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Effects of Depressurization on Caverns

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Effects of Depressurization on Cavern and Well Integrity

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Abstract

Crude oil storage caverns at the United States Strategic Petroleum Reserve are depressurized for well workovers. The depressurization changes the forces within the salt around the cavern resulting in increased cavern closure rate, changes in neighboring cavern behaviors, and possible surface subsidence. These effects are all associated with changes within the salt around the cavern. Conclusions about the effects at the Strategic Petroleum Reserve include: the majority of cavern volume is lost at the start of a workover; two behaviors, one an increase in pressurization rate and one a tracking of the workover cavern pressure, are seen in neighboring caverns; surface subsidence must take into account recent workovers for accurate site-wide evaluation. Impacts on cavern integrity and well integrity were not assessed at this time, modeling for integrity will be informed by the results of this study.

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EXECUTIVE SUMMARY

An increase in the number of workovers being done at the United States Strategic Petroleum Reserve has highlighted the need to understand the effects workovers have on caverns. The analysis of various effects depressurization has on caverns have been studied in this work. These effects include volume loss, pressure fluctuations in other caverns on the site, and impacts on the surface. Analysis of workovers on all Strategic Petroleum Reserve caverns since 2010 are included in the volume and pressure analyses; analysis of surface impacts was conducted on the Big Hill site.

Results showed that cavern volume loss, and associated ullage loss, is primarily associated with initial depressurization and not the length of the workover. This is particularly true for workovers taking less than three months. Losses vary by site and cavern construction phase in a way that is consistent with known geologic characterization of the salt at the sites. The effects of back-to-back workovers could not be analyzed due to insufficient data.

Pressure trends for the neighboring caverns of a cavern under workover were also studied. Results show two common behaviors (labeled Behavior I and II) were found. Behavior I is characterized by an increase in the pressurization rate of the neighboring cavern. Behavior II is characterized by a fractional addition of the pressure signal within the cavern under workover to the neighboring cavern pressurization rate. Behavior I was observed at all sites, while Behavior II was most visible at the Big Hill and West Hackberry sites. The Big Hill site results indicate that Behavior II may be influenced by geometry of the caverns or other geologic features, but additional modeling is needed to explore this hypothesis.

Analysis of the surface subsidence data over the Big Hill site has shown that cavern depressurizations and workovers do effect the rate of subsidence of the whole site. Improvements in data collection, particularly the addition of interferometric synthetic aperture radar data, allow for an increased study on immediate effects of workovers that is currently being studied.

Conclusions from this study include:

- Most cavern volume and ullage loss occurs in the first few weeks of a workover.
- Average cavern volume lost can only be estimated on a per-cavern or small group of caverns basis, not by site or across all sites.
- Two behaviors noted during workovers, both appear to occur with regularity.
- Cavern depressurization does effect the rate of subsidence of the site.

Recommendations for future research include:

- The analysis of impact on well integrity (casing strain and microannuli formation).
- Geomechanical modeling of workovers informed and validated by data collected in this report.
- Continued analysis of new interferometric synthetic aperture radar data to isolate subsidence effects due to workovers.

NOMENCLATURE

Abbreviation	Definition
BBL	Barrel (42 US gallons, approx. 0.16 m^3 at standard conditions)
BC	Bayou Choctaw SPR site (in Louisiana)
BH	Big Hill SPR site (in Texas)
BM	Bryan Mound SPR site (in Texas)
CRF	Creep rate factor
DOE	U.S. Department of Energy
FFPO	Fluor Federal Petroleum Operations (SPR M&O contractor)
InSAR	interferometric synthetic aperture radar
M&O	Management and Operations
MBBL	thousand barrels (approx. 159 m^3 at standard conditions)
MIT	Mechanical Integrity Test
MPa	megapascal
MMBBL	million barrels (approx. 158 987 m^3 at standard conditions)
N_2	nitrogen gas
OPR	operating pressure range
PSI	pounds per square inch (a measurement of pressure)
SNL	Sandia National Laboratories (a DOE facility)
SPR	U.S. Strategic Petroleum Reserve (a DOE facility)
U.S.	United States
W/O	Workover (of a well)
WH	West Hackberry SPR site (in Louisiana)

1. INTRODUCTION

Caverns at the United States (U.S) Strategic Petroleum Reserve (SPR) are depressurized for workovers on wells and for well logging, such as multi-arm caliper logs on hanging string wells and SONAR logs on single cavern wells. The past five years have seen an increase in the number of workovers due to aging infrastructure. This increase has led to situations where multiple caverns are being worked over simultaneously, with up to three caverns having zero wellhead pressure simultaneously. Where this situation was unusual in the past, multiple simultaneous workovers are likely to continue in the near future.

This report aims to answer questions regarding the visible effects of a cavern workover on caverns. These effects include volume losses during a workover, pressure fluctuations in other caverns on the site, and impacts on the surface. It does not address impact on cavern integrity, nor does it address the impact workovers have on well integrity. These issues will be addressed in proposed additional work involving geomechanical modeling that can be informed and validated by the data analyses and conclusions in this report.

2. BACKGROUND

During normal operations, SPR caverns are generally held in a *static* or *shut-in* configuration. This means that there are no major fluid movements (drawdowns or withdrawals) taking place. Salt is a dynamic material and is continuously trying to fill in voids, like caverns, to equalize the pressure throughout the salt. The property of the salt that determines the speed at which it moves is defined as the *creep*. When the cavern is full of compressible gases or open to the surface, the salt creep will cause a decrease in the cavern size (closure). The *creep rate* is a function of both the salt creep and the differential pressure between the lithostatic pressure in the salt and the pressure inside the cavern. The *closure rate* is defined as the change in volume over time, and is a function of the creep rate and the cavern geometry and contents.

Because oil, and especially brine, have low compressibility, the cavern volume can only decrease minimally without expelling some of the cavern contents. When a cavern is in a static state, the pressure within the cavern rises continually due to the salt creep. At the wellhead, this pressure is monitored and kept within a specified range, which is defined as the operating pressure range (OPR). When the pressure exceeds the maximum of the OPR, a small volume of fluid is released from the cavern to bring the pressure back down to the bottom of the OPR. The time between fluid transfers when the cavern is static is called a *pressure cycle*. Figure 2-1 shows the wellhead pressures for the oil in a particular cavern. The OPR ranges from 850 pounds per square inch (PSI) to 1,000 PSI (5.86 to 6.9 MPa). There are six full-pressure cycles followed by an interrupted pressure cycle where the cavern was depressurized for workover on a well (November 2016). Figure 2-1 illustrates typical cavern pressure cycles within the operating range.

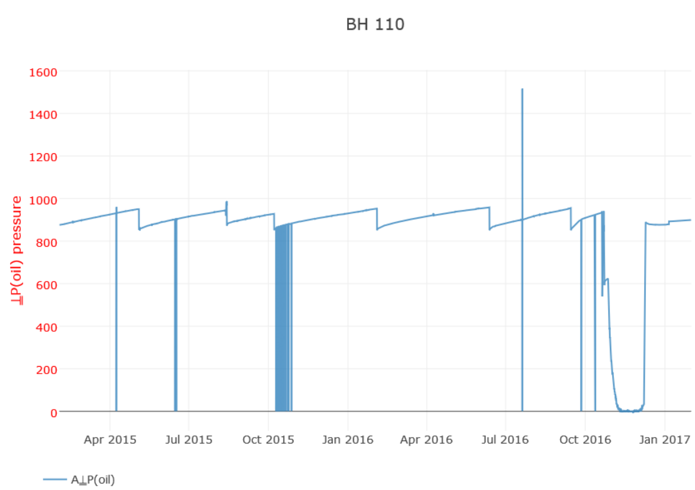


Figure 2-1: Pressure history for BH110 cavern that shows typical pressure cycles are in within the prescribed operating range. In Nov 2016, cavern pressure was brought to zero for a workover.

The OPR is optimized to maintain well integrity at the top of the range and to minimize cavern closure rates. A smaller differential pressure between the cavern pressure and lithostatic pressure means less volume change and a slower rise in pressure during the pressure cycle. Because pressure increases with depth, it is important to understand how the wellhead pressure is related to the downhole pressure (particularly at the casing shoe). Figure 2-2 provides an explanation of the pressures that exist while the cavern is shut in.

The lithostatic pressure along the outer perimeter of the wellbore and cavern will act inward toward the wellbore and cavern centerline, and varies linearly with depth. This means it remains constant in time. Lithostatic pressure acts in the same direction as salt creep. The pressure on the inner perimeter of the cavern and any unlined portion of the borehole is comprised of the fluid pressure at depth plus the wellhead pressure. Like the lithostatic pressure, fluid pressure increases with depth but acts in the opposite direction from the lithostatic pressure. The difference between the two curves is defined as the *pressure differential*.

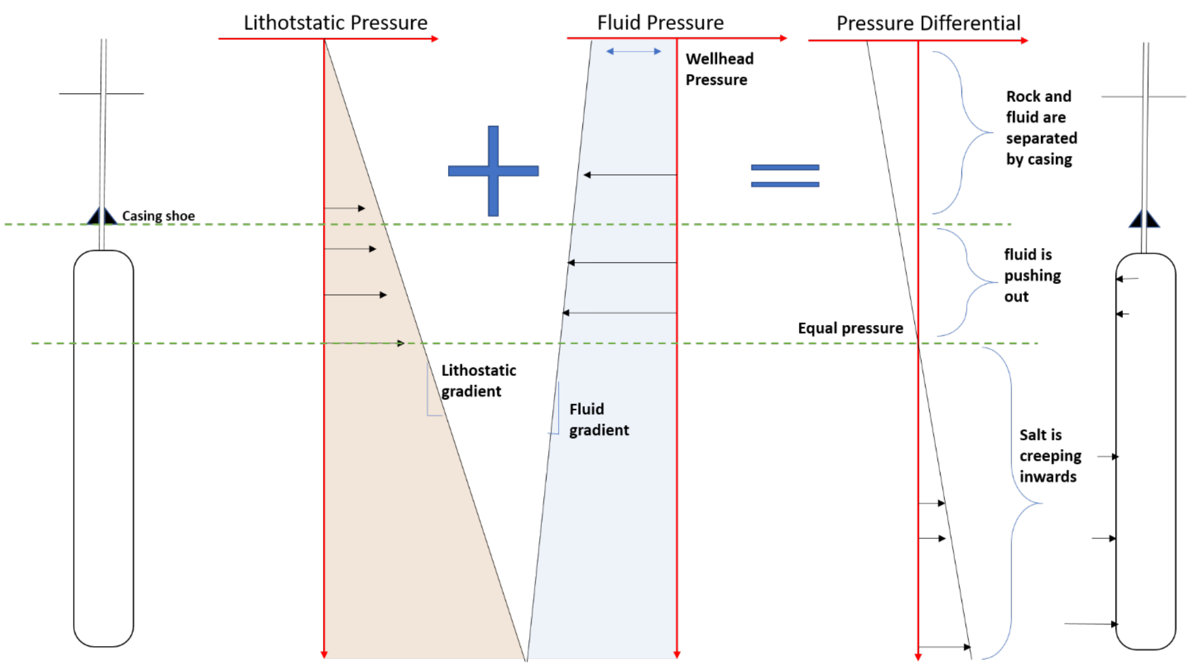


Figure 2-2: Cartoon schematic of pressure distribution in salt cavern if the pressure range is exceeded; equal pressure should occur within the cased part of the well.

When the cavern pressure is held within the OPR, the pressure differential is relatively small. As seen in Figure 2-2 above, the fluid pressure at the surface is larger than the lithostatic pressure at the surface due to the addition of the wellhead pressure. Moving down through the well and into the cavern, an equilibrium point (zero pressure differential) is reached; this point is generally within the cased portion of the well.

Because the fluids do not compress, the pressure differential causes strain on the salt. In an infinitely thin skin of salt on the salt/fluid boundary, and an infinitely thin skin of fluid the same boundary, the forces must be equal. Because salt is compressible and the fluids are not, this causes a pressure gradient within the salt where the boundary skin of salt is at the hydrostatic pressure and at some point deeper into the salt the pressure has increased to the lithostatic pressure. This causes an area of strain within the salt which is highest on the cavern sides and nonlinearly decreases as it moves into the salt. The distance the strain extends into the salt increases with time and inversely with differential pressure. This strain becomes important during cavern workovers.

For safety reasons, SPR personnel perform workovers on wells (such as remediation and many logging activities) with the wellhead at zero pressure. This means that the pressure differential within the cavern changes significantly. Figure 2-3 shows this change conceptually. Without the additional wellhead pressure, the pressure differential points inward throughout the entire cavern and well. Because the cavern is no longer shut-in, salt creep immediately causes volume loss rather than a pressure increase. In addition, the pressure differential is at the maximum possible when the wellhead pressure is zero. This means there is maximum salt creep and cavern closure.

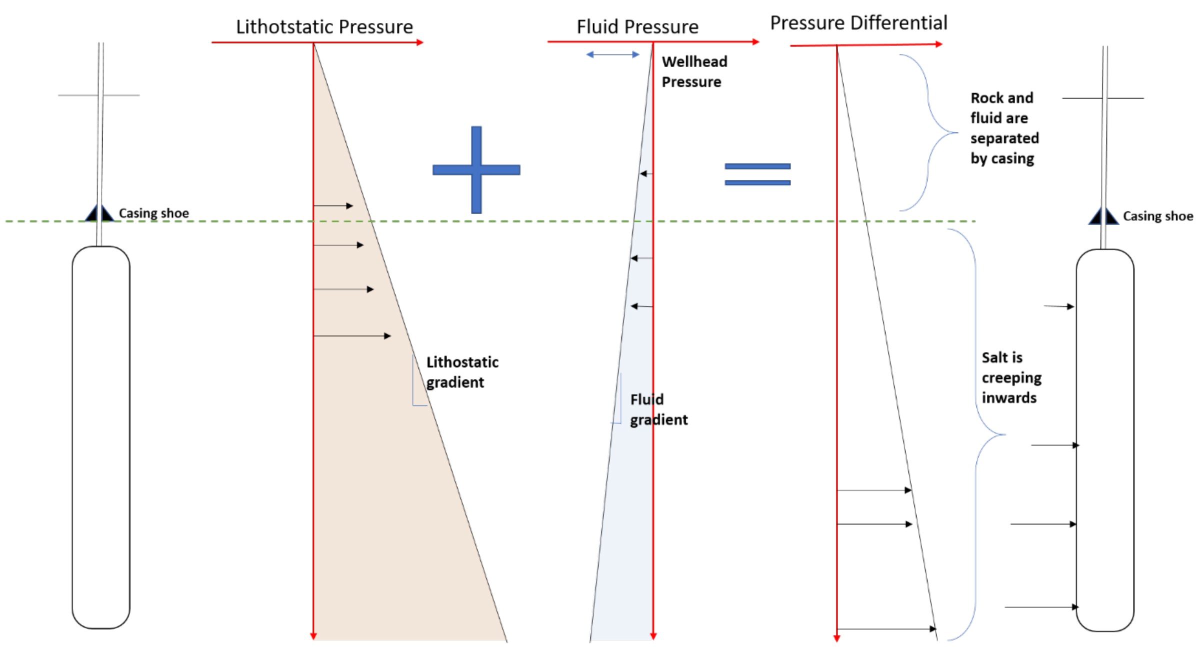


Figure 2-3: Schematic of pressure distribution in a depressurized salt cavern.

To reduce pressure at the wellhead to zero, fluid must be withdrawn from the cavern. To avoid the possibility of moving the brine below the end of the hanging string, oil is typically removed. Because the contents are pressurized, there is no need to pump out the oil because it will simply be forced out as the volume of the cavern shrinks due to the "pent up" salt creep that has previously been seen as pressure increase. Additionally, the strain that has moved into the salt around the cavern will push the salt inward as the strain redistributes toward an equilibrium. This release of strain leads to some additional cavern volume loss, though the total loss is still less than what would be seen in a depressurized cavern over the same time period. As the workover proceeds, it is necessary to allow small volumes of fluid out at regular intervals to keep the wellhead pressure at zero.

The Oil that is removed from a cavern for a workover is usually injected into another cavern. Because the second cavern needs to remain within its OPR, brine is withdrawn from this second cavern to maintain its total volume. When the workover is complete, brine is typically used to repressurize the cavern that underwent workover. However, the volume of fluid needed to repressurize a cavern is always less than the fluid that was removed to reach zero wellhead pressure. In part, this is due to the creep that occurs during the workover, but there is also some permanent cavern volume loss due to the redistribution of the strain within the salt.

The redistribution of strains can have far-reaching effects beyond the cavern itself. Radiating outward, nearby caverns frequently show a change in the wellhead pressure when a cavern is depressurized. The geomechanics of these changes are still being studied; however, the effects are clearly visible in pressure records which can be analyzed without modeling. Radiating upward, the depressurization of a cavern can impact the surface even through caprock. This can be visible to surveys and other subsidence monitoring as changes in ground level or orientation. In both these cases, understanding the data is critical in differentiating between the normal effects of a cavern undergoing workover and something that may indicate that there is an anomaly needing further investigation.

This report documents three analyses to help understand the effects of cavern depressurizations for workover on cavern systems at the SPR. It does not incorporate the geomechanical modeling, but the results should help inform the modeling and provide data for model validation. This report also does not make any inferences or evaluations of the effect of workovers on cavern integrity or the impact on wells. The three sections include:

Section 3: The impact of workover length on cavern volume loss as determined by flow measurements.

Section 4: The impact of depressurization on pressures seen within neighboring caverns.

Section 5: The impact of fully depressurized caverns on surface subsidence and visibility with advanced survey tools (such as InSAR [interferometric synthetic aperture radar]).

These sections will be followed by a summary of the conclusions and proposed work needed to fully understand the geomechanical processes at work and impacts on integrity. Data from all four sites were analyzed for workovers between 2010 and 2017. Additional tables and figures will be provided in the appendices.

3. WORKOVER EFFECTS ON CAVERN VOLUME

As described in the previous section, an increased pressure differential leads to an increased closure rate; therefore, a cavern under pressure loses less volume per day than a cavern that is depressurized when pressure is measured at the wellhead. Because workovers occur at zero wellhead pressure, the longer the workover takes the more cavern volume is lost; however, the magnitude of this loss has not been well documented for the SPR caverns.

3.1. Cavern Volume

Calculating cavern volume loss analytically is difficult because it is affected by the creep properties of the salt, the cavern geometry, and the pressure differential as a function of depth. This loss can be calculated empirically by two different methods. The first method is to measure the volume of the cavern with SONAR before and after a workover. The drawback to this method is that it is expensive and it requires the cavern to be depressurized during the SONAR. Complex SONAR maps of caverns also have measurement limitations that limit usefulness in measuring changes of relatively small magnitudes (i.e., two months of closure).

The second method is to measure the fluid flowing in and out of the cavern. Depressurization from the OPR involves fluid flowing out of the cavern, and repressurization back to the OPR involves moving fluid into the cavern; therefore, cavern closure means that these two volumes can never be equal. Assuming that the same fluid with the same properties (i.e., density, temperature, compressibility) is injected after the workover, and that the cavern pressure is raised back to the original pressure. The difference between the two fluid volumes should equal the volume lost to salt creep.

In practice, the fluid properties are not the same. As described in the background section, it is typical to withdraw oil and inject brine to avoid contaminating the brine string with oil. The oil that comes out is typically hot—approximately the temperature of the salt at the top of the cavern (110 degrees Fahrenheit [˚F] to 130 ˚F). Brine that goes in is usually at the ambient surface temperature (50˚F to 80˚F). All these differences make the difference in fluids an imperfect measure of cavern volume loss.

Flow into and out of the caverns is metered at the surface and is the most eas data available. The error introduced by assuming that the pressures and the fluids extracted and injected are the same is at least several orders of magnitude less than the volumes involved. For example, at 900 PSI, a change of 1 PSI is approximately the equivalent of a volume change of 70 barrels (BBL) of oil. The average volume of oil removed over the course of a workover is 179 million BBL, which is over three orders of magnitude greater. The errors introduced by simplifying the fluid properties are of a similar magnitude. Sandia believes that even with simplifications, the differential volume method is sufficiently accurate to provide an overall understanding of workover effects.

3.2. Ullage Volume

Ullage volume refers to the ullage of a cavern or the ullage at a site.

The ullage of a cavern is the volume available for product storage. Figure 3-1 shows the different regions within an oil storage cavern. The ullage of a cavern changes as fluid is added and removed. To calculate the volume directly, the three-dimensional cavern geometry, the current oil-brine interface level, and the string length must be known. The cavern geometry can be determined by SONAR and the oil-brine interface through several logging methods. The ullage of a site is the sum of the ullage in all caverns.

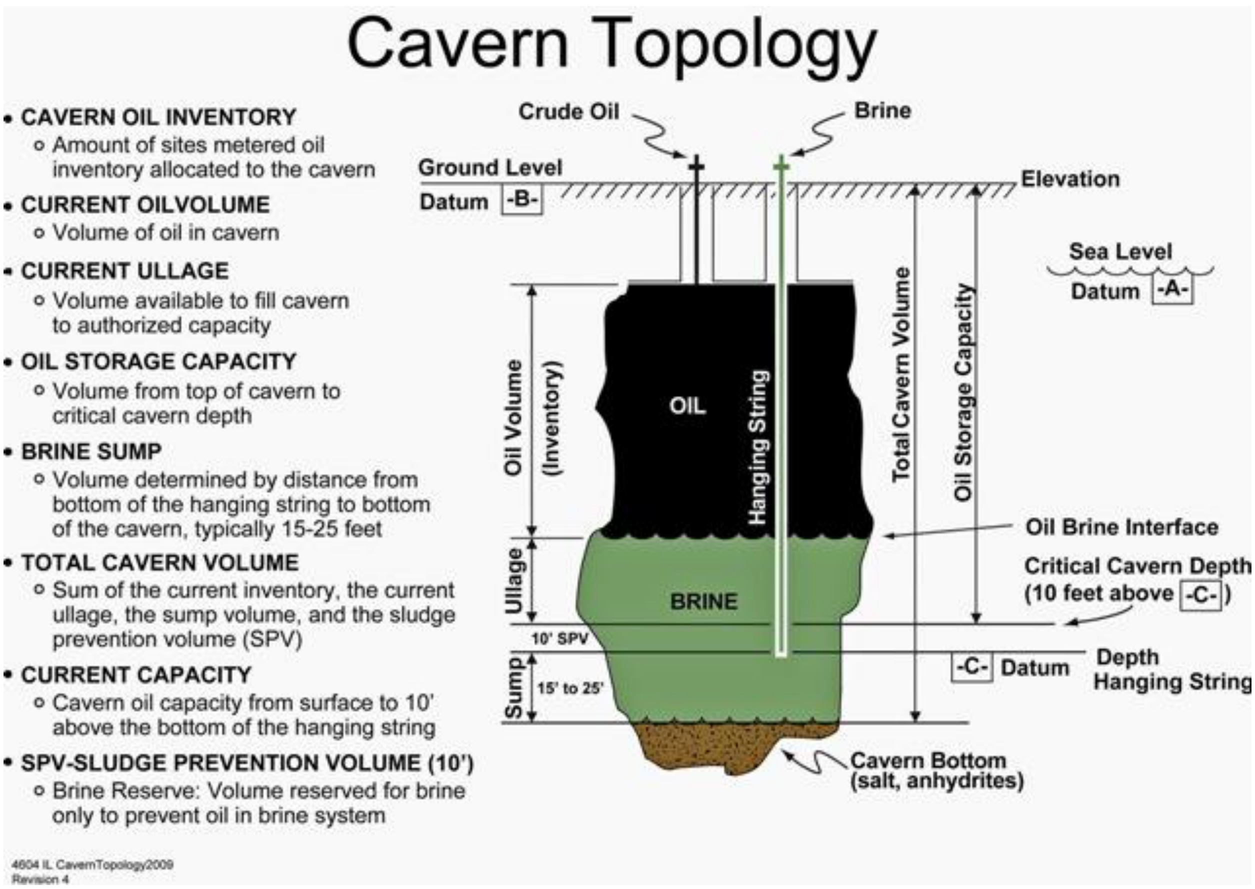


Figure 3-1: Illustration of ullage definition in a solution mined cavern used for oil storage.

It is difficult to calculate actual change in ullage in a single cavern that undergoes workover; however, it is possible that the ullage in the cavern itself actually increases as oil is taken out and brine is replaced. While the cavern volume will decrease, the volume available for oil may increase.

The ullage of the site, however, is guaranteed to decrease after a cavern is worked over. Essentially, the total cavern volume of the site has decreased, but the oil volume has remained the same. Because this loss must come from somewhere, it comes from loss of brine volume, and therefore, the ullage lost is some fraction (close to 1) of the cavern volume lost. It is a fraction because one additional factor not previously discussed, which is a volume increase due to dissolution of salt due to incompletely saturated brine. While this volume is typically very small for the volumes involved in a workover, it is important to remember it is non-zero, and if fresh water were used, it could become significant.

A summary of the simplifications and assumptions made, and the method of calculating ullage is as follows:

- Assume the fluid in and the fluid out are sufficiently similar for differences in hydrostatic gradients to be small.
- Assume that flow meters are accurate for the volumes considered.
- Assume that brine injection is with nearly fully saturated brine (not fresh water) and that leaching and dissolution are minimal.
- Assume that the pressure before and after workover are close enough for the equivalent volume difference is small compared to cavern closure volume.

An assumption that cannot be made is that the geometries and salt properties of different caverns and sites are equal. The four sites are known to have significantly different salt properties, including some sites where the salt varies significantly even across the site. Caverns are also at different depths and different shapes (particularly Phase I caverns). Therefore, generalizations must be limited to individual caverns or groups of caverns at the same site and SPR phase.

3.2.1. Per-Site Analyses

Because volumes between caverns vary widely, it would be useful to normalize the volume lost by some common factor. Normalizing by a volume, such as the cavern volume, is the logical choice. The other logical choice is to normalize over time. In the tables which follow, there are several different metrics presented, all of which convey slightly different information about cavern volume loss. The following symbols are used: ΔV represents the cavern volume lost during a specific workover, V_{cav} is the cavern volume, V_u is a theoretical site-wide ullage volume.

Table 1 through Table 4 provide information for each cavern analyzed. The first column contains the cavern name followed by the number of workovers available for analysis. The third column gives the average cavern volume lost per workover, in MBBL; this provides some information about each individual cavern that was analyzed. This value is normalized by the cavern volumes in column five. Column four contains the average barrels lost per day of workover. This information becomes important when analyzing when the majority of cavern volume is lost (see Section 3.1).

The remaining columns in the right half of the table, provide a quick guide to the impact an average workover on a specific cavern has on site-wide ullage. Theoretical ullage values are provided, ranging from V_u =10 thousand barrels up to V_u = 5 million barrels. Knowing the current ullage at the site and the average loss for a specific cavern, the impact of a workover on the cavern can then be estimated. The range is taken from examining 2014 ullage calculations, where individual caverns had as little as a few thousand barrels of ullage, and from a site-wide perspective, broken into sweet and sour, most sites had between one and five million barrels of ullage; BM had an atypical 17 MMBBL ullage at that time due to oil loans.

The average workover length was 60 days at Bryan Mound, 75 days at Big Hill, and 90 days at both West Hackberry and Bayou Choctaw.

Table 1. Calculated volume lost during workover for BC caverns.

Cavern	Num. W/O in calc.	ΔV per W/O (MBBL)	ΔV/day (BBL)	$\Delta V/V_{cav}$ (%)	Equivalent ullage loss given theoretical V_u					
					V_u=10 MBBL	V_u=50 MBBL	V_u= 100 MBBL	V_u= 500 MBBL	V_u=1 MMBBL	V_u=5 MMBBL
BC-15/17	1	-33	-500	-0.26%	>V_u	66%	33%	7%	3%	0.7%
BC-C018	1	-90	-490	-0.48%	>V_u	>V_u	91%	18%	9%	1.8%
BC-C019	1	-49	-590	-0.38%	>V_u	98%	49%	10%	5%	1.0%
BC-C101	1	-55	-1000	-0.42%	>V_u	>V_u	55%	11%	6%	1.1%
BC Site	**4**	**-57**	**-620**	**-0.39%**	**100%**	**100%**	**57%**	**11%**	**6%**	**1.1%**

Table 2. Calculated volume lost during workover for BM caverns.

Cavern	Num. W/O in calc.	ΔV per W/O (MBBL)	ΔV/day (BBL)	$\Delta V/V_{cav}$ (%)	Equivalent ullage loss given theoretical V_u					
					V_u=10 MBBL	V_u=50 MBBL	V_u= 100 MBBL	V_u= 500 MBBL	V_u=1 MMBBL	V_u=5 MMBBL
BM-C001	1	-25	-220	-0.29%	>V_u	50%	25%	5%	3%	1%
BM-C002	1	-19	-590	-0.27%	>V_u	38%	19%	4%	2%	0%
BM-C004	2	-43	-1400	-0.19%	>V_u	86%	43%	9%	4%	1%
BM-C005	1	-8.3	-170	-0.02%	83%	17%	8%	2%	1%	0%
BM-C101	3	-53	-1600	-0.35%	>V_u	>V_u	53%	11%	5%	1%
BM-C102	1	-32	-200	-0.22%	>V_u	64%	32%	6%	3%	1%
BM-C103	4	-76	-2500	-0.52%	>V_u	>V_u	76%	15%	8%	2%
BM-C105	1	-64	-1700	-0.56%	>V_u	>V_u	64%	13%	6%	1%
BM-C106	1	-12	-650	-0.94%	>V_u	24%	12%	2%	1%	0%
BM-C107	1	-50	-2400	-0.33%	>V_u	>V_u	50%	10%	5%	1%
BM-C108	1	-31	-1100	-0.25%	>V_u	62%	31%	6%	3%	1%
BM-C109	3	-77	-2900	-0.60%	>V_u	>V_u	77%	15%	8%	2%
BM-C110	2	-54	-1800	-0.48%	>V_u	>V_u	54%	11%	5%	1%

Cavern	Num. W/O in calc.	ΔV per W/O (MBBL)	ΔV/day (BBL)	$\Delta V/V_{cav}$ (%)	Equivalent ullage loss given theoretical V_u					
					V_u=10 MBBL	V_u=50 MBBL	V_u= 100 MBBL	V_u= 500 MBBL	V_u=1 MMBBL	V_u=5 MMBBL
BM-C111	2	-69	-3100	-0.55%	$>V_u$	$>V_u$	69%	14%	7%	1%
BM-C112	3	-130	-1800	-0.99%	$>V_u$	$>V_u$	$>V_u$	26%	13%	3%
BM-C114	1	-76	-2200	-0.87%	$>V_u$	$>V_u$	76%	15%	8%	2%
BM-C115	1	-78	-4300	-0.70%	$>V_u$	$>V_u$	78%	16%	8%	2%
BM-C116	1	-77	-2800	-0.63%	$>V_u$	$>V_u$	77%	15%	8%	2%
BM Site	**30**	**-67**	**-1900**	**-0.51%**	***100%***	***100%***	**50%**	**11%**	**5%**	**1%**

Table 3. Calculated volume lost during workover for WH caverns.

Cavern	Num. W/O in calc.	ΔV per W/O (MBBL)	ΔV/day (BBL)	$\Delta V/V_{cav}$ (%)	Equivalent ullage loss given theoretical V_u					
					V_u=10 MBBL	V_u=50 MBBL	V_u= 100 MBBL	V_u= 500 MBBL	V_u=1 MMBBL	V_u=5 MMBBL
WH-C007	1	-16	-160	-0.12%	$>V_u$	32%	16%	3%	2%	0.3%
WH-C008	1	-124	-740	-1.19%	$>V_u$	$>V_u$	$>V_u$	25%	12%	2.5%
WH-C009	1	-74	-1600	-0.73%	$>V_u$	$>V_u$	74%	15%	7%	1.5%
WH-C011	1	-45	-990	-0.54%	$>V_u$	90%	45%	9%	5%	0.9%
WH-C101	1	-56	-640	-0.46%	$>V_u$	$>V_u$	56%	11%	6%	1.1%
WH-C102	1	-45	-400	-0.38%	$>V_u$	90%	45%	9%	5%	0.9%
WH-C103	1	-29	-460	-0.24%	$>V_u$	58%	29%	6%	3%	0.6%
WH-C105	2	-70	-1600	-0.47%	$>V_u$	$>V_u$	70%	14%	7%	1.4%
WH-C107	1	-101	-1200	-0.80%	$>V_u$	$>V_u$	$>V_u$	20%	10%	2.0%
WH-C108	1	-219	-1100	-1.83%	$>V_u$	$>V_u$	$>V_u$	44%	22%	4.4%
WH-C111	1	-53	-1200	-0.45%	$>V_u$	$>V_u$	53%	11%	5%	1.1%
WH-C112	1	-172	-2900	-1.55%	$>V_u$	$>V_u$	$>V_u$	34%	17%	3.4%
WH-C113	1	-104	-800	-0.88%	$>V_u$	$>V_u$	$>V_u$	21%	10%	2.1%
WH-C114	1	-117	-550	-1.07%	$>V_u$	$>V_u$	$>V_u$	23%	12%	2.3%
WH-C115	1	-78	-1600	-0.73%	$>V_u$	$>V_u$	78%	16%	8%	1.6%
WH-C117	4	-88	-1500	-0.73%	$>V_u$	$>V_u$	88%	18%	9%	1.8%
WH Site	**20**	**-86**	**-1200**	**-0.74%**	***100%***	***100%***	**87%**	**17%**	**9%**	**1.7%**

Table 4. Calculated volume lost during workover for BH caverns.

Cavern	Num. W/O in calc.	ΔV per W/O (MBBL)	ΔV/day (BBL)	$\Delta V/V_{cav}$ (%)	Equivalent ullage loss given theoretical V_u					
					V_u=10 MBBL	V_u=50 MBBL	V_u= 100 MBBL	V_u= 500 MBBL	V_u=1 MMBBL	V_u=5 MMBBL
BH-C101	1	-140	-3000	-0.99%	$>V_u$	$>V_u$	$>V_u$	28%	14%	2.8%
BH-C102	1	-170	-2900	-1.27%	$>V_u$	$>V_u$	$>V_u$	34%	17%	3.4%
BH-C103	4	-90	-1600	-0.67%	$>V_u$	$>V_u$	90%	18%	9%	1.8%
BH-C104	2	-110	-1700	-0.83%	$>V_u$	$>V_u$	$>V_u$	22%	11%	2.2%
BH-C105	3	-110	-2100	-0.87%	$>V_u$	$>V_u$	$>V_u$	22%	11%	2.2%
BH-C106	2	-120	-2300	-0.91%	$>V_u$	$>V_u$	$>V_u$	24%	12%	2.4%
BH-C107	2	-110	-2000	-0.83%	$>V_u$	$>V_u$	$>V_u$	22%	11%	2.2%
BH-C108	2	-110	-1600	-0.83%	$>V_u$	$>V_u$	$>V_u$	22%	11%	2.2%
BH-C109	1	-170	-1300	-1.37%	$>V_u$	$>V_u$	$>V_u$	34%	17%	3.4%
BH-C110	1	-130	-2000	-1.00%	$>V_u$	$>V_u$	$>V_u$	26%	13%	2.6%
BH-C111	1	-170	-3200	-1.31%	$>V_u$	$>V_u$	$>V_u$	34%	17%	3.4%
BH-C112	1	-110	-1400	-0.83%	$>V_u$	$>V_u$	$>V_u$	22%	11%	2.2%
BH-C113	2	-150	-1600	-1.14%	$>V_u$	$>V_u$	$>V_u$	30%	15%	3.0%
BH-C114	2	-180	-2000	-1.44%	$>V_u$	$>V_u$	$>V_u$	36%	18%	3.6%
BH Site	**25**	**-124**	**-2000**	**-0.96%**	***100%***	***100%***	***100%***	**27%**	**13%**	**2.7%**

3.2.2. Volume change analyses

Based on the results presented in Tables 1–4, several conclusions can be made. First, each site behaves differently, and within the site different caverns show different closure rates. Caverns should be grouped for analysis by site and by cavern construction phase. Figure 3-2 shows a box-and-whisker statistical plot for these groupings. The box, in blue, shows the 25th to 75th percentile range for the volume lost; the red line inside the box represents the mean value. The whiskers, dashed lines with a line marking the end, represent the range for the 5th to 95th percentile of the volume changes. Outliers are marked with red plus signs.

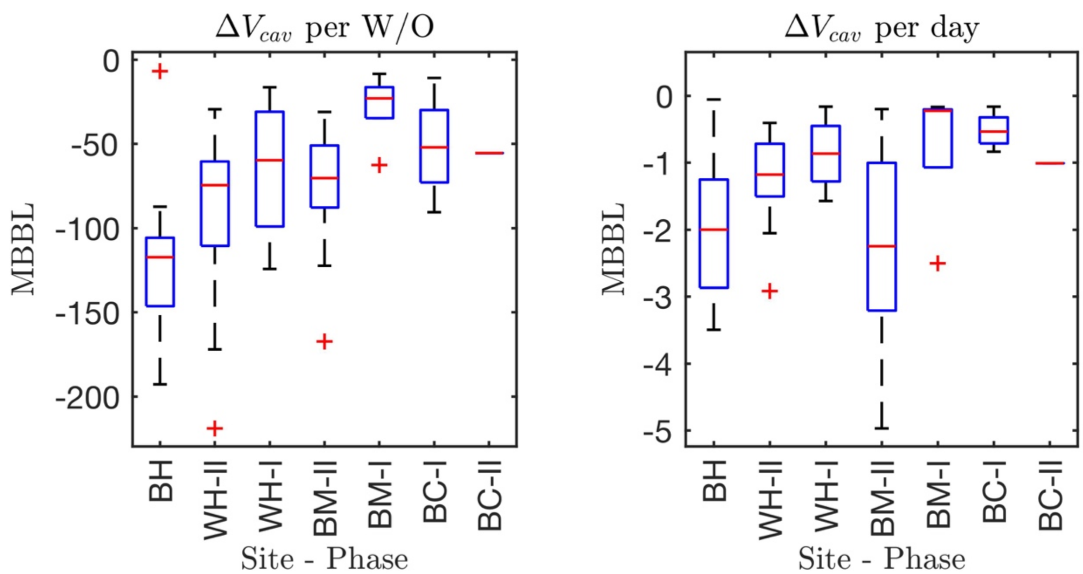


Figure 3-2. Box-and-whisker statistical plot showing mean and ranges of total cavern volume lost per workover and average daily cavern volume change during a workover by site and SPR construction phase.

This results shown in Figure 3-2 are consistent with general geologic characterizations of the sites. Bayou Choctaw has the least active salt and shows the least amount of closure during workovers. Big Hill and West Hackberry are considered to have the most dynamic salt and shows the highest closures. Bryan Mound shows the highest average change per day, but also had, on average, the shortest workovers. Bryan Mound Phase I caverns also had the least volume lost on average across all groups, since these caverns are comparatively shallow compared to other caverns and thus have much lower lithostatic pressure to cause creep.

3.2.3. Correlation Between Depressurization Time and Cavern Closure

The correlation between very high rate of closure at Bryan Mound, with short workovers, and much lower rates of closure at West Hackberry indicated a possible link between depressurization time and cavern closure volumes. Analysis shows that total cavern volume lost is typically consistent for a specific cavern regardless of the length of the workover (or the length of time the cavern is completely depressurized). Figure 3-3 shows this result graphically; each symbol represents a different set of caverns or site, and each point represents a single workover. While there appears to be some trend of greater losses with longer workovers (particularly because of the data shown for W/O's longer than 150 days), this is expected; cavern creep will continue throughout the workover. What is significant is that the slope of that change is very small, and the R^2 value is low, indicating no significant correlation (less than 0.15). The majority of the cavern volume lost is lost regardless of workover length.

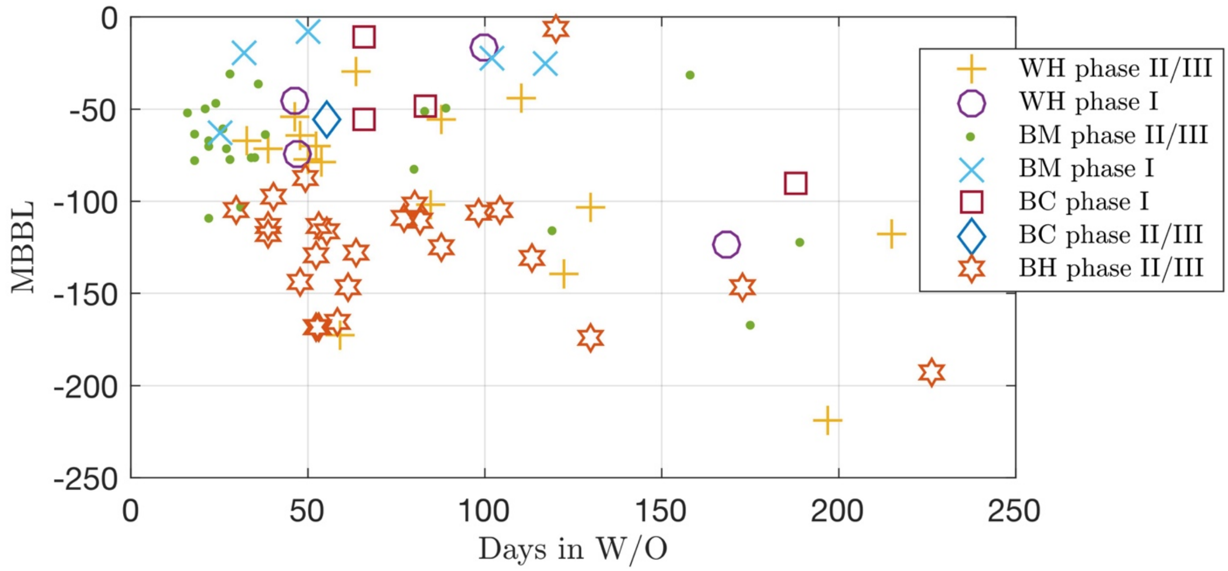


Figure 3-3. Cavern volume lost as function of length of workover. Markers by site and SPR phase.

Looking at the calculated volume change per day, Sandia see a supporting trend. The highest rate of closure occurs in short workovers. Long workovers have a much lower volume change per day. This is true both for the total workover length (including depressurization and repressurization time) and when looking only at the time the cavern is at zero wellhead pressure. The conclusion is that the majority of volume loss, including irrecoverable volume loss, occurs during the first few weeks of a workover, after which creep returns to normal. Figure **3**-**4** shows this effect; the volume lost during each workover is plotted against the total workover time (time not at OPR) and against the time the cavern was at zero pressure.

