Attachment 3

Caprock Integrity Analysis
For its Borealis project, Cenovus Energy Inc. (CVE) commissioned BitCan to undertake a rigorous geomechanical program to address the caprock integrity issue during the SAGD operation. Major works include:

(1). A total of 13 mini-frac tests were run from 3 separate wells with each well being tested at 4 or 5 different depths.
(2). Clearwater shales (CWTR) caprock cores from Well 8-26-94-3 were preserved on-site according to the geomechanical test standards.
(3). 5 room-temperature geomechanical laboratory tests were done on the shales.
(4). 4 high-temperature geomechanical laboratory tests are on-going.
(5). Geomechanical simulations were run before the lab tests to design the lab test conditions and refined after the lab tests using the lab-measured mechanical properties and site-measured in-situ stress condition.

Further supported by the typical reservoir geology and SAGD simulation data forwarded by CVE, the above works have demonstrated that the CWTR caprock is safe against the possible failure mechanisms being investigated for a maximum SAGD operating pressure at 1.35 MPa.

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and temperatures up to 200 °C. Neither tensile nor shear failure mechanisms are seen in the simulations.

The mini-frac test results were described in an earlier report and are thus not repeated here. For the convenience, Figures 1 to 3 re-plot the stress profiles measured from the mini-frac tests on the 3 wells. Figure 4 summarizes the numeric values of the measured in-situ minimum stress, Smin. These stress measurements support an assumption that a horizontal fracture stress regime is present in both reservoir and caprock. The overburden weight is the minimum stress. Such a stress condition will be used in the following simulations.

The following description summarizes the work program including major results and assumptions behind. Conclusions and discussions are given at the end.

**PRESERVED SHALE CORING**

Good-quality geomechanical tests on shales start with obtaining preserved shale cores. Shale coring is different from the conventional oilsands coring. BitCan was on site to preserve the shale cores from well: 8-26-94-3.

Cores were immersed in mineral oil at the well site immediately after they were brought to the surface. All the cores were stored in warm temperatures and then transported to Calgary. Shortly after, the cores were inspected for their structural quality and the suitable ones were sampled into about 6” long for the 3”-diameter cores. They are stored in mineral oil until the geomechanical laboratory tests. Through the above procedures, the cores were never frozen. Their virgin moisture content is preserved all the time. These conditions are essential for good-quality shale samples.

**GEOMECHANICAL LABORATORY TESTS**

The tests are planned to measure the compressive strength, deformation properties, thermal expansion coefficients and impact of temperatures on the mechanical strengths. Both the room-temperature (R-T) tests and high-temperature (H-T) tests are planned. A total of 5 R-T tests were completed and their test conditions are summarized in Table 1. The H-T tests are on-going. A detailed description about the laboratory tests is not warranted here, but the key test details are summarized below:

1. The tested R-T samples were taken from the Clearwater shale formation at depths from -90 m to -110 m on Well 8-26-94-3. The test samples are plotted on the well logs as shown in Figure 5.

2. The tests are done on whole core samples. Therefore, no plugging or sample preparation on the cylindrical surfaces is done, i.e. no further disturbance beyond the coring is introduced.
3. Drained condition is maintained with the pore pressure equal to 1.5 MPa, which is comparable to the designed SAGD operating pressure (1.35 MPa). The pore pressure fluid is made chemically compatible with the pore fluid inside the shale samples so that no artificial hydration is introduced during the tests.

4. A slow strain rate of 2e-7 1/s was used in the triaxial tests to ensure uniform pore pressure distribution inside the sample during triaxial loading. Uniform pore pressure distribution inside the sample during the compressive loading is critical for measuring the compressive strength. Drained conditions are established when mechanical loading induced sample volume change does not produce any measurable excess pore-water pressure. The strain rate was estimated according to soil mechanics standards. The formula requires the sample permeability as input which was measured on most of the samples tested here. At such a low strain rate, a typical triaxial test took about 7 to 10 days continuously.

5. The effective confining pressures, C’p, used in the tests ranged from the low 0.5 MPa to the high 3 MPa, i.e., 0.5MPa, 1.0 MPa, 2.0MPa, 2.5 MPa and 3.0 MPa. It represents the range of effective confining pressure conditions expected in the caprock during the SAGD operations. Geomechanical simulations were run before the lab tests to estimate the stress condition expected in the caprock.

