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Strategic Petroleum Reserve Cavern Leaching Monitoring CY20

Todd R. Zeitler, Raquel Valdez, David Hart

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

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ABSTRACT

The U.S. Strategic Petroleum Reserve is a crude oil storage system run by the U.S. Department of Energy. The reserve consists of 60 active storage caverns spread across four sites in Louisiana and Texas, near the Gulf of Mexico. Beginning in 2016, the SPR began executing U.S. congressionally mandated oil sales. The configuration of the reserve, with a total capacity of greater than 700 MMB, requires raw water to be used instead of saturated brine for oil withdrawals such as for sales. All sales will produce leaching within the caverns used for oil delivery.

Twenty-five caverns had a combined total of over 39 MMB of water injected in CY20 as part of the Exchange for Storage program; oil was withdrawn in the same manner as for congressionally mandated sales. Leaching effects were monitored in these caverns to understand how the oil withdrawals may impact the long-term integrity of the caverns. While frequent sonars are the best way to monitor changes in cavern shape, they can be resource intensive for the number of caverns involved in sales and exchanges. An intermediate option is to model the leaching effects and see if any concerning features develop.

The leaching effects were modeled here using the Sandia Solution Mining Code (SANSMIC). The results indicate that leaching induced features are not of concern in the majority of the caverns, 19 of 25. Six caverns, BH-107, BH-113, BH-114, BM-4, BM-106, and WH-114 have features that may grow with additional leaching and should be monitored as leaching continues in those caverns.

Ten caverns had post sale sonars that were compared with SANSMIC results. SANSMIC was able to capture the leaching well, particularly the formation of shelves and flares. A deviation in the SANSMIC and sonar cavern shapes was observed near the cavern floor in caverns with significant floor rise, a process not captured by SANSMIC. These results suggest SANSMIC is a useful tool for monitoring changes in cavern shape due to leaching effects related to sales and exchanges.

ACKNOWLEDGEMENTS

This work was funded by the U.S. Department of Energy, Office of Fossil Energy, Strategic Petroleum Reserve Program. The technical reviewer was David Lord, Sandia National Laboratories.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
bbl	barrel (of oil); 1 bbl = 42 gal (US) ≅ 0.158987 m^3
BH	Big Hill site
BM	Bryan Mound site
CAVEMAN	cavern management software; tracks fluid movements and cavern pressures
CY	calendar year
EOT	depth of end of brine string tubing
EP	period of equilibration during which leaching occurs
MB	thousand barrels
MMB	million barrels
Max Mod OBI_i	Maximum Modified Initial Oil Brine Interface; the deepest initial OBI in all leaching phases auto selected by the SANSMIC code
Min OBI_f	Minimum Final Oil Brine Interface; the shallowest final OBI in all leaching phases
Mod EOT	Modified End of Tubing; End of Tubing auto selected by the SANSMIC code
OBI	oil-brine interface
SANSMIC	Sandia solution mining code
SPR	Strategic Petroleum Reserve
WH	West Hackberry site

1. INTRODUCTION TO CAVERN LEACHING MONITORING

The U.S. Strategic Petroleum Reserve (SPR) is a crude oil storage system run by the U.S. Department of Energy (DOE). The reserve consists of 60 active storage caverns spread across four sites near the Gulf of Mexico. The Big Hill (BH) and Bryan Mound (BM) sites are located in Texas, and the Bayou Choctaw (BC) and West Hackberry (WH) sites are located in Louisiana. The fall 2020 storage capacity of the SPR is 714 million barrels (MMB).

The purpose of the SPR, as it was designed, is to handle emergency supply disruption of crude oil within the U.S. and in fulfilling International Energy Agency treaty obligations. Because of the large size of the reserve, brine drive has never been a part of the SPR; instead, oil is withdrawn – or drawn down – using raw water. Raw water is water that is fresh to saline in its salt content and is highly undersaturated when compared to (fully saturated) brine.

With respect to the SPR, when a cavern is fully emptied of oil all at once it is referred to as a full drawdown. When only part of the oil within a cavern is removed followed by an extended waiting period, then it is called a partial drawdown. While a full drawdown may have short breaks between oil removal activities, or delivery batches, multiple partial drawdowns can be identified by the presence of waiting periods that are long enough that the brine sump equilibrates back to a fully saturated state.

1.1. Partial Drawdowns Used to Deliver Oil for Sales and Exchange for Storage

The SPR is currently involved in crude oil sales mandated by congressional legislation. To sell oil from the reserve, oil is withdrawn using water displacement where water is injected into the cavern pushing oil out of it (Figure 1-1). Additionally, in 2020, oil was received and drawn down as part of the Exchange for Storage program; oil was withdrawn in the same manner as for congressionally mandated sales. "Raw" drive water for SPR is obtained from naturally occurring surface water near the sites and is not saturated with brine. As such, raw water injection reduces the salinity of the brine in the cavern below the oil. The now undersaturated brine that is in contact with the cavern walls dissolves the salt at the cavern walls, and this process constitutes cavern leaching.

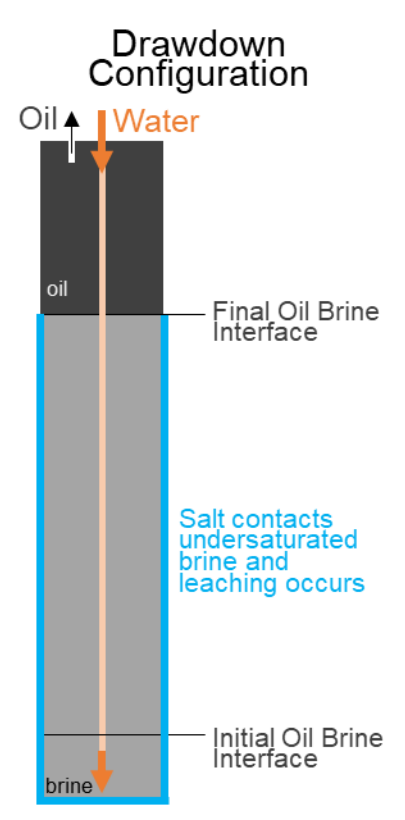

Figure 1-1. Schematic of drawdown configuration which results in cavern wall leaching.

The impact of leaching on cavern shape depends on the type of leaching that occurs. Sales generally involve partial drawdowns of the oil inventory in several caverns. The leaching pattern for a single-phase partial drawdown generally involves a "flare" pattern with the greatest growth at the depth of the end of the brine string tubing (EOT) that tapers up to the final oil-brine interface (OBI) depth (Figure 1-2) [1][8]. This pattern reflects the concentration of salt in the injected water over time, as the well-mixed brine in the region between the EOT and OBI is lower in concentration compared to the rest of the cavern brine—with greater exposure times to undersaturated brine near the EOT, there is a resultant greater radial growth. If the EOT is relatively high above the cavern floor, the flared part of the cavern is not at the cavern floor and a feature, referred to here as a shelf, may form.

Many SPR caverns have multiple phases of leaching and the final leaching pattern depends on the cumulative effects for all phases. This report shows that caverns with multiple leaching phases have a range of leaching outcomes which deviate from the single-phase flare pattern and are difficult to predict *a priori* from any single metric. Thus, SANSMIC modeling was particularly helpful in understanding the potential leaching outcomes for these caverns.

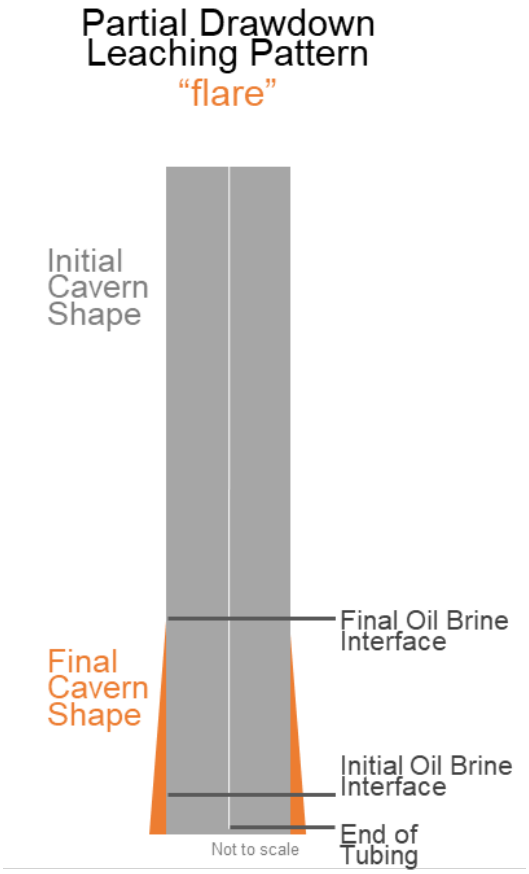

Figure 1-2. Schematic of leaching pattern from a partial drawdown.

Longer time exposure to brine with undersaturated salt concentrations will produce the greatest leaching of the salt walls and corresponding radial growth of the cavern. Thus, the greatest radial growth for a partial drawdown is at the depth of the end of tubing, as shown schematically by the difference in position between the pre- (grey) and post- (orange) cavern shapes.

A full drawdown, while still having more leaching at the bottom of the cavern than the top, is sufficiently fast that the entire cavern sees relatively more evenly distributed leaching, in terms of changing cavern radius. The contrast between the resulting cavern geometry for a cavern undergoing a full drawdown and one that exhibits "flaring" due to partial drawdowns can be quite dramatic, particularly when a cycle of small partial drawdowns followed by refilling the cavern results in the "flare" being applied multiple times at the same depth.

