Depressurization Effects in Salt Dome Caverns

Salt, Safety and the Environment

Keywords: Salt Caverns, Cavern depressurization, salt creep, subsidence, SPR

Abstract

Underground caverns leached in salt domes are often used for oil and gas storage. While most of these caverns are kept pressurized to minimize cavern closure (salt creep) tendencies, they must be routinely depressurized for workovers or for integrity diagnostics. The depressurization tends to enhance the salt creep. Cavern depressurization and the consequent salt creep enhancement can have large effects on the cavern, such as loss of ullage (cavern closure) and subsidence, and the wells, putting extra strain on the casing and well cement.

This work analyzes the effect of cavern depressurization and enhanced creep on 62 caverns in 4 different salt domes belonging to the Strategic Petroleum Reserve (SPR). During a prolonged depressurization (1-2 months) we found a cavern volume loss that can vary depending on salt properties, cavern shape, size and length of depressurization. The creep rate response is not limited to the time of depressurization but extends to a few months following the cavern re-pressurization. It has also been observed that a change in the salt creep rate has a substantial and repeatable effect on the neighboring caverns. Two separate neighboring behaviors were discovered.

Additionally, depressurization events affect the localized subsidence of the surface immediately above the cavern. This study has attempted to relate the relative magnitude and time response of the surface deformation (InSAR and elevation surveys) with cavern pressures and the size of the affected area.

Background

The Strategic Petroleum Reserve (SPR) operates 62 solution mined caverns in salt domes that store about 727 million barrels of crude oil. Salt is a viscoplastic material that will creep under stress. In a cavern, the salt *creep rate* is a function of both the salt properties and the differential pressure between the lithostatic pressure in the salt and the pressure inside the cavern.

During normal operations, SPR caverns are held in a *static* or *shut-in* configuration. Due to the low compressibility of crude oil, a cavern in static configuration will have a continually increasing pressure due to salt creep. At the wellhead, this pressure is monitored and kept within a specified range, 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*. Each pressure cycle, specifically the rate of cavern pressurization, is used to monitor the integrity of the cavern/well system. If deviations from the expected are found, flags (and alarms) are triggered to start investigating the cause and remediate if necessary. Figure 1 shows the wellhead pressures for the oil in a particular cavern. 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 1 illustrates typical cavern pressure cycles within the operating range.

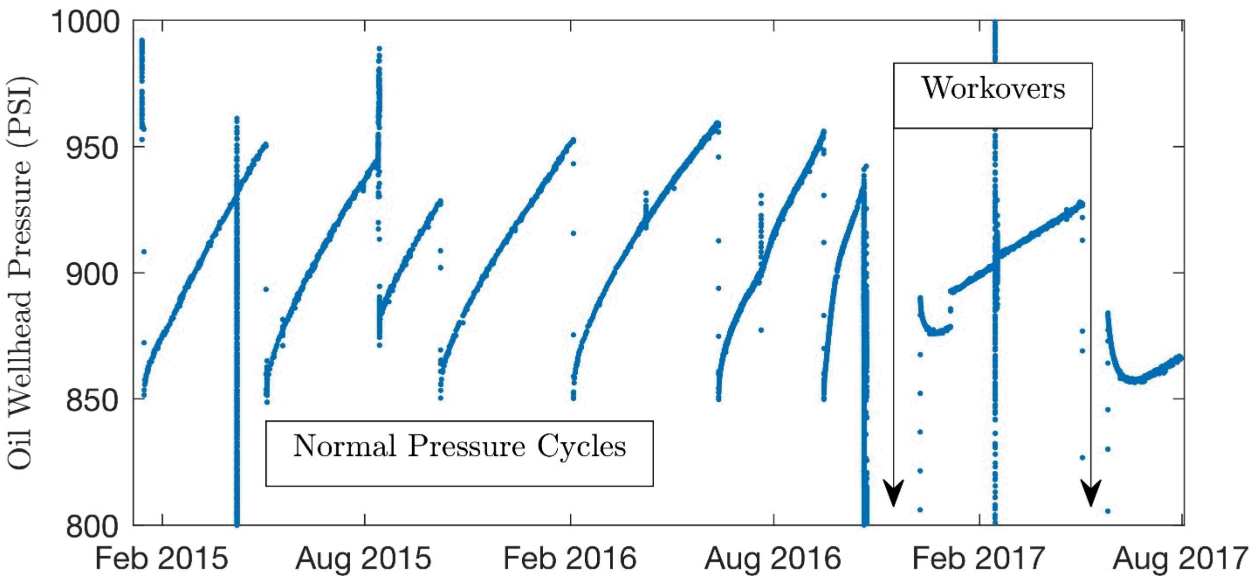

Figure 1: Pressure history for BH110 cavern that shows typical pressure cycles. In Nov 2016, cavern pressure was brought to zero for a workover.

