ACID SOLUBILITY TESTING OF GREYWACKE CORE AND IMPLICATIONS FOR WELL PERMEABILITY ENHANCEMENT

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ABSTRACT

Acidizing of geothermal wells can be a cost-effective and attractive option to recover well permeability and productivity compared to drilling new wells. Understanding how the reservoir rock may react to acid injection is important to ensure that damage to the reservoir formation does not occur and also to help understand if permeability can be improved. In an effort to investigate the effect of acid stimulation on Greywacke core, a series of core plugs were extracted from core taken from an injection well hosted in Greywacke. These plugs were measured for porosity, density, seismic wave velocity, and permeability. The samples were then selected to have a first suite exposed to HCl acid, a second to both an initial HCl treatment followed by HCl/HF treatment and a third untreated to act as control. The samples were re-measured for changes in their physical properties following acid exposure. The initial HCl testing results show changes in physical properties across the samples. The HCl/HF testing also resulted in changes to physical properties. Permeability increased in all samples exposed to acid treatment. Further, after physical characterization, the samples were mechanically tested to determine Uniaxial Compressive Strength (UCS). Strength decreased in all samples treated with acid. The results of the testing are discussed here and the implications for changes to reservoir permeability and strength are explored with respect to acid treatments on both injection and production wells hosted in Greywacke.

1. INTRODUCTION

1.1 Acid Stimulation as a Permeability Recovery Technique

Matrix acidizing of hydrocarbon and geothermal wells is a long established method to recover permeability lost through both production and injection of reservoir fluids. The formation of near well damage (skin) results in a net increase of pressure at the well/reservoir interface which results in lost productivity or injectivity. The damage can be addressed through the application of a specialized chemical blend to dissolve material deposited at the well face that depends on the nature of material deposited. In geothermal wells, calcite and silica scaling are the two most commonly observed precipitates that decrease well deliverability, with calcite mainly affecting production wells and silica mainly affecting injection wells (Flores-Armenta, 2010; Malate et al, 1998).

Hydrochloric acid is generally chosen to address calcite scaling (although formic and nitric acids have also seen some success) and a blend of hydrochloric and hydrofluoric acid is generally preferred to treat silica scaling (Flores-Aremnta, 2010).

2. MATERIALS AND METHODS

To provide indications of the effects of down-hole acidizing, core from an active injection well (KA-50) was selected for this study representative of the Greywacke reservoir at Kawerau. The laboratory testing component of this study was carried out at the University of Canterbrury Department of Geological Sciences.

2.1 Sample Material Description

The core material is sourced from well KA-50 taken from approximately 2740m at Kawerau. The original core was 100 mm in diameter with 4.2 m recovered on the original core run (Rae et al, 2010). The core is composed of Torlesse Greywacke, which comprises foliated dark grey argillite, and quartzo-feldspathic meta-sandstone, and is intensely veined with calcite and quartz infilled fractures. Veining is most intense in the meta-sandstone facies of the Greywacke. For this study, we focused on the meta-sandstone facies as this was is most competent section of the core.

2.2 Sample Preparation

Cylindrical cores were taken from a 500 mm long section of 100 mm diameter core; 20 mm core plugs were drilled from the larger core and cut and ground to 40 mm in length according to ISRM Standards (Ulusay and Hudson, 2007a). The fractured nature of the core proved to be somewhat difficult for preparing cylinders of the required specifications but 12 samples were machined adequately for characterization and testing.

2.3 Characterization of sample properties

Prior to acid treatment, physical characterization was carried out that comprised of measuring mass, density, porosity (Ulusay and Hudson, 2007b), and dry and saturated ultrasonic velocity profiling to determine baseline material properties of the samples (for further detail on the methods used see Siratovich et al, 2015).

2.4 Acid treatment of samples

After the baseline was established, three separate sets of samples were established: the control group which would see no acid treatment (referred to as “as cut”), the HCl group which would only see HCl treatment, and the HF group which would undergo HCl treatment followed by HCl/HF treatment.