1.2. Review Leaching History in Sonars

The actual leaching history was examined for each cavern by comparing past sonars. This comparison was used to understand if leaching has occurred in the caverns and if it was radial or asymmetric. If it was generally radial in the past, it may also be radial in the future. An example leaching history is shown in Figure 1-3 for BH-101. Sonars taken in well A from 2000 and 2012 are shown on the left, with the surface color coded by depth with blue being the deepest. A comparison of vertical cross sections through each sonar are shown in the middle, with the 2000 sonar represented by the blue line and the 2012 sonar represented by the orange line. The change in vertical profile from 2000 (blue) to 2012 (orange) in this cavern indicates that the cavern floor has

risen 50 ft between sonars and the base of the cavern has spread radially. The radial spread at particular depths of 4050' and 3800' are shown in the later cross sections which again compare the 2000 (blue) and 2012 (orange) cavern extents. The depths of the lateral cross sections were chosen to illustrate the change in radius of different parts of the cavern. At both depths in this cavern, the leaching pattern looks to be approximately radial: a relatively simple radial extension of the 2000 profile (blue) reaches out to the 2012 (orange) profile. And based on this information, it would be expected that any water injected after the 2012 sonar would continue to leach the cavern relatively symmetrically.

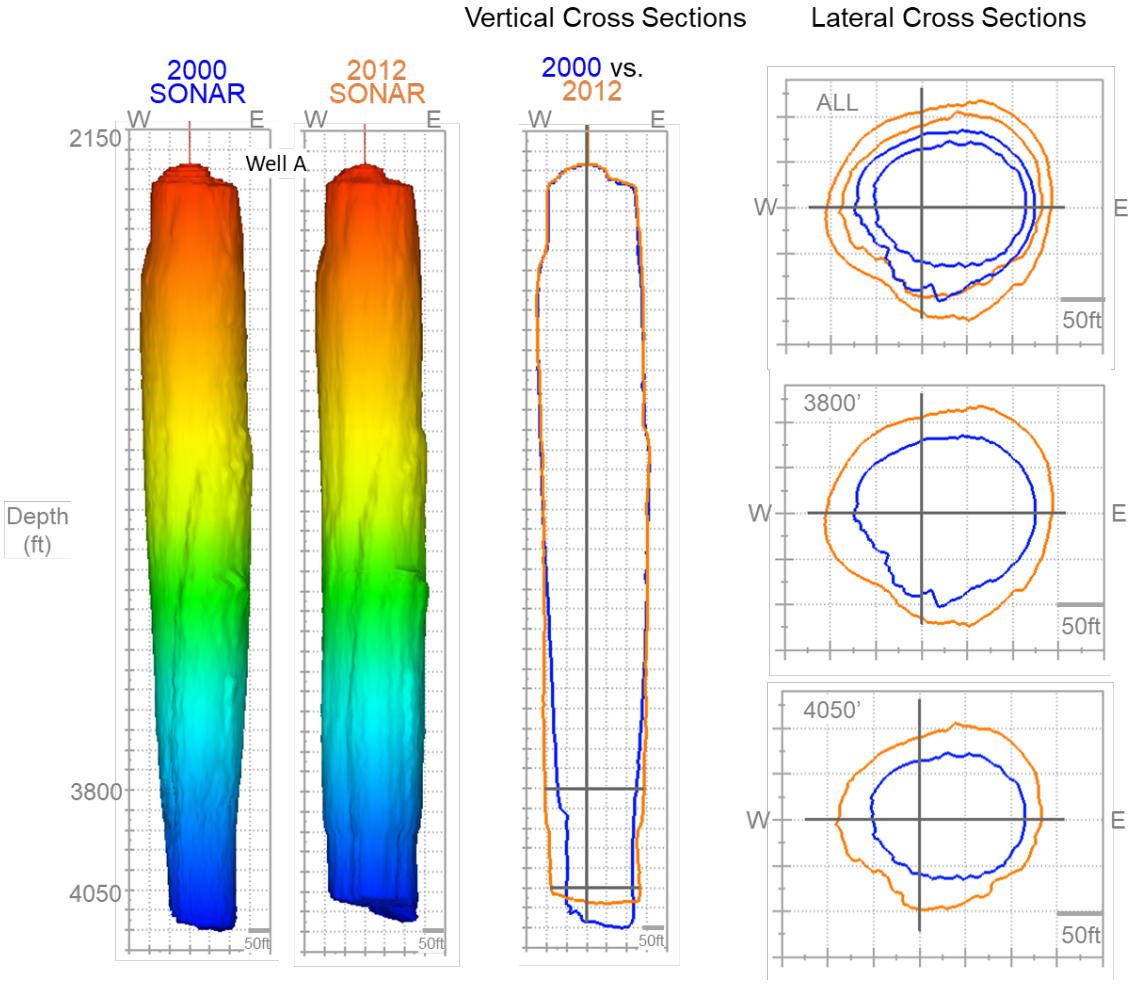

Figure 1-3. Example leaching history for BH-101.

1.3. Monitor Partial Drawdown Leach Effects Using SANSMIC

Changes in cavern shape may impact the integrity of the cavern over time if features are introduced into the cavern geometry that concentrate stress. The best way to monitor for adverse leaching effects on the caverns is to take regular sonar measurements of the cavern geometry; however, this is resource intensive and may not be necessary for all caverns. Instead, leaching effects are being modeled in all sales caverns to predict changes in caverns which may be less geomechanically favorable. These simulations can then inform decisions regarding the choice of caverns to sonar to ensure long term cavern integrity while executing mandatory sales.

Leaching effects are modeled with the **San**dia **S**olution **Mi**ning **C**ode (SANSMIC) [9]. SANSMIC was developed in the early 1980's to model the effects of leaching on the cavern shape and volume. The code uses standard salt dissolution models that account for the salinity of the injected water, temperature and flow velocity [9]. Simulations use sonar derived cavern shapes at the start of the simulation, the actual casing depths, and the field-reported injected water volumes. The model computes the effects of leaching on cavern shape and volume, treating the cavern as a stack of cylindrical disks and limiting leaching to cavern depths below the OBI. The OBI moves as fluids are moved into the cavern.

SANSMIC was validated for conventional leach (both direct and reverse) capabilities by comparison with cavern creation data [10]. Subsequent comparisons between SANSMIC modeled cavern geometries and sonar measurements following the 2011 oil sale and subsequent remedial leach activities indicated the simulated cavern radius is within 5% of the measured cavern radius and the leached volumes are within 10% [1]. A re-validation of SANSMIC in withdrawal, direct and reverse leach modes for caverns leached by SPR indicated that simulated radial profiles match sonar observations within 1.5% - 12 % and the observed leach volume was simulated within 1% -13% [4].

It is important to note that, after discussion with sonar vendors, Sandia uses an assumed volumetric accuracy for a sonar survey of ±1% of the volume. With older sonar surveys, irregularly shaped caverns, and with very wide caverns, the error bounds increase. SANSMIC predictions also depend on the vertical resolution of the input cavern geometry; EOT depths, OBI depths, and final depths are rounded to the nearest cell boundary, which can impact results depending on the cell size chosen.

SANSMIC simulations start from a known cavern geometry, EOT and OBI depths, and injected water volumes. The cavern geometry is usually taken as the last sonar prior to injection. A 2-D, axisymmetric representation of the cavern geometry with an equivalent cavern volume is then calculated and used as the initial geometry. A comparison is shown in Figure 1-4 of the 3D sonar (blue lines) and the 2D axisymmetric representation (orange lines) for BH-101. For this cavern, the lateral cross sections show that the circular cross section assumption was likely a reasonable approximation as the cavern only has small variations from circular.

The EOT and OBI depths are taken from the daily site reports, however they are included in SANSMIC as a distance above the cavern floor, herein called a rise, rather than a depth. SANSMIC automatically modifies the value (in part, based on rounding the input rise values in order that they land on a cell edge) for the EOT and OBI and those values are referred to as mod EOT rise and mod OBI rise. The daily raw water injection amounts are taken from CAVEMAN and daily site reports and phases of water injection are identified. For each phase (period of time), an average injection rate is calculated from the daily rates over the stage duration. This approach is illustrated in Figure 1-5 for BH-101. For phase 1, there were 5 days of injection in 2014 for a total of 53,697 bbl. That was modeled as a 5-day long injection with 10,739 bbl injected each day. SANSMIC results appear sensitive to monthly variations, hence the phases, but insensitive to daily variations, hence an average rate used for each day.

Leaching occurs during and after injection, called the equilibration period (EP). The EP is generally chosen as 60 days to ensure the simulations have enough time to reach equilibrium as indicated by the specific gravity of the fluid in the outlet reaching a value of 1.2, the expected value for fully saturated brine (temperature dependent) [11]. The injection history is therefore composed of injection periods followed by equilibration periods as shown in Figure 1-6. The simulation results are evaluated using the efficiency of the leach, the ratio of the change in cavern volume to the volume of

injected water, which is expected to be around 15% (the exact value is dependent on the initial specific gravity and the cavern temperature).

The final cavern geometry after leaching was modeled and compared with the pre-leaching geometry to understand the leaching effects from CY20 water injection. An example is shown in Figure 1-7 for BH-101. The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar, which is the SANSMIC input, is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The volume of injected water that led to the leaching pattern is shown with a grey arrow, in this case 1.0 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which are the slight radial spread of the cavern floor in this case. The character of that radial spread at a given depth is also seen in the lateral cross sections.

