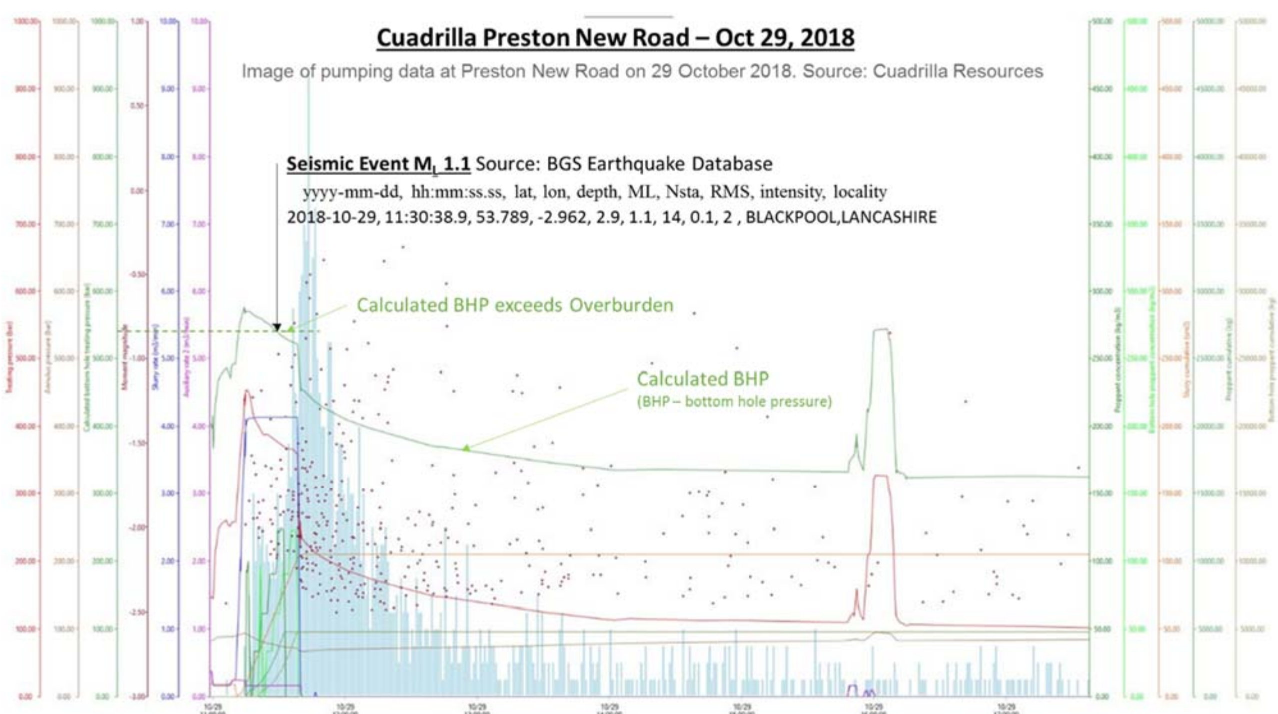
August 15, 2019

Preston New Road Stimulations

Data has been recently released by the UK Oil & Gas Authority of Cuadrilla Resources PNR-1Z horizontal well fracturing operations conducted in 2018 at Preston New Road, Lancashire, UK – data can be sourced from https://www.ogauthority.co.uk/onshore/onshore-reports-and-data/preston-new-road-pnr-1z-hydraulic-fracturing-operations-data/. From a review of this available data, it is clear that the geology impeded the vertical height growth of the induced fractures, similar to the Preese Hall Well 2011 stimulations, of which GeoSierra's Executive Summary review of October 2016 follows. The operator then allowed the BHP (Bottom Hole Pressure) in the PNR-1Z well to rise thus opening hyper-sensitive bedding planes and thus giving rise to a heighten risk of induced seismicity with minimal enhanced gas production. These seismic events were induced by small pumped fluid volumes, as were the events induced in the Preese Hall well. By allowing the BHP to rise sufficiently to open the hyper-sensitive bedding planes, the operator has significantly heightened the risk of induced seismicity from their operations.

