elastic

185   strain measurements in the presence of lattice rotations of several degrees. Stresses were estimated from

186   the elastic strain measurements following the approach of Britton and Wilkinson (2012) and employing

187   the elastic constants for olivine at room temperature from Abramson et al. (1997). Measured elastic

188 strains are relative to the unknown strain state of the reference point and therefore provide maps of stress

189 heterogeneity. We rotated measured stress tensors from the reference frame of the EBSD maps into the

190 reference frames of the measured crystal orientations to obtain the shear stresses resolved on each slip

191 system (David Wallis et al. 2017). A comprehensive overview of all data acquisition and processing

192 procedures for HR-EBSD is provided by Wallis et al. (2019).

193 # 3 Results

194 ## *3.1 General creep behavior*

195 Figure 1 presents stress and strain as a function of time for the first 800 s of experiment 170616 with

196 sample OxR0009, which is a typical example of the response of all samples. In this particular experiment,

197 the strain rate did not significantly evolve, but was instead approximately constant over the first ~1% of

198 strain (120 to 200s in Figure 1). In other experiments, the strain rate after initial loading was observed to

199 decrease or increase with progressive strain before a steady-state strain rate was reached, which we refer

200 to as "normal" or "inverse" transients, respectively. Table 1 indicates the type of transient observed for

201 each experiment. Figure 1 also illustrates that, once a steady-state strain rate was clearly achieved, stress

202 reduction tests were executed. At the end of each reduction test, the stress was increased to approximately

203 the same value as the initial stress. During these high-stress intervals, the strain rate returned to a similar

204 strain rate to that just prior to the initial stress reduction.

205 Figure 2 compares the steady-state strain rate from each experiment to predictions of the flow laws for

206 single crystals of San Carlos olivine from Bai and Kohlstedt (1992a). These data are also reported in

207 Table 1. In general, samples loaded in the $[110]_c$, $[101]_c$, and $[011]_c$ orientations exhibit good agreement

208 with the flow-law predictions for olivine deformed at 1250°C and 1300°C. The maximum differences

209 between measured and predicted strain rates are on the order of a factor of two.

3.2 Stress-reduction tests

The results of individual stress-reduction tests are compiled in Figure 3. To obtain these data, we partition each time series of strain into ranges spanning the point just before the stress reduction to the point just before the stress was increased back to the initial stress. The strain at the beginning of this range (i.e., just before the reduction) was set to 0, and the strain data were then corrected for the compliance of the apparatus. This corrected strain after the stress reduction is presented as a function of time in the left column of Figure 3. Small stress reductions result in a small elastic lengthening (negative strain) of the sample that is immediately followed by continued shortening (positive strain). Large stress reductions result in correspondingly large elastic lengthening of the sample, but that lengthening is followed by an additional, time-dependent lengthening of the sample that we refer to as anelastic reverse strain. The period of anelastic lengthening lasts for 10s to 100s of seconds depending on the magnitude of the stress reduction.

We further analyze these data following the method of Blum and Finkel (1982). Many early analyses of stress-reduction experiments (e.g., Ahlquist and Nix 1971) relied on measuring strain rates after the anelastic reverse strain as a means to assess the "constant microstructure" mechanical behavior. Similar methods have been applied to some geological materials such as ice (Caswell, Cooper, and Goldsby 2015). Unfortunately, strain rates are generally not constant during this increment of stress-reduction tests, and therefore identifying the best segment for calculating a strain rate is not trivial. In contrast, the method of Blum and Finkel (1982) does not rely on measuring strain rates but instead on measuring the magnitude of anelastic reverse strain after the stress reduction and prior to subsequent forward creep. We identify the total amount of reverse strain (both elastic and anelastic) using the minimum strain recorded after the stress reduction. Based on the noise in the strain data, this selection process may overestimate the total reverse strain by $\sim10^{-4}$ (roughly 10% of the maximum anelastic reverse strain). We also identify the

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233   elastic component of the reverse strain as the strain at the first data point after the reduced stress level is

234   reached.

235   The total and elastic reverse strains are presented for all experiments in the middle column of Figure 3.

236   For most experiments, the elastic strains are linearly correlated with the magnitude of the stress change

237   and in good agreement with the strains predicted given the Young's modulus in the specific crystal

238   orientation (dashed lines). Agreement with the elastic modulus provides confidence in the apparatus

239   correction and the method of identifying the elastic strain. However, for samples deformed at smaller

240   initial stresses, some elastic strains are smaller than predicted by the elastic modulus (e.g., OxR0009b and

241   OxR0010), which may indicate the apparatus compliance is overestimated at small loads.

242   We take the difference between the total reverse strain and the elastic reverse strain to represent the

243   anelastic reverse strain, which is plotted as a function of the magnitude of the stress reduction in the right

244   column of Figure 3. Crystals deformed in the $[110]_c$ and $[101]_c$ orientation exhibit maximum anelastic

245   reverse strains $>10^{-3}$, but significant anelastic reverse strain is only observed following stress reductions

246   greater than ~40% of the initial stress. In contrast, the crystal deformed in the $[011]_c$ orientation exhibits

247   anelastic reverse strains that gradually increase with the magnitude of the stress reduction, even for small

248   stress reductions.

3.3 Microstructures

250   Figure 4 presents HR-EBSD maps of sample OxR0009. The dataset collected near the bottom edge of the

251   sample after deformation to 17% strain exhibits lattice rotations dominated by the ω_{12} component. The

252   map of this component exhibits a smooth gradient from the upper-right to lower-left, i.e., in the [100]

253   direction. For the mapped crystal orientation, the ω_{12} component corresponds to rotations around the

254   [001] axis, and large magnitudes of that component are therefore consistent with the presence of

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255   (010)[100] edge dislocations (David Wallis et al. 2016). Signal in the maps of the ω_{13} and ω_{23}

256   components has magnitudes many times lower than that of ω_{12}, precluding major contributions from other

257   dislocation types to the mapped lattice curvature. The map of shear stress resolved on the (010)[100] slip

258   system (i.e., σ_{ab}) also exhibits gradients in the [100] direction, varying by magnitudes on the order of 100

259   MPa over distances of a few hundred microns. The dataset collected from near the centre of the sample at

260   the final strain of 38% exhibits lattice rotations similar to those in the dataset collected at lower strain.

261   The stress distribution is homogeneous over the length scale of the map, which is notably smaller than

262   that collected at 17% strain. However, the dataset collected near a side edge of the sample at 38% strain

263   exhibits more discontinuous rotation and stress fields. Each component of the lattice rotation exhibits two

264   linear discontinuities corresponding to subgrain boundaries. The boundaries have traces parallel to [010]

265   and are most pronounced in the map of ω_{12}, consistent with them being dominated by (010)[100] edge

266   dislocations. The boundaries also coincide with discontinuities in the map of σ_{ab}. These stresses have the

267   greatest magnitudes, i.e., are localised, adjacent to the boundaries. Across the boundaries, the stresses

268   exhibit changes in sign and changes in magnitude on the order of 100 MPa. The orientation gradients

269   between the upper-right and lower-left corners of each map of ω_{12} correspond to average GND densities

270   in the range 4×10^{11} m^{-2} to 8×10^{11} m^{-2} (David Wallis et al. 2016). We emphasize that subgrain boundaries

271   are essentially not observed at low strains, and at high strains are only observed in small portions of the

272   sample.

273   # 4 Discussion

274   In this study we present results of stress-reduction tests carried out on single crystals of San Carlos

275   olivine. The key observations are: 1) prior to stress reductions, strain rates reach a steady state in

276   agreement with previously published flow laws for olivine, 2) after stress reductions of sufficient

277   magnitude, an anelastic reverse strain is observed, 3) the magnitude and duration of anelastic reverse

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278   strain is a strong function of the magnitude of the stress reduction, 4) significant heterogeneity in the

279   residual stress is correlated with gradients in lattice orientation (i.e., with GNDs). To interpret these

280   observations, we first compare previously published interpretations of stress reduction tests to our data

281   and then reanalyze our data in the context of recent work on the plastic deformation of olivine.

282   ## *4.1 Comparison to previous interpretations of stress-reduction tests*

283   Stress-reduction tests have been a common technique for investigating the microphysics of creeping,

284   crystalline materials. Two primary aspects of the microphysics have been investigated with stress

285   reduction tests. The first is the concept of a backstress (or internal stress), which is related to the details of

286   the microstructural evolution during deformation. The observation of backstress in single crystals

287   indicates that it arises from the long-range elastic interactions among dislocations. Dislocation arrays can

288   result in a net Burgers vector with a long-range internal stress field that opposes the macroscopically

289   applied stress, hence the term backstress. As described in detail by Bayley et al. (2006), the net backstress

290   associated with an array of dislocations is strongly dependent on the spatial gradients in dislocation

291   density, rather than simply the number of dislocations, and therefore the backstress is sensitive to the full

292   dislocation microstructure, including mobile dislocations, subgrain boundaries, and their spatial

293   distributions. The macroscopic creep rate is assumed to result from the action of an effective stress, σ_e,

294   which is the difference between the externally applied stress and the net backstress, $\sigma_e = \sigma - \sigma_b$, where σ is

295   the former and σ_b is the latter. Macroscopic forward creep results from positive values of σ_e, and reverse

296   creep results from negative values of σ_e.

297   Early experiments on pure metals by Gibbs (1966), solid-solution alloys by Ahlquist and Nix (1971), and

298   ionic crystals by Menezes and Nix (1971) demonstrated that the average backstress could be determined

299   with stress-reduction tests (for a review, see Takeuchi and Argon 1976). In this method, the

300   microstructure and associated σ_b are presumed to remain constant during the nearly instantaneous stress

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301 reduction. Just after the reduction, the immediate strain rate is observed to be positive, negative, or

302 approximately zero, depending on the magnitude of the stress reduction. These scenarios are presumed to

303 indicate that the applied stress after the reduction is either greater than, less than, or equal to the

304 backstress, respectively. Therefore, the reduced stress at which the subsequent strain rate is approximately

305 zero is taken to be equal to the backstress. However, there is some controversy about the practical aspects

306 of identifying a zero strain rate (for a review, see Nix and Ilschner 1979), and therefore we adopt the

307 method of Blum and Finkel (1982), as described above. In this latter method, the reduced stress at which

308 anelastic reverse strain becomes measurable is taken as equal to the average backstress.

309 These methods have been used to characterize net backstresses in a wide range of materials. Two well-

310 cited studies, in particular, had remarkably consistent results, estimating backstresses at 52% of the initial

311 stress in both pure metals (Evans, Roach, and Wilshire 1985) and solid-solution alloys (Blum and Finkel

312 1982). Many subsequent modeling efforts therefore have taken this value as a constant in the creep of

313 metals (e.g., Biberger and Gibeling 1995). Similar values have been observed in some ceramics such as

314 $Gd_3Ga_5O_{12}$ (Z. Wang, Karato, and Fujino 1996), which exhibited a backstress of 62% of the initial stress.

315 However, broader compilations of backstress estimates (Takeuchi and Argon 1976; Argon and Takeuchi

316 1981; Čadek 1987; Milička, Trojanová, and Lukáč 2007) demonstrate that the relationship between the

317 backstress and initial stress varies systematically as a function of the initial stress. For instance, Menezes

318 and Nix (1971) reported values of the backstress in LiF that vary systematically between 21% and 83%.