6. The tests were carried out according to the following procedures: a). cyclic isotropic compression, b). saturation, c). transient permeability tests, and d). triaxial compression tests. The cyclic compression stage loads and unloads the sample around the anticipated in-situ confining pressure, meant to compact the samples close to their original state. For example, the micro-cracks caused during the coring process should be closed after this stage. The saturation stage is used to saturate the sample at a given pore pressure. The permeability is estimated via a transient test protocol. The triaxial compression tests are conducted to investigate the shale’s strength. A detailed description of these procedures is out of the scope of this summary report, but can be found in a published paper.

Five drained triaxial compression tests were conducted at room-temperatures. Their stress-strain curves and volumetric strain-axial strain curves are shown in Figure 6. Photos of the tested samples are given in Figure 7. Shear bands (fractures) are clearly seen on each of the deformed samples. Major observations on the measured deformation and strength behaviour can be summarized as follows:

1. In general, strain-hardening ductile deformation behavior was observed in the tests. The samples could withstand more and more axial loading as they were being deformed. The volumetric strain exhibited continuous compression. But two tests appear as exceptions and are to be explained below.

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2). Opposite to the ductile deformation is strain-softening brittle deformation behavior where a peak stress is seen during the sample deformation after which, there is an obvious stress drop and the volumetric compaction before the peak changes to dilative, meaning that shear-induced dilation starts.

3). Although not significant, Sample C8T8S2 exhibits the brittle deformation behavior. The cause is related to its extremely low effective confining pressure (C’p=0.5 MPa).

4). The brittle deformation behavior was obvious on Sample C6T8S2. Tested under a higher confining pressure (C’p=2 MPa), it has a much higher peak strength and more obvious stress drop after the peak and the associated dilation. Clearly, this sample goes against the trend: ductile deformation behavior under relatively high confining pressures. Exact causal reasons are not known. It is BitCan’s experience that the mechanical behavior of Clearwater shales tested under relatively low confining stress condition is more sensitive to the mineralogy and microscopic structures. High quartz content can cause the high peak strength. XRD analysis on the sample should be performed if one is interested in proving this possible link.

However, lack of the knowledge about the above causes does not affect the current analysis. Below in deriving the compressive strength parameters, Sample C6T8S2 is dropped out of the data set. This represents the conservative approach. Inclusion of such strong sample in the curve-fitting can only increase the compressive strength.

5). Sample C8T8S2 tested at C’p=0.5 MPa had a higher peak strength than sample C7T7S1 tested at a higher C’p=1.0 MPa. Theoretically, higher effective confining pressures tend to give samples more compressive strength. Again, as explained in 4), variations in the mineralogy and micro-structure may be responsible.

6). The plastic yield stresses from the different tests are summarized in Figure 8 in the Mises vs. mean effective stress diagram to derive the Drucker-Prager (DP) strength parameters. The thus-derived DP friction angle is 32º and cohesion is 443 kPa. The yield stress defines the start of plastic deformation. For samples exhibiting the brittle deformation behaviour, the peak stress is selected as the yield stress. For samples showing the ductile behaviour, the stress where the stress-strain curve deviates from the early straight line trend and starts to level off is used as the yield stress.

7). Correspondingly, the yield stress can be fit to the Mohr-Coulomb (MC) strength criterion as shown in the deviatoric vs. mean effective stress diagram in Figure 9. The MC friction angle=16.4º and cohesion=207 kPa.

8). The elastic deformation properties can be calculated from the linear parts on the stress-strain curves before the peak stresses. Figure 10 illustrates how the Young’s modulus is calculated from the R-T tests. It ranges from 28 MPa at the low confining pressure, C’p=0.5 MPa to 108 MPa at C’p=3.0 MPa. The exceptionally strong sample: C6T8S2 has a Young’s modulus=196 MPa.
In summary, a serious geomechanical laboratory test program was undertaken on the CWTR shale samples. It involved properly-preserved whole cores, drained condition with a constant pore pressure=1.5 MPa close to the designated SAGD operating pressure and a slow strain rate. The thus-measured compressive strength parameters are: friction angle at 32º and cohesion at 443 kPa if fit to the DP strength theory or 16.4º and 207 kPa if fit to the MC theory. This agrees with the general published data although it lies on the lower side. The latter may be related to the shallow depths where these samples were taken.

GEOMECHANICAL SIMULATIONS

The simulations here are to assess the potential for the CWTR caprock shale to fail in plastic deformation or tensile fracturing modes under the designed SAGD operating pressure and temperature conditions. Thus, the failure modes to be studied include both shear failure and tensile fracturing. The simulations used the lab-measured material properties and field-measured in-situ stresses as described in the above. It should be noted at the very onset that the occurrence of plastic failure does not necessarily mean that the caprock integrity will be compromised. But absence of the plastic failure definitely supports the caprock integrity.