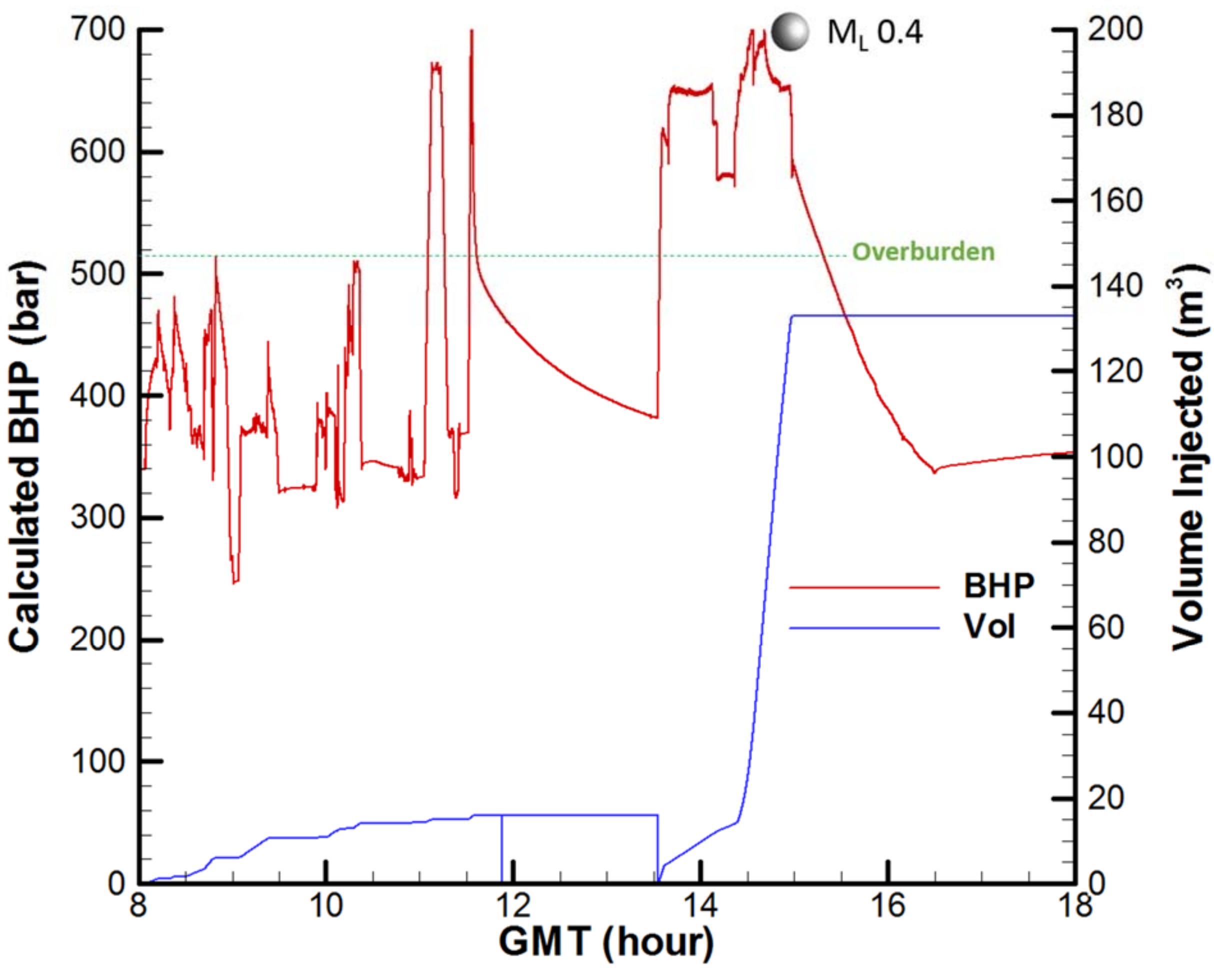
A figure of the calculated BHP and associated timing and magnitude of seismic events is shown below for the operations of the well PNR-1Z on 29th October 2018. It is also clear that attempting to stimulate PNR-2 well in a similar fashion will lead to the same heightening risk of induced seismicity, if the operator does not limit the BHP, and thus avoid opening the hyper-sensitive bedding planes, which significantly increases the risk of inducing seismic events at the site.



Pumping Data and Seismic Event PNR-1Z October 29th, 2018

Analysis of pumping data and seismic events for the following dates 23rd, 24th, 26th, 27th and 29th October, and 11th December 2018, have been analyzed and plots of calculated BHP and volume injected plus seismic events of ML ≥ 0.1 are detailed in the following figures. Cuadrilla's report of the fracturing operations of well PNR-1Z is provided at the following https://www.ogauthority.co.uk/media/5845/pnr-1z-hfp-report.pdf.

In the Daily Reports, the operator states that all hydraulic induced fractures are near vertical bi-wing fractures with half lengths of 120m to 200m and heights of 52m to 100m for the sleeve injections analyzed here. Also closure pressures could not be determined for these injections by the operator as closure was not observed, as stated in the Daily Reports. These interpretations are completely contradictory to what has been concluded in this review. That is, all of the hydraulic induced vertical fracs are extremely limited in extent, their vertical height being terminated by the slickensided bedding planes, and the near horizontal hyper-sensitive bedding planes were opened by the high frac pressures, into which the injected frac fluid flowed.