319 In addition, Wang et al. (1993) reported backstresses in $SrTiO_3$ up to ~100%.

320 The second aspect of the microphysics of creep investigated with stress reduction tests is the rate limiting

321 process at constant microstructure. As noted above, the specific dislocation arrangements are considered

322 to be unchanged (neglecting unbowing of dislocations) during the stress reduction. Therefore, in the case

323 that the stress reduction is small and no anelastic strain occurs, the forward strain rate just after the

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324 reduction is a function of the same microstructure as before the reduction. A variety of studies (for a

325 review, see Biberger and Gibeling 1995) have evaluated these types of tests and found that the strain rates

326 after a stress reduction are fit well by a flow law with an exponential dependence of strain rate on the

327 stress, which is one member of a class of equations used to describe plastic deformation limited by the

328 glide velocity of dislocations (e.g., Kocks, Argon, and Ashby 1975; Weertman 1957). Furthermore, the

329 dependence of the strain rate on the reduced stress can be related to the apparent activation area of gliding

330 dislocations (the area of slip plane traversed in a single activation event), which was shown to have a

331 direct relationship to the observed spacing of free dislocations in subgrain interiors. These results led the

332 authors (and authors cited therein) to conclude that the strain rates directly after a load reduction are

333 dominated by the kinetics of gliding dislocations rate limited by the lattice friction (i.e., the Peierls-

334 Nabarro mechanism). Similar conclusions based on stress-reduction tests have been drawn for LiF

335 (Müller, Biberger, and Blum 1992), SrTiO3 (Z. Wang, Karato, and Fujino 1993), and $Gd_3Ga_5O_{12}$ (Z.

336 Wang, Karato, and Fujino 1996).

337 The observations described above have played a large part in informing the development of composite

338 models to describe both transient and steady-state creep properties of crystalline materials. Key early

339 models include those proposed by Hart (1976), Nix and Ilschner (1979), and Mughrabi (1980), although a

340 variety of elaborations have been proposed (e.g., Korhonen, Hannula, and Li 1987; Garmestani, Vaghar,

341 and Hart 2001; Bammann 1989). The key features of these models are that 1) plastic deformation across a

342 wide range of conditions is effectively controlled by the glide of dislocations, 2) the glide velocity of

343 those dislocations is moderated by the long-range stresses associated with heterogeneity in the state

344 variables that describe the microstructure (what we refer to as a net backstress), and 3) the macroscopic

345 behavior can be modified by different recovery mechanisms (such as dislocation climb and annihilation)

346 that modify the backstress. We use these three concepts as a foundation for analyzing our data for olivine

347 in the next section.

16

4.2 Linking stress reductions to backstress evolution and dislocation-glide kinetics

Our working hypothesis based on the discussion above is that deformation after a stress reduction is controlled by the glide of dislocations, and the anelasticity observed after larger stress reductions is controlled by the net backstresses associated with the long-range stress fields of the dislocation microstructure. Plastic deformation and the evolution of backstresses were recently investigated for olivine by Hansen et al. (2019). In that work, the authors used experiments conducted at temperatures as a low as room temperature to examine the yield strength and hardening behavior of single crystals and polycrystalline samples of San Carlos olivine. Notably, the hardening behavior of single crystals is indistinguishable from the hardening behavior of polycrystalline aggregates, which we interpret to indicate that the dominant processes leading to strain hardening are intragranular. Furthermore, they observed a distinct Bauschinger effect, which supports the conclusion that the hardening is associated with long-range interactions of dislocations (see section 2.5 in Kassner 2015). This conclusion is further supported by microstructural correlations of the GND density field with residual stress fields in the same samples (David Wallis, Hansen, Kumamoto, et al. 2020). In support of the hypothesis that these long-range stress fields are also important during deformation at high temperatures, we see spatial correlations between lattice rotation gradients (i.e., GND densities) and stresses in our samples (Figure 4) and the similar samples of Wallis et al. (2017). Furthermore, Wallis et al. (2020) highlighted the similarities between stress fields in aggregates of olivine deformed at temperatures of 1150–1250°C and those deformed at room temperature. These similarities include the magnitudes, the forms of the probability distributions, and the characteristic length scales of the stress heterogeneity, along with a causative link to GNDs in both temperature regimes.

17

370   *4.2.1 Magnitude of anelastic reverse strain*

371   To further analyze these data, we assess the magnitude of anelastic reverse strain after a stress reduction.

372   We use the equations describing plasticity in olivine outlined by Hansen et al. (2019). The basic rate

373   equation is derived following the classical treatment (e.g., Weertman 1957) and assumes the dislocation

374   velocity is proportional to a Boltzman distribution ($\exp\left[\frac{\Delta G}{RT}\right]$, where ΔG is the Gibbs free energy, R is the

375   gas constant, and T is the temperature) describing the probability of the dislocation overcoming the

376   energy barrier to its motion. Under application of a stress, ΔG becomes stress dependent. Hansen et al.

377   (2019) used a common simplification that ΔG is a linear function of the applied stress, although we

378   recognize that a variety of nonlinear relationships have been proposed to describe energy barriers, such as

379   the lattice friction, of different shapes (chapter 4 in Caillard and Martin 2003; chapter 6 in Suzuki,

380   Takeuchi, and Yoshinaga 2013; p. 141 in Kocks, Argon, and Ashby 1975). Additionally, Hansen et al.

381   (2019) used sinh instead of an exponential, which was originally proposed by Garofolo (1963), and later

382   given physical justification by considering the potential for forward and backward fluctuations of the

383   dislocation (Wu and Krausz 1994; Krausz 1968; Wilson and Wilson 1966). These considerations yield a

384   flow law for the plastic strain rate from gliding dislocations, $\dot{\varepsilon}_{\mathrm{p}}$, of the form

$$\dot{\varepsilon}_{\mathrm{p}} = A_1 \exp\left(\frac{-\Delta F}{RT}\right) \sinh\left(\frac{\Delta F}{RT}\frac{\sigma - \sigma_{\mathrm{b}}}{\Sigma}\right), \tag{1}$$

385   where A_1 is a constant with units of s^{-1}, ΔF is the activation energy, σ is the applied stress, σ_{b} is the

386   backstress, and Σ is stress to overcome the barrier at 0 K. Equations of this form or similar can be used to

387   describe a wide variety of barriers to dislocation motion, such as precipitates, forest dislocations, or grain

388   boundaries in the general context of "low-temperature plasticity" (chapter 2 in Frost and Ashby 1982).

389   However, in regards to creep of single crystals of olivine, we are primarily concerned with the barrier

390   presented by the fundamental motion of dislocations through the lattice (aka, lattice friction or the Peierls-

391   Nabarro mechanism) by, for instance, the formation and migration of kink pairs. In this case, Σ is referred

392   to as the Peierls stress.

393   As described above, the effective stress ($\sigma - \sigma_b$) determines the glide velocity of dislocations, and

394   therefore any evolution of the strain rate during a test at constant stress results from the evolution of σ_b. It

395   is important to note that $\dot{\varepsilon}_p$ will be negative if $\sigma_b > \sigma$. Hansen et al. (2019) provided an evolution equation

396   for σ_b,

$$\frac{\mathrm{d}\sigma_b}{\mathrm{d}\varepsilon_p} = \gamma\left[\sigma_{b,max} - \mathrm{sgn}(\dot{\varepsilon}_p)\sigma_b\right], \tag{2}$$

397   where γ is a rate constant and $\sigma_{b,max}$ is the maximum backstress. That is, if there is zero initial backstress,

398   the initial rate of increase is given by $\gamma\sigma_{b,max}$, and the steady-state backstress is $\sigma_{b,max}$. Although they

399   implemented this equation in an empirical manner, there are physical meanings to each of these terms

400   (e.g., Mecking and Kocks 1981). Assuming the backstress is related to the dislocation density (e.g.,

401   Taylor 1934), $\gamma\sigma_{b,max}$ is related to the dislocation nucleation rate, and γ is related to the dislocation

402   recovery rate associated with dynamic recovery, which operates at high stresses and low temperatures. At

403   elevated temperatures, additional recovery terms should be included to account for effects such as

404   dislocation climb or grain-boundary migration. The explicit links between backstress evolution and the

405   dislocation microstructure in olivine will be explored in future work.

406   An analytical solution exists for equation 2, providing the evolution of the back stress as a function of

407   strain,

$$\sigma_b(\varepsilon_p) = \mathrm{sgn}(\dot{\varepsilon}_p)\sigma_{b,max} + \left(\sigma_{b,0} - \mathrm{sgn}(\dot{\varepsilon}_p)\sigma_{b,max}\right)exp\left(-\gamma\varepsilon_p\mathrm{sgn}(\dot{\varepsilon}_p)\right), \tag{3}$$

19

408   where $\sigma_{b,0}$ is the initial back stress. This equation can be rearranged to predict the total plastic strain

409   necessary for σ_b to reach a final value, $\sigma_{b,f}$,

$$\varepsilon_p = \left[\mathrm{sgn}(\dot{\varepsilon}_p)\gamma\right]^{-1}\ln\left[\frac{\sigma_{b,f} - \mathrm{sgn}(\dot{\varepsilon}_p)\sigma_{b,max}}{\sigma_{b,0} - \mathrm{sgn}(\dot{\varepsilon}_p)\sigma_{b,max}}\right]. \tag{4}$$

410   In the case of a large stress-reduction test, $\dot{\varepsilon}_p < 0$ just after the reduction. The backstress at the

411   time of the reduction, $\sigma_{b,0}$, is some fraction, β, of the initial applied stress prior to the reduction, σ_i. After

412   the reduction, the backstress will decrease until a value of $\sigma_{b,f}$ is reached. This final value cannot, by

413   definition, be larger than the applied stress after the reduction, σ_r, and it will only reduce further than σ_r if

414   some additional recovery process is involved, such as "static" annealing of the dislocation density (e.g.,

415   annihilation by dislocation climb). Based on published static annealing rates for mobile dislocations in

416   olivine (Toriumi and Karato 1978; S.-I. Karato, Rubie, and Yan 1993) as a proxy for relaxation of the

417   backstress, estimates for the total recovery for the longest durations of anelastic strain (100s of seconds)

418   range from <1% to ~10%. Therefore, we assume that static recovery is negligible during the anelastic

419   portion of these experiments, and we expect that $\sigma_{b,f} = \sigma_r$ at the end of anelasticity and prior to subsequent

420   forward creep. These considerations allow us to rewrite equation 4 for the maximum anelastic reverse

421   strain after a stress reduction as $\dot{\varepsilon}_p$

$$\varepsilon_p = \frac{-1}{\gamma}\ln\left(\frac{\sigma_r + \sigma_{b,max}}{\beta\sigma_i + \sigma_{b,max}}\right). \tag{5}$$

422   Note that the assumption made above is only valid for the case in which anelastic reverse strain occurs

423   (i.e., when $\sigma_r < \beta\sigma_i$). If the applied stress is not reduced below this threshold, then no anelastic reverse

424   strain occurs (i.e., $\varepsilon_p = 0$).

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425   Equation 5 can be compared to our experimental data to find values for key parameters. We assume that

426    $\sigma_{b,max}$ = 1.8 GPa according to the results of our experiments at low temperatures (Hansen et al. 2019). We

427   then compare the measured anelastic reverse strains for large stress reductions to equation 5 to find the

428   best-fit values of γ and β (and therefore the backstress prior to the stress reduction from equation 4).

429   Values for these parameters are presented in Table 1 and a comparison of equation 5 to anelastic reverse

430   strains is presented in Figure 5.

431   These results indicate that, in olivine deformed in the $[110]_c$ and $[101]_c$ orientations, the magnitudes of

432   anelastic reverse strain are consistent with backstresses between 48 and 61% of the initially applied stress,

433   which are largely consistent with most previously reported values in other materials (see section 4.1

434   above). Interestingly, our results for olivine deformed in the $[011]_c$ orientation suggest that the backstress

435   is nearly equal to the applied stress. This difference in backstress between different crystal orientations,

436   and therefore between different activated slip systems, is likely a result of different rates of dislocation

437   recovery, as will be explored later in this section.