The HCl and HCl/HF groups were then acidized in 10% HCl for 65 minutes. We then repeated the physical characterization for all samples in these two groups. The HCl+HF group was then acidized in 10% HCl + 5% HF for 98 minutes. We then repeated the physical characterization for all samples in this group. Between acid treatments the cores were flushed with fresh water until the pH of the effluent water was neutral (pH 6.5-7) and then flushed for another 5 minutes.

Some samples showed macroscopic failure following treatment and were either discarded from the study or cut to square to allow further characterization, this was done as the core material is difficult and expensive to obtain and valuable for use in other research areas.

2.5 Further Characterization

In addition to the physical measurements described above, permeability measurements were made on select samples to explore the impact of acid treatments on permeability. Finally, a series of samples were strength tested in axial compression at a strain rate of 1x10-5 s^{-1} to determine the unconfined compressive strength (UCS) and the elastic modulus (Young's Modulus).

3. RESULTS

3.1 Visual and Textural Observations

The images in Figure 1 show the physical and color changes undergone by representative sample 7 during the stages of acid treatment. Figure 1a shows the grey meta-sandstone texture crosscut by both silica and calcite filled fractures. Following the first acid treatment with HCl, the overall color of the samples remained the same; however fractures previously filled with calcite were clearly etched and opened (Figure 1b). The removal of calcite also led to the failure of part of the sample (arrow figure 1b). After HCl/HF treatment, the sample showed further etching of the surface and a distinct color shift from grey to pale greenish-grey (figure 1c) The fractures, however, do not appear to display a clear macroscopic change after the HF treatment (figures 1c and 1d). The samples also appeared to be more friable and fragile following HCl+HF treatment.

3.2 Physical Property Changes- First HCl Treatment

After acidizing with 10% HCl, 8 samples were re-analyzed for changes in mass, density and porosity. Mass loss ranged from -0.43 to -1.5%. Density decreased in all samples ranging from -0.62 to -28.35 kg/m^3. Porosity increased in all samples showing a range of 0.1-0.9% increase in connected porosity (connected porosity increased from an average of 2.5% to 2.9%).

Further, we characterized the change in ultrasonic wave propagation and dynamic moduli. As Kawerau is a liquid dominated system, we preferred the saturated modulii to give an indication of changes to the bulk rock characteristics. Saturated P-wave (Vp) velocity showed changes ranging from -348 to +19 m/s. Saturated shear wave velocity (Vs) showed both attenuation and amplification with changes ranging from -721 to +729 m/s change with an average decrease of -116 m/s in wave propagation speed for all acidized samples.

3.3 Physical Property Changes- After HCl and HCl+HF Treatment

As previously discussed, a further set of samples were acidized with an HCl/HF mixture following the initial HCl treatment. Four samples were examined in this portion of testing and we found that mass loss ranged from -3.3 to -4.3%. Density also showed a decrease from -48 to -101 kg/m^3 dry mass density change. Porosity has also increased significantly with all four samples showing porosity ranging from 5.1-5.7% connected porosity (an average net change of 2.8% increase in connected porosity).

The ultrasonic velocities were also dramatically changed by the application of HF acid. Vp was attenuated from -99 to -1059 m/s. Vs also showed a change in all samples with a range of change from -94 to +360 m/s in wave speeds.