Caverns were selected for CY20 SANSMIC modeling based on the criteria that at least 10,000 bbls of raw water had been injected in CY20 and there has been no sonar subsequent to the final raw water injection. The modeling results for the 24 caverns that met those criteria are described in Section 2. Additionally, there 10 caverns for which sonars were taken in 2020, allowing for comparison with the latest SANSMIC modeling prior to the sonar (BC-18 is the only cavern to have at least 10,000 bbls of raw water injection in 2020 and a 2020 sonar). Those comparisons are described in Section 3.

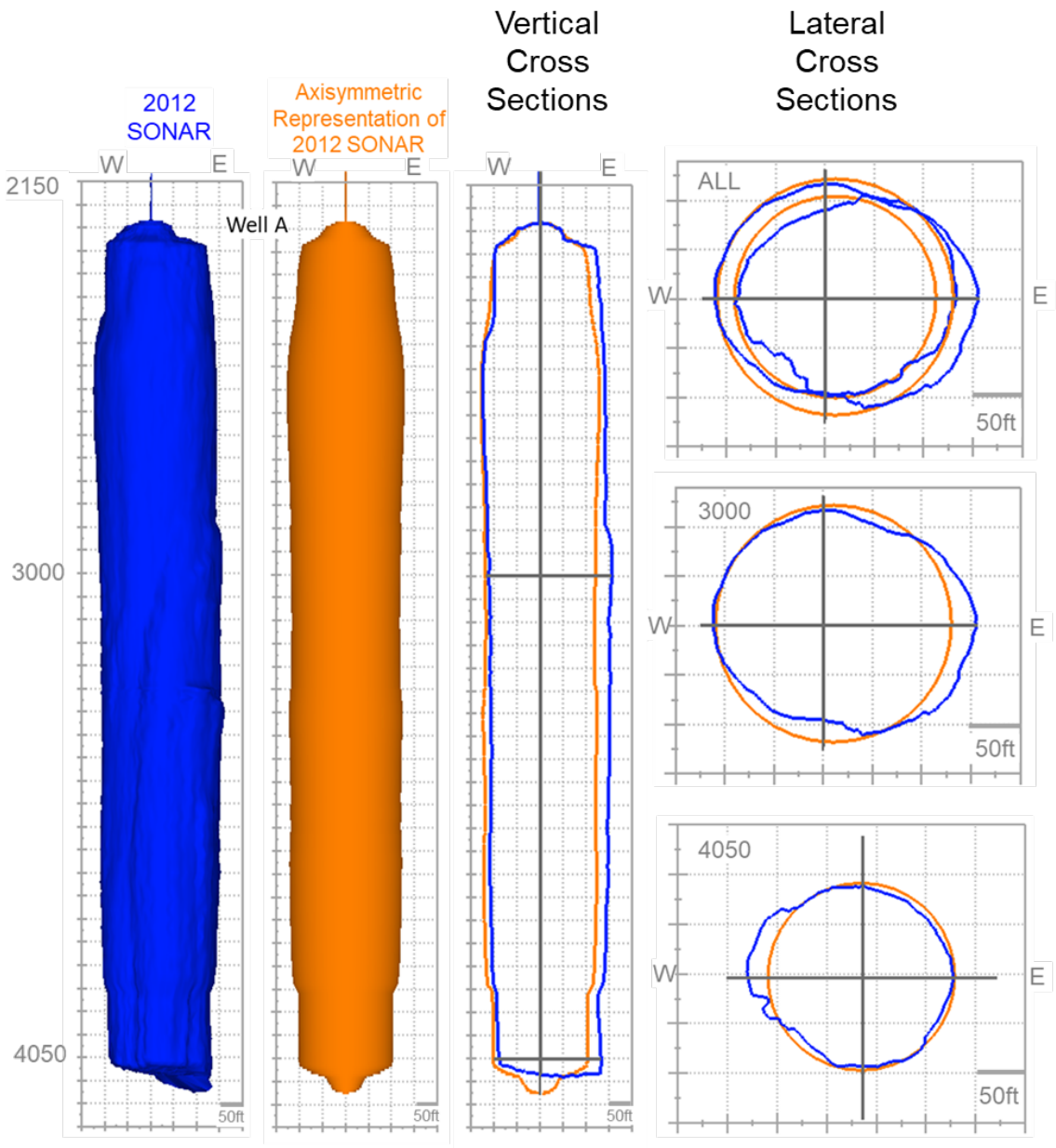

Figure 1-4. Example of 2D axisymmetric representation (orange) of 3D cavern geometry (blue) for BH-101.

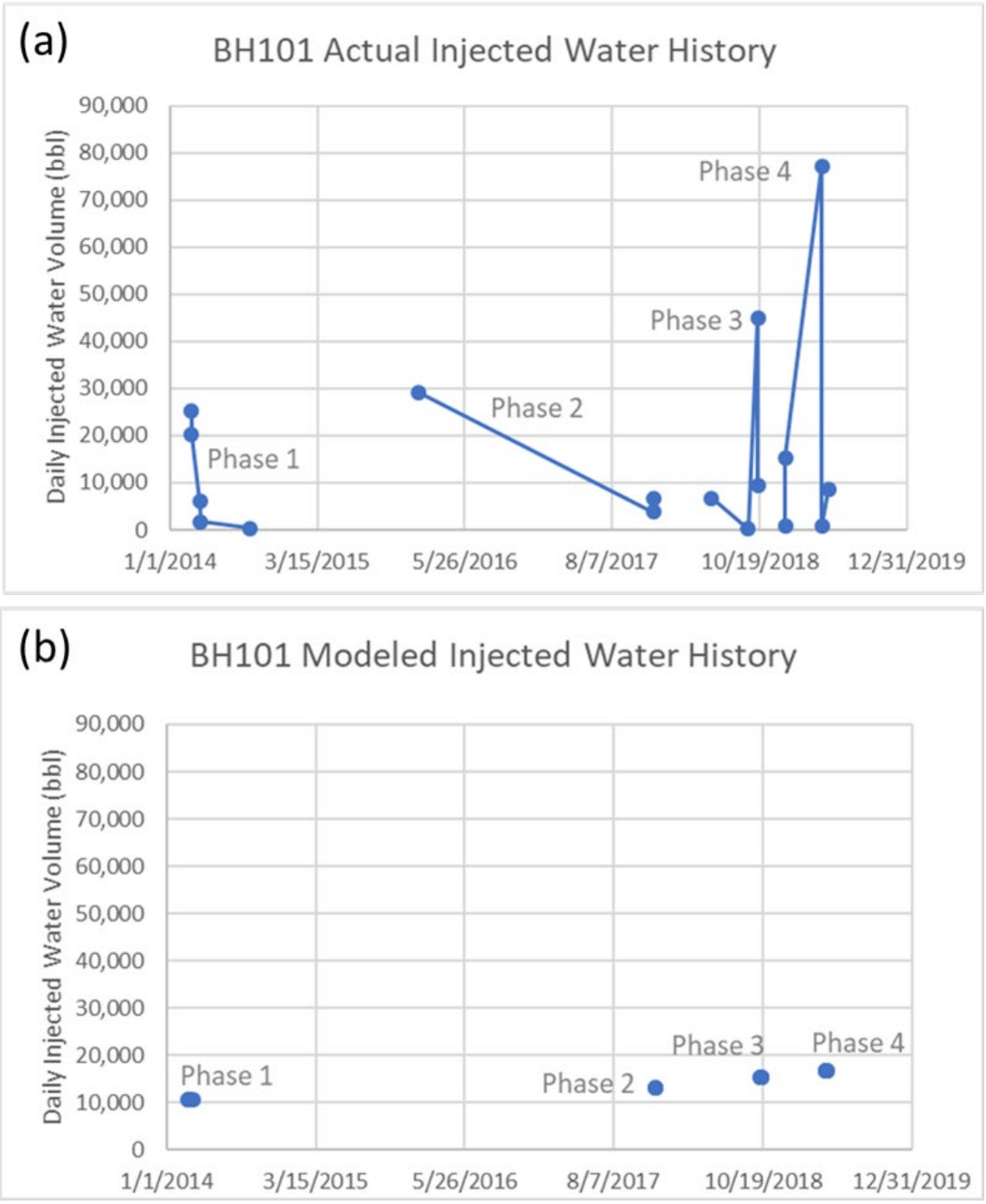

Figure 1-5. Example of (a) actual and (b) modeled injected water history for BH-101.

