Creep Rheology of Antigorite: Experiments at Subduction Zone Conditions

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Abstract

Novel fluid medium pressure cells were used to deform antigorite under constant stress creep conditions at low temperature, low strain rate \(10^{-9} - 10^{-4} \text{ s}^{-1}\), and high pressure (1 GPa) in a Griggs-type apparatus. Antigorite cores were deformed at constant temperatures between 75°C and 550°C, by applying 8–12 stress-strain steps per temperature. The microstructures of deformed samples share features documented in previous work (e.g., shear microcracks), and highlight the importance of basal shear and kinks to antigorite plasticity. Rheological data were fit with a low temperature plasticity law, consistent with a deformation mechanism involving large lattice resistance. When applied at geologic stresses and strain rates, the extrapolated viscosity agrees well with predictions based on subduction zone thermal models.

Plain Language Summary

The rheology of Antigorite, a hydrous mineral that is present on top of subducting slabs and in the stagnant mantle wedge, could control subduction structure. Instead of deforming antigorite with our motor set to a constant speed, we redesigned the deformation assembly and machine to accurately servo-control the stress on deforming samples. Measuring strain rate at several stresses and temperatures allows us to construct a flow law to extrapolate behavior to subduction zone stresses/strain rates. The microstructure of samples cut open after deformation suggests antigorite rheology is controlled by the resistance of defects to movement along the crystallographic sheet structure.

1. Introduction

Subduction zones are among the most seismically active tectonic environments on Earth. The wide spectrum of brittle and ductile behavior in the down-going slab and nearby mantle control seismic coupling, deep fluid transport, and local mantle convection. The interplay between rheology and metamorphic reactions is key to understanding tectonic dynamics and evolution of subduction structure at depth. To explain a range of observations from subduction zones (e.g., heat flow, location of volcanic front, slab seismicity, seismic structure of the mantle wedge), thermal models require slab decoupling from the mantle wedge down to a depth of approximately 80 km (e.g., Syracuse et al., 2010; Wada et al., 2008). Owing to its relative weakness compared to other lithospheric minerals, the presence of serpentine along the interface has been called on to promote this decoupling (e.g., Wada & Wang, 2009). In altered oceanic lithosphere and mantle wedge, antigorite is the stable serpentine polytype at these high pressure/high temperature conditions (Schwartz et al., 2013; Wunder & Schreyer, 1997).

The rheology of antigorite at high pressure has been investigated in a wide range of experimental studies. Flow laws constrained by strain rate stepping experiments from these studies have reported both dislocation creep behavior (\(\dot{\epsilon} \propto \sigma^n\), with \(n = 3 - 4\) (Auzende et al., 2015; Hilairet et al., 2007)) and/or flow laws with greater stress-dependence consistent with low-temperature plasticity or semi-brittle flow (effective \(n > 10\) (Chernak & Hirth, 2010; Hirauchi et al., 2020; Proctor & Hirth, 2016; Shao et al., 2021)). Such large variation in estimated stress-dependence leads to large uncertainties when extrapolating flow laws to the relevant geologic conditions. The uncertainty in the extrapolation can be resolved by conducting deformation experiments at strain rates lower than previously examined experimentally (almost all previously published data were collected at constant strain rates greater than \(10^{-6} \text{ s}^{-1}\)). For low strain rate deformation, constant-stress creep tests are generally advantageous because deformation typically stabilizes over a small strain interval, allowing mechanical measurements of lower strain rates than is practical during constant strain-rate tests. However, constant-stress experiments also present technical challenges because load, confining pressure, and displacement are measured externally. These measurement challenges necessitated the development of new experimental approaches for our study.

We conducted creep tests on solid cores of isotropic antigorite at constant differential stress. To improve the resolution of both stress and strain rate we redesigned the dynamic seals, sample assembly, and mechanical control
of a Griggs-type deformation apparatus (Burdette, 2021) optimized for the relatively low temperature conditions where antigorite is stable. After deformation, samples show many microstructural features documented in previous work, including shear microcracks (Escartin et al., 1997). However, the microstructures are not dominated by faulting or comminution, and provide evidence for the important contribution of basal slip and kinking to strain accommodation.