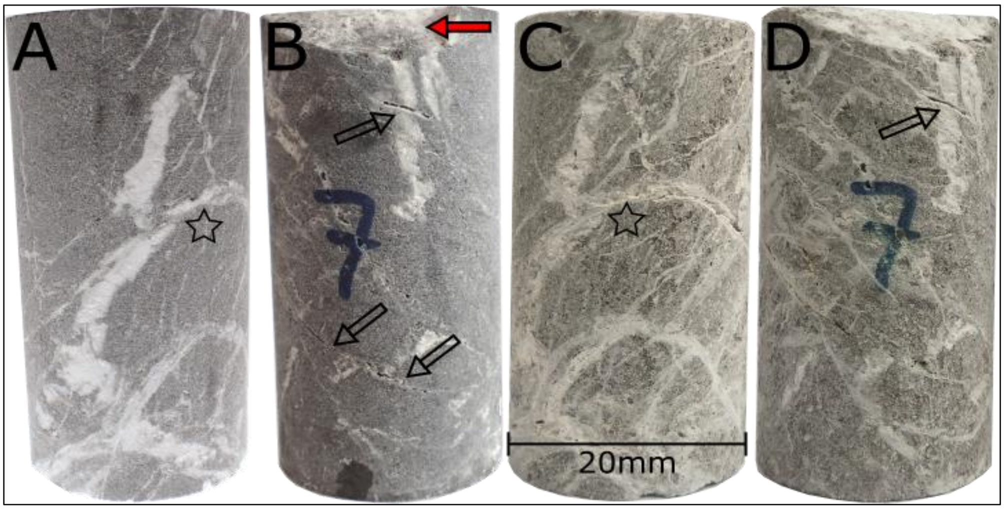

Figure 1: Photos of sample #7: a) as cut with no acid treatment; b) following HCl treatment with etched calcite fractures (open arrows) and failed top edge (red arrow); c) following HCl+HF treatment (with open star to orient sample as same view seen in (a); d) same view as (b) following HCl+HF treatment with open arrow showing etched fracture.

3.4 Permeability

Permeability was tested on four of the twelve original samples both before and after acidizing treatments (samples 1, 7(a), 8 and 11). Initial permeability at 3 MPa confinement averaged 2.0 $x10^{-17}$ m^2 with a range from 3.0 $x10^{-18}$ m^2 to 5.2 $x10^{-17}$ m^2. The change in the four samples following the initial HCl acidizing was significant with a change in permeability ranging from one to three orders of magnitude increase in flow potential (Table 1). Further, the permeability was markedly increased in the samples that underwent HF treatment (Table 1).

The permeability increases with minor corresponding increase in porosity after the HCl treatment, and with larger increase in porosity after the HCl/HF treatment (Figure 2).

Table 1: Permeability results for 4 samples following acid treatments.

Permeability to Nitrogen at 3MPa confining pressure (m^2)			
Sample #	**As cut**	**After 10% HCl**	**After 10% HCl and 10%HCl + 5% HF**
1	3.5 E-17	1.4 E-16	1.3 E-15
7a	3.0 E-18	2.4 E-17	-
8	3.1 E-18	1.8 E-15	-
11	6.9 E-18	1.9 E-15	4.4 E-15

3.5 Strength and P-wave velocity

A general trend of decreasing strength with increasing porosity is shown in Figure 3, as observed elsewhere (eg. Siratovich et al., 2014; Wyering et al., 2014). The acid treatment increases porosity, which decreases strength. The porosity increase after the HCl/HF treatment does not decrease the strength as significantly as the HCl treatment.

The saturated P-wave velocity in general similarly decreases with increased porosity (Figure 4) as observed elsewhere (eg. Siratovich et al., 2014; Wyering et al., 2014). The porosity increase resulting from the acid treatment also decreases saturated P-wave velocity.

4. DISCUSSION

Application of HCl and HF acids clearly changes the physical properties of the Greywacke core plugs that we have tested in this study. In order to make sense of the data, we have summarized our interpretation of the results in the following sections.

4.1 Effects of Acidizing with Hydrochloric Acid

After treatment with HCl, all samples show an increase in porosity that is likely the result of dissolution of calcite infilling fractures. This is apparent in Figure 1 where pore space has clearly been etched in the veins. Further, the reaction with HCl was quite vigorous indicating the dissolution of calcite.