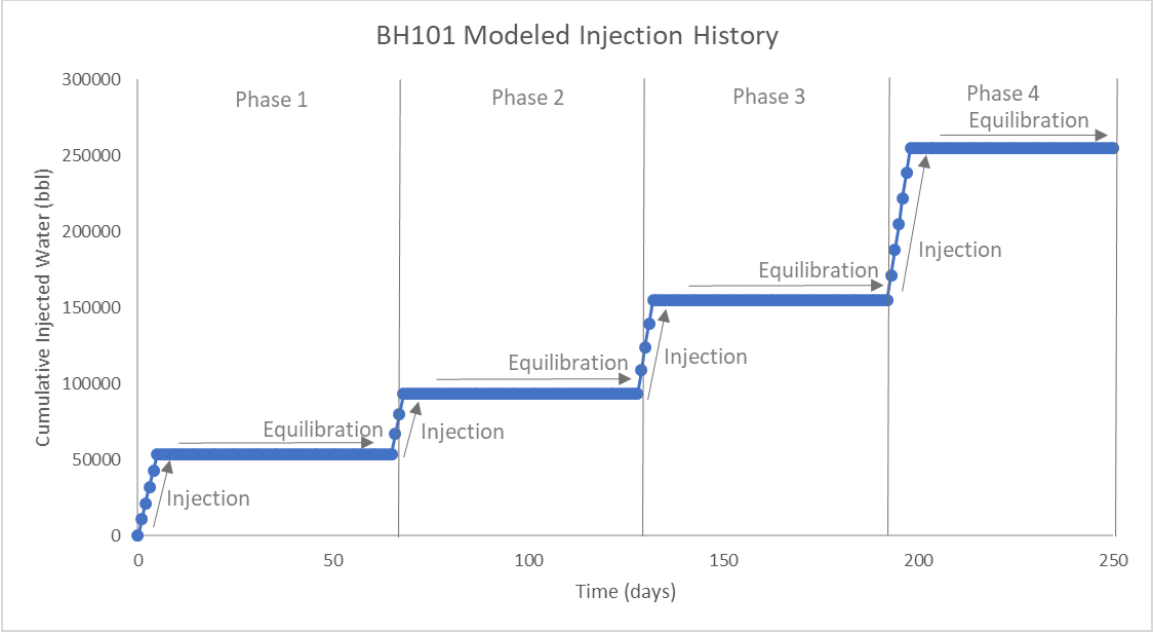

Figure 1-6. Example of modeled injection history for BH-101 showing injection and equilibration periods.

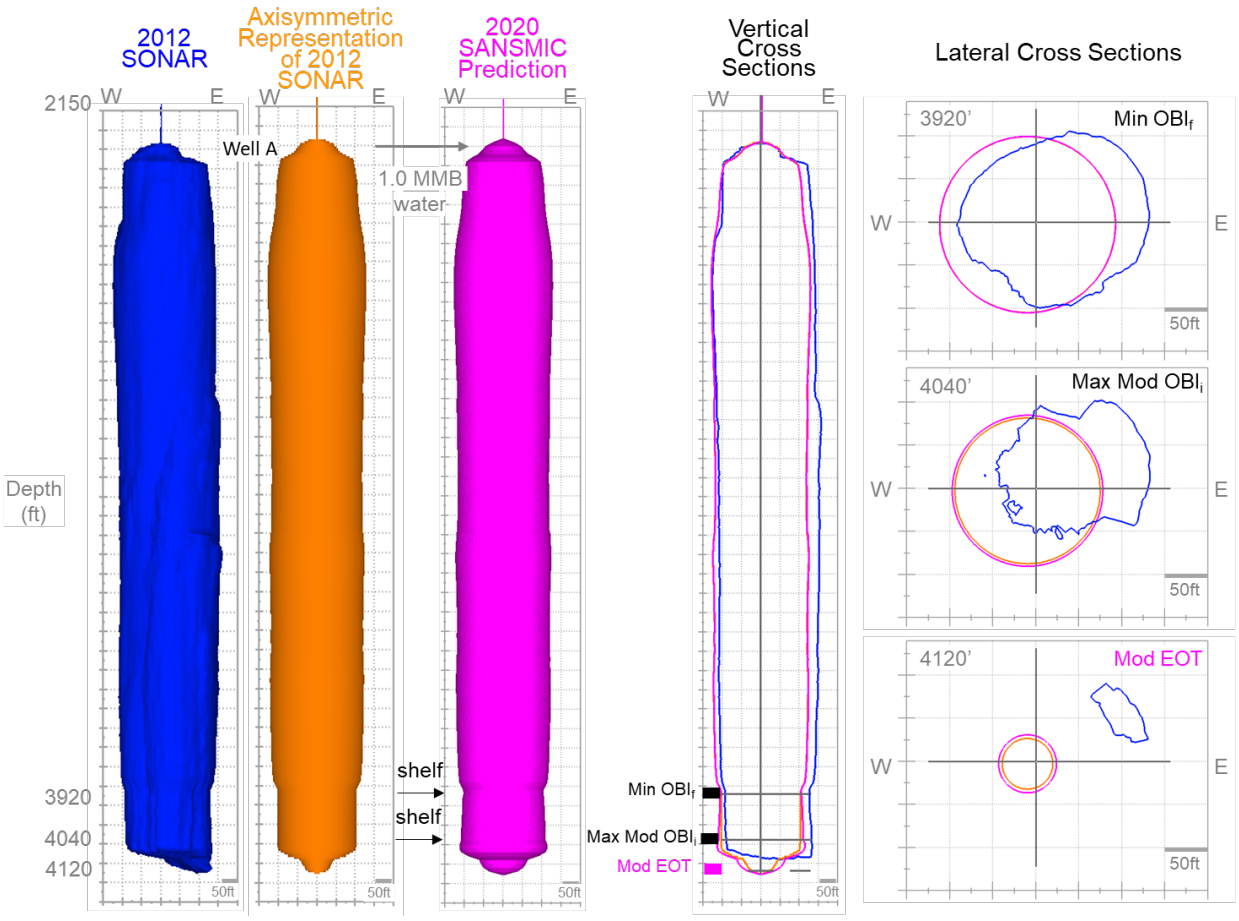

Figure 1-7. Example model results for BH-101.

2. SIMULATED CAVERN LEACHING RESULTS FOR CY20

Water was injected into caverns at all four sites in CY20. Leaching was simulated for caverns at all sites and the results are described in Sections 2.1 (Big Hill), 2.2 (Bryan Mound), 2.3 (West Hackberry), and 2.4 (Bayou Choctaw).

2.1. Big Hill

Simulation results for Big Hill are summarized in Table 2-1, including the volume of raw water injection simulated with SANSMIC modeling and any potential concerns observed. Ten caverns had at least 10 MB of raw water injected in CY20. Three of those caverns have had at least 3 MMB of raw water injected since the last sonar. While all caverns do not have a leaching induced feature of concern at this time, three caverns, BH-107, BH-113, and BH-114, have features which should be monitored as leaching continues in those caverns. A brief leaching history and the results of SANSMIC modeling of leaching since the last sonar are discussed below for each cavern.

Table 2-1. Caverns at Big Hill with water injected in CY20.

Cavern	Last Sonar	Injected Water Volume (MMB)*	Concerns
BH-101	2012	0.97	No
BH-102	2013	4.3	No
BH-104	2018	3.3	No
BH-105	2013	0.64	No
BH-107	2019	0.45	Monitor flare near cavern floor
BH-108	2019	0.84	No
BH-109	2020	0.084	No
BH-110	2020	0.54	No
BH-113	2015	0.31	Monitor flare near cavern floor
BH-114	2013	3.6	Monitor flare near cavern floor

* Since last sonar

2.1.1. BH-101

2.1.1.1. Leaching History

Sonars taken in the A well of BH-101 in 2000 and 2012 are shown in Figure 2-1. Floor rise and spread occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 11.8 MMB of water injected into this cavern between sonars to create this change in cavern shape. Leaching was primarily radial from 2000 to 2012, suggesting that radial leaching should be expected for the 1.0 MMB of water that has been injected since the 2012 sonar.

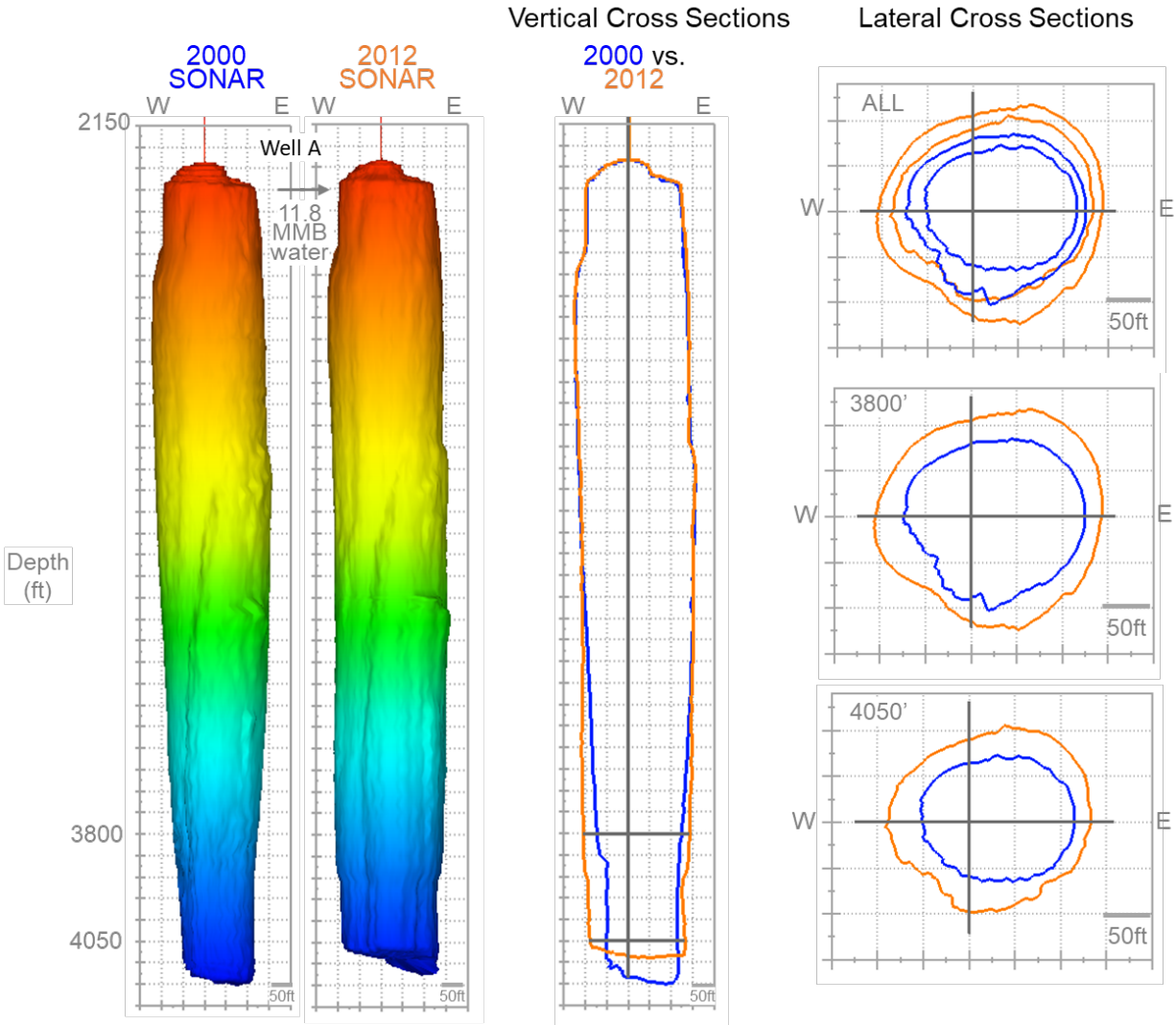

Figure 2-1. Leaching history in BH-101 from 2000 (blue) to 2012 (orange) via sonars in well A.