438   The values of the best-fit rate constant, γ, also differ between crystal orientations. Olivine deformed in the

439    $[110]_c$ and $[101]_c$ orientations is characterized by values of γ between 5 and 28. However, olivine

440   deformed in the $[011]_c$ orientation is characterized by a value of γ of 55, suggesting some anisotropy in

441   the hardening behavior. The former values are considerably smaller than the value of $\gamma = 75 \pm 20$

442   determined in low-temperature experiments (Hansen et al. 2019). However, the value of $\gamma = 55$ for the

443   crystal deformed in the $[011]_c$ orientation is within error of that determined in previous experiments.

444   Those previous experiments examined both polycrystalline aggregates and single crystals, but only single

445   crystals in the $[011]_c$ and $[111]_c$ orientations were investigated, and both orientations should have a large

446   part of the dislocation content on the (010)[001] slip system. Therefore, at least where comparisons can be

447   made, this analysis of the anelastic reverse strain is consistent with the same mechanism of deformation

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448   being responsible for transient deformation at low and high temperatures, as suggested by the

449   microstructural interpretations of Wallis et al. (2020). Furthermore, these results provide initial evidence

450   that transient deformation on the strongest slip system may dominate the transient response of a

451   polycrystalline sample, which is inconsistent with some recent theoretical treatments of transient creep in

452   olivine suggesting the transient is controlled by the weakest slip system (Masuti et al. 2019).

453   *4.2.2 Strain rates immediately after a stress change*

454   If the physics of backstress associated with dislocation interactions (equation 2) can explain the

455   magnitude of the anelastic reverse strain, then following from previous treatments for metals (e.g.,

456   Biberger and Gibeling 1995), we hypothesize the physics of dislocation glide can explain the strain rates

457   observed just after a change in stress. This hypothesis is similar to the suggestion by Cooper et al. (2016)

458   that load relaxation experiments on olivine single crystals are rate limited by the glide of dislocations. We

459   plot strain rates just after our stress reductions in Figure 6a as a function of the effective stress, σ_e, which

460   was determined by subtracting the value of σ_b determined in Figure 5 from the reduced stress. In other

461   words, we suggest these stresses and strain rates in Figure 6a reflect the rheological behavior of olivine

462   when no backstress is present. Only strain rates for small stress reductions without any measurable

463   anelastic reverse strain are presented. Strain rates from the crystal deformed in the $[011]_c$ direction are not

464   plotted because all tests for that sample exhibit some anelasticity. The observed strain rates are

465   consistently faster than the strain rates predicted for steady-state creep, and interestingly, the apparent

466   power-law exponent is ~1. This observation may initially seem at odds with the hypothesis that creep at

467   "constant microstructure" is controlled by the glide of dislocations. However, as recently discussed in the

468   context of olivine deformation by Cooper et al. (2016), the apparent stress exponent of an exponential

469   flow law decreases with decreasing stress, and therefore, these data could indeed be explained by an

470   exponential function. In fact, the sinh function employed by Hansen et al. (2019) and described in

471   equation 1 results in a linear relationship between strain rate and effective stress at low stresses.

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472   We also compare these strain rates to data from previously published experiments at high temperatures in

473   Figure 6b. To do so, we need data from experiments in which the backstress, and therefore the effective

474   stress, is known. We suggest that the strain rates just after initial loading of constant-stress experiments

475   reasonably represent a case in which the backstress is zero since very little strain has accumulated to

476   produce a backstress. Data of this type are available for single crystals of San Carlos olivine (Hanson and

477   Spetzler 1994; Cooper, Stone, and Plookphol 2016) and polycrystalline aggregates of San Carlos olivine

478   (Chopra 1997). We also include the yield stresses from single crystals deformed at room temperature at

479   constant strain rate (Hansen et al. 2019). A complication in comparing data from the first increments of

480   strain in constant-stress (or constant-strain-rate) tests is that the initial strain rate (or stress) is likely highly

481   sensitive to the density of mobile dislocations present in the starting material. Therefore, we normalize the

482   strain rates in Figure 6b by the dislocation density at the beginning of the measurement. For our data, the

483   initial dislocation density is calculated from the initial stress before the reduction using the dislocation-

484   density piezometer of Bai and Kohlstedt (1992b). The initial values of dislocation density in the previous

485   studies noted above are not available, but we estimate the starting density of single-crystal samples as 10^{10}

486   m^{-2} based on observations in untreated San Carlos olivine (Toriumi and Karato 1978) and of

487   polycrystalline samples as 10^{12} m^{-2} based on observations of hot-pressed Anita Bay dunite (S.-I. Karato,

488   Paterson, and FitzGerald 1986).

489   The comparison in Figure 6b provides two key observations. First, the apparent stress exponent differs for

490   each individual data set, systematically increasing with increasing stress. This observation is consistent

491   with deformation just after a stress reduction being controlled by the glide of dislocations following an

492   exponential or sinh flow law. Second, we also plot the flow law from Hansen et al. (2019) (equation 1 and

493   dashed lines in Figure 6b). This flow law does well at predicting the strain rates in the room-temperature

494   experiments on which the flow law is based, but does poorly at predicting the strain rates at high

495   temperatures. The flow law overpredicts strain rates from this study by approximately six orders of

23

496   magnitude. This discrepancy at high temperatures is not that surprising since the temperature-dependence

497   is the most poorly constrained component of the flow law. Not only was the flow law primarily calibrated

498   with data collected at room temperature, but data at higher temperatures were either subject to low

499   resolution in temperature measurement or were taken from other studies conducted with different

500   methods. Furthermore, the apparent temperature dependence of equation 1 depends strongly on the

501   assumption that the activation energy for glide is linearly dependent on stress. A nonlinear dependence, or

502   even a transition in the dependence as a function of temperature is possible (chapter 4 in Caillard and

503   Martin 2003). Therefore, we suggest that (1) our data are *consistent* with transient deformation being

504   controlled by the process of dislocation glide but that (2) existing flow laws for glide-controlled plasticity

505   in olivine need to be recalibrated before extension to such high temperatures.

506   *4.2.3 Recalibration of the flow law for dislocation glide*

507   Here we recalibrate the flow law for dislocation glide in olivine using the data presented in Figure 6b.

508   However, we must modify equation 1 to reasonably apply this flow law to the range of data in Figure 6b,

509   which covers a temperature range from 20°C to 1300°C. Although the form of the flow law calibrated by

510   Hansen et al. (2019) was derived from the Orowan equation (see their equation 6), the density of mobile

511   dislocations that actually produce strain was assumed to be relatively constant and therefore was

512   incorporated into A_1. This assumption is generally justified for applications to low-temperature, high-

513   stress deformation because the stress dependence of the sinh term far outweighs the stress dependence of

514   the mobile dislocation density. However, this is not necessarily the case at high temperatures or low

515   stresses, and therefore we suggest a more robust form of the flow law as

$$\dot{\varepsilon}_{\mathrm{p}} = A_2 \rho \exp\left(\frac{-\Delta F}{\mathrm{R}T}\right)\sinh\left(\frac{\Delta F}{\mathrm{R}T}\frac{\sigma - \sigma_{\mathrm{b}}}{\Sigma}\right), \tag{6}$$

24

516 where A_2 is a constant and ρ is the density of mobile dislocations. As with equation 1, this flow law

517 inherently assumes a linear dependence of ΔG on the effective stress (see section 4.2.1). A nonlinear

518 relationship may better characterize the fundamental physics of dislocation glide in olivine, but as

519 demonstrated by Jain et al. (2017)

520 Figure 6b compares our compiled data for strain rates controlled by dislocation glide to a best fit to

521 equation 6. In the applied fitting procedure, we fixed Σ = 3.1 GPa, which is well constrained by the

522 previous calibration using low-temperature data, and conducted a grid search to find the optimum values

523 of A_2 and ΔF. The best-fit values of these parameters are $A_2 = 10^{11.1\pm0.2}$ m^{2}s^{-1} and ΔF = 827$\pm$20 kJ/mol.

524 This value for ΔF is much higher than most previous estimates for dislocation glide flow laws in olivine,

525 which are generally between 300 and 600 kJ/mol (see the compilation by Demouchy et al. 2013). Our

526 choice of a linear relationship between ΔG and effective stress likely biases the best-fit activation energies

527 to high values. One outlier of previous work is an estimate of 1480 kJ/mol from Long et al. (2011)

528 Although our calibrated flow law uses a simplified form, at least empirically it is able to capture the

529 observed behavior over a wide range in temperatures, reasonably predicting both the magnitudes of the

530 strain rates as well as the change in the apparent stress exponent as a function of temperature.

531 Furthermore, combining equation 6 with a parameterization of the backstress evolution, such as that in

532 equation 2, allows the complete transient to be predicted. Different values of γ can be used to predict the

533 transient behavior of different slip systems, as discussed in relation to Figure 5. However, we note that

534 the dislocation recovery mechanisms implicit in equation 2 are only calibrated for use at low

535 temperatures. Therefore, prediction of the steady-state strain rates at elevated temperatures requires high-

536 temperature recovery mechanisms (e.g., dislocation climb) to be accounted for. Incorporating these

537 recovery mechanisms into a parameterization of dislocation creep in olivine will be a key topic addressed

538 in future work.

25

539   We can, however, assess the magnitude of the backstresses at high temperature. To restate the discussion

540   above, we suggest that equation 6 controls the macroscopic strain rate in both transient and steady-state

541   creep, and the evolution between the two regimes reflects the evolution of the net backstress. In this

542   framework, at steady state, the steady-state strain rate would be equal to equation 6, which allows us to

543   solve for the backstress at steady state,

$$\sigma_{\mathrm{b}} = \sigma - \mathrm{asinh}\left[\frac{\dot{\varepsilon}_{\mathrm{ss}}}{A_2\rho}\exp\left(\frac{F}{\mathrm{R}T}\right)\right]\frac{\mathrm{R}T\varSigma}{F}, \tag{7}$$

544   where $\dot{\varepsilon}_{\mathrm{ss}}$ is the steady-state strain rate. In Figure 7, we present values of the steady-state back stress

545   estimated with equation 7. These values were calculated using steady-state strain rates predicted by the

546   flow laws for single-crystal olivine from Bai and Kohlstedt (1992a) and dislocation densities predicted by

547   the dislocation-density piezometer from Bai and Kohlstedt (1992b). These calculated backstresses

548   compare favorably to those observed in stress-reduction tests, which provides further confidence in our

549   calibration of equation 6 and in our suggestion that equation 6 can be used to predict the steady-state

550   strain rate if the backstress is known.

551   Notably, the calculated curves in Figure 7 capture the orientation dependence of the backstress. Equation

552   7 correctly predicts that crystals compressed along $[011]_{\mathrm{c}}$ have a backstress nearly equal to the applied

553   stress, and that crystals deformed in other orientations have a backstress that is approximately 50% of the

554   applied stress. Because we use the same values of A_2, F, and $\varSigma$ regardless of orientation, the orientation

555   dependence of the calculated backstress results entirely from the different steady-state flow laws.

556   Therefore, there is a clear link between the anisotropy of the steady-state creep rate and the anisotropy of

557   the backstress evolution, which we suggest is primarily a reflection of anisotropic rates of dislocation

558   recovery (e.g., L. Wang et al. 2016). We reiterate and emphasize that, although we propose dislocation

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559 creep during the transient and steady state is governed by equation 6, the steady-state strain rate can still

560 be set by the kinetics of dislocation climb that counteract the buildup of additional backstress.

