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Influence of temperature on brittle creep in sandstones

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[1] The characterization of time-dependent brittle creep, promoted by chemically active pore fluids, is fundamental to our understanding of the long-term evolution and dynamics of the Earth's crust. Here we report results from a study of the influence of temperature on both short-term strength and time-dependent brittle creep in three sandstones under triaxial stress conditions. We show that an increase in temperature from 20° to 75°C significantly enhances stress corrosion cracking in all three sandstones, leading to (1) a systematic reduction in strength during constant strain rate experiments and (2) an increase by several orders of magnitude in brittle creep strain rates during stress-stepping creep experiments. We also show that a conventional creep experiment performed at 75°C exhibits a qualitatively similar three-stage brittle creep curve as that observed at ambient temperature. Extrapolation of our results suggests that temperature is likely to be the dominant influence on the evolution of creep strain rate with depth in the shallow crust. **Citation:** Heap, M. J., P. Baud, and P. G. Meredith (2009), Influence of temperature on brittle creep in sandstones, *Geophys. Res. Lett.*, *36*, L19305, doi:10.1029/2009GL039373.

1. Introduction

[2] Saturated rock is ubiquitous in the Earth's brittle crust. The presence of a pore fluid phase within pores and cracks has been seen to exert a significant influence on rock deformation through both mechanical and chemical processes. Mechanically, pressurized pore fluids act to weaken rocks through the well-known effective stress principle [*Jaeger et al.*, 2007]. Chemically, the presence of a pore fluid phase weakens rock by: (1) the reduction of surface free energy as the result of the absorption of pore fluid onto the internal pore surfaces [*Rehbinder*, 1948], and (2) subcritical crack growth, of which stress corrosion is the most important mechanism in the shallow crust [*Atkinson*, 1984].

[3] Double-torsion fracture mechanics experiments have provided much information on the growth of single cracks by the process of stress corrosion (see *Atkinson* [1984] and *Atkinson and Meredith* [1987] for reviews). However, few studies have focused on the effect of an elevated temperature on the rate of stress corrosion cracking. *Meredith and Atkinson* [1982] studied the effect of temperature in cracking in synthetic quartz as a function of water vapor pressure, and showed that crack velocity increased by 3 orders of magnitude as temperature was raised from 20° to 100°C at a constant stress intensity factor and water vapor pressure of 300 Pa. Crack velocities in Black gabbro and Westerly granite have been observed to increase by about 5 and 7 orders of magnitude, respectively, on increasing the temperature from 20° to 300°C [*Meredith and Atkinson*, 1985]. In liquid water, an increase in crack velocity of about 1.5 orders of magnitude was observed in Whin Sill dolerite on increasing the temperature from 20° to 75°C [*Meredith and Atkinson*, 1983].

[4] *Kranz et al.* [1982] reported the results of constant differential stress (Q) experiments on samples of Westerly granite under triaxial stress conditions at 24° and 200°C. The increase in temperature produced a decrease of about 2 orders of magnitude in the time-to-failure. Such time-dependent behavior of bulk rock deforming in the brittle regime at constant Q is referred to as brittle creep ('static fatigue' in the engineering literature). Bulk rock deforming in this manner generally exhibits a trimodal curve when strain is plotted against time, classically interpreted in terms of three creep phases: (1) primary or decelerating creep, (2) secondary or steady-state creep, and (3) tertiary or accelerating creep [*Baud and Meredith*, 1997; *Heap et al.*, 2009]. Brittle creep deformation is most commonly characterized by the value of the constant strain rate during the secondary portion of the creep curve. To date, no experimental results on the influence of elevated temperature, a vital consideration in the study of crustal processes where temperature increases with depth, on creep strain rates during brittle creep in rocks have been presented. We therefore report results from an experimental study on the influence of temperature on brittle creep strain rates in three sandstones. The characterization of thermally-activated, chemically-enhanced time-dependent brittle rock deformation is fundamental to understanding the long-term mechanical behavior of the crust. Furthermore, it is considered to be responsible for the precursory cracking and accelerating seismic activity that commonly precedes earthquake rupture [*Main and Meredith*, 1991] and volcanic eruptions [*Main*, 1999].