SPR Caverns are often depressurized for workovers on wells (string repairs or liner installation) or for well logging, such as multi-arm caliper logs on hanging string wells and SONAR logs on single cavern wells. During a workover, cavern depressurization causes enhanced salt creep due to the increased pressure differential between the cavern walls and the fluid in the cavern. Enhanced salt creep results in a greater *cavern closure rate*. Depressurization of these caverns will also affect the surrounding salt creep rates resulting in a variation of pressurization rates in neighboring caverns (Hart, 2017). Additionally, the past five years have seen an increase in the number of workovers due to aging infrastructure and the need for more frequent monitoring. This increase has led to situations where multiple caverns are being worked over simultaneously, with up to three caverns having zero wellhead pressure simultaneously.

This work aims to analyze and quantify the effect of depressurization in these caverns with respect to the overall volume loss, the effects on neighboring caverns, as well as surface expression due to subsidence. This study is the first step in informing operators on consequence so that benefits vs. drawbacks can be weighed before a cavern is taken out of its operating range. Additionally, for the case of neighboring caverns, the goal is to be able to predict these behaviors to avoid triggering unnecessary flags and remediation.

Workover Effects on Cavern Volume

Changes in cavern volume can be calculated empirically by two different methods: measuring the volume of the cavern with SONAR before and after a workover, or measuring the fluid flowing out (depressurization) and in (repressurization) of the cavern pre- and post-workover.

The SONAR method is relatively expensive and, depending on the complexity of the cavern shape, may not have the accuracy to measure small volume changes. Flow into and out of the caverns is metered at the surface and is the most easily and inexpensively obtained data available. There is some error introduced in the approximation by assuming that the fluids extracted and injected are directly related to the pressure and volume change. However, the error is at least several orders of magnitude less than the volumes involved. Because volumes between caverns vary widely, the volume lost has been normalized by cavern volume.

79 workovers were analyzed and results showed that each site behaves differently and that within the site different caverns show different closure rates. A summary of the results statistics is shown in Table 1. These results are consistent with the geologic characterizations for each site. Bayou Choctaw has the slowest creeping salt and shows the least amount of closure during workovers. Big Hill and West Hackberry are considered to have the fastest creeping salt and show the highest closures. Bryan Mound shows the highest average change per day, but also had, on average, the shortest workovers.

Cavern	Num. W/O in calc.	ΔV per W/O (MBBL)	ΔV/day (BBL)	ΔV/Vcav (%)
BC-15/17	1	-33	-500	-0.26%
BC-C018	1	-90	-490	-0.48%
BC-C019	1	-49	-590	-0.38%
BC-C101	1	-55	-1000	-0.42%
BC Site	**4**	**-57**	**-620**	**-0.39%**
BM-C001	1	-25	-220	-0.29%
BM-C002	1	-19	-590	-0.27%
BM-C004	2	-43	-1400	-0.19%
BM-C005	1	-8.3	-170	-0.02%
BM-C101	3	-53	-1600	-0.35%
BM-C102	1	-32	-200	-0.22%
BM-C103	4	-76	-2500	-0.52%
BM-C105	1	-64	-1700	-0.56%
BM-C106	1	-12	-650	-0.94%
BM-C107	1	-50	-2400	-0.33%
BM-C108	1	-31	-1100	-0.25%
BM-C109	3	-77	-2900	-0.60%
BM-C110	2	-54	-1800	-0.48%
BM-C111	2	-69	-3100	-0.55%
BM-C112	3	-130	-1800	-0.99%
BM-C114	1	-76	-2200	-0.87%
BM-C115	1	-78	-4300	-0.70%
BM-C116	1	-77	-2800	-0.63%
BM Site	**30**	**-67**	**-1900**	**-0.51%**