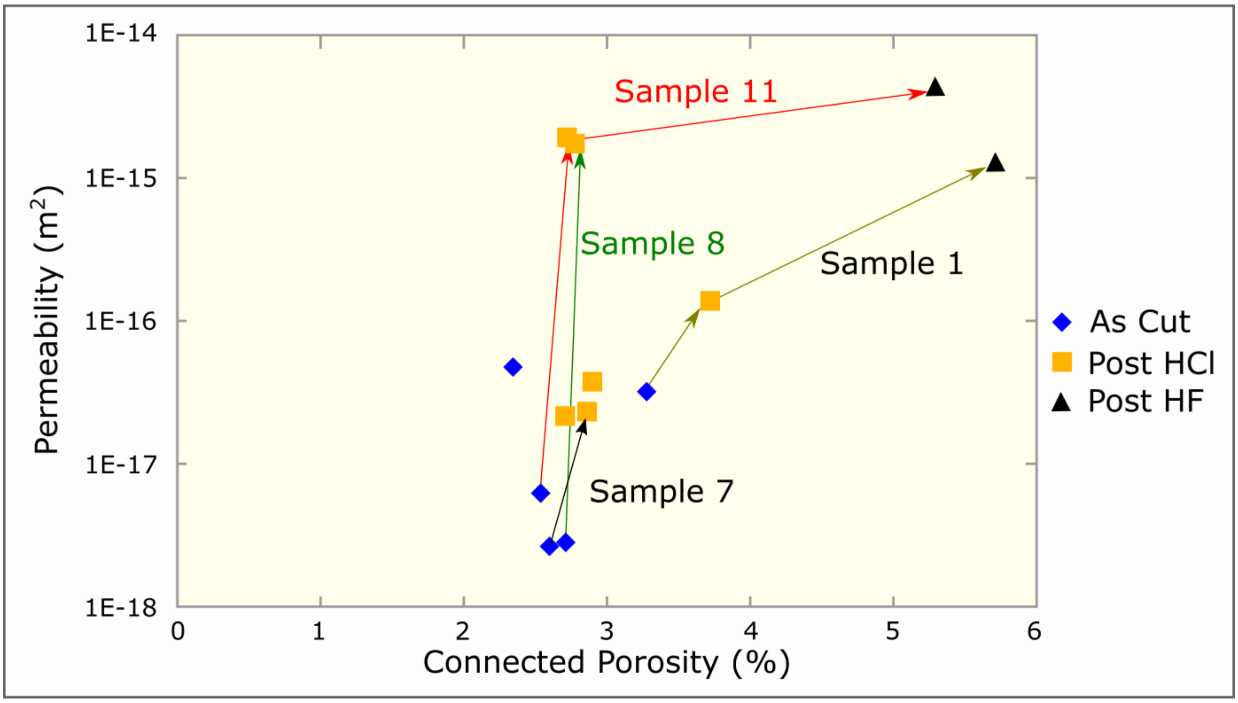

Figure 2: Permeability-porosity plot for all tested samples at 3 MPa confinement, presented according to treatment. Only four samples were measured in this way, corresponding to the four arrows. The other points represent single measurements. Arrows show progressive increases in porosity and permeability with treatment stages.

