

Hydrothermal healing and constitutive behavior of fault gouge at hydrothermal conditions.

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Investigation Undertaken

In our previous project (Compaction, shear, and sealing of fault gouge under hydrothermal conditions, 99HQGR0046), we found a new type of fault healing mechanism (referred to as "hydrothermal healing" here) that operates under the realistic hypocentral conditions. This year, we conducted tests with hot steam, instead of hot water, as pore fluid, to see if this type of healing still occurs. This was to distinguish between two possible candidates, namely, solution-transfer and stress corrosion, of the mechanism underlying the hydrothermal healing. The results have demonstrated unambiguously that the hydrothermal healing is from solution-transfer mechanism. In addition, by monitoring the silica concentration in pore fluid, we could confirm that the presently observed hydrothermal healing can proceed in saturated pore fluid. So, it has been demonstrated that local mass redistribution, not requiring net dissolution, is enough for this healing mechanism. Except when noted otherwise, experimental conditions are the same as those reported in [99HQGR0046], which we refer to as "our standard experiments."

Results

Steam vs. Water.

In our previous project [99HQGR0046], we have made the case that hydrothermal conditions activate a logarithmically time-dependent healing, which we claim is not Dieterich-type healing, which dominates in room temperature experiments [e.g., Dieterich, 1972]. Here, we show further experimental results to constrain the mechanism of this hydrothermal healing.

Though it is true that Dieterich-type healing is not affected drastically by moderate hydrothermal conditions as employed in the present study, it is also true that H₂O plays a critical role for Dieterich-type healing. As demonstrated by experiments under controlled

humidity, the underlying mechanism of Dieterich-type healing is thought to be stress corrosion cracking, whose rate is governed by the chemical activity of H_2O . In our experiments at 200°C dry [99HQGR0046] the sample pore space was open to the laboratory atmosphere through a long and narrow conduit. Hence, the mol fraction of H_2O (~ chemical activity) in the heated sample pore space could be very low. So it is possible to argue that the lack of healing in the 200°C dry experiment is due to the low activity of H_2O and further argue that the observed hydrothermal healing could actually be Dieterich-type healing. To check this possibility, we carried out an experiment employing hot steam instead of hot water as pore fluid.

Fig. 1a shows that experiment. Following the cycling during hold #0, the pore water was turned into steam by lowering pore pressure to 0.7 MPa (the water-phase boundary is 1.55 MPa at 200°C). A slightly lower confining pressure (55 MPa) was used for this experiment to have the effective normal stress level similar to standard experiments. From the change of the total volume of pore fluid, we could confirm about 1.5 ml of steam was generated, which is greater than the initial pore volume (1.2 ml) of the sample. In this experiment, we applied a coil heater directly above the sample area to assure that the sample is the hottest part of the system. Hence, it is expected that the sample pore space was filled with steam.

The healing in this hot steam experiment was minimal (Fig. 1a), showing that liquid water is essential for hydrothermal healing. Though some minor strengthening was observed in the first 21 hours hold (#1), some liquid phase H_2O may have remained in this hold period, judging from similar hold time later in the experiment (#5) yielded almost no healing. The longest hold (#3) also showed small but noticeable healing. This could be because some liquid phase H_2O still remained then, or because another but much slower healing mechanism that does not require the existence of liquid pore water was operating. In any case, the sharp contrast between the hot steam experiment and the hot water experiment clearly proves that the presently observed hydrothermal healing was mostly achieved through the aid of liquid water, strongly suggesting the involvement of some solution-transfer mechanism. Since the pore gas in the hot steam experiment is 100% H_2O , the chemical activity controlling the stress corrosion cracking should have been the same as in the hot water experiments. Therefore, stress corrosion cracking, the underlying mechanism of Dieterich-type healing, is ruled out as the candidate of the underlying mechanism of the presently observed hydrothermal healing.

Figure 1b shows the result of a control experiment for the hot steam experiment. In this experiment, P_p of 2.5 MPa was maintained throughout the experiment. The same heater configuration as in the hot steam experiment was employed. This experiment showed the same extent of healing as in our standard experiments [99HQGR0046] with $P_p = 10$ MPa, proving that neither the difference of pore pressure itself nor the different heater configuration are responsible for the disappearance of hydrothermal healing in the hot steam experiment.