ABAQUS4 --- a large-scale reputed commercial stress analysis software was used as the basic simulation tool for this project. The following key physical mechanisms were considered in the models:

1. **Coupled thermal-hydro-mechanical process** - Our specially-designed ABAQUS driver took the SAGD pressure (p) and temperature (T) condition in the reservoir as the input. It then simulates the coupled thermal-hydro-mechanical processes in the caprock to calculate the stress and deformation. The temperature (T) and pressure (p) condition in the reservoir diffuses into the caprock. The hydro-mechanical coupling is 2-way, namely the pressure diffusion and rock deformation influences each other fully. But the thermo-mechanical coupling is one-way, i.e., the temperature diffusion affects the rock deformation only while the mechanical deformation does not affect the temperature. The p and T condition in the reservoir was forwarded by CVE from their thermal reservoir simulations.

2. **Non-linear porosity-mobility model in the caprock**: Such permeability models account for the permeability change as a result of rock deformation and failure.

3. **Effective stress** - Changes in the pore pressure and total stress are combined to evaluate the effective stresses, which controls the strength of materials;

4. **Poroelastic effects** – Changes in the total stress caused by the changing pore pressure are considered;

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5. **Thermo-elastic effects** - Changes in the total stress caused by the changing temperature are also considered;

6. **Nonlinear elastic and elasto-plastic constitutive models with dilation** – The Drucker-Prager elasto-plastic constitutive model was used to simulate the deformation and failure of the reservoir as well as overburden materials including CWTR caprock. Dilation is allowed in both reservoir and caprock, depending on the prevailing stress condition and material strength.

7. **Two failure modes in the caprock --- shear and tensile** - The material constitutive models used in the simulations can automatically distinguish the plastic shear failure and tensile fracturing.

**Computational model and material properties**

The computational model is 2-D cut perpendicular to the SAGD wells. Extracted from the general regional geology based on well logs, the model consists of four strata as shown in Figure 11:

1. The 145-m underburden limestone is added for proper boundary conditions to the area of our interest: reservoir and the caprock above.
2. Top of the reservoir payzone is at -125 m deep with a thickness of 30 m. The 30-m thickness was simulated in the SAGD model forwarded by CVE in its reservoir simulations.
3. The CWTR caprock shale occupies the depth range from -75 to -125 m.
4. The remaining overburden (OB) from the ground downwards to the top of CWTR shale is included with mechanical properties resembling the general glacial till behaviour.

The horizontal extent of the model is 50 m which is forwarded by CVE in its SAGD reservoir model. A symmetrical boundary condition is set along the left and right-hand sides of the model, meaning that the SAGD is operated in a series of well pairs with a distance at 100 m between.

The mechanical properties used in the simulations for the different strata are listed in Table 2. DP constitutive model and nonlinear porous elastic model were used for the reservoir and overburden. Material properties assigned to the CWTR shale come from the room-temperature laboratory tests as summarized in the above. A perfectly plastic model is used in the simulations. This provides a safe and conservative evaluation for caprock failure given that in general, the strain-hardening behavior was observed in the lab tests.

Site-specific material properties for the overburden (Quaternary till) are unavailable since no lab tests were done on the till materials. In the simulations, they are chosen from the available public literatures. MacDonald and Sauer (1977)\(^5\) conducted a series of lab tests to investigate the

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geotechnical properties of Quaternary till in north Saskatchewan region. According to their test results, the Quaternary till has the average MC friction angle of 22º and cohesion of 10 kPa. The underburden is assumed linearly elastic. It is appropriate since it is further away from the area of our interest and its influence is expected to be minimal.

The nonlinear porous elastic model used for the reservoir can account for the pressure-dependence of the elastic compressibility. Also, the plasticity model is used for the reservoir sands to account for the pressure and temperature-induced dilation. The CWTR caprock shale is prescribed with a constant Young’s modulus and Poisson’s ratio based on the average of their corresponding laboratory-measured values.

The CWTR shale is assigned with a porosity dependent nonlinear permeability model, which uses the averaged value of our lab measurements as the initial value. This porosity-dependent permeability model can reflect the effect of rock deformation on the fluid flow.

