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Historical Cavern Floor Rise for All SPR Sites

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Abstract

The Strategic Petroleum Reserve (SPR) contains the largest supply is the largest stockpile of government-owned emergency crude oil in the world. The oil is stored in multiple salt caverns spread over four sites in Louisiana and Texas. Cavern infrastructure near the bottom of the cavern can be damaged from vertical floor movement. This report presents a comprehensive history of floor movements in each cavern. Most of the cavern floor rise rates ranged from 0.5-3.5 ft/yr, however, there were several caverns with much higher rise rates. BH103, BM106, and BH105 had the three highest rise rates. Information from this report will be used to better predict future vertical floor movements and optimally place cavern infrastructure. The reasons for floor rise are not entirely understood and should be investigated.

Acknowledgment

I would like to thank David Rudeen and Leigh Cunningham for their thorough review of this work. Their feedback was greatly helpful in improving this report. This work was funded by the Strategic Petroleum Reserve program administered by the Office of Fossil Energy of the U.S. Department of Energy.

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Executive Summary

The Strategic Petroleum Reserve (SPR) is the largest stockpile of government-owned emergency crude oil in the world. There are four different sites in two different states. In total, SPR contains approximately 714 million barrels of crude oil stored in underground salt caverns. Throughout SPR's history there have been instances of infrastructure damage near cavern floors. Damages are likely due to vertical floor movements from creep and salt falls. To better understand future floor movements and prevent further damage, historical floor rise rates are presented herein.

The data in this report comes from four different sources: sonar surveys, weekly survey reports, and two databases. Each dataset has its own reliability and frequency of measurements. The sonar and weekly surveys were most reliable but least frequent. On the other hand, data from databases were less reliable but more frequent. Data deemed unreliable were flagged and removed from the analysis. Next, the data were interpolated at constant intervals to accurately estimate and compare average rise rates. The cavern floor rise trends were then plotted as functions of time and space.

Cavern floor movements usually exhibited a constant rise between 0.5-3.5 ft/yr. Generally, Bayou Choctaw and West Hackberry saw some of the lowest rise rates while Big Hill and Bryan Mound experienced some of the highest. The largest rise rate occurred in BH 103 with an average rate of 9.72 ft/yr. Most of this floor rise occurred over a short period of time indicating that it was likely caused by salt masses falling from the cavern walls. Bryan Mound 106 had the next highest total rise rate of 8.38 ft/yr. Bryan Mound also had three other caverns rising at a rate greater than 5 ft/yr. The largest rise rate seen in Bayou Choctaw was in cavern 102 (2.99 ft/yr). West Hackberry only had two caverns rising at a rate greater than 3 ft/yr with 106 being the highest (3.79 ft/yr).

Despite rise rates, there were other trends discussed in this report. One of the most significant is spatial correlation. Big Hill and Bryan Mound both exhibited areas of higher floor rise rates. Spatial correlation within Bayou Choctaw and West Hackberry remain inconclusive. There are several possible causes for the rise rates seen at each SPR site including pressure change, natural creep, salt falls, etc. Currently, the correlation between possible causes and floor rise is still not completely understood. More research is necessary to determine correlations and predict future floor rise rates.

Bayou Choctaw		**Big Hill**		**Bryan Mound**		**West Hackberry**	
Cavern	Rise Rate	Cavern	Rise Rate	Cavern	Rise Rate	Cavern	Rise Rate
BC102	2.99 ft/yr	BH103	9.72 ft/yr	BM106	8.38 ft/yr	WH106	3.79 ft/yr
BC17	2.31 ft/yr	BH105	7.40 ft/yr	BM112	6.29 ft/yr	WH103	3.68 ft/yr
BC20	1.45 ft/yr	BH104	2.20 ft/yr	BM103	5.90 ft/yr	WH108	2.67 ft/yr

Table 0.0.1: Three highest average cavern floor rise rates seen at each site

Nomenclature

BC	Big Choctaw site
BH	Bigh Hill site
BHF	Bradenhead Flange
BM	Bryan Mound site
DOE	Department of Energy
SPR	Strategic Petroleum Reserve
WH	West Hackberry

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Chapter 1

Introduction

The Strategic Petroleum Reserve (SPR) has four sites across Louisiana and Texas each with its own set of solution mined salt caverns. These caverns are used to store approximately 714 million barrels of crude oil [4] for the United States in case of an unexpected fuel shortage, national defense needs, as well as upholding international agreements with the International Energy Agency to maintain emergency oil stocks. Within each cavern, there is a mixture of oil and brine with the lighter oil being at the top and the denser brine being near the bottom. Both fluids comprise all of the cavern volume are monitored to assure a safe operating pressure within each cavern.

Since the oil is meant for national energy security it must be able to be safely withdrawn and replaced within a reasonable time frame. To withdraw oil from the cavern, more brine must be introduced to keep the cavern pressure within safe limits. The opposite is true for replacing oil. Brine must be taken out to store more oil. Since the brine is denser and sits at the bottom of the cavern, a portion of the well must extend into the brine zone. This section of the well is commonly referred to as the hanging string.

The hanging brine string is usually placed as deep as possible to maximize the effective storage volume of the cavern but can be damaged if it is too close to the bottom as any movement due to creep or salt falls could easily damage the string. If a string is damaged there are several remediation options. First, is to shorten the string by cutting. If explosives are used they might damage the string in the process thus inhibiting any instrumentation from safely passing through the end of the string.An alternative, yet costly method would be to replace the string entirely. Neither option is as attractive as optimizing string depth to account for floor rise.

In order to prevent further damage to cavern infrastructure from vertical floor movement a better understanding of past movements must be realized. To begin, the historical floor depth measurements were compiled to examine all vertical floor movements over the life of the caverns. These measurements were taken from four different sources, each with varying amounts of accuracy and frequency. Only measurements that were interpreted to be actual cavern depths were analyzed.

Most of the original survey data were taken at irregular intervals which cannot be directly compared. As such, Matlab was used to interpolate the data to create regular intervals and later to analyze the data. Once the data were interpolated, a statistical analysis was done to determine the floor rise characteristics in each cavern. The results indicate that Bayou Choctaw and West Hackberry have relatively stable floor rise while Big Hill and Bryan Mound had several caverns with accelerated floor rise rates. Additionally, there is the possibility there is a spatial correlation in rise rates but the cause could not be confirmed. While there are several possible causes for the anomalous floor rises nothing has been confirmed and more work is needed.

Chapter 2

Methodology

There were several steps taken to determine the cavern floor rise rates. First the data were compiled from various sources. Next, anomalous survey data were removed. Data not removed were interpolated to create regular intervals between time steps. Finally, a spatial analysis was done to visualize the floor rise rates within each site.

While much of the data storage was done in Microsoft Excel the majority of the analysis was performed in Matlab. Several types of information were stored in Excel including: the SPR site, cavern number, well name, total depth, survey date, and survey source. There was also a flag to record the validity of the point. Criteria for this flag will be discussed in detail later in this report.

2.1 Data sources

Data were taken from several sources that included sonar surveys, LAS data, and temperature logs. The reliability and frequency of the data changed between each datatype. The most reliable measurements were typically taken from survey databases while the least reliable were from databases not meant specifically for cavern surveys. While unreliable, the database measurements were typically the most frequent. Figure 2.1.1 contains histograms of the number of available data points obtained from each data source used in the following analysis. Below is a description of each database used

Sonar Survey The first set of data was sourced from sonar surveys [1]. The sonar surveys were conducted at semi-annual intervals during the leeching of the caverns. Once the caverns were leeched, the sonar surveys were conducted at least once every 10 yrs. This is the least frequent data type but also the most reliable data as the cavern bottoms are explicitly stated.

Access Database The second type of data used in the survey was from a Microsoft Access database that was maintained until the early 2000's [2]. The data come from various types of surveys. This data is the most frequent but is often unreliable. Much of the total depths were reported using inconsistent datums which often made the results unusable.

Log Library Spreadsheet Another large source of data came from the LogLibrary Excel spreadsheet that recorded data from the mid-2000's to present day [3]. Like the Access database there were many total depths reported using a datum other than the one used in the original surveys. Work is currently being done to reinterpret the surveys to determine the true cavern depths.

Weekly Survey Report The next type of data used came from weekly survey reports [5]. Data contained in this set is typically reliable. Cavern engineers interpreted and recorded the cavern bottom depths. This data is also relatively numerous after the year 2000.

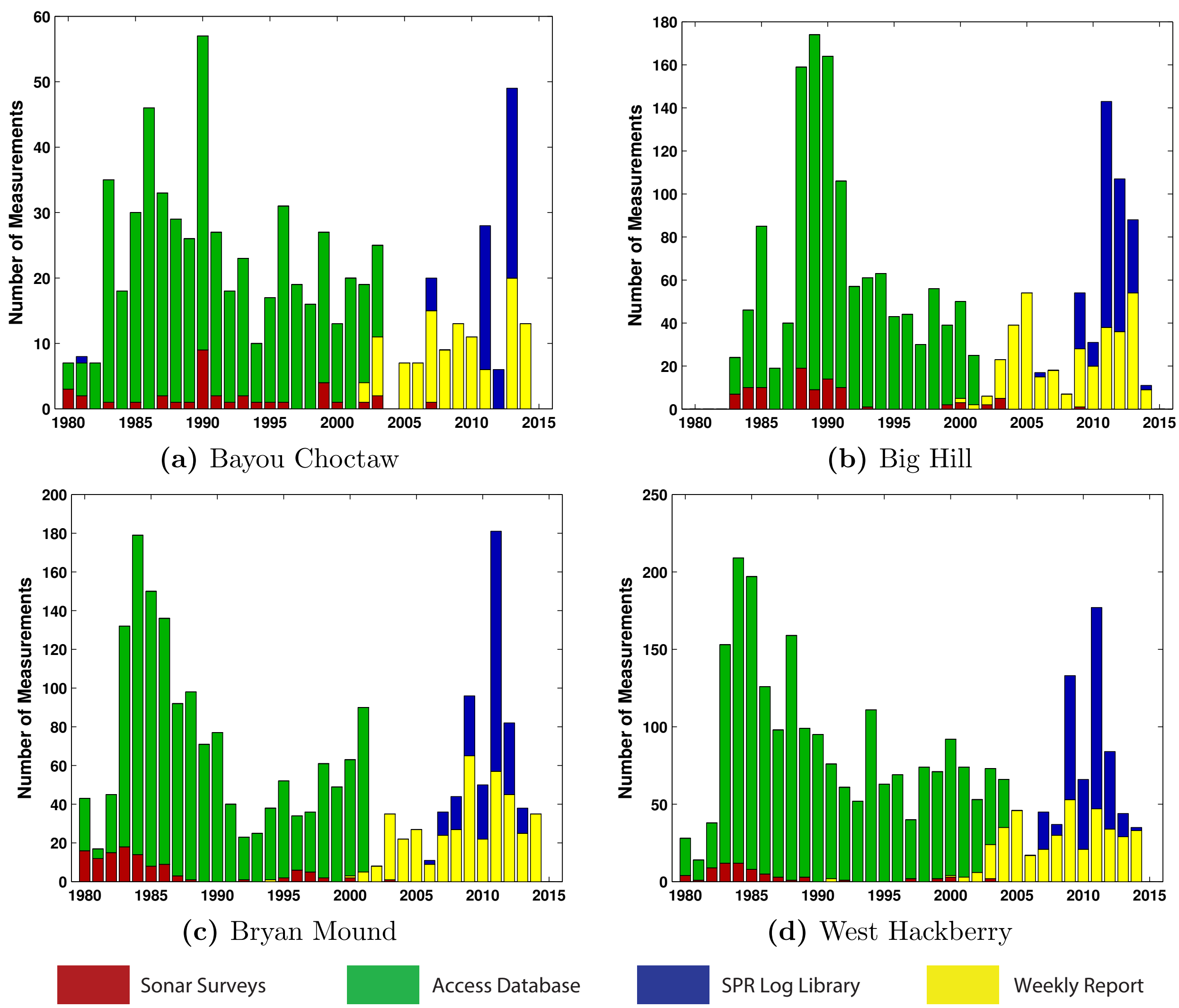

Figure 2.1.1: Histogram of data sources used for all four SPR sites.

2.2 Quality Assurance

There was a significant percentage of data that were excluded from the analysis due to measurement error or recording error. Measurement errors were expected but could not be uniquely identified. The more common type of error in the data occurred when the wrong quantity was misrecorded as the total cavern depth. For example, the survey reports may indicate the total depth as the total survey depth instead of the total cavern depth. This type of error was typically identified since these readings were significantly different from the baseline measurements. Any inconsistent data were identified, noted, and subsequently excluded from the analysis.

2.3 Data Import and Cleanup

Next, the data in Excel were exported to Matlab while all of the flagged data were excluded. The wells in each cavern then were averaged to get a single, approximate well/cavern location. The data were then separated into their respective wells. Any wells with multiple measurements in one day were averaged to prevent any abrupt changes in floor depth.

2.4 Analysis

To work around the irregular time between measurements a linear interpolation was taken to standardize the frequency of the data. A period of 30 days between interpolated values was chosen based on memory requirement and frequency of the actual data. The interpolated data were used for the majority of the calculations as it can be directly compared with interpolated data from another caverns in the same site.

2.5 Rise Calculation

Before the rise calculations were performed, all of the interpolated data for a single cavern were averaged to get an average cavern depth. Once that was complete, a central difference calculation was performed to get the approximate rise for each of the interpolated values. If there were more than ten data points the average, quartiles, and standard deviations were taken from each set.

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Chapter 3

Results

In general, most of the caverns have experienced a gradual and constant floor rise. There are, however, several exceptions at the Big Hill and Bryan Mound sites. The results presented below are presented in four different sections for each site. First, depth below the bradenhead flange (BHF) is presented graphically through time along with a short discussion of unique characteristics. For comparison purposes, the total change in depth shown in each time series is 300 ft. It should be noted, however, that the absolute depth below the BHF changes between graphs. The second section presents cavern statistics over a given time period and are discussed. Finally, any spatial trends or anomalous results are examined. Caverns with low/insignificant rise rates have average rise rates less than 1 ft/yr. Moderate cavern floor rise rates are between 1 ft/yr and 4 ft/yr. Any floor rise greater than 4 ft/yr is considered high/significant.