The experiment with $P_p = 2.5$ MPa (Fig. 1b) provides another important constraint on the mechanism of the observed healing. Though we could not measure the sample permeability reliably, it could be sometimes pretty low. Though we maintained a constant fluid pressure at the both sides of the sliding surface (Fig. 1), it is not impossible that the pore pressure inside the sample was reduced significantly by dilation during reloading, resulting in strengthening. However, the maximum possible magnitude of such effect is limited by the P_p . In the experiment shown in Fig. 7b, P_p was only 2.5% of the effective normal stress and dilatancy hardening could not cause more than 2.5% increase in shear strength, whereas up to 10% strengthening occurred

in this experiment. In addition, the magnitude of healing for various hold times agrees well between the experiments with $P_p = 10$ MPa and 2.5 MPa (squares in Fig. 3). Hence we conclude that the presently observed strengthening primarily reflects a real increase of frictional strength of the gouge.

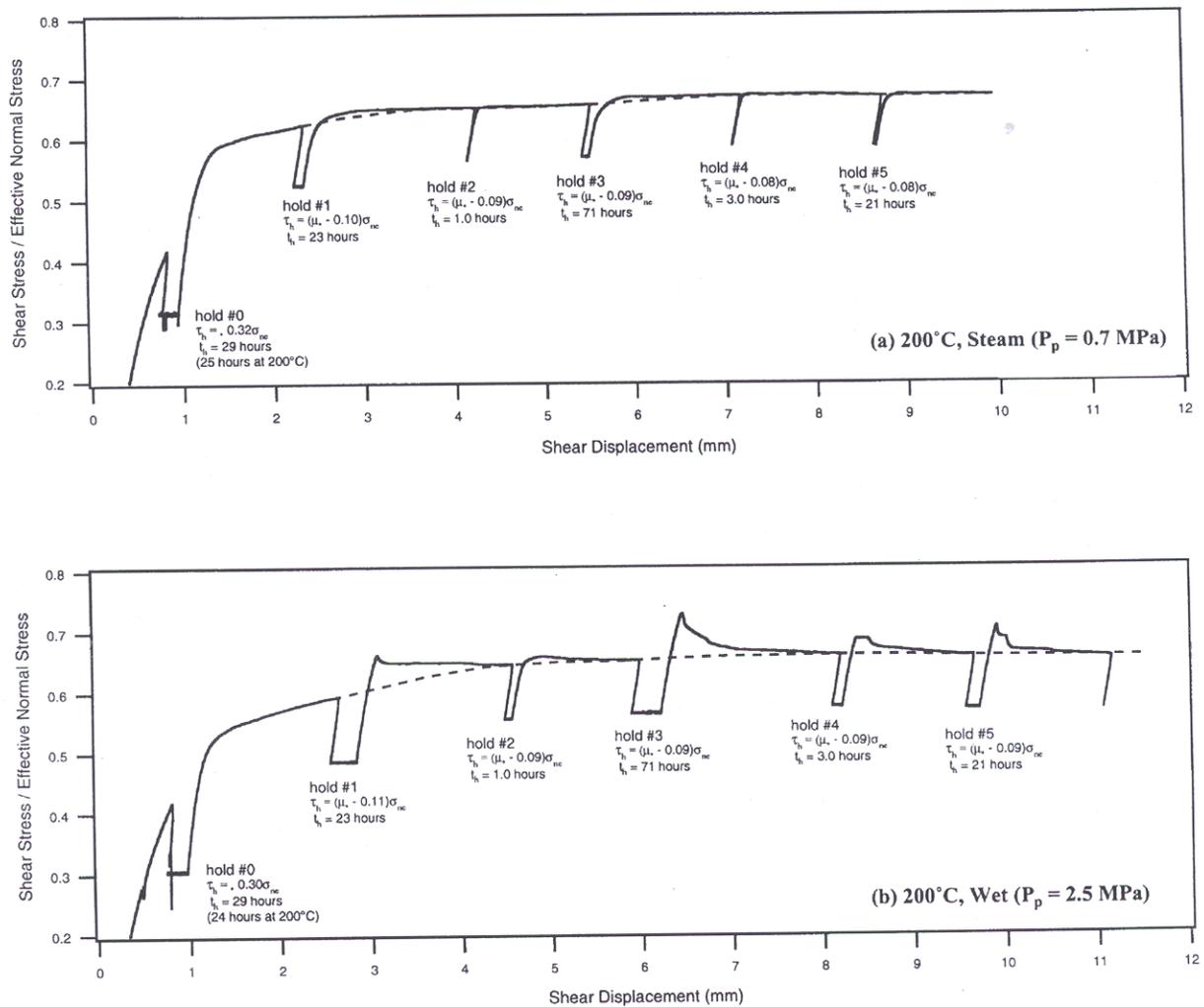


Figure 1. A diagnostic experiment where hot steam was used as pore fluid (a) and its control experiment (b). Confining pressure was 55 MPa in these experiments to adjust for the lower pore pressure. The broken line indicates the inferred base level friction that changed with cumulative displacement.

Fluid Chemistry.

As shown above, it is clear that the existence of liquid pore water is essential for the presently observed healing to occur. This makes the dissolution and precipitation of quartz a top suspect for the underlying mechanism. In this section, we report the silica concentration of the pore fluid that can affect dissolution/precipitation kinetics.

If the pore water is saturated, a net mass transfer between the grain system and pore water does not occur. Considering the fast dissolution kinetics in quartz, this may be a condition prevailing at seismogenic depths, where the temperature and the surface area is high. However, even with the saturated fluid, redistribution of solid mass within the grain aggregate can proceed through a local solubility gradient. Hence, we wanted to do our healing tests with saturated pore fluid to look for a "robust" healing mechanism, unaffected by the flow rate and silica concentration.