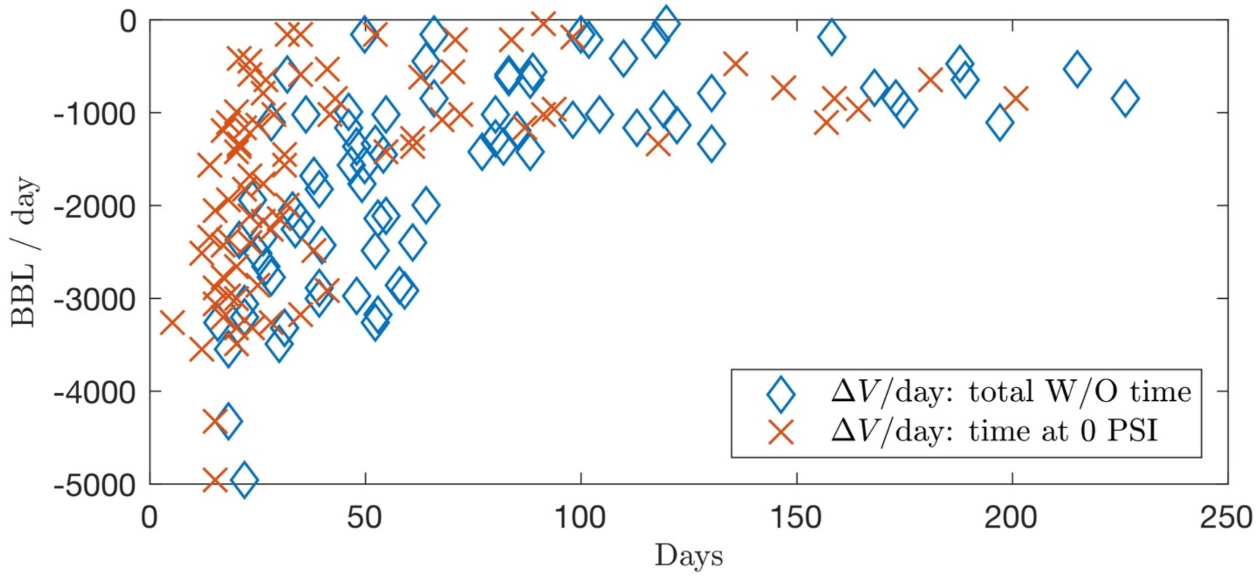


Figure 3-4. Cavern volume lost averaged over days in workover for equivalent daily closure rate. Plotted against both total W/O length and time cavern held at zero-pressure.

3.3. Closely Spaced Repeated Workovers

There are few cases where workovers were repeated with less than one year between the start dates. There is only one case where the second workover occurred within three months of the end of the first. This occurred at West Hackberry 117 in 2012-2013. There are too few data points to make any generalizations, even regarding WH-C117. The workover in 2012 had a volume loss of 140 MBBL. The workover in 2013, 94 days later, had a volume loss of 70 MBBL. However, the first workover was 122 days long and the second was only 33 days long; the first was four times longer, and thus had much longer for the normal creep to affect the volume. Two additional workovers, in late 2013 and 2015 were of similar length to the second workover, around one month, and showed the same, 60 to 70 MBBL volume loss.

This lack of data makes it impossible to make a determination as to whether closely spaced workovers lose more or less volume that a single, long workover.

4. WORKOVER EFFECTS ON NEIGHBORING CAVERNS

During a workover, cavern depressurization causes additional flow of the salt due to the increased pressure differential (see Section 2). The changes in the differential can cause effects in neighboring caverns that are visible in their wellhead pressure measurements. The response of neighboring caverns has been seen many times, particularly at the Big Hill site. In Checkai, et al. (2014), a characteristic behavior was identified at Big Hill where neighboring caverns show an increase in the pressurization rate when a cavern is depressurized. During this study, a differing behavior, that also appears to be a “normal” behavior in certain circumstances, was discovered, and is described here.

Workovers were identified for all four SPR sites from 2010 through 2017, the period for which ‘raw’ DCS/SCADA data was available. Prior to 2010, the historical DCS/SCADA data was available in New Orleans on backups, and daily pressures were recorded in CAVEMAN; daily data was not sufficient for the analysis presented here. Some of the results from the analysis done for the Big Hill site are also available in Hart, et al., 2017.

In addition to the effects of a single cavern being depressurized, the sheer number of caverns means that more than one cavern is undergoing workover simultaneously. The effects of multiple workovers was also examined by comparing pressure responses in the neighboring caverns. The following are several possible scenarios:

1. A single cavern is depressurized.
2. Two or more caverns undergo workovers and the periods of depressurization overlap, and:
    a. The caverns under workover are direct neighbors.
    b. The caverns under workover share neighbor caverns, but are not direct neighbors themselves.
    c. The caverns share no neighbors and are not neighbors themselves.

The following two behaviors (described in detail in the following section) are:

I. Depressurization in Cavern A causes an increased rate of pressurization – i.e., increased closure rate in Cavern B. This increase is sharpest at the beginning of depressurization and occurs again during repressurization.

II. Depressurization in Cavern A is “tracked” by Cavern B at a fractional level. In other words, after de-trending the pressurization and overlaying the wellhead pressures for Caverns A and B, the pressures have the same shape and pattern, with the pressure changes in Cavern B a fraction of a percent of the pressure changes in Cavern A.

Each site will be discussed in turn, with emphasis given to the Big Hill site in the text, and full information for all sites provided in Appendix B.

4.1. Behaviors identified

The various types of interactions discussed above can be seen clearly in the pressure logs taken during the Big Hill Cavern 104 workover in 2016 and the subsequent and partly concurrent workover on Big Hill Cavern 109. In Figure 4-1, the behaviors are shown during the depressurization of Cavern 104. The cavern was depressurized in two stages: in the first, lasting only a day, the pressure was dropped to around 700 PSI from approximately 950 PSI. The second stage occurred a week later, and lasted just over a week. The second stage shows an exponentially decreasing flow out of the cavern as cavern pressure went to zero. This type of depressurization, in two stages, is used with close to the same frequency as using a single depressurization event.

In the example, the first stage is fast enough that it is hard to discern the responses. The second stage, however, shows the two different behaviors clearly. In the Figure 4-1 (middle), the wellhead oil annulus pressure is shown for the surrounding caverns. In five of the caverns, the characteristic increase in pressurization rate – Behavior I – can be seen (dashed lines); Cavern 105 (purple dashed lines) shows a change in rate from approximately 5 PSI/week to 20 PSI/week. The solid line, representing Cavern 108, shows Behavior II; it is included with the Behavior I pressure logs to show the very different scale of Behavior II responses.

Figure 4-1 (bottom) shows the brine response in Cavern 113 in a separate axis to allow for the detail of a Behavior II response to be clearly seen. The "heartbeat"-like fluctuations in the pressure log is due to daily fluctuations at the pressure transducer. It is uncertain if these fluctuations are due to solar radiance heating the surface tubing from wellhead to instrument, or atmospheric pressure, or some other surface effect, but it is certain that these are *instrumentation* fluctuations, not changes within the cavern. Despite this surface noise, the impact of the depressurization in Cavern 104 can be seen from 20 July to 28 July in Cavern 113, as pressurization stops, drops slightly, then continues back at the original pressurization rate after Cavern 104 is fully depressurized.

It is very important to note that the Behavior II effect is not true cavern "communication" as is seen in caverns with small pillar-to-diameter ratios (such as Bayou Choctaw Caverns 15 and 17, which must be operated simultaneously). The Behavior II response is typically only a few PSI decreased in response to a hundreds of PSI change in the cavern being depressurized. The cause of this behavior is currently unidentified, but modeling is being planned to try to identify possible salt properties that may make this response occur. The typically small magnitude of the response also makes it difficult to identify in pressure logs, as the daily fluctuations in sensor noise combined with DCS historian compression algorithms make mask the behavior when it is less than a 1 PSI change. It is also possible that Behavior II always occurs at some minute level, but is overwhelmed but the Behavior I responses when those occur. The data at this time is not sufficiently accurate to discover the answers to those possibilities.

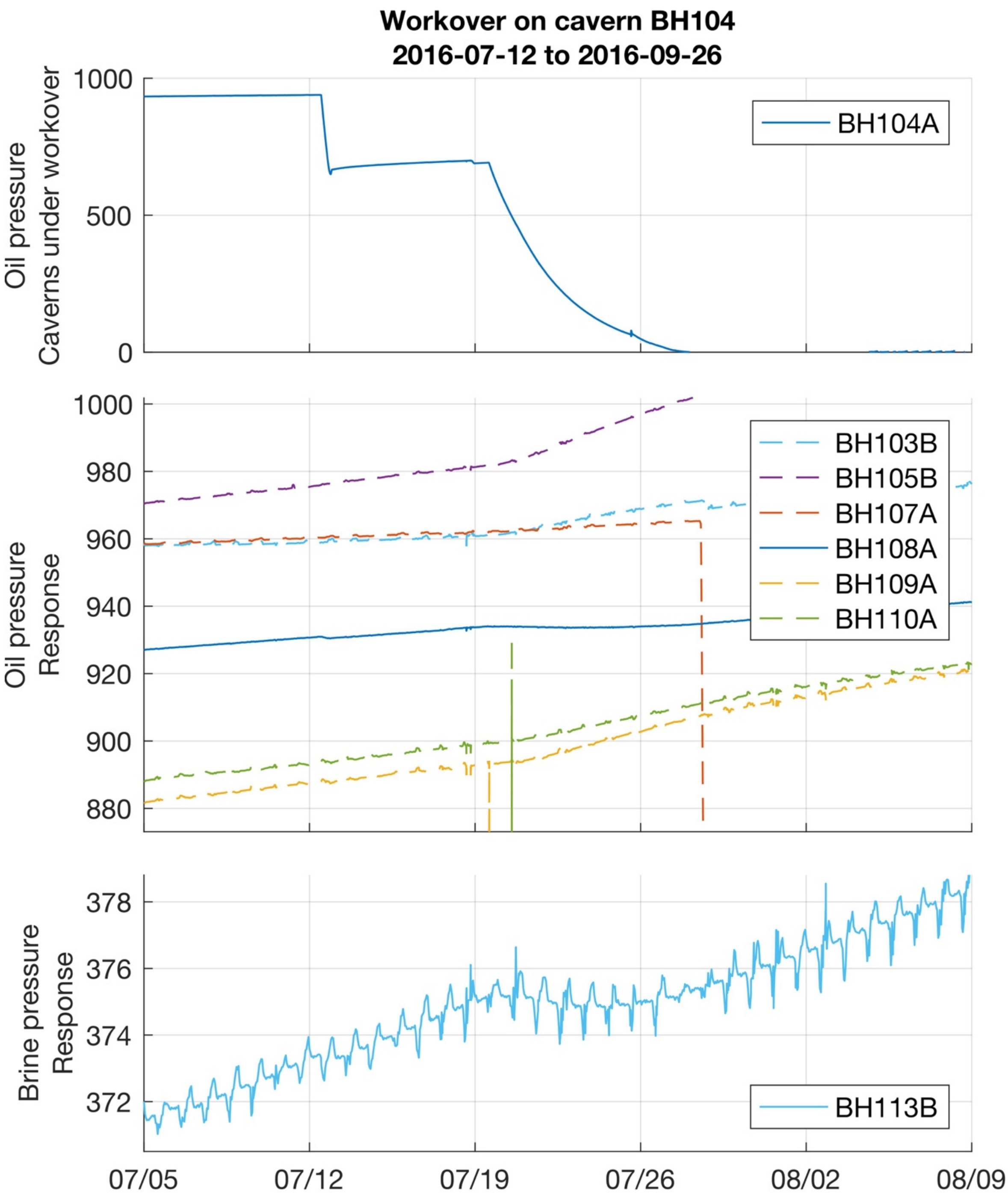


Figure 4-1. Different behaviors observed in neighboring caverns during a W/O. (Top) shows the pressure within the cavern undergoing W/O; (middle) shows oil responses; (bottom) shows a brine response.

In overlapping depressurizations, it can be more difficult to identify behaviors. In Figure 4-2, the pressure responses are shown when Big Hill Cavern 109 is depressurized for W/O midway through the workover on Cavern 104, shown previously. The stage one depressurization, marked with "A," produces Behavior II responses in Cavern 113 and 112 pressure logs (circled along arrow "A"). There is also a Behavior II response in Cavern 108, as the pressurization rate changes between points A and B; Cavern 113 sees the pressurization rate go to zero, and the impact is much clearer than in the Cavern 108 response. Figure 4-2 also shows pressure cycling of Cavern 110, which makes it difficult to verify that it responded, though it seems likely.

Points C and D on Figure 4-2 show another effect of workovers, not focused on in this report, which is the re-pressurization after workover. At point C, the pressurization rate of both caverns 113 and 108 jump during the fluid transfer, and go back to normal immediately afterwards. While in this specific example, both these caverns show a Behavior II response to the W/O, this kick up in pressurization rate at the end of the workover occurs with both Behavior I and II caverns. The fact it is not seen in the Behavior I caverns here is possibly linked to the impact of multiple caverns being depressurized, but modeling is needed to investigate this hypothesis.

Figure 4-3 shows a zoomed in view of the Cavern 113 response to this multiple workover. In Figure 4-1 the Behavior II response by Cavern 113 can be seen to the first workover in the series (Cavern 104). When Cavern 109 is depressurized approximately two months later, a larger Behavior II response can be seen – this makes intuitive sense, since Cavern 104 is roughly twice the distance from Cavern 113 than Cavern 109 is. Extending the pressurization curve for Cavern 113 prior to the W/O depressurization in Figure 4-1, there is approximately a 2 PSI differential between where the pressure would have been on 7/25 and where it actually was. Doing the same analysis on the data in Figure 4-3, there is approximately a 6 PSI differential. The drop at point A, the first stage of depressurization, is also very clear in the second example.

This leads to the final example of the behaviors, which shows that the same two caverns can have different interactions and behaviors with respect to workovers at different times and cavern configurations. In 2010, Cavern 109 was depressurized without any other caverns being depressurized at the same time. The results, as seen in Figure 4-4, were that Cavern 113 showed a Behavior I response, not the Behavior II response seen in 2016. Because there are a limited number of workovers to examine, and because fluid transfers to do the W/O depressurization may make comparing two caverns impossible, modelling is needed to determine if the interaction of two caverns being down for workover or if some other geomechanical reason is the cause of the change.

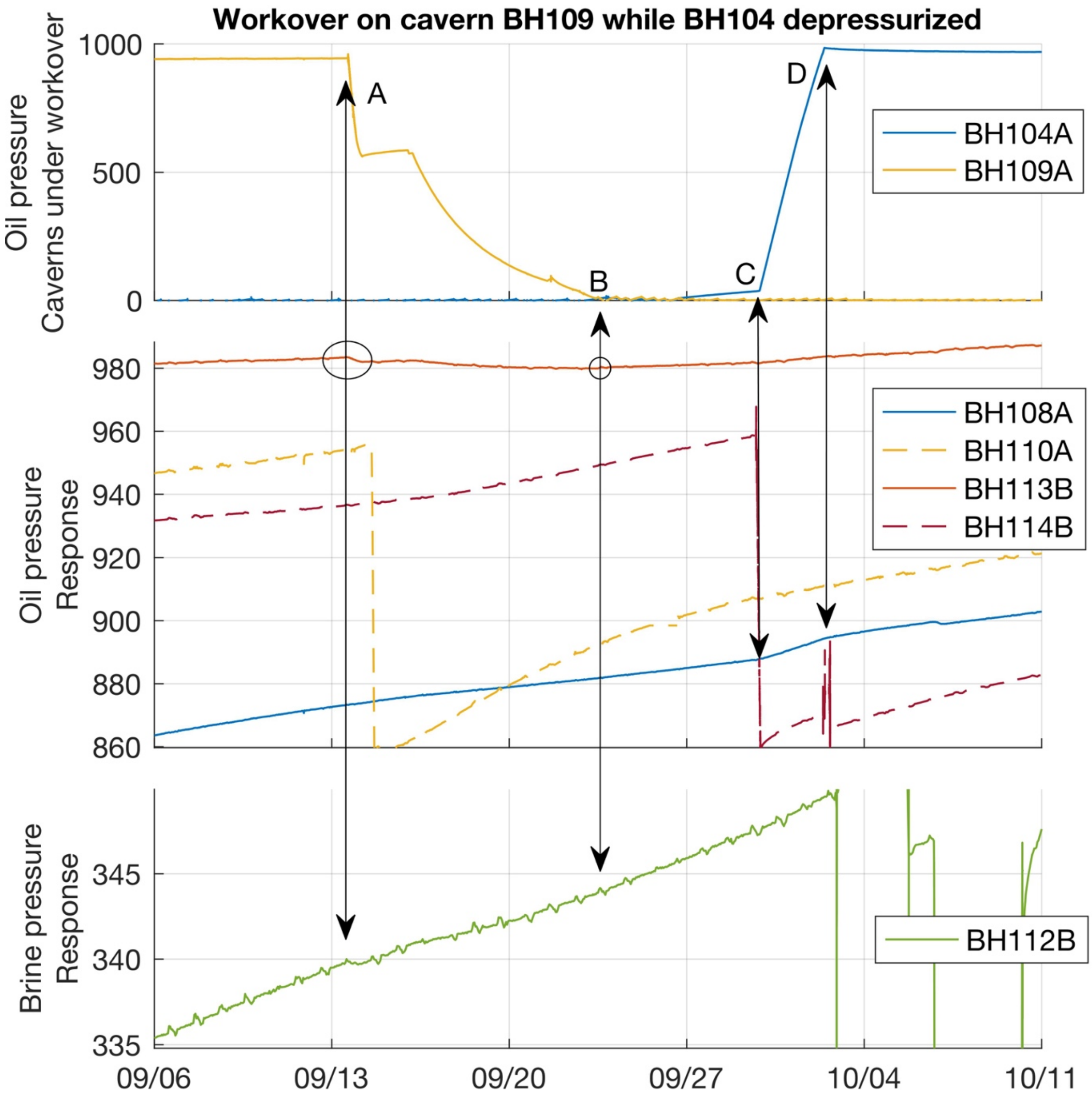


Figure 4-2. Example of multiple cavern depressurization and associated behaviors.

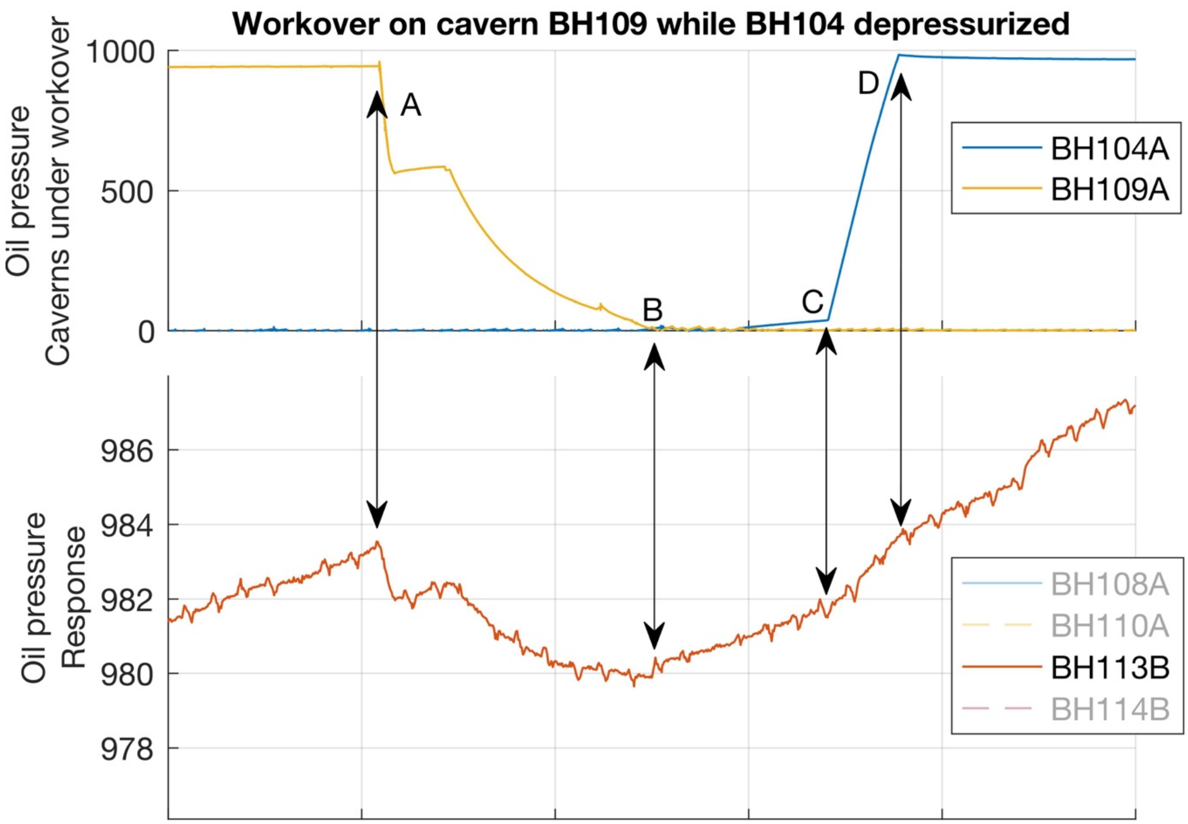


Figure 4-3. Closeup of cavern BH113 response to BH104 and BH109 workovers.

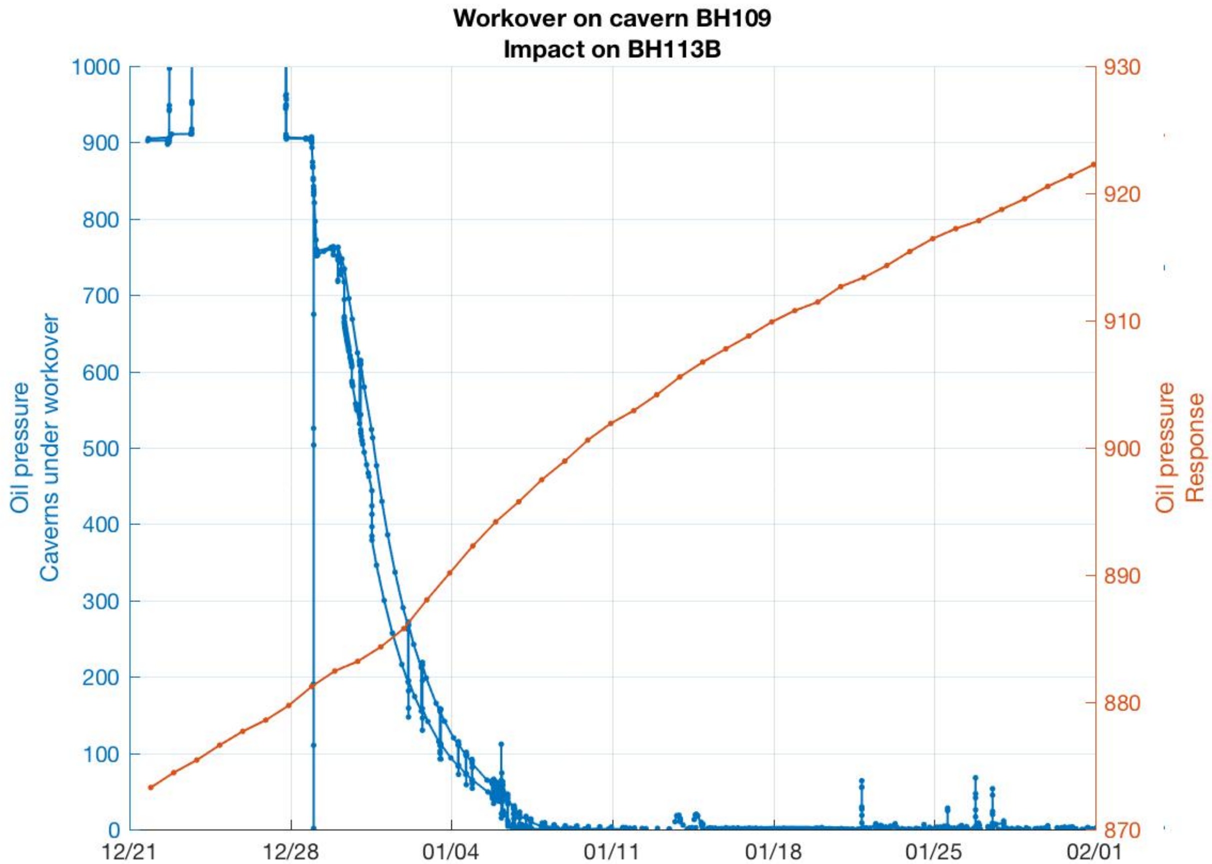


Figure 4-4. Behavior I response between caverns BH113 and BH109 from 2010.

4.2. Site-by-site analyses

Every workover between January 2010 and January 2017 were analyzed to look for Behavior I or Behavior II responses between well pairs. The full set of graphics where a response was detected is presented in Appendix B. If a pair of caverns does not have a graphic showing a response, it *does not* necessarily mean that there was no response; in many cases the neighboring cavern may be part of the fluid movement necessary for depressurizing the cavern under workover, or there may have been data issues, or the response may have simply been too small or too tenuous to be included with any degree of confidence. Therefore, the information provided should be used to provide insight into what has occurred in the past, and not a reference for what constitutes "normal" behavior between two caverns interacting due to a workover.

4.2.1. Bayou Choctaw

The Bayou Choctaw site is very difficult to analyze due to the unique conditions of the caverns. There are six active SPR caverns, eight decommissioned SPR caverns, plus Cavern Lake, and eleven non-SPR caverns within a small salt dome.

Additionally, cavern 20 is extremely close to the salt dome edge, and caverns 15 and 17 are operated as a single unit. Because there are effectively only five active caverns, with cavern 20 beginning the process of being emptied during the time of study and Cavern 15 and 17 being lumped together, taking a cavern out of service for workover makes it likely that neighboring caverns are used to take in oil or brine, and thus the response cannot be observed. The only interactions that could be reliably examined are between Caverns 15/17 and Cavern 18, where Cavern 18 showed Behavior I in response to 15/17 W/O. Figure 4-5 shows these effects graphically, where arrows point from the caverns under workover towards the cavern where a response is seen, and solid green arrows indicate Behavior I response (increased pressurization rate) and dashed orange arrows indicate Behavior II response (pressure signature tracking).

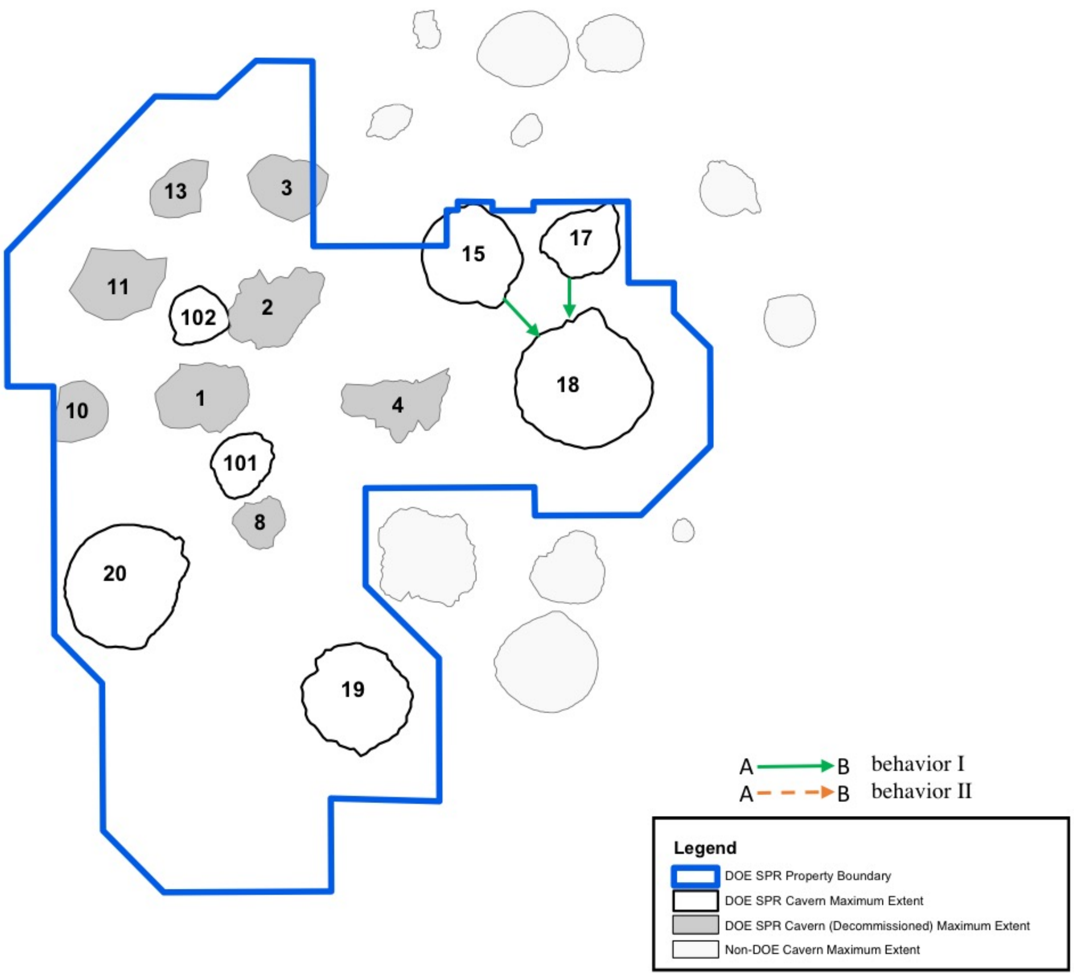


Figure 4-5. Map of W/O behaviors at Bayou Choctaw. Arrows start and cavern under W/O and end at responding cavern.

4.2.2. Big Hill

The Big Hill site has the most regular placement of caverns, contains only Phase II caverns of similar depth and size, and has no major, non-SPR caverns in the surrounding area. The site does have a salt shear zone through the middle, which complicates the geology and may play a role in cavern interactions.

Both Behaviors I and II (increase and decrease in neighbor caverns, respectively) are seen at the Big Hill site, as is shown in Figure 4-6. The following features, based on currently available date, are of primary interest:

- Caverns on the western and eastern edge show only Behavior I.
- Caverns directly east or west from each other only show Behavior I.
- Excepting Cavern 112, for which insufficient data is available, all caverns which exhibit Behavior II also exhibit Behavior I in during different W/O events
- All the 'second neighbor' cavern pairs – (i.e., those greater than 1,000 apart) are insufficiently distinct to classify with confidence, except those on the western side of the site.

The significant impact of alignment on response behavior type seems to indicate that there is a spatial and/or geometric component to the reason there are two different behaviors that have been identified. Arrows point from the caverns under workover towards the cavern where a response is seen, and solid green arrows indicate Behavior I response (increased pressurization rate) and dashed orange arrows indicate Behavior II response (pressure signature tracking). Missing arrows indicate either insufficient data or non-response, but should not be assumed that a response will not occur. Multiple workovers that show the same response do not have additional arrows.

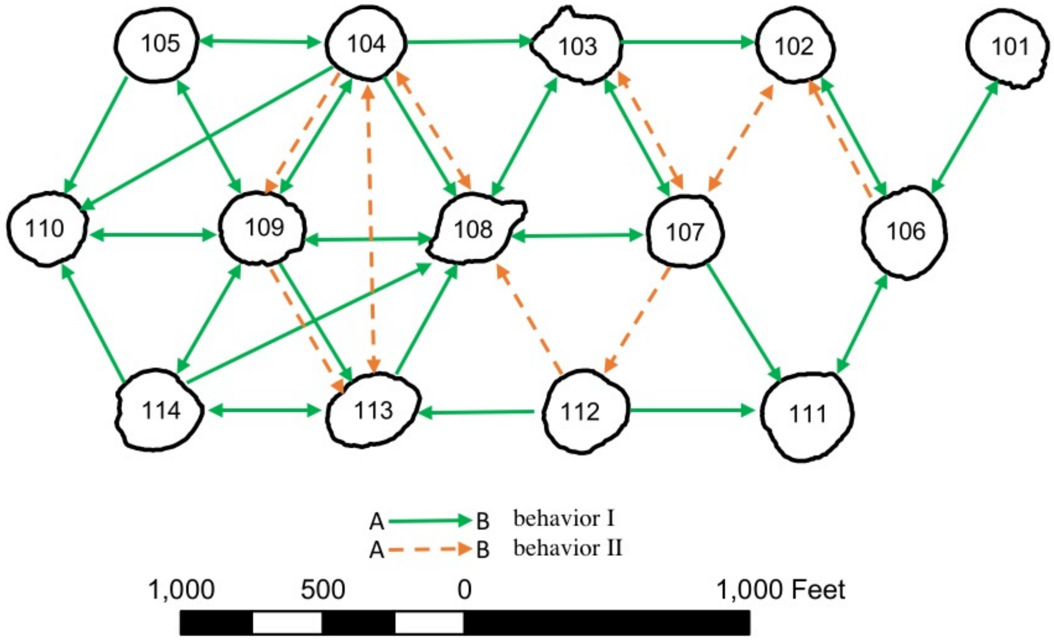


Figure 4-6. Map of W/O pressure responses at Big Hill. Arrows start at the cavern under W/O and end at responding cavern. Double-headed arrows indicate two arrows, one in each direction, not simultaneous W/O.

4.2.3. Bryan Mound

The caverns at Bryan Mound are more difficult to analyze, as there were many cases when neighboring caverns appear to have been used to receive the fluid moved to depressurize the caverns for workover. Behavior II is far more common in the Phase II and Phase III caverns than in the Phase I caverns, and Behavior I more common in the Phase I caverns. However, there is no pattern of behavior that is discernable based on the data available. Bryan Mound caverns tend to be depressurized at a much higher rate, leading to a sharp pressure drop rather than the exponentially decreasing flow seen at other sites, but no correlation can be found to the rate of depressurization, either. A map of the responses that Sandia can classify with confidence is shown in Figure 4-7. Arrows point from the caverns under workover towards the cavern where a response is seen, and solid green arrows indicate Behavior I response (increased pressurization rate) and dashed orange arrows indicate Behavior II response (pressure signature tracking). Missing arrows indicate either insufficient data or non-response, but should not be assumed that a response will not occur. Multiple workovers that show the same response do not have additional arrows.

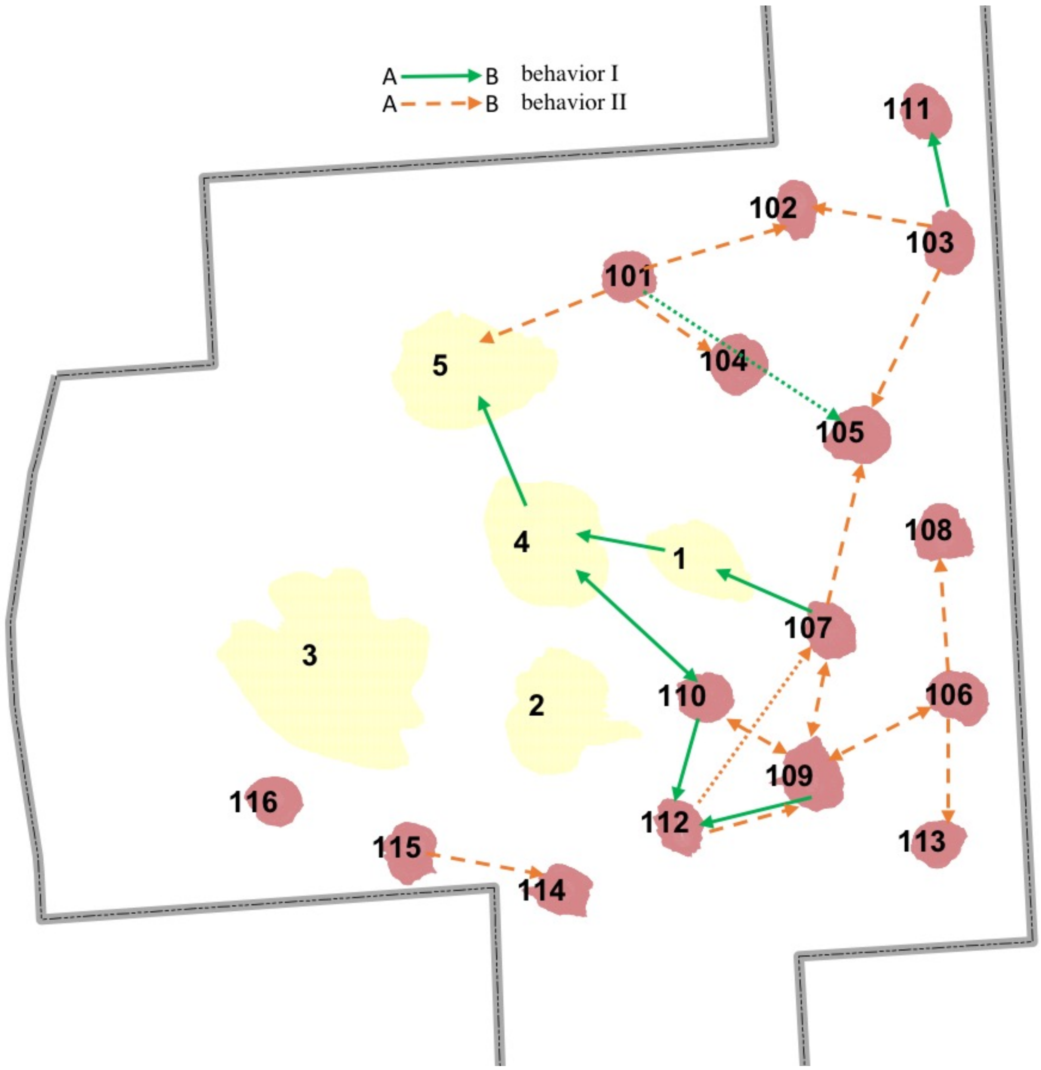


Figure 4-7. Map of W/O pressure responses at Bryan Mound. Arrows start at the cavern under W/O and end at responding cavern. Double-headed arrows indicate two arrows, one in each direction, not simultaneous W/O.

4.2.4. West Hackberry

The West Hackberry site shows almost exclusively Behavior I responses to workover events. The Behavior II responses are limited to workovers at Cavern 115 in the north and workovers at Cavern 11 or which Cavern 11 responds to. Figure 4-8 shows these responses. Arrows point from the caverns under workover towards the cavern where a response is seen, and solid green arrows indicate Behavior I response (increased pressurization rate) and dashed orange arrows indicate Behavior II response (pressure signature tracking). Missing arrows indicate either insufficient data or non-response, but should not be assumed that a response will not occur. Multiple workovers that show the same response do not have additional arrows.

The Phase II caverns at West Hackberry are approximately the same distance apart, generally speaking, as at the Big Hill site, and are the same cavern shape. There are far more cases at West Hackberry, relative to Big Hill, where a response cannot be discerned because fluid movements were going on at the same time.

Cavern 11 is a Phase I cavern, so a different behavior involving this cavern may be explainable by the location of the caverns. Because Cavern 115 is the only cavern to cause both behaviors in Phase II caverns it may be desirable to gain extra data from surrounding caverns during the next workover of 115.

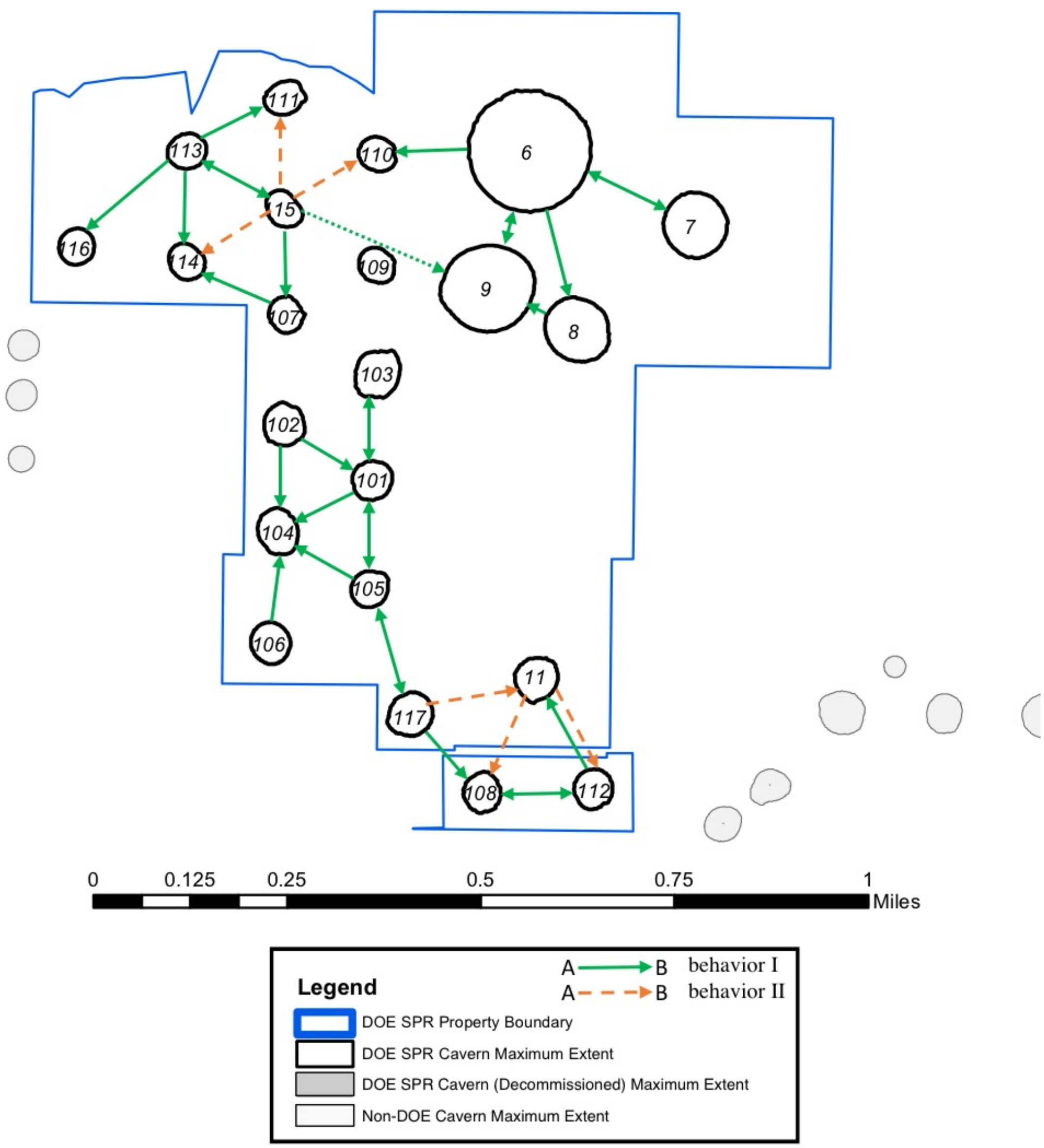


Figure 4-8. Map of W/O pressure responses at West Hackberry. Arrows start at the cavern under W/O and end at responding cavern. Double-headed arrows indicate two arrows, one in each direction, not simultaneous W/O.