Cavern	Num. W/O in calc.	ΔV per W/O (MBBL)	ΔV/day (BBL)	ΔV/Vcav (%)
WH-C007	1	-16	-160	-0.12%
WH-C008	1	-124	-740	-1.19%
WH-C009	1	-74	-1600	-0.73%
WH-C011	1	-45	-990	-0.54%
WH-C101	1	-56	-640	-0.46%
WH-C102	1	-45	-400	-0.38%
WH-C103	1	-29	-460	-0.24%
WH-C105	2	-70	-1600	-0.47%
WH-C107	1	-101	-1200	-0.80%
WH-C108	1	-219	-1100	-1.83%
WH-C111	1	-53	-1200	-0.45%
WH-C112	1	-172	-2900	-1.55%
WH-C113	1	-104	-800	-0.88%
WH-C114	1	-117	-550	-1.07%
WH-C115	1	-78	-1600	-0.73%
WH-C117	4	-88	-1500	-0.73%
WH Site	**20**	**-86**	**-1200**	**-0.74%**
BH-C101	1	-140	-3000	-0.99%
BH-C102	1	-170	-2900	-1.27%
BH-C103	4	-90	-1600	-0.67%
BH-C104	2	-110	-1700	-0.83%
BH-C105	3	-110	-2100	-0.87%
BH-C106	2	-120	-2300	-0.91%
BH-C107	2	-110	-2000	-0.83%
BH-C108	2	-110	-1600	-0.83%
BH-C109	1	-170	-1300	-1.37%
BH-C110	1	-130	-2000	-1.00%
BH-C111	1	-170	-3200	-1.31%
BH-C112	1	-110	-1400	-0.83%
BH-C113	2	-150	-1600	-1.14%
BH-C114	2	-180	-2000	-1.44%
BH Site	**25**	**-124**	**-2000**	**-0.96%**

Table 1: Tabulated results for cavern volume loss presented by cavern and site.

Other results that can be drawn from the analysis are that the total cavern volume lost is found to have very little correlation to the length of the workover. This can be seen in Figure 2 where the average volume loss is plotted against the workover length. As previously explained, scatter in the data is also due to the different salt properties at each site.

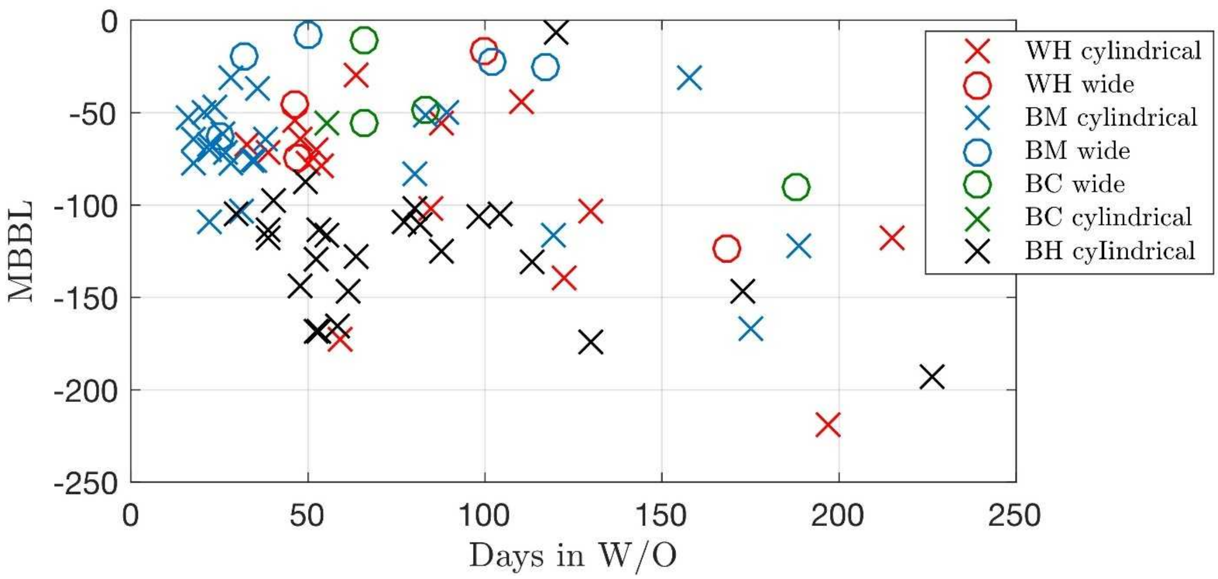

Figure 2. Cavern volume lost as function of length of workover. Markers by site and SPR phase.