2.1.1.2. Simulated Leaching Between 2012 Sonar and End of CY20

The last sonar taken in BH-101 was in 2012. Since that sonar, around 1.0 MMB of raw water have been injected into the cavern. The injections occurred over 56 days in 2014 and 2016 - 2020 (see Table 2-2). The injection history was modeled using five separate leaching phases with an EP of 60 days following each injection phase. To represent CY20 water injection, a single phase was added to the four phases modeled for the CY18-19 report [8]. This cavern has had a single Mod EOT rise. The initial OBI in phases 3 and 4 were automatically selected by SANSMIC based on the final OBI of the previous phase.

Table 2-2. Summary of Simulation Input for BH-101

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	03/05/14-08/28/14	4160	17	10	81	80	10,739	5	53,695
2	01/08/16-12/09/17	4160	18	10	48	50	13,234	3	39,702
3	05/29/18-10/15/18	4160	18	10	Auto	60	15,313	4	61,252
4	04/23/19-05/12/19	4160	18	10	Auto	70	16,730	6	100,380
5	08/01/20-09/26/20	4160	18	10	94	90	18,926	38	719,188
ALL	N/A	N/A	N/A	N/A	N/A	N/A	N/A	56	974,217

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of the EP. The leaching efficiency was anomalously high for phase 2, as observed in the 2018-19 leaching report [8]. SANSMIC-generated leaching efficiencies higher than about 16%, as observed here and for other caverns in this report, are abnormally high and the sources of these anomalies are currently being investigated separately. As summarized in Table 2-3, the overall leaching efficiency for this cavern was 16.4%.

Table 2-3. Summary of Simulation Output for BH-101

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	90	1.1993	8,000	14.9
2	60	1.1997	11,000	27.7
3	70	1.1977	11,000	18.0
4	90	1.1984	17,000	16.9
5	210	1.1975	113,000	15.7
ALL	90	1.1975	160,000	16.4

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2012 sonar and the end of CY20 (see Figure 2-2). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 1.0 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which include the slight radial spread of the cavern floor. The spread can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-3) that is about 200 ft tall and extends from the 2020 EOT to just below the 2020 final OBI. The radial growth was greatest near the EOT, with over 15 ft of radial growth predicted. SANSMIC predicts shelf formation near the Max Mod OBIi, which may be at least partly related to the pre-existing geometry of the cavern at that depth and was previously reported [8]. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

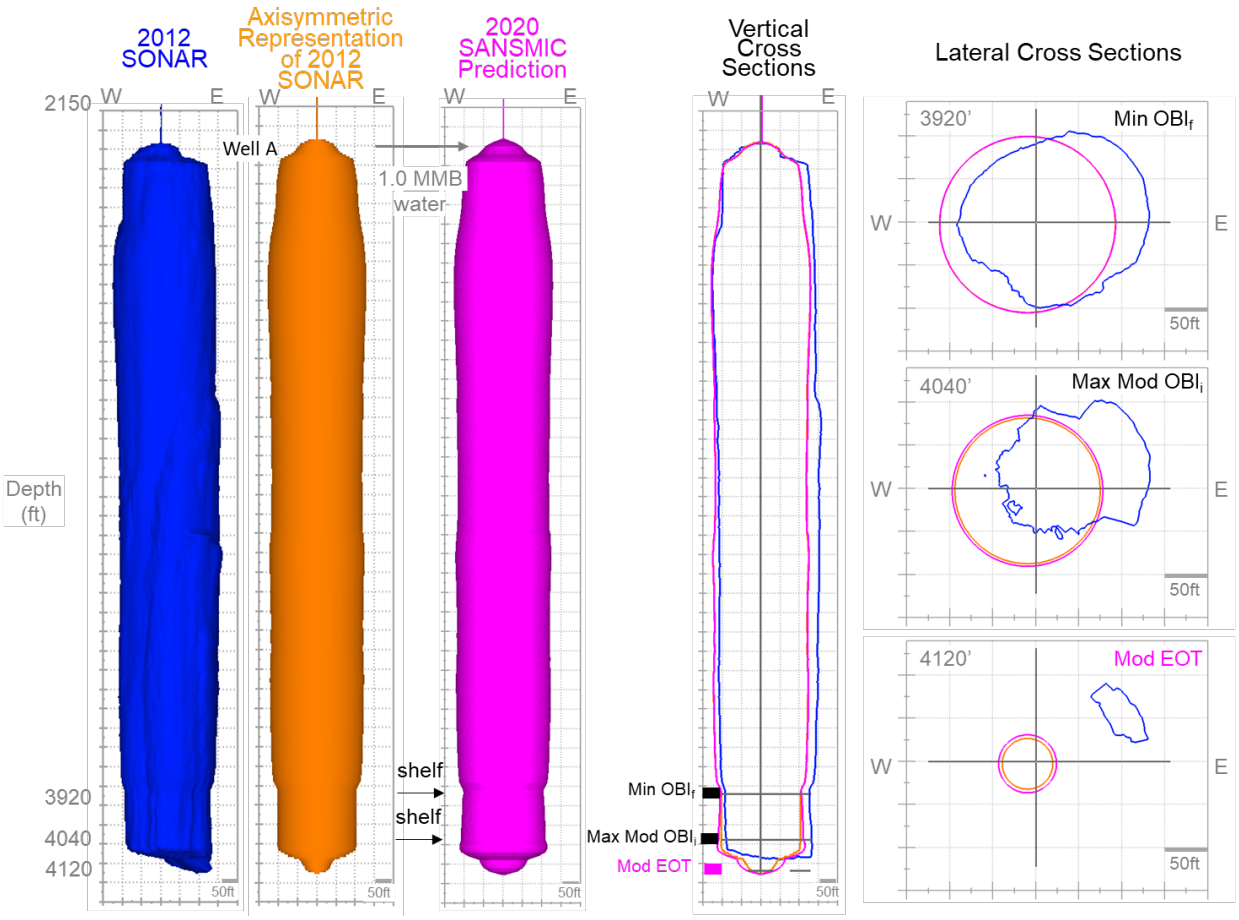

Figure 2-2. BH-101 Modeling Results for Leaching Between 2012 Sonar and End of CY20.

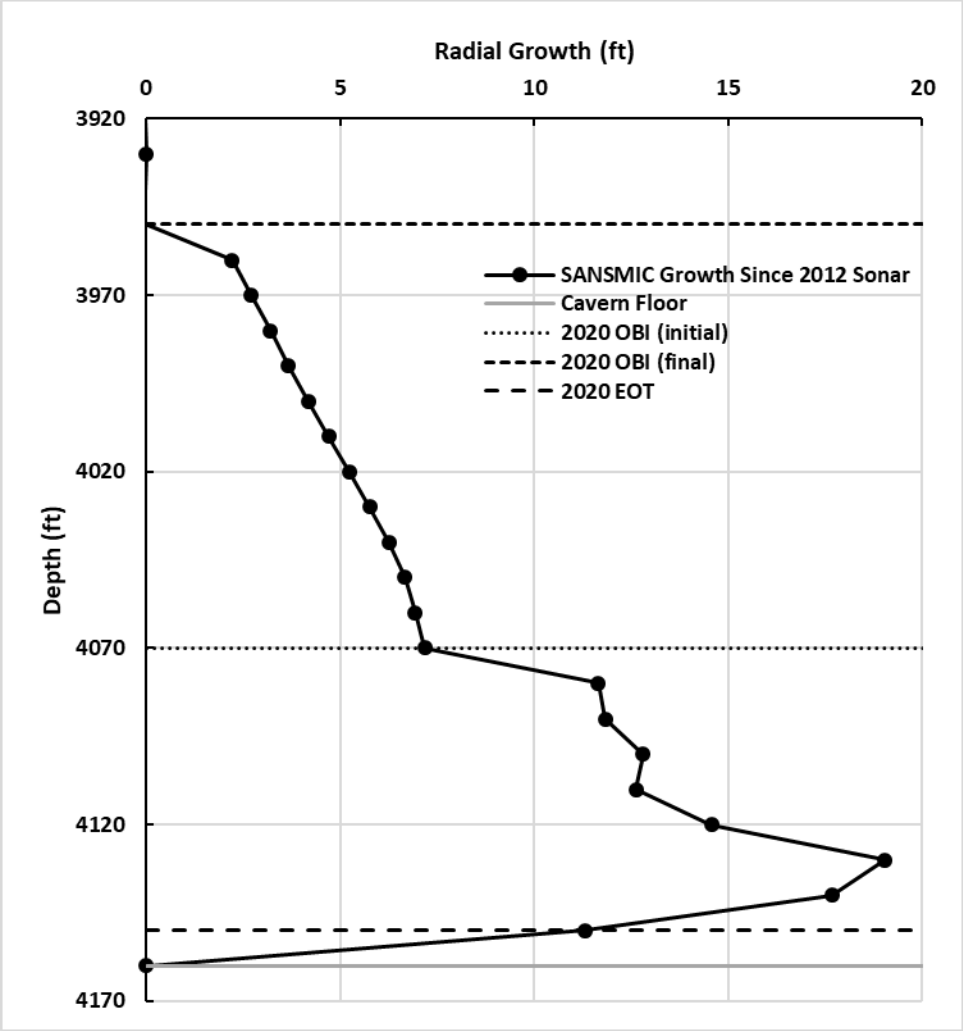

Figure 2-3. BH-101 SANSMIC-Predicted Radial Growth since 2012 Sonar (exaggerated horizontal scale).