All the overburden strata, including CWTR shale, are given a linear thermal expansion coefficient, $\alpha = 2.8e-5 \ 1/°C$. We currently don't have high temperature tests data on the Borealis samples. Thus, this thermal expansion coefficient was taken from BitCan's internal database on the similar formations. We will re-run the simulation after the high-temperature tests are completed and the thermal expansion is measured. The reservoir payzone is prescribed with $\alpha = 2e-4 \ 1/°C$ which is relatively larger than the pure sands reflecting the bitumen-saturated nature. The thermal expansion of formation water is taken as $1.4 \ e-4 \ 1/°C$, which is much larger than the thermal expansion of solid rock matrix. Thus, thermal fracturing is possible if the formation is heated too fast.

Reservoir temperatures will propagate into the overburden rocks via both conduction and convection. The conduction dominates when the rock is intact and no convection occurs. It is characterized by the thermal diffusivity as summarized in Table 2. The convection becomes important when the rock fails allowing the movement of the hot reservoir fluid into the overburden. It is difficult to account for the convection in the current numerical analysis. It will be seen later that no plastic failure occurs in the caprock shale. Therefore, the lack of convection in the simulations is not important for the thermal transport in CWTR shales.

Initial, boundary and field conditions

Initial conditions for the current simulations include the initial in-situ stresses, pore pressure and temperature:

1. The in-situ stresses have 3 components: vertical (Sv), minimum (SHmin) and maximum (SHmax) horizontal stresses. Sv comes from the overburden weight calculated from the density logs which is 21.6 kPa/m. Mini-frac tests in the area showed that in the CWTR shale caprock and reservoir, the vertical stress is the minimum in-situ stress. Thus, the other two horizontal stress components are unavailable from the minifrac tests. Generally speaking, it is hard to get the maximum and intermediate stress components. Therefore, a series of sensitivity analysis on the SHmin and SHmax were conducted to investigate their effects on caprock integrity. The maximum horizontal stress (SHmax) was assumed
to be 1.1*Shmin. Three cases were simulated by varying the Shmin: Shmin=1.1*Sv, Shmin=1.3*Sv and Shmin=1.5*Sv. Based on the above analysis, a stress profile was built as shown in Figure 12.

2. The initial reservoir temperature is 8°C as used in CVE’s reservoir simulations. The initial temperatures inside the overburden and underburden are assumed the same as reservoir temperatures.

3. The initial reservoir pressure is around 1000 kPa and the maximum SAGD operating pressure is 1350 kPa as used in CVE’s reservoir simulations.

Boundary conditions are set as follows: left and right as well as bottom boundaries of the model are symmetric, i.e. normal displacement, heat fluxes and fluid flows are zero. The top of the model is the ground surface and thus stress-free and pore pressure free. Thermal boundary condition at the top as well as the initial temperature throughout the model is prescribed with a constant temperature of 8°C.

The driving forces for the caprock deformation are the temperatures and pore pressures inside the reservoir during the SAGD operations, which were forwarded by CVE to BitCan after their SAGD thermal simulations. They are then input to the geomechanical simulations described herein. The total simulated time is 5 years. Figure 13 shows some example temperature and pore pressure distributions in the reservoir at different days into the SAGD operation. It should be noted that temperatures and pore pressures in the overburden are calculated based on thermal conduction and pore fluid diffusion through the coupled analysis. The associated material properties are listed in Table 2.

It can be noticed that the steam chamber occupies the top of the reservoir at the early stage of the SAGD operations (Figure 13). We suspect that it may be caused by a geological layer with a large steam mobility on top of the reservoir. Our numerical simulation will show that the caprock integrity may benefit from this permeable zone, which causes the rigid body-like movements of the entire caprock.

Major simulation results

For the three sensitivity analysis on the Shmin profile, the simulation results demonstrate that, given the designed operating condition, the CWTR caprock shale does not enter into plastic failure during the entire 5-year SAGD operation life. At the end of the SAGD operations, no plastic strain is detected in CWTR as shown in Figures 14 for all the Shmin profiles.

The equivalent plastic strain (PEEQ is the term used in ABAQUS) is used in describing the plastic yielding or failure. It can be viewed as a measure of the plastic deformation energy and mathematically defined below, following ABAQUS:

\[ \text{PEEQ} \]

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$$\text{PEEQ} = \varepsilon^{pl} = \int_{0}^{\text{time}} \frac{\sigma : d\varepsilon^{pl}}{\sigma_0} dt$$

where $\sigma$ is the stress tensor and $d\varepsilon^{pl}$ is the incremental plastic strain tensor. Therefore, $\text{PEEQ}=0$ means no plastic failure. Basically, when $\text{PEEQ}=0$ means no plastic yielding or caprock failure.