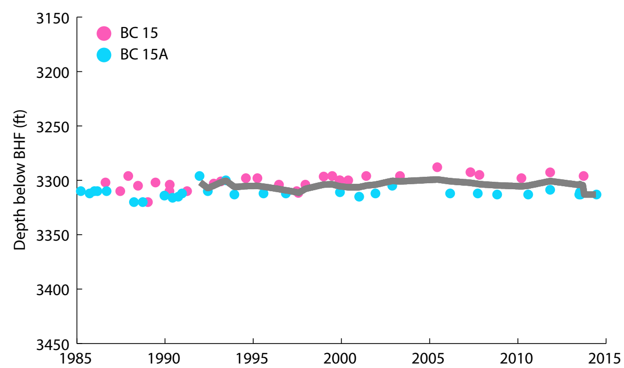
3.1 Bayou Choctaw

3.1.1 Cavern Measurements

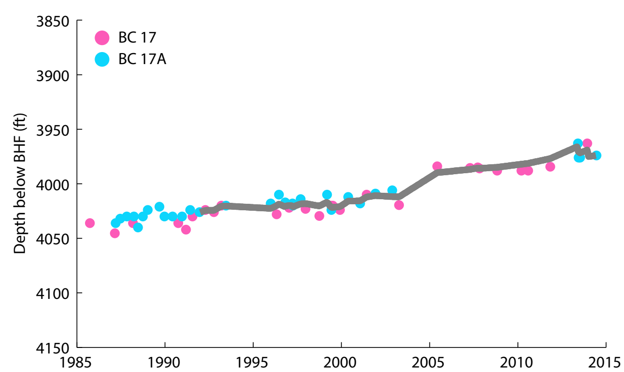
The following section shows the cavern depths used to calculate the floor rise rates at Bayou Choctaw and discusses particular behaviors seen in each study. Readings from each well are represented by a circular marker colored to represent a certain well. The gray line in each figure shows the average floor depth interpolated on a 30 day interval. All of the caverns had sufficient points for an accurate interpolation except for Bayou Choctaw 4 which only had 6 points.

Bayou Choctaw 4 This cavern had only 6 points, two of which were taken before 1985. As such, there was no interpolation for BC04 and was not included in the statistical or spatial analyses. Regardless, the floor has experienced very little vertical movement over 40 yrs.

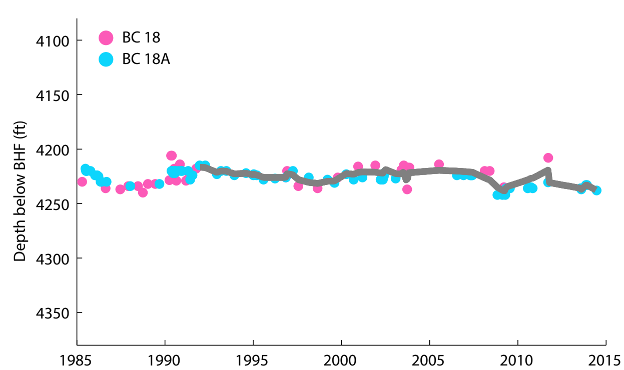
Bayou Choctaw 15 Measurements were taken from two wells (A and an unlabeled well). There is variation between measurements although it could be due to measurement error. Overall, the cavern floor stayed constant throughout the life of measurements and on average, actually became deeper (-0.48 ft/yr).



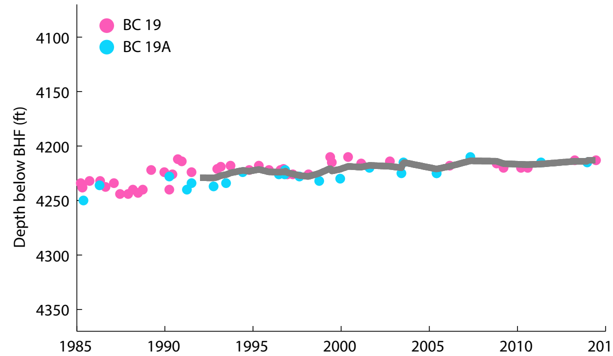
Bayou Choctaw 17 Measurements from this cavern were taken from an unlabelled well beginning in 1972 and from well A beginning after 1985. Both wells show a fairly constant rate of cavern floor rise which was the highest of any of the older Bayou Choctaw caverns (2.31 ft/yr). It should also be mentioned that there is a 12 year gap in data after the initial measurement.



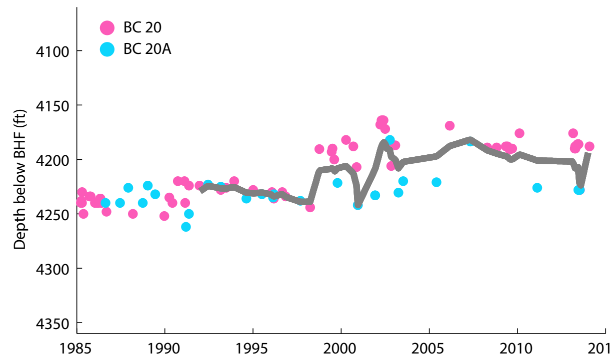
Bayou Choctaw 18 Two wells (A and an unlabeled well) were used for cavern depth measurements. The variation in BC18 is likely caused by measurement errors. Additionally, the cavern showed signs of becoming slightly deeper after 1990 (-0.92 ft/yr).



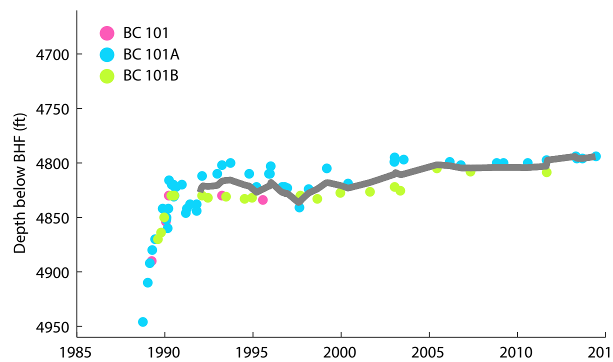
Bayou Choctaw 19 Measurements from this cavern were taken from Well A and another unlabelled well. Both wells agree that the cavern floor is rising but at a very low rate (0.72 ft/yr).



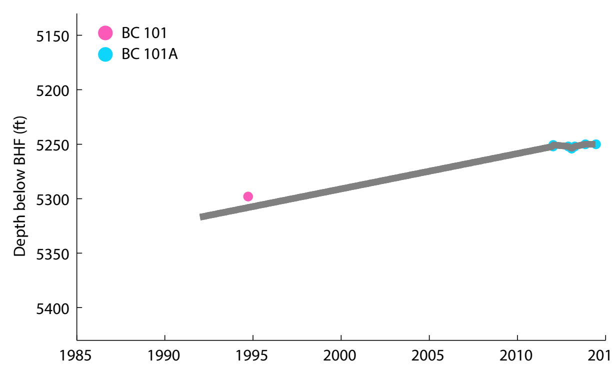
Bayou Choctaw 20 Like most of the wells, measurements were taken from an unlabeled well and Well A. While there is significant variation between measurements, which may or may not be caused by measurement error, there is marginal rise in the cavern floor (1.45 ft/yr).



Bayou Choctaw 101 Measurements were taken from Well A and B. Well A had slightly more variation than Well B but both sets of measurements are in agreement that there is only moderate floor rise (1.36 ft/yr).



Bayou Choctaw 102 Measurements for this cavern were taken from two wells: Well A and an unlabeled well. It is unclear if readings from the unlabelled well were actually mislabeled measurements from Well A. The gap in measurements are due to a change of ownership in the cavern. The cavern was created by DOE but subsequently sold to another entity. It was recently purchased by DOE and measurement frequency is now similar to those in other caverns.



3.1.2 Overall Statistics

The rise was calculated from 1992 onwards so that total rise amounts were not affected by some of the newer cavern construction periods. All eight wells are presented in Figure 3.1.1 to show the total cavern rise since 1992. The overall statistics were included in Table A.1.1 for seven of the eight caverns and represented graphically in Figure 3.1.2. Cavern 4 was excluded as there was an insufficient number of measurements made to create a meaningful set of statistics.

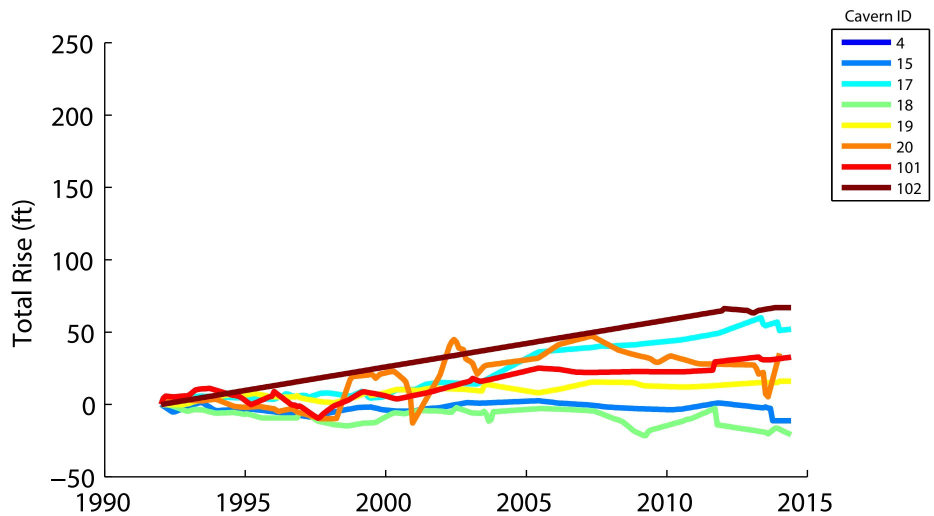


Figure 3.1.1: The total floor rise for Bayou Choctaw since 1992

According to the available data Bayou Choctaw experienced the least average floor rise over the four sites. None of the floor rise rates were above 3 ft/yr. Caverns 102, 17, and 20 have the highest rise rates while caverns 15 and 18 seem to have actually become deeper. In addition, there were no obvious anomalous jumps in floor depth.

3.1.3 Spatial Trends

The highest floor rise rates were seen near the western edge of the dome as shown in Figure 3.1.3. Cavern 102 was not included in the spatial analysis as there were too few points to get an accurate depiction of floor rise rates. Based off the few points that were recorded, Cavern 102 shows the highest rise rate at Bayou Choctaw and it is also at the western edge of the site. It is unclear if this correlation is coincidental or if there are actual phenomena occurring at the site that drives greater floor rise.

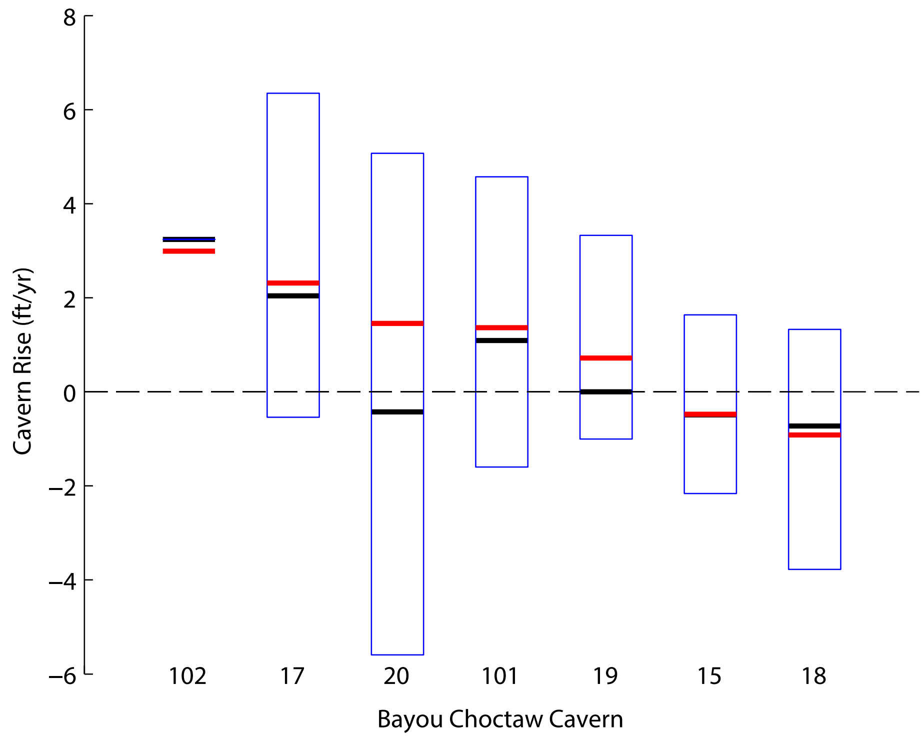
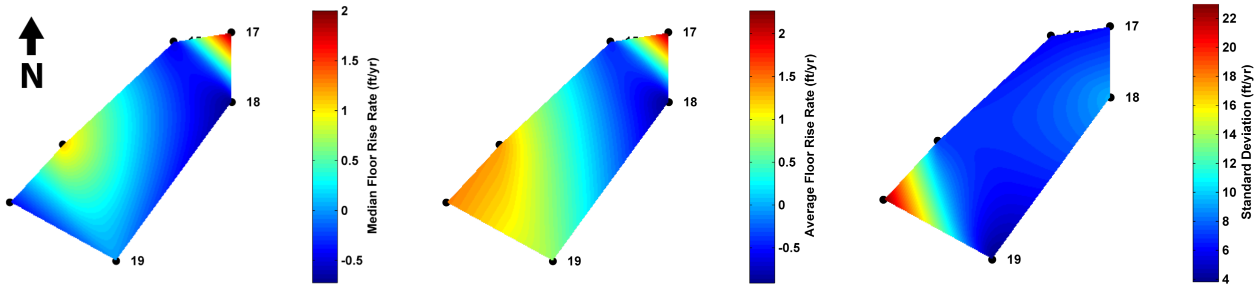


Figure 3.1.2: The rise rates at Bayou Choctaw ordered based on average rise (red line). The 25th and 75th percentiles are represented by the lower and upper boundaries of the blue rectangle while the median is represented by the black line.