2.1.2. BH-102

2.1.2.1. Leaching History

Sonars taken in the A well of BH-102 in 2003 and 2013 are shown in Figure 2-4. Floor rise and spread occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 4.0 MMB of water injected into this cavern between sonars to create this change in cavern shape. One notable feature in the lateral cross section at 3950 ft depth is the presence of a notch in the cavern wall a little west of North. That notch was not in the lateral cavern profile at 3950 ft depth in 2003 and may represent a geologic control (change in salt properties potentially due to impurities) on cavern leaching. That same feature is evident in both the 2003 and 2013 lateral cross sections at 3700', suggesting that geologic control extends vertically along the cavern. Despite that feature, leaching was primarily radial from 2003 to 2013, suggesting radial leaching should be expected for the 4.3 MMB of water that has been injected since the 2013 sonar.

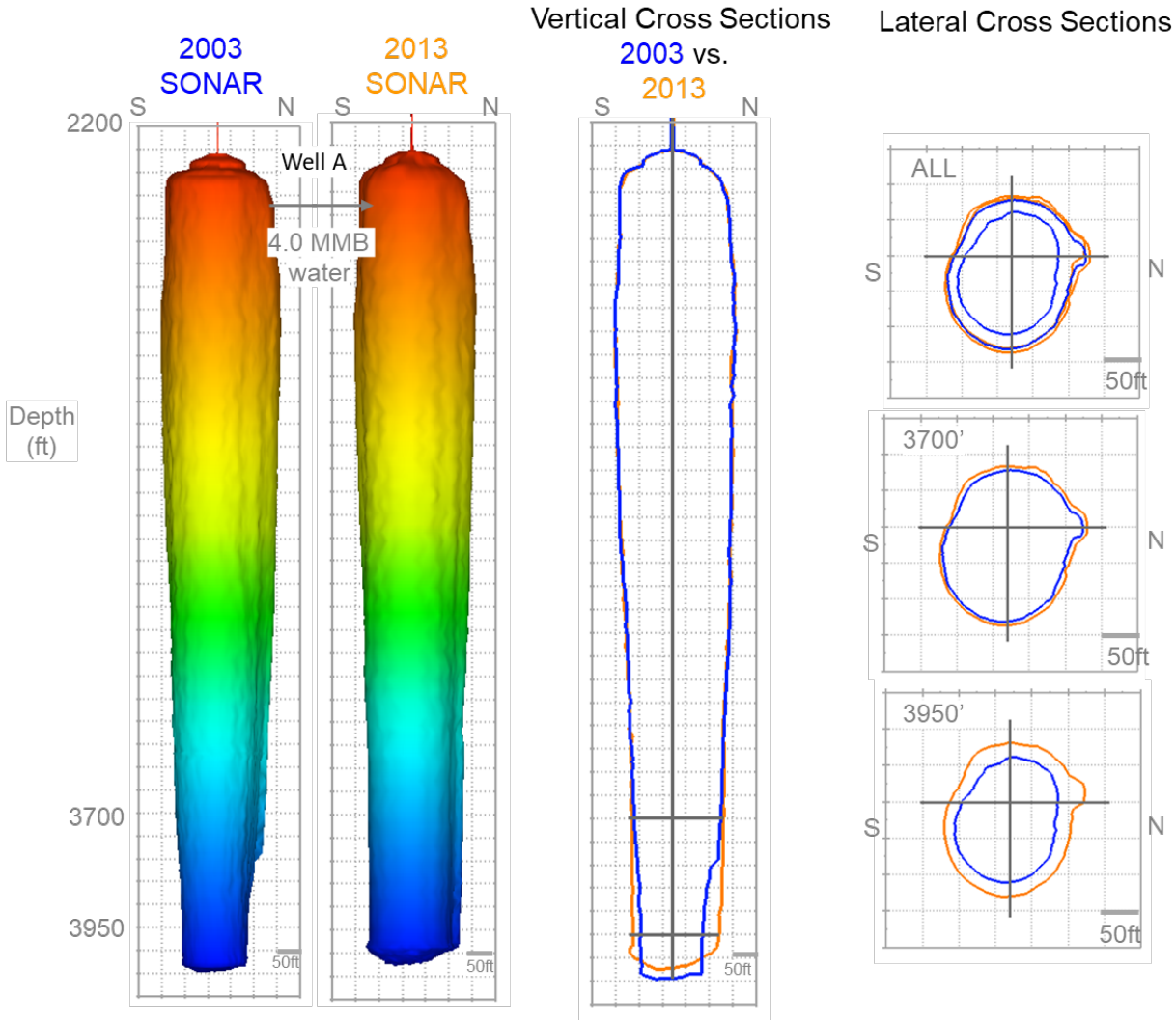

Figure 2-4. Leaching history in BH-102 from 2003 (blue) to 2013 (orange) via sonars in well A.

2.1.2.2. Simulated Leaching Between 2013 Sonar and End of CY20

The last sonar taken in BH-102 was in 2013. Since that sonar, over 4.3 MMB of raw water have been injected into the cavern. The injections occurred over 97 days in 2013, 2014, 2015, and 2017-2020 (see Table 2-4). The injection history was modeled using eight separate leaching phases with an EP of 60 days following each injection phase. To represent CY20 water injection, a single phase was added to the seven phases modeled for the CY18-19 report [8]. This cavern has had two Mod EOT rises. The initial OBI in phases 2, 5, and 7 were automatically selected by SANSMIC based on the final OBI of the previous phase.

Table 2-4. Summary of Simulation Input for BH-102

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	08/31/13-09/04/13	4060	107	90	361	360	73,354	5	366,770
2	01/31/14-01/11/15	4060	107	100	Auto	420	27,918	5	139,590
3	02/25/17-05/07/17	4060	107	100	410	410	32,352	31	1,002,912
4	11/29/17-12/02/17	4060	107	100	567	570	17,559	3	52,677
5	04/19/18-06/02/18	4060	107	90	Auto	570	140,533	5	702,665
6	09/15/18-12/21/18	4060	107	100	683	680	5,020	3	15,060
7	04/23/19-05/29/19	4060	107	100	Auto	690	35,636	9	320,724
8	08/01/20-09/26/20	4062	107	100	449	450	47,232	36	1,700,352
ALL	N/A	N/A	N/A	N/A	N/A	N/A	N/A	97	4,300,750

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of the EP. As summarized in Table 2-5, the overall leaching efficiency for this cavern was 15.6%.

Table 2-5. Summary of Simulation Output for BH-102

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	420	1.1989	53,000	14.5
2	440	1.2003	26,000	18.6
3	570	1.1986	161,000	16.1
4	570	1.2017	8,000	15.2
5	680	1.1985	108,000	15.4
6	690	1.2019	3,000	19.9
7	730	1.2003	48,000	15.0
8	690	1.1979	262,000	15.4
ALL	690	1.1979	669,000	15.6

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2013 sonar and the end of CY20 (see Figure 2-5). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 4.3 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which include the slight radial spread of the cavern floor. The spread can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-6) that is about 800 ft tall and reflects the variation of OBI depths since the last sonar. The radial growth was greatest in the ~500 ft immediately above the EOT, with over 10 ft of radial growth predicted. SANSMIC predicts shelf formation near the Mod EOT (~100 ft above the cavern floor), which was previously reported [8]. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