561 *4.2.4 Implications for the type of transient creep and load relaxation*

562 Our hypothesis linking low-temperature plasticity, transient creep, steady-state creep, and the evolution of

563 backstress predicts several other phenomena. A key phenomenon is variation in the sign of the strain

564 acceleration during the transient. That is, whether or not the strain rate decreases (a "normal" transient) or

565 increases (an "inverse" transient) during the evolution to steady state. Hanson and Spetzler (1994)

566 observed that the type of transient depends on the crystal orientation, and Cooper et al. (2016) observed a

567 transition in the type of transient in the same experiment as the applied stress was increased in steps.

568 Figure 8a schematically describes how the model presented here can predict both types of transients. We

569 suggest that the strain rates for olivine will generally be described by the lflow law for dislocation glide

570 (equation 6). After initial application of stress to the sample, the mobile dislocation density and backstress

571 evolve toward their steady-state values. This change in the microstructural parameters shifts the flow law

572 to higher or lower strain rates until a steady state is reached. Thus, we hypothesize that the apparent

573 steady-state power law is fundamentally defined by the relationship between the steady-state backstress

574 and the applied stress. At the onset of deformation, if the dislocation-glide flow law predicts faster strain

575 rates than the steady-state strain rate, then the initial strain rate will be fast, and the flow law will

576 gradually shift to slower rates (a normal transient) due to an increasing backstress. Conversely, if the

577 initial strain rate dictated by the flow law is slower than at steady-state, the flow law will shift to faster

578 rates (an inverse transient) due to an increase in the density of mobile dislocations. Therefore, we suggest

579 that the intersection of the dislocation-glide flow law and the steady-state power law can be used to

580 predict whether normal or inverse transients will occur. Figure 8b presents the type of transient predicted

581 by this method over a range of temperatures and pressures for all three orientations of olivine. The

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582   predictions are in excellent agreement with observations in this study (Table 1), as well as with the

583   observations made by Hanson and Spetzler (1994) and Cooper et al. (2016) .

584   We additionally note that, while this analysis correctly predicts a normal transient for the initial loading of

585   olivine along $[011]_c$, it also predicts that once steady state is reached, any subsequent stress increase

586   would lead to an inverse transient. Therefore, this model also correctly predicts the change in the type of

587   transient from normal to inverse observed by Cooper et al. (2016) in progressive load-stepping

588   experiments (see their Figure 4a).

589   We finally point out that our model is similar to that developed by Stone (1991) (in turn, fundamentally

590   inspired by the phenomenological theory of Hart (1970)) and applied to geological materials such as

591   halite (Stone, Plookphol, and Cooper 2004) and olivine (Cooper, Stone, and Plookphol 2016). Stone

592   (1991) describes a "master curve" or equation of state relating stress, strain rate, and the hardness, which

593   is a state variable related to the aspects of the microstructure that control the material response. The

594   "master curve" described by that model is analogous to the flow law presented here. The key difference

595   lies in the choice of microstructural variable that controls the hardness and translates the master curve in

596   stress–strain-rate space. Stone advocates that the self-similar nature of the microstructure in creeping

597   materials, which involves many different length scales, allows the essential aspects of that distribution to

598   be described by a single state variable. Stone uses the subgrain size as that variable. Instead, here we use

599   the net backstress as a representation of the full dislocation microstructure, which includes the stress

600   fields associated with subgrain boundaries. This distinction is important because the backstress is a more

601   general description of the microstructure and therefore can be applied to our samples, which generally do

602   not include appreciable subgrain boundaries.

603   An additional difference between the model of Stone (1991) and that presented here lies in the nature of

604   the relationship between the microstructural variable and the master curve. The master curve of Stone

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605   (1991) represents, at high stresses, a plastic yield stress controlled by the subgrain size, and at low

606   stresses, a flow law describing Nabarro-Herring creep among subgrains. The transition of Stone's master

607   curve to Nabarro-Herring creep at low stresses was inspired by strain rates during load relaxation that

608   approached a linear relationship with stress. The flow law presented here results in a similar

609   phenomenological response, which includes, at high stresses, an exponential dependence of strain rate on

610   effective stress, and at low stresses, a linear dependence of strain rate on effective stress. In our model,

611   this full range of behavior results from a single flow law due to the nature of the sinh term in equation 6.

612   The model of Stone (1991) explains load-relaxation data for halite exceptionally well (Stone, Plookphol,

613   and Cooper 2004), collapsing the data set to a master curve when scaled by the subgrain size. In contrast,

614   in load relaxation experiments on single crystals of olivine in the $[011]_c$ orientation, Cooper et al. (2016)

615   found that the master curve is not shifted by the subgrain size. In fact, they demonstrated that the load-

616   relaxation response is unchanged by the initially applied stress and any associated changes in

617   microstructure, always falling on the same stress–strain-rate curve. Therefore, Cooper et al. (2016)

618   suggested that a different physical process controls the relaxation response of olivine, dislocation glide

619   with kinetics described by an exponential flow law. Our data and analysis provides an alternative, but

620   related, explanation that can be applied to both halite and olivine in load-relaxation experiments.

621   As described by equation 6, the backstress shifts the dislocation-glide flow law in stress–strain-rate space.

622   Figure 7 illustrates that the backstress for crystals deformed in the $[011]_c$ orientation is essentially equal to

623   the applied stress. This observation suggests that, during the initial evolution to steady state, the

624   backstress reaches a value equal to the applied stress before the flow law can shift to lower rates to reach

625   the steady-state rate. Therefore, during a load-relaxation experiment, the effective stress is initially zero,

626   and forward strain only proceeds due to the reduction of the backstress associated with dislocation

627   recovery. The need for recovery implies that load-relaxation in this context is not a constant

628   microstructure test, and indeed Cooper et al. (2016) observed a reduction in dislocation density during

629 relaxation. Continued forward strain and reduction of backstress would occur in lock step and simply

630 follow the steady-state power law regardless of the initial stress, again consistent with the observation of

631 Cooper et al. (2016). In contrast, for halite (Gupta and Li 1970) and other orientations of olivine (Figure

632 7), the backstresses are a smaller portion of the applied stress, and therefore the effective stress is both

633 finite and a function of the applied stress. In this context, a stress relaxation experiment would follow the

634 low-temperature plasticity flow law prior to any relaxation of the backstress. Therefore, we predict that

635 stress relaxation experiments conducted on other orientations of olivine would exhibit a similar response

636 as halite, following the flow law for dislocation glide and dependent on the magnitude of the initial stress.

637 ## *4.3 Consequences for transient creep in the upper mantle*

638 Rheological models employed to analyze geodynamic scenarios vary widely in their form and behavior.

639 In terms of models that capture transient behavior, by far the most common is the Burgers model, which

640 contains two viscous elements, one describing the initial viscosity at the onset of loading and the other

641 describing the steady-state viscosity. Burgers models (and related variations including multiple anelastic

642 elements) have been calibrated for deformation of olivine dominated by diffusive mass transfer (Sundberg

643 and Cooper 2010; e.g., Faul and Jackson 2005) and by dislocation motion (Chopra 1997). The former

644 result in a linear viscoelastic model for which the viscosities do not depend on the level of stress applied,

645 whereas the latter result in nonlinear viscoelastic models for which the viscosities are stress dependent.

646 Linear viscoelastic models based on a Burgers model have been widely applied to a range of phenomena

647 including glacial isostatic adjustment (Yuen et al. 1986; e.g., Rumpker and Wolff 1996), postseismic

648 creep (e.g., Hetland and Hager 2005; Pollitz, Bürgmann, and Banerjee 2006), tidal dissipation (e.g.,

649 Nimmo, Faul, and Garnero 2012; Nimmo and Faul 2013; Bierson and Nimmo 2016), and seismic

650 attenuation (Carcione et al. 2014; S.-I. Karato 2012). Linear Burgers models have likely seen application

651 to such a wide range of processes because of the relative mathematical ease of their implementation and

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652   the recognition that nonlinear viscoelasticity is generally restricted to large stress and strain amplitudes,

653   whereas most of these processes involve small stresses. However, nonlinear viscoelastic models have

654   seen increasing application to scenarios with larger stress changes, especially postseismic creep (Freed,

655   Hirth, and Behn 2012; Masuti et al. 2016). The viscosities in these nonlinear models are assumed to

656   follow power laws, motivated by the power-law behavior of olivine during steady-state dislocation creep.

657   However, the stress dependence is assumed to be the same for both the initial and the steady-state

658   viscosity. Therefore, in both linear Burgers models and nonlinear variations for upper mantle rocks, the

659   ratio of the initial and steady-state viscosities is generally taken to be a constant.

660   Our results and analysis presented above demonstrate that the rheological behavior of olivine can be quite

661   different than the behavior implemented in previous modelling efforts. As demonstrated by our data in

662   Figure 6 and illustrated schematically in Figure 8a, during initial loading, we predict the strain rate of

663   olivine to be close to linearly dependent on the stress at low stresses, with increasingly higher sensitivities

664   to stress with increasing stress (Figure 6b also illustrates that the transition between linear and nonlinear

665   behavior is not particularly dependent on temperature). Therefore, we predict the nonlinearity of the

666   initial viscosity to be a function of the stress. This conclusion is particularly noteworthy because, for

667   example, the apparent viscosity associated with geodynamic phenomena on short timescales could

668   potentially follow linear viscoelastic behavior even when dislocation glide is the main strain producing

669   process. Furthermore, if the nonlinearity of the initial viscosity is dependent on stress and temperature,

670   then the ratio of the initial viscosity to the steady-state viscosity will also be a function of the stress.

671   We note that the transient deformation behaviour of rocks may be subject to additional effects not

672   captured in our experiments on single crystals, including grain-boundary strengthening (Hansen et al.

673   2019; Kumamoto et al. 2017), recovery from grain-boundary migration (e.g., Toriumi 1982), stress

674   transfer between grains (Duval, Ashby, and Anderman 1983; Masuti et al. 2019), additional deformation

31

675   mechanisms, and the effects of other minerals and/or fluids. Nonetheless, the dislocation-mediated

676   processes that we analyse here should be ubiquitous across relevant geological conditions regardless of

677   the occurrence of other effects. Therefore, the model that we present provides a fundamental starting

678   point for analysing transient creep that allows isolation of the contribution from intragranular processes,

679   with the benefit that departures from such behaviour in polycrystalline or polyminerallic materials may

680   constrain contributions from additional processes.

681 # 5 Conclusions

682   Here we present a series of deformation experiments to investigate the microphysical mechanisms

683   controlling transient creep in olivine. We conducted stress-reduction tests on olivine single crystals at

684   elevated temperatures in a variety of crystal orientations. Our results reveal that stress-reductions are

685   often accompanied by anelastic reverse strain. The magnitude of the reverse strain is dependent on the

686   magnitude of the stress reduction. In certain crystal orientations, small stress reductions result in no

687   reverse strain, indicating that a backstress is present in the crystals that is a fraction of the initially applied

688   stress.

689   We recognise that deformation of olivine is fundamentally controlled by the glide velocity of dislocations,

690   and therefore hypothesize that a flow law based on the kinetics of dislocation glide can be applied across

691   a wide range of temperatures. The buildup of backstresses associated with strain hardening in low-

692   temperature plasticity is quantitatively consistent with the magnitudes of observed reverse strains. This

693   hypothesis also predicts that the strain rates just after a stress reduction can be predicted with a flow law

694   calibrated at low temperatures, however, the existing flow law considerably overpredicts the strain rates

695   observed here. Therefore, we recalibrate the activation energy of the flow law to be consistent with initial

696   strain rates in our experiments, initial strain rates in previously published high-temperature experiments,

697   and yield stresses in low-temperature experiments.