5. WORKOVER EFFECTS ON THE SURFACE

A possible expression of workovers effects on a cavern system is the resultant subsidence. As described in Section 2, during a cavern workover the pressure is dropped to zero (at wellhead), and the rate of salt creep within the cavern increases. This has been shown to impact surface subsidence. An example of this behavior was noted at the Big Hill SPR site and documented by Lord in two reports from 2014. These reports described the observations for the 2012–2013 subsidence rates (Figure 5-1) where a subsidence bowl was found towards the center of the site. Comparison with previous calculated Big Hill subsidence rates indicated that subsidence had significantly increased over the cavern field.

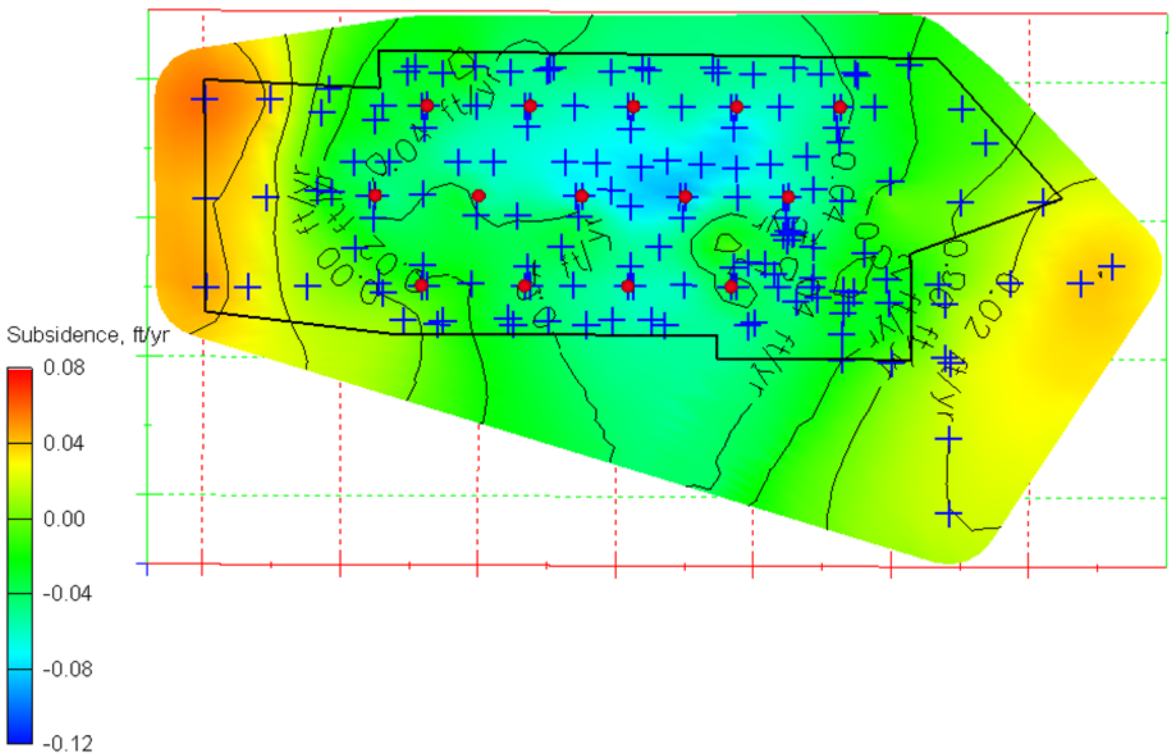


Figure 5-1. Contour plot of subsidence rates (ft/yr) from May 2012 to May 2013. Negative rates indicate subsidence, whereas positive rate indicates uplift. Monument locations are noted by crosses. Cavern well locations are depicted as red circles (from Lord 2014a, Fig. 1).

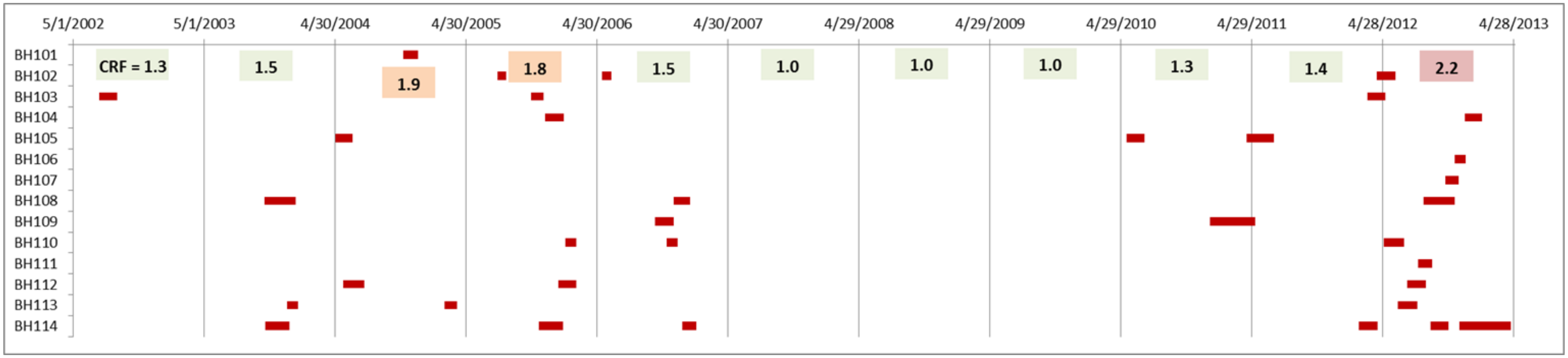
In the course of assessing the reason for the increase in subsidence rates, workover number and durations were analyzed. Between the period of 2010-2013 Big Hill site was subjected to a large number of workovers (see Appendix A). The pressure data from between 2002–2013 was looked at in two different ways during this period, (1) by focusing primarily on the date and duration that each cavern was under a workover and, for this reason, was drawn down to a wellhead pressure of zero, and (2) by considering the effects of all pressure events on creep rate, such as workovers, fluid transfers, and degas operations, where caverns operate below the normal operating pressure range. It was noted that between February 2010 and early 2013 eleven of the 14 cavern were placed under a workover and several of the wells were depressurized for many months at a time. The creep rate factor (CRF) was calculated for each cavern for each day of each year considering both workovers and depressurization of during fluid transfer of degas operations. The daily values for each cavern, over a one-year time span, were averaged to generate one CRF per cavern. Next the 14 caverns' CRFs were averaged together (equivalent to a uniform volume weighting factor of 1) to calculate one value to represent a site CRF for a said year. The largest yearly CRF calculated was 2.2 calculated for this past year (May 2012–May 2013). Figure 5-2 presents the workovers and duration, CRF, and the historical subsidence trend. The comparison of data suggests the increase in recent workover activity had directly contributed to the subsidence response.

The anticipated surface response to a decrease in workover activity, and hence the re-pressurization of the caverns previously under workover, would be a surface rebound. In other words, the surface would be expected to "pop" back up to previously recorded elevations and continues to subside along the expected trend. The survey data acquired the following year in 2014 did suggest that surface deformation recovered from the numerous workovers (Figure 5-3).

In summary, the subsidence rates documented between May 2012 and May 2013 correlate to the massive number of workovers that occurred at the Big Hill site that year. By July 2014, the workovers had ceased or diminished, and the subsidence rates were back at the expected trend seen historically. Additionally, the ground surface is thought to have rebounded once the caverns under workover were re-pressurized.

Going forward, to really understand the surface behavior more frequent data acquisition and improved density of data points need to be collected , technology such as InSAR acquisition and analysis would allow for an increase in both coverage and frequency. Currently, InSAR has been deployed for a two year study over the Bryan Mound site. Both ascending and descending satellite data was acquired every 16 days, which allows for ground deformation be observed in both the east-west direction as well as true vertical. The data has yet to be analyzed, but an initial look shows there is a lot to be gained from a two-dimensional analysis. This type of data collection would allow for a comprehensive data set with an acquisition regularity at increment that allows for a nearly real-time examination of surface deformation behavior, which would allow for a better understanding of the source causing the recorded deformation. This would allow for a differentiation between a cavern integrity concern or a change in cavern operations.

(a)



(b)

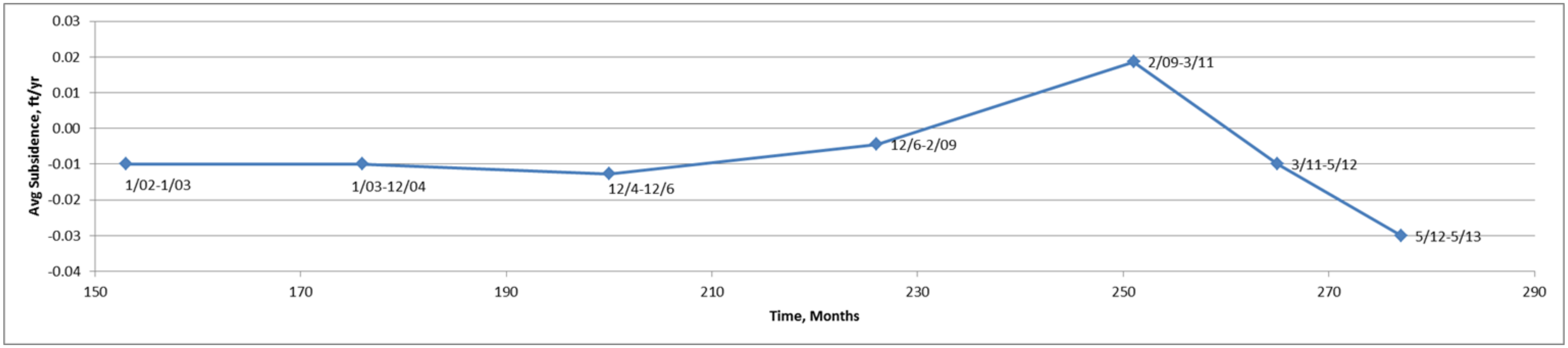


Figure 5-2. (a) Bar chart depicting the date and duration that each Big Hill cavern was subjected to a workover. Creep rate factors (CRFs) are listed for each year across the top of the chart, (b) Plot of average subsidence rate versus time (from Lord 2014a)

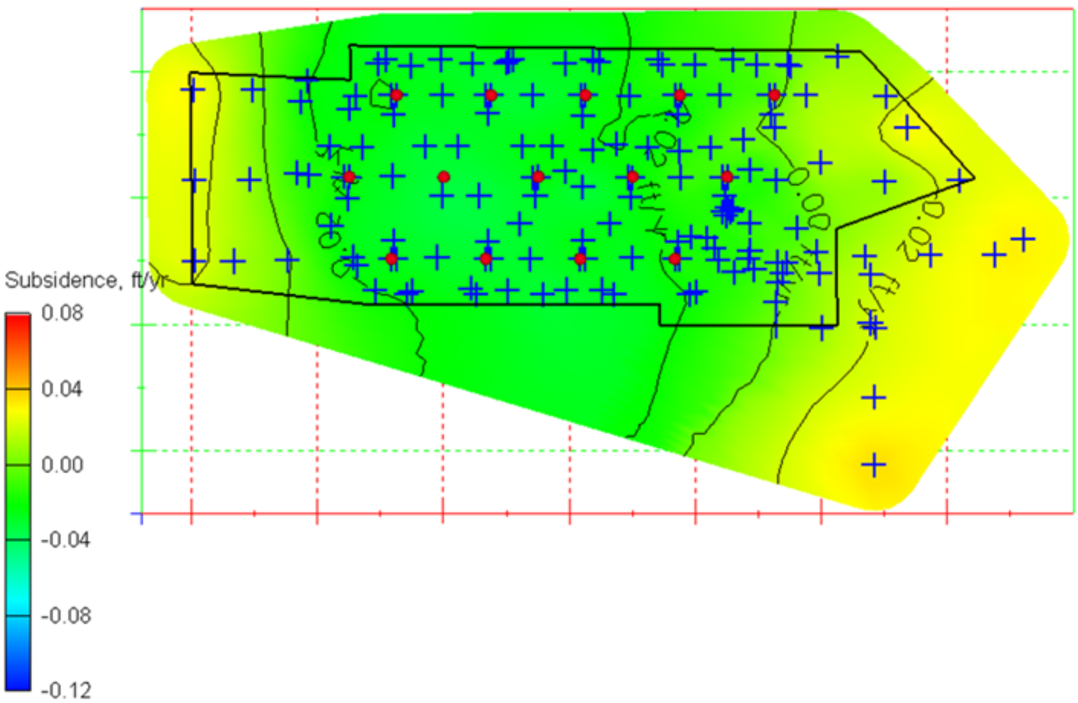


Figure 5-3. Contour plot of subsidence rates (ft/yr) from May 2012 to July 2014 (26 months). Negative rates indicate subsidence, whereas positive rate indicates uplift. Monument locations are noted by crosses. Cavern well locations are depicted as red circles (from Lord 2014b, Figure 3).

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The effects of workovers and cavern depressurization have been analyzed throughout report. Emphasis was placed on effects of volume loss, cavern pressure response as well as neighboring caverns, and surface subsidence. Results based on cavern data analysis had showed that the following:

- Cavern volume loss (and related ullage loss) does not change in a statistically significant way based on the length of the workover, particularly for workovers with a duration of less than six months.
- As expected, each site exhibits different closure rates. Data from Bryan Mound shows the highest average loss, followed by Big Hill, West Hackberry, and Bayou Choctaw.
- Depressurization of a cavern does affect pressure in the neighboring caverns, and two different behaviors are associated with this finding. Behavior I exhibits an: increase in the neighbor pressurization rate, and Behavior II exhibits neighbor pressure tracks (at a fractional level) with the depressurizing cavern.
- Behavior I is most common and was found in all sites, Behavior II was clearly visible at Big Hill and West Hackberry sites, and the Big Hill site appears to show some spatial preference where Behavior II is observed.

Analysis of subsidence data over the Big Hill site has shown that cavern depressurizations and workover effect the rate of subsidence of the whole site.

6.2. Recommendations for future research

This report does not include a comprehensive of all effects that depressurization can have on the cavern system; however, a subsequent report, planned for fiscal year 2018, will focus on the effects on wellbores. Additionally, to further understand the implications that conducting a workover has, Sandia recommends the following for future research:

- Geomechanics simulation study to understand the cause of neighboring effects. In other words, what causes the different behaviors found and can they be predicted?
- As part of CAVEMAN, Sandia recommends further modeling of cavern closure phenomena to verify the conclusions obtained from the cavern volume loss analysis.
- InSAR study, at much greater data frequency (position and time), to verify effect of workover on site subsidence.

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APPENDIX A: WORKOVER DATE TABLES

This appendix lists all workovers examined in the different parts of this report. List by order of date the workover started, grouped by site in the order: BH, WH, BM, BC.

Cavern	Start to depressurize	Depressurized	Start to re-pressurize	OPR reached	Length (days)
BH-C105	2010-05-13	2010-05-24	2010-07-01	2010-07-04	52
BH-C109	2010-12-28	2011-01-07	2011-05-05	2011-05-07	130
BH-C105	2011-04-11	2011-04-27	2011-06-27	2011-06-30	80
BH-C114	2012-02-20	2012-03-08	2012-04-12	2012-04-13	53
BH-C103	2012-03-14	2012-04-04	2012-05-04	2012-05-06	53
BH-C102	2012-04-04	2012-04-27	2012-05-22	2012-06-01	58
BH-C110	2012-04-30	2012-05-17	2012-06-18	2012-07-03	64
BH-C113	2012-06-01	2012-06-23	2012-07-16	2012-08-01	61
BH-C112	2012-06-09	2012-07-23	2012-08-12	2012-08-25	77
BH-C111	2012-07-23	2012-08-14	2012-09-11	2012-09-13	52
BH-C108	2012-08-19	2012-09-03	2012-10-28	2012-11-15	88
BH-C114	2012-09-06	2012-09-19	2013-04-08	2013-04-20	226
BH-C101	2012-10-01	2012-10-21	2012-11-08	2012-11-18	48
BH-C107	2012-10-17	2012-11-01	2012-11-16	2012-11-25	39
BH-C106	2012-11-14	2012-11-22	2012-12-12	2012-12-14	30
BH-C104	2012-12-05	2012-12-26	2013-01-18	2013-01-29	55
BH-C109	2013-08-15	2013-08-29	2013-09-30	2013-10-06	52
BH-C105	2013-09-19	2013-09-28	2013-10-15	2013-10-29	40
BH-C103	2013-11-27	2013-12-16	2014-02-22	2014-03-05	98
BH-C113	2015-02-09	2015-02-18	2015-07-27	2015-08-01	173
BH-C108	2015-03-02	2015-03-14	2015-04-09	2015-04-20	49
BH-C103	2015-03-19	2015-04-04	2015-04-24	2015-04-27	39
BH-C106	2015-06-17	2015-07-03	2015-09-28	2015-10-08	113
BH-C107	2015-09-09	2015-09-17	2015-12-17	2015-12-22	104
BH-C103	2016-01-19	2016-01-19	2016-04-19	2016-05-18	120
BH-C104	2016-07-12	2016-07-27	2016-09-26	2016-10-02	82
BH-C109	2016-09-13	2016-09-23	2016-10-18	2016-10-22	39
BH-C112	2016-10-05	2016-10-20	2016-11-09	2016-11-16	42
BH-C110	2016-10-20	2016-11-10	2016-12-01	2016-12-09	50
WH-C006	2010-09-28	2010-10-02	2011-01-04	2011-03-11	164
WH-C108	2011-01-07	2011-01-21	2011-06-27	2011-07-23	197
WH-C006	2012-05-25	2012-06-03	2012-08-15	2012-09-11	109
WH-C117	2012-07-17	2012-08-20	2012-09-14	2012-11-16	122
WH-C106	2012-10-07	2012-10-13	2012-11-08	2013-01-11	96

Cavern	Start to depressurize	Depressurized	Start to re-pressurize	OPR reached	Length (days)
WH-C105	2012-11-06	2012-11-12	2012-12-04	2012-12-15	39
WH-C115	2012-11-30	2012-12-07	2013-01-07	2013-01-19	50
WH-C112	2013-01-03	2013-01-12	2013-02-22	2013-03-03	59
WH-C117	2013-02-18	2013-02-28	2013-03-15	2013-03-23	33
WH-C008	2013-04-12	2013-04-23	2013-09-17	2013-09-27	168
WH-C117	2013-09-13	2013-09-27	2013-10-28	2013-11-06	54
WH-C011	2013-10-09	2013-11-02	2013-11-22	2013-11-24	46
WH-C113	2014-02-21	2014-03-01	2014-03-27	2014-07-01	130
WH-C009	2014-03-20	2014-04-03	2014-04-17	2014-05-06	47
WH-C107	2014-04-11	2014-04-28	2014-05-15	2014-07-05	85
WH-C103	2014-05-13	2014-06-08	2014-07-01	2014-07-16	64
WH-C114	2014-12-06	2015-04-30	2015-06-10	2015-07-09	215
WH-C105	2015-01-23	2015-01-30	2015-02-20	2015-03-16	52
WH-C111	2015-08-15	2015-08-26	2015-09-17	2015-09-30	46
WH-C102	2015-07-17	2015-07-31	2015-08-21	2015-11-04	110
WH-C007	2015-12-24	2016-01-08	2016-02-09	2016-04-02	100
WH-C117	2016-04-05	2016-04-09	2016-04-30	2016-05-23	48
WH-C109	2016-09-22	2016-10-02	2016-10-27	2016-11-14	53
WH-C101	2016-07-07	2016-09-01	2016-09-28	2016-10-03	88
BM-C114	2010-04-08	2010-04-10	2010-05-06	2010-05-13	35
BM-C112	2011-06-22	2011-06-26	2011-07-20	2011-07-23	31
BM-C106	2011-06-29	2011-06-30	2011-12-28	2012-01-04	189
BM-C108	2011-07-22	2011-07-29	2011-08-16	2011-08-19	28
BM-C111	2011-09-07	2011-09-11	2011-09-26	2011-09-29	22
BM-C103	2011-09-29	2011-10-05	2011-10-20	2011-10-21	22
BM-C110	2011-10-21	2011-10-27	2011-11-16	2011-11-17	27
BM-C107	2011-11-25	2011-11-26	2011-12-14	2011-12-16	21
BM-C109	2011-12-29	2012-01-02	2012-01-30	2012-02-01	34
BM-C102	2012-01-08	2012-01-13	2012-04-20	2012-06-14	158
BM-C101	2012-02-04	2012-02-08	2012-02-22	2012-03-01	26
BM-C115	2012-03-02	2012-03-04	2012-03-19	2012-03-20	18
BM-C001	2012-04-23	2012-04-27	2012-07-03	2012-07-04	72
BM-C002	2012-04-24	2012-05-01	2012-05-24	2012-05-26	32
BM-C004	2012-07-02	2012-07-12	2012-07-24	2012-07-27	25
BM-C105	2012-08-11	2012-08-14	2012-09-06	2012-09-18	38
BM-C116	2012-09-11	2012-09-15	2012-10-02	2012-10-09	28
BM-C005	2012-11-07	2012-11-18	2012-12-23	2012-12-27	50
BM-C103	2013-12-28	2014-01-01	2014-01-13	2014-01-15	18

Cavern	Start to depressurize	Depressurized	Start to re-pressurize	OPR reached	Length (days)
BM-C111	2014-01-15	2014-01-17	2014-02-03	2014-02-06	22
BM-C109	2014-02-04	2014-02-07	2014-02-12	2014-02-20	16
BM-C004	2014-03-03	2014-03-03	2014-05-26	2014-06-13	102
BM-C103	2014-06-11	2014-06-17	2014-08-28	2014-08-30	80
BM-C112	2014-07-14	2014-07-21	2014-10-23	2014-11-10	119
BM-C101	2014-08-27	2014-09-05	2014-11-07	2014-11-18	83
BM-C001	2014-11-02	2014-11-06	2015-01-16	2015-02-27	117
BM-C103	2015-09-28	2015-10-10	2015-12-19	2015-12-26	89
BM-C112	2016-03-30	2016-04-06	2016-09-17	2016-09-21	175
BM-C110	2016-05-05	2016-05-10	2016-06-08	2016-06-10	36
BM-C101	2016-06-07	2016-06-10	2016-06-28	2016-07-01	24
BM-C109	2016-06-28	2016-07-05	2016-07-25	2016-07-29	31
BM-C106	2017-01-15	2017-01-18	2017-03-08	2017-03-10	54
BC-C019	2013-01-09	2013-02-25	2013-04-01	2013-04-02	83
BC-C101	2013-03-29	2013-04-09	2013-05-21	2013-05-23	55
BC-C015	2013-05-18	2013-05-25	2013-07-16	2013-07-23	66
BC-C017	2013-05-18	2013-05-24	2013-07-06	2013-07-23	66
BC-C018	2013-07-18	2013-07-23	2013-12-06	2014-01-22	188

APPENDIX B: NEIGHBORING CAVERN WORKOVER GRAPHICS

The following pages present graphs showing the depressurized cavern wellhead pressures (in blue), and the corresponding oil or brine wellhead pressure (noted on the axis label and plotted in red). Only those graphs, showing a discernible Behavior I or Behavior II response, were included. Many cavern pairs were excluded due to a lack of visible response, or because the observing cavern was in an active state at the time.

BAYOU CHOCTAW WORKOVERS


Workover on cavern BH101
Impact on BH107A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
950
900
850
800
750
700
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600
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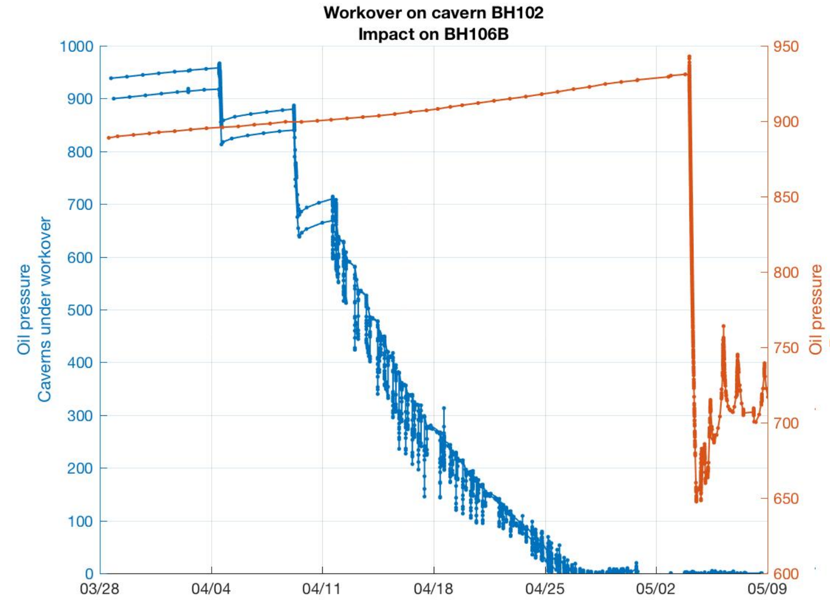
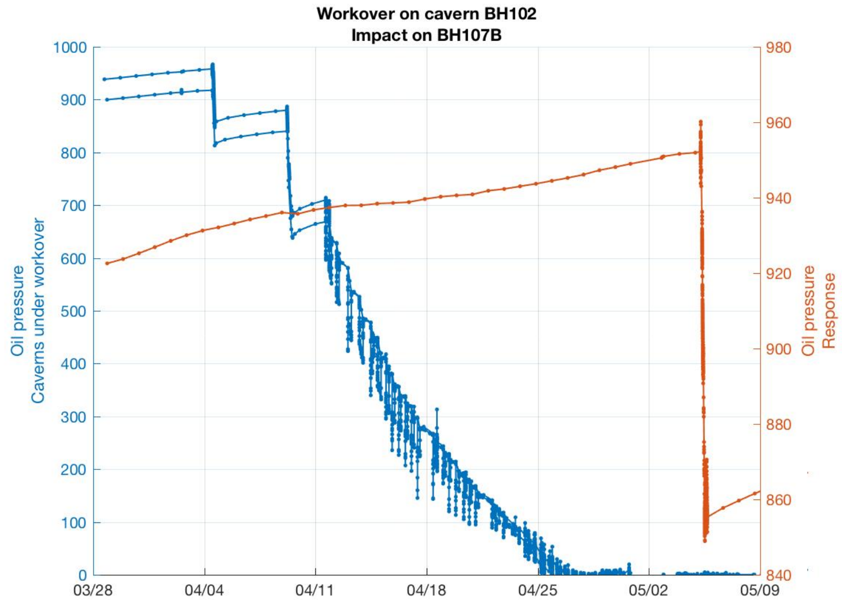
10/01
10/08
10/15
10/22
10/29
11/05


Workover on cavern BH102
Impact on BH106B
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
950
900
850
800
750
700
650
600
03/28
04/04
04/11
04/18
04/25
05/02
05/09


Workover on cavern BH101
Impact on BH106A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
950
940
930
920
910
900
890
880
870
09/24
10/01
10/08
10/15
10/22
10/29
11/05


Workover on cavern BH102
Impact on BH107A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
940
920
900
880
860
840
820
03/28
04/04
04/11
04/18
04/25
05/02
05/09

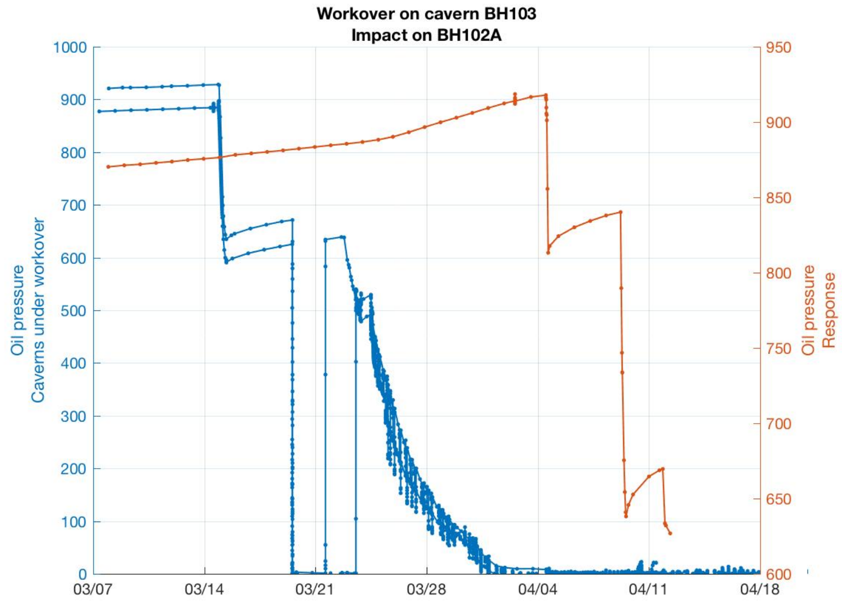

Workover on cavern BH102
Impact on BH107B
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
980
960
940
920
900
880
860
840
03/28
04/04
04/11
04/18
04/25
05/02
05/09

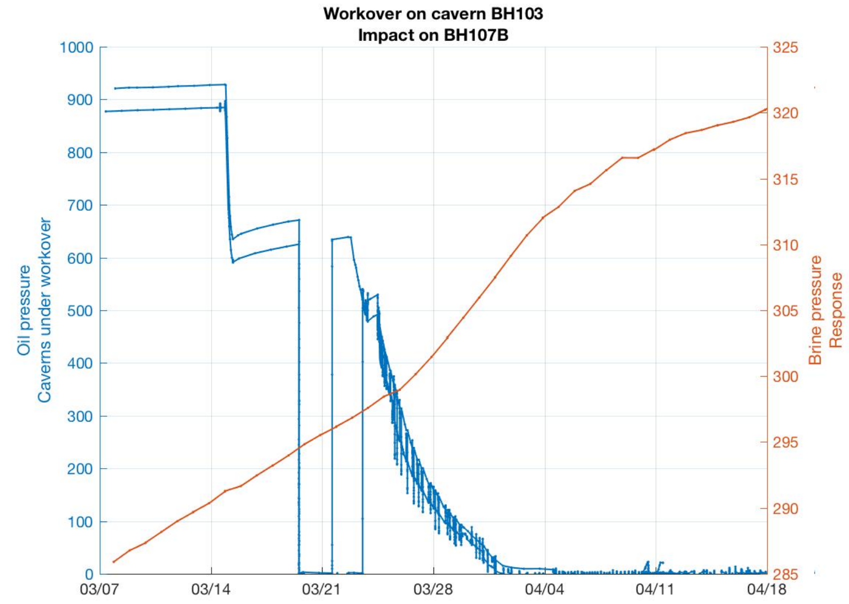

Workover on cavern BH102
Impact on BH107B
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
980
960
940
920
900
880
860
840
03/28
04/04
04/11
04/18
04/25
05/02
05/09

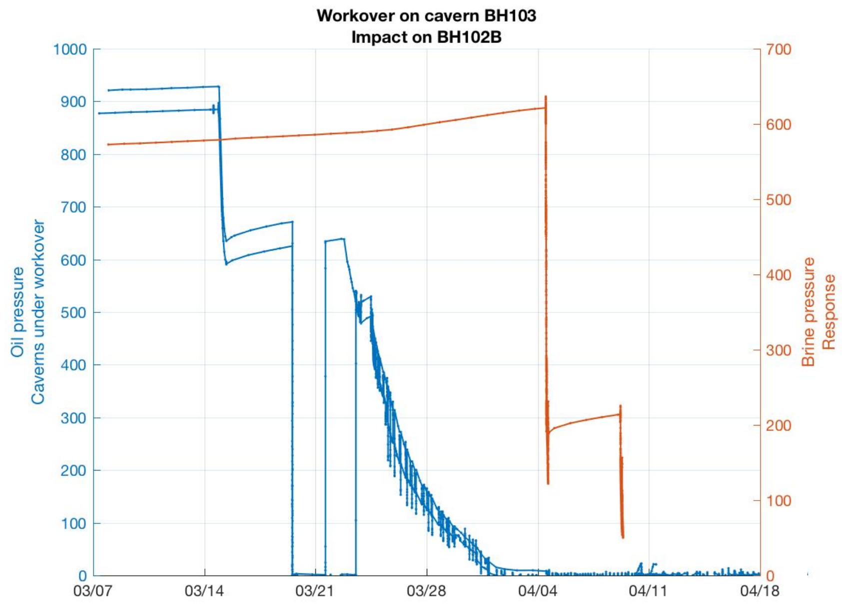

Workover on cavern BH102
Impact on BH107B
Oil pressure
Caverns under workover
Brine pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
600
550
500
450
400
350
300
250
200
150
03/28
04/04
04/11
04/18
04/25
05/02
05/09

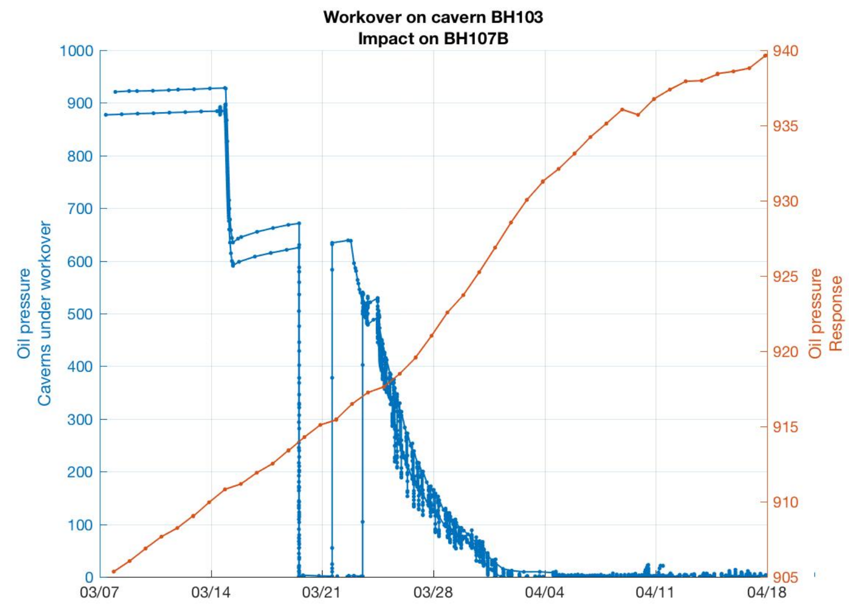

Workover on cavern BH102
Impact on BH111A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
960
940
920
900
880
860
840
03/28
04/04
04/11
04/18
04/25
05/02
05/09