Figure 2 shows silica concentration in the fluid samples taken from the bottom pore pressure intensifier and measured with a DCP. The overall error of the chemical analysis is less than 10%. Since our intention was to prove that the sample was supplied with already saturated fluid that does not allow net dissolution, we sampled the fluid in the intensifier rather than the fluid that has just come out of the sample. In each sampling, the first 1.2 ml was discarded to flush the sampling valve, and the next 1.2 ml was collected, except that the last data points in Fig. 2 are from the whole volume of the fluid remaining in the intensifiers.

Fluid was kept cycling throughout these experiments. For technical reasons, we cycled a part (5.1 ml for the experiment shown in Fig. 2a, 15-26 ml for the experiment shown in Fig. 2b) of the fluid in the system rather than the entire volume. This cycled volume was greater than the sum of the initial pore volume (1.2 cc) and the volume (2 ml) of the line connecting the sample and the intensifiers but was much smaller than the volume of water in the pore fluid system. The total water volume, for example for the experiment shown in Fig. 2a, was 66 ml at the start of the experiment and by the end of hold #5 reduced to 41 ml because of sampling. All the experiments employed similar volumes of water.

Figure 2a shows the result from an experiment at 200°C. By the end of hold #0 (24 hours), Si concentration has reached 125 ppm, about the saturation level of non-stressed quartz at this temperature. Though there is some scatter, the silica concentration stayed around this level throughout the rest of the week duration of the experiment, showing that the main part (from hold #1) of the 200°C experiment was done with saturated fluid. Since the saturation seems to have completed within the first 24 hours (hold #0), we expect that the saturation was accomplished also in our standard experiments at 200°C where cycling was maintained only for the first 24 hours. Therefore, the hydrothermal healing, at least those observed at 200°C, occurred thorough local redistribution of mass by some solution-transfer mechanism that can proceed even in saturated fluid.

On the other hand, the silica concentration at 100°C (Fig. 2b) continued to increase at least for three days beyond the 24 hours of preparation phase (hold #0), showing that our preparatory phase for 24 hours (hold #0) is not long enough at this temperature.