Another way to look at the results is to plot the average volume loss per day for each of the workovers. The value can be considered as an equivalent daily cavern closure rate. This is illustrated in Figure 3 as a function of workover duration. The plot suggests that most of the volume is lost in the first month or so of the cavern being depressurized.

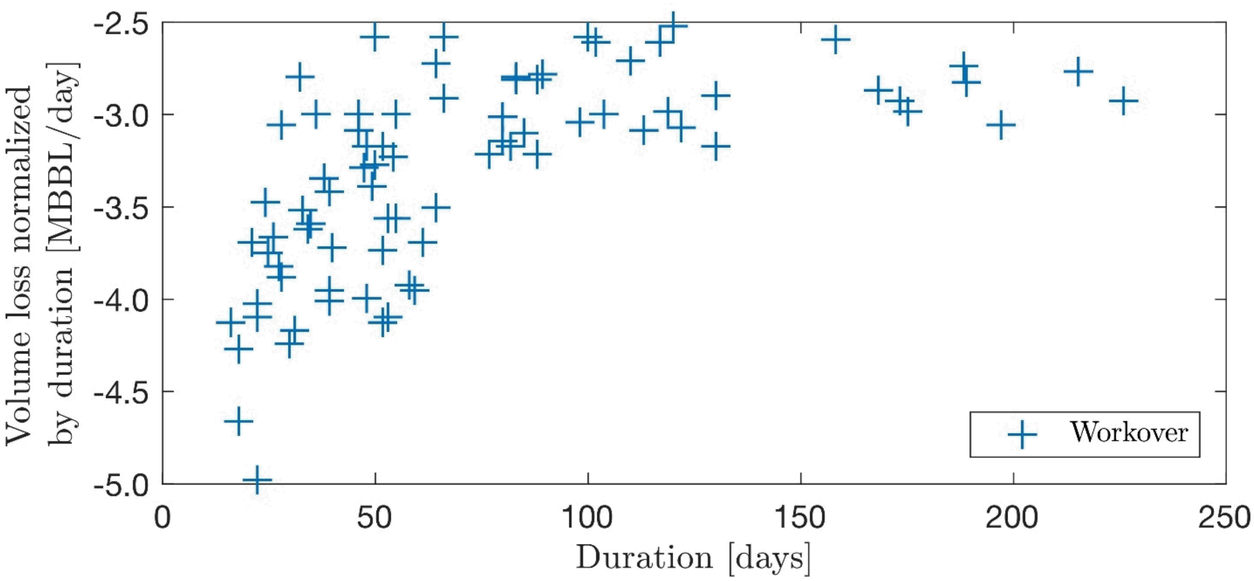

Figure 3. Cavern volume lost (for each workover) averaged over the duration of the workover.

Workover Effects on Neighboring Caverns

While depressurization affects cavern creep rate, these effects are not limited to the immediate surrounding but can be measured in neighboring caverns (Checkai, 2014). Due to the large number of caverns at SPR, at times, more than one cavern must be depressurized at the same time. To better understand workover effects on neighboring caverns the following scenarios were investigated:

1. A single cavern at a site is depressurized.
2. Two or more caverns in the same site undergo workovers (are depressurized) 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.

Analysis of the results from 79 separate workovers (depressurization) between 2010-2016 at all 4 sites has allowed the identification of two distinctive behaviors:

Behavior I. Depressurization in Cavern A causes an increased rate of pressurization (increased closure rate) in Cavern B. This increase is sharpest at the beginning of depressurization and occurs again during repressurization.

Behavior II. Depressurization in Cavern A causes a decrease in the pressure rate in Cavern B (pressure is “tracked” by Cavern B). Often, 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.

An example of both behaviors is illustrated by Big Hill Cavern 104 during a workover in 2016 and its interaction with its neighbor, Big Hill Cavern 109, that underwent a concurrent workover.

Figure 4 (top) shows the wellhead pressure response of BH104 during depressurization. The cavern was depressurized in two stages: the first, lasting only a day, while the second lasted just over a week. The second stage shows an exponentially decreasing flow out of the cavern as the pressure approaches zero which is typical for an SPR cavern.