2. Experimental Materials and Methodology

[5] The three sandstones used in this study were Darley Dale sandstone (DDS) (Derbyshire, England), Bentheim sandstone (BHS) (Bentheim, Germany) and Crab Orchard sandstone (COS) (Tennessee, USA), chosen to span a wide range of initial porosities. Their modal compositions and physical properties are summarized in Table 1.

[6] All samples were cored perpendicular to bedding to a diameter of 40 mm, cut to a length of 100 mm and ground flat and parallel to within ±0.02 mm. Samples were then vacuum-saturated in distilled water for 24 hours prior to experimentation. Experiments were performed in the

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Table 1. Physical Properties and Modal Compositions of the Experimental Materials

Rock Type	Bentheim Sandstone	Darley Dale Sandstone	Crab Orchard Sandstone
Porosity (%)	23.4 ± 1.2	13.3 ± 0.8	3.3 ± 0.17
Grain size (μm)	50–500	100–800	250
σ_p at Peff = 30 MPa (MPa)			
20°C	140 ± 6	155 ± 6	405 ± 5
75°C	132	142	395
Composition	95% quartz, 3% kaolinite, 2% feldspar	69% quartz, 26% feldspar, 3% clay, 2% mica	85% quartz, 10–12% feldspar, 5% clay, 1–2% mica
Reference	*Klein et al.* [2001]	*Heap et al.* [2009]	*Benson et al.* [2003]

large-volume servo-controlled triaxial rock deformation apparatus in the Rock & Ice Physics Laboratory (RIPL) at University College London. Three independent measures of deformation and damage were monitored continuously throughout each experiment: (1) axial strain was monitored using LVDT displacement transducers; (2) porosity change was measured by means of a servo-controlled pore fluid volumometer; and (3) output of acoustic emission (AE) energy (the area under each waveform envelope) was recorded by a Vallen AMSY-5 AE recording system using PZT-5A transducers (1 MHz longitudinal resonant frequency) mounted on steel inserts embedded within the rubber sample jacket (see *Heap et al.* [2009] for details).

[7] Elevated temperatures during experimentation were achieved using a two-zone electric heater embedded within the pressure vessel (described by *Eccles* [2005]). Temperature equilibrium in the sample was reached after approximately 75 minutes, and the thermal gradient along the sample was less than 1°C/cm. Experiments were performed at temperatures from 20° to 75°C because previous studies suggest (1) that thermal cracking in many crustal rocks commences around 100°C [*Glover et al.*, 1995], so is likely to be minimised or precluded over this range, and (2) that this range is sufficient to significantly influence the rate of stress corrosion [*Meredith and Atkinson*, 1983].

[8] A suite of conventional constant strain rate (10^{-5} s^{-1}) experiments were first performed under the conditions of an effective confining pressure (Peff) of 30 MPa (confining pressure (Pc) of 50 MPa and pore fluid pressure (Pp) of 20 MPa) at both 20° and 75°C. Such experiments were