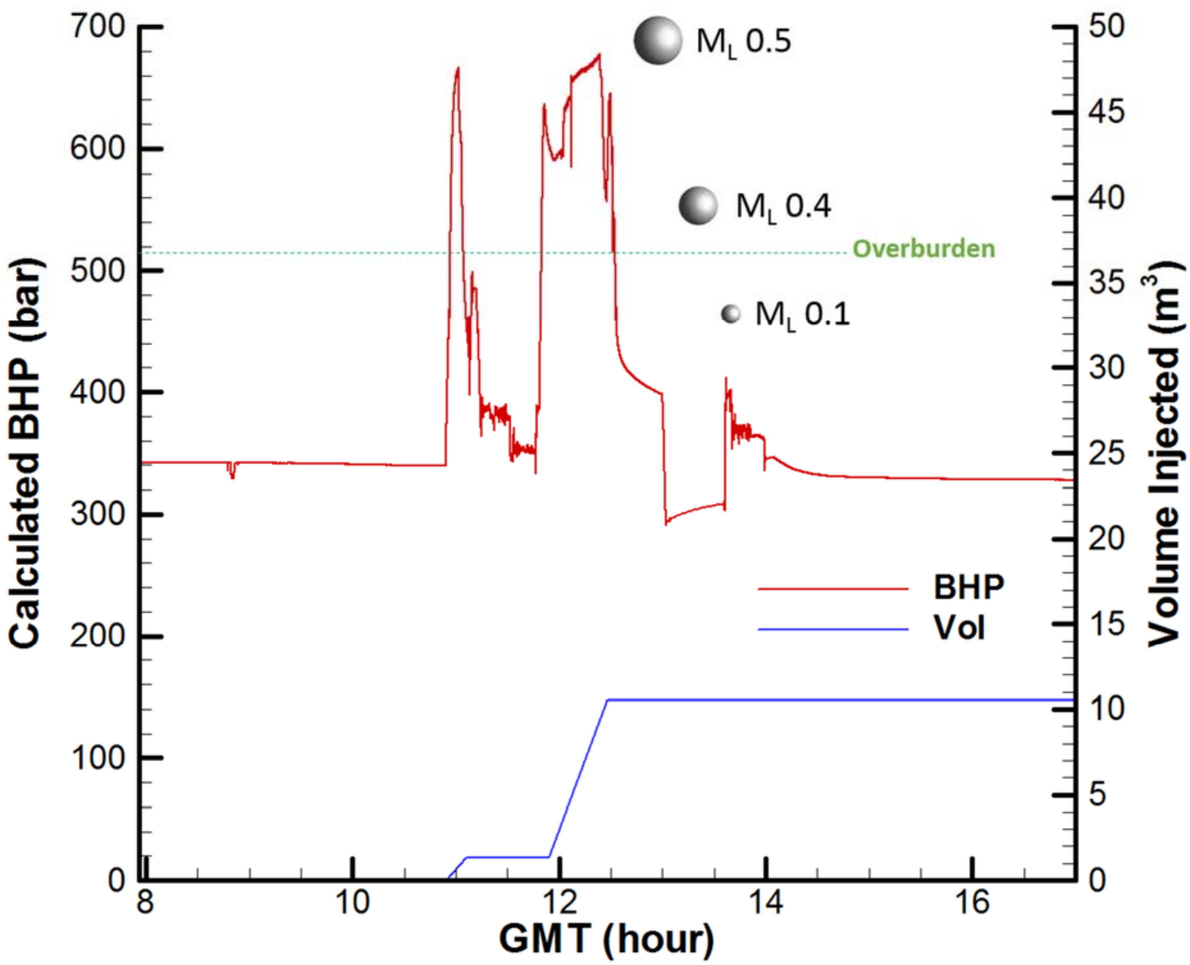


Pumping Data and Seismic Event of Sleeve 14, PNR-1Z October 23rd, 2018

Sleeve 14 was stimulated on the 23rd October 2018, initially as a mini-frac and then a main frac, as shown in the figure above. The injection involved high bottom hole pressures far exceeding overburden, and shortly after pumping was stopped, a seismic event of M_L 0.4 occurred. The final shutin declining pressure is far different than a typical normal decline, e.g. compared the end of pumping decline to the decline following the mini-frac, i.e. times of ~noon and 15:00 GMT. Even so, the closure pressures are both high, indicating that near horizontal bedding planes were open during injection. Overburden pressure at this sleeve depth is 515bar. This stimulation opened bedding planes and induced a M_L 0.4 seismic event immediately after pumping ceased for a total injected volume of 129m^3.

The high fracturing pressure rise far exceeding overburden, indicates that the initially induced fractures were small in extent, their vertical height growth was terminated by the slickensided bedding planes, resulting in high fracturing pressures to open the bedding plane, and thus allow slick frac fluid to migrate some distance from the injection point. In fact, the bedding planes are hyper-sensitive to normal stress, as is described in more detail in the GeoSierra 2017 review of the Preese Hall 2011 stimulations, that can be sourced from http://www.geosierra.com/files/122554754.pdf.

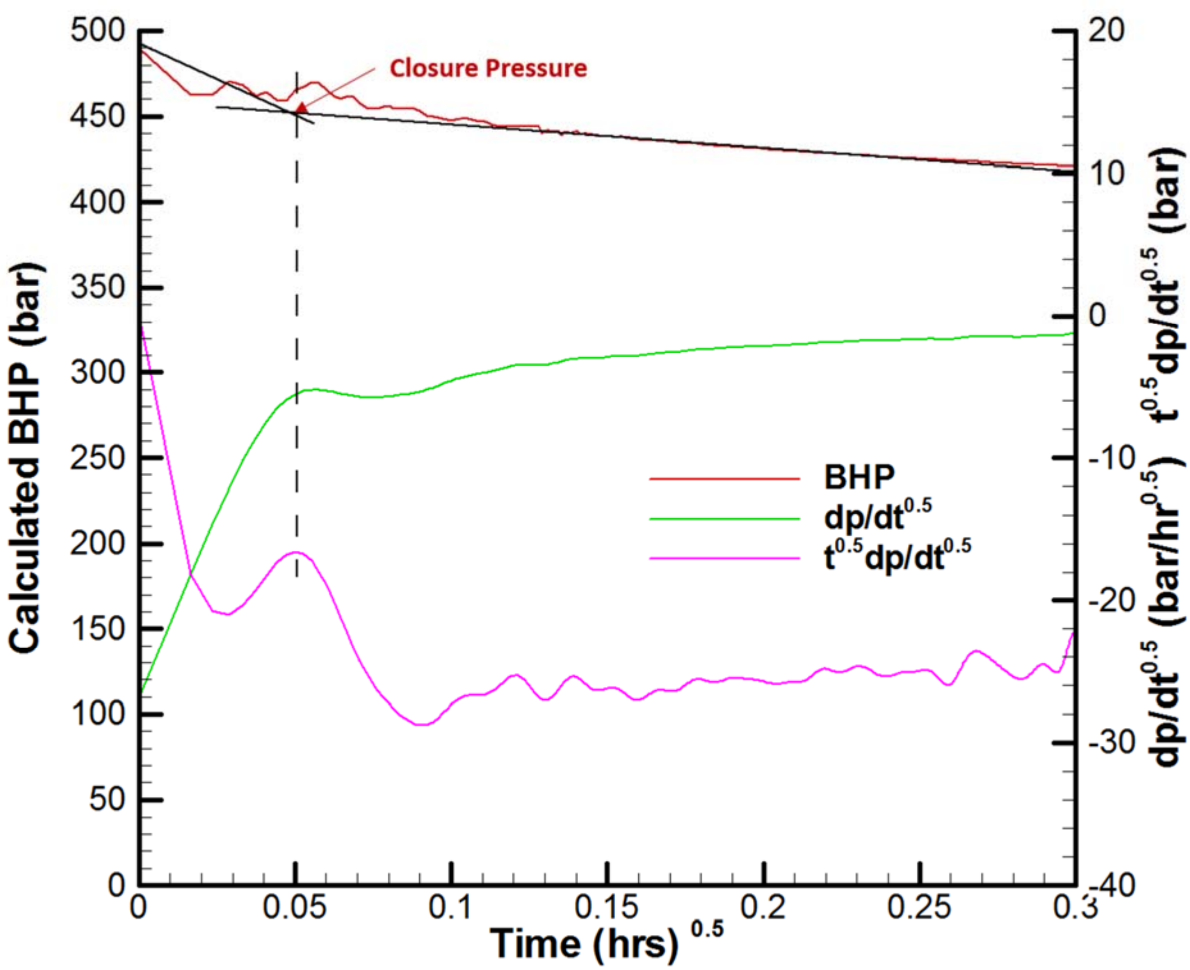
The data for the mini-frac of sleeve 18 on the 24th October is particularly interesting, not only for the seismic events that occurred shortly after pumping, but the high fracturing pressures and closure pressure, clearly demonstrating that bedding planes were opened in this stimulation. Note the immediate drop in BHP when the seismic event of M_L 0.5 occurred, as shown below.