It should be noted that the caprock integrity benefits from the highly permeable zone on top of the reservoir. This permeable zone causes the steam chamber to occupy the entire upper part of the reservoir, leading to the rigid body movements of the caprock. The rigid body movement does not induce any stresses inside the caprock. Thus, no plastic failure will occur. If this permeable zone is not the prevailing reservoir condition, it is suggested to re-run the simulations.

For the case with minimum Shmin value (Shmin=1.1*Sv), the variation of the horizontal effective stress (S11) with time for two elements in CWTR caprock right above the steam chamber is given in Figure 15. It shows that for the element above the steam chamber, the effective horizontal stress become less compressive (but still far away from the tensile stress region) during the early SAGD stage, in which steam chamber is expanding. After the steam chamber passes, compressive stress is developed in the horizontal direction.

Because of the larger difference in the 3 stress components, the case where Shmin=1.5*Sv, the initial stress state inside the caprock is closer to the failure surface than the other two cases. The stress path for two elements above the steam chamber is plotted in Figure 16. It is shown that, even in this "worst" initial stress case (SHmin=1.5*Sv), the stress state close to the SAGD chamber still remains inside the elastic region.

**CONCLUSIONS AND DISCUSSIONS**

The following major conclusions can be drawn from the work program:

1. Mini-frac tests have demonstrated that the caprock is safe against inadvertent vertical fracture propagation from the deeper payzone upwards. The fractures should turn horizontal in the CWTR shale caprock as dictated by the change in the in-situ stress regime. More details were described in an earlier report submitted on the mini-frac tests.

2. The CWTR shale cores were preserved properly by being immersed in mineral oil all the time and transported in warm temperatures above the freezing. The samples for the laboratory tests were structurally intact based on the visual observation. No calcite nodules were selected for the laboratory tests.

3. Great care was executed in the geomechanical laboratory tests on the CWTR shales. Whole cores were used to avoid further damage. Drained condition was maintained during the tests with pore pressures up to the designed SAGD pressures (1.5 MPa). Correspondingly, a slow strain rate was used to achieve relatively uniform pore pressure condition inside the samples during the tests.

4. The DP friction angle and cohesion are measured to be 31.8° and 0.443 MPa and the MC friction angle and cohesion to be 16.4° and 0.207 MPa.
5. Coupled thermal-hydro-mechanical simulations were conducted to calculate the induced stress and deformation in the CWTR caprock. They used the lab-measured mechanical strength and deformation properties as well as in-situ stress condition measured in the mini-frac tests.

6. Geomechanical simulations showed that the CWTR shales are safe from the general matrix plastic failure under the designed SAGD pressure (1.5 MPa) and temperature conditions (200ºC). Neither tensile nor shear failure modes are seen in the caprock.

7. It should be noted again that, the above safe-caprock statement is based on the SAGD simulation forwarded by CVE which contains a permeable zone on top of the reservoir. If the permeable zone on top of the reservoir is not the prevailing reservoir geological condition, new reservoir simulation data should be forwarded to BitCan in order to re-evaluate the caprock integrity issue.

In short, the above works are sufficient to conclude: Given the provided reservoir simulation data, the CWTR shale caprock is safe against the investigated failure mechanisms: tensile and shear failure.

For the future large-scale commercial operations, it should be understood that the caprock integrity is a complex issue and its influencing factors encompass many in-situ (geology and material properties) and operating conditions. Some probable mechanisms that are not investigated in the current work program should be considered in the future:

1. Chemical corrosions. The cyclic steam stimulation (CSS) operation in Cold Lake suggested that it is one of the prevalent casing failure mechanisms and therefore, affects the caprock integrity. Steam or fluid leaks from the corroded casing spots, if any, would compromise the caprock integrity. Proper casing material selection is important.

2. Re-activation of pre-existing weak planes. This is another important mechanism for the casing failure in Cold Lake’s CSS operations. Presence of such weak planes in the caprock should be assumed for the worst-case scenario designs. Proper coordination in operation among the SAGD well pairs can be used to manage such mechanism. Surface heave monitoring can provide early warning signals.

3. Furthermore, for large-scale commercial production over a large area, it is important to check out for possible localized mechanically weak spots in the region. This can only be done by calculating the mechanical strength from the well logs in the region. However, at the current state of the art, there are not many data to derive quality strength-log correlations yet. BitCan is aggressively moving towards this direction. At the time of the commercial operation, it is expected that more data become available and such correlations will occur.