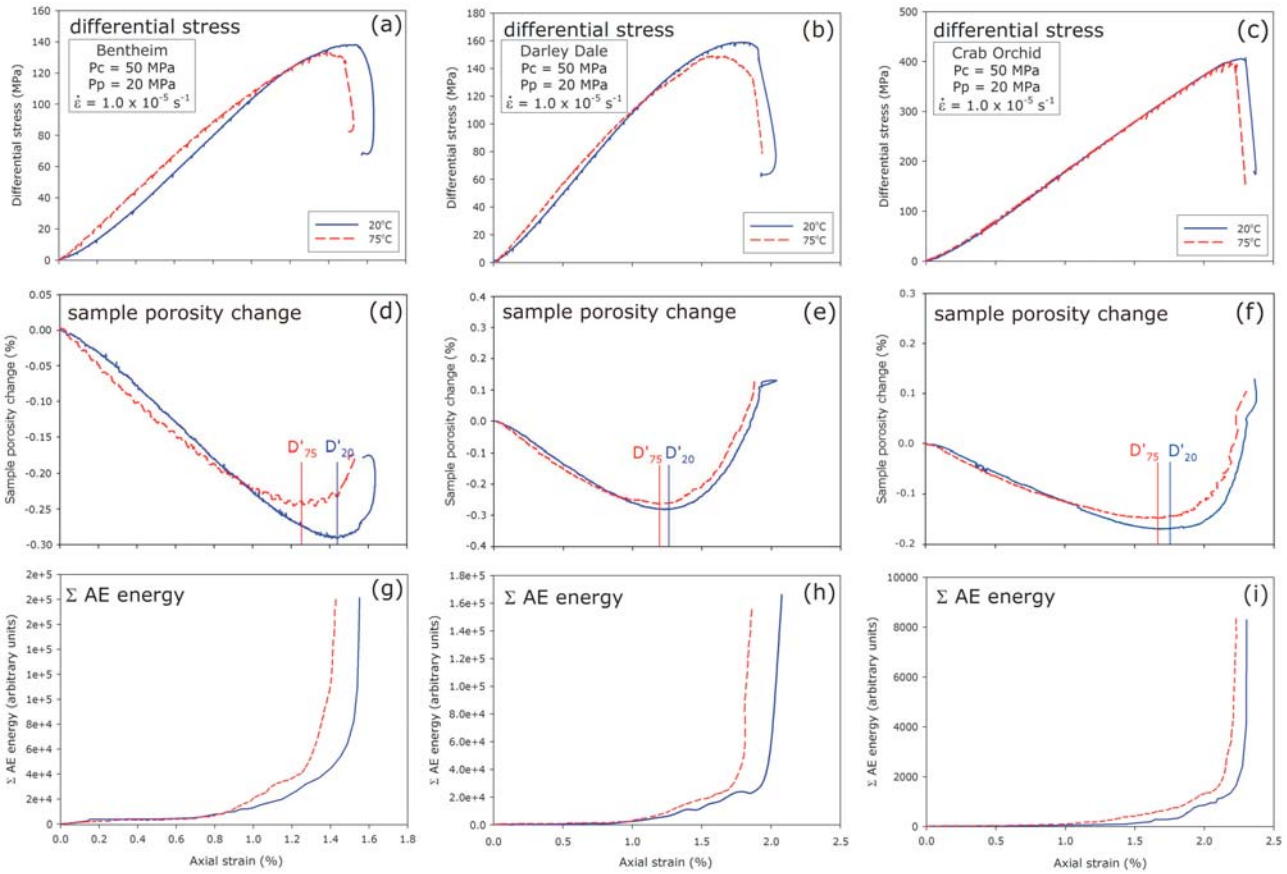

Figure 1. Constant strain rate experiments on samples of BHS, DDS, and COS at both 20° (solid blue lines) and 75°C (dashed red lines): (a–c) stress-strain curves, (d–f) porosity change curves, and (g–i) the output of cumulative AE energy for each of the sandstones.