Pumping Data and Seismic Events of Sleeve 18, PNR-1Z October 24th, 2018

The analysis of the shutin data for this sleeve, shown below, yields a closure pressure of 450bar, which is comparable to the total normal stress on the bedding planes. Overburden pressure at this sleeve depth is 515bar. This stimulation opened bedding planes and induced a M_L 0.5 seismic event immediately after pumping ceased for a total injected volume of only 10.5m^3. This mini-frac coalesced with the main frac of sleeve 14 of the day before, onto the same near horizontal bedding plane, and the small injected volume of this mini-frac was sufficient to induce the M_L 0.5, 0.4 and 0.1 seismic events, that occurred shortly after pumping ceased, with an extremely small injected volume of 10.5m^3.

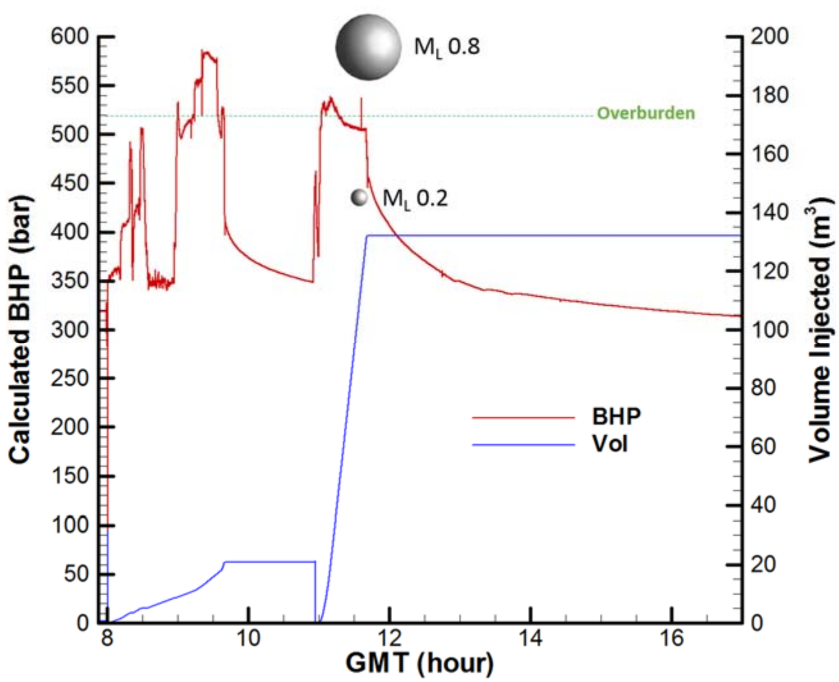
The analysis of the shutin data for this sleeve was conducted by the square root of time method, which yielded a closure pressure of 450bar, and an ISIP of ~500bar. Slickensided bedding planes, which were present in the Preese Hall well will terminate the vertical height growth of vertical induced fractures, leading to an increase in BHP until the bedding planes are opened. The bedding planes being hyper-sensitive to normal stress, allow slick frac fluids to migrate considerable distances from the injection point. In the case of the Preese Hall 2011 stimulations, frac fluids migrated some 1,700' from the well with little drop in pressure, thus leading to a significant heightened risk of inducing seismic events, even from small injected volumes, with the events occurring some considerable distance from the injection point.



Analysis of Shutin Pumping Data of Sleeve 18, PNR-1Z October 24th, 2018

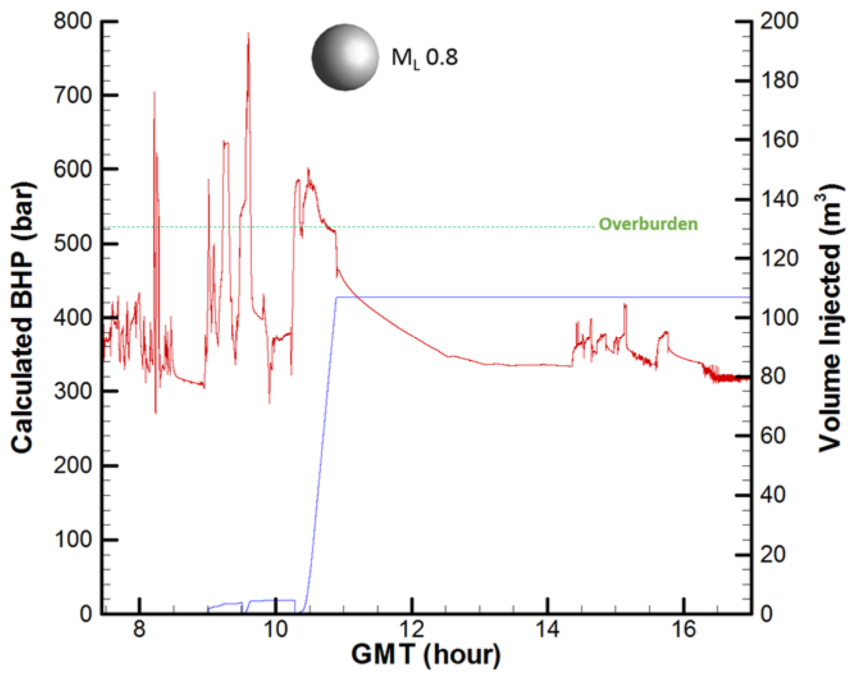
The pumping of sleeves on the 26th, 27th and 29th October 2018, all induced a seismic event of $M_L > 0.5$ during pumping and were all thus shut down as per the hydraulic fracture plan. All of these stimulations have high fracturing pressures that opened near horizontal bedding planes, as is clearly seen if closure pressures are analyzed. In all of these cases, the closure pressure was 450bar, comparable to the total normal stress acting on the bedding planes. Overburden pressure at these sleeve depths is 520bar.