Ongoing monitoring is already requested by ERCB for any SAGD operations and being implemented by AOSC. BitCan recommends the surface heave monitoring to be added to the monitoring program. Despite its appealing advantages, InSAR technology should be scrutinized closely for its suitability in North Alberta due to its unique weather and muskeg environment. Automated surface levelling survey is a better alternative. Microseismic monitoring cannot provide the early warnings needed. SAGD is temperature-driven. The temperature process is
transient. When the microseismic events are detected, it is too late already for managing the field operation to avoid the caprock failure.

BitCan further recommends full integration of all the monitored data to assess the subsurface steam chamber growth and health of the caprock integrity. Temperature and pressure monitoring, surface heave and other observation data are inversed in the background of the site-specific geological models to infer about the subsurface processes.
Table 1: Summary of test conditions for the geomechanical triaxial tests.

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<td>Axial Strain, End of test, %</td>
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Table 2: Summary of the material properties input for the simulations.

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<td>$E / \kappa$</td>
<td>$\nu$</td>
<td>$\phi$</td>
<td>$c$</td>
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<td>OB</td>
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<td>0.3</td>
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</table>

Note:
1. $E$ is the Young’s modulus; $\kappa$ the logarithmic modulus for nonlinear porous elasticity; $\nu$ Poisson’s ratio; $\phi$ DP friction angle; $c$ DP cohesion; $\psi$ DP dilation angle, $C_v$ thermal diffusivity and $\alpha$ is the linear coefficient of thermal expansion.
2. The material parameters for the CWTR shale are based on our RT triaxial tests results and those for the oil sands reservoir and underburden are from BitCan’s internal databases.
3. Porosity dependent permeability is considered in this simulation. The permeability value given in above table is the initial permeability for CWTR shale.
4. MC plasticity was used for overburden (OB), which is quaternary till.
Figure 1: Location of the mini-frac tests (red dotted lines) superimposed on the GR log and summary on the in-situ minimum stresses measured from well 1-35. “Sv” denotes the vertical overburden stress calculated from the density log. “Smin” in squares is the interpreted minimum stress from the mini-frac tests.
Figure 2: Location of the mini-frac tests (red dotted lines) superimposed on the GR log and summary on the in-situ minimum stresses measured from well 2-27.
Figure 3: Location of the mini-frac tests (red dotted lines) superimposed on the GR log and summary on the in-situ minimum stresses measured from well 8-7.
<table>
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<th>Depth, m</th>
<th>Min. stress</th>
<th>Vert. stress</th>
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<td>Well ballooning Test inconclusive.</td>
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Figure 4: Summary of the test depths and measured in-situ minimum stresses at each test well.


**Figure 5:** Location of the samples obtained from the field and those tested so far.
Figure 6: Stress-strain curves measured during the room-temperature triaxial tests. Positive volumetric strain means dilation.
Figure 7: Photos of the tested samples for the room-temperature tests.
Figure 8: Drucker-Prager (DP) strength parameters extracted from the room-temperature triaxial tests. C6T8S2 was dropped out of the fitting because of the reasons described in the text.
Figure 9: Mohr-Coulomb (MC) strength parameters extracted from the room-temperature triaxial tests. C6T8S2 was dropped out of the fitting because of the reasons described in the text.
Figure 10: Stress-strain curves used to calculate the elastic modulus from the room-temperature tests.
Figure 11: The 2-D geomechanical simulation model cut perpendicular to the SAGD wells. “NT11” in the legend means temperature in the unit of °C. The same holds in the following figures.
Figure 12: In-situ stress profile input into the geomechanical simulations.
Figure 13: Temperature and pore pressure distribution at different days into the SAGD operation. Forwarded by CVE and input into the geomechanical simulation as the driving force to the caprock deformation. POR in the legend means the pore pressure in the unit of kPa.
Figure 14: Contours of equivalent plastic strain (PEEQ) in the caprock and temperatures (NT11) in the reservoir at different days into the SAGD operation for the three Shmin profiles.
**Figure 15:** Effective horizontal stress (S11) changes with time on two elements in the CWTR caprock shale above the steam chamber for the case of $Sh_{min}=1.1*S_v$. 
**Figure 16:** Stress paths on the two elements in the CWTR caprock shale above the steam chamber for the case of Shmin=1.5*Sv.