3.1.4 Anomalous Readings

Caverns 101 and 102 experienced a large jump in floor rise during construction. This is likely due to the settling of cavern insolubles [7]. This behavior is seen in other DOE built caverns during the period after construction.



(a) Median **(b)** Average **(c)** Standard Deviation

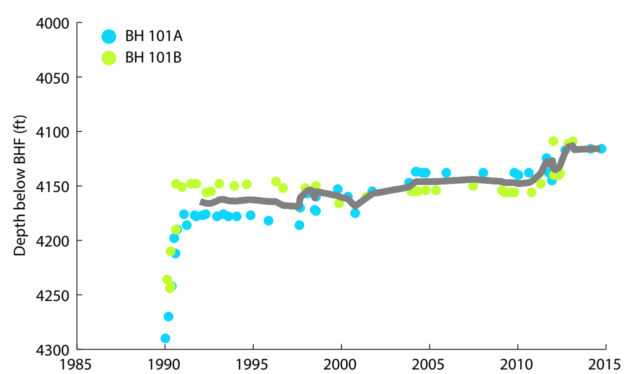
Figure 3.1.3: Bayou Choctaw Floor Rise Map

3.2 Big Hill

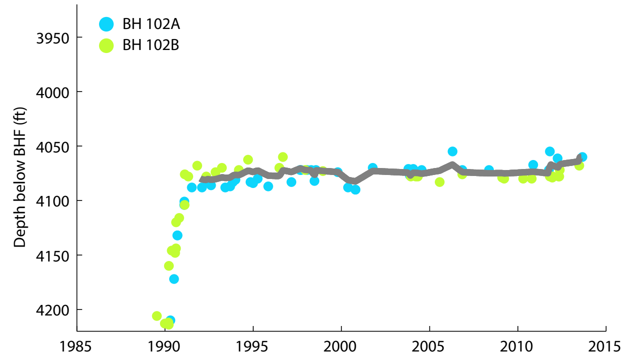
3.2.1 Cavern Measurements

The following section shows the cavern depths used to calculate the floor rise rates at Big Hill and discusses particular behaviors seen in each study. Since Big Hill is the only site that was created wholly by DOE, each of the well histories begin at relatively the same time and showed large floor rise during development generally followed by relatively slow steady rise. There are 14 caverns in total with two wells each. Readings from each well are represented by a circular marker colored to represent a certain well. Interpolations are represented by a gray line.

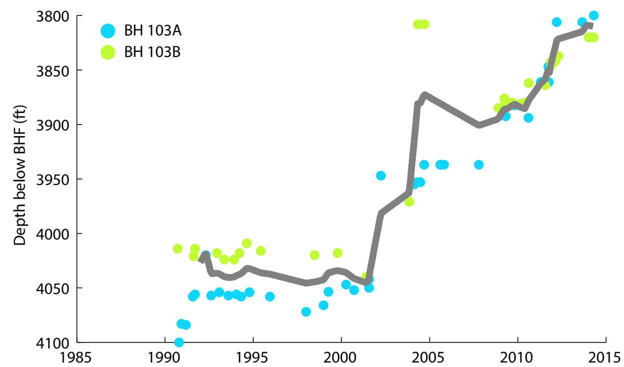
Big Hill 101 Wells A and B showed there was a greater than average floor rise (2.15 ft/yr). It should also be noted that Well A is rising at a higher rate than Well B.



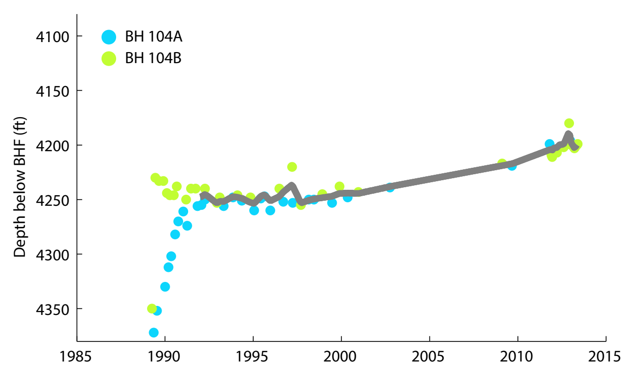
Big Hill 102 Both Well A and B depths had similar depths with low rise rates (0.93 ft/yr).



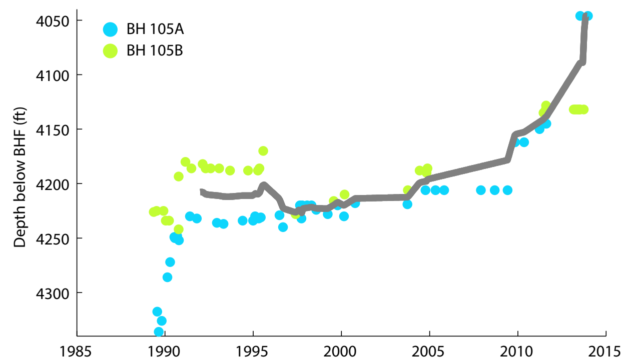
Big Hill 103 Overall, this cavern had the greatest floor rise of all the SPR sites (9.72 ft/yr). Readings from both Wells A and B showed there were several events that lead to a large floor rise that were likely due to salt falls [8]. The first anomaly was seen in Well A in late 2002. Another anomaly was seen just before 2005 in Well B. After the initial floor rise event in each well there was a slight fall in floor rise likely caused by leveling after a salt fall. It was later discovered there was a salt fall in Big Hill 103 [6], however, the cavern floor rise has continued at a greater rate than seen in other caverns.



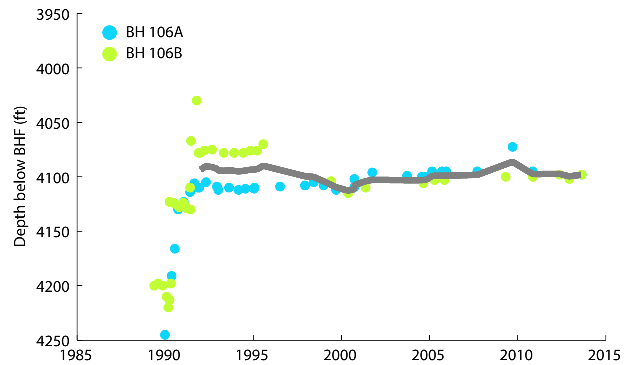
Big Hill 104 Both Wells A and B showed similar results after the initial construction period. There was an initial jump seen in Well B during construction but eventually the floor depth fell to the same depth as Well A and subsequently began to rise at a steady rate (2.20 ft/yr).



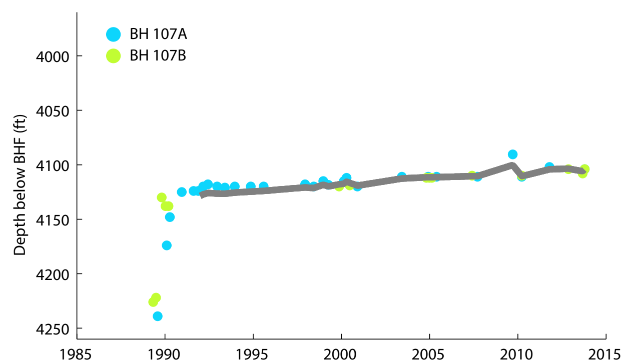
Big Hill 105 Measurements were taken from both Well A and Well B. Well A followed a typical path during construction. Well B had several floor rise jumps before eventually returning to the same depth as Well A. There are also several unexplained floor rise jumps after the year 2010. The more recent jumps could not be confirmed as there were no recent measurements. If these points are accepted as true, Big Hill 105 has the third highest average floor rise rate across all sites (7.40 ft/yr).



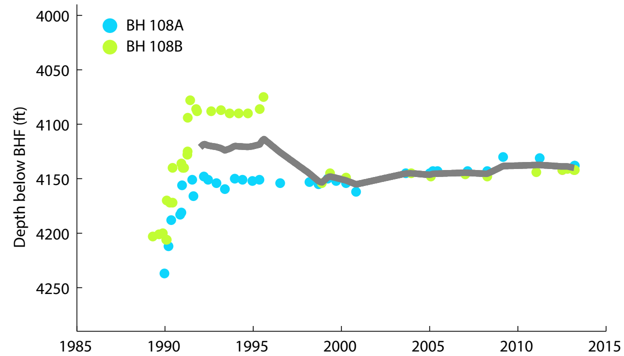
Big Hill 106 Well A followed a typical construction depth but Well B experienced several jumps during construction. The floor under Well B was shallower than under Well A until the year 2000 when they once again had similar floor depths. Big Hill 106 experienced very little floor rise, and on average, became slightly deeper over the years (-0.24 ft/yr).



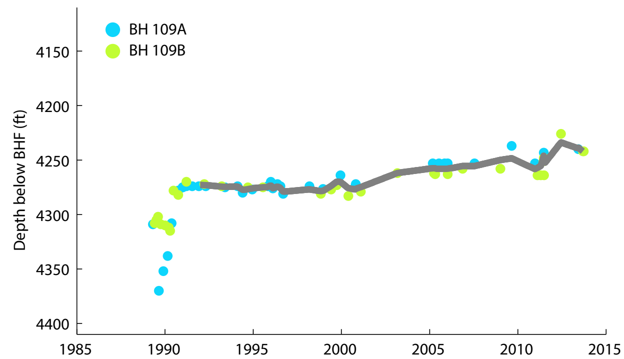
Big Hill 107 Measurements from Wells A and B share similar values but measurements from Well B are sparse. BH 107 has a moderate floor rise rate (1.06 ft/yr).



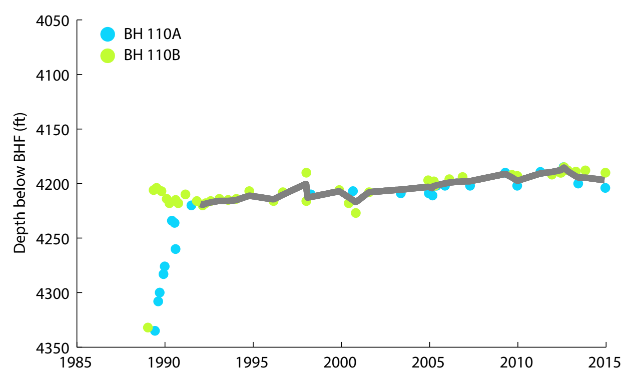
Big Hill 108 Measurements from Big Hill 108 were taken from Wells A and B. Like several other floor depths, the area under Well B experienced jumps during construction and was higher than the area under Well A until the year 2000 where they became the same. BH 108 is unique as the difference in floor depth readings between wells A and B are much higher than seen in other Big Hill caverns.



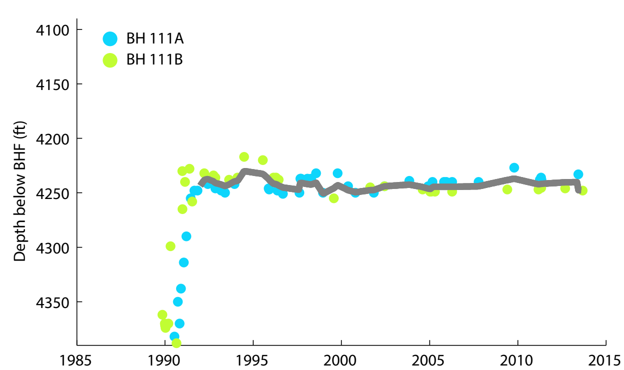
Big Hill 109 Readings from both wells A and B suggest there is a moderate floor rise rate in BH 109 (1.45 ft/yr).



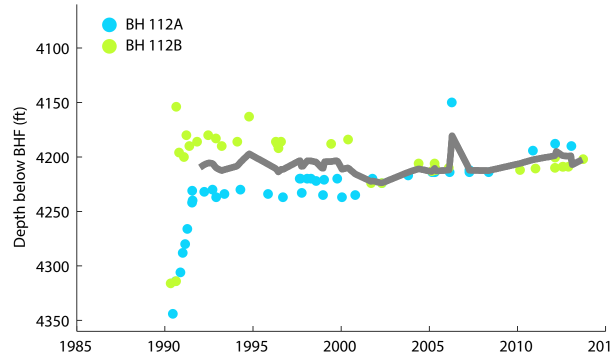
Big Hill 110 Besides a floor rise jump seen under Well B at the end of the construction phase, both wells suggest this cavern is experiencing a low to moderate rise rate (0.97 ft/yr).



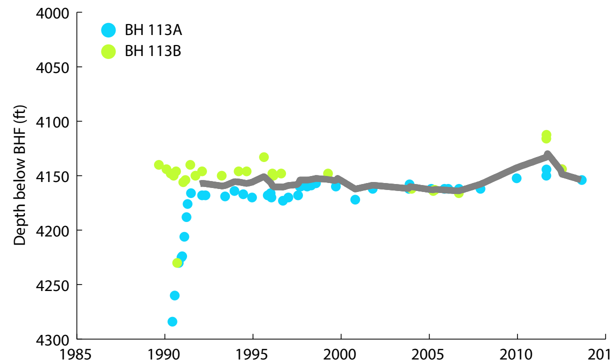
Big Hill 111 There is some variance in Well B during construction but eventually shows similar results taken under Well A.



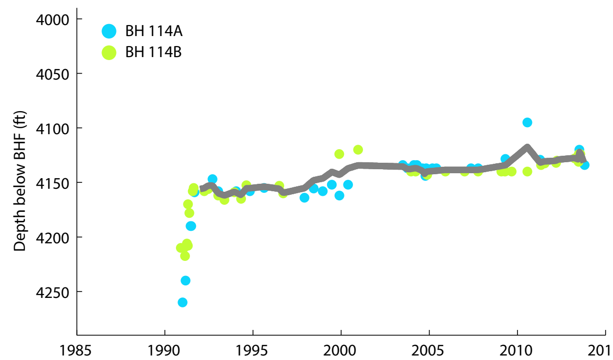
Big Hill 112 Readings taken from Well B show the same jumpy behavior seen in several other caverns where the floor under Well B is higher until some point at which they become similar. There is an additional, single point anomaly seen under Well A that is likely due to measurement error.



Big Hill 113 Despite the early jump in floor rise during construction under Well B, this cavern is experiencing very little floor rise (0.17 ft/yr).