2. Materials, Cell Designs, and Methods

2.1. Materials and Sample Preparation

Antigorite samples were cored in one direction from a single block of serpentinite collected from the Nagasaki metamorphic belt in Japan as 12.7 mm length, 6.35 mm diameter cylinders. This material (which was also used in the studies of Proctor and Hirth (2015) and Okazaki and Hirth (2016)) is predominantly antigorite (98%) with minor diopside, spinel and magnetite. The original microstructure of cored samples shows a generally isotropic, interpenetrating or interlocking texture (Wicks & Whittaker, 1977) which results in many antigorite grains with basal planes oriented around 45° to the axial compression direction. Thin section images (Figure 1) highlight these grains with maximum birefringence at ±45° to polarizers. However, there is no macroscopic foliation.

2.2. Sample Assemblies

Constant-stress experiments present technical challenges, which necessitated the development of new experimental approaches for our study. Samples were dried at 100°C, jacketed in 0.125 mm thick annealed copper or silver sleeves and deformed at 1 GPa confining pressure in one of four modified Griggs-type deformation assemblies, depending on the experimental temperature (Figure 2). For T ≥ 400°C, a eutectic partial melt salt (0.15AlCl3–0.85NaCl mol, which produces 15 + % melt during experiments) was used in a molten salt assembly (Figure 2a). For T = 200°C, a modified molten salt assembly was fabricated with molten Bi-Sn alloy replacing the inner salt, and machined Teflon replacing pyrophyllite (Figure 2b). For experiments at T = 75°C, a weak Bi-Sn-Pb eutectic (95°C) alloy was cast into a tube filling the space between samples and the pressure vessel walls (Figure 2c). The entire pressure vessel and cell were heated above 75°C by flowing hot water through the standard cooling rings, causing the confining alloy to become very weak and presenting low resistance to sample barreling and piston advancement. This arrangement was repeated with liquid hydraulic oil surrounding the sample in a second experiment (diagram in Supporting Information S1).

The incorporation of fluid components into the assembly motivated the use of axial thermocouples placed below the sample, rather than a radial thermocouple entering through the furnace toward the center of the sample. Thermal modeling (Moarefvand et al., 2021; Burdette, 2021, Section C.1) and previous studies (Kirby & Kronenberg, 1984) indicate that the axial thermocouple measures a 10°C colder area of the sample column, representing a more reliable (due to much lower thermal gradients), but also lower bound on the sample temperature.

Low dynamic friction is critical for characterizing samples with large stress sensitivity. To decrease friction, we replaced the beveled miter-ring seal used in Griggs-type apparatuses with a tight-tolerance polished carbide bushing and graphite-filled PEEK washer (Figure 2). This design limits extrusion of seal material and promotes excellent piston alignment. We tested the new design by conducting deformation tests on brass using paraffin wax as a confining medium (Burdette, 2021, Figure 2.16). With these improvements, both the magnitude and rate-dependence of dynamic seal friction were reduced by approximately a factor of five. Axial loads were corrected for static friction measured in each experiment.

Acoustic emission (AE) data were acquired using a 6.35 mm diameter passive piezoelectric transducer with 2.5 MHz resonant frequency and 40 dB amplification. Emissions were recorded at 50 MHz when signal amplitude exceeded the 10 mV amplified noise floor. Counts were determined after the experiment, following five
point median filtering and thresholding to 10 mV on the signal envelope. The transducer was located in the base plate, below the sample assembly (Okazaki et al., 2021).

2.3. Stress Stepping Methods

In all creep experiments on antigorite cores, the deformation piston was first advanced until it “hit” the sample and loaded to starting stress. The sample was then allowed to creep at constant stress for 2–24 hr (these data would potentially be impacted by a number of issues, including squeeze-out of metal foil between sample and piston, thermal equilibration, and relaxation of stresses in the assembly, and were conservatively not used in the determination of flow laws). For each subsequent stress step, strain rate was monitored and allowed to stabilize after reaching the target stress. Examples of transients observed at low strain after the achievement of a target stress are illustrated in Figure 3. Strain rate data for each stress was taken from slope of the strain-time curve recorded at the end of each step.