BIG HILL WORKOVERS

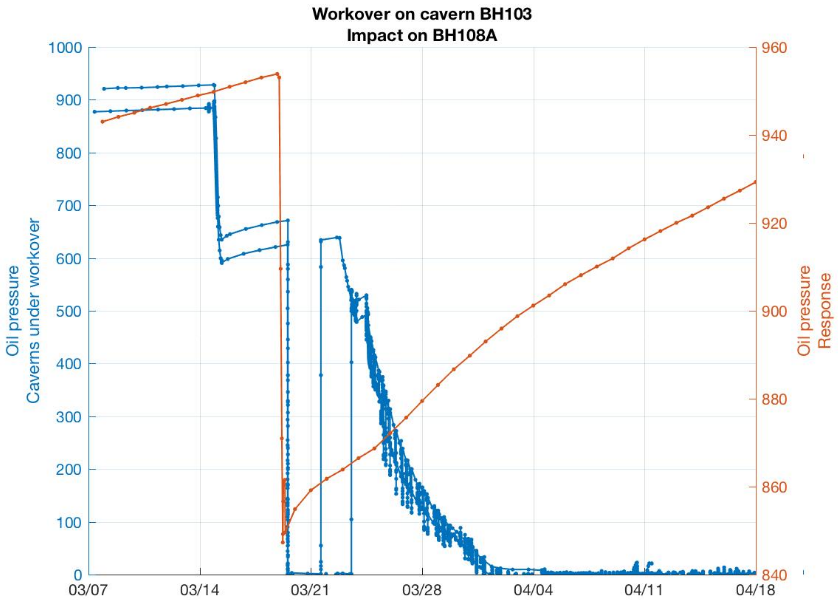


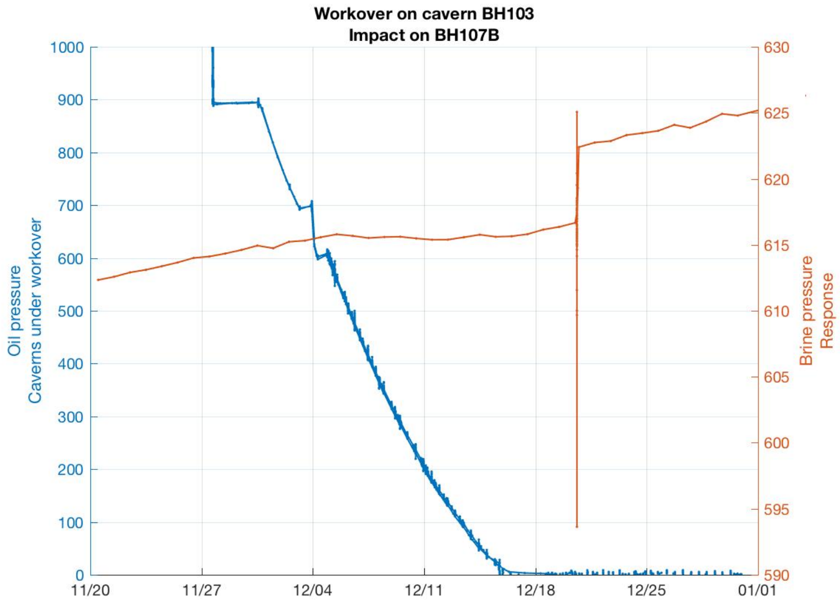


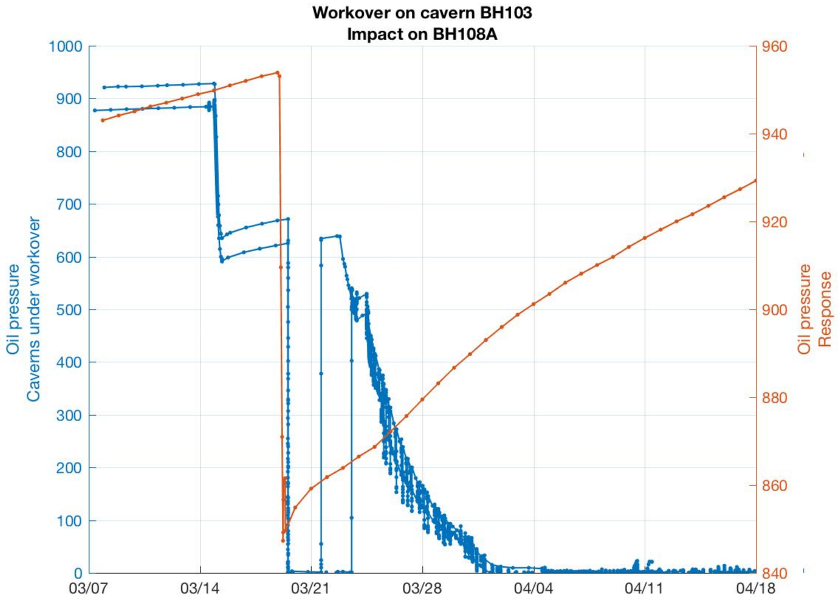


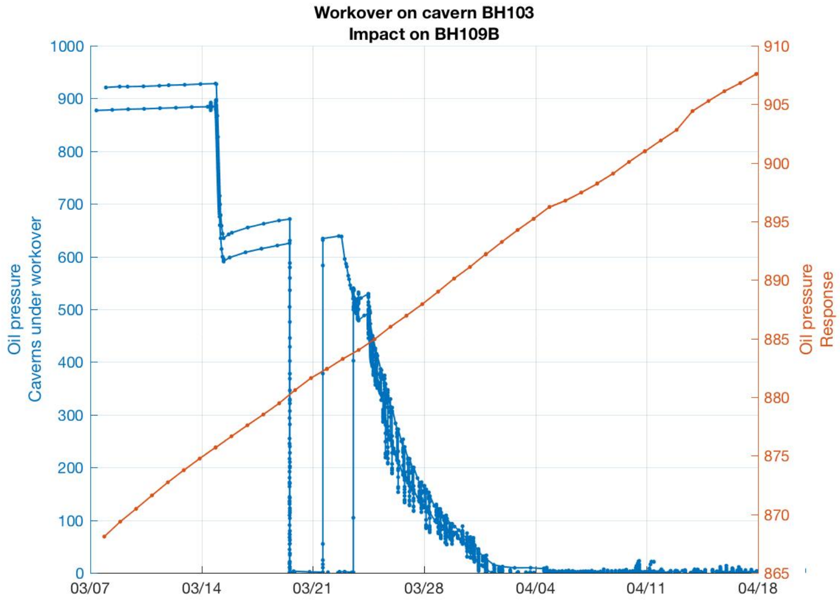


Big Hill Workovers

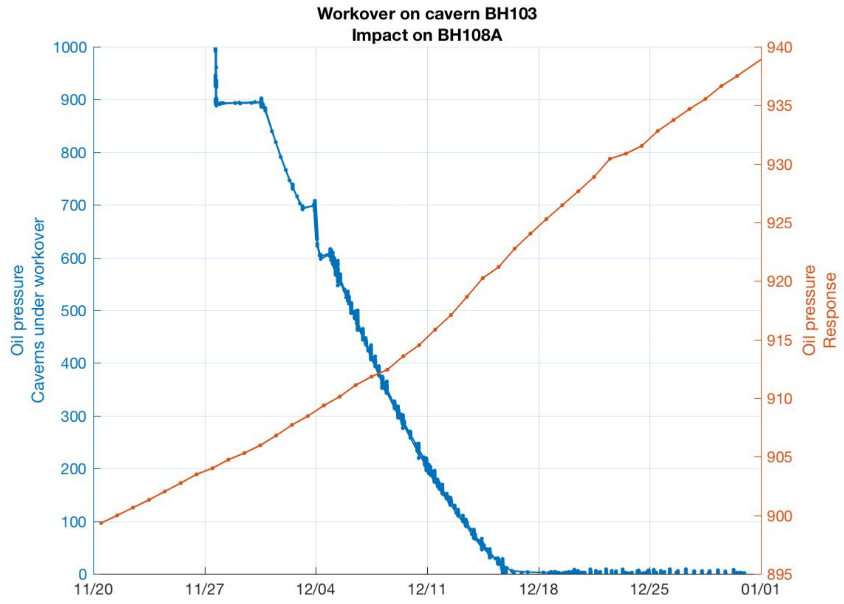


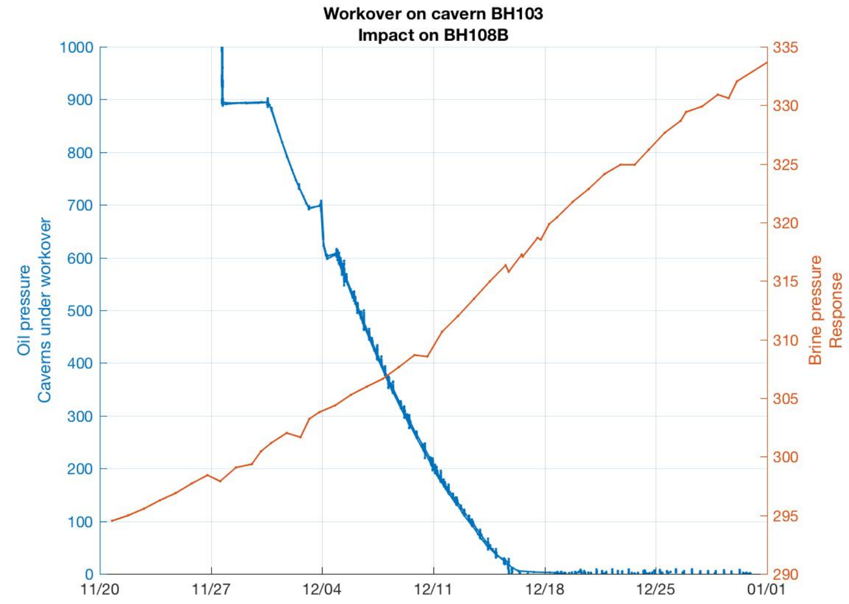


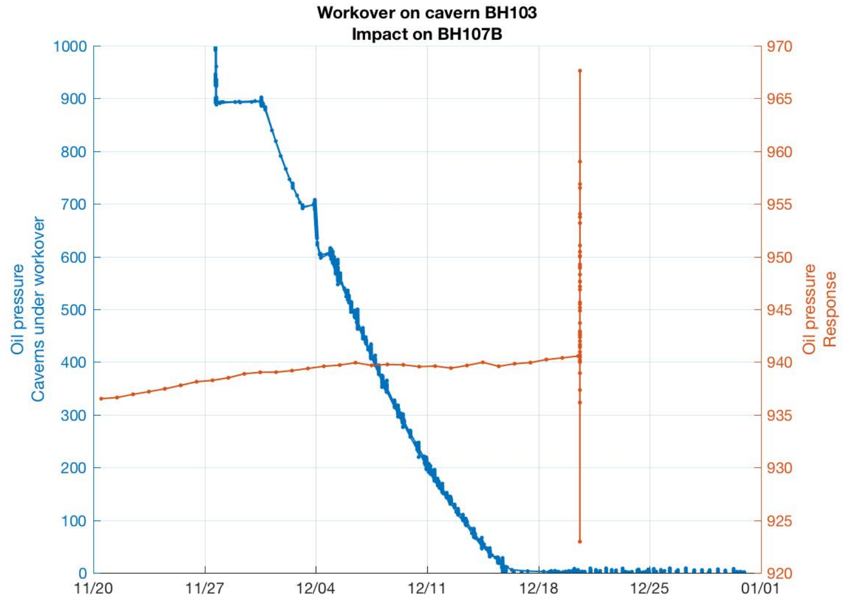


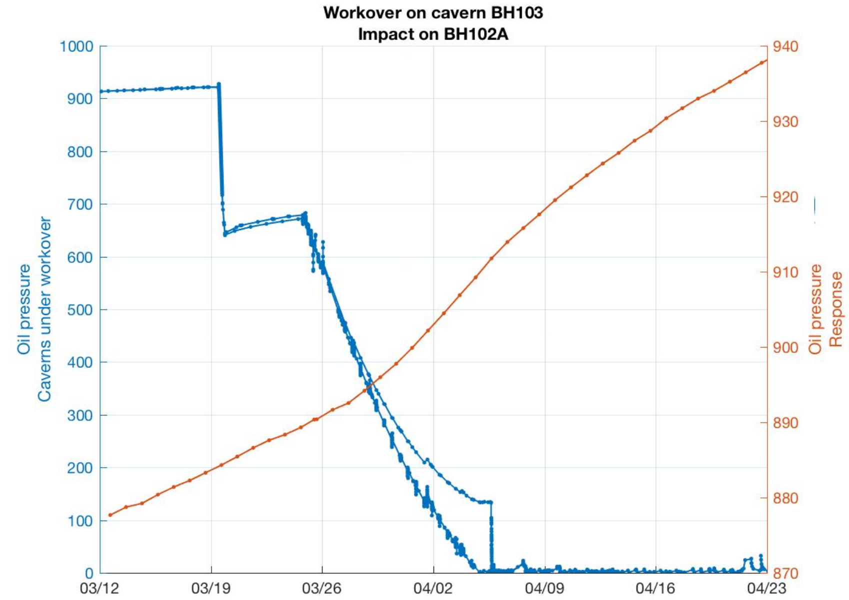


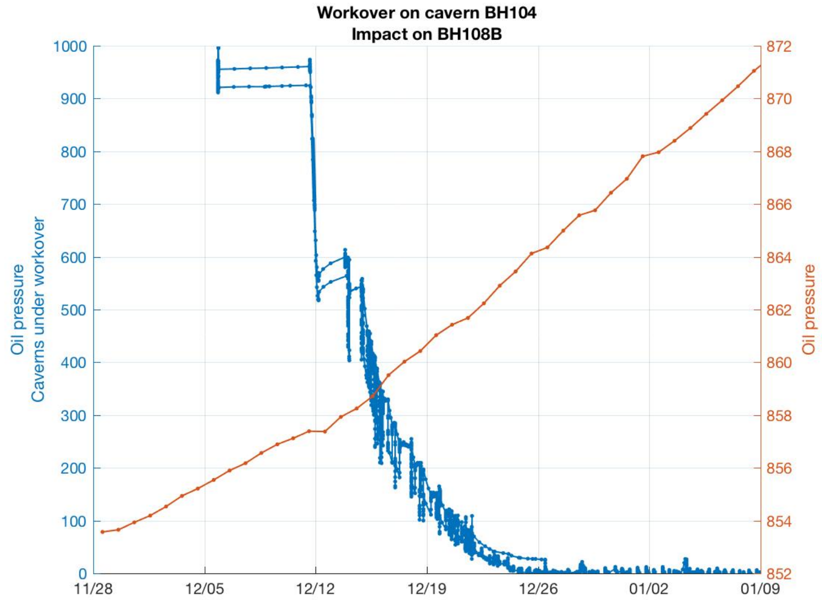
Big Hill Workovers



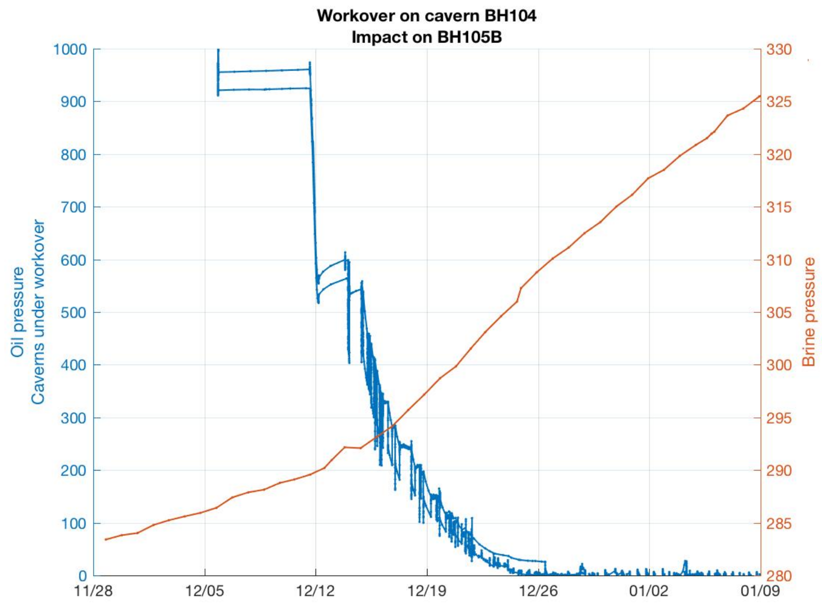


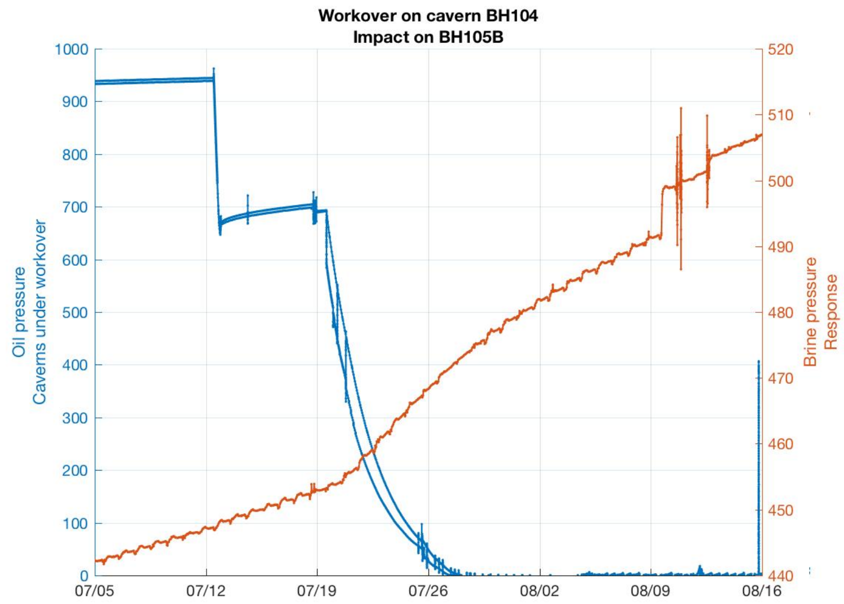


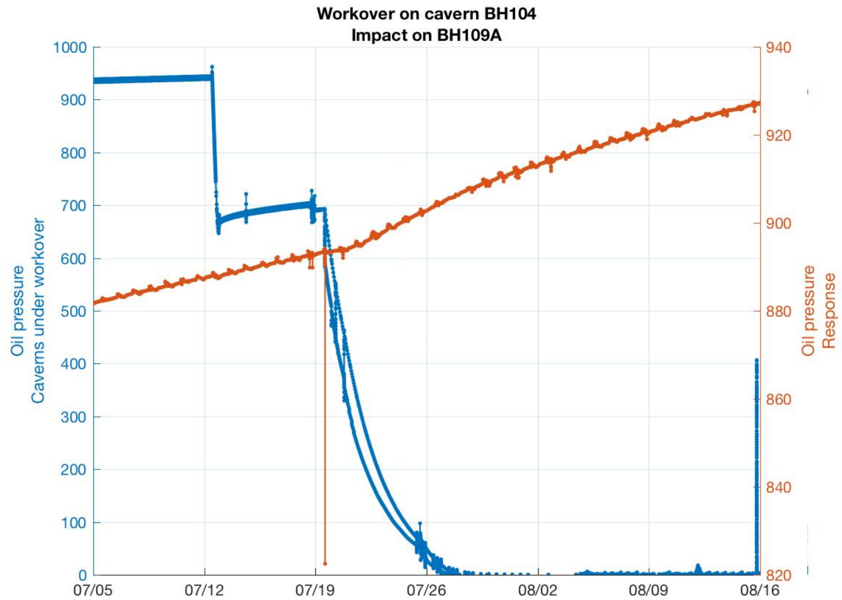



Workover on cavern BH104
Impact on BH108B
Oil pressure
Caverns under workover
Oil pressure
Response
11/28
12/05
12/12
12/19
12/26
01/02
01/09


Workover on cavern BH104
Impact on BH103B
Oil pressure
Caverns under workover
Oil pressure
Response
07/05
07/12
07/19
07/26
08/02
08/09
08/16


Workover on cavern BH104
Impact on BH105B
Oil pressure
Caverns under workover
Brine pressure
Response
11/28
12/05
12/12
12/19
12/26
01/02
01/09


Workover on cavern BH104
Impact on BH105B
Oil pressure
Caverns under workover
Brine pressure
Response
07/05
07/12
07/19
07/26
08/02
08/09
08/16


Workover on cavern BH104
Impact on BH109A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
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880
860
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07/12
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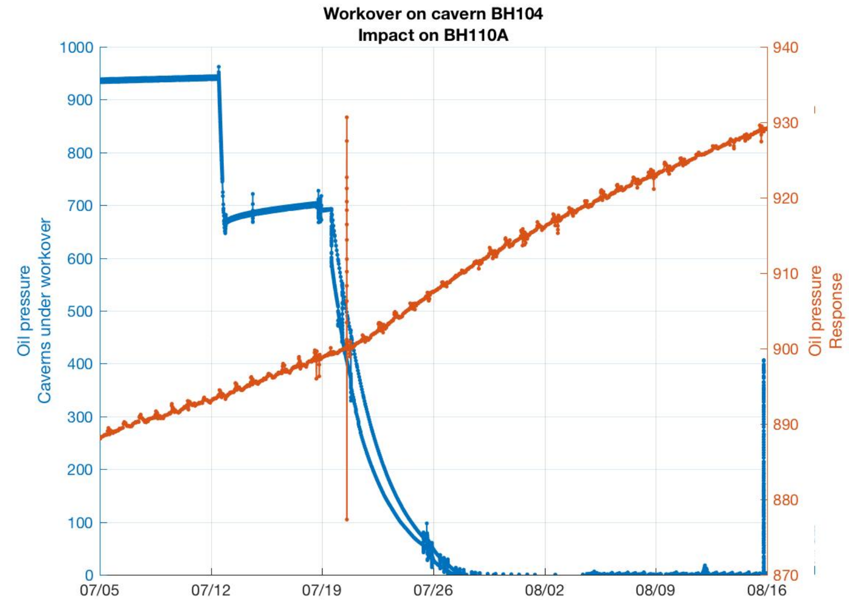
07/26
08/02
08/09
08/16


Workover on cavern BH104
Impact on BH110A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
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300
200
100
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07/05
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08/02
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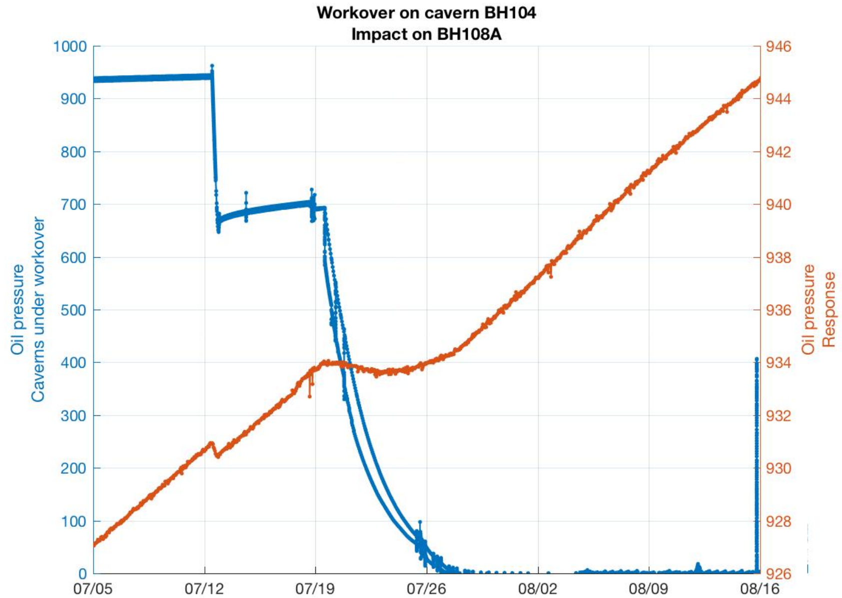
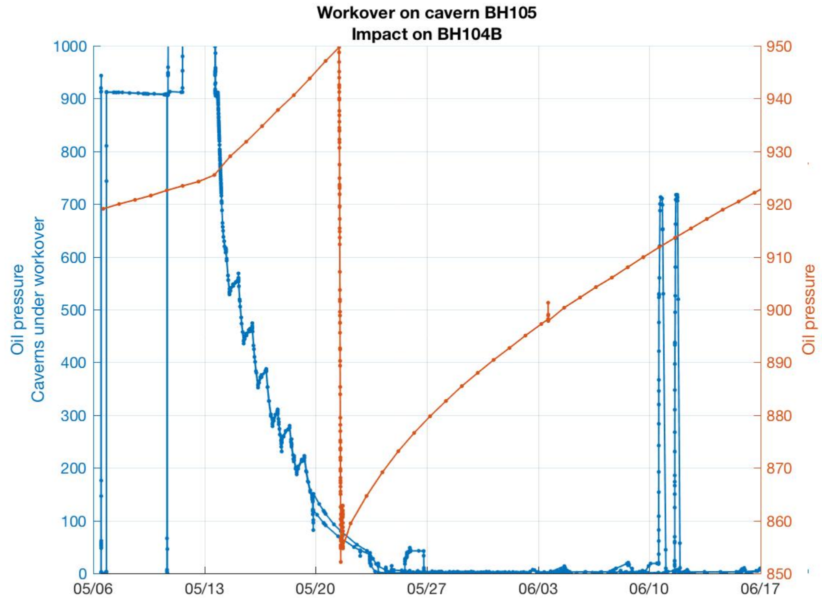
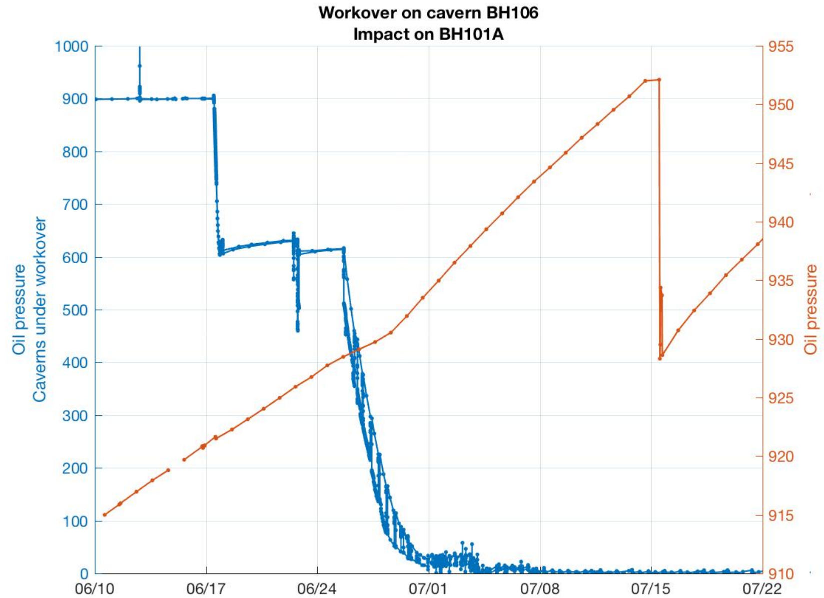
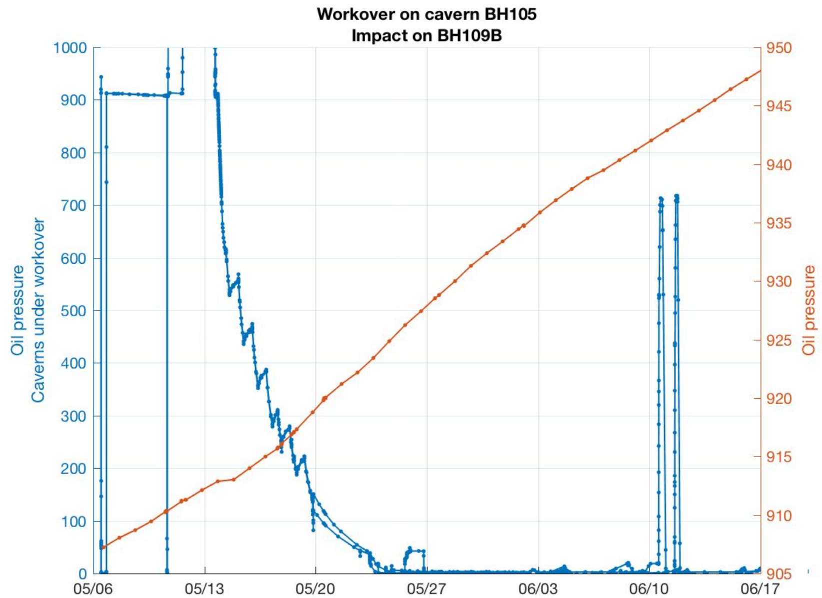
08/16

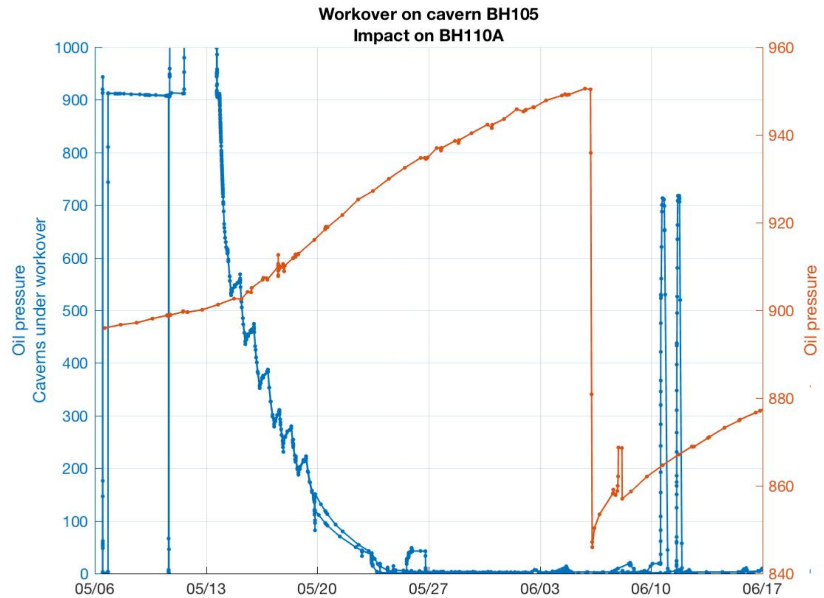

Workover on cavern BH104
Impact on BH108A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
946
944
942
940
938
936
934
932
930
928
926
07/05
07/12
07/19
07/26
08/02
08/09
08/16


Workover on cavern BH104
Impact on BH113B
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
978
976
974
972
970
968
966
07/05
07/12
07/19
07/26
08/02
08/09
08/16

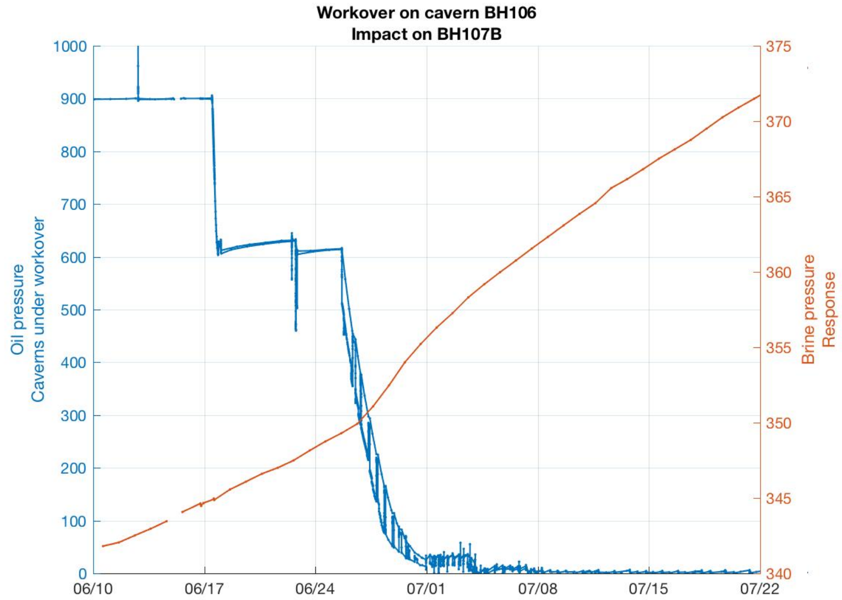

Workover on cavern BH105
Impact on BH104B
Oil pressure
Caverns under workover
Oil pressure
Response
05/06
05/13
05/20
05/27
06/03
06/10
06/17

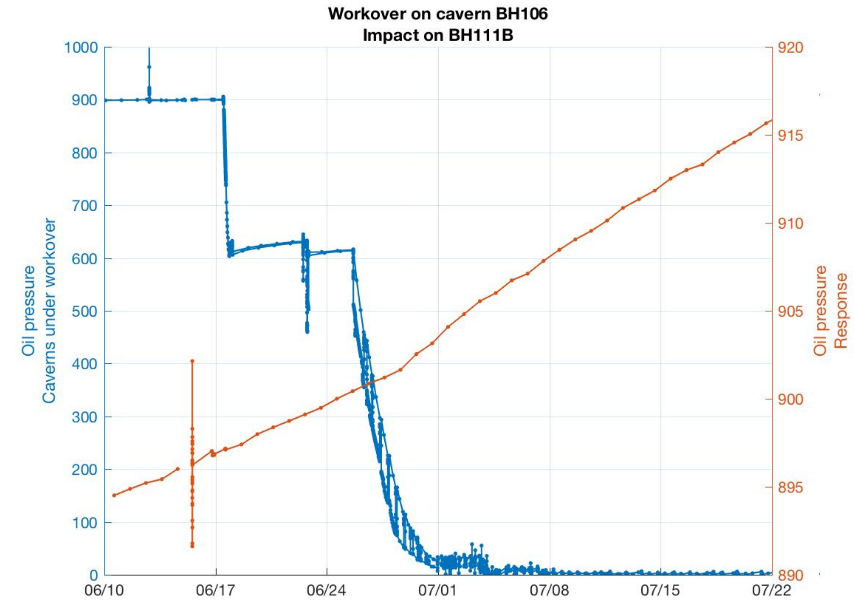

Workover on cavern BH106
Impact on BH101A
Oil pressure
Caverns under workover
Oil pressure
Response
06/10
06/17
06/24
07/01
07/08
07/15
07/22

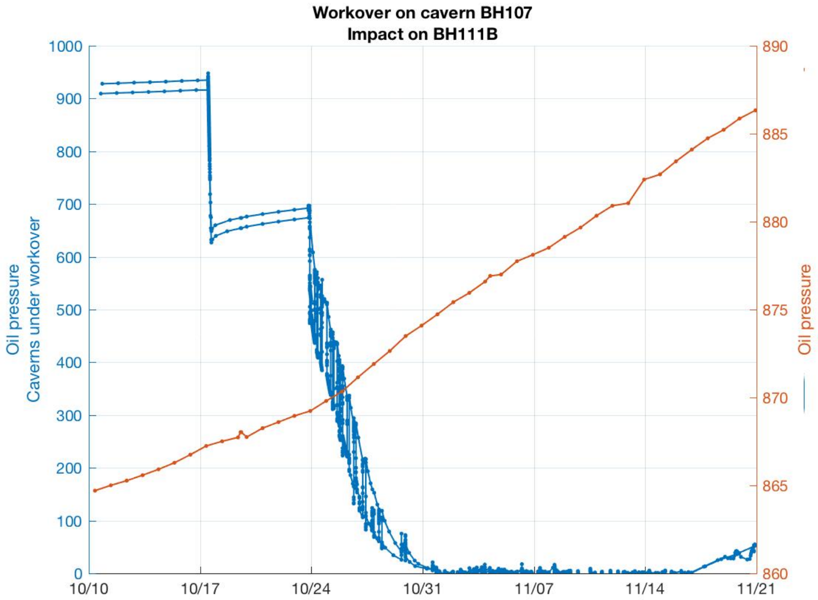

Workover on cavern BH105
Impact on BH109B
Oil pressure
Caverns under workover
Oil pressure
Response
05/06
05/13
05/20
05/27
06/03
06/10
06/17

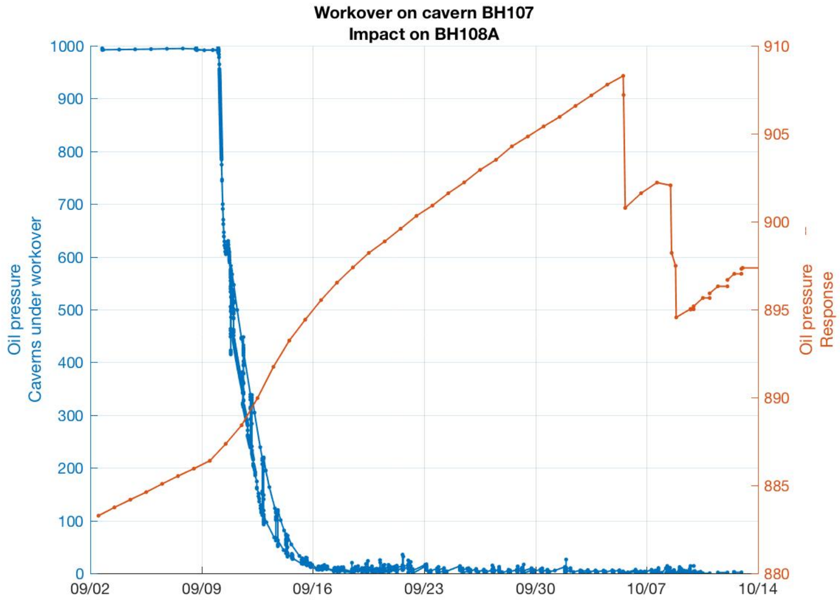

Workover on cavern BH105
Impact on BH110A
Oil pressure
Caverns under workover
Oil pressure
Response
05/06
05/13
05/20
05/27
06/03
06/10
06/17

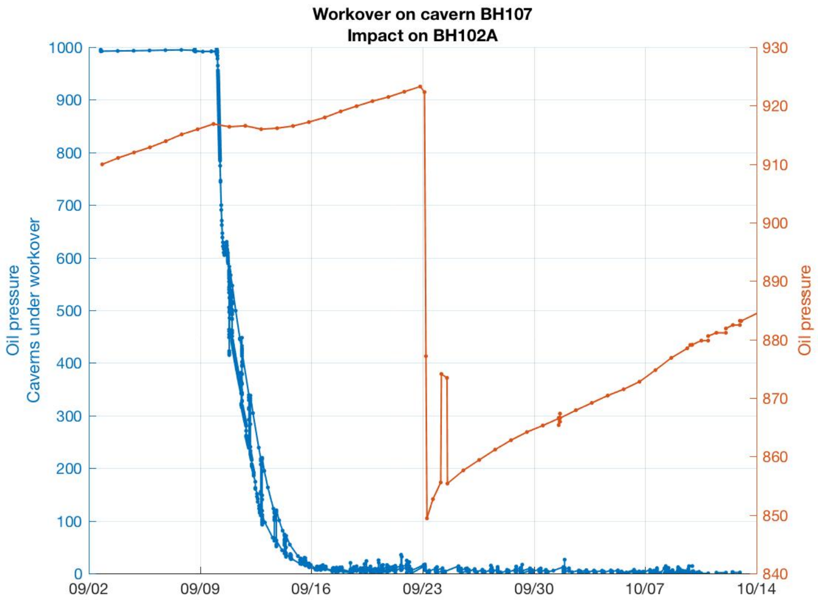
Big Hill Workovers

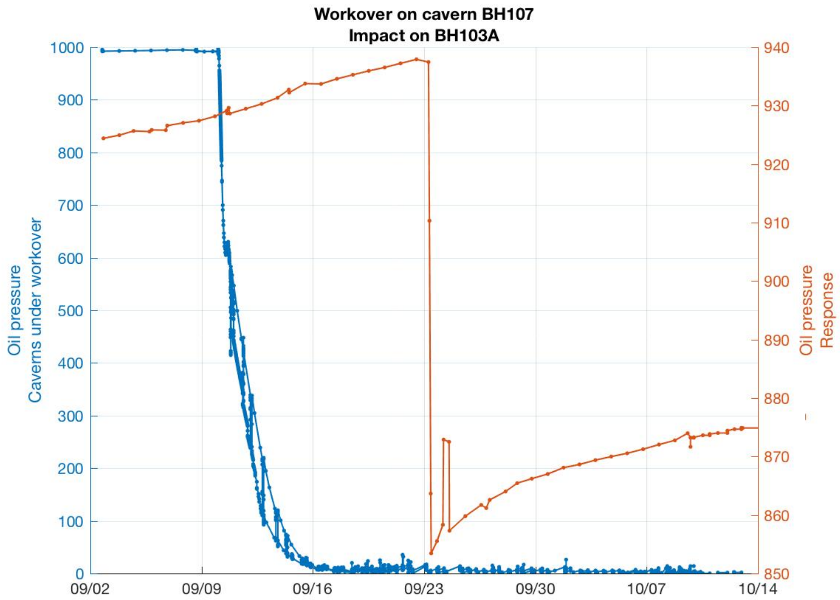




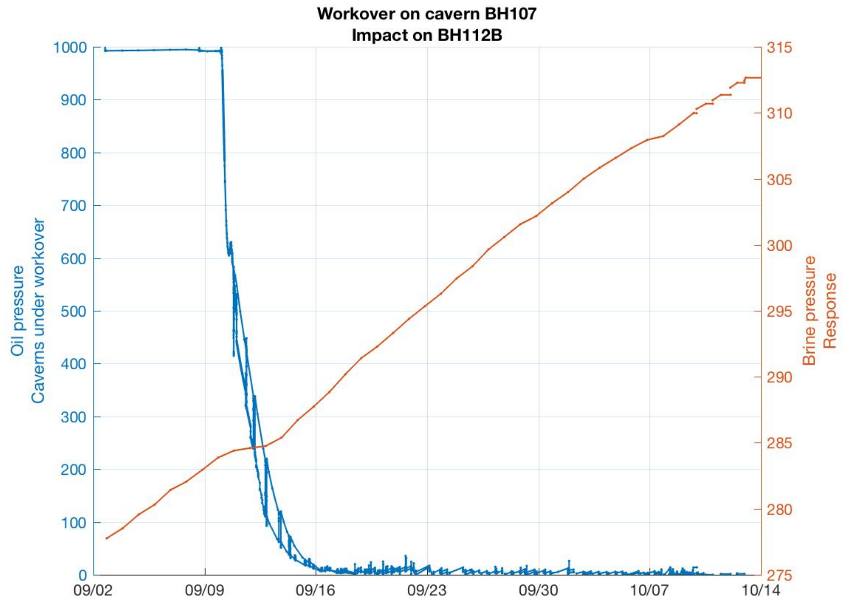

Workover on cavern BH107
Impact on BH111B
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
890
885
880
875
870
865
860
10/10
10/17
10/24
10/31
11/07
11/14
11/21

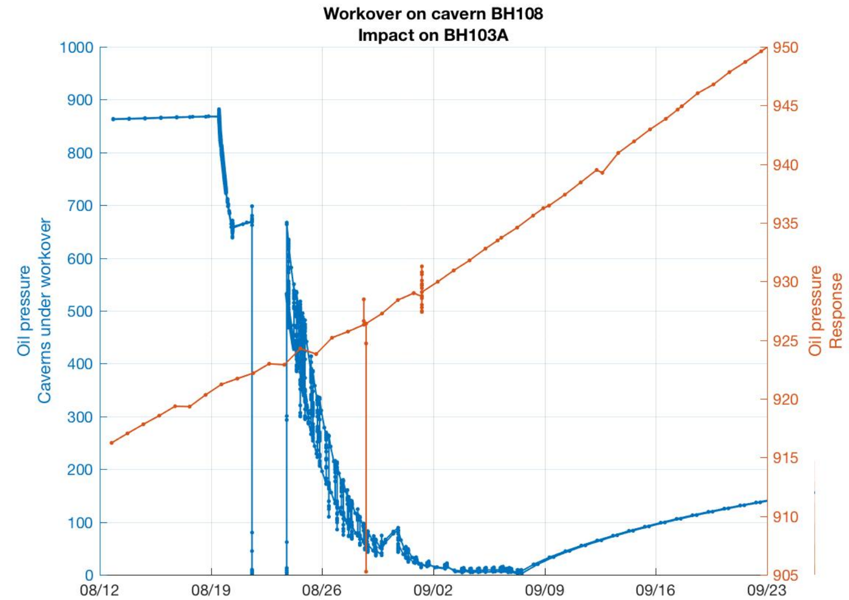

Workover on cavern BH107
Impact on BH108A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
910
905
900
895
890
885
880
09/02
09/09
09/16
09/23
09/30
10/07
10/14

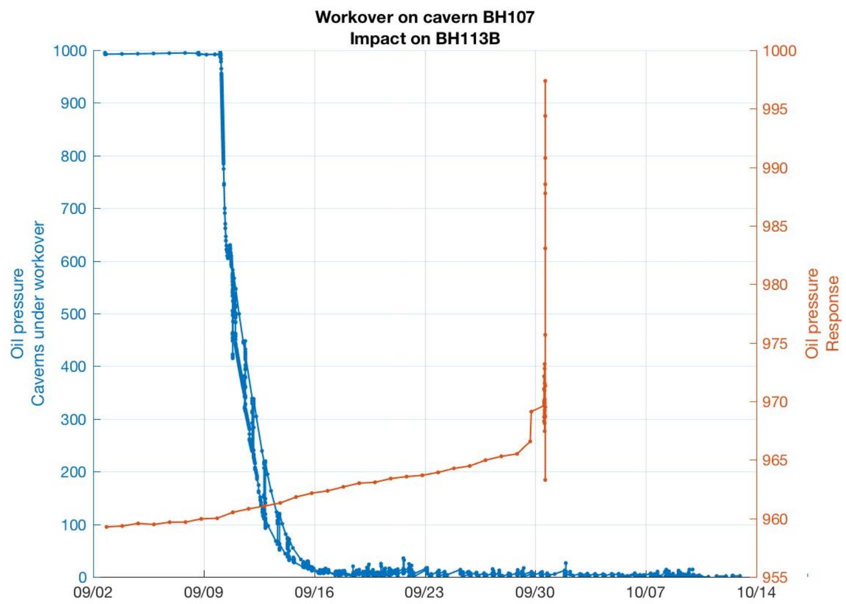

Workover on cavern BH107
Impact on BH102A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
930
920
910
900
890
880
870
860
850
840
09/02
09/09
09/16
09/23
09/30
10/07
10/14

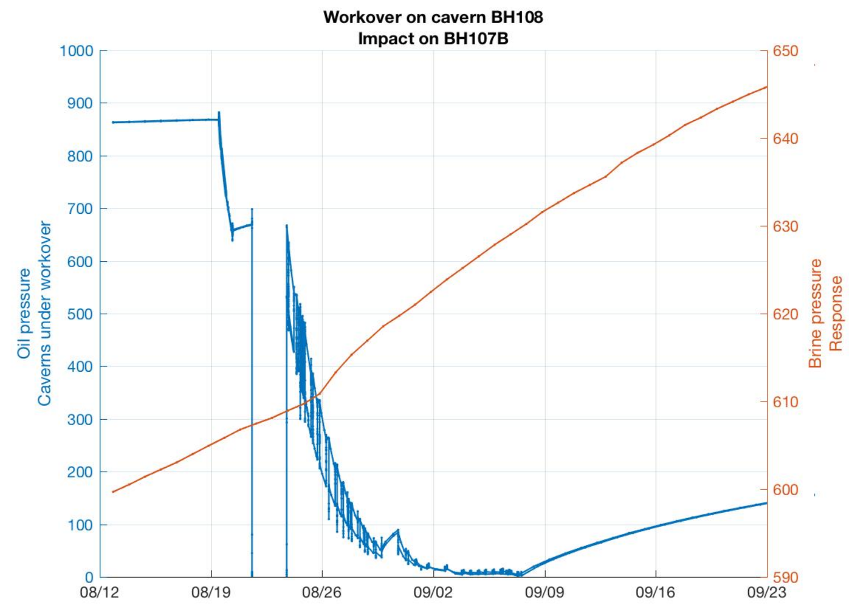

Workover on cavern BH107
Impact on BH103A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
940
930
920
910
900
890
880
870
860
850
09/02
09/09
09/16
09/23
09/30
10/07
10/14