Big Hill 114 Measurements from both Wells A and B suggest BH 114 is experiencing moderate floor rise (1.20 ft/yr).



3.2.2 Overall Statistics

Big Hill is unique in that it is made up entirely of similarly shaped caverns constructed by DOE. Most of the caverns at Big Hill showed a moderate rise rate, however, there were several caverns that showed anomalous readings. Two caverns in particular demonstrated accelerated floor rise rates. Cavern's 103 and 105 each show floor rise much greater than in other caverns at the site (Figure 3.2.1). It has been clearly documented that cavern 103 experienced a salt fall in the early 2000's [6]. Beyond 2003, caverns 103 and 105 have experienced floor rise at approximately the same rate.

While not as high as 103 or 105, cavern 104 has the third highest average floor rise rate (Figure 3.2.2). All three caverns are adjacent and in the same area of the site (Figure 3.2.3). This may indicate floor rise rate Big Hill is spatially correlated. Caverns 101 and 104 are also located at the northern edge of the site and have similar, higher than average rise rates.

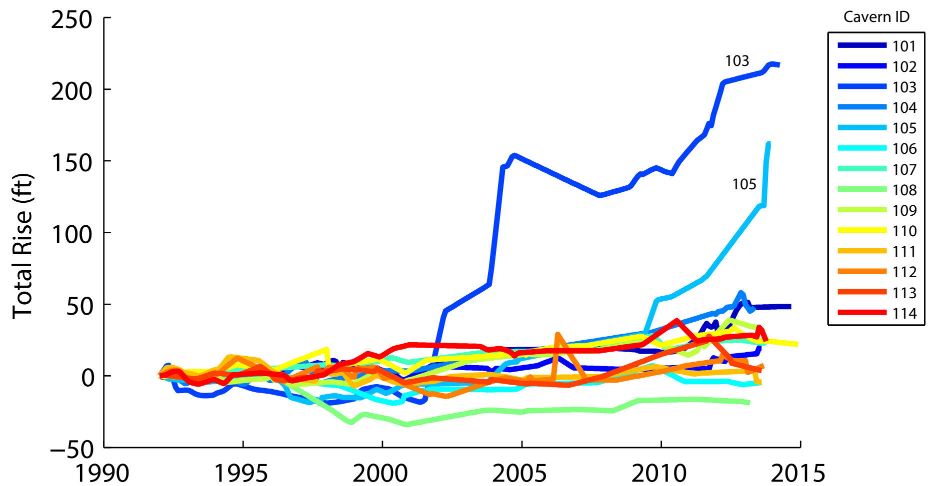


Figure 3.2.1: The total floor rise for Big Hill since 1992

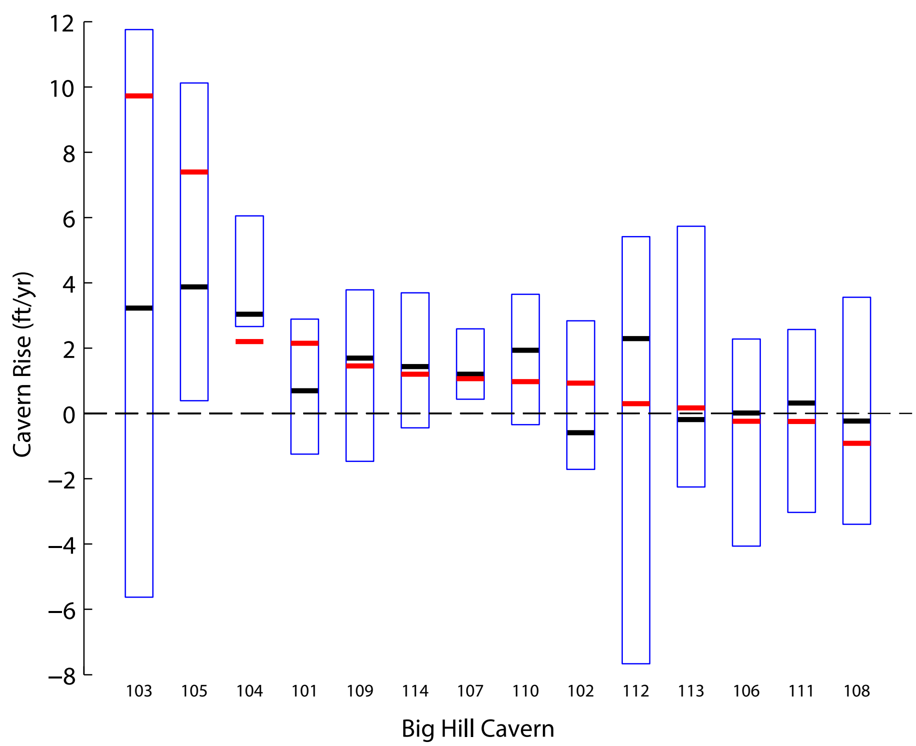
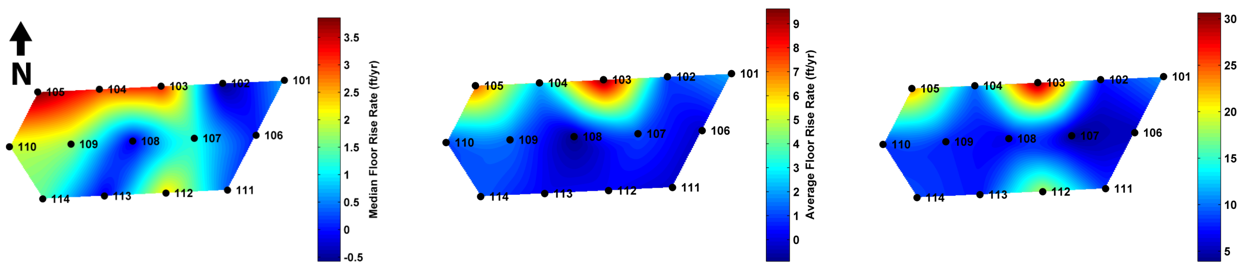


Figure 3.2.2: The rise rates at Big Hill ordered based on average rise (red line). The 25th and 75th percentiles are represented by the lower and upper boundaries of the blue rectangle while the median is represented by the black line.

3.2.3 Spatial Trends

Looking at the spatial distribution of floor rise rate shown in Figure 3.2.3, it is clear the highest floor rises occurred at the northern edge of the Big Hill site near the center of the salt dome. 103, 104, and 105 all experienced higher floor rise rates and all happen to be in close proximity to one another. Big Hill demonstrates the greatest case for an effect due to spatial correlation of floor rise rates but it is still unclear what is causing the rise or if it is merely coincidental.



(a) Median **(b)** Average **(c)** Standard Deviation

Figure 3.2.3: Big Hill Floor Rise Map

3.2.4 Anomalous Readings

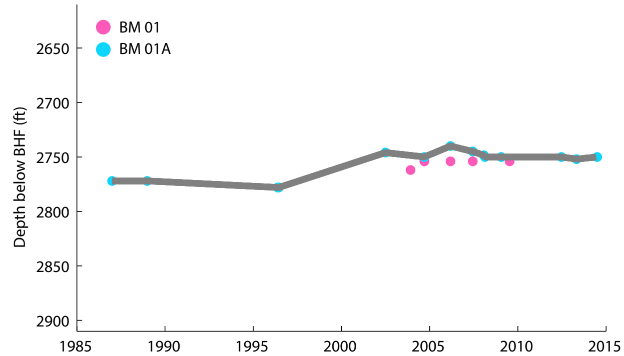
Big Hill 101, 105, 106, 108, 110, 112, and 113 all show erratic behavior during and after construction under each of their well labeled B. The B wells were consistently higher than the A wells. This difference occurred before the year 2000, after which, readings from both wells came to a consensus. This phenomenon could be caused by an engineering decision to refrain from measuring beyond the end of the hanging string. The B wells in Big Hill brine wells that house the hanging string. The engineers may have decided not to measure past the end of the string due to the possibility the measurement tool getting stuck.

3.3 Bryan Mound

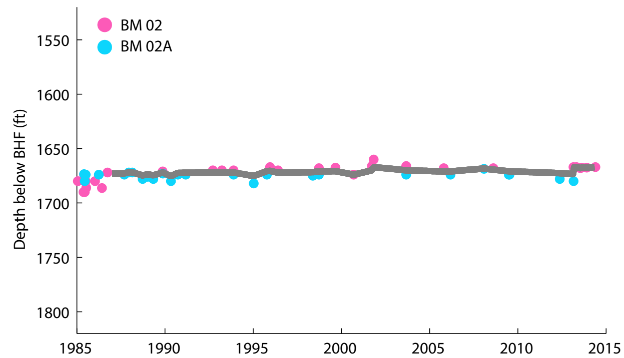
3.3.1 Cavern Measurements

The following section shows the cavern depths used to calculate the floor rise rates at Bryan Mound and discusses particular behaviors seen in each study. There are 20 caverns with information from various time periods. All of the caverns have at least two wells with some having having three. Readings from each well are represented by a circular marker colored to represent a certain well. Interpolations are represented by a gray line.

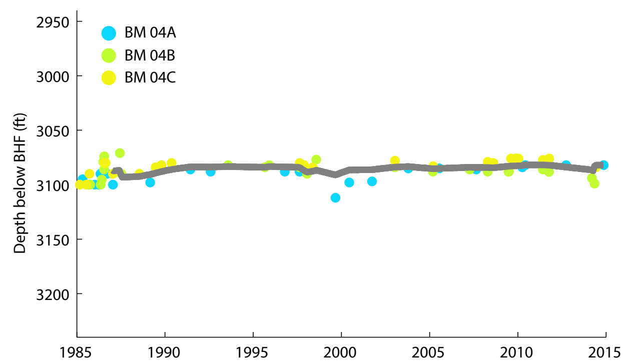
Bryan Mound 1 Measurements were taken from two different wells. Well B only has 5 points over a short amount of time and was not considered. Using the other 13 measurements from Well A, Bryan Mound shows a low overall floor rise (0.80 ft/yr).



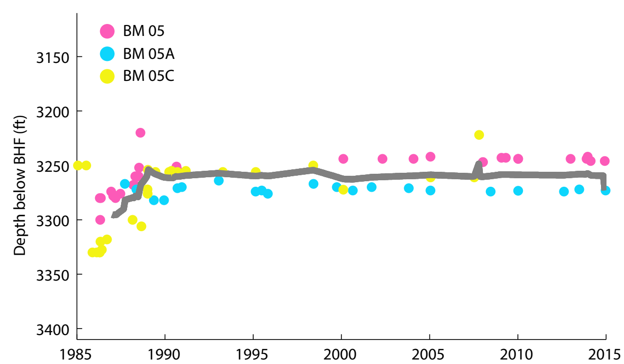
Bryan Mound 2 This cavern experienced very little floor rise (0.21 ft/yr) underneath both an unlabeled well and Well A.



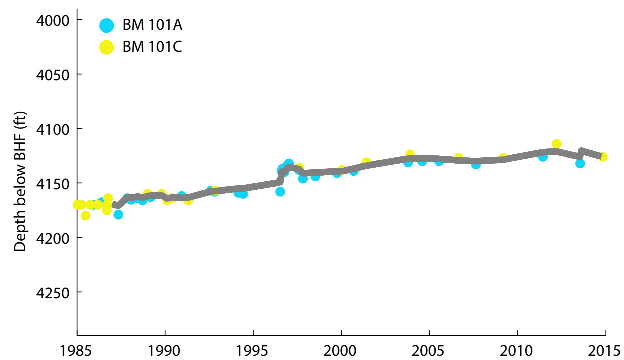
Bryan Mound 4 Measurements were taken from three wells: A, B, and C. All show little to no floor rise (-0.18 ft/yr).



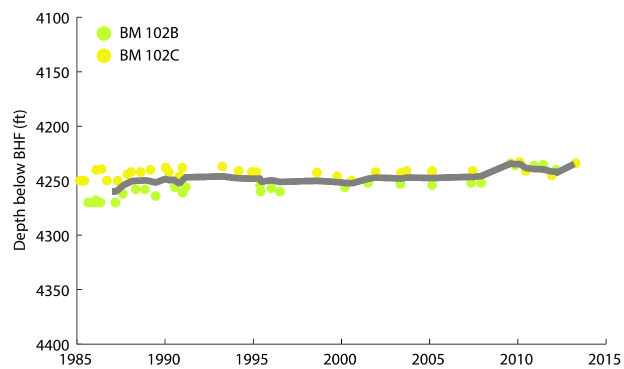
Bryan Mound 5 Measurements were taken from an unnamed well, Well A, and Well C. These measurements indicate a moderate floor rise rate within the cavern (1.05 ft/yr).



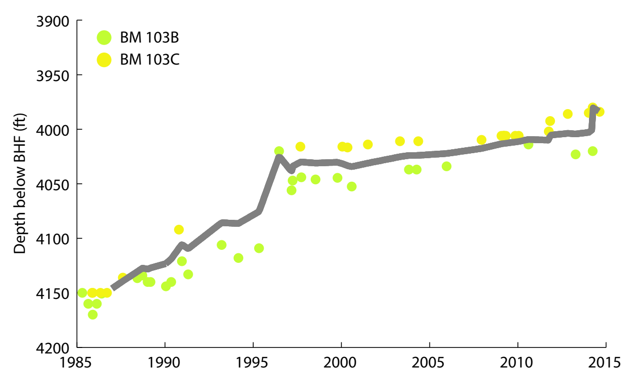
Bryan Mound 101 Wells A and C suggest Bryan Mound 101 has a moderate floor rise rate (1.59 ft/yr). There was a slight jump in floor rise after 1995 followed by leveling.



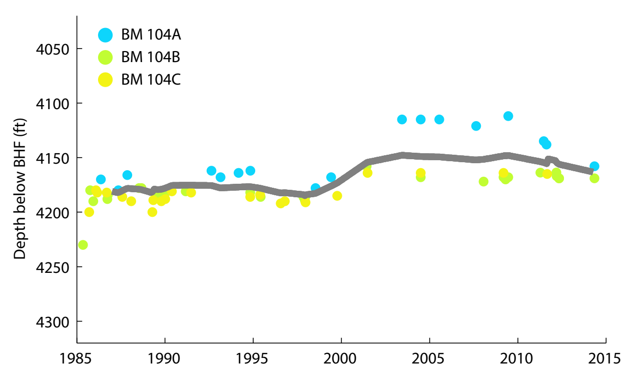
Bryan Mound 102 Measurements from Wells B and C suggest there is a low to moderate floor rise rate after construction (0.96 ft/yr).