The stimulation of sleeves 30 and 31, opened bedding planes and induced M_L 0.8 seismic events, for injected volumes of 142 and 112m^3, respectively. The stimulation of sleeve 32, opened bedding planes and induced a M_L 1.1 seismic event, for an injected volume of 119m^3. Any proppant injected in these stimulations would do little to enhance gas production, since the proppant would become embedded in the walls of the slickensided bedding planes. The fact that ISIPs do not change from sleeve to sleeve, highlights that no stress shadowing is occurring as the induced vertical fracs are extremely limited in extent. Their vertical height being terminated by the slickensided bedding planes, and that these near horizontal hyper-sensitive bedding planes were opened, into which the injected frac fluid flowed.

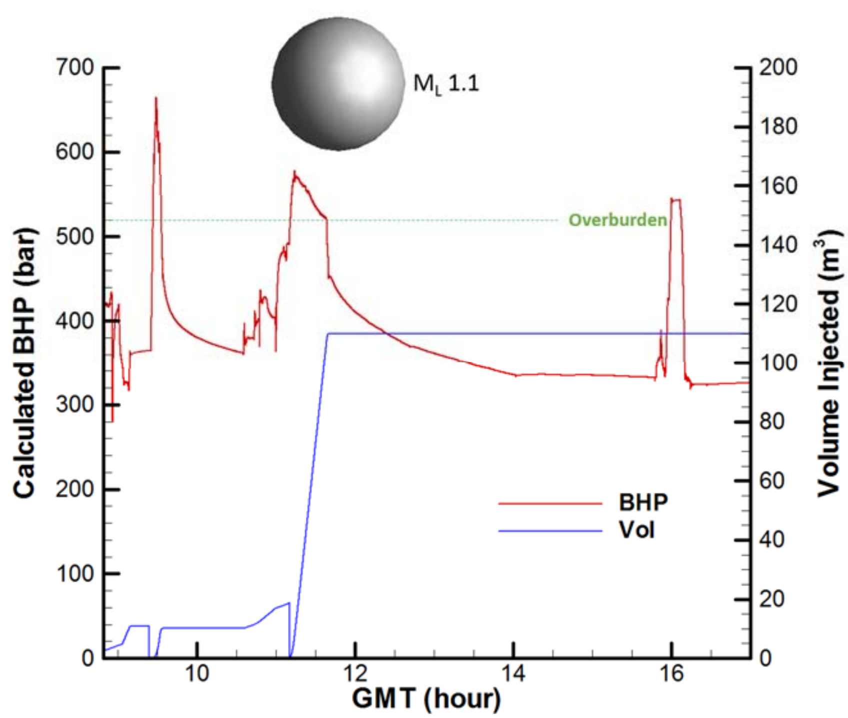


Pumping Data and Seismic Events of Sleeve 30, PNR-1Z October 26th, 2018

From the daily logs, sleeves 30 and 31 were recorded as being stuck in the open position after fracturing. Thus, on the 27th sleeves 30 and 31 were both open, and on the 29th all three sleeves were open, i.e. 30, 31 and 32. Not knowing how the operator isolated the sleeves, with packers or cups, it doesn't change the interpretation of the pumping data, such as mitigated vertical height growth of the induced hydraulic fractures, resulting in high fracturing pressures and closure pressures, opening of near horizontal bedding planes, that are hyper-sensitive to normal stress, thus significantly increasing the risk of induced seismicity, with minimal enhancement of gas production.