BIG HILL WORKOVERS

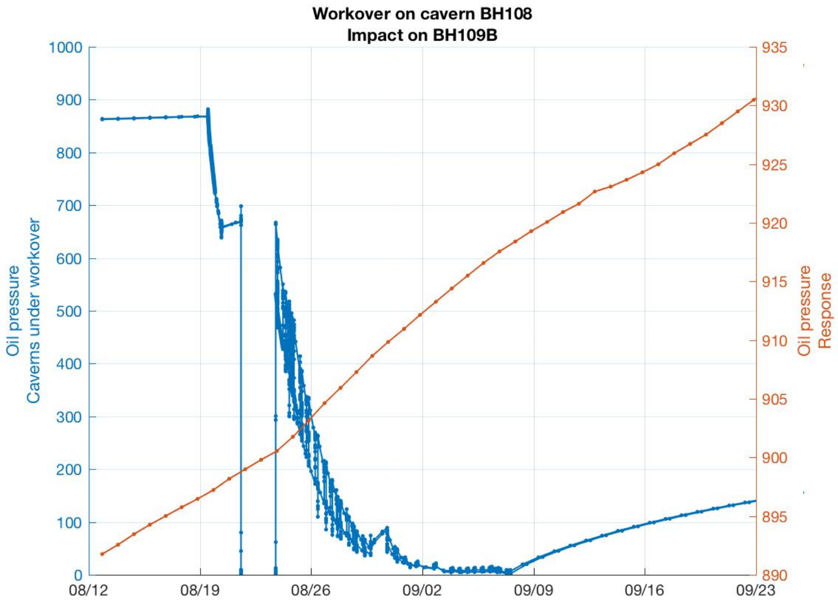


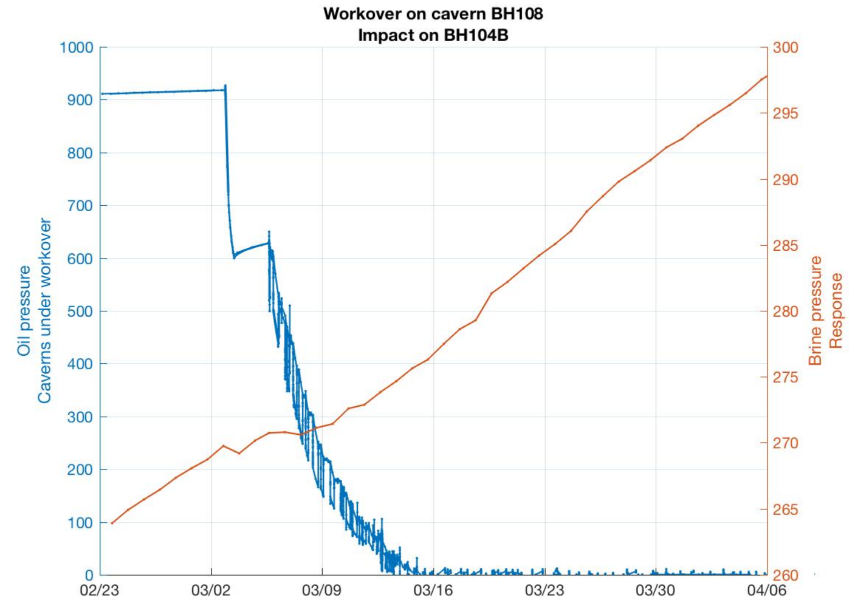


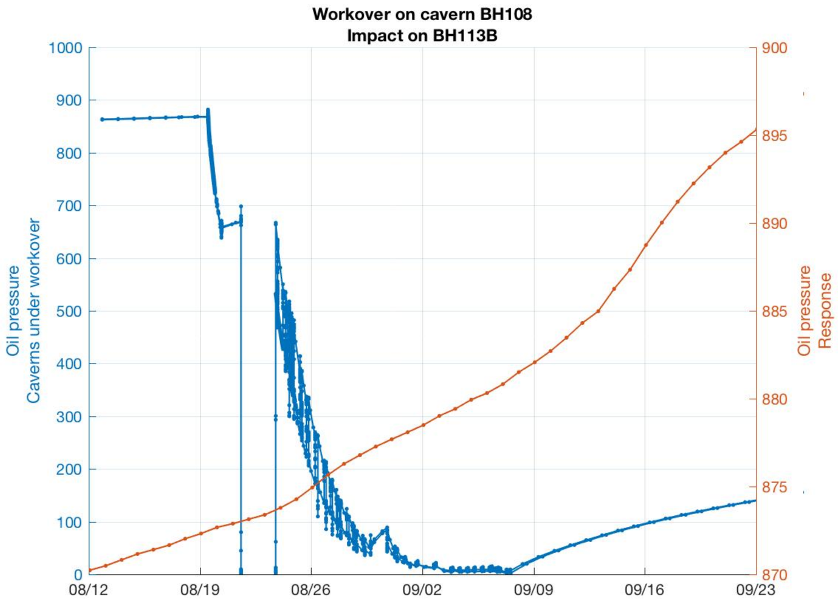


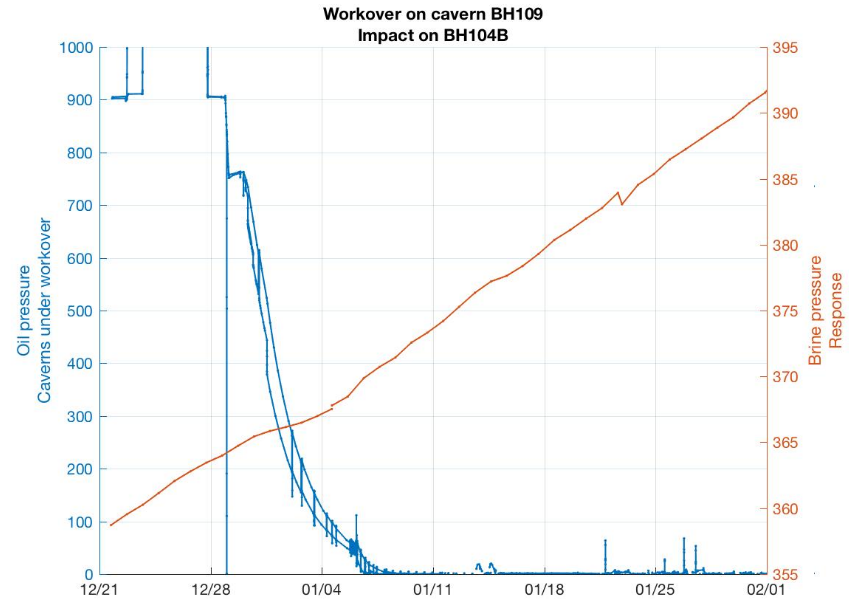


Big Hill Workovers

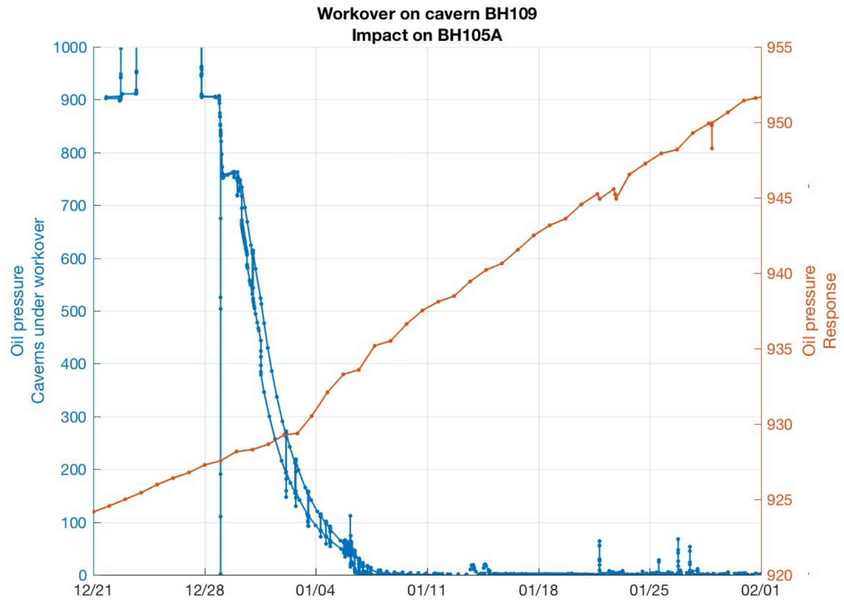


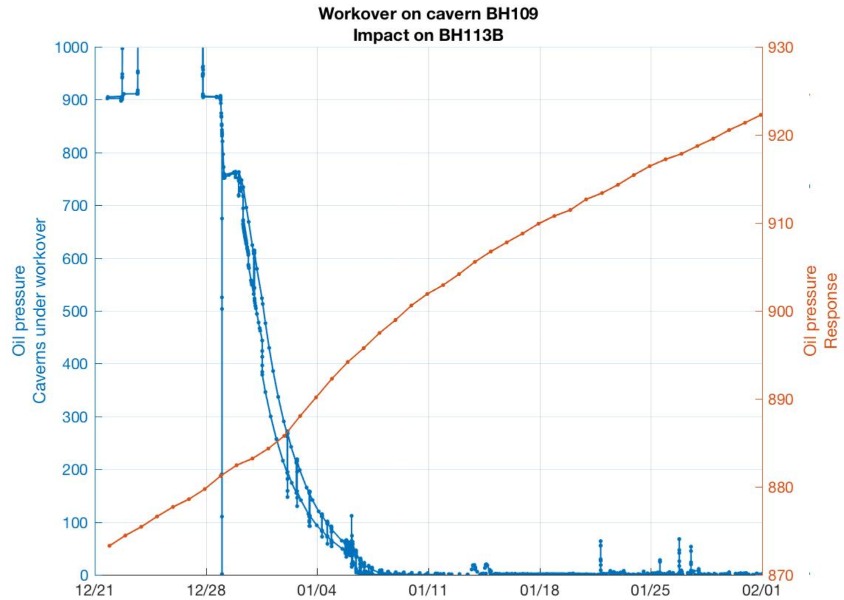


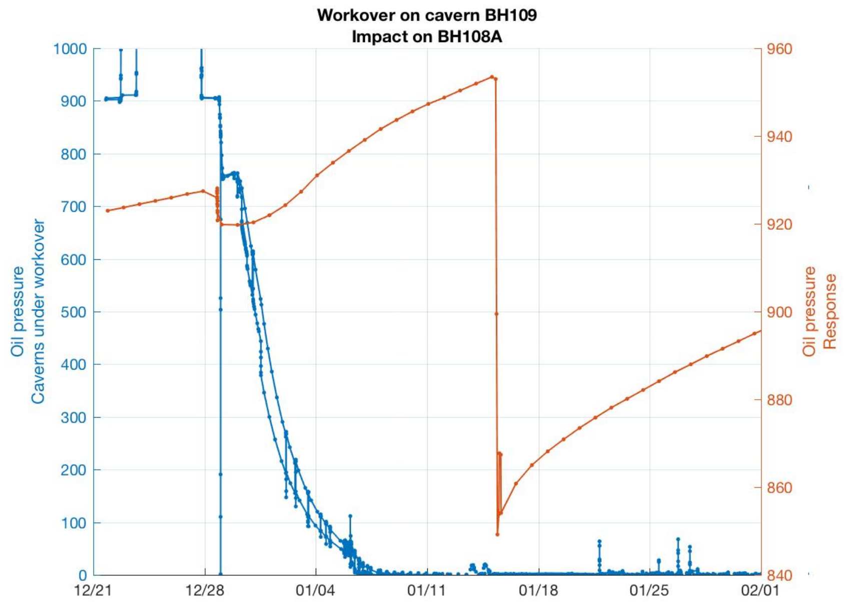


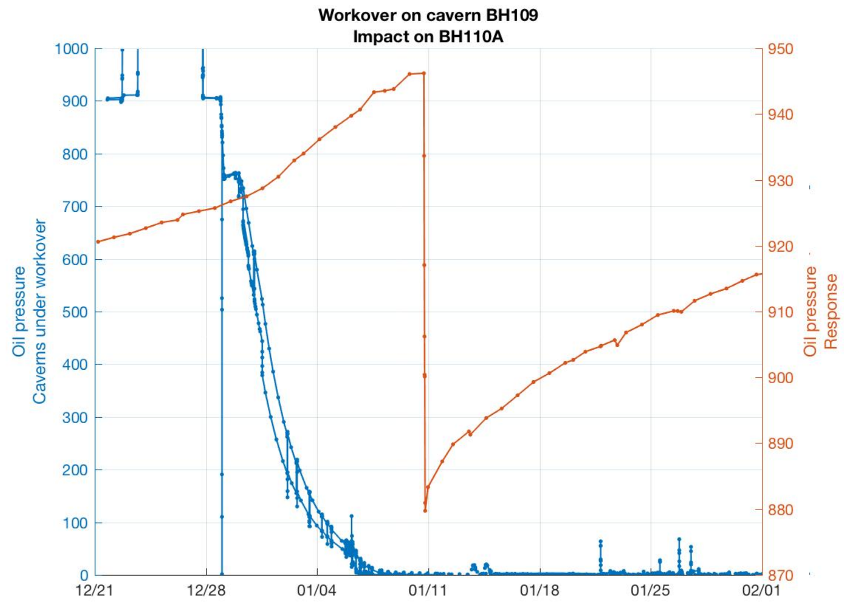


Big Hill Workovers

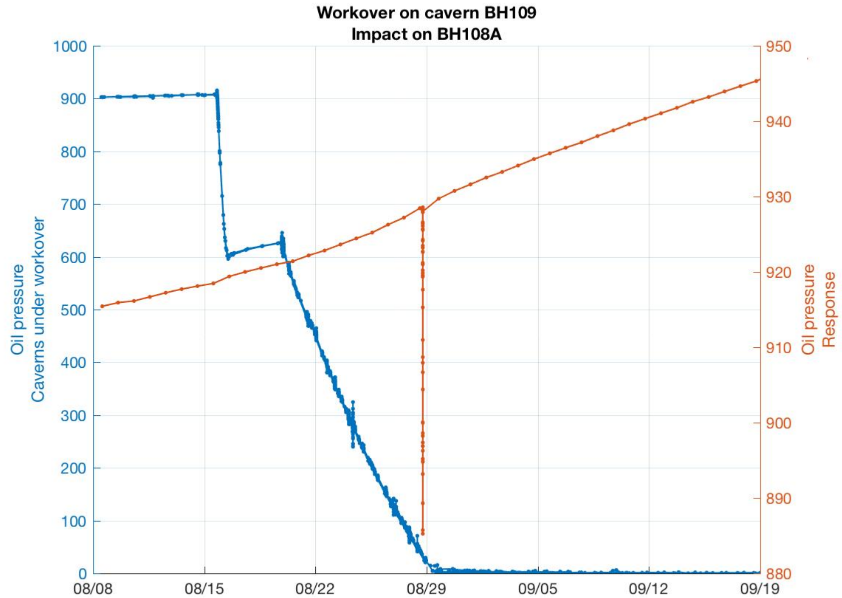


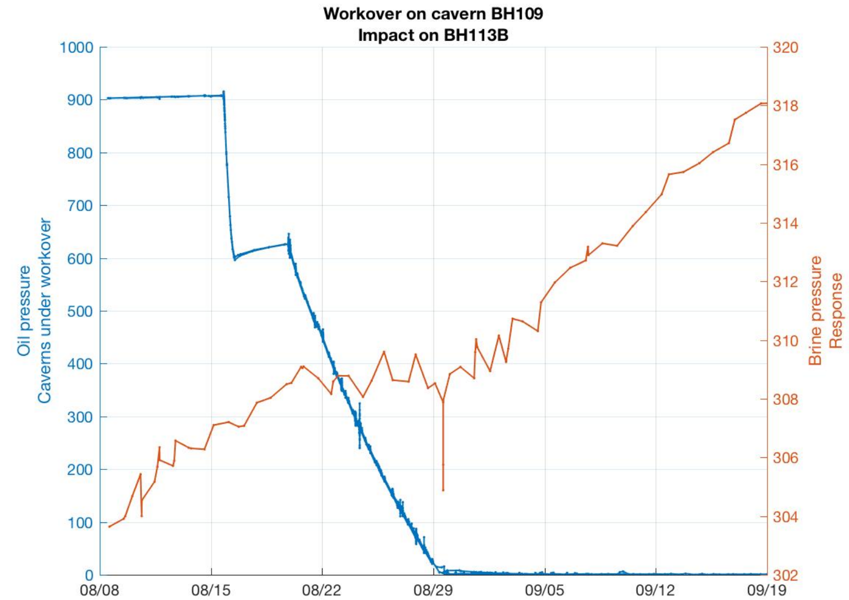


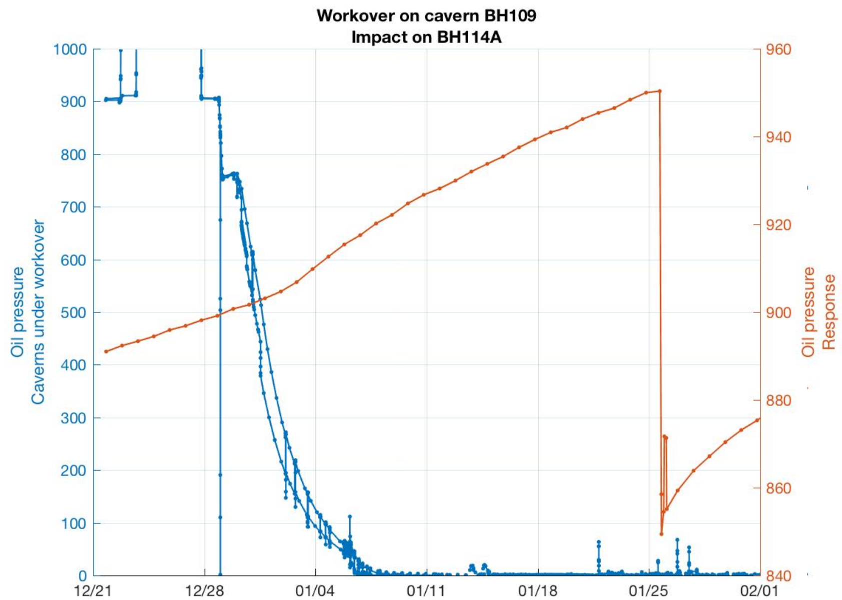


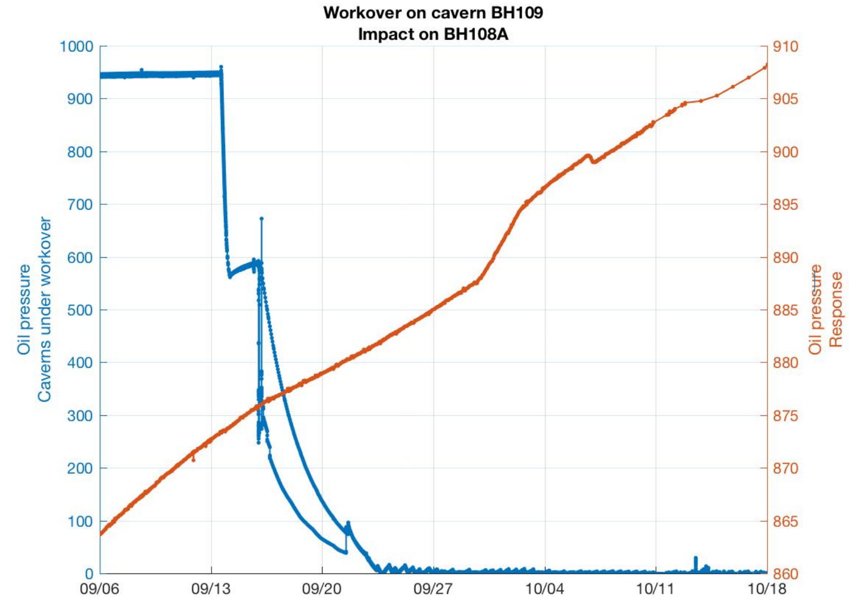


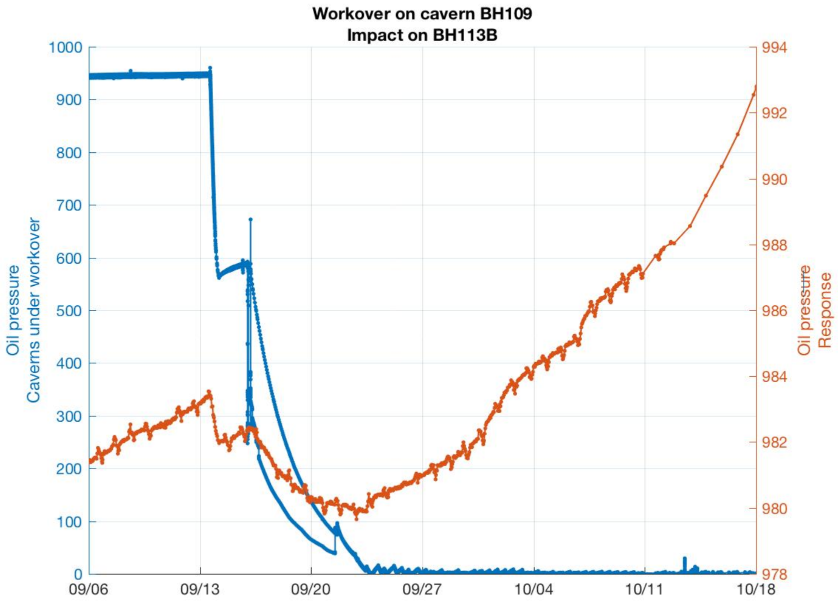
Big Hill Workovers

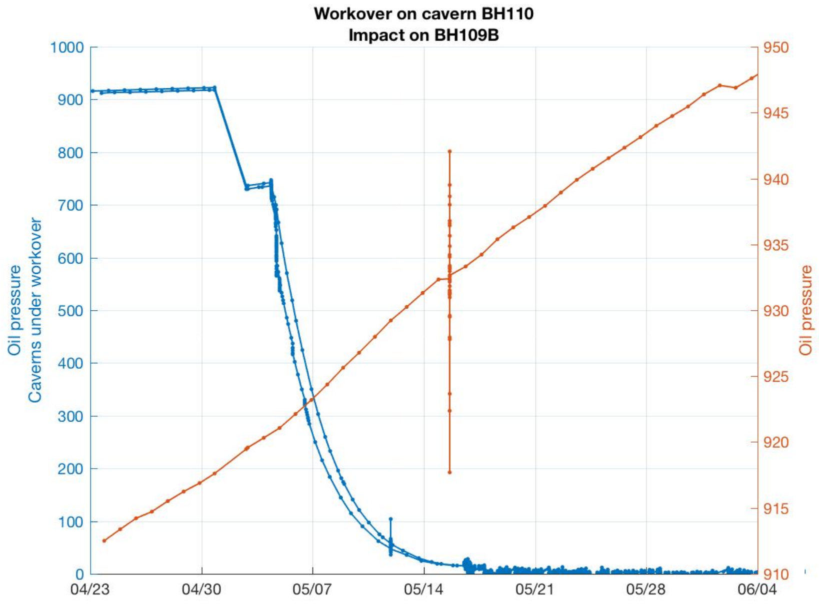


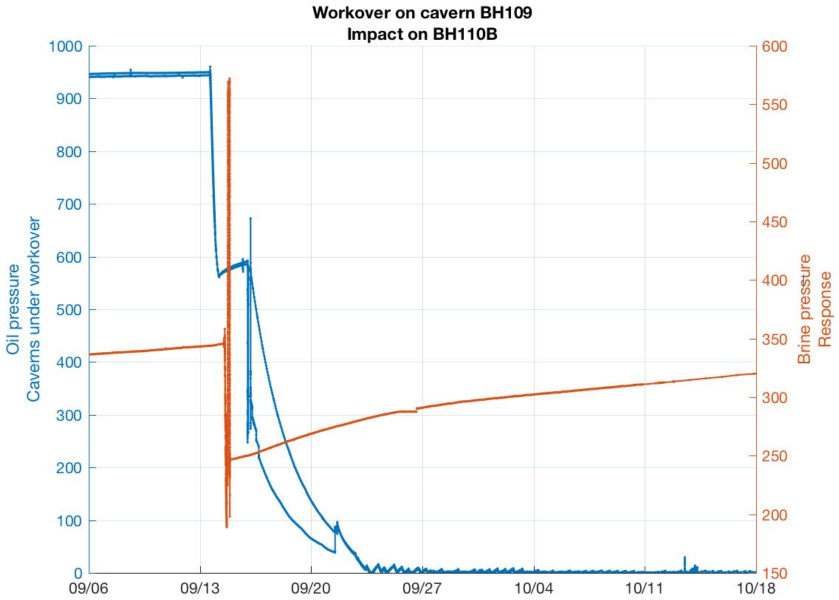


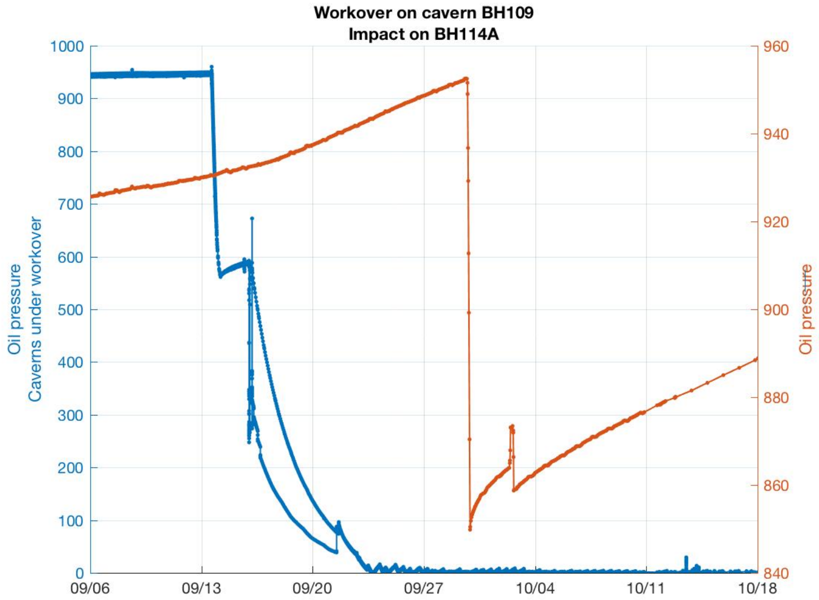




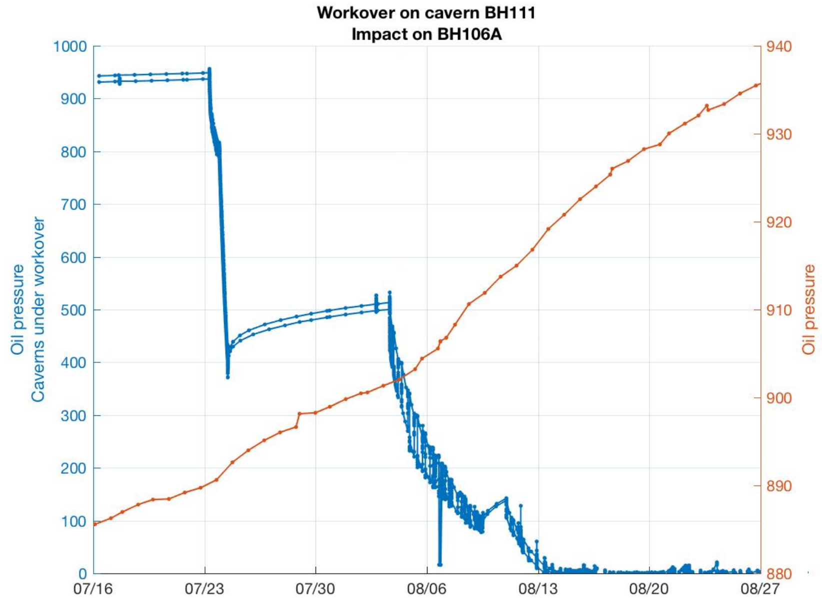

Workover on cavern BH109
Impact on BH113B
Oil pressure
Caverns under workover
Oil pressure
Response
09/06
09/13
09/20
09/27
10/04
10/11
10/18

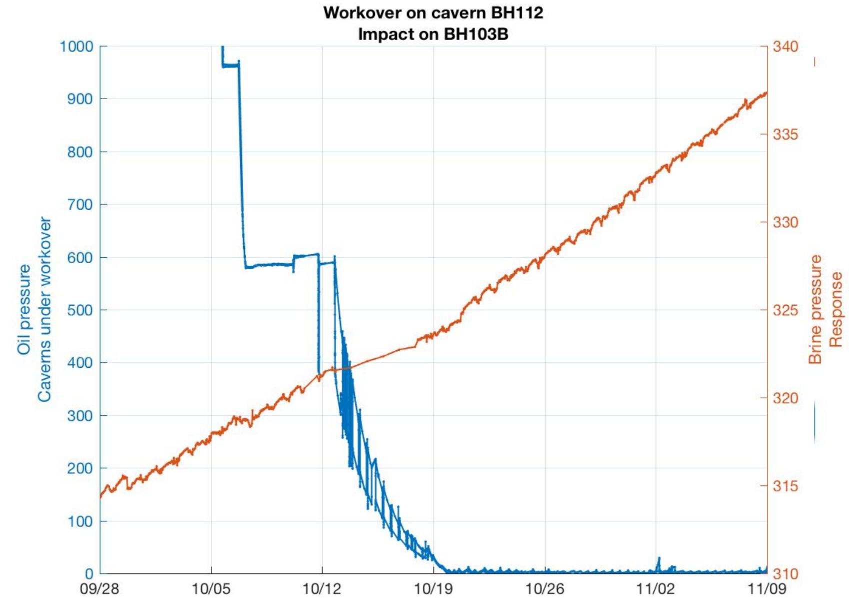

Workover on cavern BH110
Impact on BH109B
Oil pressure
Caverns under workover
Oil pressure
Response
04/23
04/30
05/07
05/14
05/21
05/28
06/04

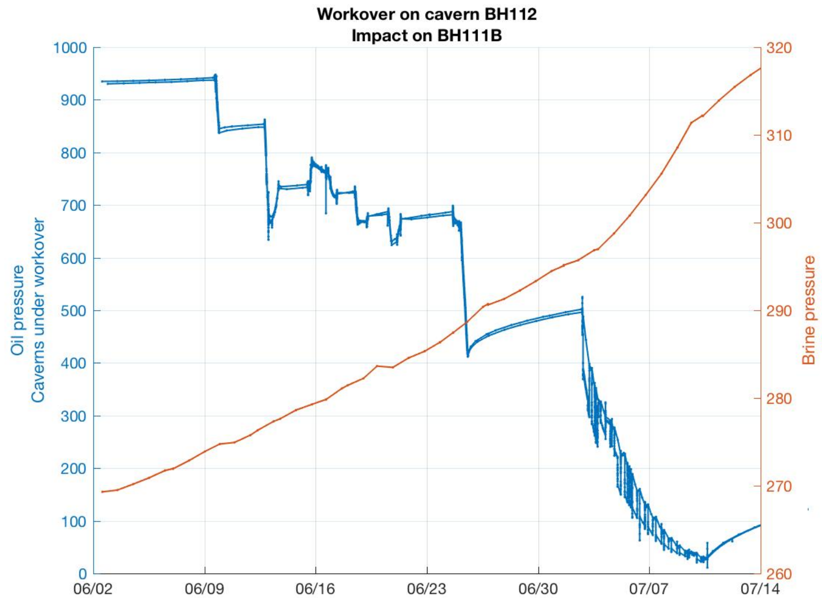

Workover on cavern BH109
Impact on BH110B
Oil pressure
Caverns under workover
Brine pressure
Response
09/06
09/13
09/20
09/27
10/04
10/11
10/18

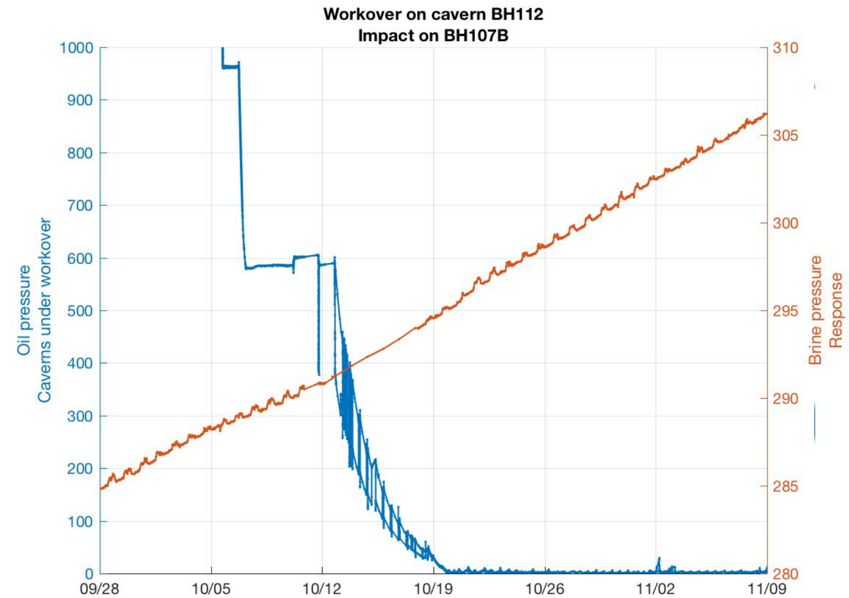

Workover on cavern BH109
Impact on BH114A
Oil pressure
Caverns under workover
Oil pressure
Response
09/06
09/13
09/20
09/27
10/04
10/11
10/18

Big Hill Workovers

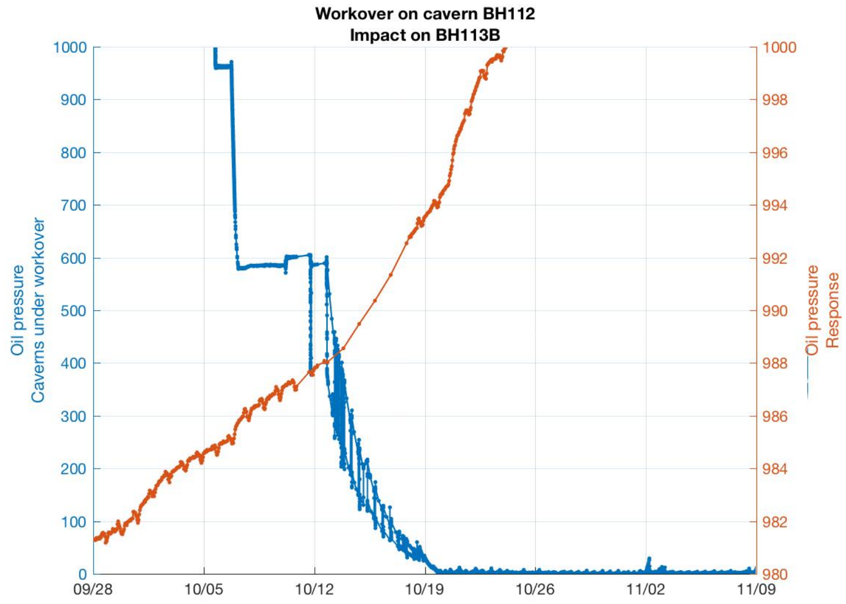


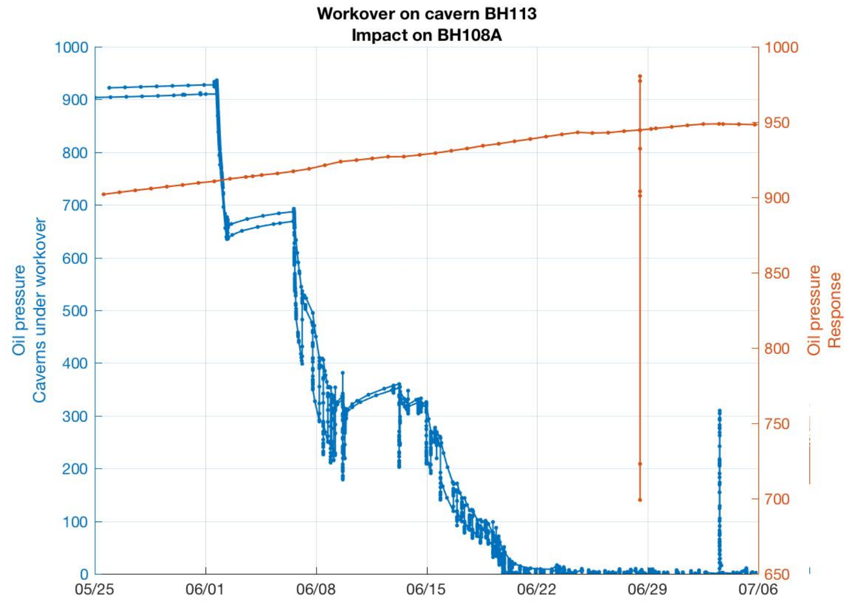


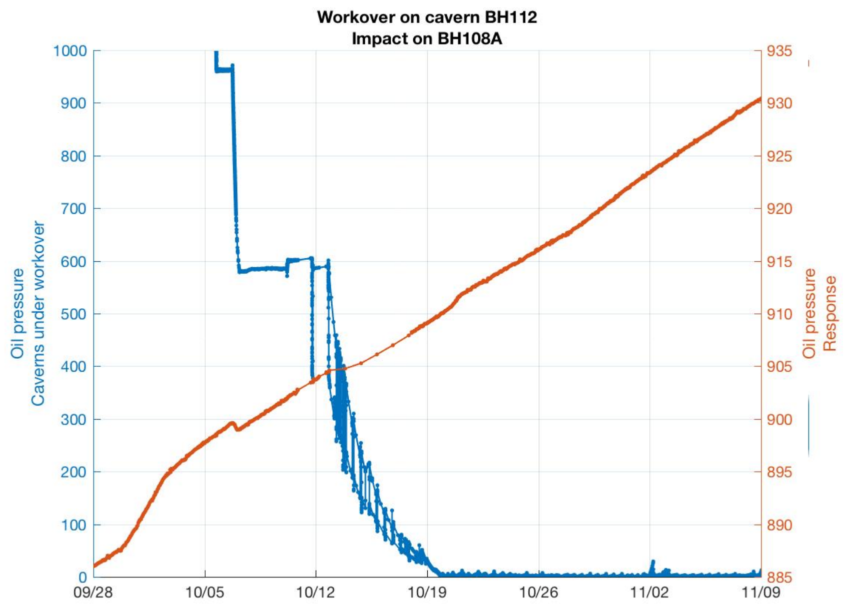


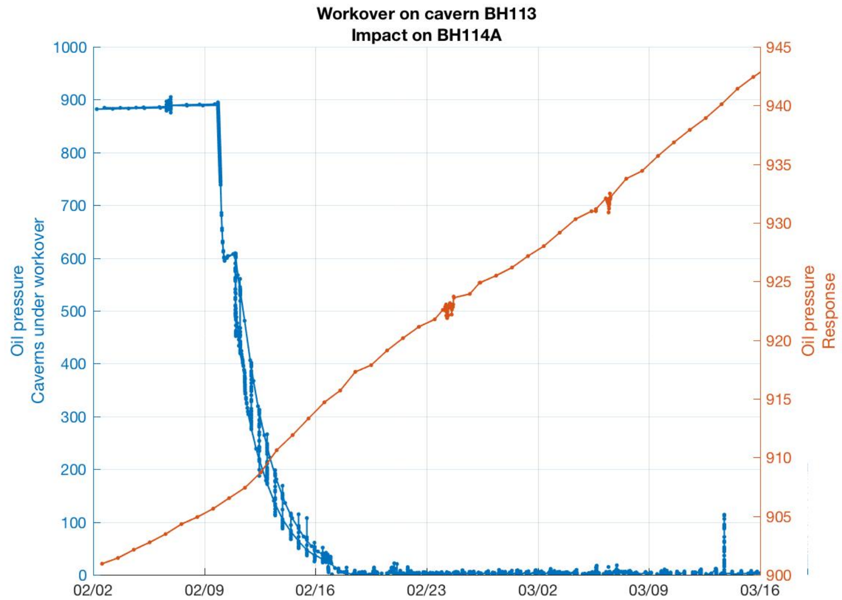


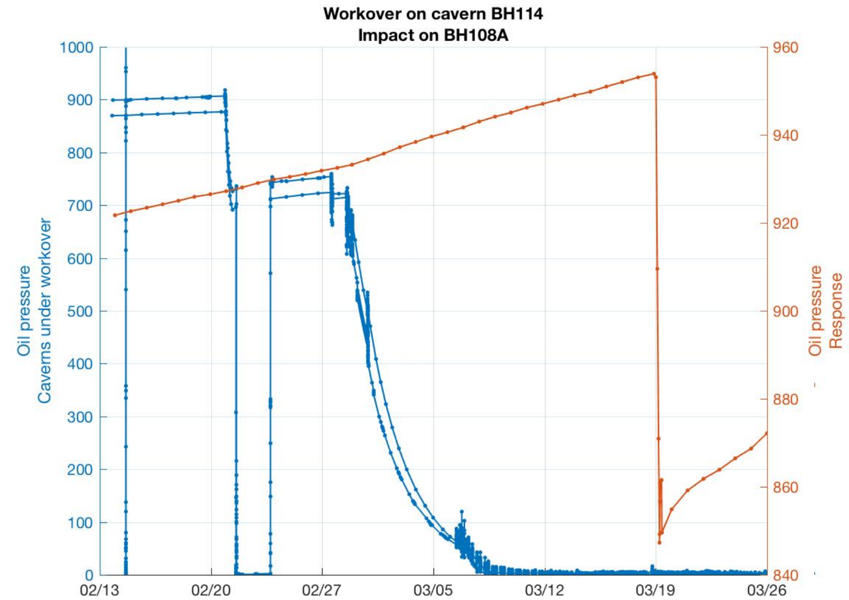
Big Hill Workovers

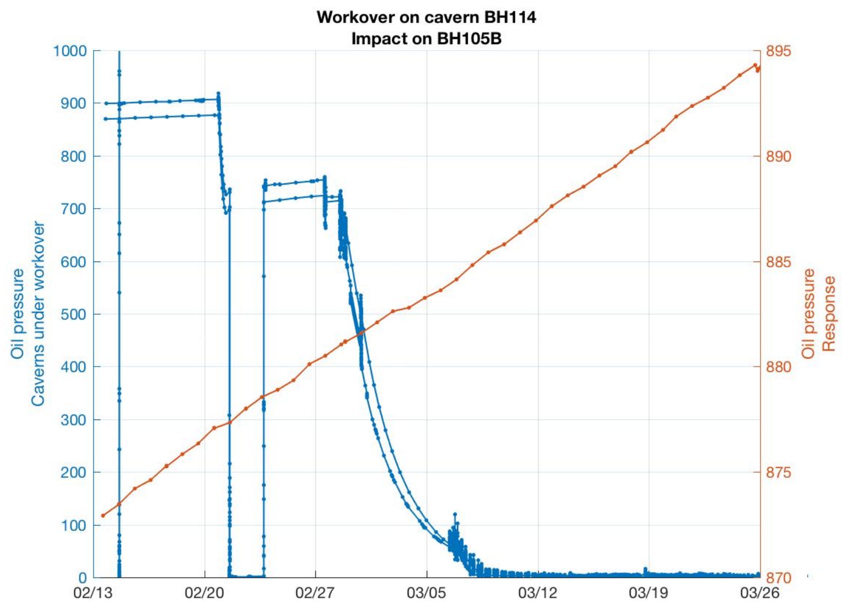


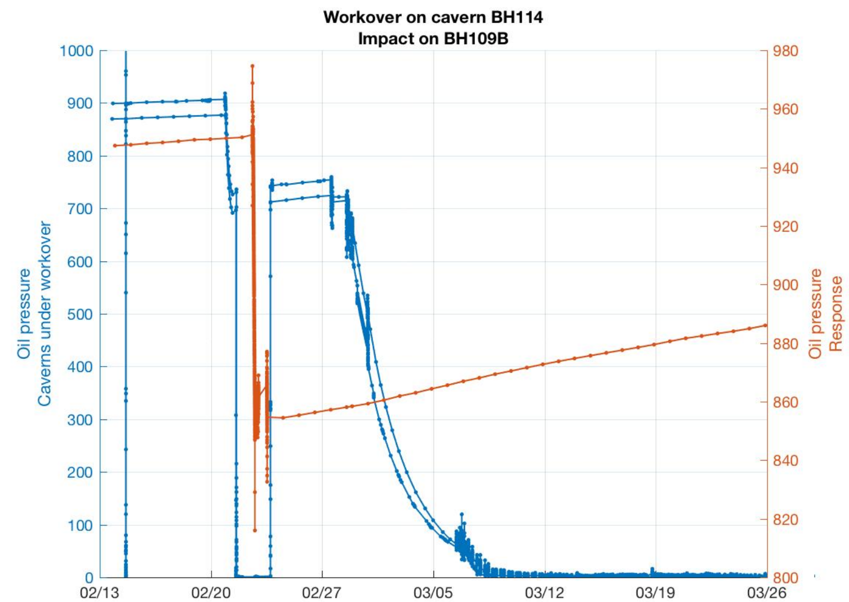




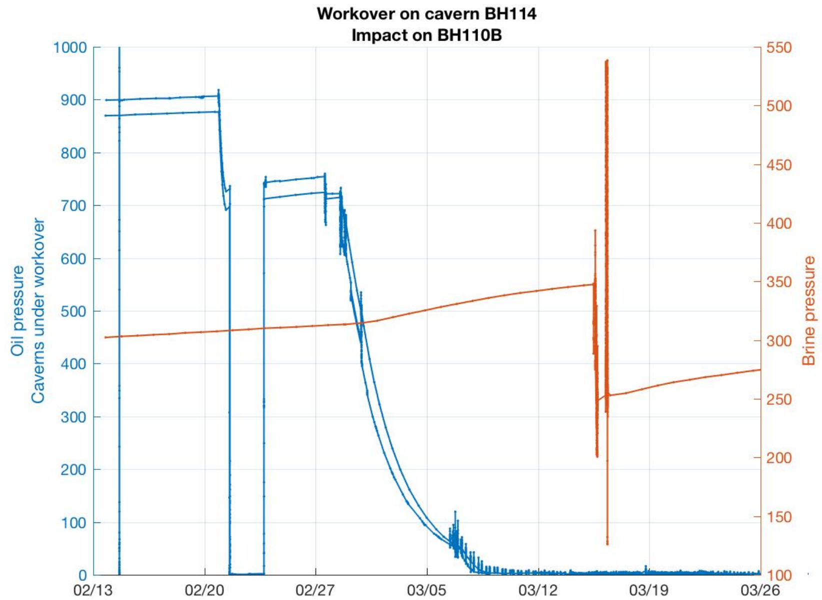

Workover on cavern BH113
Impact on BH114A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
945
940
935
930
925
920
915
910
905
900
02/02
02/09
02/16
02/23
03/02
03/09
03/16