While the short duration of the first stage makes it difficult to discern the neighboring responses, the second stage clearly illustrates the two different behaviors identified in BH104 neighbors (Figure 4 (middle)). In five of the caverns presented, an increase in pressurization rate – Behavior I – is found (dashed lines); for example, Cavern 105 pressurization rate (purple dashed lines) jumped from 0.7 [psi/day] to 2.8 [psi/day]. Behavior II, on the other hand, was found in cavern 108 (solid line). In general, and as shown in the plot, the magnitude of the pressure response in behavior II is much smaller than in behavior I.

BH113, also exhibits a type II behavior. Its pressure response (brine) is shown in a separate axis Figure 4 (bottom). 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.

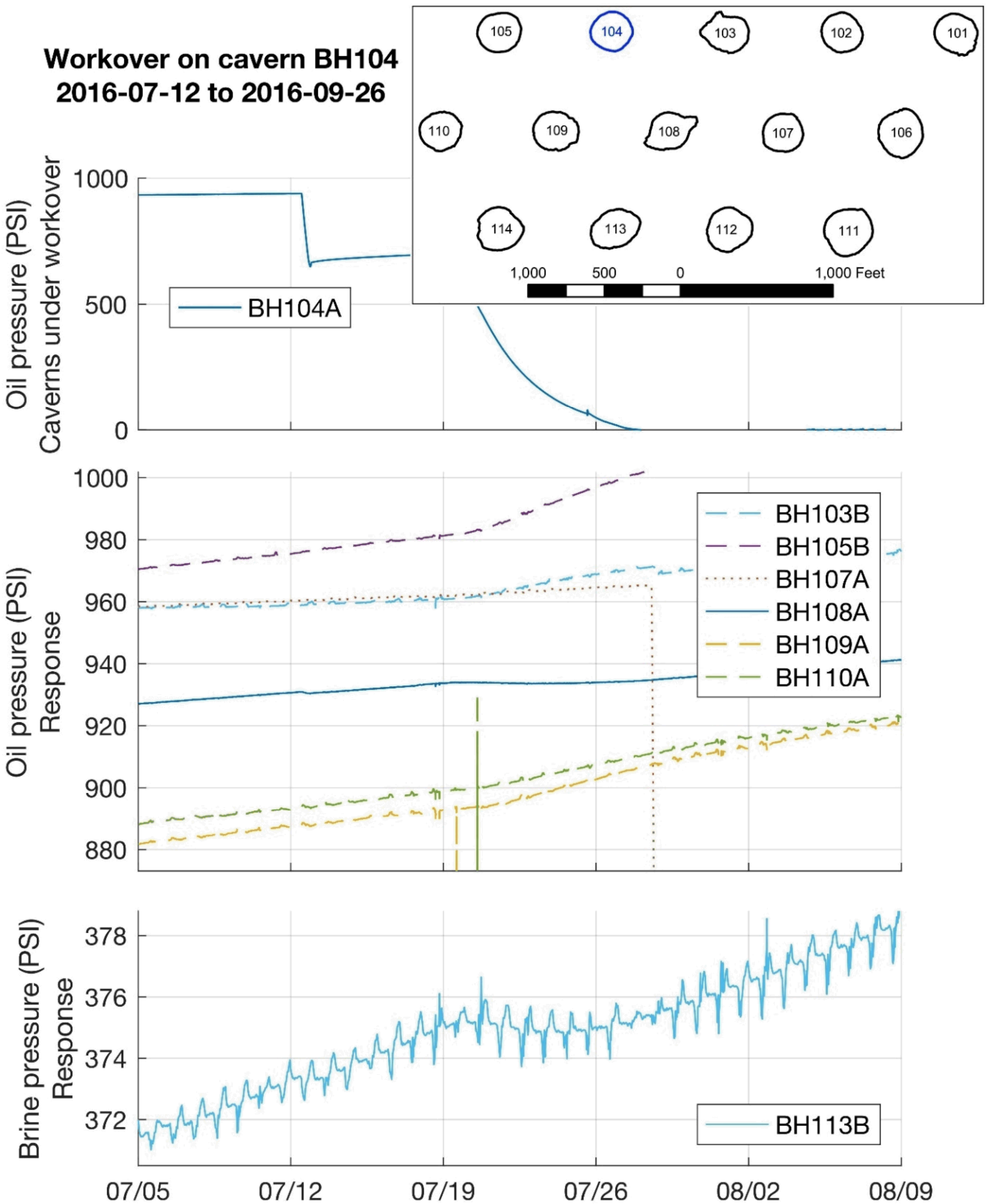

Figure 4. Different behaviors observed in neighboring caverns during the depressurization of BH104 cavern. The top image shows BH104 wellhead pressure response during depressurization. The middle image shows the wellhead pressure response of BH104 neighboring caverns and the bottom image shows wellhead pressure of BH113 (a neighbor to BH104) during the same time period (brine).

As previously described, multiple workovers and cavern depressurizations can happen simultaneously. In this case, neighboring pressure behavior can be more difficult to identify. Figure 5 illustrates an example of the complexity associated with these phenomena.

During the BH104 workover (previous example), BH109 was also depressurized. During stage one depressurization, marked with “A” in the figure, Cavern 113 and 112, respond with a type II (circled along arrow “A”). Cavern 108 also exhibits a type II response as the pressurization rate changes between points A and B, while the pressurization rate for Cavern 113 is zero during this time. Points C and D on Figure 5 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 type II response to the workover, this increase in pressurization rate at the end of the workover occurs with both type I and II behaviors. The fact that it is not seen in the type I responses here is possibly linked to the impact of multiple caverns being depressurized, but modeling is needed to investigate this hypothesis.