698   We suggest that this recalibrated flow law can be used to predict the transient and steady-state creep strain

699   rates by taking into account the evolution of the backstress and dislocation density. By combining the

700   recalibrated flow law with previously published flow laws for the steady-state creep of olivine single

701   crystals, we are able to correctly predict the magnitude of the observed backstress and its orientation

702   dependence. We are also able to predict whether strain rates decrease (normal) or increase (inverse)

703   during transient creep in our experiments and previously published experiments. This model also provides

704   an explanation for the results of previous stress-relaxation experiments.

705   The results and analysis presented here indicate that the rheological behaviour of olivine during transient

706   creep is fundamentally different from that incorporated into analyses of geodynamic processes. We

707   suggest that the initial viscosity after a stress change, if controlled by dislocations, can range from linear

708   to nonlinear, depending on the stress magnitude. Therefore, the ratio between the transient and steady-

709   state viscosities is likely a function of the stress.

710   Acknowledgements

720   Oxford. All data used in this study are available from the University of Minnesota Digital Conservancy

721   (http://conservancy.umn.edu).

722 **Figure Captions**

723   Figure 1: Axial strain and stress as functions of time for the first 800 s of deformation of sample
724   OxR0009. Seven stress reductions are illustrated after the primary loading phase. The initial stress used to
725   set the microstructure was 105 MPa. After each stress reduction, the reverse strain was composed of both
726   an elastic and an anelastic component, as denoted by annotations. Elastic strains in this figure are a
727   combination of the elastic distortion of both the apparatus and the sample.

728   Figure 2: Comparison between strain rates from the steady-state portions of the experiments and
729   published flow laws for single crystals of San Carlos olivine. Symbols represent data from this study
730   (following Table 1), and lines represent flow laws from Bai and Kohlstedt (1992a). Color indicates crystal
731   orientation and symbol indicates experiment. Open symbols and dashed lines indicate a temperature of
732   1300°C, and filled symbols and solid lines indicate a temperature of 1250°C.

733   Figure 3: Compilation of data from all stress-reduction tests. (left) Strains after each reduction are aligned
734   and plotted in grayscale. The grayscale indicates the order of the reductions, with darker colors indicating
735   stress reductions earlier in the experiment. (middle) Magnitude of the stress reduction as a function of the
736   strain after the reduction. Small markers indicate the elastic reverse strain, and larger markers indicate the
737   total reverse strain. The dashed line indicates the Young's modulus for each crystal orientation based on
738   the data of Abramson et al. (1997). (right) The anelastic reverse strain as function of the magnitude of the
739   stress reduction. Anelastic reverse strains are calculated as the difference between large markers and
740   small markers in the middle column. Marker shapes and colors are as designated in Table 1.

741   Figure 4: HR-EBSD maps of sample OxR0009, which was compressed in the [110]c orientation indicated
742   in the pole figure, at different strains and locations in the sample annotated on the left. Lattice rotations
743   (ω_{ij}) and shear stress on the (010)[100] slip system (σ_{ab}) are relative to the orientation and stress state,
744   respectively, of the reference points marked in black. The greyed-out areas in the top stress map indicate
745   regions where the stress measurements are unreliable due to the large distances and large lattice rotations
746   relative to the reference point.

747   Figure 5: Anelastic reverse strain as a function of the magnitude of the stress reduction at two different
748   temperatures. Marker shapes and colors are as designated in Table 1. Solid lines are fits to equation 5.
749   Only data with clearly measurable anelastic reverse strain are included in fits.

750   Figure 6: Analysis of strain rates measured immediately after stress reductions. (a) Strain rates measured
751   after small reductions for which no anelastic reverse strain was detected. Stresses are effective stresses,
752   that is, the applied stress minus the measured backstress given in Table 1. Marker shapes and colors are as
753   designated in Table 1. Dashed and solid lines are flow laws for single crystals of olivine from Bai et al.
754   (1991). (b) Strain rates as in (a) compared to previously published data. Strain rates from previous high-
755   temperature creep tests (Hanson and Spetzler 1994; Cooper, Stone, and Plookphol 2016; Chopra 1997)
756   were taken from the beginning of experiments in which the backstress is expected to be negligible. Data
757   from Hansen et al. (2019) are yield stresses measured in constant-strain-rate experiments. Dashed lines

758 represent the flow law from Hansen et al. (2019). Solid lines represent the flow law calibrated in this
759 study.

760 Figure 7: Measured and predicted backstresses as a function of the applied stress. Markers indicate
761 backstresses determined using the analysis presented in Figure 5. The two thin black lines are guides for
762 values of backstress equal to the applied stress (1:1) or half of the applied stress (1:2). The curves are
763 backstresses predicted from equation 7.

764 Figure 8: Evaluation of the proposed model in the contexts of the shape of the transient and of stress
765 relaxation. (a) Schematic description of our model. The initial stress applied to a sample leads to a strain
766 rate controlled by flow law for dislocation glide (equation 6) without any backstress. If this strain rate is
767 higher than the steady-state strain rate, we predict that the transient will be normal and controlled by the
768 increase in backstress. If this strain rate is lower than the steady-state strain rate, we predict that the
769 transient will be inverse and controlled by the increase in density of mobile dislocations. In this
770 schematic, the backstress is assumed to always be less than the minimum stress on the plot. (b)
771 Conditions leading to inverse or normal transients calculated with the concept presented in (a). Data for
772 comparison come from the initial strain rates at the start of experiments presented by Cooper et al. (2016),
773 Hanson and Spetzler (1994), and this study. (c) Schematic prediction of different responses during stress
774 relaxation experiments. If steady state is reached before the backstress equals the applied stress, then
775 subsequent relaxation will follow the flow law. If the backstress increases to equal the applied stress at the
776 steady state, then subsequent load relaxation only results in forward strain as the backstress relaxes,
777 following the steady-state power law.

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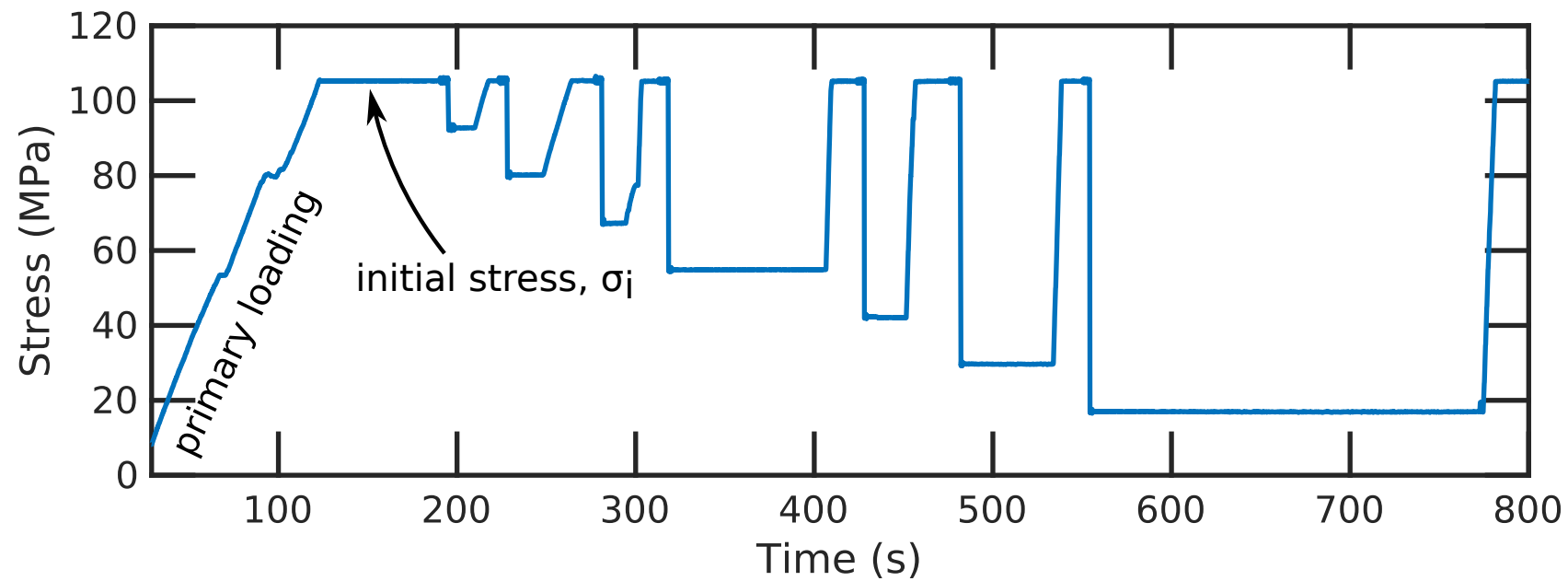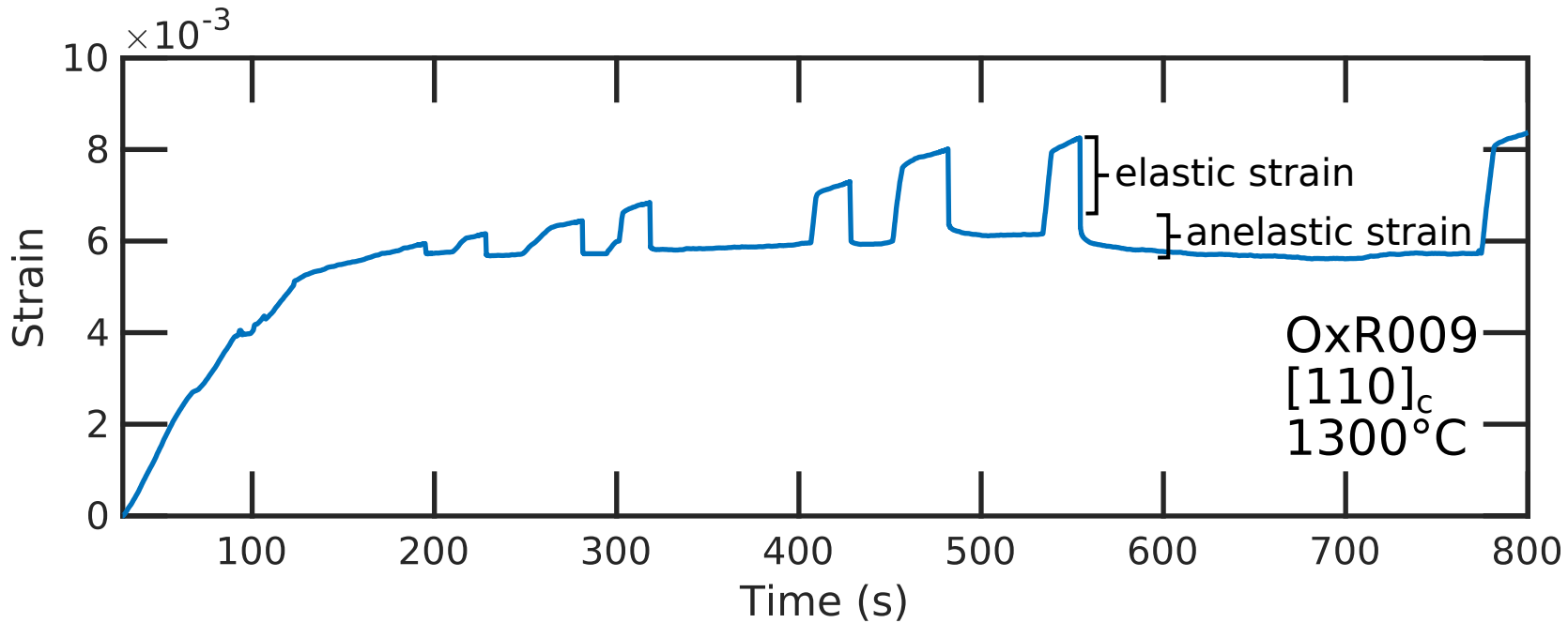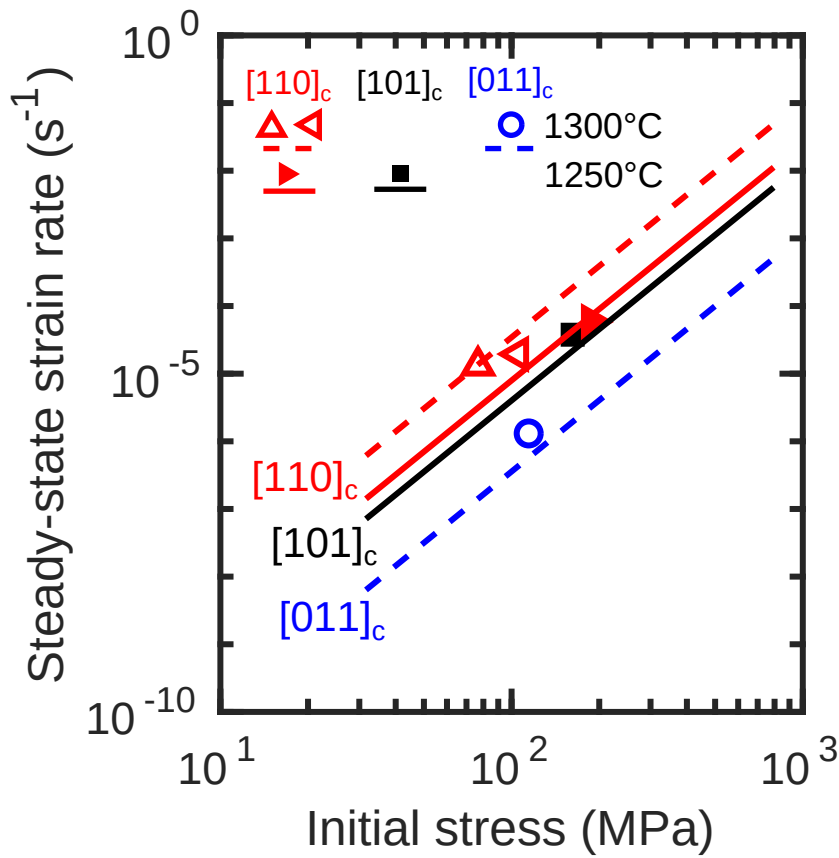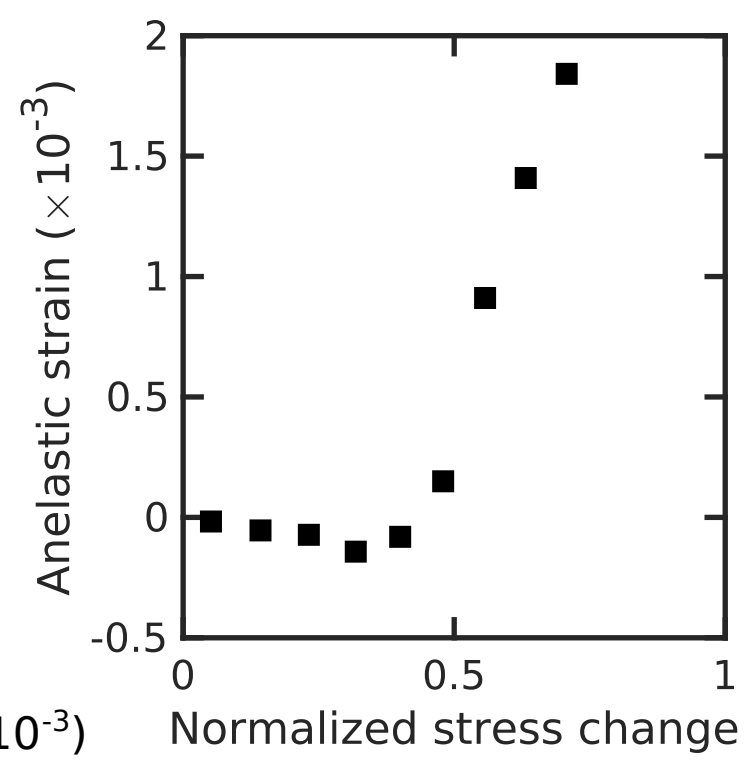1034   118 (11): 2013JB010408.