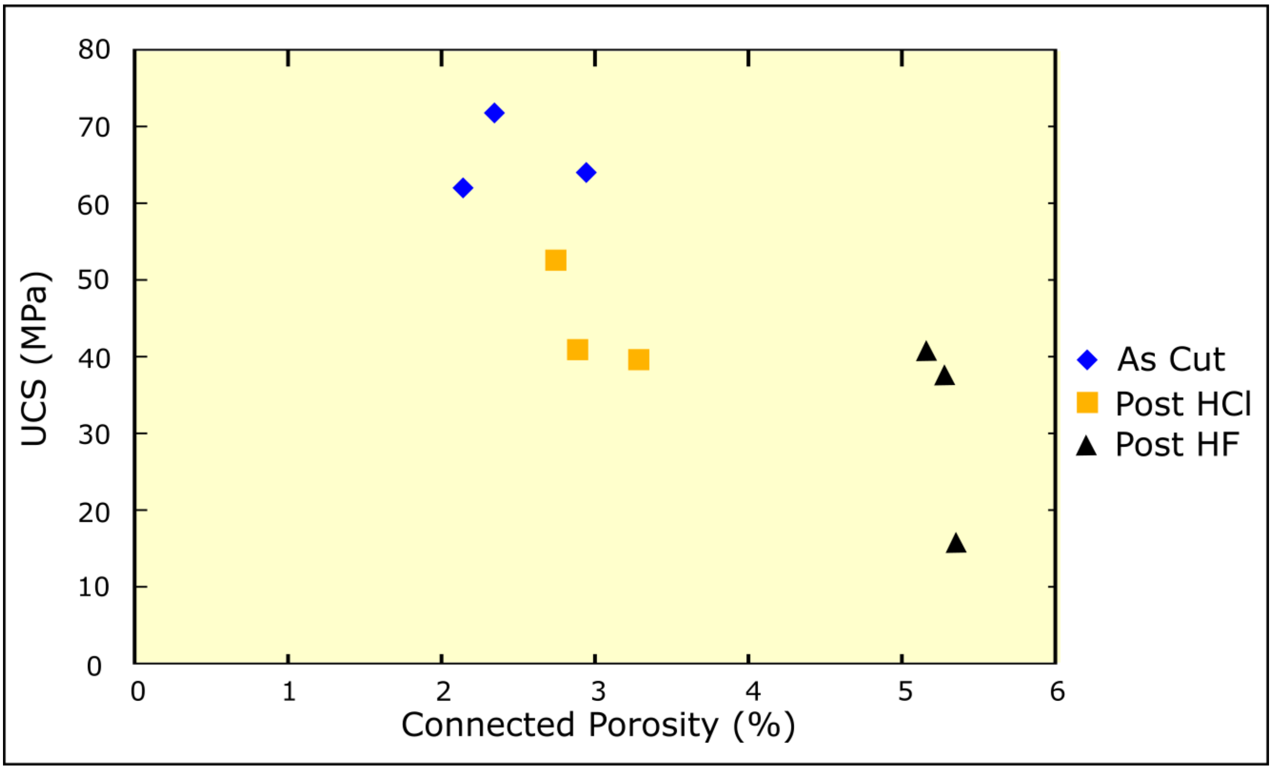

Figure 3: Strength-porosity plot for all tested samples, presented according to treatment.