To test the performance of the new dynamic seal, we conducted experiments on Westerly granite (Tullis & Yund, 1977) which satisfied our testing requirement of high strength and published data at low strain rates. We conducted stress stepping creep tests on Westerly granite at confining pressure of 200 MPa and temperature of 75°C in the low temperature assembly. Results were compared to published data acquired in a gas-confining medium apparatus (Brantut et al., 2012). We note that Brantut et al. (2012) report their data as differential stress normalized to peak strength to provide a quantity referenced to a representation of the rock’s fracture toughness. As shown in Figure 4 our data compare favorably, showing good agreement with previous work for strain rates down to $5 \times 10^{-7}$/s.

3. Results

3.1. Mechanical Results

The creep rate of antigorite systematically increases with increasing temperature and exhibits a stress dependence that decreases with temperature. As shown in Figure 5b, For strain rates $>10^{-6}$ 1/s, data for a given temperature
show a nominally constant stress exponent, varying from \( n \approx 20 \) at 75°C to \( n \approx 5 \) at 550°C. Inspection of data from the highest temperatures illustrates a decrease in \( n \) below strain rate of \( 10^{-7} \) 1/s. The fit to a low temperature plasticity (LTP) flow law is plotted in Figure 5 and discussed in Section 4.1. A list of experiments is included in Table 1. Stress, strain rate, and strain data are included in Supporting Information S1.

We monitored AE activity during the antigorite creep experiments, and emissions were not detected (e.g., Ferrand et al., 2017; Gasc et al., 2017; Okazaki & Hirth, 2016). In contrast, we observed hundreds of emissions during our creep test on Westerly granite, with an event frequency that increased proportional to strain rate (Figure 4).

### 3.2. Deformation Microstructure

Microstructures in deformed samples provide evidence that basal slip along the antigorite grains leads to interactions between neighboring grains with different orientations within the interlocking texture (X-shaped structures). As described next, these textures vary with temperature. Sample scale photos of the deformed samples are included in Figure 6. Shear microcracks (e.g., cracks formed preferentially along (001) basal cleavage at high
resolved shear stress orientations (Escartin et al., 1997) decorate deformed regions of samples and scatter light to appear brighter in sample-scale images.

Samples deformed at 75°C exhibit deformation primarily along a 1 mm wide, banded structure oriented 35° from the axial compression direction (Figure 6). Within the deformation zone, there are several <1 mm long cracks at high shear stress orientations which do not connect, and a high density of relatively tight kinks (Figure 7c). There is little evidence for comminution in the strongly deformed zone. We define kink angle as the deviation from an uninked plane (180° less/minus the inner “opening” angle between the traces of visible cleavage planes) so that slight bending corresponds to a small kink angle. The average kink angle at 75°C in Figure 7c is 54° (29 measurements, minimum 40°, maximum 68°). This value is approximately twice the period doubling angle (defining the angle between the orientation of the radium of curvature of the adjacent segments of the alternating antigorite structure) observed in polygonal serpentinite samples (Grobety, 2003).

The core deformed at 200°C also displays deformation marked by shear microcracks at 35° to axial compression, but the deformed zone is wider (2 mm width, Figure 7a). Kinks are observed throughout the deformed zone and are often present at the intersection of grains whose basal planes have opposing orientations for high shear stress (±45°), forming X-shaped structures (Figure 7b). When the kink angle is small (see Figure 7b), the sheets are mostly intact along their length. The average kink angle in Figure 7b is 23° (9 measurements, minimum 15°, maximum 33°).