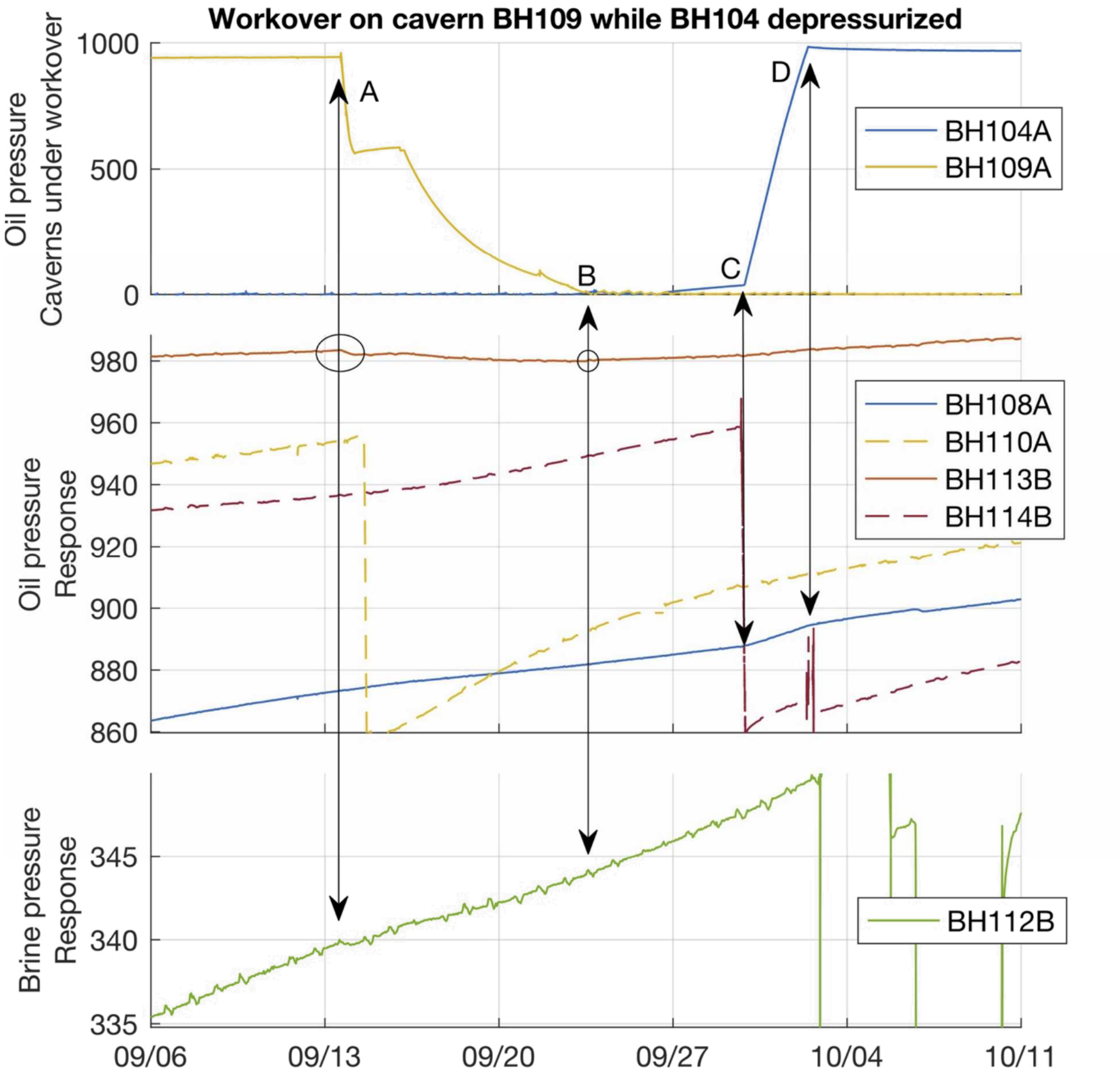

Figure 5. Example of multiple cavern depressurization and associated behaviors.

As shown in these two examples, neighboring effects can be complex and no clear trend was discovered as to when type I or type II is expected. As a result of this analysis a geomechanical study has been initiated to understand the physical mechanism that leads to each behavior.

Workover Effects on the Surface

A possible expression of workover effects on a cavern system is the resultant subsidence. As previously