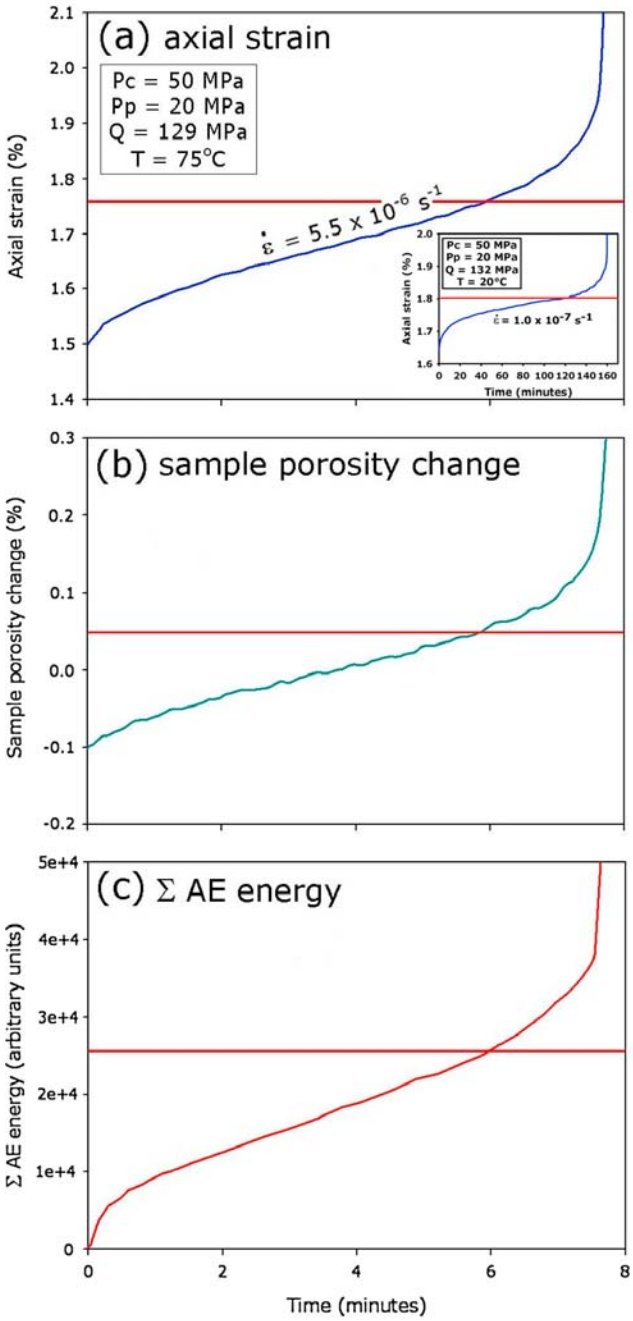

Figure 2. Conventional creep experiment on DDS showing the evolution over time of (a) axial strain, (b) porosity change, and (c) cumulative AE energy under a constant Q of 129 MPa. Red lines indicate the estimated positions at which the sample enters accelerating tertiary creep. Inset in Figure 2a shows a curve from an experiment at 20°C held under a similar constant stress [from *Heap et al.*, 2009].

necessary to ascertain the short-term peak stress (σ_p) of each rock type at each temperature (see Figure 1). Our previous work has demonstrated that stress-stepping experiments are the most efficient method to study brittle creep in rocks [*Heap et al.*, 2009]. Nevertheless, a conventional creep experiment was first performed to investigate whether the type of trimodal creep curve observed at ambient temperature is also seen at 75°C. Following this, stress-stepping creep experiments were performed on each rock type at temperatures of 20° and 75°C, under the same Peff using the methodology described by *Heap et al.* [2009]. Prior to loading, the samples were held in the pressure vessel at the desired test temperature for 120 minutes to ensure temperature equilibration. They were then loaded at a constant strain rate of 10^{-5} s^{-1} to the desired stress for the start of the constant Q creep experiment. Previous studies have demonstrated that the optimum Q for starting creep experiments is that at which the deformation becomes dilatancy-dominated [*Heap et al.*, 2009]. This corresponds to the minimum in the porosity change curve, marked as D' on the curves in Figure 1. Following the constant strain rate loading, samples were then allowed to deform under constant Q until the sample had undergone a sufficient amount of steady-state strain to allow the creep strain rate to be accurately determined. In most cases this corresponded to approximately 150 μm of axial shortening (or axial strain of 0.15%). Following this initial increment of creep, the Q was stepped up by 5 to 7 MPa and the process repeated. Stress-stepping was continued in this way until the sample eventually failed.