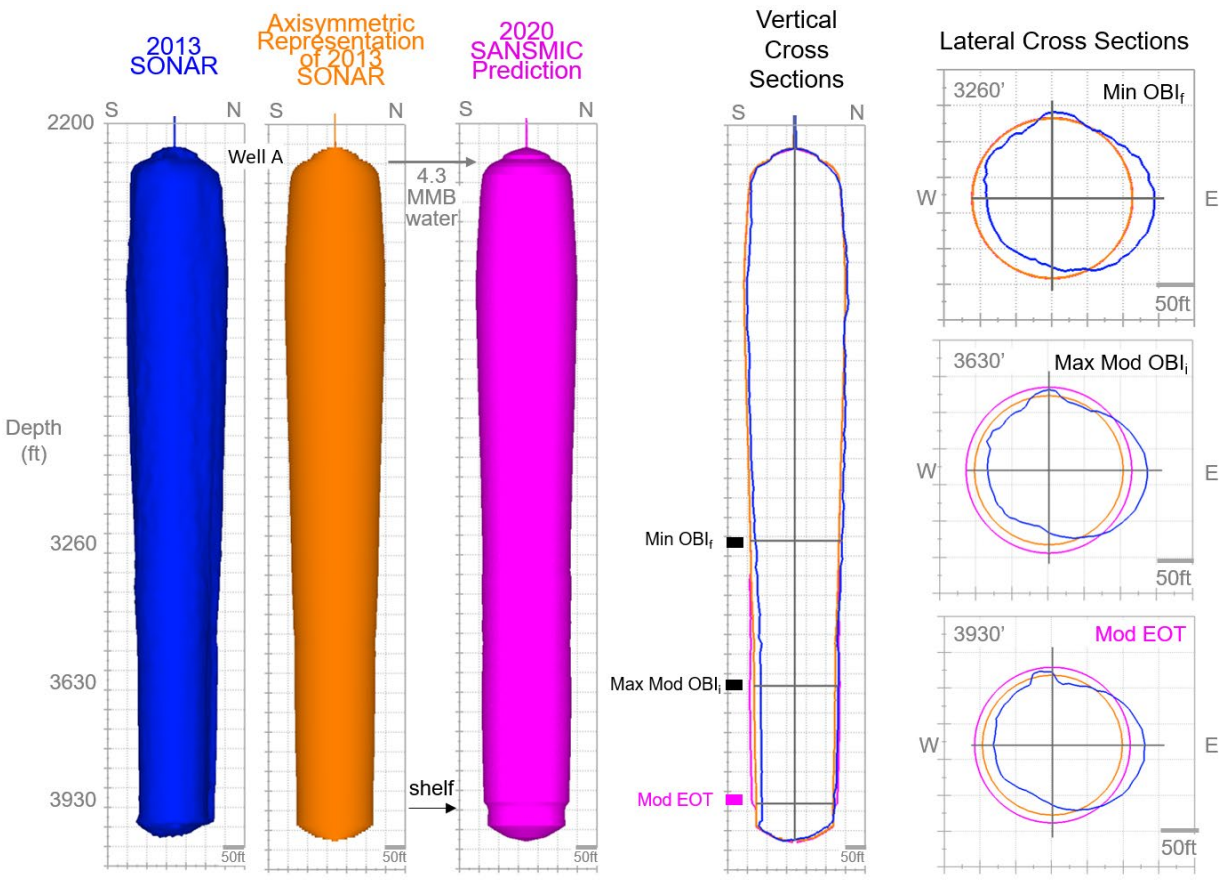

Figure 2-5. BH-102 Modeling Results for Leaching Between 2013 Sonar and End of CY20.

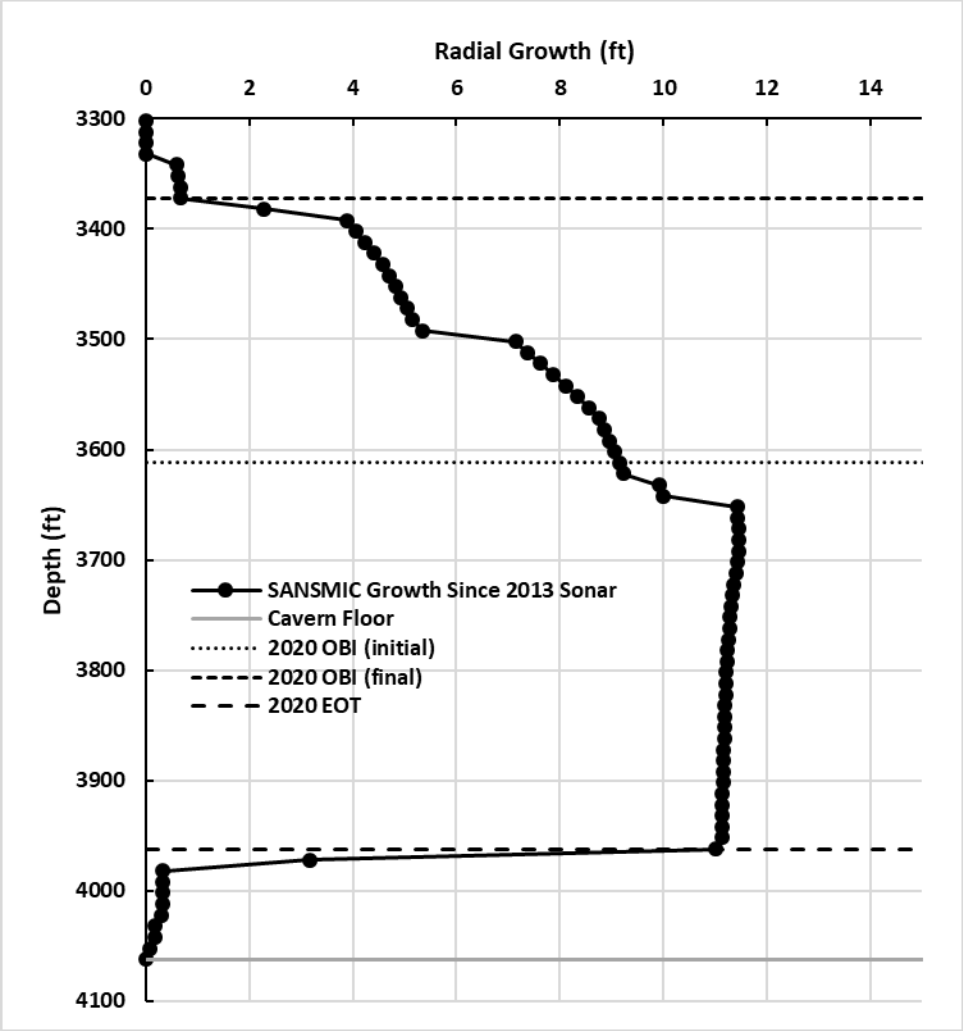

Figure 2-6. BH-102 SANSMIC-Predicted Radial Growth since 2013 Sonar (exaggerated horizontal scale).

2.1.3. BH-104

2.1.3.1. Leaching History

Sonars taken in the A well of BH-104 in 2010 and 2018 are shown in Figure 2-7. Floor rise and spread occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 14.7 MMB of water injected into this cavern between sonars to create this change in cavern shape. Leaching was primarily radial from 2010 to 2018, suggesting radial leaching should be expected for the 3.3 MMB of water that has been injected since the 2018 sonar.

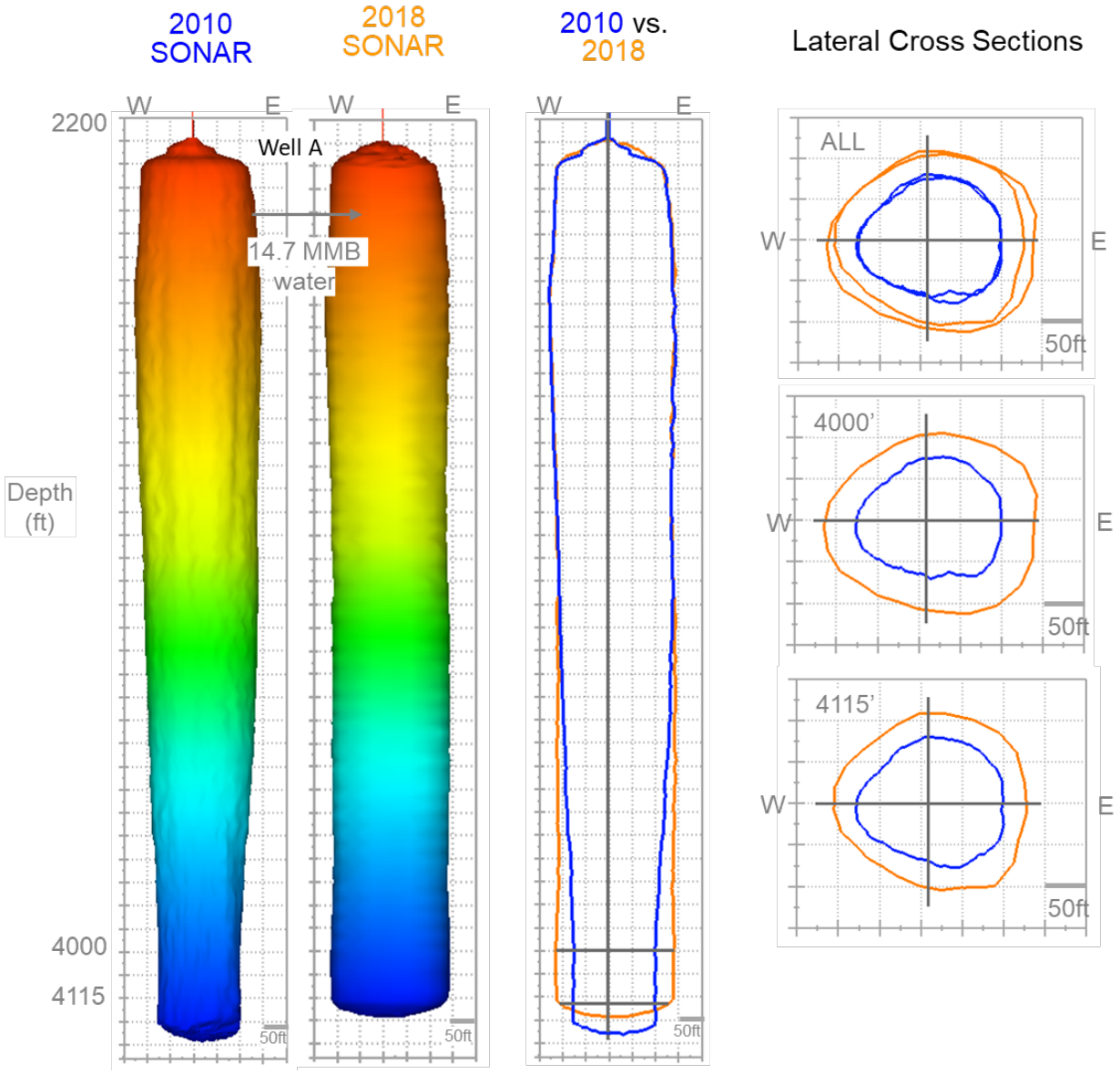

Figure 2-7. Leaching history in BH-104 from 2010 (blue) to 2018 (orange) via sonars in well A.