described, 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 (Lord, 2014). These reports described the observations for the 2012–2013 subsidence rates (Figure 6) 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.

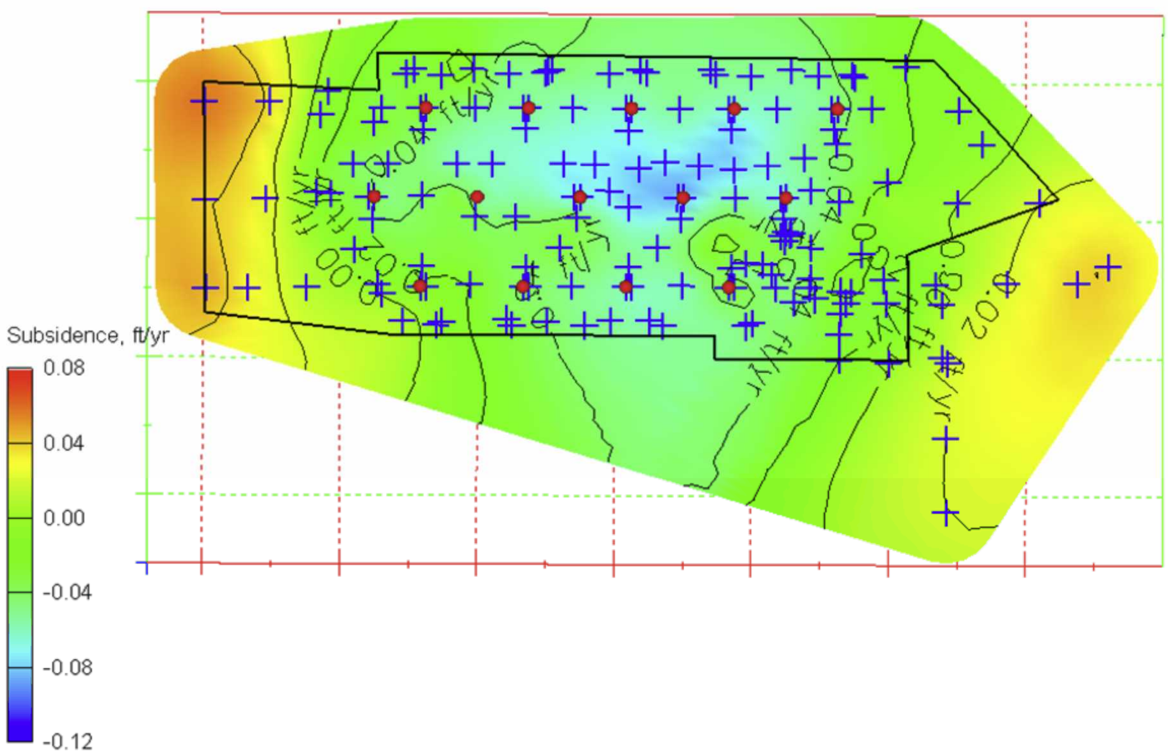

Figure 6. Contour plot of subsidence rates (ft/yr) from May 2012 to May 2013. Negative rates indicate subsidence, whereas positive rate indicates uplift. Monument locations are noted by crosses. Cavern well locations are depicted as red circles (from Lord 2014a, Fig. 1).