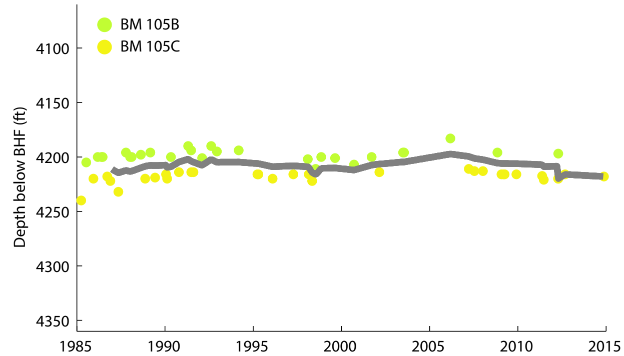
Bryan Mound 103 Measurements from both Well B and C show a jump in floor rise after 1995. This cavern has the third highest overall floor rise rate within Bryan Mound (5.90 ft/yr).



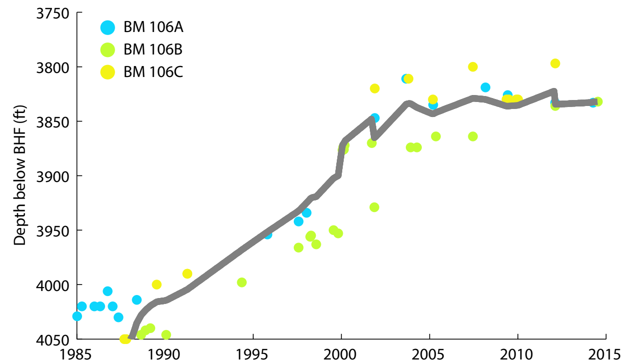
Bryan Mound 104 Overall, measurements from Wells A, B, and C indicate that there is very little overall floor rise (0.66 ft/yr). There was, however, an anomalous period seen under Well A where the floor rose and later receded. It is unclear if it due to measurement error or an actual event.



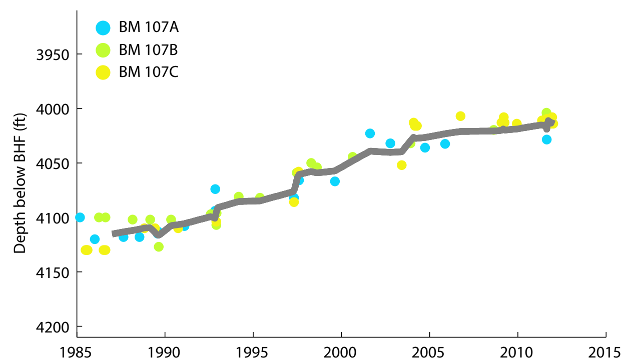
Bryan Mound 105 After the construction phase, both Wells B and C show no signs of uplift (-0.23 ft/yr).



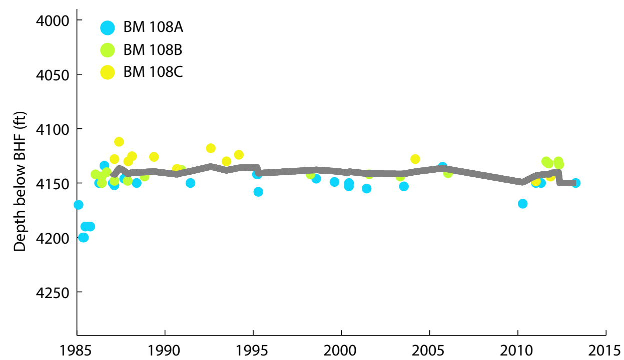
Bryan Mound 106 Measurements were taken from 3 wells: A, B, and C. All wells indicate a large amount of steady floor rise. BM 106 had the greatest average floor rise within Bryan Mound and had the second highest of all SPR caverns (8.38 ft/yr).



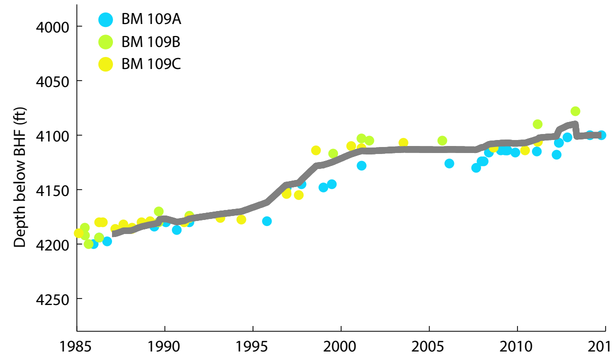
Bryan Mound 107 BM 107 also had a consistently large floor rise in all wells (4.15 ft/yr).



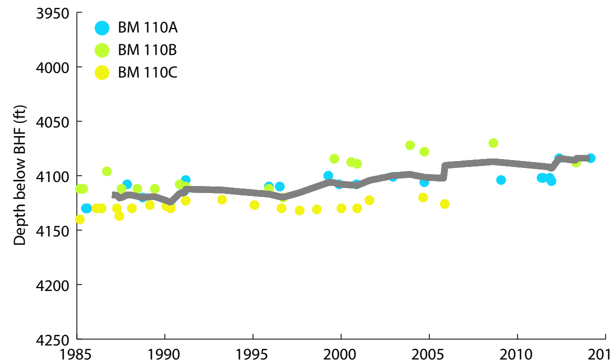
Bryan Mound 108 After the construction phase, there was little to no significant floor rise (-0.34 ft/yr). The floor under Well C showed a substantial jump during the construction phase but then returned to depths similar to those under the other wells.



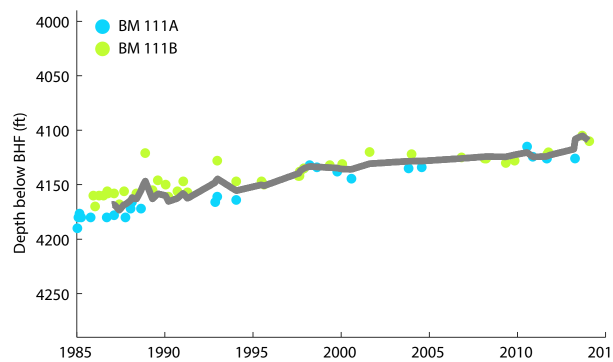
Bryan Mound 109 This cavern, overall, is experiencing a moderate cavern floor rise (3.27 ft/yr) as seen in Wells A, B, and C. It should be noted that there was a significant increase in floor rise rates between 1995 and 2005.



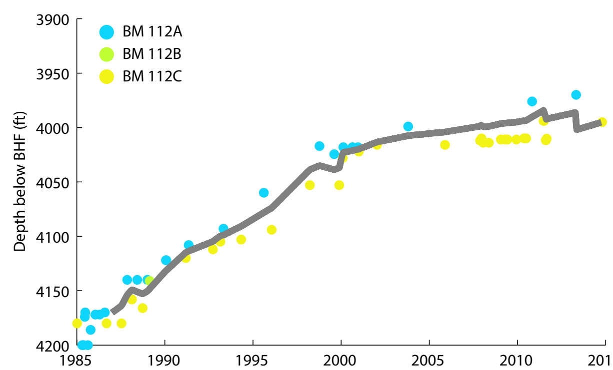
Bryan Mound 110 This cavern has a moderate floor rise after the construction period (1.24 ft/yr). The floor readings did diverge after 1995 with the floor under Well A staying relatively constant while the floor under Well B rose slightly. It should also be noted that measurements from Well C ceased in the mid 2000's.



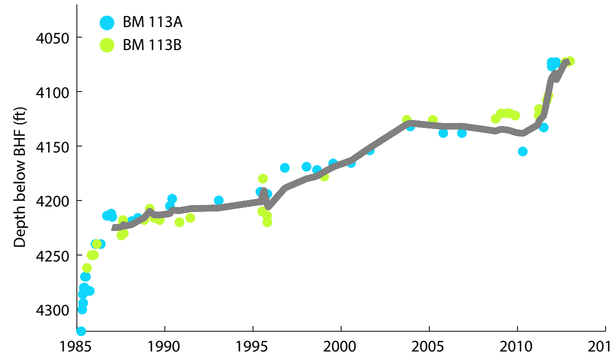
Bryan Mound 111 Measurements taken from both Wells A and B indicate a moderate floor rise (2.20 ft/yr). Shortly after construction, the measurements from Well B were somewhat erratic. This behavior is likely due to measurement error of salt fall and subsequent leveling.



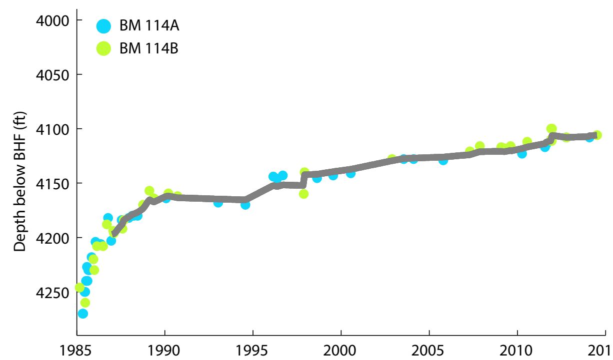
Bryan Mound 112 Bryan Mound 112 had measurements from Well A and C. After the construction phase there was a large amount of floor rise until the year 2000. After 2000, the floor rise rate wasn't as great but still increased at a semi constant rate. Overall, the rise rate was second highest within Bryan Mound (6.29 ft/yr).



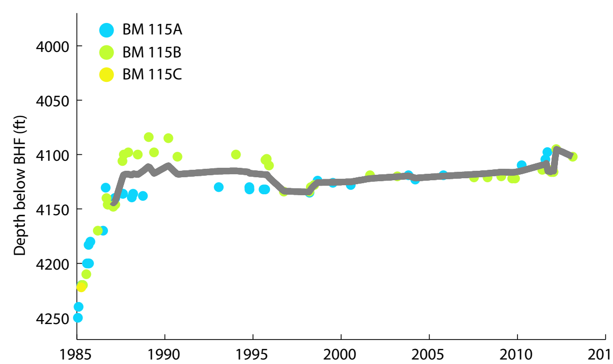
Bryan Mound 113 Due to a large uplift after 2010, cavern 113 had the fourth highest floor rise rate within Bryan Mound (5.88 ft/yr). The high uplift near the end of measurement was seen in both Wells A and B but since there are no further measurements the floor rise could not be confirmed.



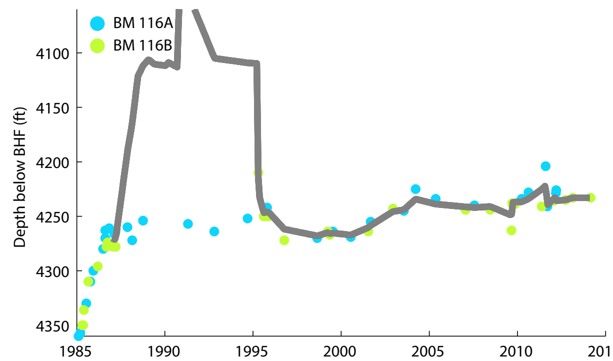
Bryan Mound 114 Both Wells A and B are very consistent and show a higher than normal floor rise after 1995. Overall the cavern experienced a moderate rise rate (3.31 ft/yr).



Bryan Mound 115 Based on measurements from Wells A and B the cavern is experiencing a moderate floor rise rate (1.63 ft/yr). There were also two measurements from Well C but were not included in the analysis as there were less than ten. There were also anomalous readings after the construction phase in which the floor under Well B was higher than in Well A. After 2000, the floor under Well B goes back to a depth similar to the floor under Well A. This set of measurements are similar to anomalous behavior seen in several of the Big Hill Caverns and could be due to an obstruction in the hanging string.



Bryan Mound 116 Overall, BM 116 experienced a moderate floor rise (1.39 ft/yr) but it is clear there is a period of anomalous measurements seen in Well B between 1987 and 1995. During this period, the floor under Well B seems to jump up approximately 300 ft and then just as suddenly drop 300 ft. It is likely this set of measurements is not reflective of actual cavern floor depth but were included in the analysis as there is no data to contradict these results. This event is likely due to an obstruction in the hanging string that prevented the survey to touch the cavern floor. There is also the curious set of measurements from Well B beyond 1995 that suggest a gradual return to a depth similar to the floor under Well A.



3.3.2 Overall Statistics

Bryan Mound experienced some of the highest and most variable floor rise rates. The caverns also experienced some anomalies throughout the lifetime of DOE ownership of the Bryan Mound site. In particular, Cavern 106 in the Southeast corner showed a very high floor rise rate during the 2000's and again in the 2010's. Out of all the SPR sites, this cavern has experienced the 2nd greatest amount of rise since it's commission (Figure 3.3.2).

The caverns with the next highest average floor rise rate are caverns 112 and 113. These caverns are also located in the southeast corner of the site. It should be mentioned, however, that the majority of the floor rise seen in cavern 113 was during a sharp spike after 2010 (Figure 3.3.1). This jump in floor elevation occurred around the time of a major leach in the summer of 2012 [8]. It should also be mentioned that leaching was stopped before completion due to odd behavior from a broken string.

The next highest floor rise occurred in cavern 103 (Figure 3.3.2). 103 is located on the eastern edge of the site. Both caverns 112 and 103 showed increased floor rise rates between 1990 and 2000. These rates subsequently declined after 2000. The current rates are typical of the rest of the site.