At 400°C the deformation appears more distributed. Kinks and shear microcracks are distributed throughout the deformed areas of the sample (bright in Figure 6). A lack of strain localization in core samples deformed to low

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**Table 1**

*List of Experiments*

| Experiment  | Sample         | Temperature (°C) | Pressure (MPa) | Confining media               | Strain |
|-------------|----------------|------------------|----------------|------------------------------|--------|
| W2394-75    | Westerly Granite | 75               | 200            | 95°C Alloy                   | 0.04   |
| W2424-550   | Antigorite      | 550              | 1,000          | NaCl – AlCl₁                  | 0.02   |
| W2439-400   | Antigorite      | 400              | 1,000          | NaCl – AlCl₁                  | 0.04   |
| W2441-75    | Antigorite      | 75               | 1,000          | 95°C Alloy                   | 0.05   |
| W2447-200   | Antigorite      | 200              | 1,000          | 60:40 Bi:Sn                   | 0.04   |
| W2520-520   | Antigorite      | 520              | 1,000          | NaCl – AlCl₁                  | 0.02   |
| W2521-75    | Antigorite      | 75               | 1,000          | Hydraulic Oil                 | 0.03   |
| W2526-480   | Antigorite      | 480              | 1,000          | NaCl – AlCl₁                  | 0.01   |
strain at 400°C is consistent with previous work (Chernak & Hirth, 2010). Although at the sample scale it appears a fault crosses the sample, it is made up of many shear fractures over a 0.5 mm wide deformed zone and is less damaged than samples deformed at 75°C. X-shaped structures are also present in the most deformed parts of the sample, but they are less densely spaced than observed at lower temperature, and accordingly the kink density is lower in the sample deformed at 400°C. The kink angles vary as a function of distance from the stress concentrating grain intersections (Figure 7d). The kink angle less than 10 μm from the annotated compression structure shown in Figure 7c is 45°, while the kink angles 20 μm away are 10–20°. This observation suggests that the kink bands grow outward with increasing deformation at the stress-concentrating feature.

Samples deformed at 550°C also retain many shear microcracks, and exhibit distributed deformation similar to the 400°C sample. However, we did not observe clear kinks. Bending of grains is observed, but only at small scales (<1 μm, micrograph included in supplement). Where these small bends in the grains appear, they do not have a clear apex as observed for lower temperate samples.

4. Discussion

The creep data in Figure 5b define a systematic stress dependence at each temperature. Variation in stress sensitivity (i.e., stress exponent) with increasing stress and temperatures is uniquely well described by a flow law used for barrier-controlled glide of dislocations. Here we discuss the fit and follow with a discussion of the deformation mechanisms. We then compare mechanisms and results to previous work, and describe how these results, including the prevalence of shear microcracks and fractures, mesh with previous work that emphasized a deformation style that is broadly called semi-brittle flow. Finally, we briefly discuss application to geologic conditions.

4.1. Low Temperature Plasticity Flow Law

Reduction of stress sensitivity (stress exponent) with increasing temperature is consistent with exponential LTP or “barrier controlled” creep laws where stress or thermal activation allows defects to pass through the ‘barrier’. LTP flow laws have the form (Frost & Ashby, 1982):

$$\dot{\epsilon} = A \left(\frac{\sigma}{\mu}\right)^2 \exp\left(\frac{-\Delta F}{RT} \left(1 - \left(\frac{\sigma}{\tau_0}\right)^p\right)^q\right)$$

where $A$ is a constant, $\sigma$ is differential stress, $\mu$ is the shear modulus, $\Delta F$ is the activation energy required to overcome the obstacle without the aid of external stress, $\tau_0$ is athermal flow stress, and $p$ and $q$ are parameters that depend on the geometry of the barrier. A normalized $\sigma^2$ term accounts for the density of mobile dislocations in the sample.