1035

Figure 1.

Figure 2.

Figure 3.

OxR0002
[101]$_c$
T = 1250°C
σ_i = 162 MPa
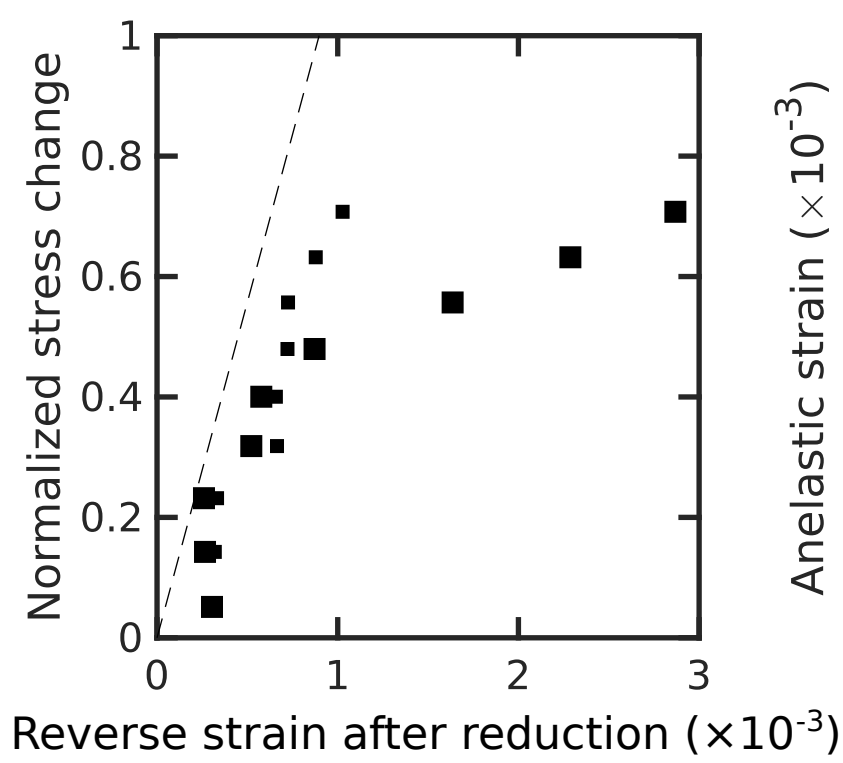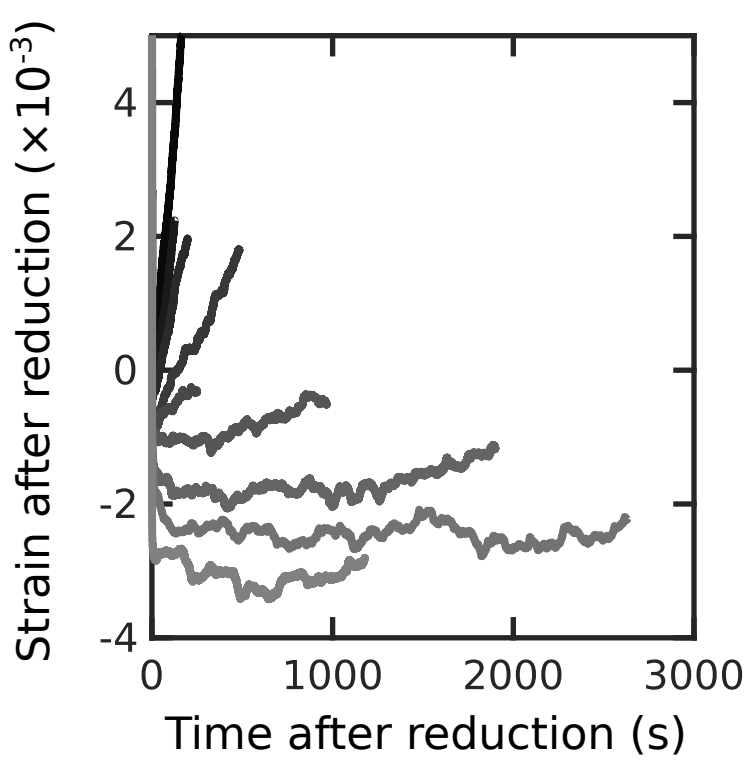
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[110]$_c$
T = 1250°C
σ_i = 189 MPa
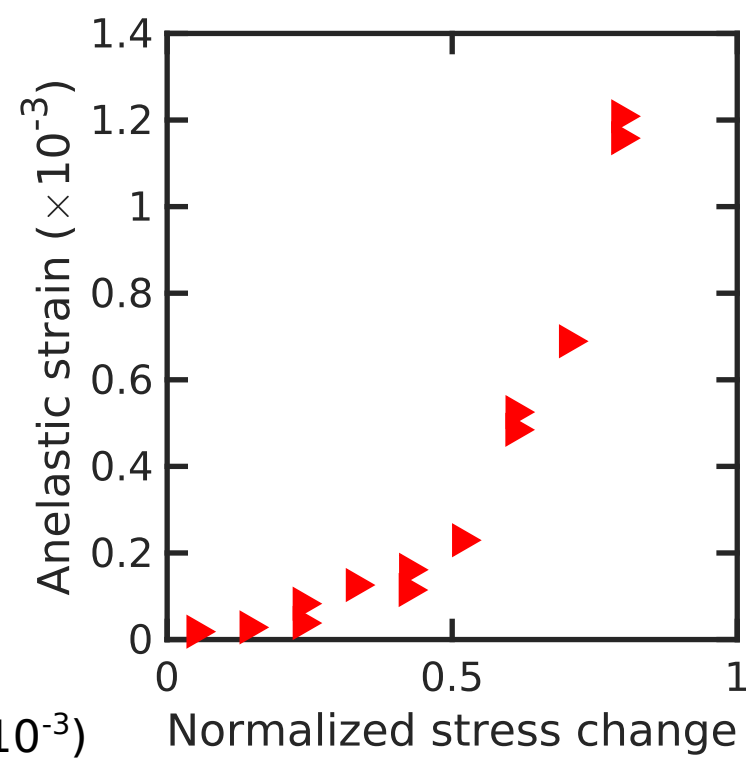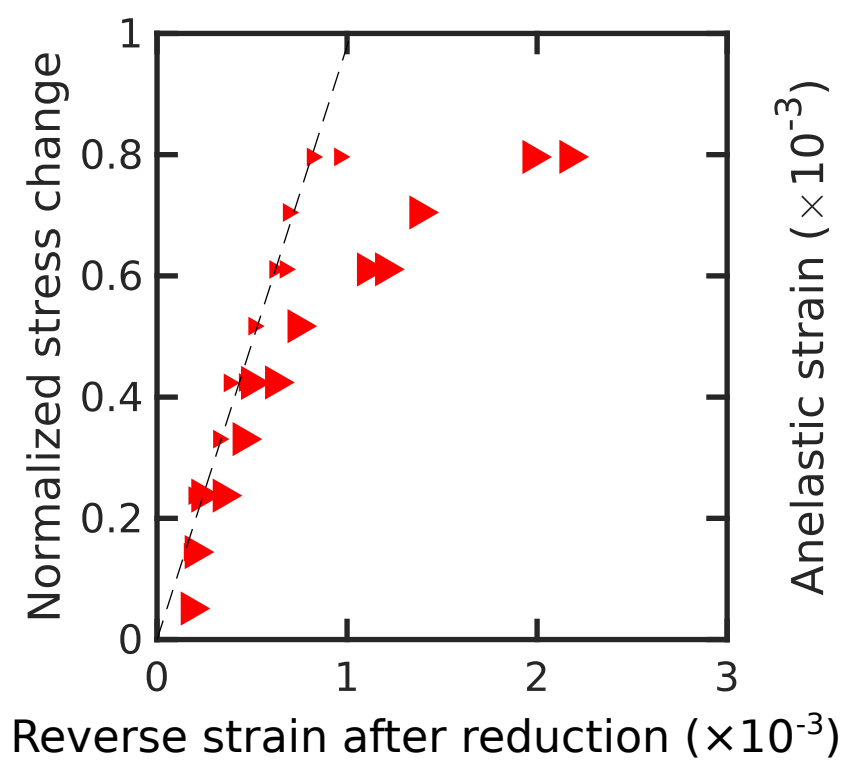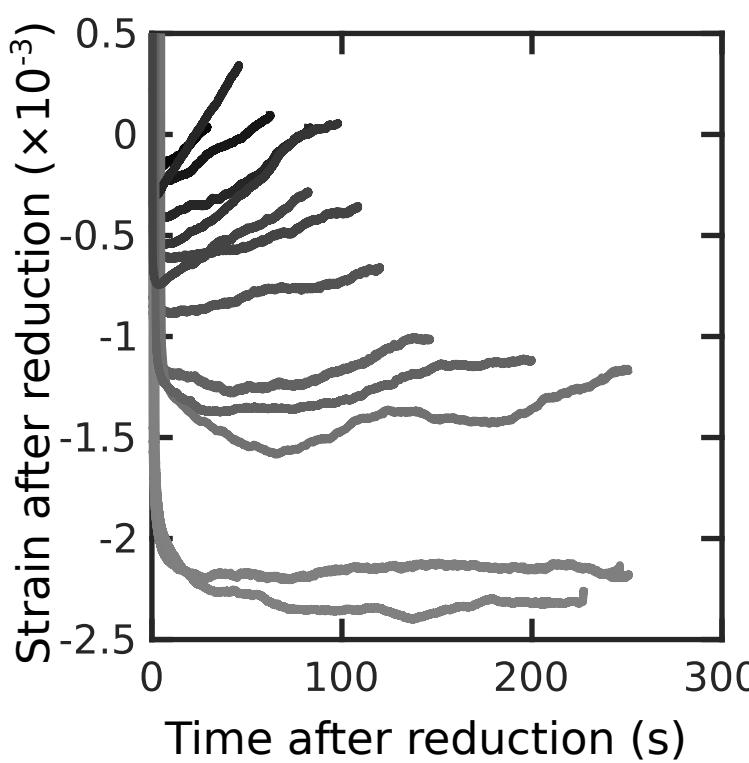