3. Results

3.1. Constant Strain Rate Experiments

[9] The results from our constant strain rate experiments are shown in Figure 1, and demonstrate that there was a systematic weakening caused by the elevation in temperature. The σ_p of BHS was reduced from 140 to 132 MPa (decrease of 6%), that for DDS was reduced from 155 to 142 MPa (9%), and that for COS from 405 to 395 MPa (3%) as temperature is increased from 20° to 75°C (see also Table 1). These reductions in σ_p, although modest, are greater than the typical variation we observe due to sample variability (Table 1). Furthermore, both σ_p and D' occur at a lower value of strain during deformation at 75° than at 20°C (Figure 1).

3.2. Constant Stress (Creep) Experiments

[10] A conventional creep experiment was performed on DDS in order to investigate the influence of an elevated temperature on a complete brittle creep curve (Figure 2). The experiment was performed at a constant Q of 129 MPa and yielded a steady-state (secondary) creep strain rate of 5.5×10^{-6} s^{-1}. A strain rate much quicker than that observed at approximately the same constant Q and under the same conditions at 20°C (Figure 2a). Figure 2 confirms that the elevated temperature creep curve is qualitatively similar to the trimodal creep curves observed at ambient temperature [*Heap et al.*, 2009].

[11] The relation between Q and creep strain rate at both temperatures for the three rock types was investigated via stress-stepping creep experiments. The results are plotted on semi-log axes in Figure 3 and show that the creep behaviour of the three sandstones was qualitatively similar. In all cases, the creep strain rate increased significantly and non-linearly with increasing Q.

[12] The effect of increasing the temperature from 20° to 75°C, for a given Q, was to increase all the strain rates by multiple orders of magnitude (Figure 3). For example, at a constant Q of 125 MPa, the creep strain rates in BHS and