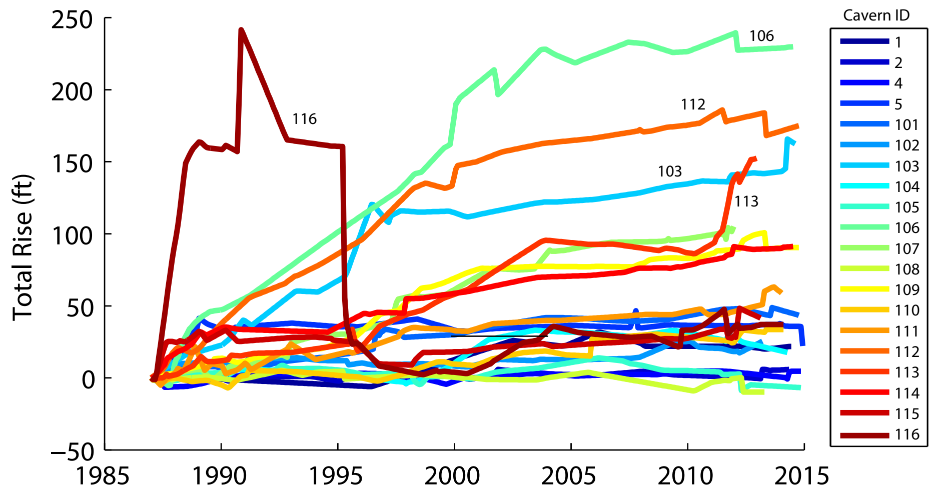
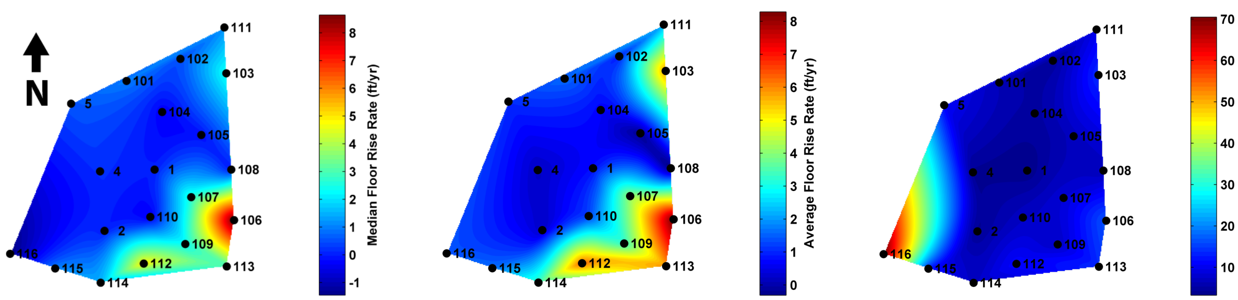


Figure 3.3.1: The total floor rise for Bryan Mound since 1987

3.3.3 Spatial Trends

Looking at the spatial distribution of floor rise throughout the site it could be inferred that there is some spatial correlation (Figure 3.3.3). The greatest amount of cavern floor rise is located in the southeast portion of the Bryan Mound site. Cavern 103 also exhibits a greater amount of uplift but is in the northeastern portion of the site. It is unclear if this correlation is coincidental or due to a phenomenon within the salt dome.



(a) Median **(b)** Average **(c)** Standard Deviation

Figure 3.3.3: Bryan Mound Floor Rise Map

3.3.4 Anomalous Readings

Some of the caverns also showed a jump in floor depth before returning to its original rise trajectory. This phenomenon is similar to that seen at the Big Hill site. Possible explanations are detailed in Section 3.2.4.

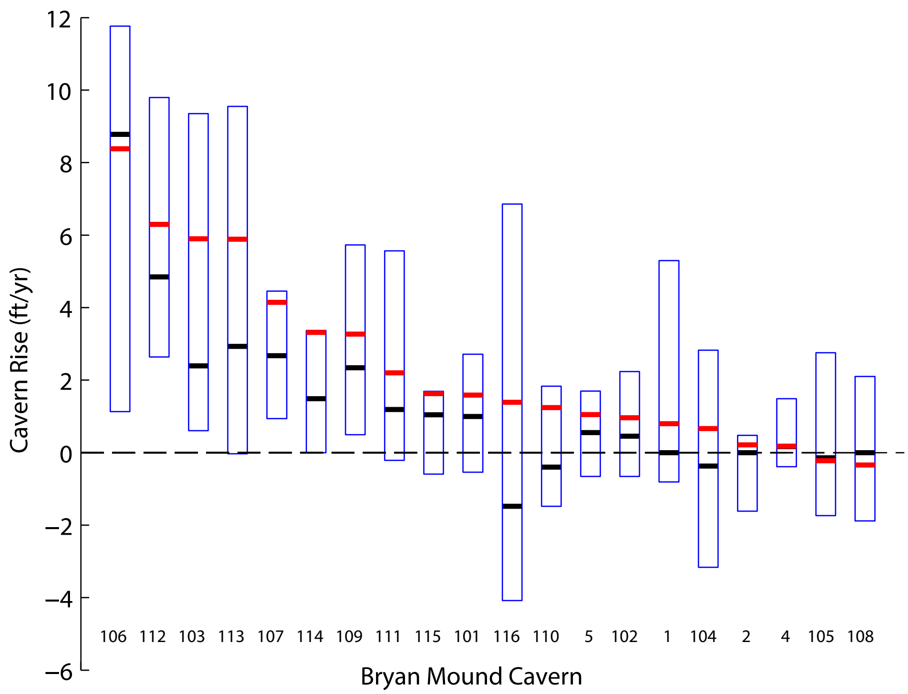


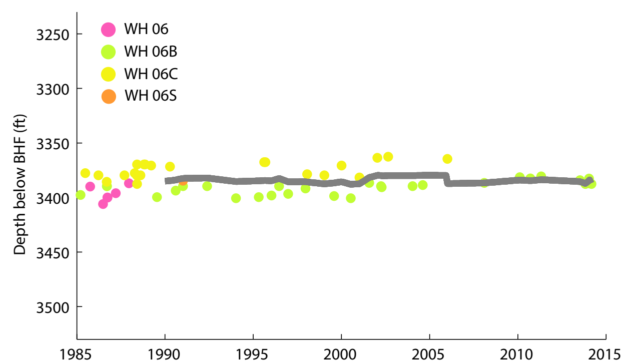
Figure 3.3.2: The rise rates at Bryan Mound ordered based on average rise (red line). The 25th and 75th percentiles are represented by the lower and upper boundaries of the blue rectangle while the median is represented by the black line.

3.4 West Hackberry

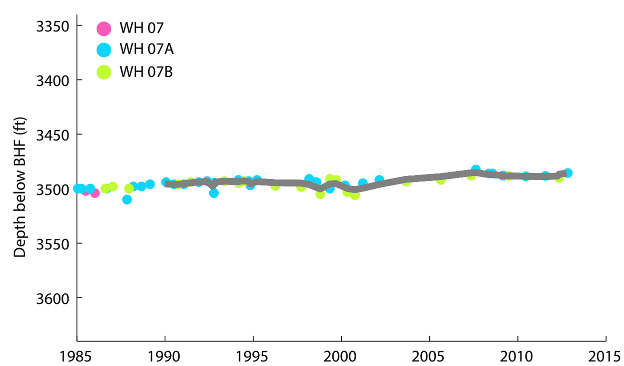
3.4.1 Cavern Measurements

The following section shows the cavern depths used to calculate the floor rise rates at West Hackberry and discusses particular behaviors seen in each study. Fifteen of the West Hackberry caverns created by DOE are single cavern wells. The exception to these single well caverns are WH 106 and 117. All of the Phase 1 acquired caverns also have multiple wells. Readings from each well are represented by a circular marker colored to represent a certain well. Interpolations are represented by a gray line.

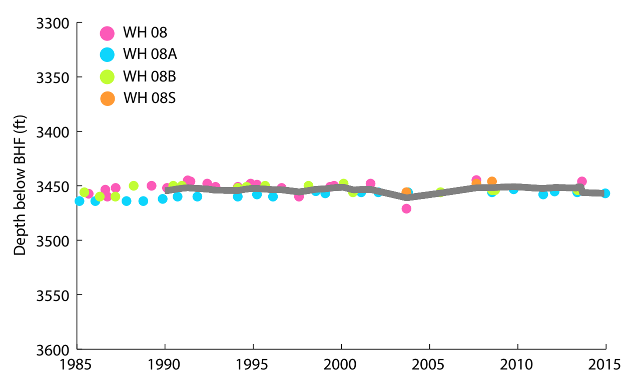
West Hackberry 6 Results were taken from four different wells: an unlabeled well, B, C, and one measurement from an S well. The single measurement from well S was disregarded during analysis. The cavern floor is relatively stable and shows no real trends.



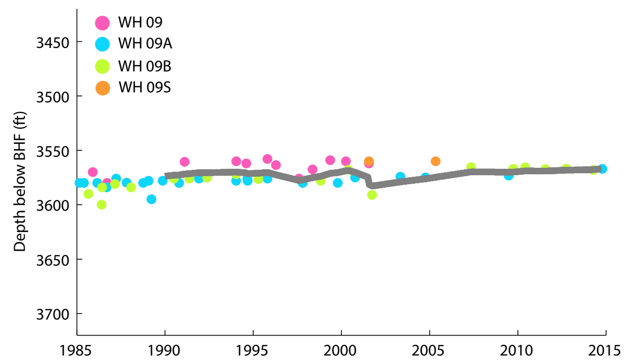
West Hackberry 7 Floor measurements were taken under Wells A and B. There were also several measurements in the early history of WH 7 from an unlabeled well that were not included in the analysis. Overall, this cavern is experiencing a slight overall floor rise (0.43 ft/yr).



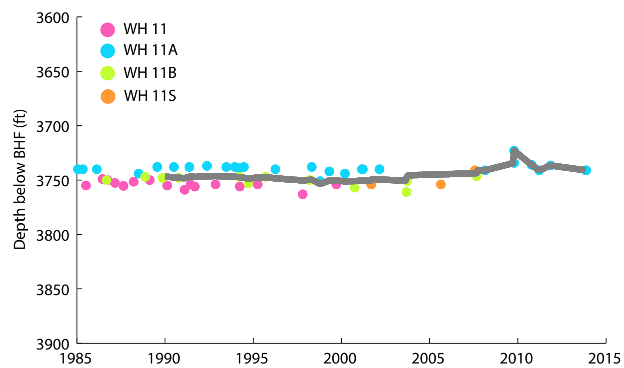
West Hackberry 8 Measurements from WH 8 were taken from 4 wells (A, B, S, and an unlabeled well). Most of the floor depths are relatively constant. It should also be noted that there were only three measurements from the Well S and were not included in the statistical analysis.



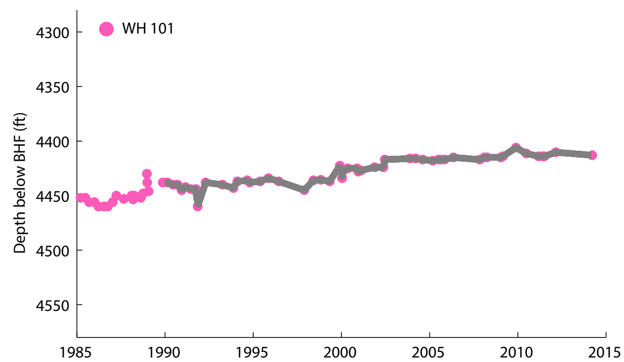
West Hackberry 9 Floor depth measurements at WH 9 were taken from an unlabeled well, Well A, and Well B. There are also two additional measurements from Well S. Overall, the cavern floor is experiencing little rise (0.27 ft/yr).



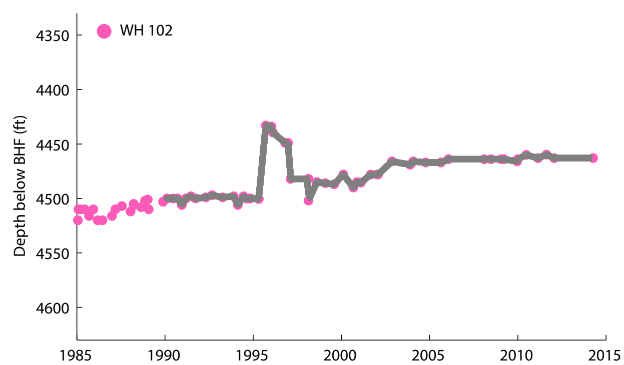
West Hackberry 11 Measurements taken from four wells (A, B, S, and an unlabeled well) indicate little floor rise in WH 11 (0.25 ft/yr). Well S had insufficient readings and was left out of the analysis.



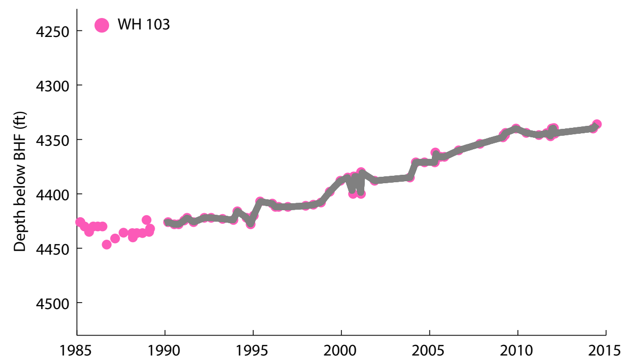
West Hackberry 101 Floor depth measurements were from a single well that suggest the floor of West Hackberry is rising a low to moderate rate (1.04 ft/yr). There was also a slight rise rate increase around the year 2000.



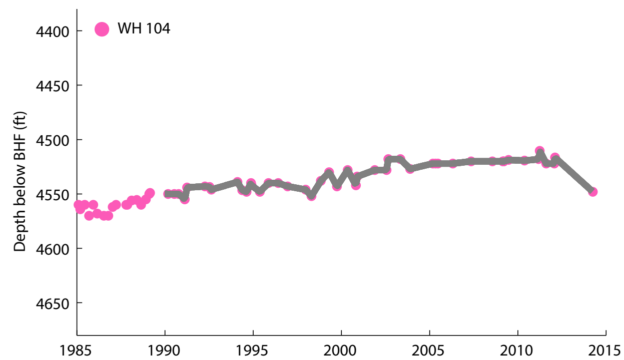
West Hackberry 102 Measurements for this well were taken from a single well and suggest the cavern floor is rising at a moderate, but constant, rate (1.57 ft/yr). There was a floor depth jump after 1995 but then went back to previous levels. It has not been determined if this jump was an actual event or measurement error.