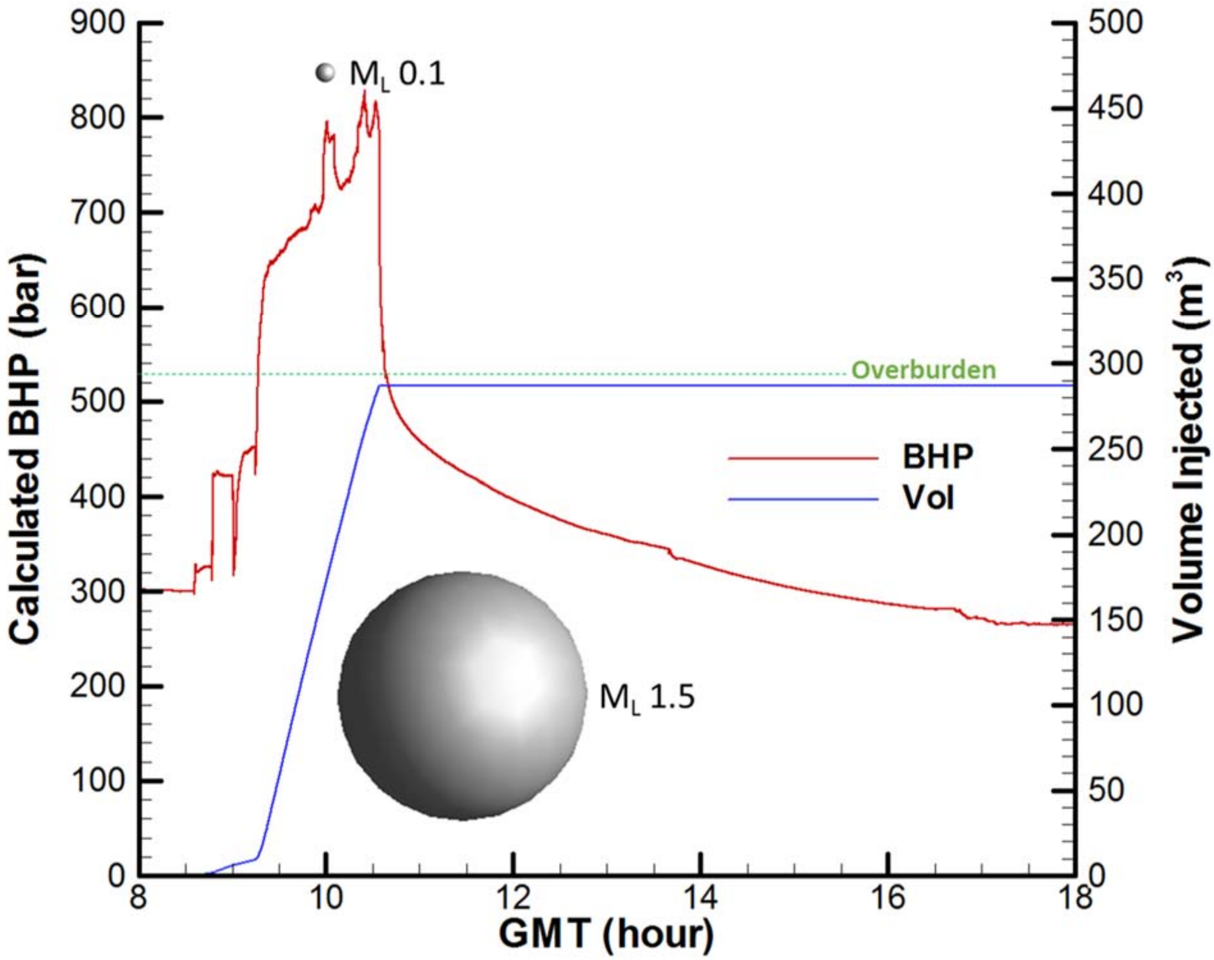


Pumping Data and Seismic Event of Sleeve 31, PNR-1Z October 27th, 2018



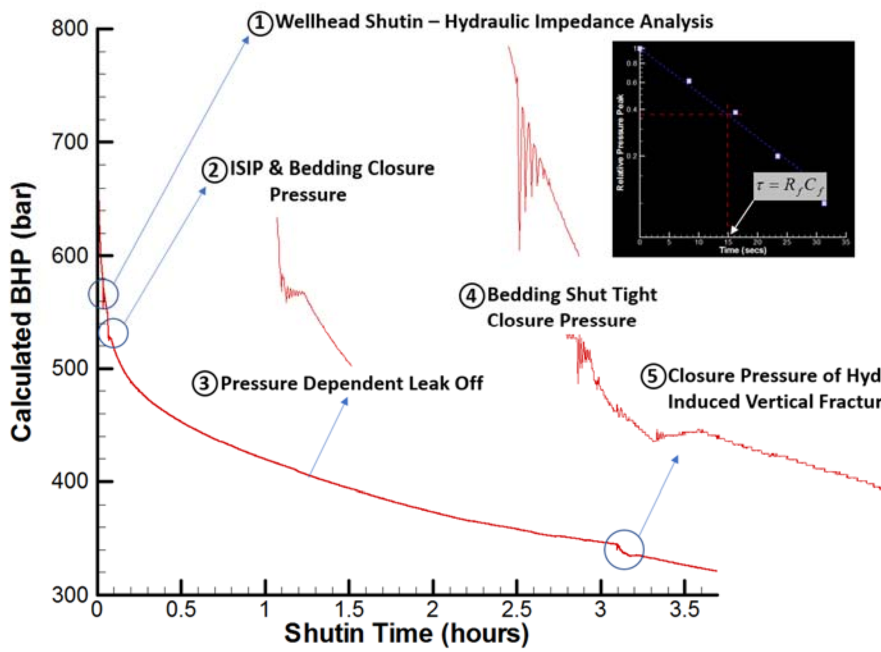
Pumping Data and Seismic Event of Sleeve 32, PNR-1Z October 29th, 2018

The stimulation of sleeve 38, opened bedding planes and induced a M_L 0.1 seismic event during pumping, with a M_L 1.5 seismic event shortly after pumping stopped, as shown below. This stimulation had extremely high injected pressures, far exceeding overburden of 530bar. The stimulation of sleeve 38, opened bedding planes and induced a M_L 1.5 seismic event, for an injected volume of 268m^3. Any proppant injected in these stimulations would do little to enhance gas production, since the proppant would become embedded in the walls of the slickensided bedding planes. The operator's Daily Report states for sleeve 38, the hydraulic induced bi-wing vertical fracture had a half length of 120m and a height of 52m for the injected volume of 268m^3, i.e. a bi-wing fracture smaller than that reported induced by the mini-frac of sleeve 18, which only had an injected volume of 10.5m^3, and had a reported half length of 129m and a height of 52m. The extremely high frac pressures opened bedding planes and thus heightened the risk of induced seismicity, without any or minimal gas production enhancement.