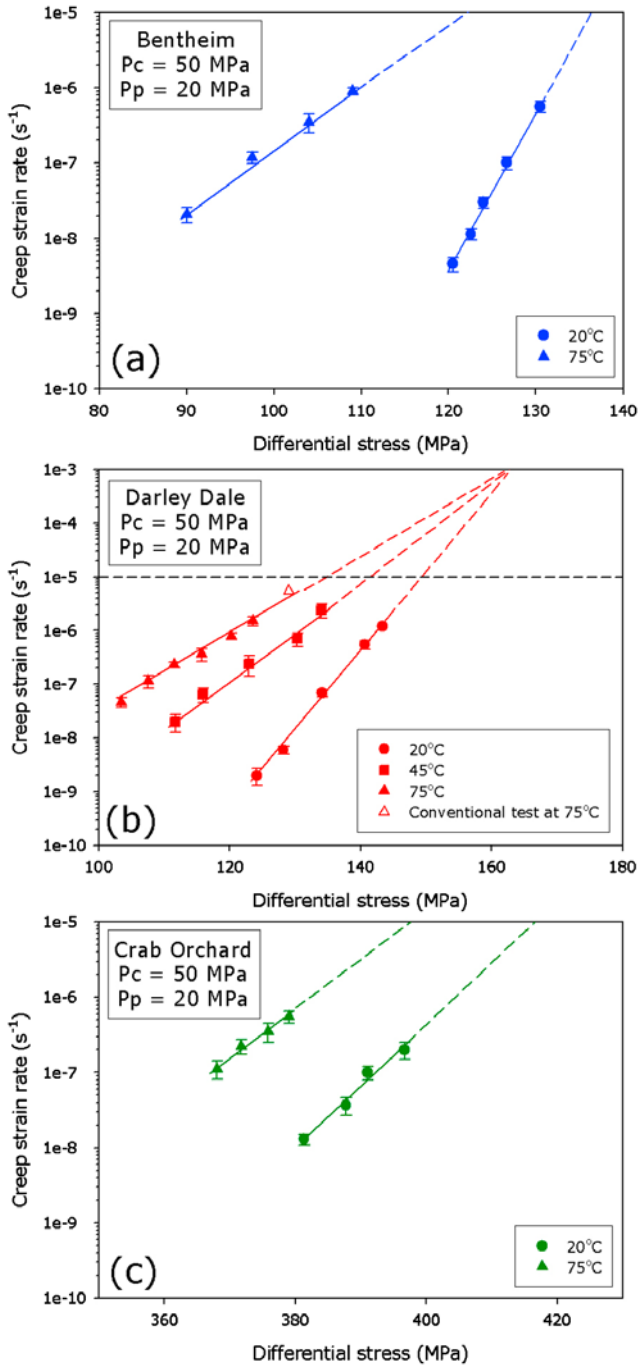

Figure 3. Creep strain rate data from stress-stepping creep experiments on samples of (a) BHS, (b) DDS, and (c) COS at both 20° (solid circles) and 75°C (solid triangles). Open triangle in Figure 3b represents the single conventional creep experiment on DDS (see Figure 2); data from an experiment on DDS at 45°C (see discussion) are also shown in Figure 3b.

DDS were increased by approximately 3 orders of magnitude (Figures 3a and 3b). For COS, the creep strain rate was increased by approximately 2 orders of magnitude over the same temperature interval at a Q of 383 MPa. Furthermore, not only did an increase in temperature shift the strain rate-Q curves to higher strain rates, but it also resulted in a decrease in the gradient of the curves. This is most pronounced in BHS and least in COS.

4. Discussion

[13] Results from our constant strain rate experiments show that the σ_p of all three sandstones is lower as temperature is increased from 20° to 75°C. The weakening is systematic and larger than any difference expected from sample variability (Table 1). Previous studies, reviewed by *Paterson and Wong* [2005], have also consistently demonstrated systematic decreases in σ_p with increasing temperature. The weakening observed in our experiments could be due either to a simple mechanical effect or to a thermally-enhanced chemo-mechanical mechanism such as stress corrosion. The most likely mechanical effect would be a thermally-induced change to the microstructure. However, we took care to run our experiments at a maximum temperature of 75°C, a temperature unlikely to induce any significant thermal cracking in these materials. We therefore suggest that the weakening is due to an enhanced rate of stress corrosion cracking at the higher temperature. We also note that our suggestion of the change in strain rate required to achieve the observed strength reduction is consistent with the observation of *Paterson and Wong* [2005], who noted that a 10^3-fold change in strain rate was required to induce an approximately 10% change in strength for a wide variety of rocks undergoing triaxial deformation.

[14] As reported earlier, we ran a conventional creep experiment on DDS at 75°C and a constant Q of 129 MPa to confirm that it displays all three phases of creep (Figure 2). In fact, axial strain, porosity change and AE energy all display trimodal curves. The trend in the AE energy output (crack damage accumulation) provides direct evidence for stress corrosion cracking. Other mechanisms of subcritical crack growth will not produce accelerating AE in response to a constant Q or show the extreme temperature dependence at such moderate temperatures as seen in this study [see *Atkinson*, 1984].

[15] The numerical value of each measure of damage at the onset of tertiary creep in our experiment at 75°C is essentially the same as those previously reported from conventional creep experiments on DDS performed at room temperature under the same Peff and Q [*Baud and Meredith*, 1997; *Heap et al.*, 2009]. This provides further support to the suggestion of *Baud and Meredith* [1997] that a critical level of damage is required to trigger the onset of accelerating tertiary creep.

[16] The creep strain rate during our conventional experiment at 75°C (Figure 2a) was 5.5×10^{-6} s^{-1}, and this is plotted as an open triangle on Figure 3b. The data from this test are completely consistent with those from the stress-stepping experiments at the same temperature, and provides further confirmation of the veracity of the latter methodology.