OxR0009
[110]$_c$
T = 1300°C
σ_i = 105 MPa
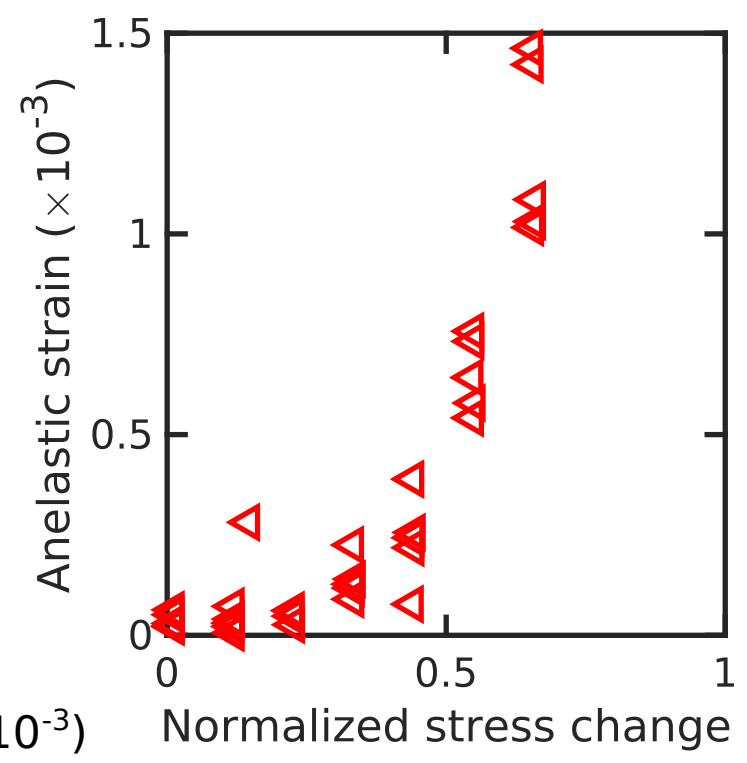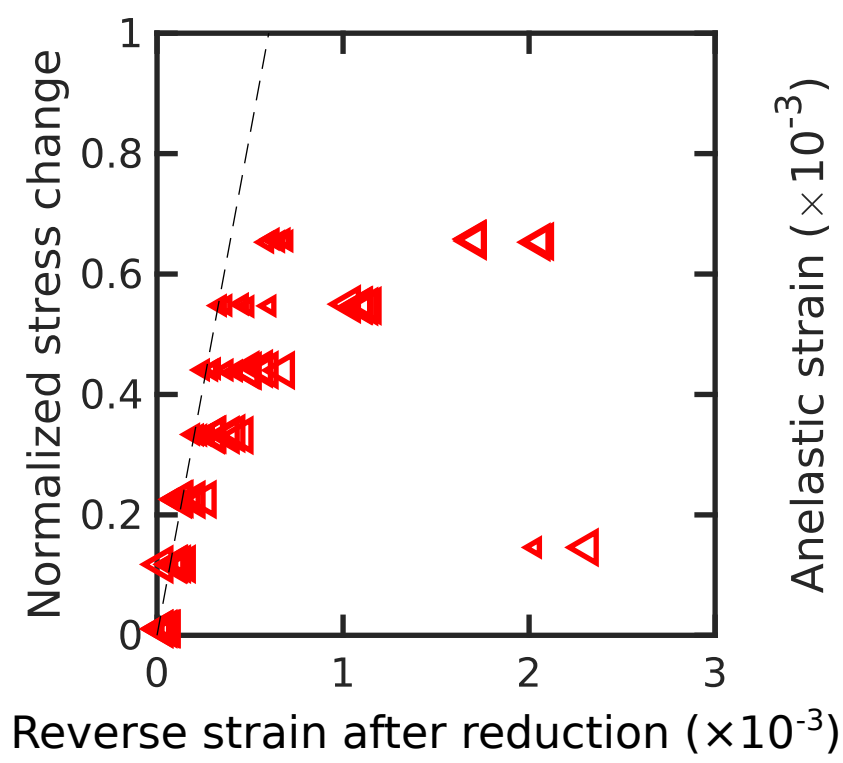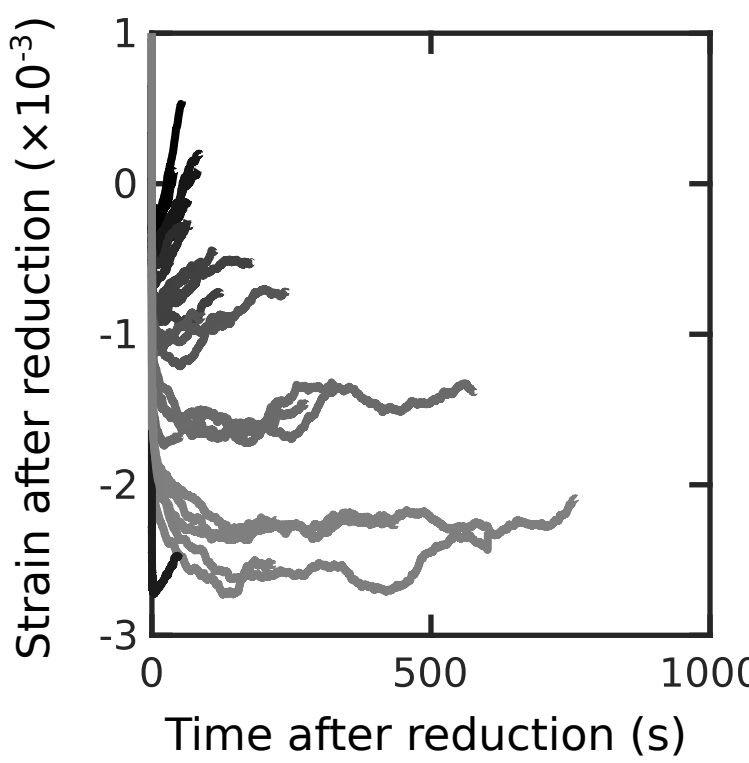
OxR0009b
[110]$_c$
T = 1300°C
σ_i = 77 MPa
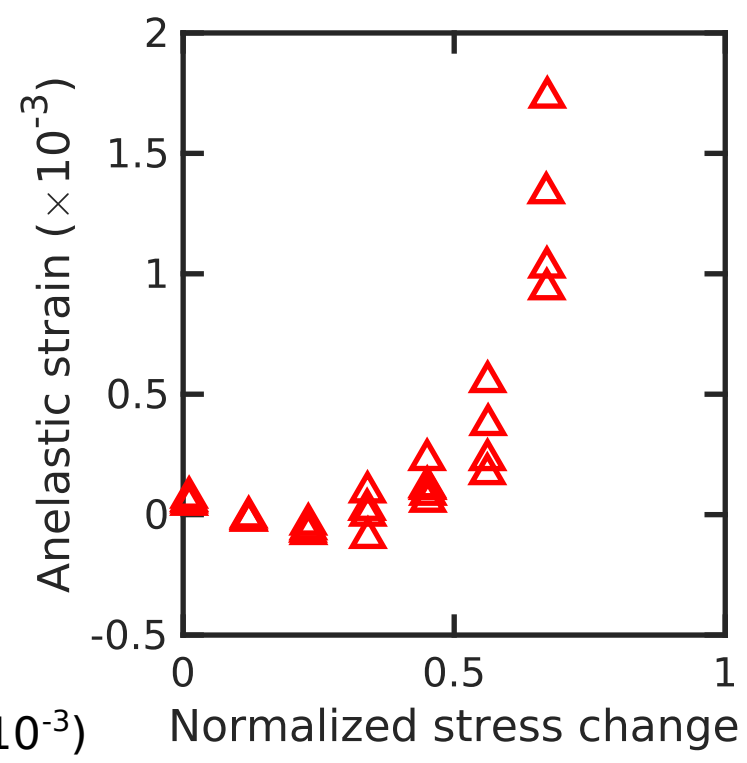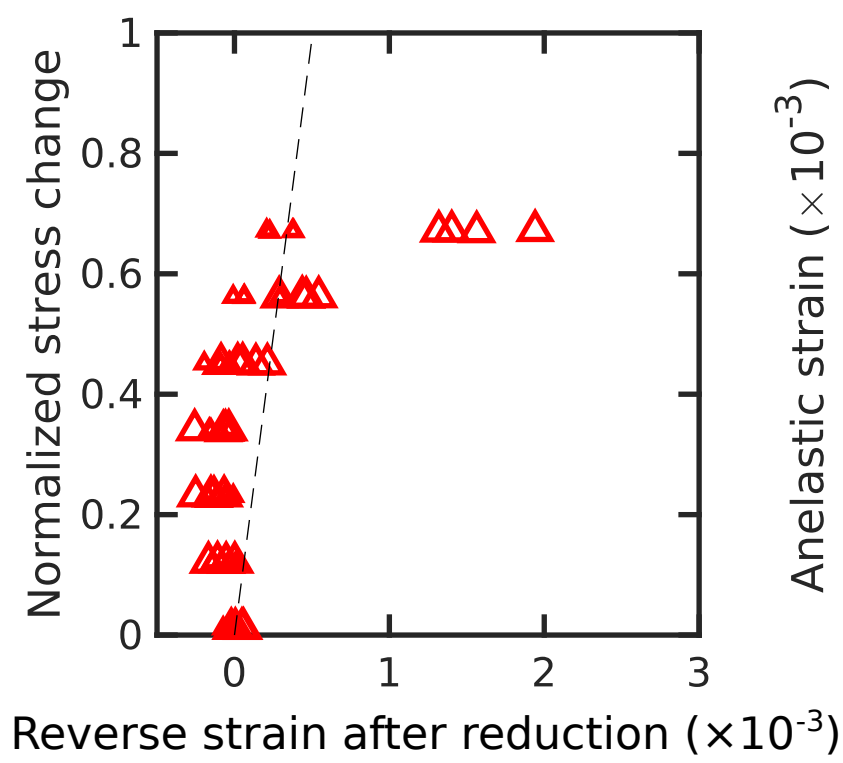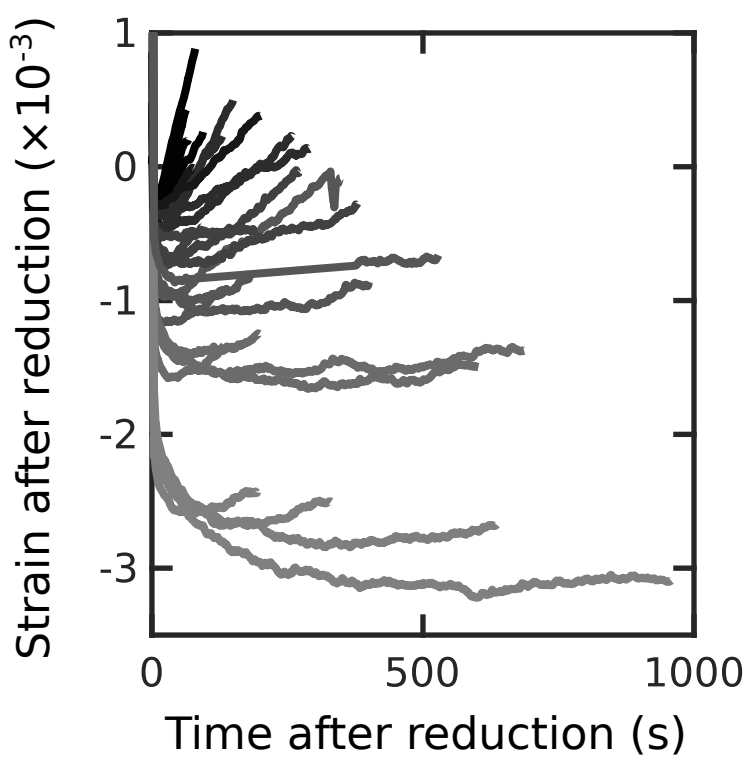
OxR0010
[011]$_c$
T = 1300°C
σ_i = 116 MPa