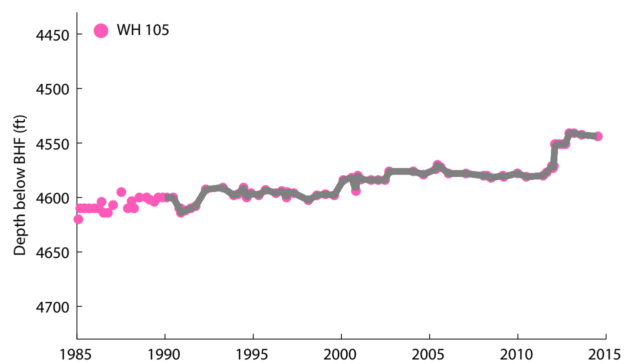
West Hackberry 103 The measurements from a single well indicate the cavern floor is rising at greater rate than most other caverns at West Hackberry (3.68 ft/yr). While this cavern has a larger rise rate, it is constant and has not experienced large jumps.



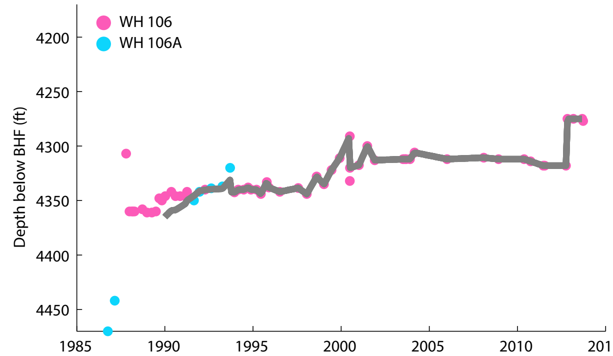
West Hackberry 104 Statistically, the cavern is experiencing little floor rise (0.12 ft/yr) but the floor depth measurements are slightly noisier than others at this site. Additionally, there is a measurement at the end of the historical data that suggests the floor depth became dramatically deeper in a short amount of time. It is unclear if this is a true measurement or measurement error as there were no measurements to confirm the last point. If this point is measurement error then the overall floor rise rate may be higher than reported.



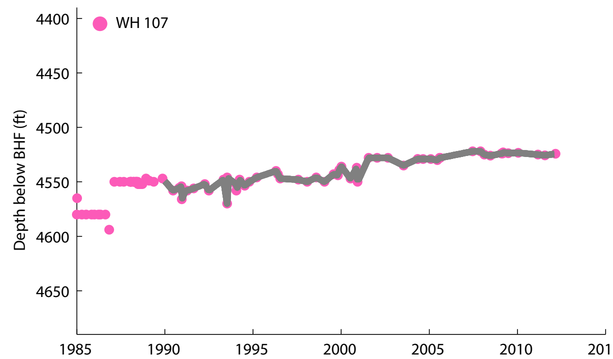
West Hackberry 105 Measurements from a single well suggest the cavern has a moderate floor rise rate (2.30 ft/yr). This cavern experienced two jumps in floor rise. The first event was around the year 2000. The second, and larger, event occurred after 2010.



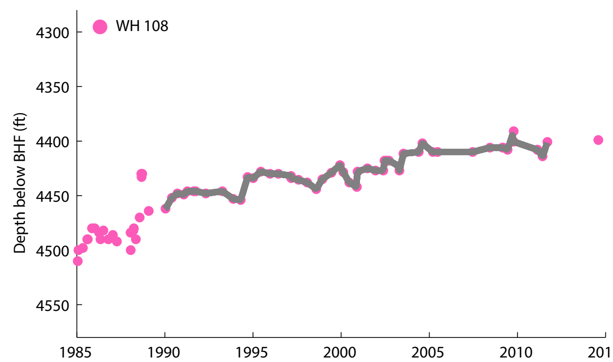
West Hackberry 106 Measurements were taken from two wells, the main well and a secondary well named Well A. Well A was only taking measurements during construction and a period shortly after. There was a small jump in floor rise near the end of the historical measurements. Overall, the cavern experienced a moderate rise rate (3.79 ft/yr)



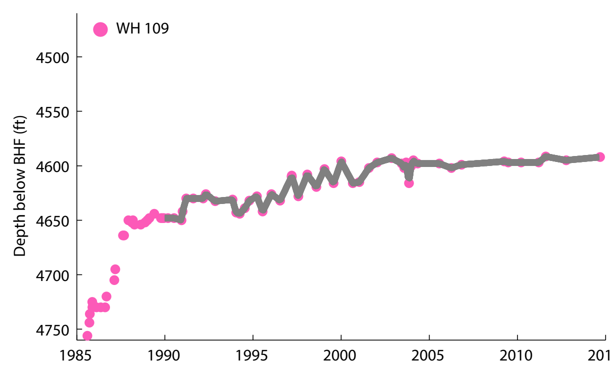
West Hackberry 107 Readings from a single well indicate there is a moderate floor rise rate in this cavern (1.17 ft/yr).



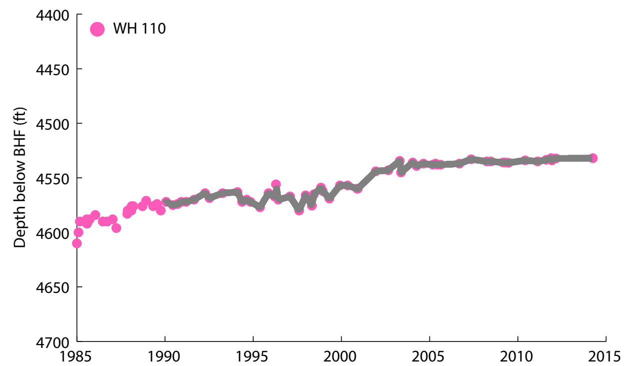
West Hackberry 108 WH 108 has a constant floor rise rate that is higher than most of the other caverns at West Hackberry (2.67 ft/yr).



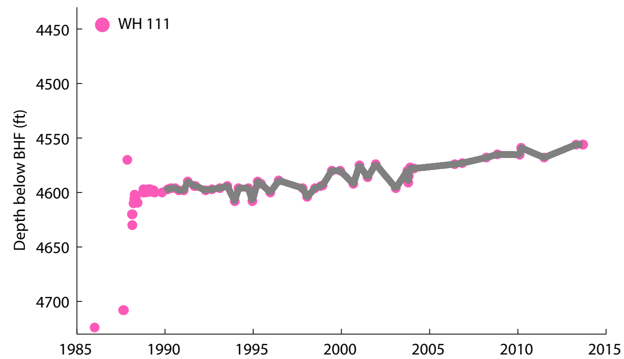
West Hackberry 109 The floor measurements from a single well show there is a moderate rise rate (2.27 ft/yr). There is also a period before 2000 that demonstrates a bimodal behavior in floor depths. It is unclear what caused this phenomenon.



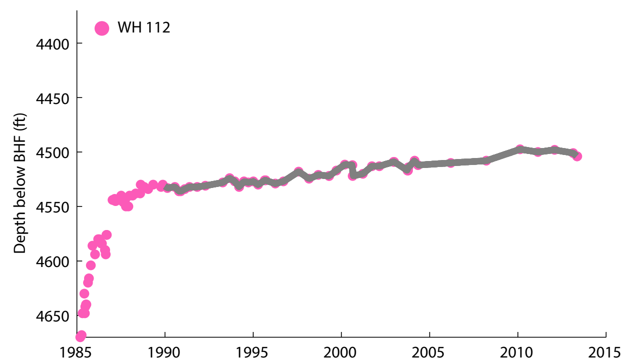
West Hackberry 110 This cavern has a moderate floor rise rate (1.69 ft/yr). There is a period between 1995 and 2005 where the measurements become noisier and looks like as if the cavern actually becomes deeper. After this time, the cavern returns to its previous rise trajectory.



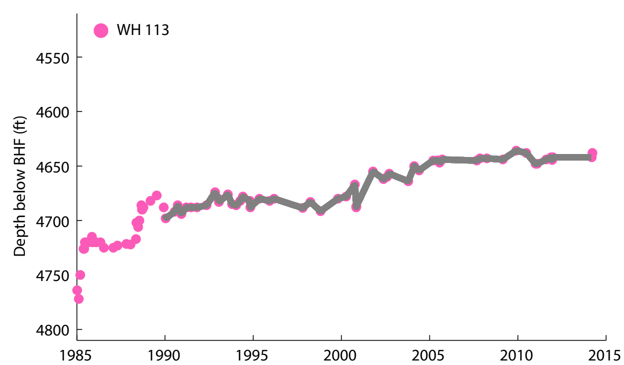
West Hackberry 111 According to measurements from a single well, WH 111 is experiencing a moderate over all floor rise (1.78 ft/yr). There is also an anomalous period during the construction phase where the settling of insolubles ceases for two years.



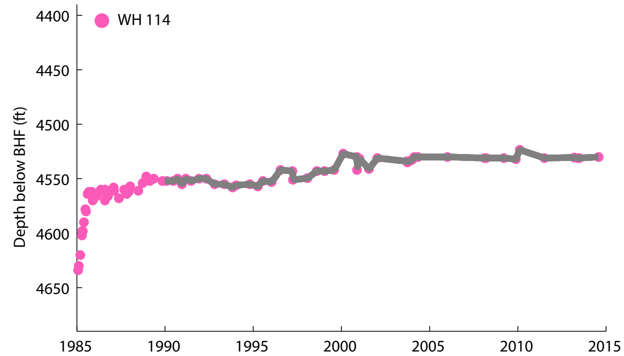
West Hackberry 112 This cavern floor is experiencing a moderate (1.24 ft/yr), but constant rise.



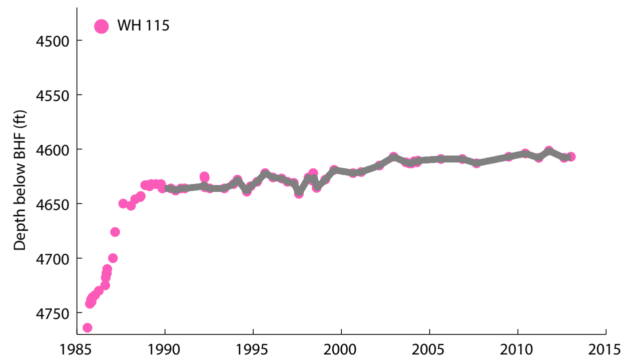
West Hackberry 113 Measurements from a single well show this cavern has been experiencing a moderate rise rate overall (2.24 ft/yr) with several anomalous periods. There was an increased floor rise rate from 2000-2005. There was also another period of abnormal floor rise after the construction phase.



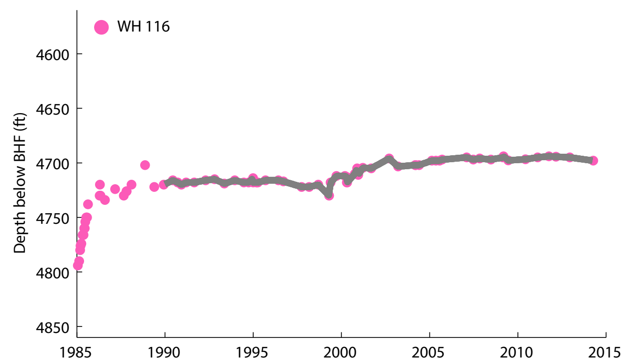
West Hackberry 114 Measurements from a single well show that WH 114 is experiencing a small and constant floor rise (0.90 ft/yr).



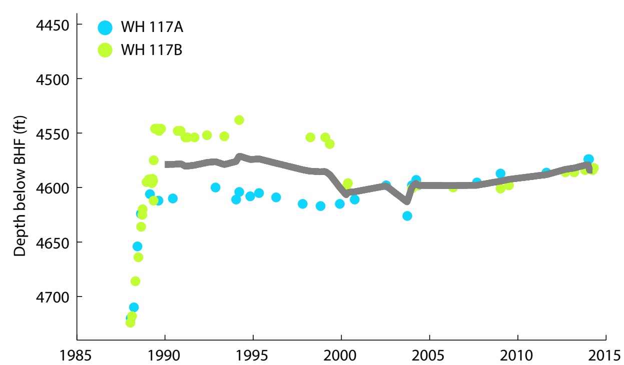
West Hackberry 115 This cavern has a moderate, but constant floor rise (1.26 ft/yr).



West Hackberry 116 This well had a smaller rise rate overall (0.88 ft/yr) but there was an increase in rate from 2000-2005. After 2005, the floor rise rate lessened and became steady.



West Hackberry 117 Measurements were taken from both Well A and B. Overall, the cavern seemed to become deeper with time (-0.22 ft/yr). This is likely due to the floor under Well B being shallower after the construction period. This behavior is seen in some of the Big Hill caverns.



3.4.2 Overall Statistics

The floor rise rates at West Hackberry were both consistent and modest (Figure 3.4.1). Caverns 106, 103, and 108 had the highest average floor rises. Caverns 106 and 103 had rise rates approaching 4 ft/yr while 108 had an average floor rise approaching 3 ft/yr (Figure **??**).

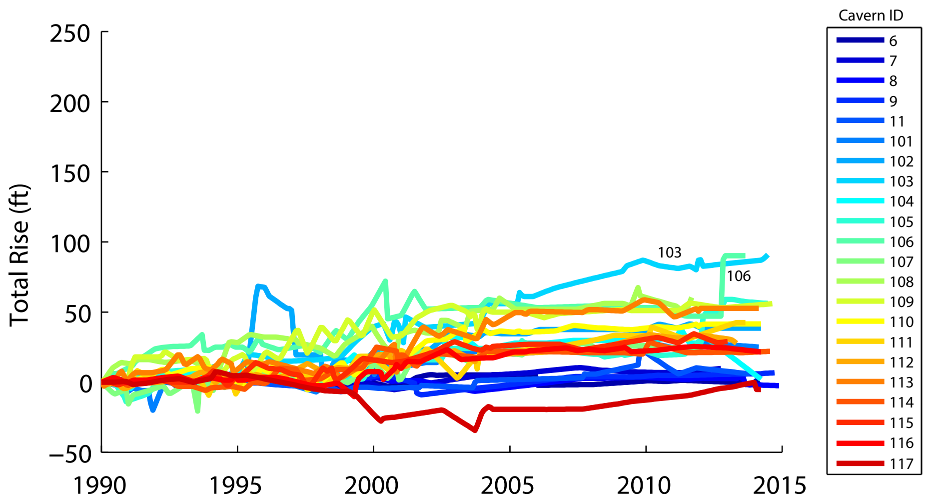


Figure 3.4.1: The total floor rise for West Hackberry since 1990

3.4.3 Spatial Trends

The higher rise rates are seen throughout the site which suggests there is little to no spatial correlation (Figure 3.4.3). It should also be noted, while there are areas of higher rise rate, they are still small compared to the other sites.