[17] The results from our stress-stepping creep experiments, illustrated in Figure 3, show that the creep strain rate response to an increase in Q for the three sandstones is qualitatively similar. Under all conditions, small increases in Q result in large increases in creep strain rate; with a 10% increase in Q resulting in increases in strain rate ranging from a factor of about 10 for BHS and DDS at 20°C to a

factor of about 300 for COS and BHS at 75°C. Again, for all three rocks, even a modest increase in temperature from 20° to 75°C results in an increase in creep strain rate of several orders of magnitude for the same Q. These increases in strain rate are at least partially expected, since we know from our constant strain rate experiments at 10^{-5} s^{-1} that σ_p decreases by 8, 13 and 10 MPa for BHS, DDS and COS respectively, over the same temperature interval. However, these decreases alone are not sufficient to explain the magnitudes of the changes seen in the data of Figure 3, where the differences in Q for the two test temperatures at a strain rate of 10^{-5} s^{-1} are 15, 18 and 17 MPa for BHS, DDS and COS respectively (as measured from the extrapolated dashed lines in Figure 3). We therefore suggest that the larger changes result from the samples being held at a continuously high level of Q throughout the creep experiments (thus enhancing stress-dependent stress corrosion), whereas this is not the case during the constant strain rate experiments.

[18] We also note in the data of Figure 3 that increasing the temperature from 20° to 75°C results in decreases in the gradients of the strain rate-Q curves for all three rocks. The severity of the decrease in gradient appears to be correlated with sample porosity; with the largest decrease seen for the highest porosity rock (BHS) and the smallest decrease seen for the lowest porosity rock (COS). At first sight this may appear counter-intuitive, since we would expect stress corrosion to be enhanced at higher temperature. This was investigated further by performing an additional set of stress-stepping creep experiments on DDS at an intermediate temperature of 45°C. The full data set is presented in Figure 3b, which shows that not only do the creep strain rates from the 45°C experiment plot between those for 20° and 75°C, but that the gradient of the strain rate-Q curve is also intermediate between the slopes for 20° and 75°C. Overall, these results suggest that the influence of Q is greatest at the lower temperature where the deformation rate is also lower.

[19] The observation that the strain rate-Q curves have different gradients at different temperatures suggests a different dependence of stress corrosion driven deformation on Q at different temperatures. We have therefore extrapolated the three curves of Figure 3b to the point where they all meet; a Q of 162 MPa and a strain rate of 1×10^{-3} s^{-1}. We tentatively suggest that this may correspond to the point where the deformation is so rapid that time-dependent processes such as stress corrosion cease to have adequate time to exert any significant influence on deformation rate. Similar observations have previously been reported for stress corrosion driven propagation of single cracks in double-torsion experiments [*Atkinson and Meredith*, 1987; *Meredith and Atkinson*, 1982].

[20] Here, we have demonstrated how creep deformation in three sandstones is influenced by increasing temperature and Q. Previously, *Heap et al.* [2009] showed how creep deformation in DDS was influenced by increasing Peff. We are therefore now in a position to estimate how the rate of deformation due to brittle creep may vary with depth in the Earth, based on our data for DDS and assuming a simple, isotropic Uniaxial Strain Model, appropriate for brittle deformation in the shallow crust [*Jaeger et al.*, 2007]. We assume an average geothermal gradient of 30°C/km, an average vertical overburden stress gradient of 25 MPa/km, a hydrostatic pore pressure gradient of 10 MPa/km, and a Poisson's ratio of 0.25. We then examine the expected changes in creep strain rate over a depth interval of 2 km. The corresponding increase in effective vertical stress is 30 MPa, and in both effective horizontal stresses is 10 MPa. Therefore the increase in effective mean stress is 16.7 MPa, and in Q is 20 MPa. Using these figures together with the experimental data for DDS from Figure 3b (this study) and those of the influence of Peff [*Heap et al.*, 2009, Figure 14], we estimate that the creep strain rate will (1) increase by about 2×10^3 due to the increase in temperature of 60°C, (2) increase by about 10^3 due to the increase in Q, and (3) decrease by about 3×10^3 due to the increase in effective mean stress. The net result is an increase in creep strain rate of the order of 7×10^2. Even though this estimate is based on a number of gross approximations, it does suggest that there is an approximate balance between the increase in creep strain rate with depth due to the increasing Q and the decrease due to the increasing effective mean stress. Overall, this then suggests that it will be the increase in temperature with depth that dominates the rate of creep deformation in the shallow crust.

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