The flow law parameters determined by fitting this LTP law are very sensitive to changes in the exponents $p$ and $q$. The sensitivity to these exponents is not obvious at laboratory strain rates, but is clearly apparent in extrapolated strain rate and viscosity. We illustrate the problem with Figure 9b, where extrapolations of fits for $A$, $\Delta F$, and $\tau_0$ at several values of $p$ and $q$ are displayed for data recorded at strain rates above $10^{-7}$ 1/s. The resulting uncertainty is also plotted in Figure 10a as a gray shaded region. Typically, LTP creep data are
not acquired at strain rates below $10^{-7}$ 1/s (e.g., Evans & Goetze, 1979) and both $p$ and $q$ are often assumed to both have values of 1. However, as illustrated in Figure 9a, inclusion of data recorded at strain rates below $10^{-7}$ 1/s provides a constraint on these exponents. The data at the lowest strain rates are better fit with $p = 1$ for all values of $q$. Based on this result, we fixed $p = 1$ in the inversion to reduce co-variance.

LTP flow law parameters were determined using a Markov Chain Monte-Carlo fitting method. The best fit using all collected data gives a constant athermal flow stress ($\tau_0$) = 2.42 ± 0.09 GPa, an inner exponent $p = 1$ (which was imposed for the fit), an outer exponent $q = 1.18 ± 0.09$, an activation energy $\Delta F = 86.3 ± 2.9$ kJ/mol, and a pre-exponential constant $A$ of $\exp(-0.624 ± 0.236)$ 1/s. $\mu$ is assumed to be a constant (35 GPa). The noted uncertainties are two standard deviations. Flow law parameters and uncertainties are summarized in Table 2, where the values at the 2.5% and 97.5% percentiles (hdi - highest density interval) of the posterior distributions are also noted. Details of the Markov Chain Monte-Carlo fitting methods are provided in the Supporting Information S1.

4.2. Rate Limiting Deformation Mechanisms

The systematic variation of our data during individual tests and consistency with the LTP flow law suggest that the creep rate is limited by the same underlying plastic mechanism over the explored range of conditions. For layered materials like antigorite, previous work shows that deformation is accommodated by basal shear mechanisms, which can involve sliding along shear microcracks or grain boundaries (e.g., “asperity friction” Escartin et al., 1997; Hansen et al., 2020; David et al., 2020; Idrissi et al., 2020), basal and sub-basal dislocations (e.g., (001), (101), and (10$\overline{1}$) systems (Amiguet et al., 2014; Auzende et al., 2015), or ripplocations (Gruber et al., 2016). The mechanical basis for the LTP law suggests that moving defects along these crystallographic planes encounter a “barrier” which can be overcome by stress or thermal activation. For antigorite the barrier could take one of several forms.

The simplest barrier would be a ‘lattice resistance’ to dislocation glide, where the barrier is the energy required to break bonds and advance a dislocation by one unit cell dimension (Burgers vector). Antigorite has a structural corrugation in the $a$ direction that defines a large unit cell (3.5–6.0 nm Mellini et al., 1987); the volume (and thus activation area Hirth et al., 1983) is approximately an order of magnitude larger than that of forsterite, suggesting lattice resistance is plausible. The volume expansion required to advance defects across the corrugation ($a$ direction) would be large. In contrast, slip in the $b$ direction parallel to corrugation only requires breaking and re-forming four shared tetrahedral corner bonds. Proposed slip on (101) and (10$\overline{1}$) in the [010] direction requires breaking many more octahedral bonds, but could still be possible as its burgers vector is small (0.9 nm Amiguet et al., 2014). Ripplocations would require even more volume expansion (several unit cells, cf. Figure 1 of Gruber et al., 2016).

Transmission electron microscopy investigations of naturally and experimentally deformed samples highlight kink bands which have orientations consistent with slip along both $a$ and $b$ directions of intact sheets (Auzende et al., 2015, Figures 4e and 4f). However, during tensile in-situ transmission electron microscopy experiments (Idrissi et al., 2020), movement of dislocations was not observed - as it was for other materials deformed using the same technique (Idrissi et al., 2016); instead evidence for grain boundary sliding parallel to grain cleavage is observed.

The stress to overcome barriers can also be influenced by grain rotation during kinking and slip. Rotation of grains between kink apexes (e.g., center of Figure 7b) or rotation at smaller subgrain scales (Padron-Navarta et al., 2012) could reduce resolved shear stress on basal planes. As a result, defects encountering the rotated planes would experience a large reduction in driving force which could act as a barrier to propagation of shear defects.