3.4.4 Anomalous Readings

Many of the older caverns showed very consistent floor depths. Since most of the West Hackberry caverns created by DOE were single well caverns, there was little to compare against within each cavern. There are also recent floor jumps in WH 105 and 106. This is likely due to leaching in the caverns [8].

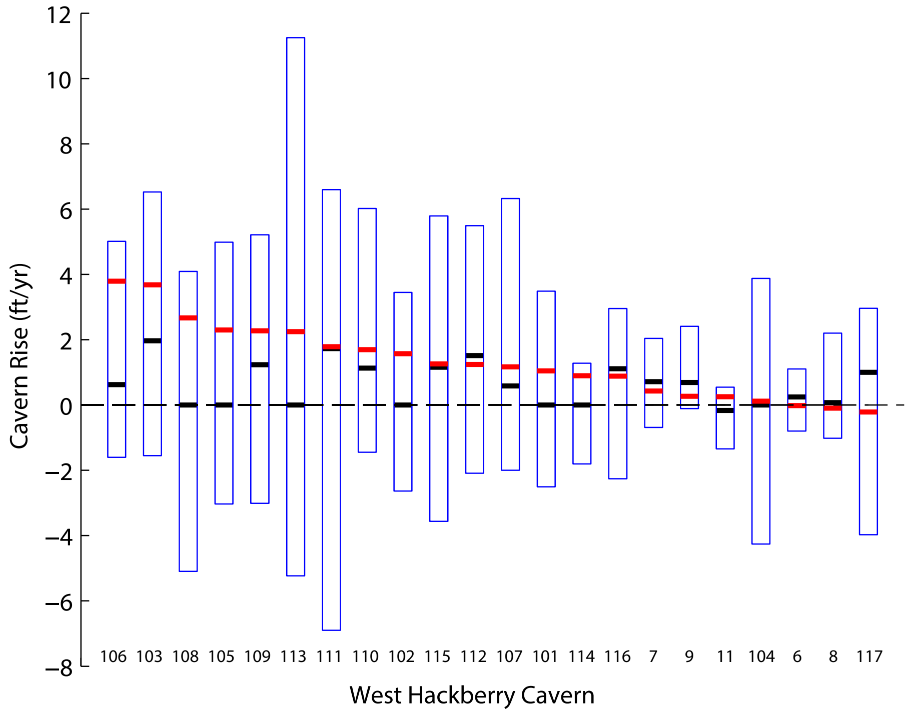
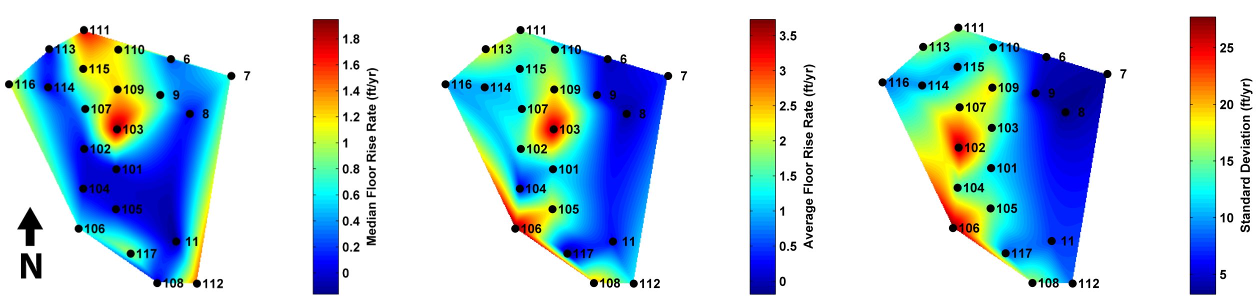


Figure 3.4.2: The rise rates at West Hackberry ordered based on average rise (red line). The 25th and 75th percentiles are represented by the lower and upper boundaries of the blue rectangle while the median is represented by the black line.



(a) Median **(b)** Average **(c)** Standard Deviation

Figure 3.4.3: West Hackberry Floor Rise Map

Chapter 4

Summary and Conclusions

This report provides a comprehensive overview of cavern floor depth data. From this data, average floor rise rates were calculated. The results indicate that Big Hill and Bryan Mound experienced the greatest average floor rise rates while Bayou Choctaw and West Hackberry experienced relatively small rise rates. This could be due to factors such as dome composition, cavern history, and site configuration. Floor rise rates were typically between 0.5 ft/yr and 3.5 ft/yr but there are several caverns that exhibited much higher rise rates. These higher rates were often due to one or two anomalous events that were thought to be salt falls. Because of these events, there are some apparent average floor rise rates near 10 ft/yr. While this, in itself is a large rise rate, the majority of the rise took place over a relatively short timeframe and in some cases was followed by a slow leveling period. In the case of Big Hill 103, the cavern floor appeared to rise 150 ft in a period of three years. This type of event, if real, is t enough to damage the hanging string near the bottom of the cavern. Another more likely scenario is that salt fall damaged the hanging string and subsequent logging could not get past the damage point. Thus the hanging sting depth were reported instead of floor depths and leveling could be due to hanging string remediation. More analysis to follow will try to clarify the issue. There are also SPR sites that exhibit some sort of spatial correlation. This spatial relationship is especially prevalent at the sites with greater amounts of floor rise (Big Hill and Bryan Mound). There is no clear explanation for this correlation and it will be a topic for investigation in future research. While the results presented in this report document the historical floor rise, there are still questions as to the cause of the anomalous floor rise events. The collection of historical floor rise data is provided in Table 4.0.1. SPR sites and caverns that have a history of large floor rise should be kept under closer watch, primarily BH 103, BH 105, BM 106, BM 112, BM 103, BM 113, & BM 107.

Bayou Choctaw		Big Hill		Bryan Mound		West Hackberry	
Cavern	Rise Rate [ft/yr]	Cavern	Rise Rate [ft/yr]	Cavern	Rise Rate [ft/yr]	Cavern	Rise Rate [ft/yr]
BC102	2.99	BH103	9.72	BM106	8.38	WH106	3.79
BC17	2.31	BH105	7.40	BM112	6.29	WH103	3.68
BC20	1.45	BH104	2.20	BM103	5.90	WH108	2.67
BC101	1.36	BH101	2.15	BM113	5.88	WH105	2.30
BC19	0.72	BH109	1.45	BM107	4.15	WH109	2.27
BC15	-0.48	BH114	1.20	BM114	3.31	WH113	2.24
BC18	-0.92	BH107	1.06	BM109	3.27	WH111	1.78
		BH110	0.97	BM111	2.20	WH110	1.69
		BH102	0.93	BM115	1.63	WH102	1.57
		BH112	0.30	BM101	1.59	WH115	1.26
		BH113	0.17	BM116	1.39	WH112	1.24
		BH106	-0.24	BM110	1.24	WH107	1.17
		BH111	-0.24	BM05	1.05	WH101	1.04
		BH108	-0.92	BM102	0.96	WH114	0.90
				BM01	0.80	WH116	0.88
				BM104	0.66	WH07	0.43
				BM02	0.21	WH09	0.27
				BM04	0.18	WH11	0.25
				BM105	-0.23	WH104	0.12
				BM108	-0.34	WH06	-0.02
						WH08	-0.10
						WH117	-0.22

Table 4.0.1: Average cavern floor rise rates seen at each site sorted highest to lowest

4.1 Further Research

There are several comparative analyses that can be done to help determine the reasons behind anomalous cavern floor rise. First, the historical floor rise rates should be compared with cavern pressure histories. Conversations with various SPR staff indicate there may be a relationship between cavern depressurization and an increase in floor rise rates [7]. Second, the floor rise results should be compared with modeled creep rates for each cavern. This would help identify caverns that have experienced unexpected events. Conversely, historical rise rates could also be used to help calibrate and validate current cavern geomechanical models. Additionally, some of the more recent floor rise jumps should be investigated. Its possible the jumps were simply due to measurement error as there were no subsequent readings to prove otherwise, or logging depth is recorded for damaged hanging strings. A better understanding of floor rise mechanisms would facilitate the optimization of hanging string depths and help prevent future in-cavern infrastructure damage.

Appendix A

Overall Cavern Statistics

The tables presented in this appendix presented the floor rise statistics for each SPR site and cavern.

A.1 Bayou Choctaw

Cavern	Measurements	Average [ft/yr]	Std. Dev. [ft/yr]	Percentile [ft/yr]		
				25th	50th	75th
15	89	-0.48	5.72	-2.16	-0.49	1.64
17	63	**2.31**	6.13	-0.54	2.04	6.35
18	124	-0.92	9.41	-3.78	-0.73	1.33
19	93	0.72	3.79	-1.00	0.00	3.33
20	115	**1.45**	23.08	-5.59	-0.43	5.07
101	127	1.36	7.20	-1.60	1.09	4.57
102	17	**2.99**	1.62	3.24	3.24	3.24

Table A.1.1: Bayou Choctaw cavern statistics from the interpolated values

A.2 Big Hill

Cavern	Measurements	Average [ft/yr]	Std. Dev. [ft/yr]	Percentile [ft/yr] 25th	50th	75th
101	124	2.15	11.03	-1.24	0.69	2.89
102	127	0.93	7.37	-1.71	-0.59	2.84
103	129	**9.72**	30.89	-5.63	3.23	11.75
104	121	**2.20**	9.66	2.66	3.04	6.05
105	113	**7.40**	23.22	0.39	3.87	10.12
106	111	-0.24	5.12	-4.06	0.01	2.28
107	66	1.06	3.89	0.44	1.20	2.59
108	109	-0.92	6.33	-3.39	-0.23	3.56
109	118	1.45	7.75	-1.47	1.70	3.79
110	81	0.97	8.22	-0.34	1.93	3.65
111	119	-0.24	8.32	-3.03	0.32	2.57
112	120	0.30	18.49	-7.67	2.29	5.42
113	115	0.17	7.34	-2.25	-0.19	5.73
114	115	1.20	8.73	-0.44	1.44	3.69

Table A.2.1: Big Hill cavern statistics from the interpolated values

A.3 Bryan Mound

Cavern	Measurements	Average [ft/yr]	Std. Dev. [ft/yr]	Percentile [ft/yr] 25th	50th	75th
1	13	0.80	3.23	-0.81	0.00	5.29
2	95	0.21	4.04	-1.62	-0.01	0.48
4	109	-0.18	4.00	-0.39	0.17	1.49
5	104	1.05	10.98	-0.66	0.55	1.69
101	87	1.59	6.25	-0.54	1.00	2.72
102	98	0.96	4.31	-0.66	0.45	2.23
103	90	**5.90**	13.95	0.60	2.39	9.35
104	111	0.66	4.95	-3.17	-0.37	2.83
105	95	-0.23	6.88	-1.74	-0.14	2.76
106	89	**8.38**	16.79	-1.13	8.78	11.76
107	93	4.15	8.58	0.94	2.67	4.45
108	106	-0.34	6.48	-1.88	0.00	2.10
109	120	3.27	7.47	0.49	2.34	5.73
110	88	1.24	7.29	-1.48	-0.40	1.83
111	112	2.20	9.96	-0.22	1.19	5.56
112	92	**6.29**	11.52	2.64	4.84	9.79
113	98	**5.88**	13.80	-0.03	2.93	9.55
114	84	3.31	6.94	0.00	1.48	3.37
115	110	1.63	12.45	-0.60	1.04	1.69
116	97	1.39	71.25	-4.08	-1.48	6.86

Table A.3.1: Bryan Mound cavern statistics from the interpolated values

A.4 West Hackberry

Cavern	Measurements	Average [ft/yr]	Std. Dev. [ft/yr]	Percentile [ft/yr] 25th	50th	75th
6	135	-0.02	4.62	-0.80	0.25	1.10
7	101	0.43	3.75	-0.69	0.71	2.04
8	109	-0.10	3.23	-1.02	0.07	2.20
9	102	0.27	4.47	-0.11	0.69	2.41
11	106	0.25	7.36	-1.34	-0.17	0.55
101	103	1.04	11.61	-2.50	0.00	3.49
102	113	1.57	27.29	-2.64	0.00	3.44
103	116	**3.68**	15.84	-1.55	1.97	6.53
104	102	0.12	13.59	-4.26	0.00	3.87
105	124	2.30	15.60	-3.03	0.00	4.98
106	134	**3.79**	28.00	-1.60	0.62	5.01
107	130	1.17	17.86	-2.00	0.58	6.32
108	123	**2.67**	16.56	-5.10	0.00	4.09
109	117	2.27	19.22	-3.01	1.24	5.21
110	119	1.69	12.76	-1.45	1.13	6.02
111	109	1.78	16.08	-6.90	1.73	6.60
112	126	1.24	8.48	-2.09	1.52	5.49
113	117	2.24	15.98	-5.23	0.00	11.25
114	113	0.90	9.74	-1.80	0.00	1.28
115	106	1.26	9.73	-3.56	1.16	5.79
116	110	0.88	8.72	-2.26	1.11	2.96
117	115	-0.22	8.25	-3.97	1.00	2.96

Table A.4.1: West Hackberry cavern statistics from the interpolated values

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[1] Various SPR Sonar Surveys, 1980-2009. Maintained by Sandia National Laboratories.

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[4] Strategic petroleum reserve. `http://energy.gov/fe/services/petroleum-reserves/strategic-petroleum-reserve`, 2015. Accessed: 2015-07-06.

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[6] Munson D., Bauer S., Rautmann C., Ehgartner B., and Sattler A. Analysis of the Massive Salt Fall in Big Hill Cavern 103. Technical Report SAND2003-0703, Sandia National Laboratories, March 2003.

[7] Lisa Eldredge. Personal communication, May 2015. Fluor Federal Petroleum Operations.

[8] David Rudeen. Personal communication, November 2015.

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