Figure 4.

ω_{12} (rad) ω_{13} (rad) ω_{23} (rad) σ_{ab} (MPa)

ε = 17 %, bottom edge

ε = 38 %, centre

ε = 38 %, side edge

200 μm

40 μm

40 μm

• Reference point

[010] [100]

[001]

Figure 5.

Figure 6.

a

[110]$_c$ [101]$_c$ [011]$_c$

1300°C

1250°C

Strain rate (s^{-1})

Stress (MPa)

b

Hansen et al. (2019)

This study

Temperature (K)

Normalized strain rate (m^{2}s^{-1})

Stress (MPa)

★ Hanson and Spetzler (1994)
✳ Cooper et al. (2016)
◇ Chopra and Paterson (1997)
✶ Hansen et al. (2019)

Figure 7.

Figure 8.

a

normal transient

inverse transient

steady-state

plasticity flow law

↑ρ

$\sigma_b = 0$

↑σ_b

initial stress

c

$\sigma_b = \sigma$ at steady-state stress relaxation follows steady state as σ_b relaxes
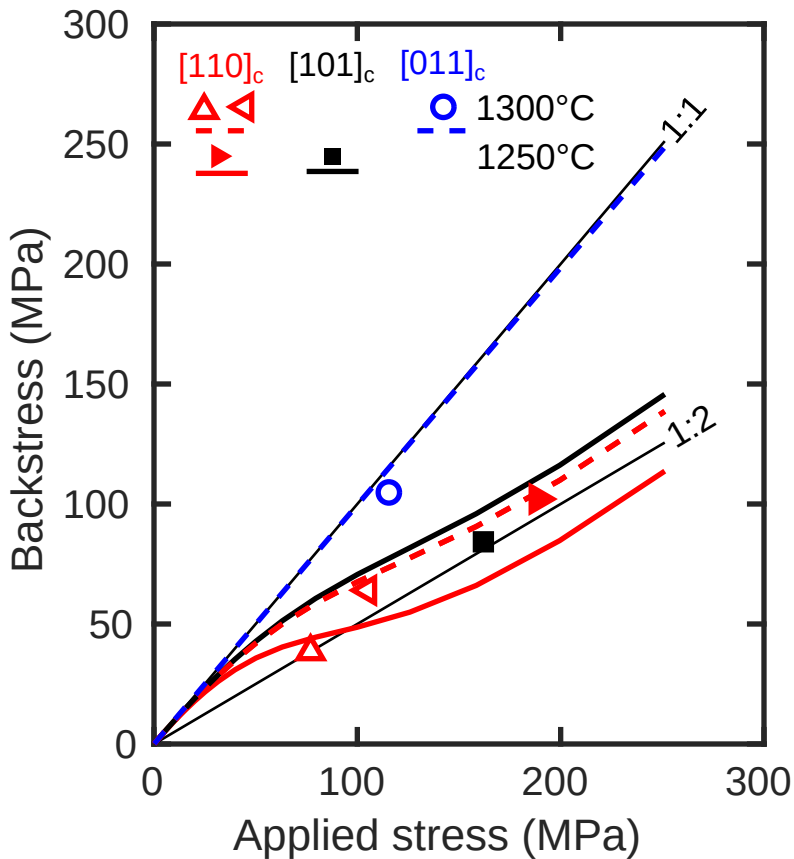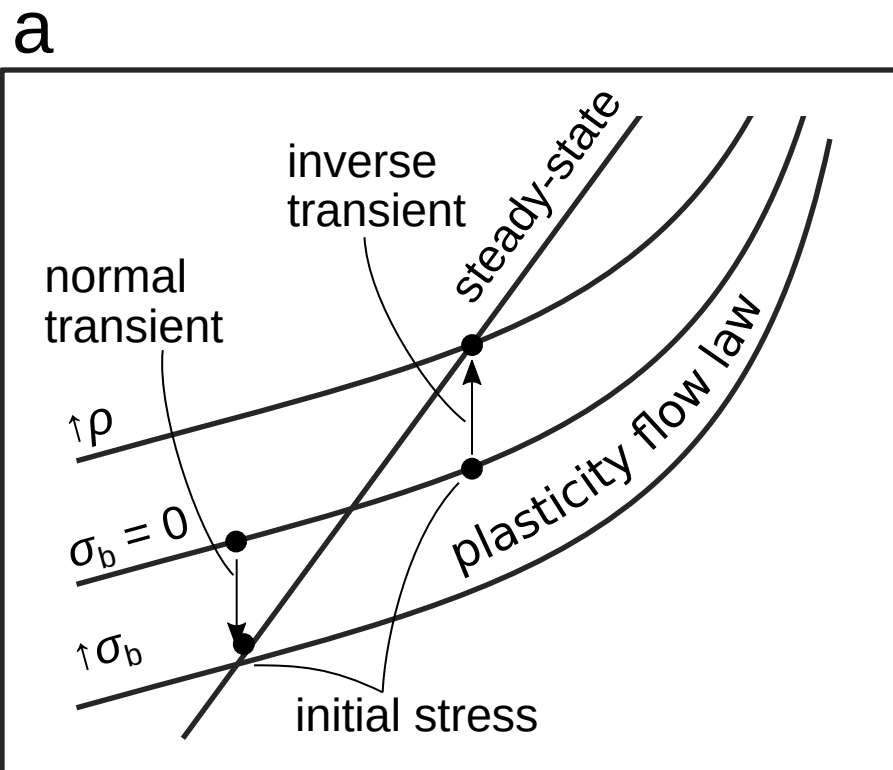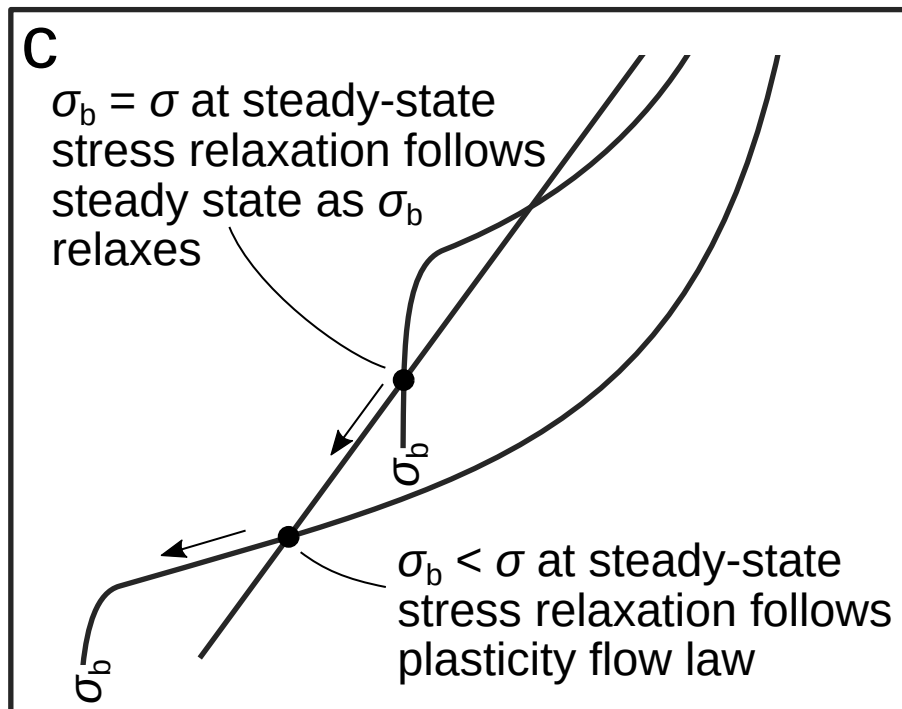
σ_b

$\sigma_b < \sigma$ at steady-state stress relaxation follows plasticity flow law

σ_b

log Strain Rate

log Stress

b

$[110]_c$

normal

inverse

Temperature (°C)

10^0 10^1 10^2 10^3

Stress (MPa)

$[101]_c$

normal

inverse

Temperature (°C)

10^0 10^1 10^2 10^3

Stress (MPa)

$[011]_c$

Temperature (°C)

	Normal	Inverse
Cooper et al.	○	●
Hanson and Spetzler	△	▲
This study	□	■

10^0 10^1 10^2 10^3

Stress (MPa)