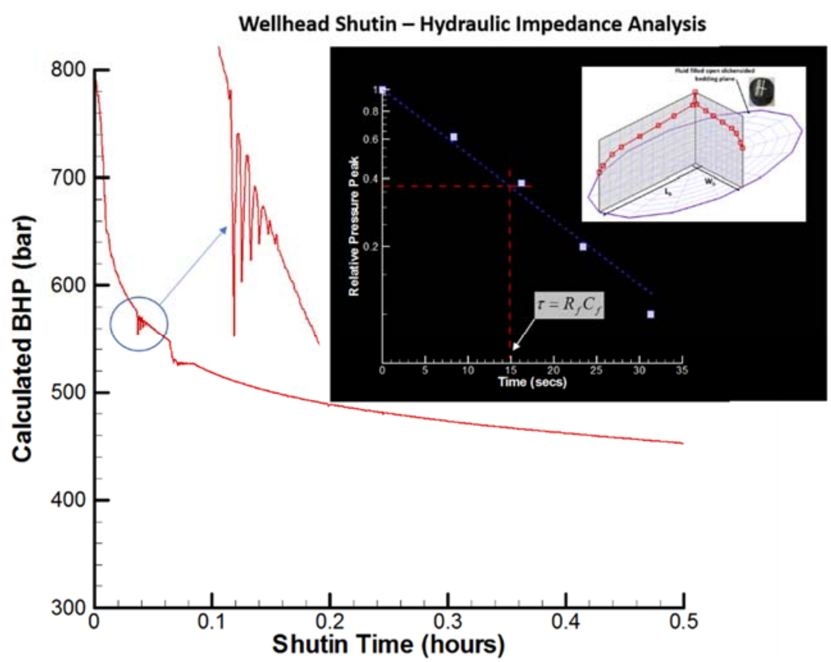
Pumping Data and Seismic Events of Sleeve 38, PNR-1Z December 11th, 2018

The analysis of the shutin data for sleeve 38 is shown below. The analysis consists of five distinct stages; being, 1) hydraulic impedance analysis of wellhead shutin to provide dimensions of opened bedding planes, 2) ISIP and Closure Pressure of the near horizontal bedding planes, 3) pressure dependent leak off providing data on the bedding fluid conductivity as a function of pressure, 4) shut tight bedding plane closure pressure, at which the bedding planes are virtually impermeable, and 5) Closure Pressure of the hydraulic induced vertical fractures.



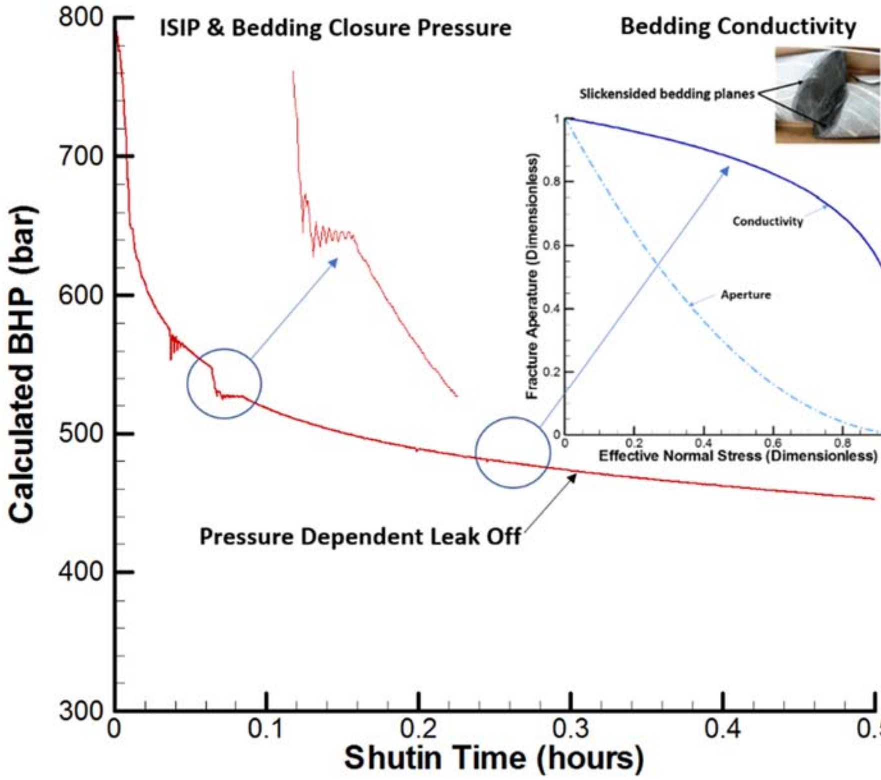
<u>Shutin Data and Analysis of Sleeve 38, PNR-1Z December 11th, 2018</u>

The various stages of the shutin analysis are shown in the following figures, with the hydraulic impedance analysis of wellhead shutin providing dimensions of the opened bedding planes at the end of pumping, conducted first as it occurs immediately following shutin.



<u>Hydraulic Impedance Analysis of Shutin, Sleeve 38, PNR-1Z December 11th, 2018</u>

The propagating wave set up by wellhead shutin, produces reflections from the opened bedding planes, so that their opened dimensions can be determined from the hydraulic impedance analysis. The relative decays of the reflected waves are plotted yielding a time constant that is proportional to the opened bedding plane's resistance and capacitance to fluid flow.



Pressure Dependent Leak Off Analysis, Sleeve 38, PNR-1Z December 11th, 2018

The pressure dependent leak off analysis quantifies the opened bedding plane fluid conductivity as a function of normal effective stress. At a normal effective stress ratio of >0.4, the bedding planes are effectively closed, and it is this shut tight closure that gives rise to the induced fluid waves shown in the data for analysis of stage 4), as detailed in the figure of the overall shutin data analysis for sleeve 38.