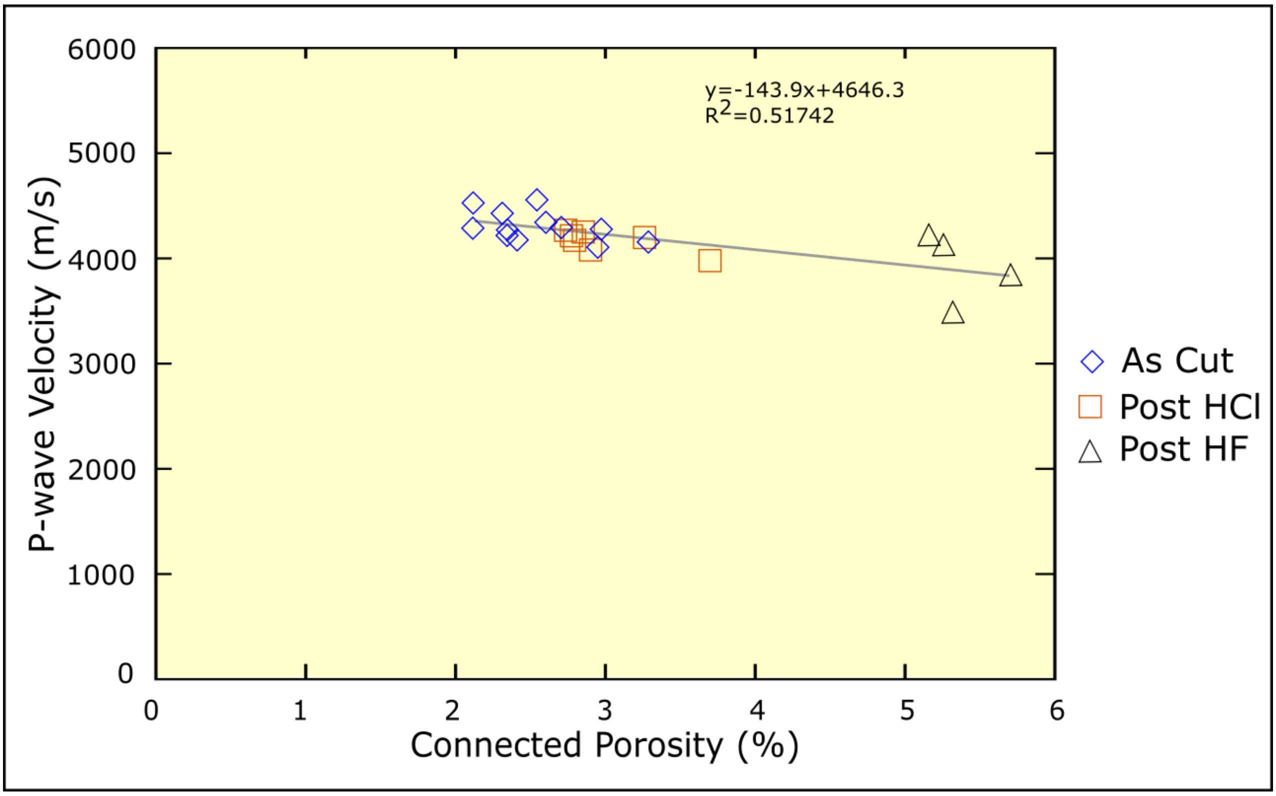

Figure 4: Saturated P-wave porosity plot, presented according to treatment.

4.2 Effects of Acidizing with HF

It is not clear how much effect the HF component of the acid treatment has on the porosity because it was not tested independently of the HCl. Visually, the HF only appears to etch the surface of the sandstone (Figure 1), whereas the HCl appears to dissolve calcite infilling the fractures. However, the increase in permeability and porosity is quite distinct following the HF treatment, and therefore requires further investigation to understand the mechanisms that drive the substantial increase in porosity and permeability.

4.3 Implications for permeability enhancement

The acid treatments significantly increased porosity, with a resultant increase of one to three orders of magnitude of permeability. This demonstrates the potential for permeability enhancement of veined Greywacke with commonly used acidizing techniques. The implications of this study are however limited to understanding permeability changes of *in-situ* Greywacke that has not been subject to deposition of calcite or silica through either production or injection.

The resultant increase in permeability that we observe however, can indicate the changes that may be expected to occur when a well has been in service and experienced decline through mineral scaling (e.g. Flores-Armeta, 2010). We suggest that for future testing, samples that have experienced calcite or silica scaling in a geothermal reservoir may provide true insight to what permeability can be recovered through acidizing. Further testing may require that fresh samples such as those used in this study are subject to induced scaling to provide proxies for conditions that exist down-hole in geothermal reservoirs.

4.4 Implications for strength and elastic modulus

The wide range of strength values we observe is related to the heterogeneity in the orientation, thickness and density of veins in each sample. Despite this variability, our results show that increased porosity from acid treatment resulted in a nearly halving of the UCS strength, which has been shown to be the main control of rock strength (e.g. Siratovich et al., 2014; Wyering et al., 2014). The implications this may have on wellbore stability must then be carefully considered and likely coupled with geomechanical models to ensure that acidizing risk to the borehole is minimized as the rock will undoubtedly experience some strength degradation during acidizing.

However, this study has focused on the whole-sale acidizing and likely longer exposure times to the rock matrix and may present worst-case degradation of strength. It is likely that down-hole application of acids will follow permeable pathways that already exist, which may limit exposure time to rock matrix and minimize weakening.

The P-wave velocities similarly decreased with acid treatment. The saturated P-wave velocity trend with porosity could provide a method for estimating porosity using downhole logging tools after acid treatment and help inform both the efficacy of the treatment and how to better design the application of acids down-hole. Further, the decrease of the velocities support the weakening that we have observed such that they may serve as a proxy for changes in strength after down-hole acidizing. The utilization of down-hole logs may therefore be useful to help confirm strength changes at the borehole wall and confirm or refute predictions from geomechanical models built from the results of the testing presented here.

5. CONCLUSION

The results of this investigation show that there is significant variability in the physical and mechanical properties of the Greywacke found at reservoir depth at Kawerau. Despite the small sample size, acidizing appears to decrease the strength and increase the permeability of the rock. Careful selection of results is required to identify outliers resulting from either prior damage or particularly weak discrete failure planes, as these can affect the interpretations of the results. A larger dataset may provide more reliable data and aid in the interpretation presented here. We also strongly believe that further testing to induce reservoir-type scaling on core samples and additional laboratory testing may help to further optimize the application of acid jobs in the future with respect to strength, permeability and overall productivity (or injectivity) of wellbores prone to geothermal scaling.

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