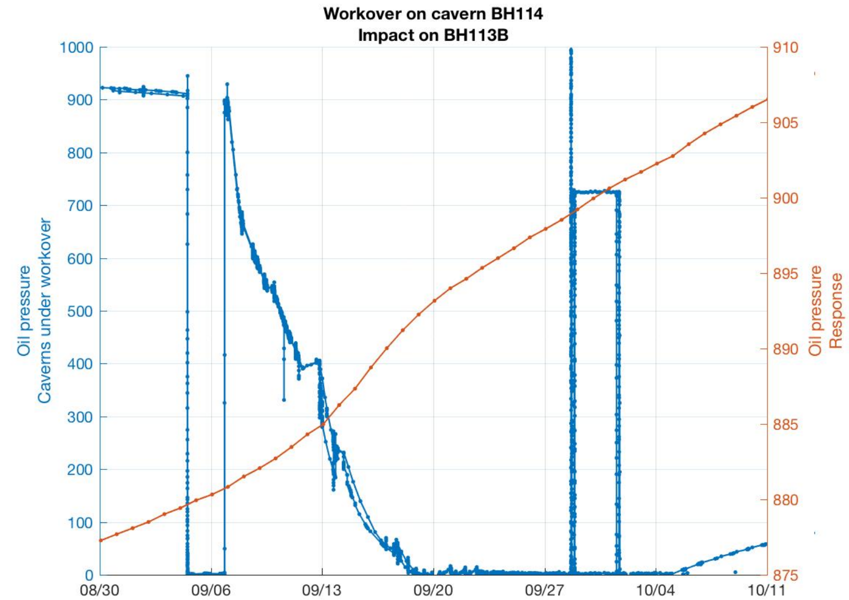

Workover on cavern BH114
Impact on BH108A
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
960
940
920
900
880
860
840
02/13
02/20
02/27
03/05
03/12
03/19
03/26

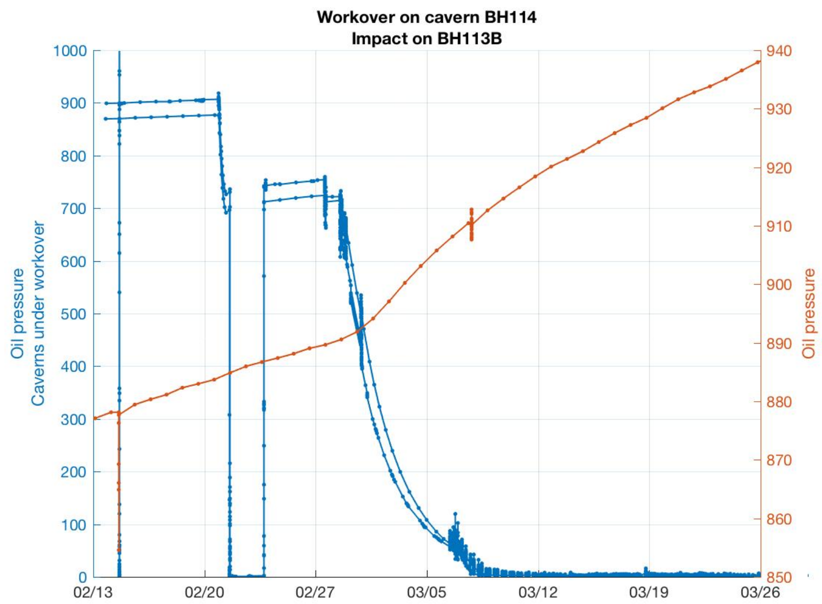

Workover on cavern BH114
Impact on BH105B
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
895
890
885
880
875
870
02/13
02/20
02/27
03/05
03/12
03/19
03/26


Workover on cavern BH114
Impact on BH109B
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
980
960
940
920
900
880
860
840
820
800
02/13
02/20
02/27
03/05
03/12
03/19
03/26

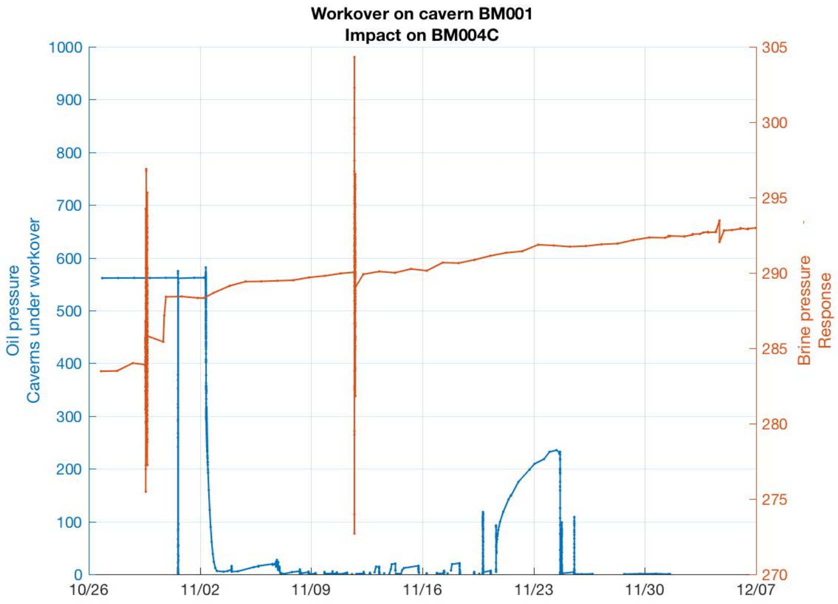
Big Hill Workovers

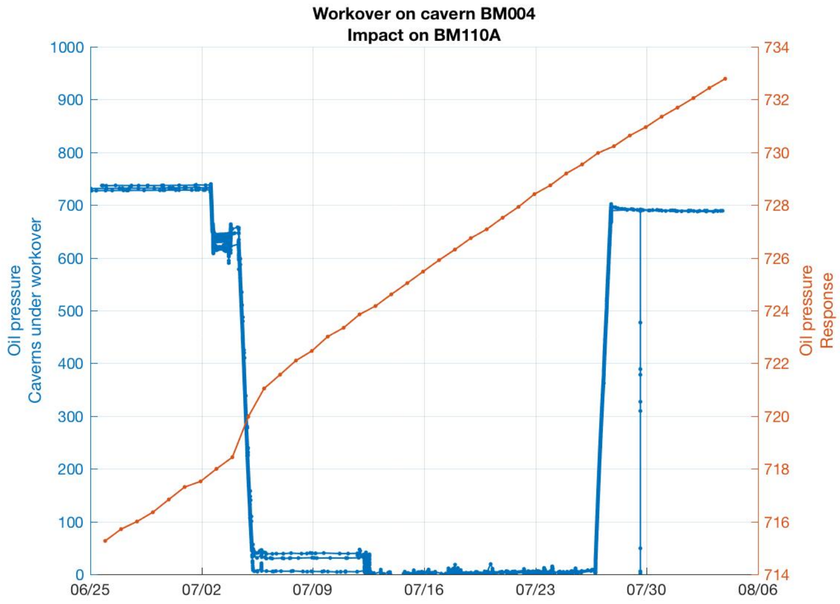


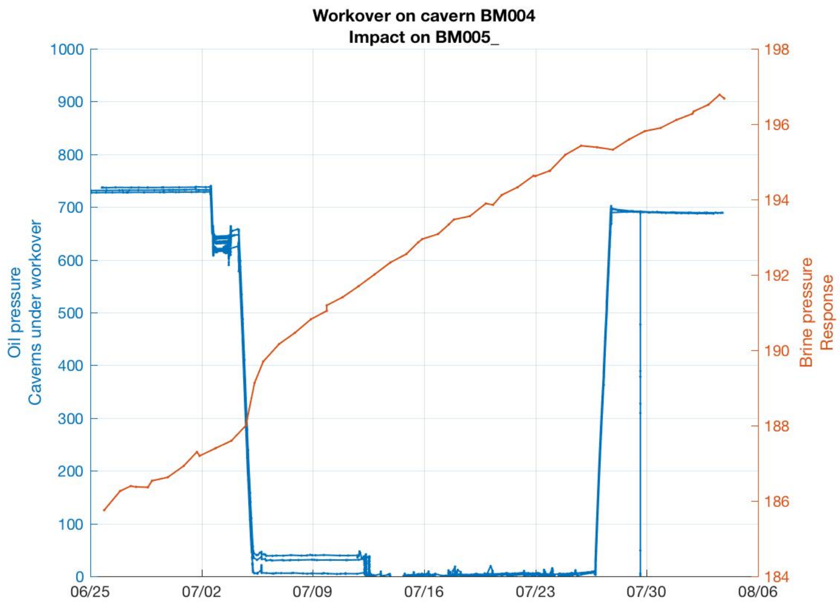




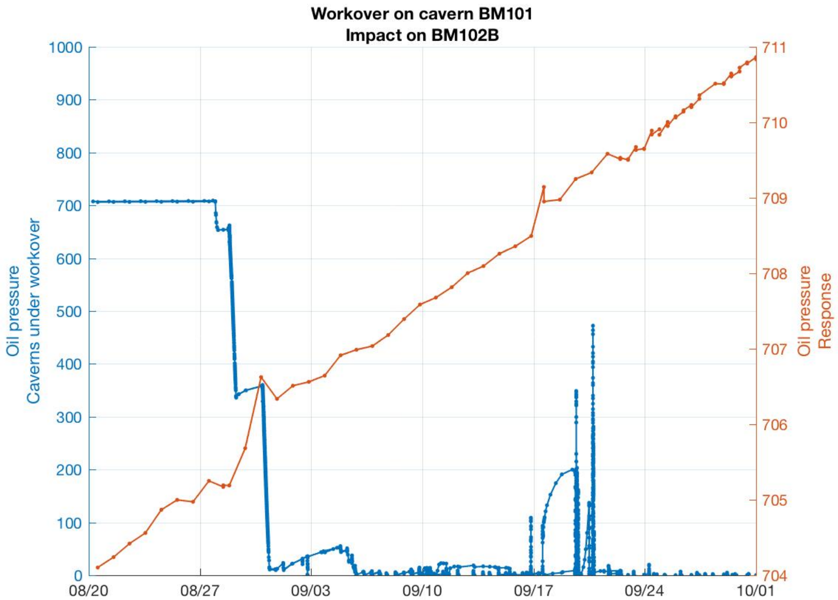
Bryan Mound Workovers

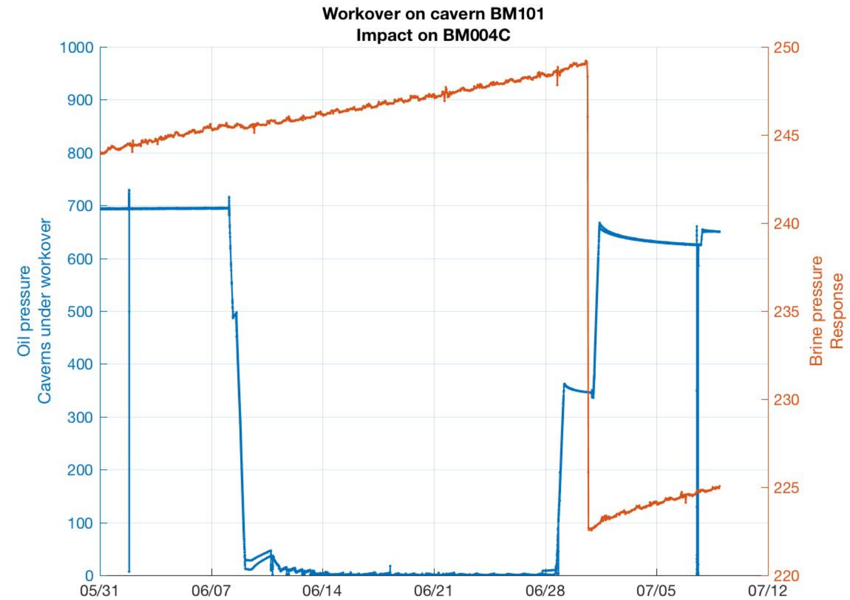


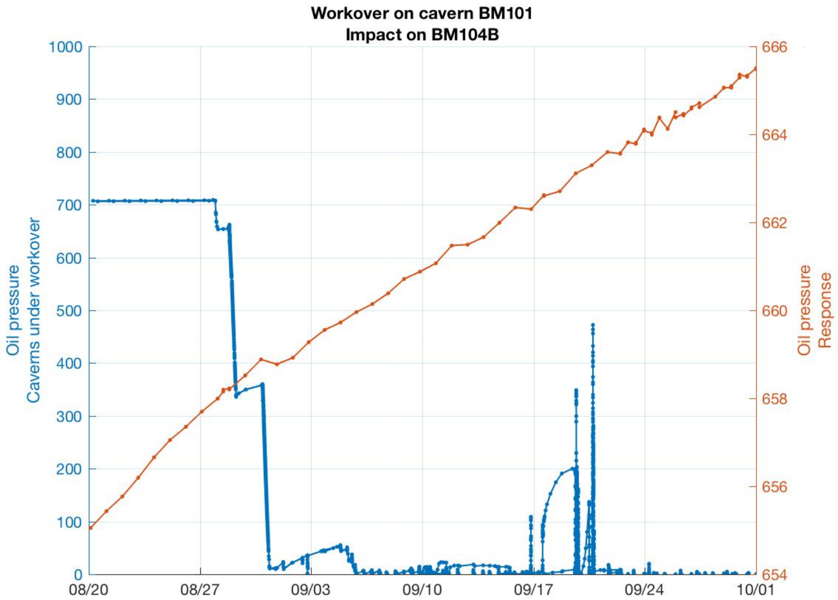


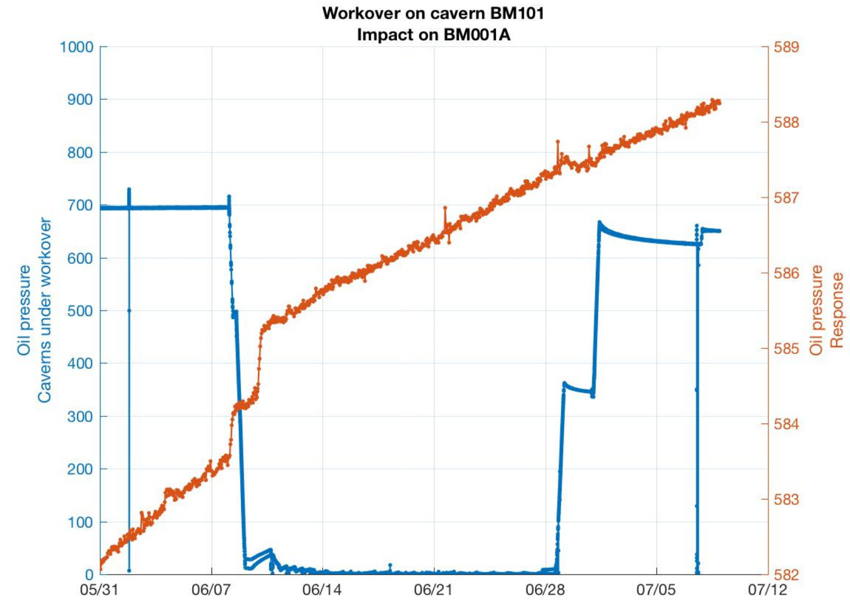


Bryan Mound Workovers

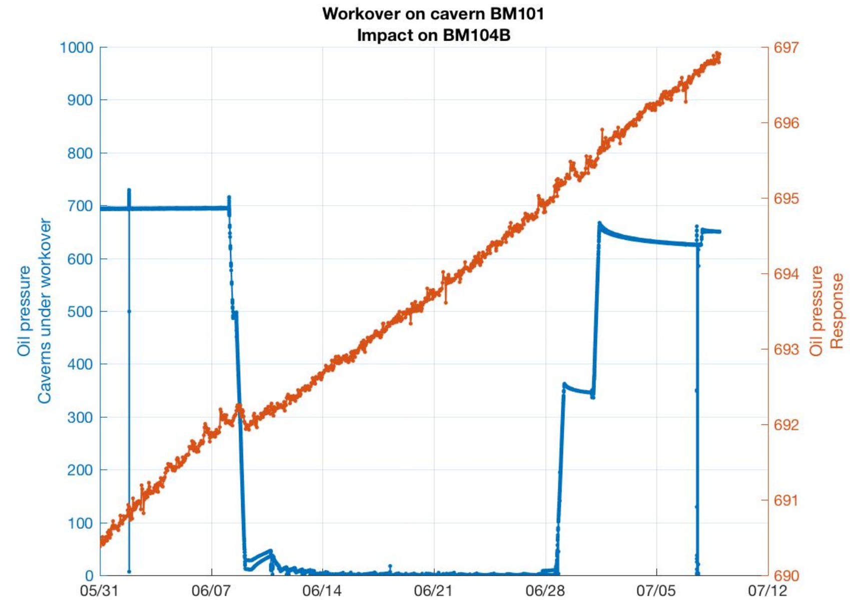


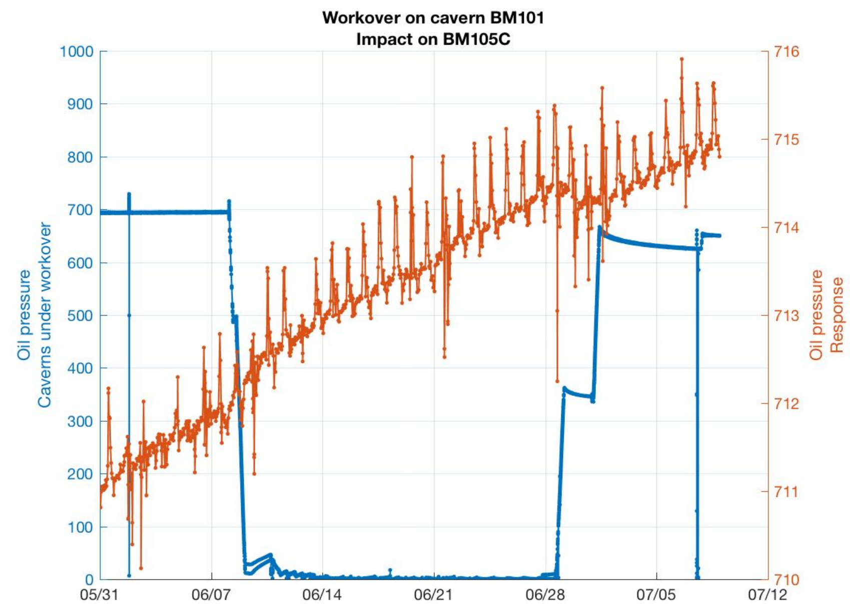




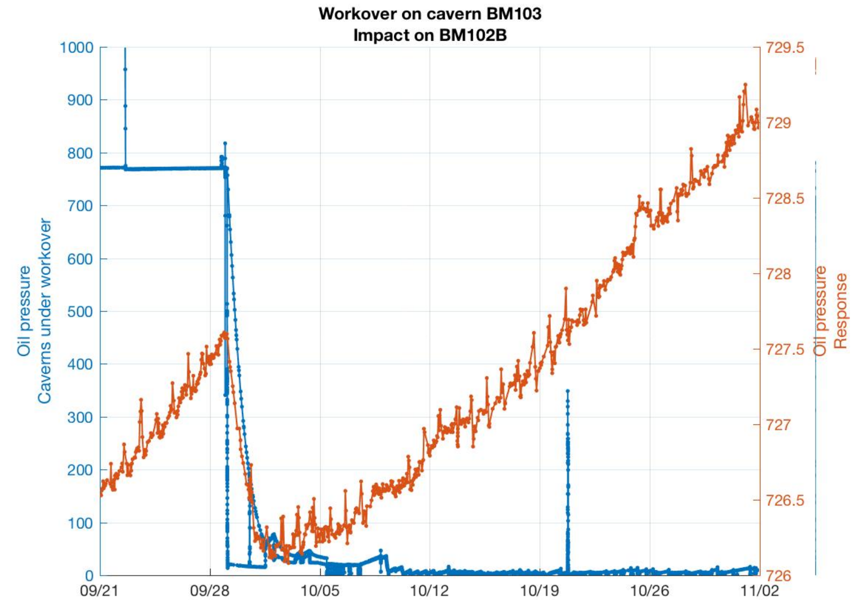


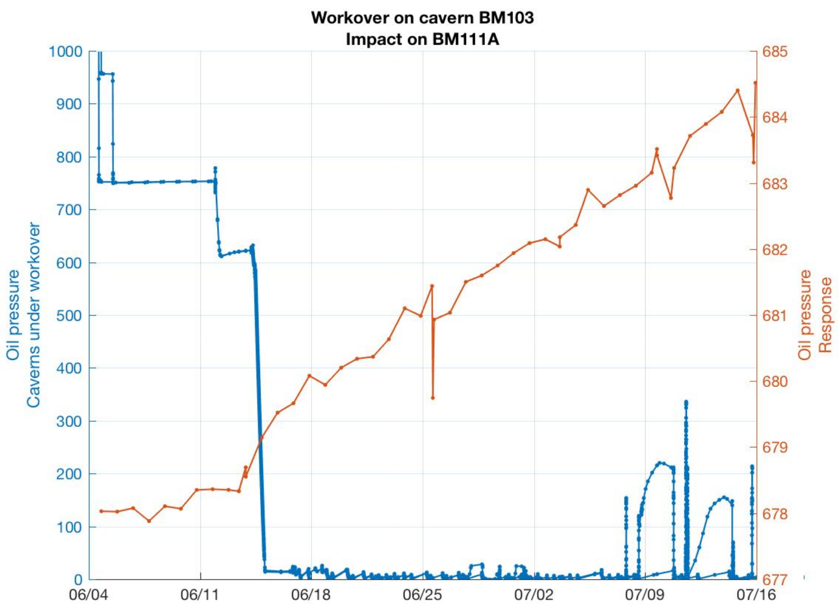
BRYAN MOUND WORKOVERS

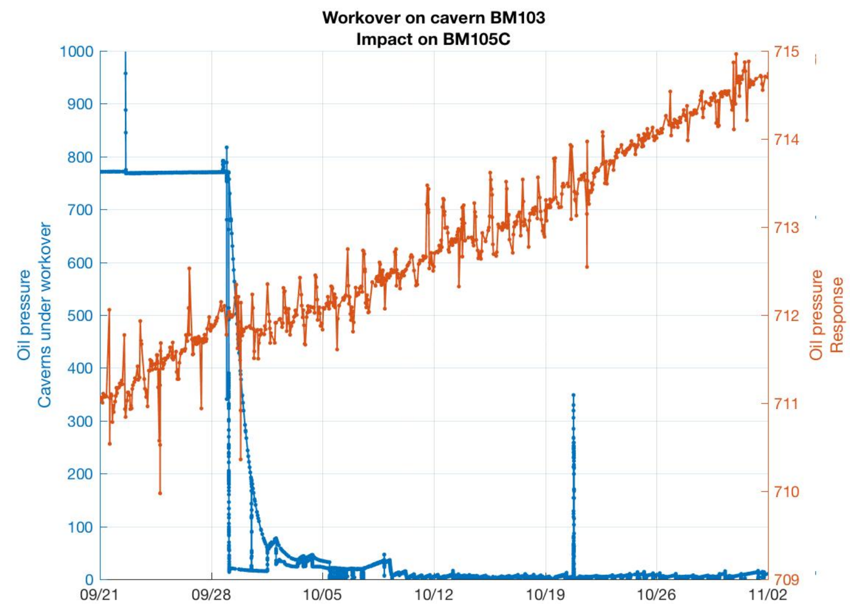




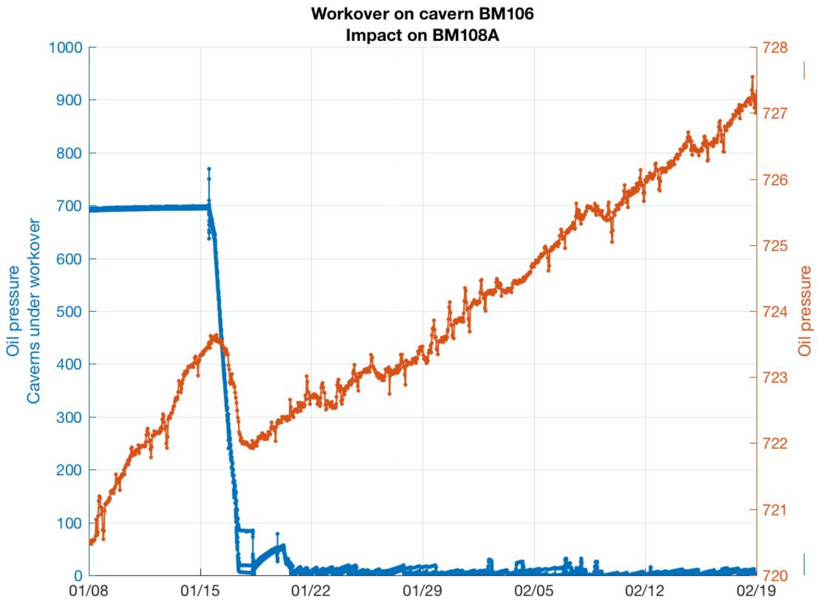
Bryan Mound Workovers

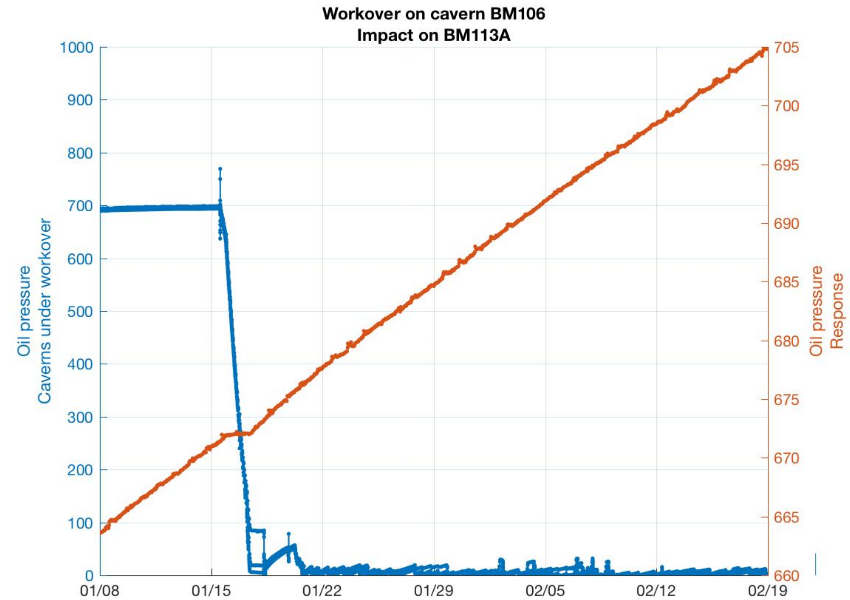


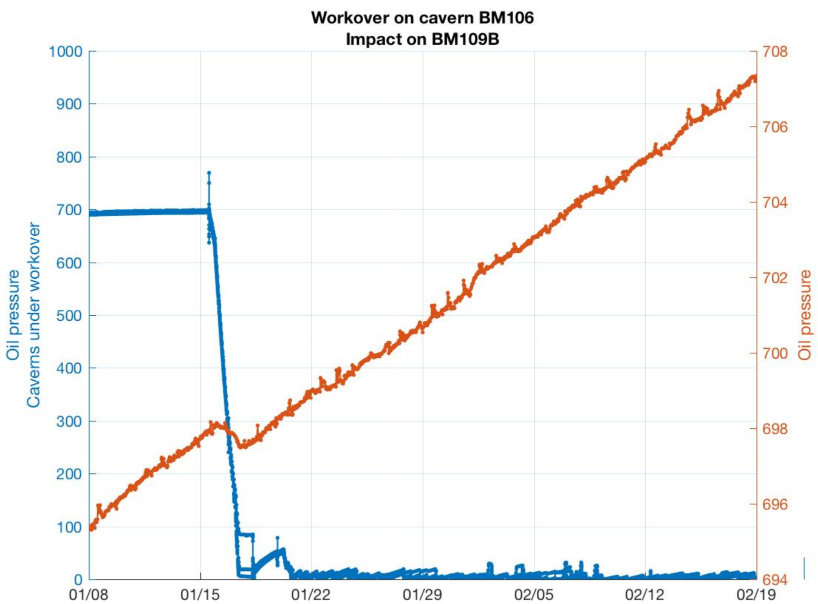




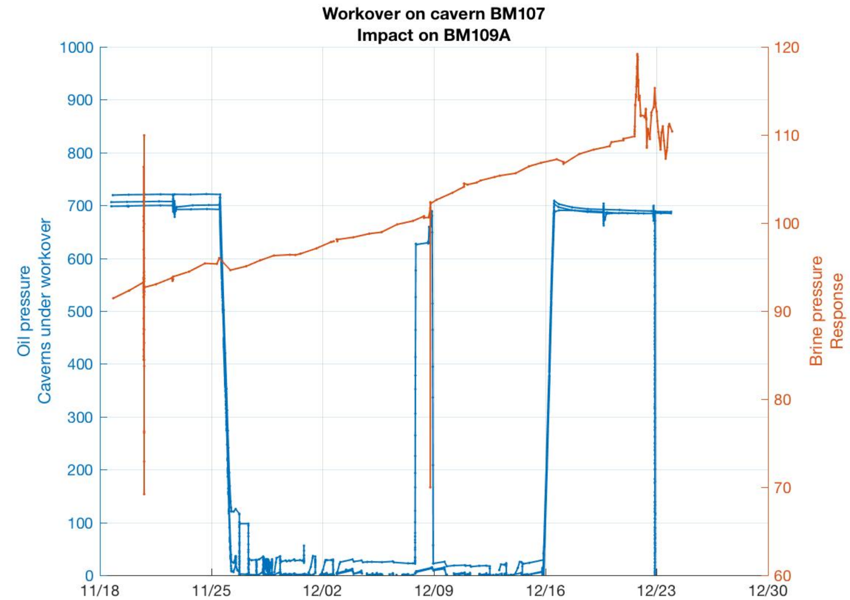
Bryan Mound Workovers

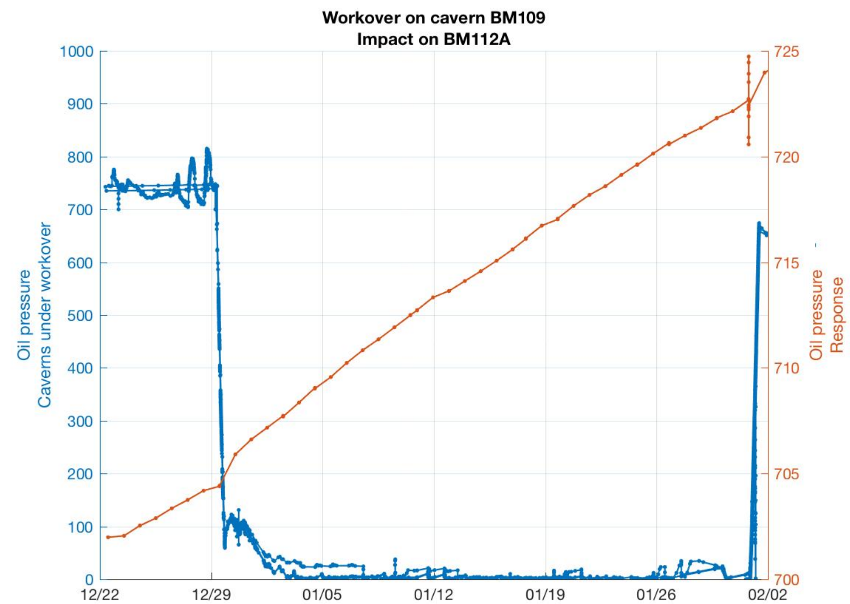






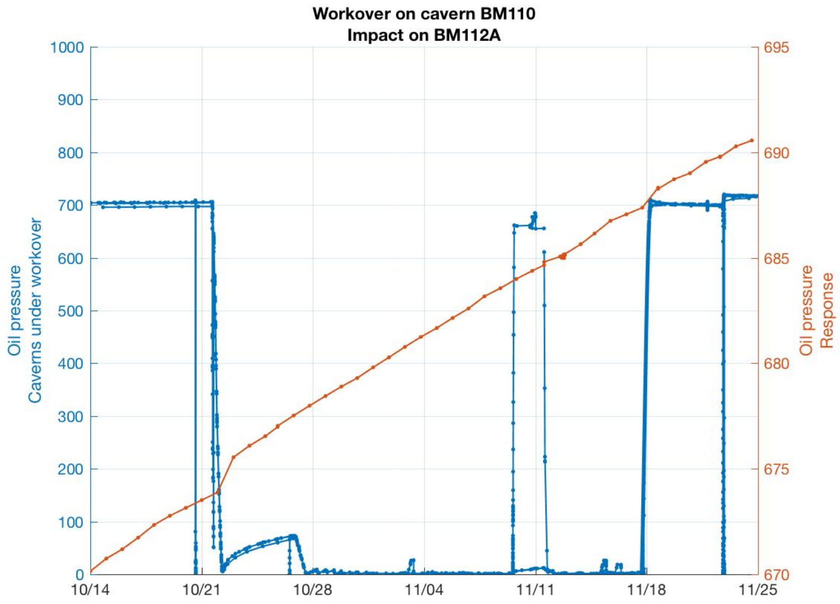
Bryan Mound Workovers

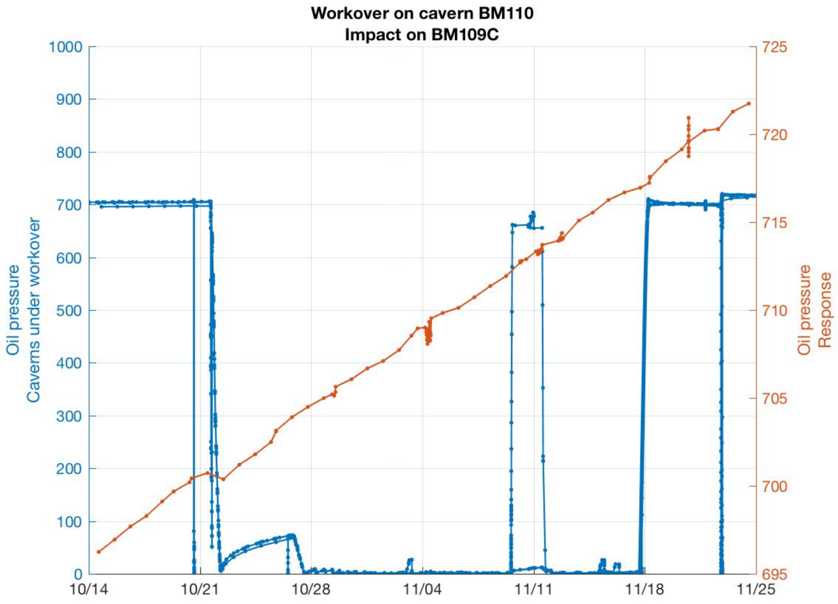


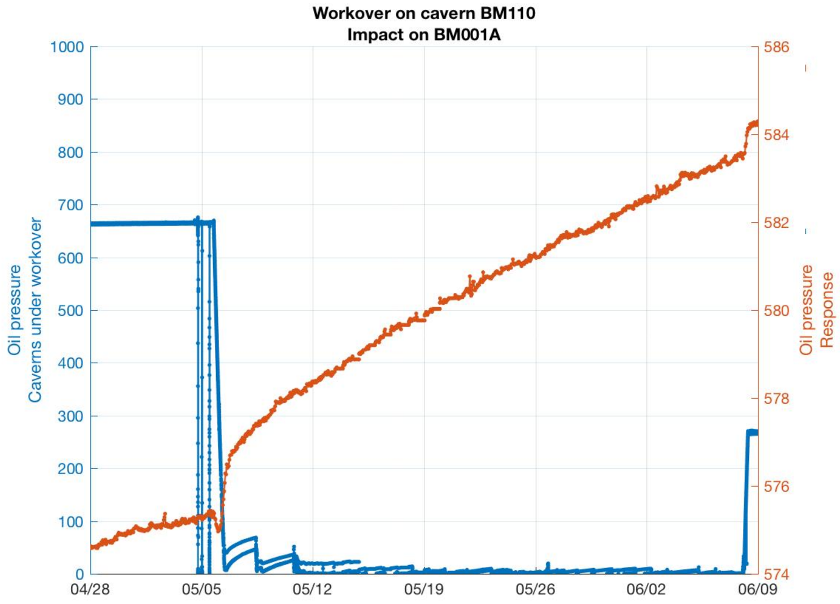


Bryan Mound Workovers

Bryan Mound Workovers







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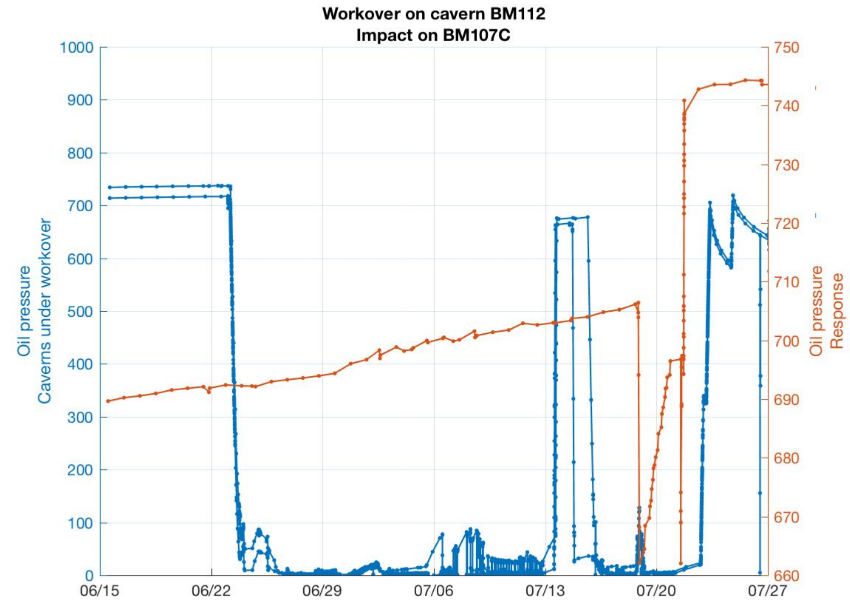

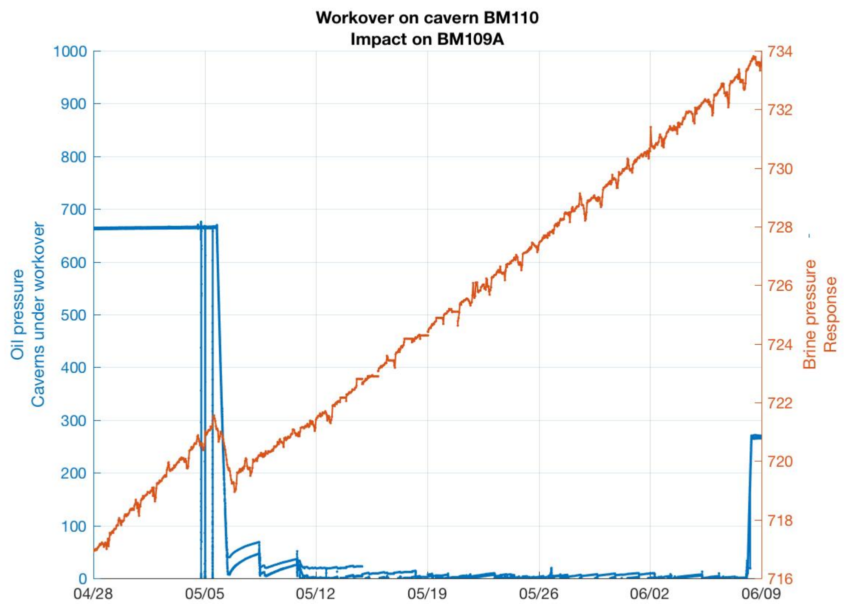

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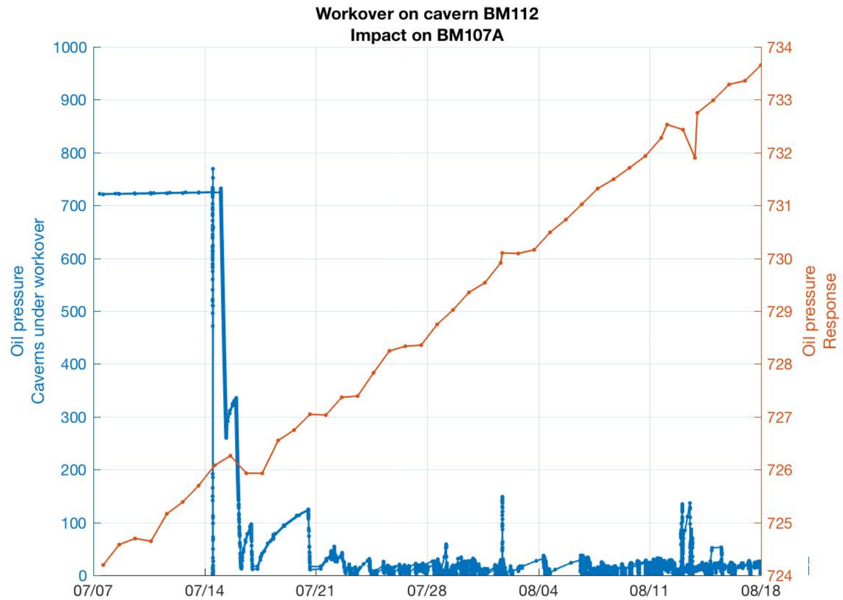