Two related effects of temperature are illustrated by our results, and implied by the form of the LTP law: reduced stress dependence (“$n$”) with increasing temperature and more distributed deformation as a result. A decrease in lattice resistance with increasing temperature in the LTP regime provides a possible mechanism for the transition to more distributed deformation. The increasing role of thermal activation leads to a lower stress dependence of strain rate (viscosity), and thus a decrease in the rheological contrast between grains with different orientations (i.e., grains with different resolved stress on the basal plane). This effect reduces the relative resistance to basal shear across grain boundaries, resulting in more distributed deformation. These effects are also apparent within
grains; at higher temperatures, many grains exhibit distributed bending, rather than a consolidation of defects around the stress concentrations that lead to the nucleation of kinks.

4.3. Role of Shear Microcracks and Brittle Deformation

Previous experimental work demonstrated that antigorite deforms by nominally non-dilatant, semi-brittle deformation mechanisms involving shear microcracks at confining pressures above 50 MPa (David et al., 2018, 2020; Escartin et al., 1997). One of these studies also showed that the acoustic velocity of antigorite does not decrease significantly after yielding (David et al., 2018), consistent with the nominally non-dilatant nature of deformation. There are a large number of shear microcracks visible in deformed specimens. We hypothesize that these shear microcracks remain closed during deformation, and “open” during depressurization of the samples, based on the lack of AE in our experiments and previous acoustic velocity data (i.e., David et al., 2018). In contrast to some previous studies in which samples were deformed to higher strains (Chernak & Hirth, 2010; Hilairet et al., 2007; Proctor & Hirth, 2016), our microstructure is not dominated by faulting or comminution. Thus, we suggest that the strain rates that we measure are limited by plastic deformation (bending, kinking, grain boundary sliding) that involves mobility of a similar defect (e.g., dislocations and/or linear grain boundary effects).

The contacts across shear microcracks in our samples likely contribute to sample strength even if they are closed at deformation conditions. They form along cleavage/basal planes, so they are likely to have very low roughness. It is possible that, as David et al. (2020) and Hansen et al. (2020) describe, sliding along shear microcracks accommodates a significant portion of the deformation. The rate limiting mechanism of friction between two mated sheet surfaces (real fractional area of contact near 1) at 1 GPa could be similar to intrinsic lattice resistance discussed in the previous sections. For comparison, the relative enhancement of dislocation glide in antigorite at low displacement rates has also been hypothesized to lead to the transition from rate weakening to rate strengthening friction during confined rotary shear experiments on antigorite b aer surfaces and gouge at confining pressures up to 125 MPa (Reinen et al., 1994). These authors observe the transition to rate strengthening at displacement rates below 0.1 μm/s (a strain rate of 6 × 10⁻⁵ 1/s for a 1 mm wide gouge layer). Application of asperity plasticity to describe friction has successfully been used to describe olivine at high temperature (e.g., Boettinger et al., 2007; King & Marone, 2012) and could be examined in more detail for antigorite in future studies. Further exploration of the competition between grain boundary (frictional) sliding and anisotropic crystal plasticity could provide new insights into application of asperity models to explain frictional behavior at high pressures.

The lack of localization at 550°C appears to contradict previous investigations (e.g., Proctor & Hirth, 2016). However, the low strain rates we investigated promote greater activity of crystal plasticity, which leads to more distributed deformation within grains and decreases the impact of grain-to-grain intersections like that shown in Figure 7b. At higher strain rates we speculate that sheets at grain intersections could tear instead of bending (due to the large stress sensitivity), leading to comminution and formation of a jagged fault. In other studies, samples are initially deformed at strain rates of 10⁻⁵ 1/s or greater, largely due to practical limitations. The brittle processes active at high strain rates could provide connections between weak areas that arise owing to collections of grains well-oriented for slip (e.g., Figure 5a Proctor & Hirth, 2016). At lower strain rates and lower strains, we hypothesize that the relative enhancement of crystal plastic deformation leads to distribution of deformation (strain) away from these regions—and the observation of more distributed deformation. Despite the microstructural evidence of localized, brittle processes in the higher strain rate samples, we illustrate in Figure 8 that the flow law defined by our lower strain rate experiments actually provides a reasonable fit to the strength of powdered gouge samples from Proctor and Hirth (2016) (prepared from same material we used). This observation is consistent with our hypothesis that the same deformation process limits strain rate over a wide range of conditions.
4.4. Effect of Texture