By placing limits on BHPs during injection, opening of near horizontal bedding planes can be avoided, and thus the heightened risk of induced seismicity, without any or minimal gas production enhancement, can be minimized. The stimulation of sleeve 38 had extremely high BHPs, up to 800bar, far exceeding overburden, opening near horizontal bedding planes, and inducing a M_L 0.1 seismic event during pumping, with an induced M_L 1.5 seismic event occurring shortly after pumping stopped. This stimulation had extremely high injected pressures, far exceeding overburden of 530bar.

The stimulation of sleeve 38, initially induced hydraulic near vertical fractures, whose height growth was terminated by the presence of open or slickensided bedding planes. As such the BHPs rose sufficiently to exceed the normal stress of the near horizontal bedding planes, opening these hyper-stress sensitive bedding planes and thus significantly increasing the risk of induced seismicity, without any or minimal gas production enhancement. This heightened risk of induced seismicity can be avoided by placing limits on BHPs during injection.

October 2016

GeoSierra's Review of 2011 Preese Hall Well Stimulations and

Proposed Alternate Stimulation Method for UK Bowland-Hodder Shale Gas

Executive Summary:

GeoSierra conducted a recent extensive in-house review of the 2011 Preese Hall well stimulations of the Bowland-Hodder shales, and from that review developed a proposed alternate method of well stimulation in the UK Bowland-Hodder shales. The complete review, written in 2017, can be viewed at - http://www.geosierra.com/files/122554754.pdf.

During the Preese Hall 2011 well stimulations, the bedding planes were opened by the high net fracturing pressures and lead to extremely high leak-off and very low fracture fluid efficiency, both contrary to what would be required to enhance production in a nano-Darcy shale. A high frequency of low friction angle 6° slickensided bedding planes dipping at 30°, and thin clay rich bands, fault gouge, parallel or subparallel to bedding, were encountered in the Preese Hall core. These features imped the vertical growth of hydraulic fractures. Once the hydraulic fractures vertical growth is stopped, the net fracturing pressures rise to allow the fracturing fluid to enter and flow along the hyper-stress sensitive bedding planes, thus giving rise to a heighten risk of induced seismicity and minimal enhanced gas production.

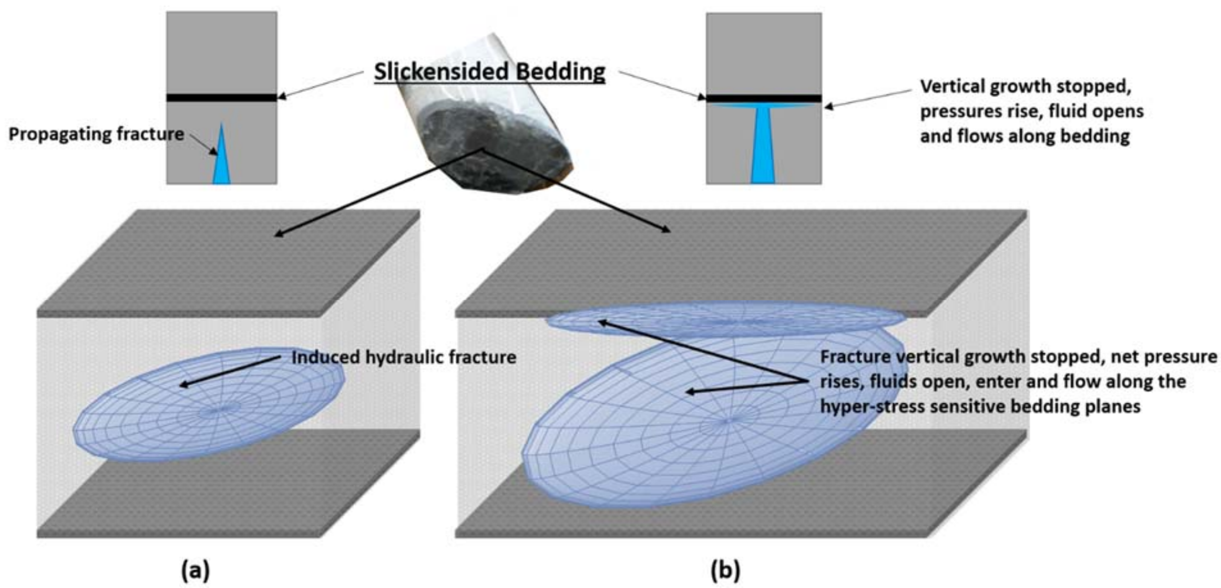


Figure 1. a) Initiated and propagating hydraulic fracture, b) fracture vertical growth impeded, net pressure rises, fluids enter and flow along the hyper-stress sensitive bedding planes.

For example, a hydraulic induced fracture in the stiff Bowland shale under strike-slip stress state can't propagate vertically through the slickensided bedding surfaces and the thin clay rich bands as detected throughout the core in the Preese Hall well at the stimulation depths. From data on stress state estimates and strength of these slickensided bedding planes and thin clay rich bands, a validated numerical model computed that the induced hydraulic fracture will terminate in height growth, net pressure will rise and the fracturing fluid open and flow along the hyper-stress sensitive bedding planes resulting in the high net pressures observed. The bedding planes being hyper-sensitive to stress will yield extremely high leak-off and extremely low fracture fluid efficiency – all features experienced in all of the Preese Hall stimulations.

Due to the hyper-stress sensitivity of the bedding plane hydraulic conductivity to effective stress, significantly elevated pore pressures ~2,500psi were computed some 1,700’ away from the stimulated well, during and after the stage 2 stimulations with a small time lag experienced during injection. The stimulations gave rise to fifty two (52) seismic events > M_L 0, all of which had similar waveforms and were in close proximity to the two largest induced events of M_L 2.3 and M_L 1.5, whose hypocenter was estimated to be ~1,200’ east of the stimulated well.