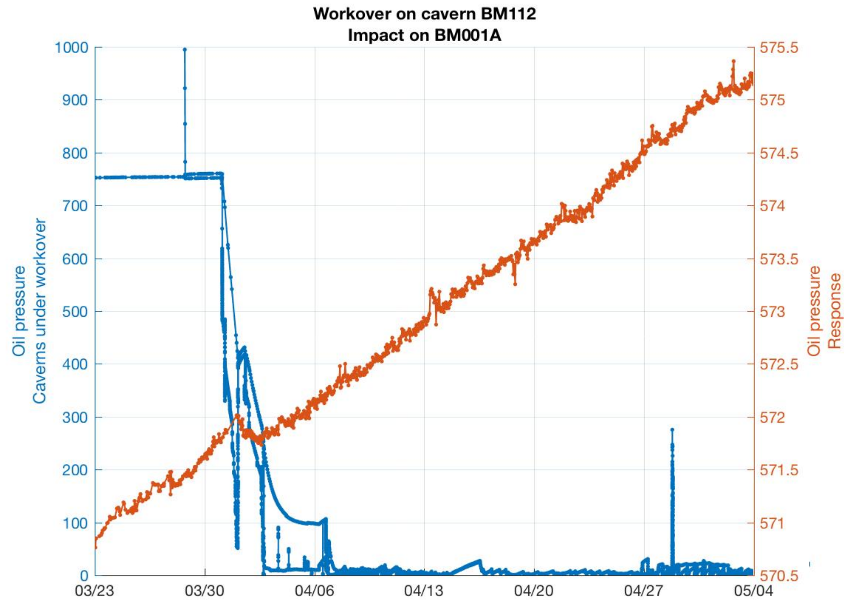

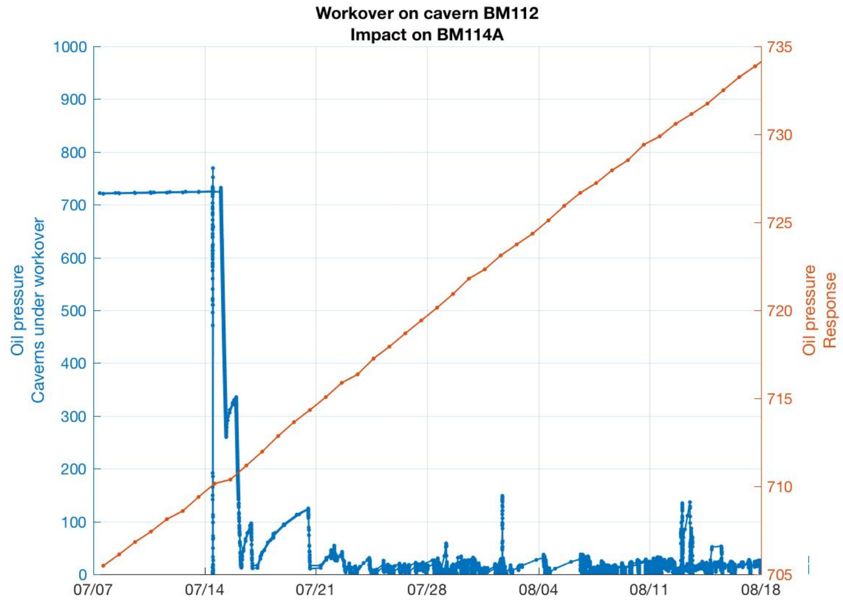

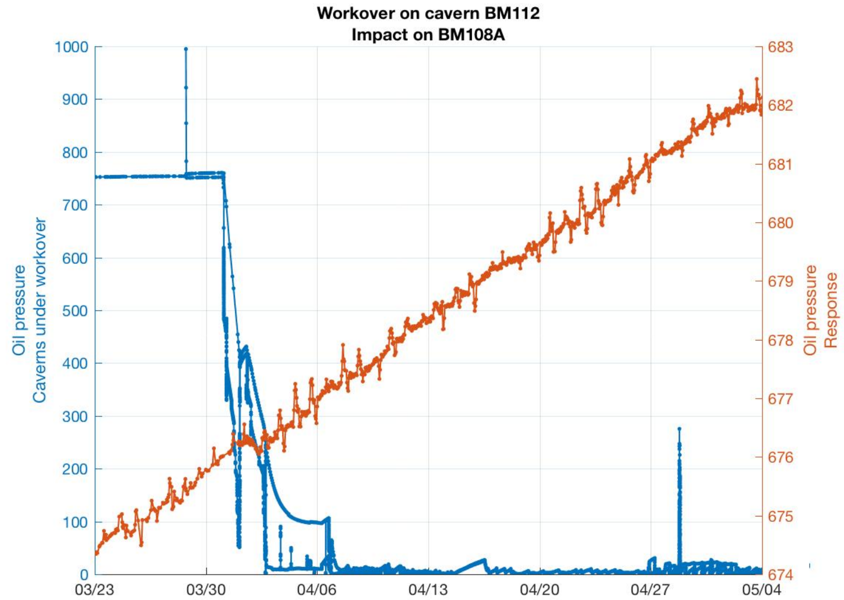

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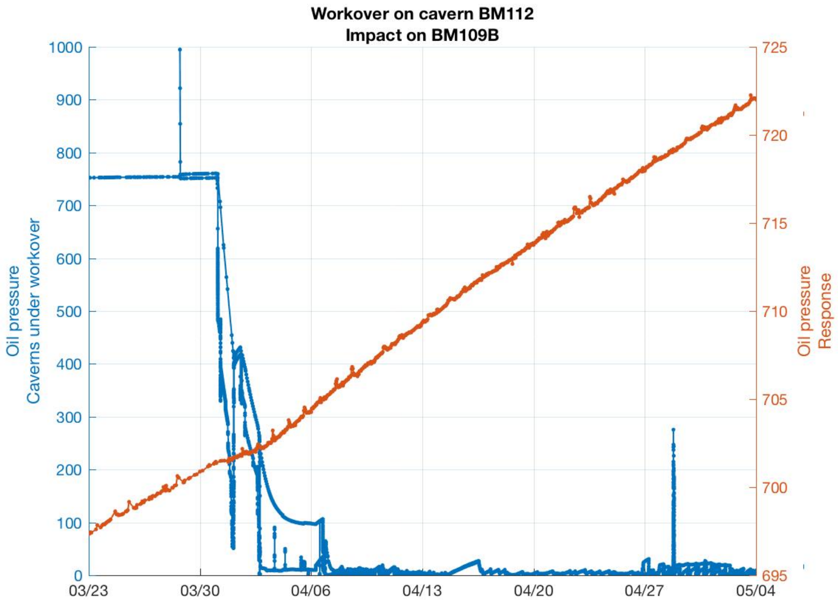
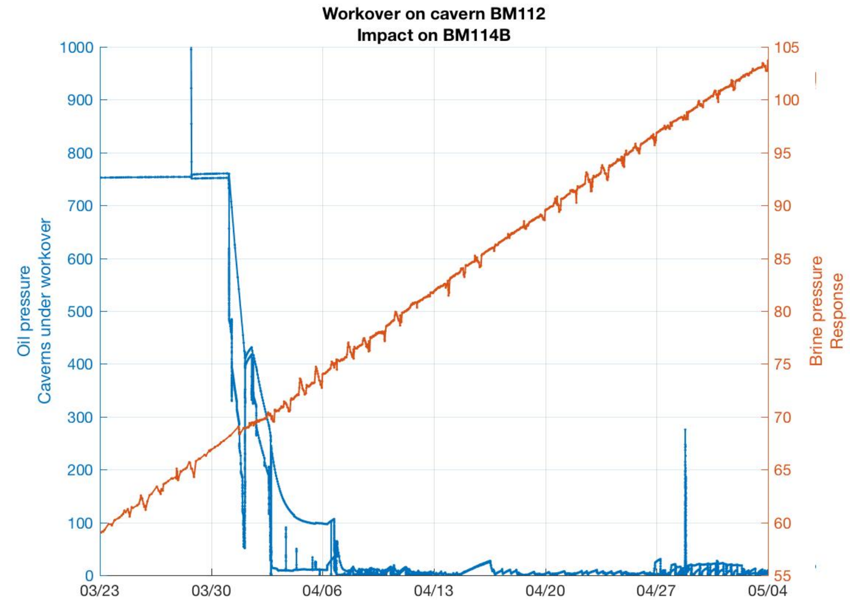
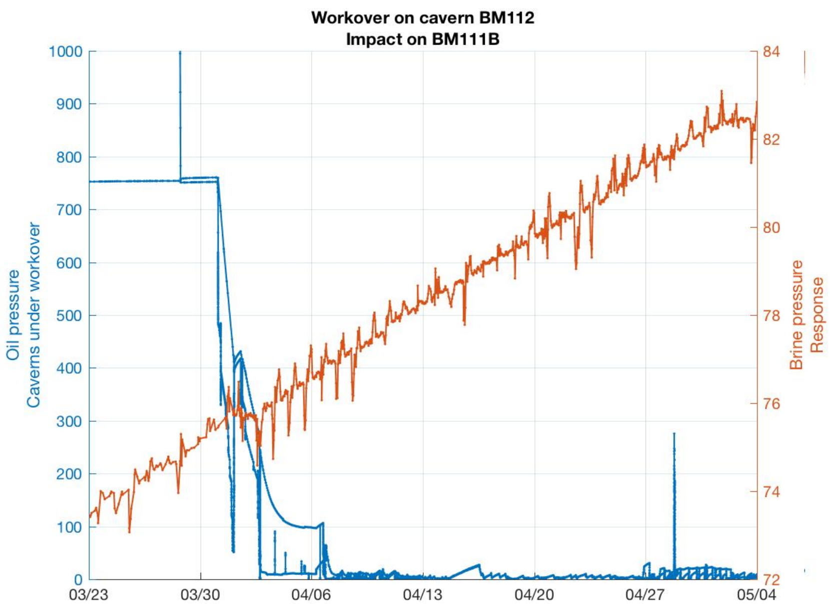
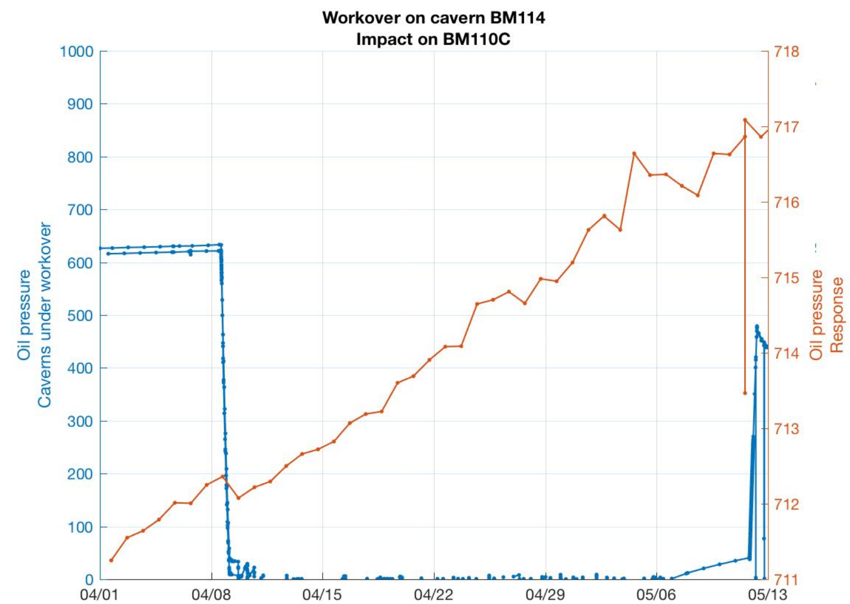
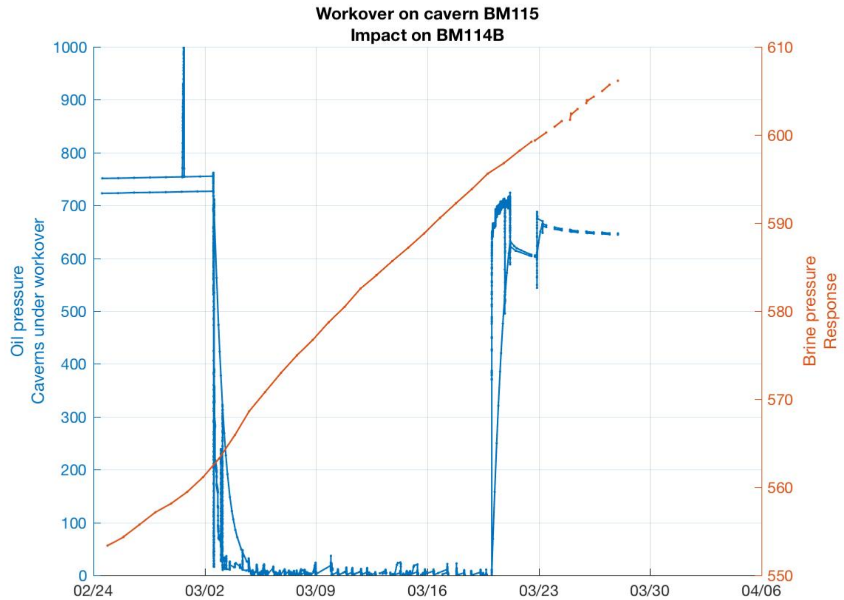
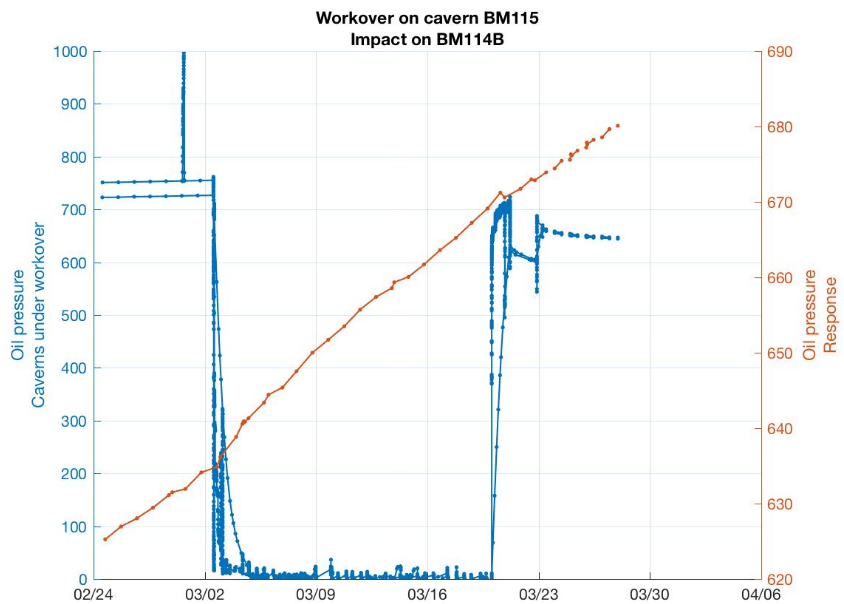




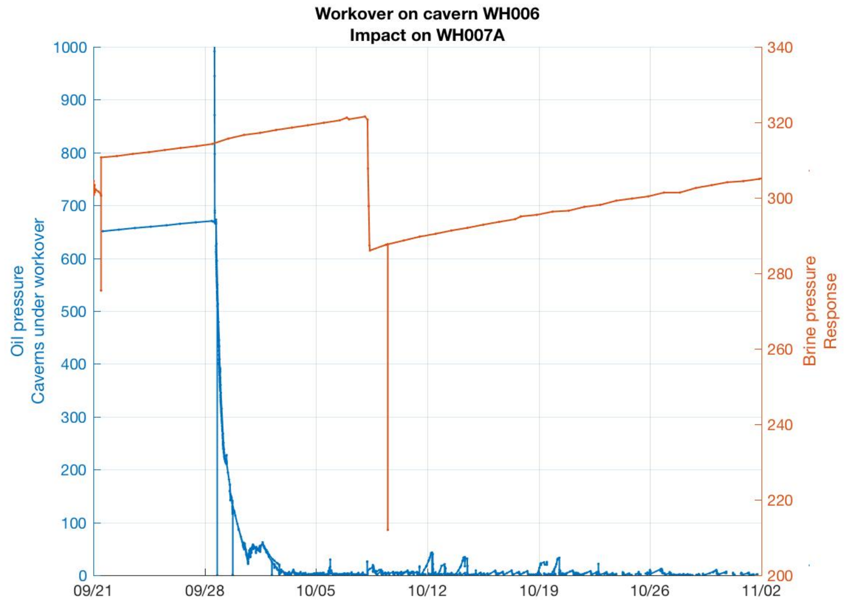


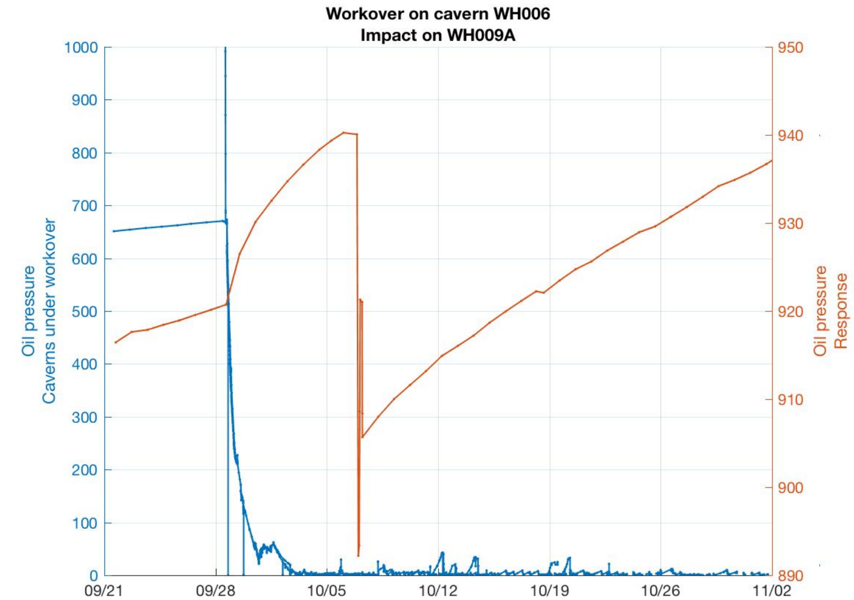


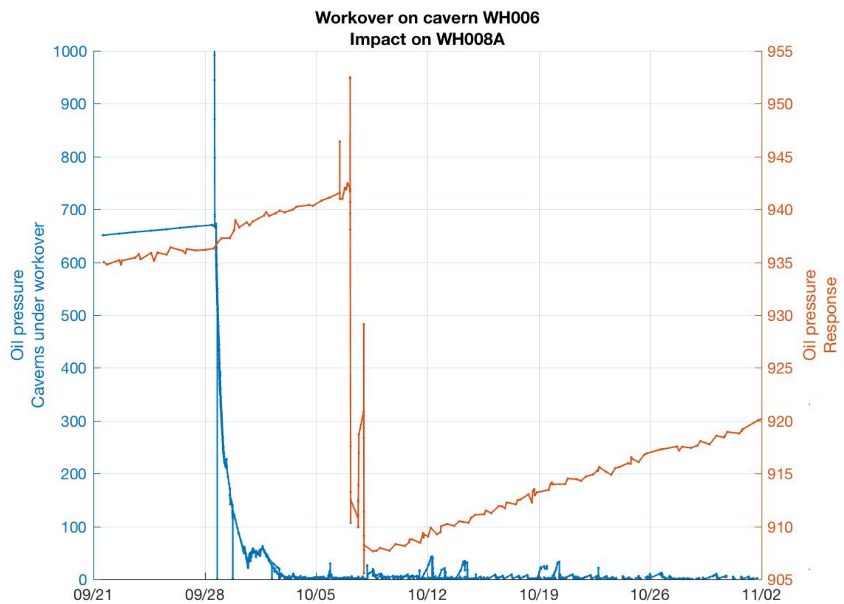

Workover on cavern BM115
Impact on BM114B
Oil pressure
Caverns under workover
Brine pressure
Response
02/24
03/02
03/09
03/16
03/23
03/30
04/06

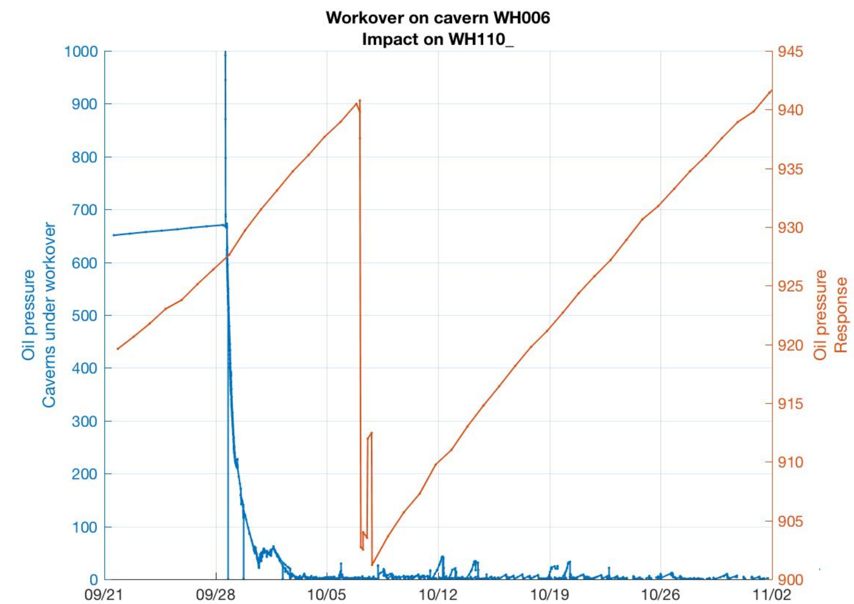

Workover on cavern BM115
Impact on BM114B
Oil pressure
Caverns under workover
Oil pressure
Response
02/24
03/02
03/09
03/16
03/23
03/30
04/06

West Hackberry Workovers









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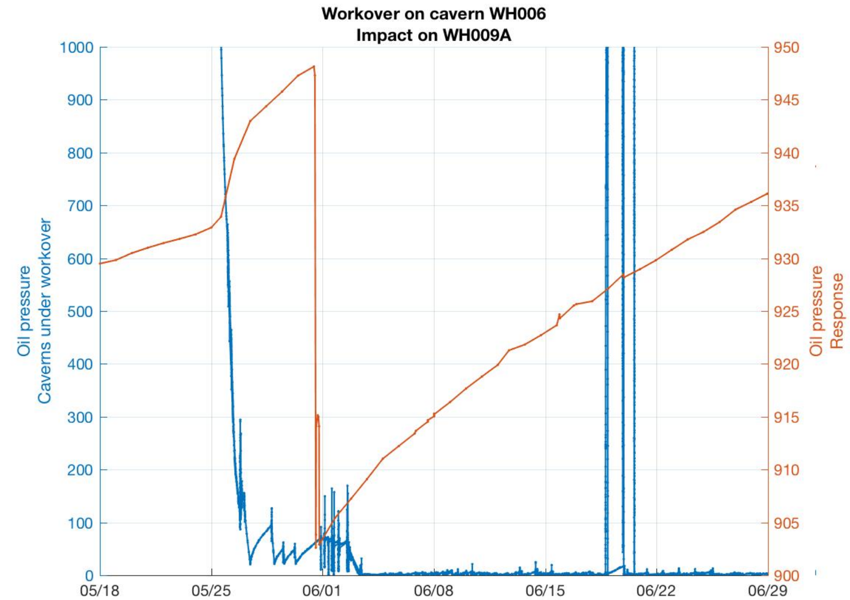

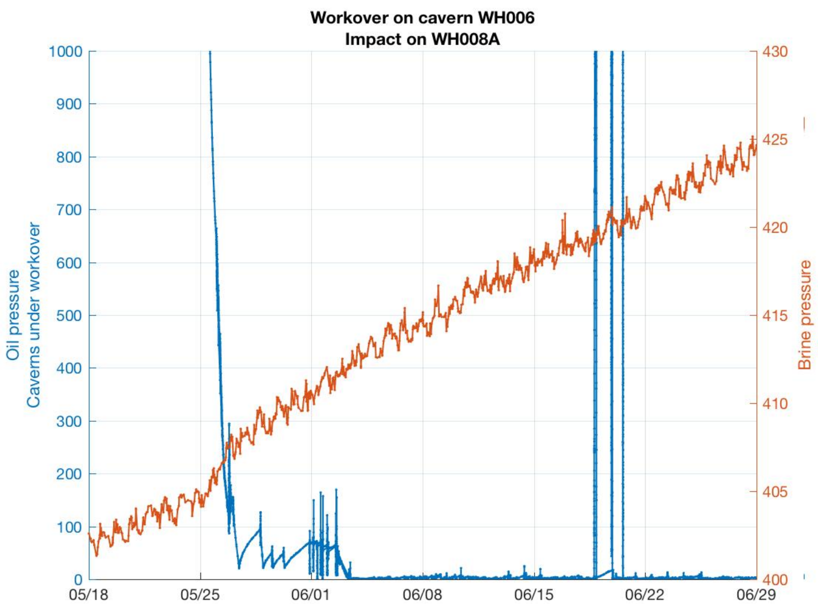

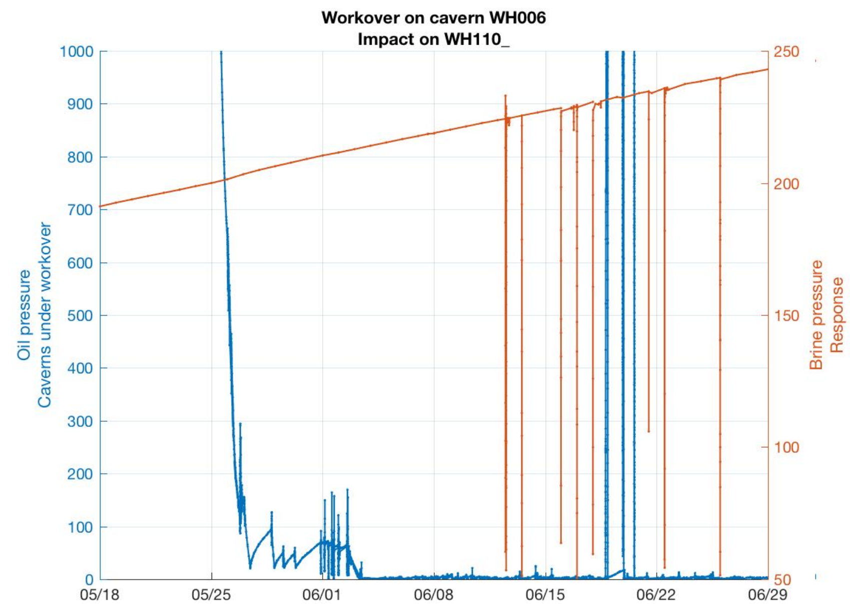

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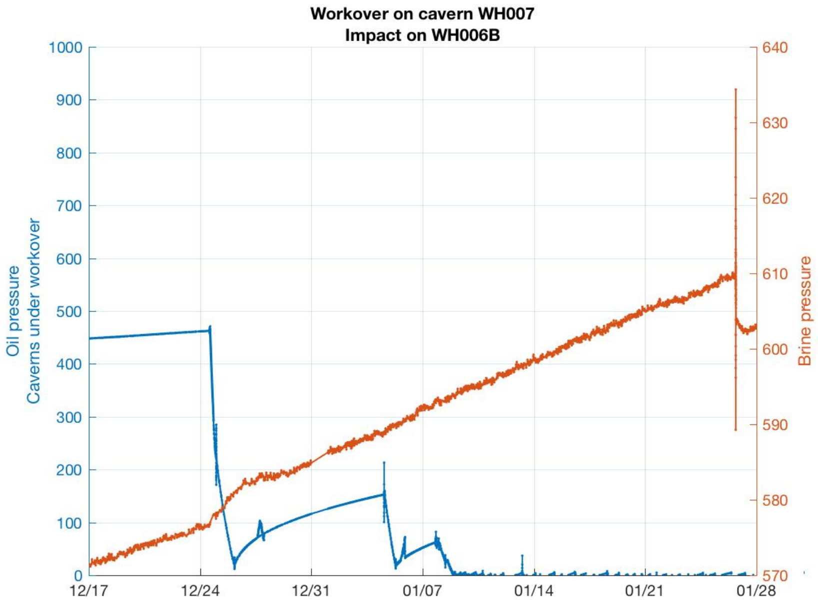

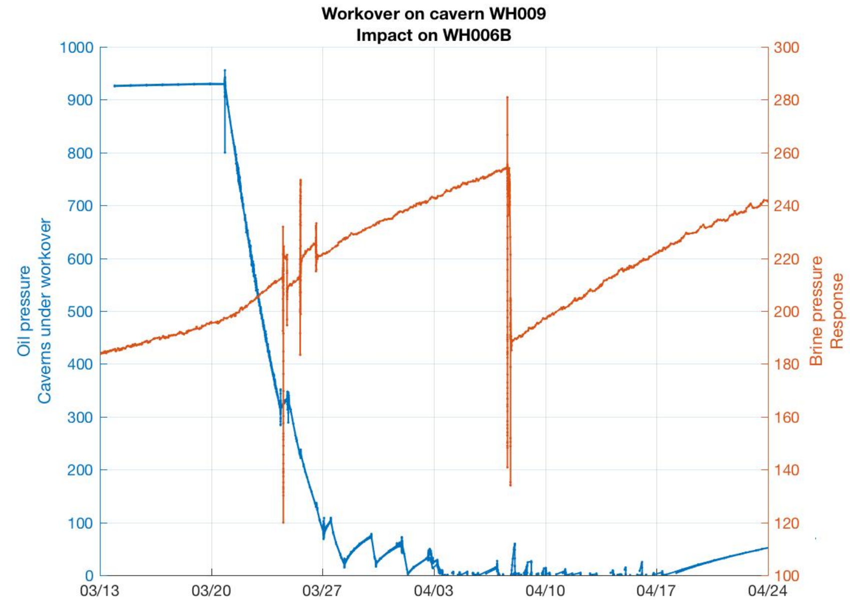

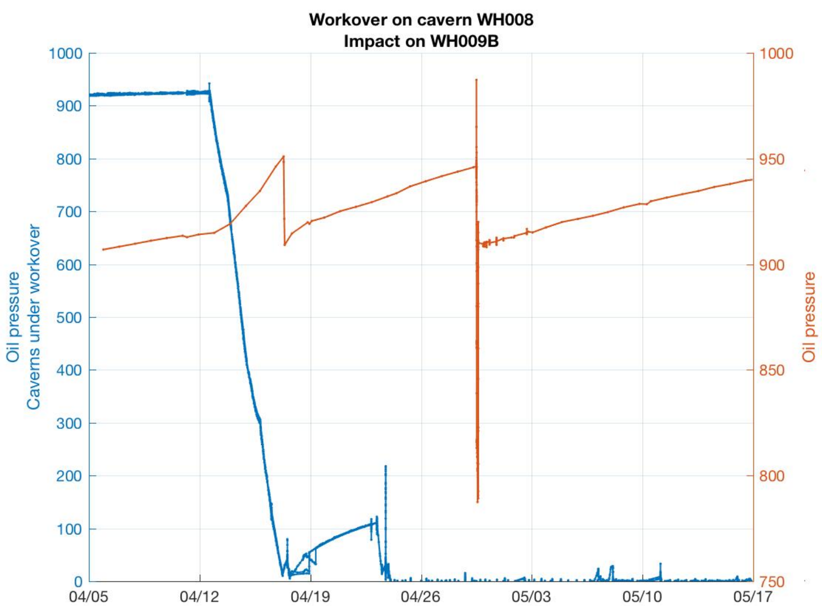

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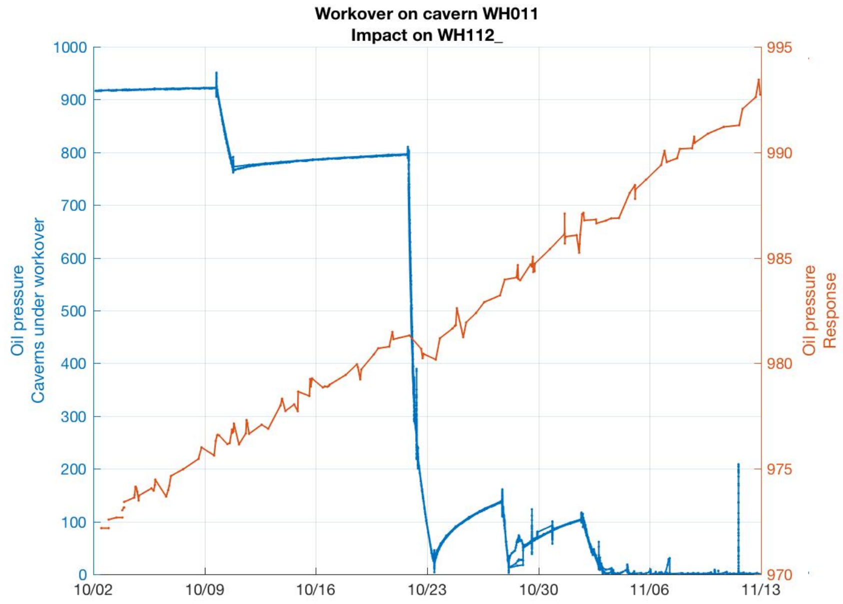

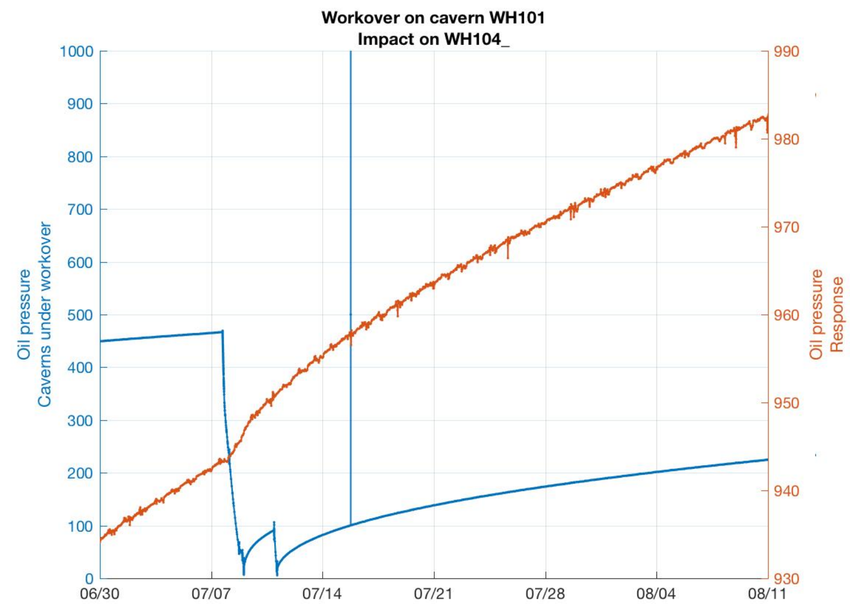

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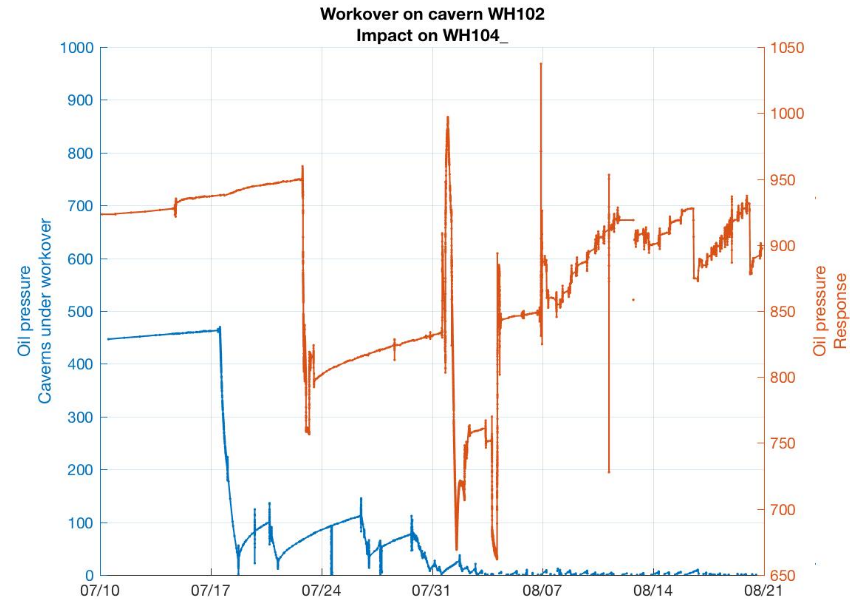

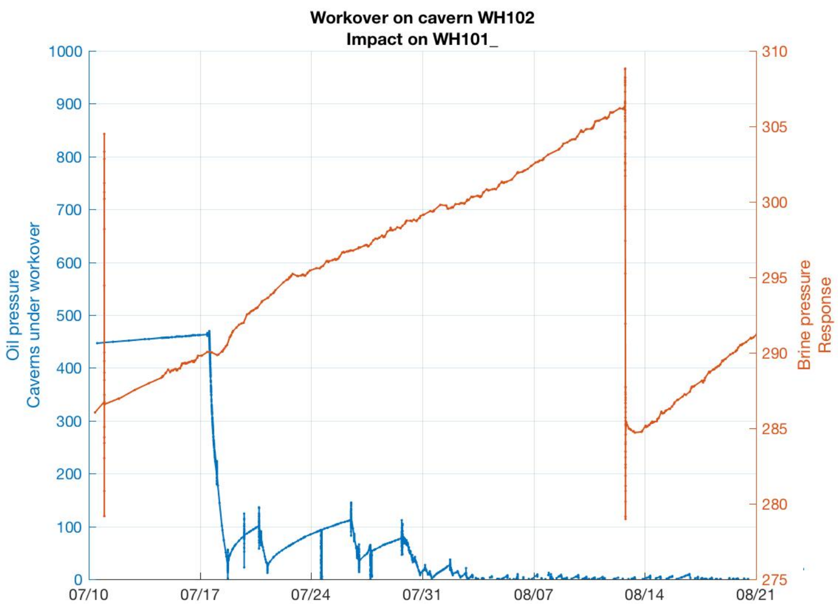

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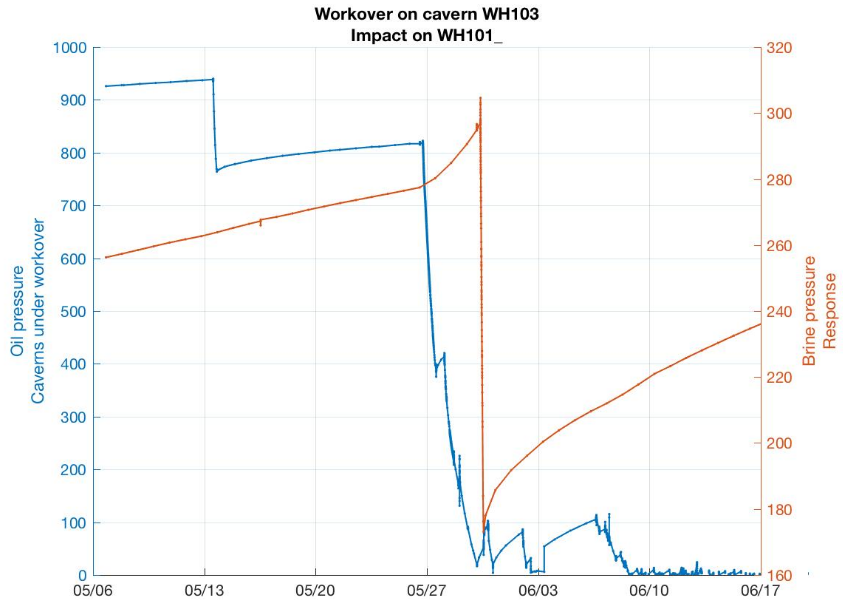