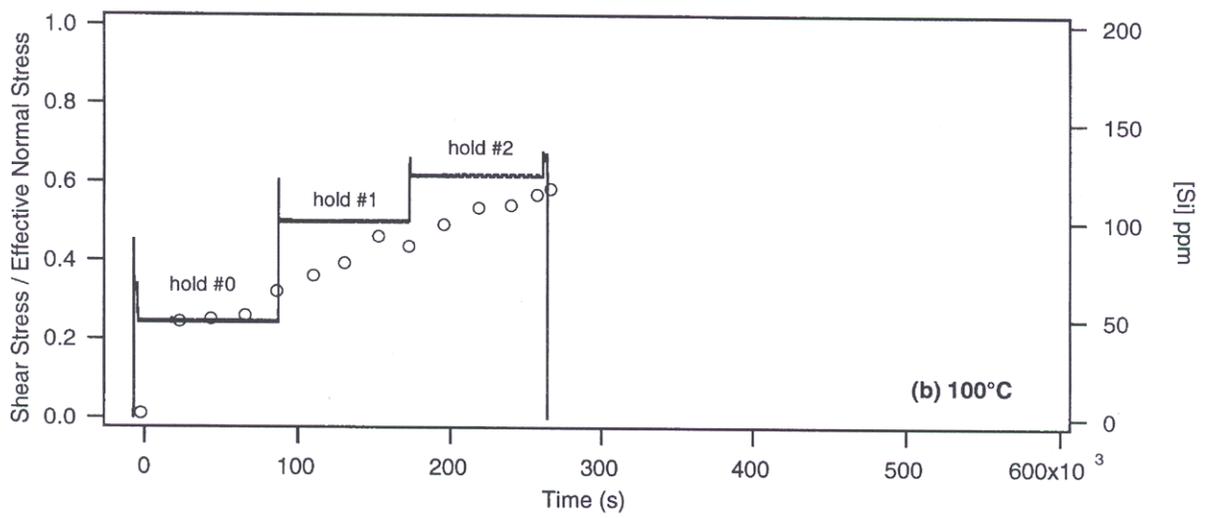
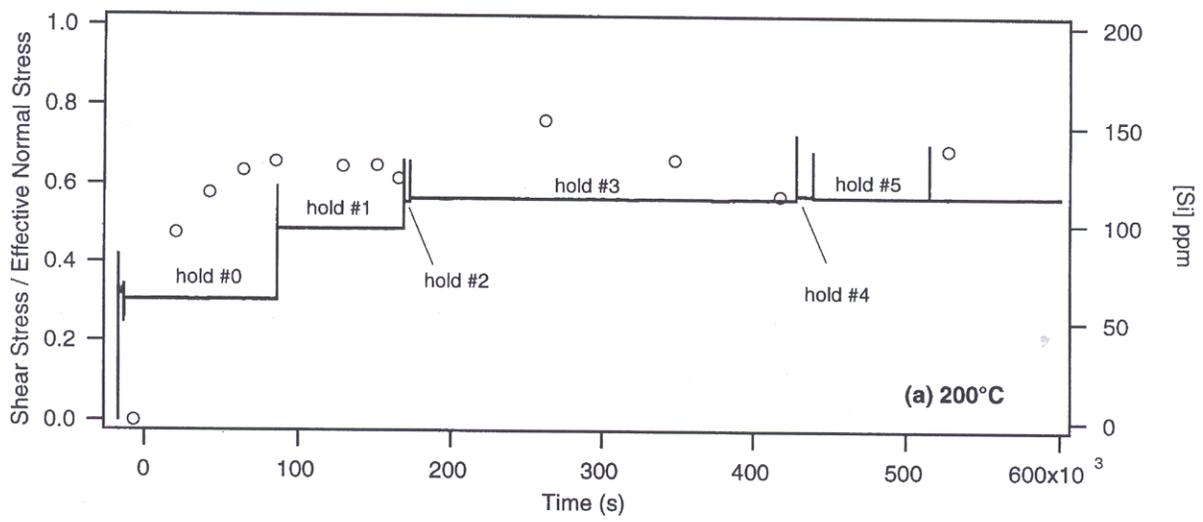


Figure 2. Silica concentration vs. time. Fluid cycling was on throughout these experiments. The time when the experimental temperature was reached is taken as zero.

Non-technical summary

We have shown two important characteristics of the water-assisted frictional healing of quartz gouge that occurs at realistic conditions (200°C) at seismogenic depths. 1) It requires the presence of liquid water. Hot steam does not cause healing. This demonstrates clearly that solution-transfer is the presently observed healing. 2) The healing proceeds in even saturated fluid, not requiring net dissolution. So this mechanism is thought to be active in natural faults.

Reports Published

Nakatani, M., Conceptual and physical clarification of rate- and state-dependent friction law: Frictional sliding as thermally activated rheology., *J. Geophys. Res.*, 106, 13,347-380, 2001.

Data Available

None.