While assessing the reason for the increase in subsidence rates, workover numbers and durations were analyzed. Between the period of 2010-2013, the Big Hill site was subjected to a large number of workovers. The pressure data from 2002 to 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 the14 caverns 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 depressurizations 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 given year. The largest yearly CRF calculated was 2.2, corresponding to the year May 2012–May 2013. The data comparison 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 repressurization 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 7).

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.

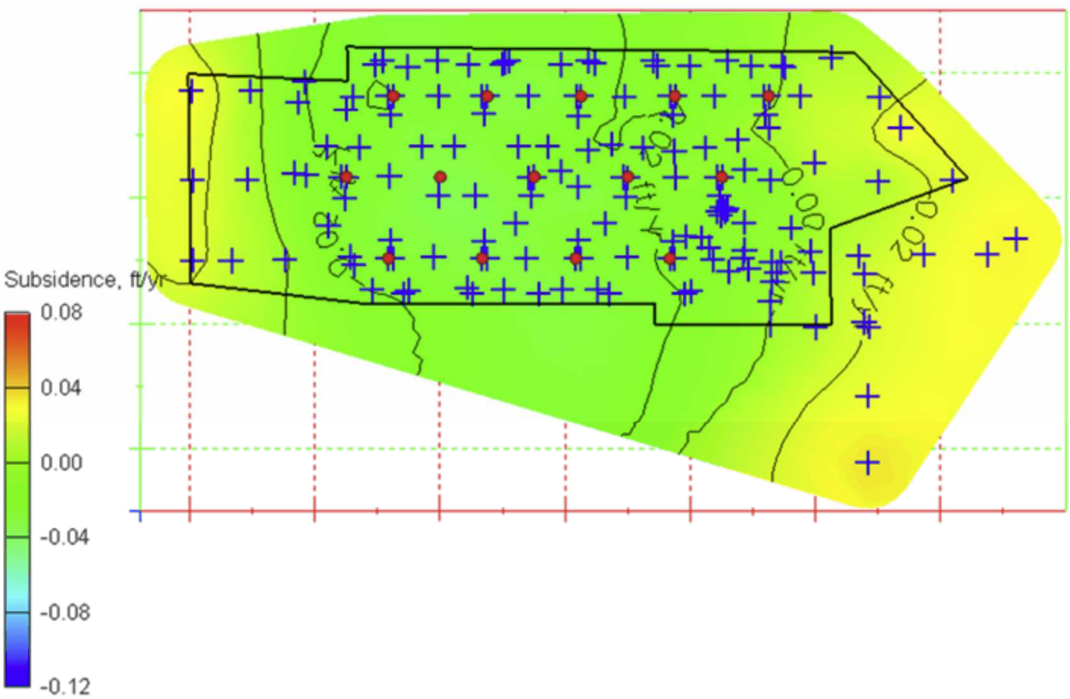

Figure 7. Contour plot of subsidence rates (ft/yr) from May 2012 to July 2014 (26 months). Negative rates indicate subsidence, whereas positive rates indicate uplift. Monument locations are noted by crosses. Cavern well locations are depicted as red circles (from Lord 2014b, Figure 3).

Conclusions

An analysis of the effect of cavern depressurization has been conducted for the SPR on 79 different workovers. Results from this analysis have highlighted that cavern volume loss during a depressurization is dependent on the salt properties and cavern shape. Average cavern volume loss can only be estimated on the basis of a single cavern or small group of caverns, not by site or across all sites. Additionally, most cavern volume loss occurs in the first few weeks of a workover. A new effect, occurring on neighboring caverns, was found. Two separate behaviors, type I where the neighboring cavern pressure increases during a depressurization, and a type II where the neighboring cavern pressure decreases in a similar manner as the depressurization, but in much small magnitude; both appear to occur with regularity. Additionally, cavern depressurization was found to affect the rate of subsidence of the site.

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