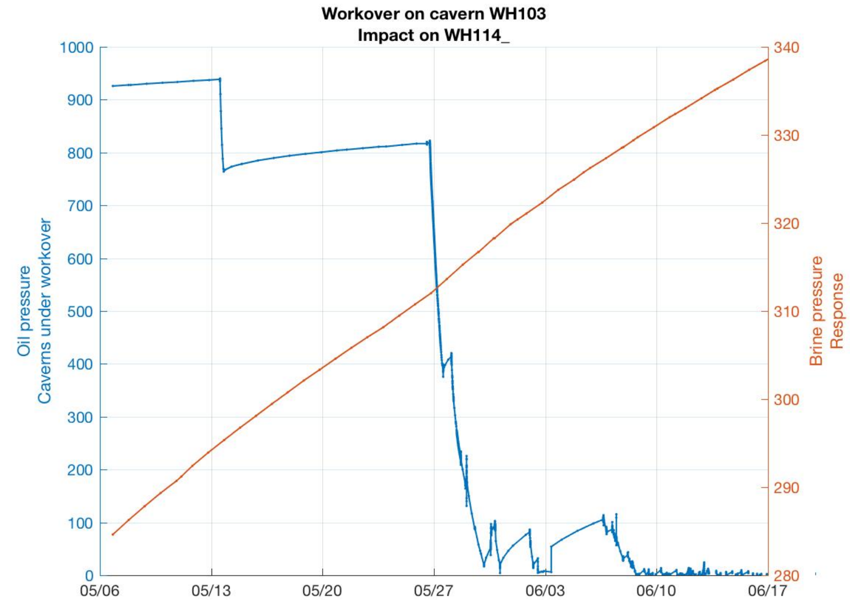

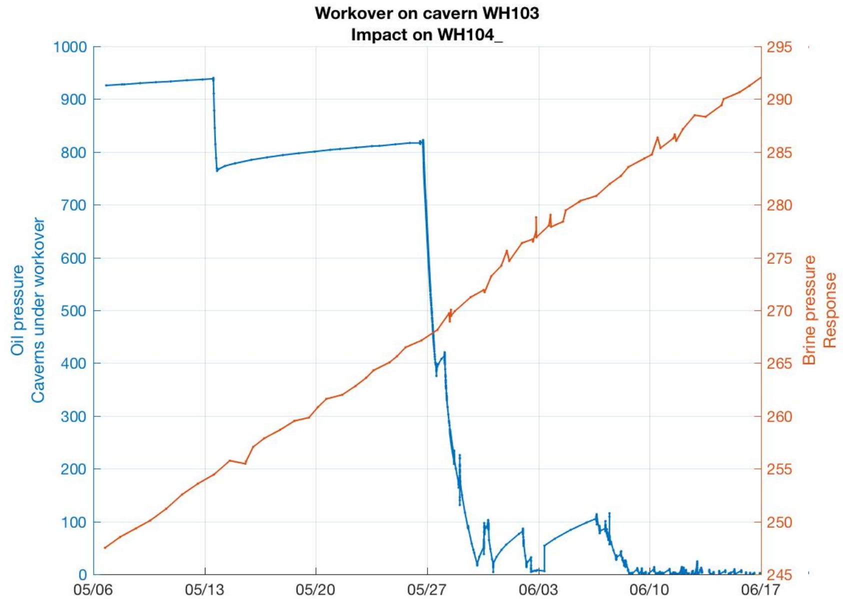

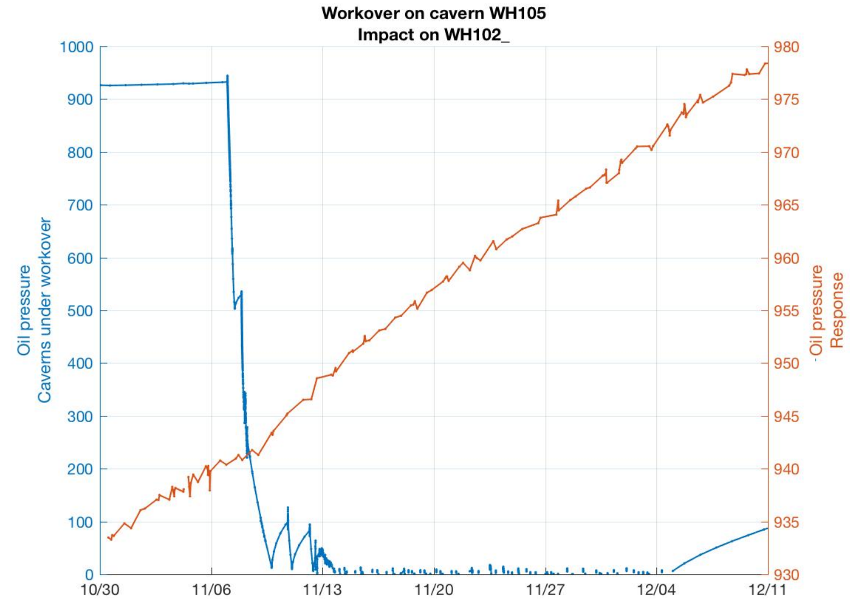

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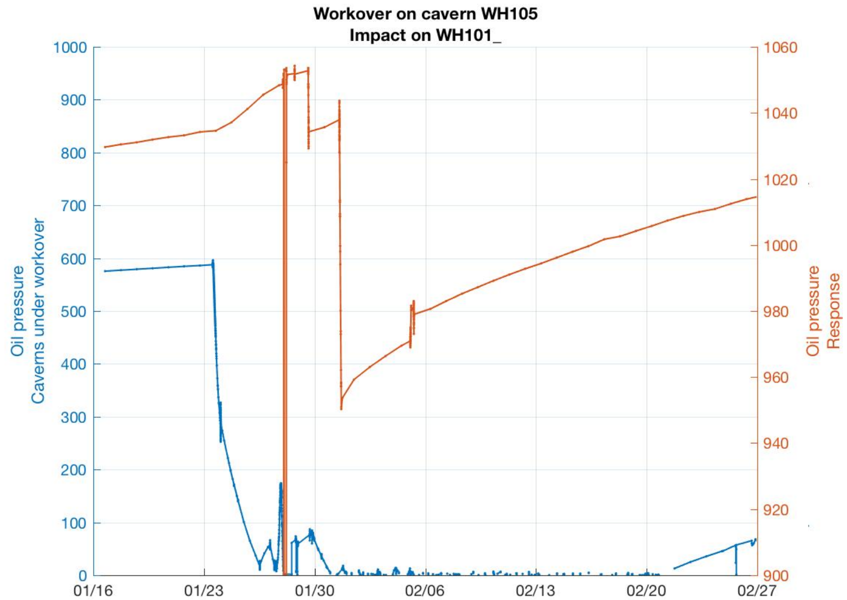
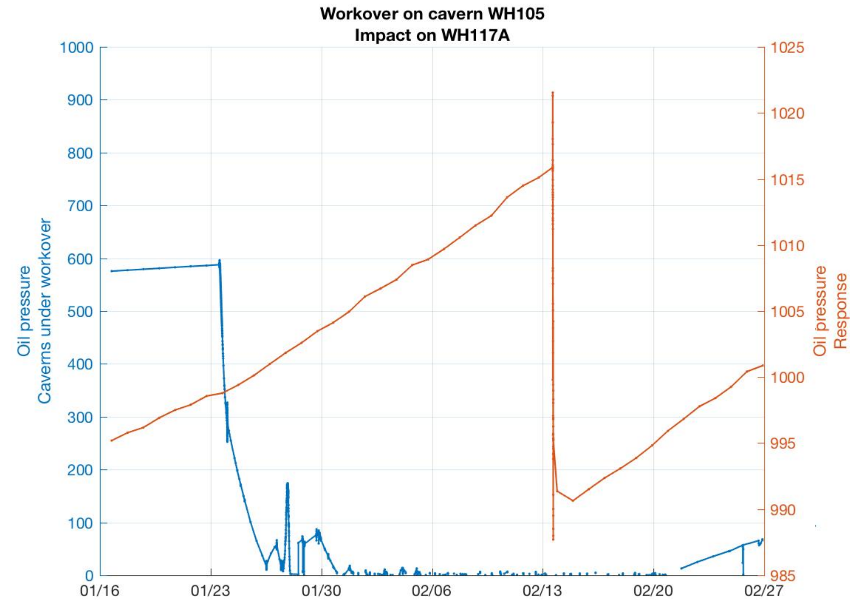
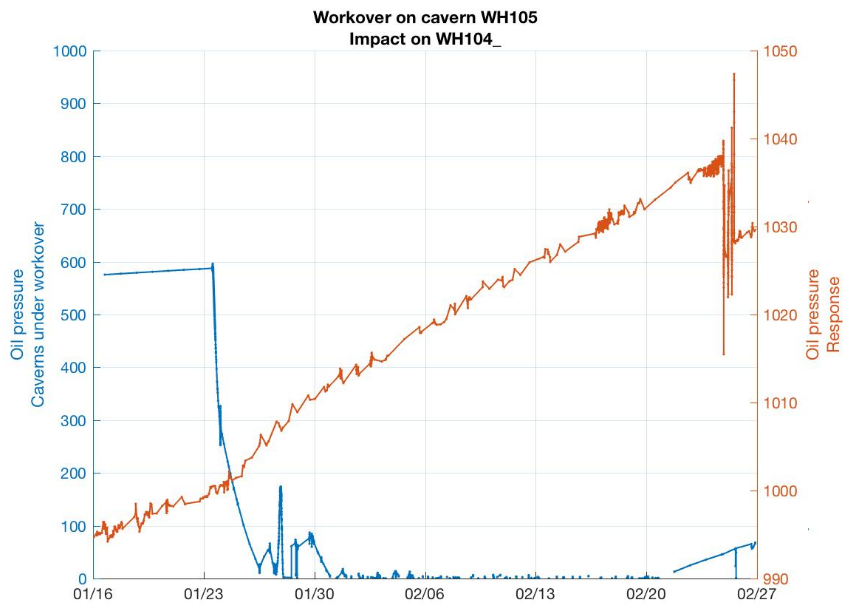
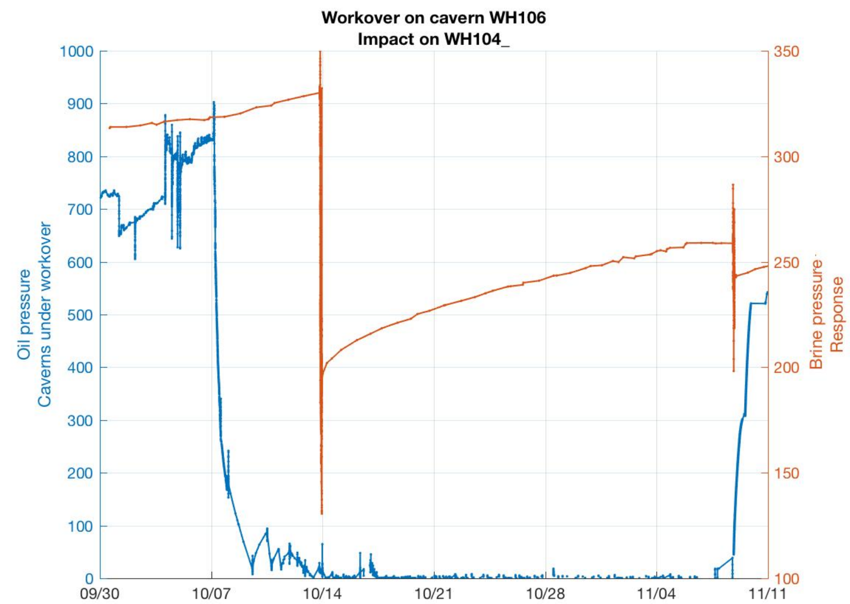
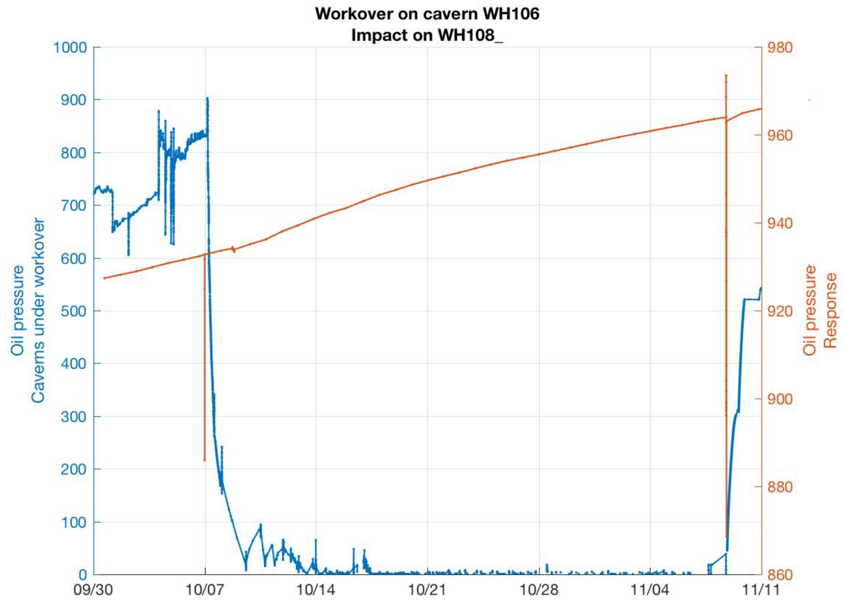


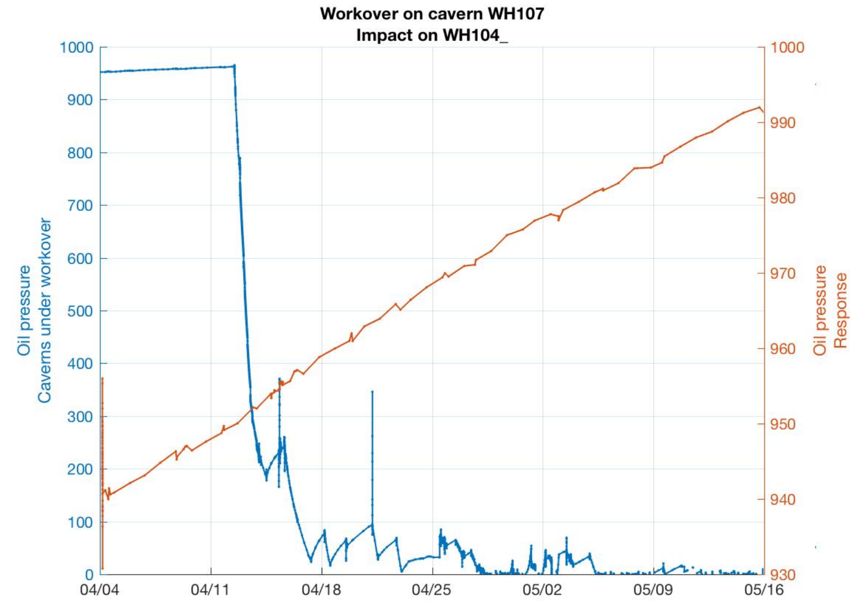


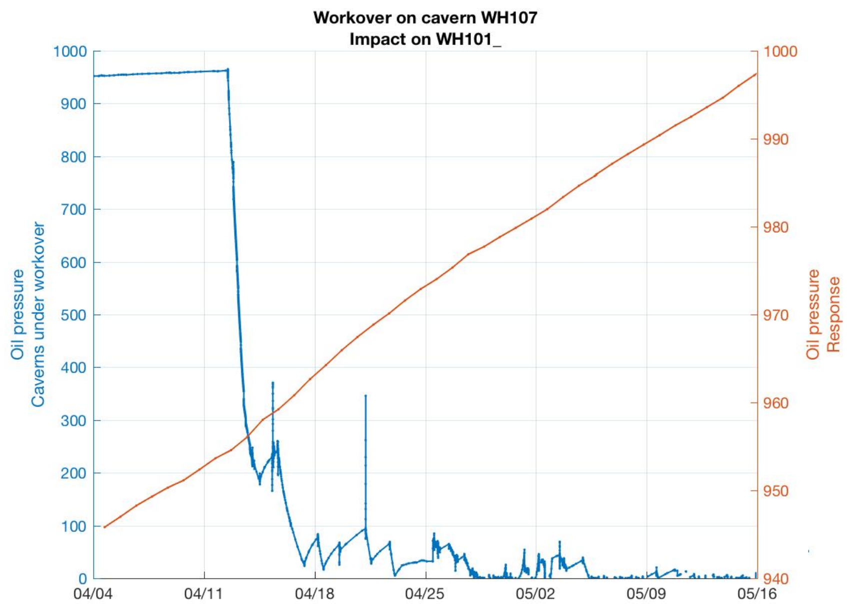


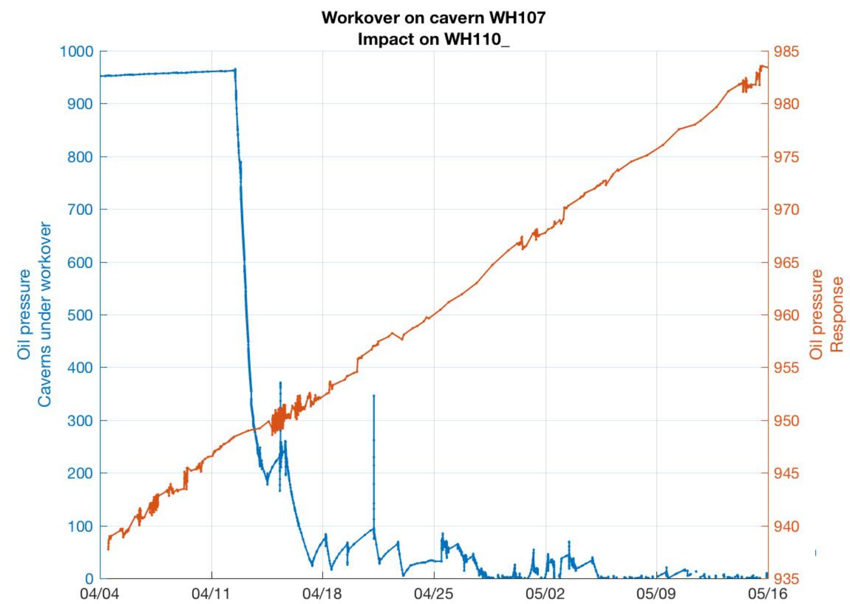


WEST HACKBERRY WORKOVERS









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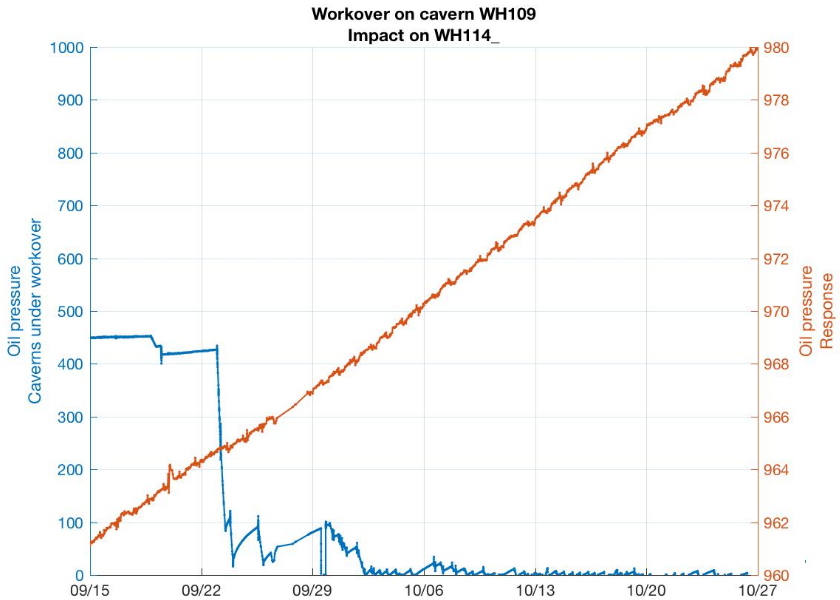

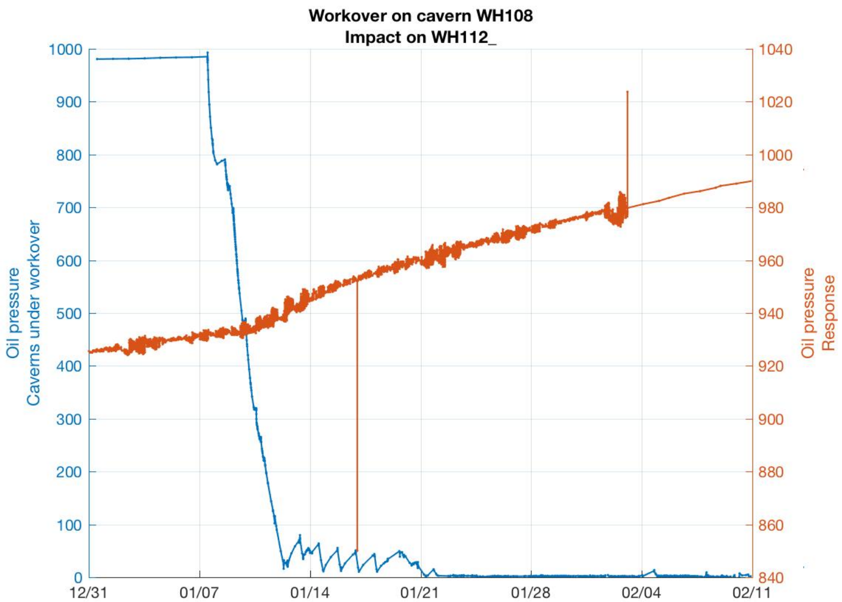

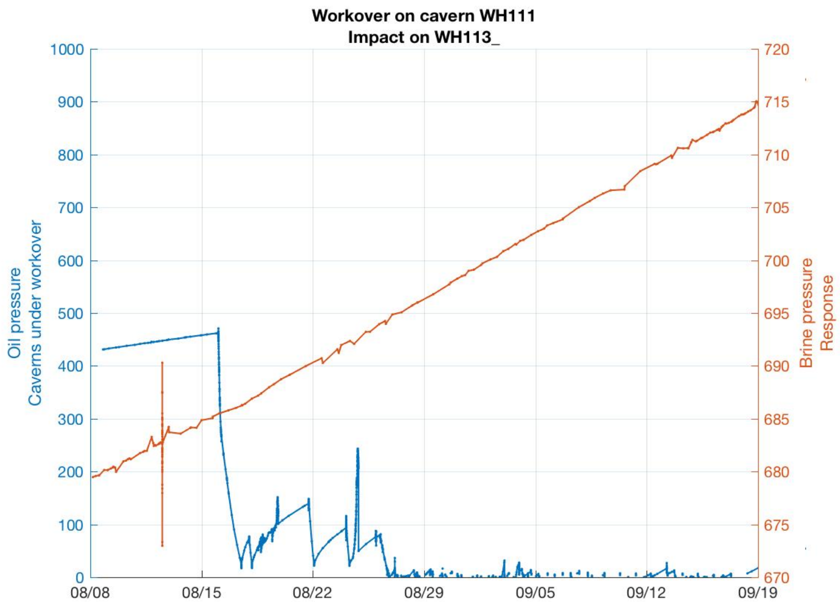

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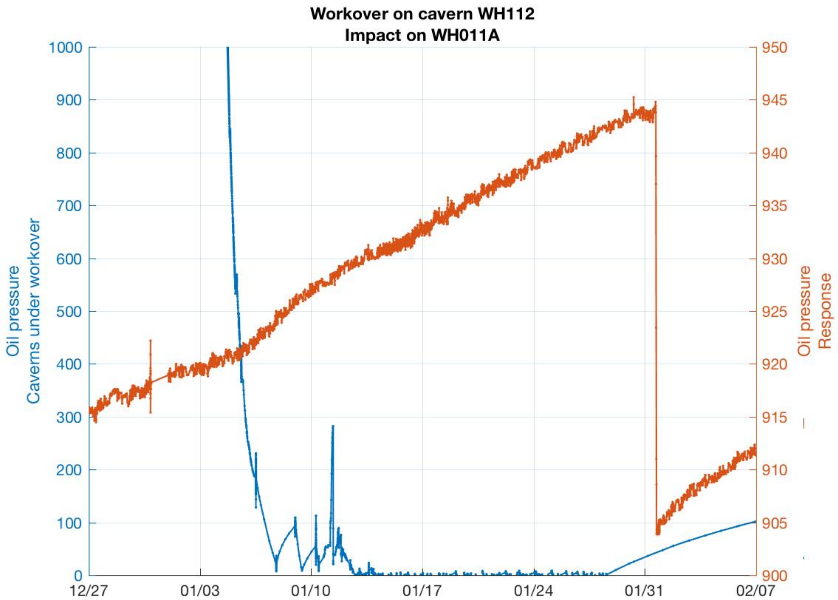

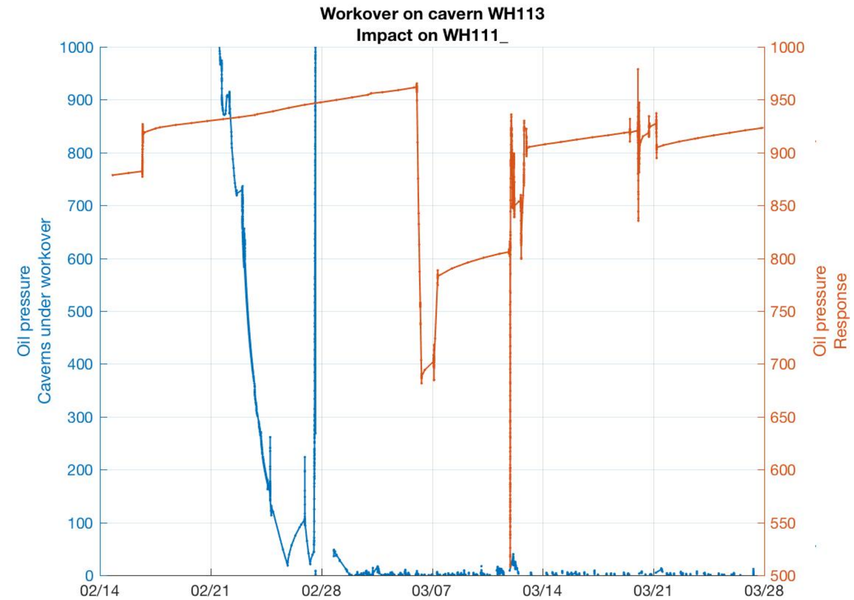

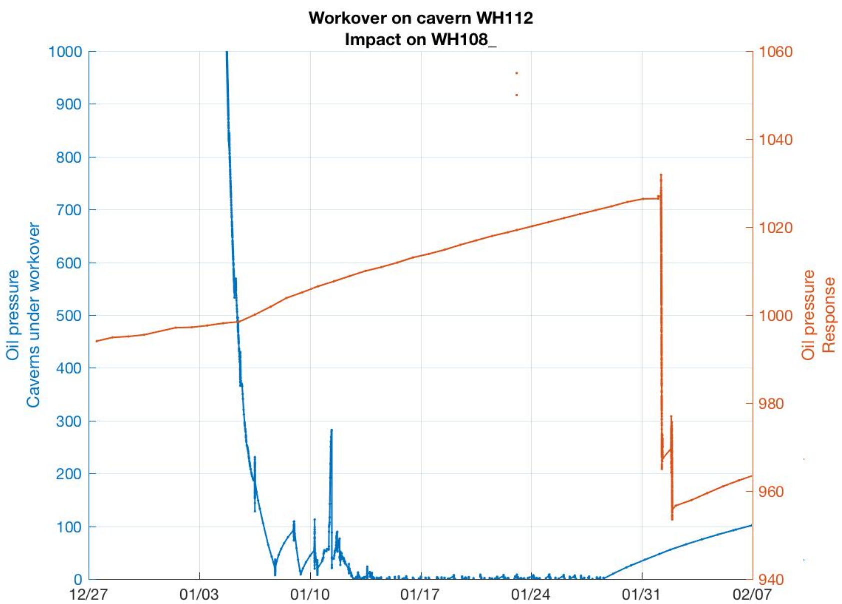

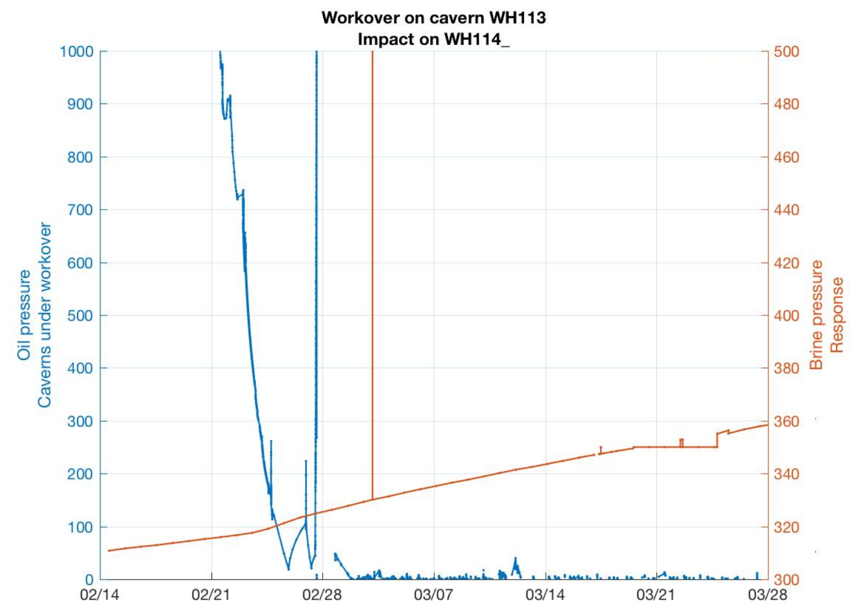

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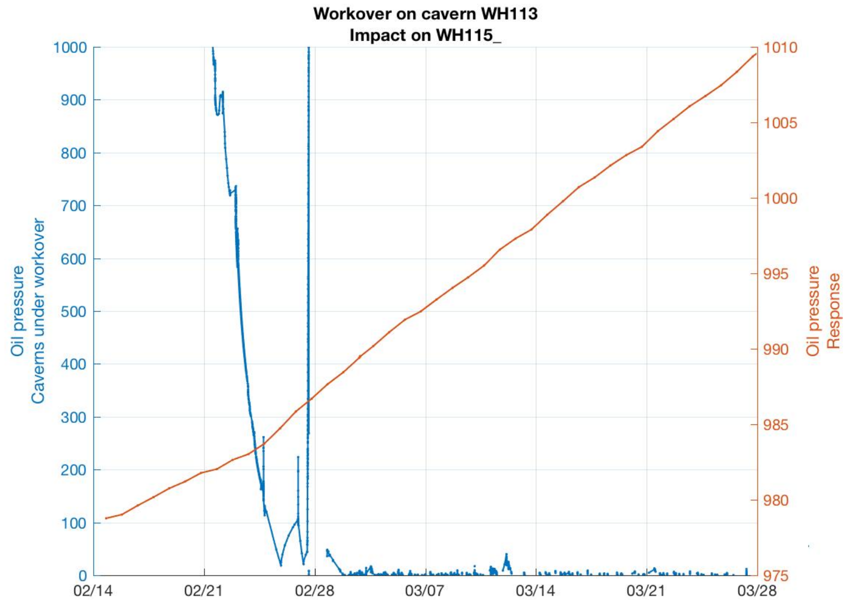

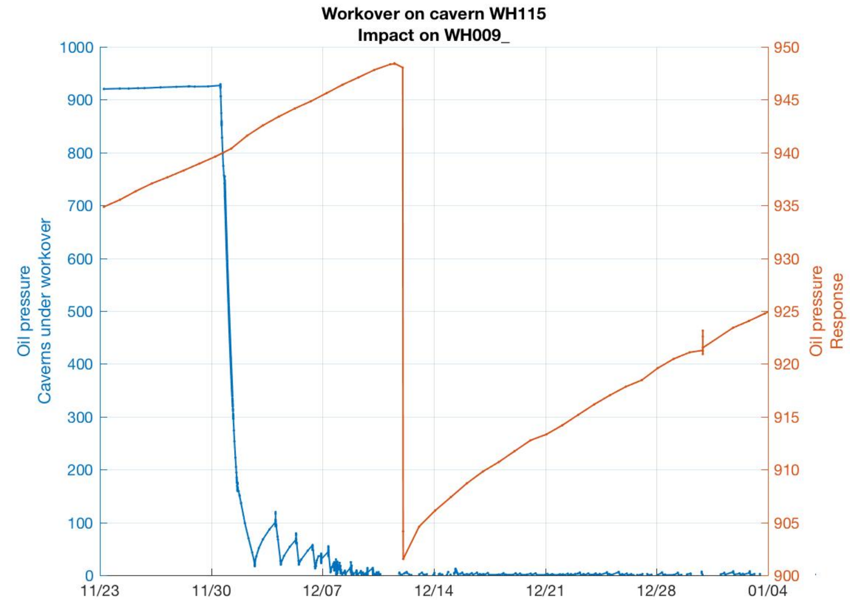

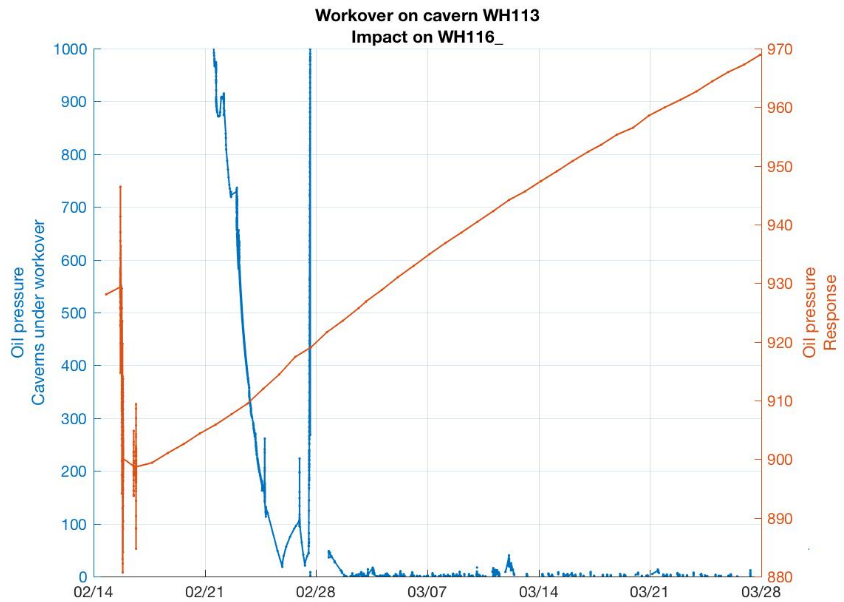

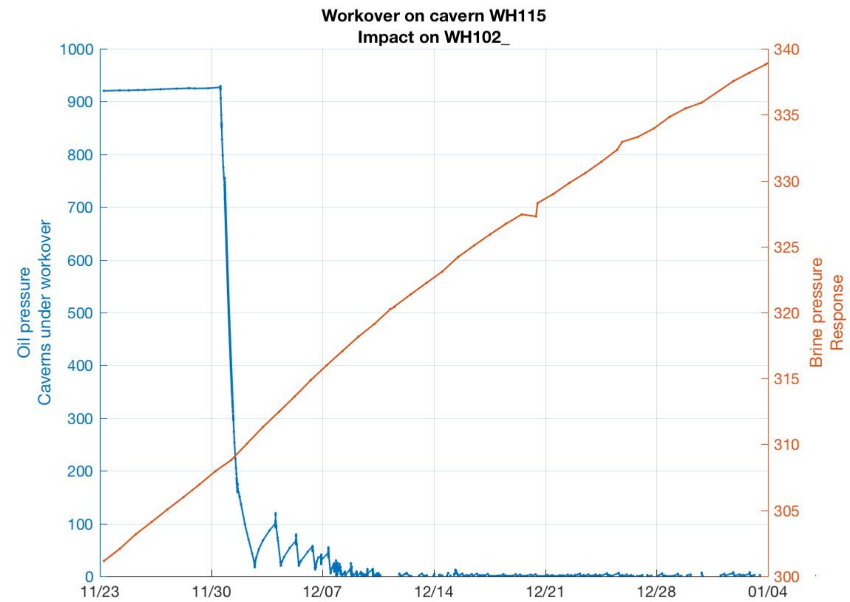

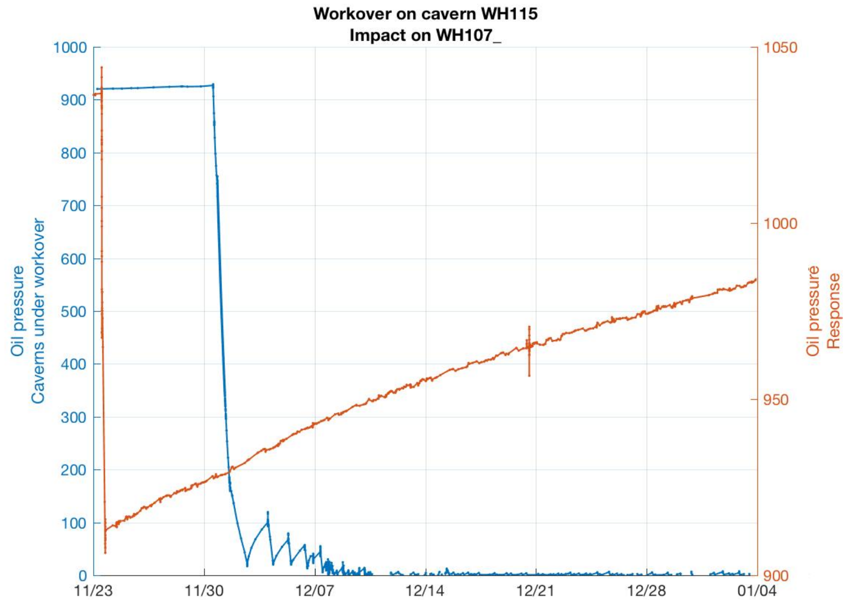
Workover on cavern WH115
Impact on WH107_
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
1050
1000
950
900
11/23
11/30
12/07
12/14
12/21
12/28
01/04


Workover on cavern WH115
Impact on WH111_
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
1050
1000
950
900
850
800
750
700
650
11/23
11/30
12/07
12/14
12/21
12/28
01/04


Workover on cavern WH115
Impact on WH110_
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
1060
1040
1020
1000
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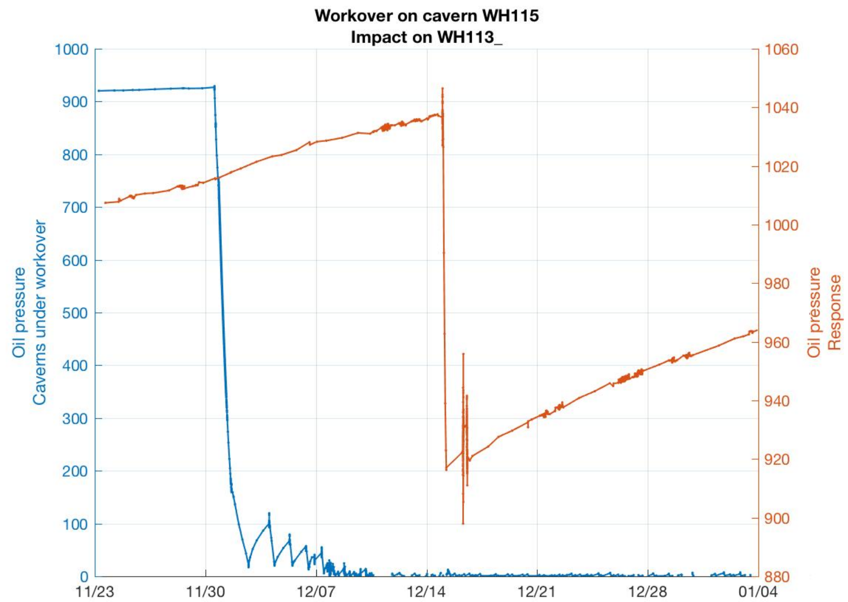
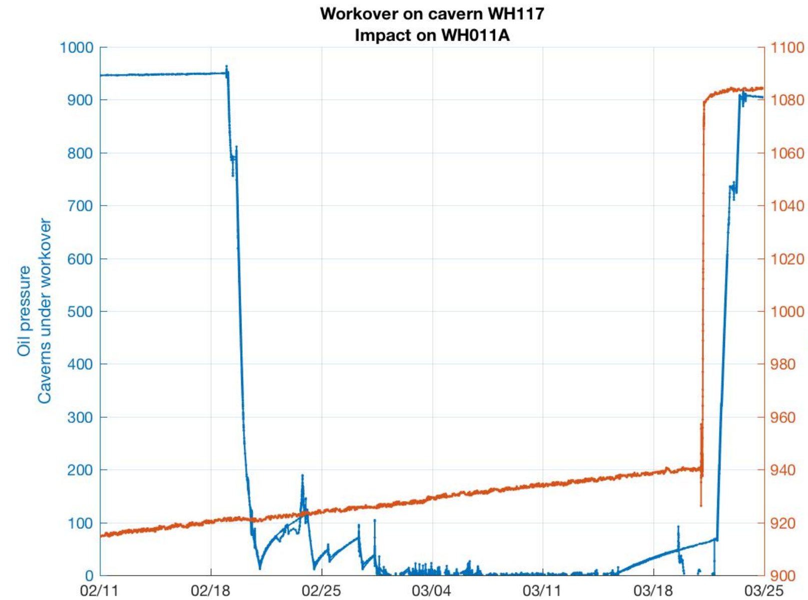
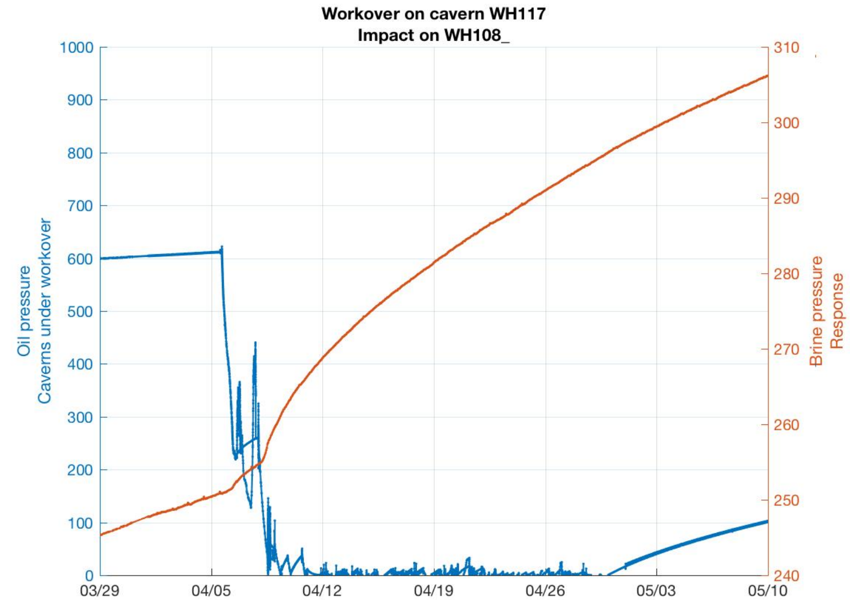
12/21
12/28
01/04

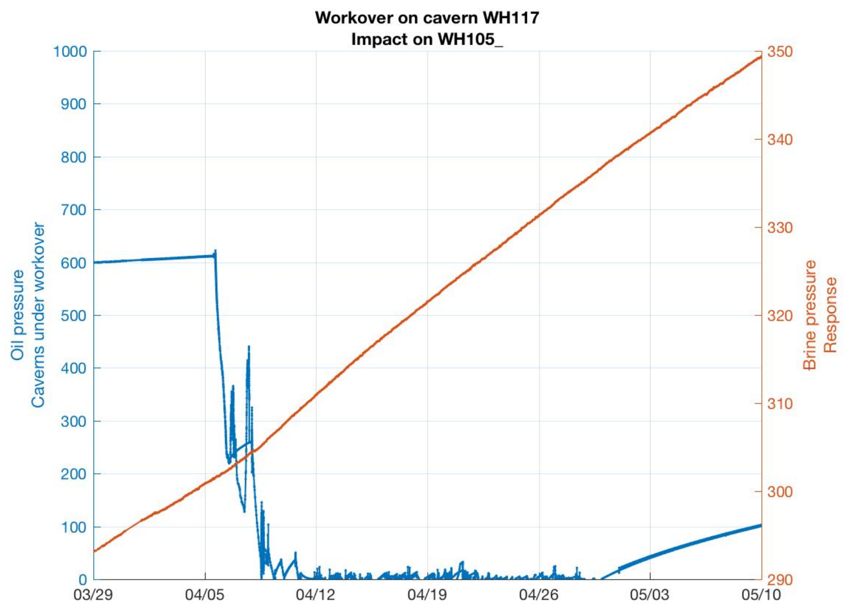

Workover on cavern WH115
Impact on WH113_
Oil pressure
Caverns under workover
Oil pressure
Response
1000
900
800
700
600
500
400
300
200
100
0
1060
1040
1020
1000
980
960
940
920
900
880
11/23
11/30
12/07
12/14
12/21
12/28
01/04

West Hackberry Workovers




Workover on cavern WH117
Impact on WH108_
Oil pressure
Caverns under workover
Oil pressure
Response
09/06
09/13
09/20
09/27
10/04
10/11
10/18


Workover on cavern WH117
Impact on WH108_
Oil pressure
Caverns under workover
Brine pressure
Response
03/29
04/05
04/12
04/19
04/26
05/03
05/10


Workover on cavern WH117
Impact on WH105_
Oil pressure
Caverns under workover
Brine pressure
Response
03/29
04/05
04/12
04/19
04/26
05/03
05/10

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