Our conclusion that deformation is limited by lattice resistance of defects slipping along basal planes is also consistent with previous work on the influence of texture (crystallographic preferred orientation) on the strength of antigorite aggregates. Our nominally isotropic antigorite starting material does not have the continuous “bladed band” structure present in many other serpentinites (Escartin et al., 1997), and instead has many sets of interpenetrating antigorite grains. This interlocking microstructure is possibly the strongest texture because basal shear is regularly impeded by grains perpendicular to the slip direction. Cores with foliation defined by grains with basal planes aligned at 45° to axial stress are weaker, and as shown in Figure 8 (e.g., Shao et al., 2021) the effect of texture is more apparent at high temperature (Chernak & Hirth, 2010; Escartin et al., 1997; Hirauchi et al., 2020; Shao et al., 2021). We emphasize that even though the experiments of Shao et al. (2021) on strongly foliated antigorite samples show lower strengths than our more isotropic samples (Figure 8), they exhibit similar stress sensitivity (stress exponent $n$) and temperature dependence to the LTP creep law defined in our study.

The deformation tests conducted by Hilairet et al. (2007) in the D-DIA apparatus show strengths significantly lower than other studies shown in Figure 8. These data were obtained from one sample that was extended and compressed through 14 deformation cycles; strains in the deformation cycles ranged from 8% to 15% (most were $\leq 12\%$). Subsequent work (Amiguet et al., 2014) showed that cold pressing and deformation led to intense grain
Table 2

| Low Temperature Plasticity Creep Fit Results | Mean | Standard deviation | hdi_2.5% | hdi_97.5% |
|---------------------------------------------|------|-------------------|----------|-----------|
| ln(A) ln(1/s)                               | -0.624 | 0.118 | -0.393 | -0.859 |
| ΔF (kJ)                                     | 86.3  | 1.4    | 83.4    | 89.1     |
| r_p (GPa)                                   | 2.42  | 0.04   | 2.33    | 2.50     |
| q                                          | 1.18  | 0.05   | 1.08    | 1.27     |

5. Conclusions

In this study we redesigned a Griggs-type apparatus and assembly for constant stress creep testing of antigorite at low temperature, low strain rate, and high pressure. Antigorite was deformed at temperatures between 75°C and 550°C, by applying 8–12 stress steps per temperature. The microstructures of samples recovered after deformation have features documented in previous work (e.g., shear microcracks), and highlight the importance of basal shear and kinks to antigorite deformation. Deformation data fits well to a barrier-controlled LTP flow law, supporting the hypothesis that lattice resistance is the rate-limiting deformation mechanism. When extrapolated to subduction conditions, the data fit surprisingly well to thermal model-based requirements for coupling along the subduction interface.

4.5. Geodynamic Implications of Flow Law Parameter Results

Thermal modeling of subduction zones suggests a 100 m thick layer of weak material at the slab surface would require viscosity between 10^{19} and 10^{18} Pa s to match heat flow measurements constraining mantle decoupling depths (Wada et al., 2008). At 400°C and a shear stress of 50 MPa, our results predict a viscosity of 10^{19.5} Pa s and at 600°C we predict viscosity of 10^{18.0} Pa s (deviatoric stress/strain rate). Extrapolation after conversion of our flow law values to shear stress and viscosity is presented in Figure 10b. The difference between the flow law and heat flow constrained values is within experimental error, and could be accounted for with a slightly thicker 200–300 m weak layer.

Data Availability Statement

Data associated with this paper are available through the Brown University Digital Repository (https://doi.org/10.26300/cdn5-he41).

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