2.1.3.2. Simulated Leaching Between 2018 Sonar and End of CY20

The last sonar taken in BH-104 was in 2018. Since that sonar, over 3.3 MMB of water have been injected into the cavern in 2018-2020 (see Table 2-6). The injection history was modeled using three separate phases of leaching with an EP of 60 days. To represent CY20 water injection, a single phase was added to the two phases modeled for the CY18-19 report [8]. This cavern has had two Mod EOT rises. The initial OBI in phase 2 was automatically selected by SANSMIC based on the final OBI of the previous phase.

Table 2-6. Summary of Simulation Input for BH-104

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	04/19/18-12/23/18	4178	24	20	269	260	14,391	48	690,768
2	04/23/19-05/13/19	4178	24	20	Auto	260	30,854	11	339,394
3	08/01/20-09/27/20	4178	20	10	110	110	53,881	43	2,316,883
ALL	N/A	N/A	N/A	N/A	N/A	N/A	N/A	102	3,347,045

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of the final EP. As summarized in Table 2-7, the leaching efficiency for this cavern was 15.7%.

Table 2-7. Summary of Simulation Output for BH-104

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	360	1.1988	109,000	15.8
2	400	1.1991	57,000	16.8
3	400	1.1958	360,000	15.5
ALL	400	1.1958	526,000	15.7

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2018 sonar and the end of CY20 (see Figure 2-8). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 3.3 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which include the slight radial spread of the cavern floor. The spread can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-9) that is about 400 ft tall and reflects the variation of OBI depths since the last sonar. The radial growth was greatest in the ~150 ft immediately above the EOT, with over 12 ft of radial growth predicted. SANSMIC predicts flare formation near the Mod EOT (~10 ft above the cavern floor), which was previously reported [8] and is predicted to have grown in size due to CY20 leaching. As previously noted [8], the floor of this cavern is now the widest part of this cavern which may result in an enhanced salt creep rate and an increased floor rise rate. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

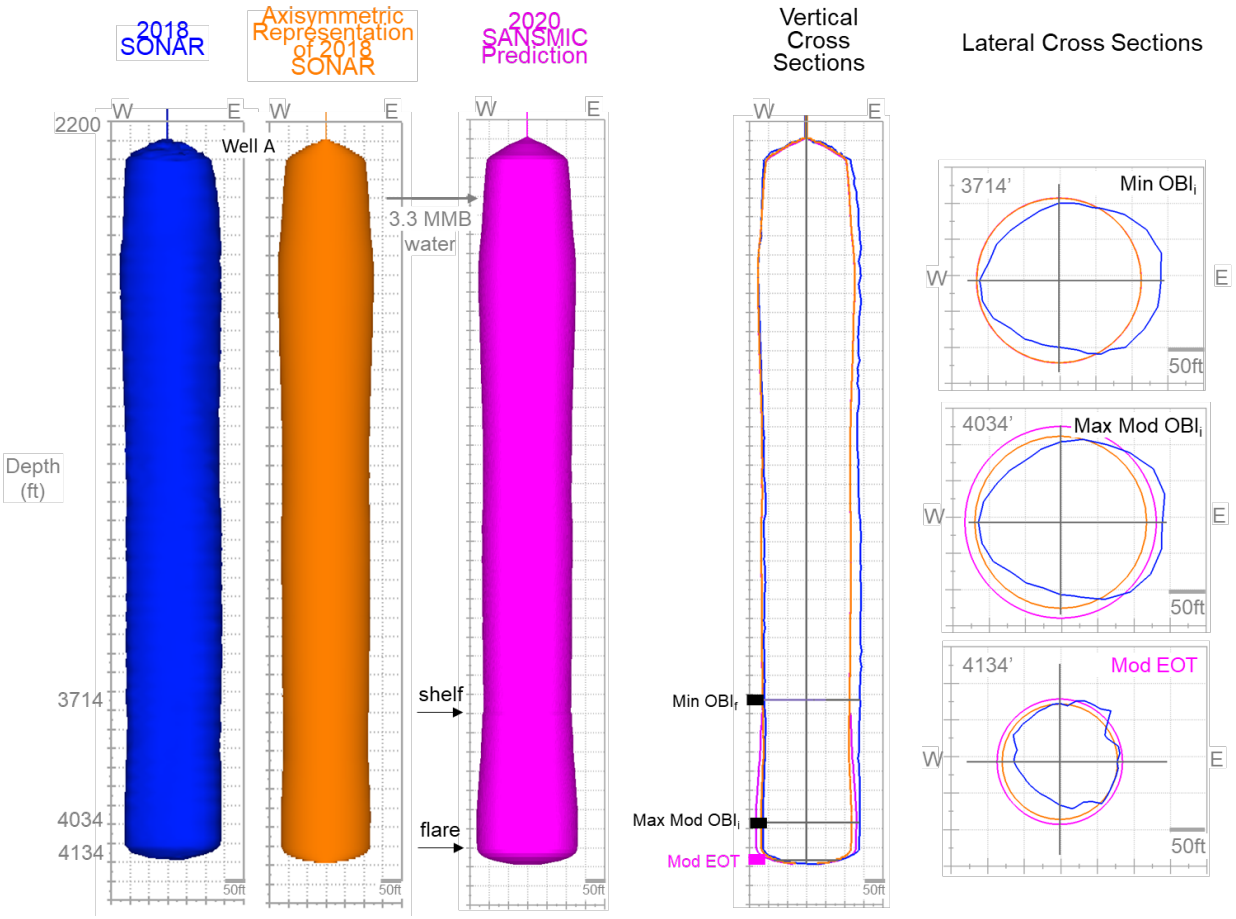

Figure 2-8. BH-104 Modeling Results for Leaching Between 2018 Sonar and End of CY20.

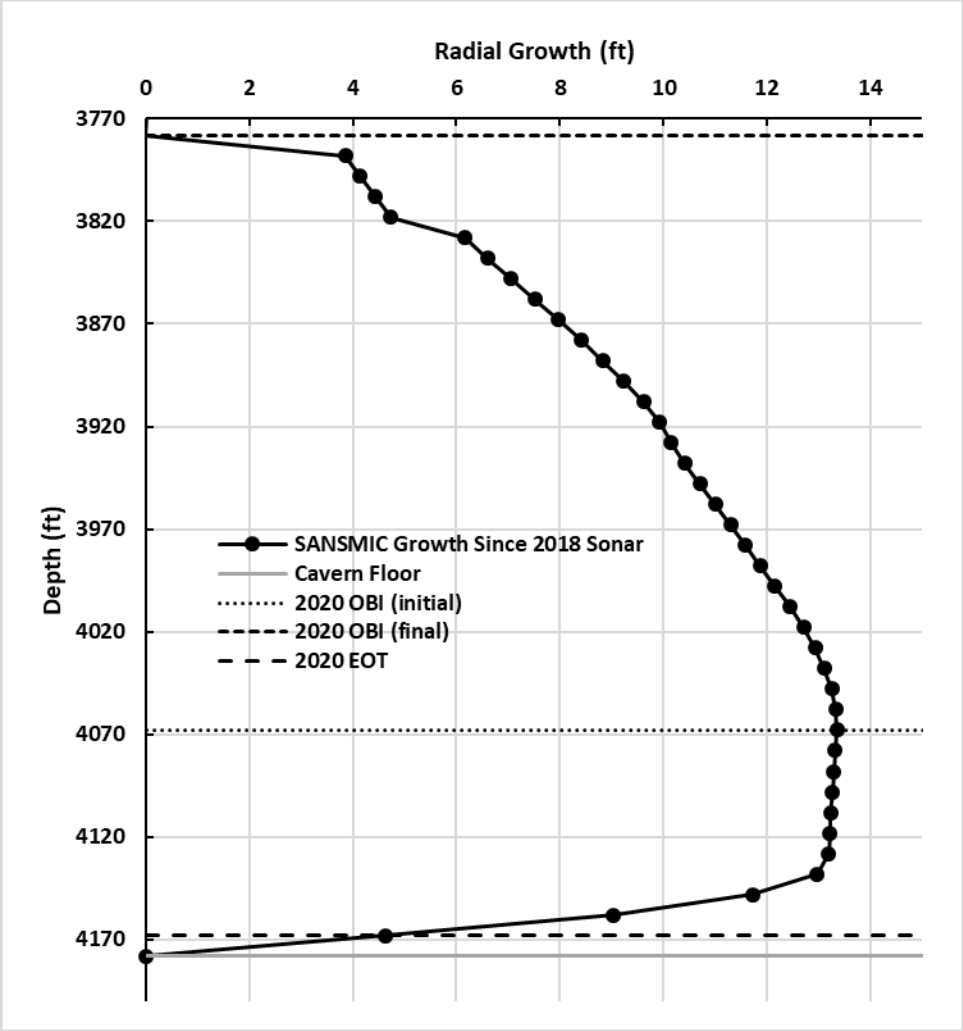

Figure 2-9. BH-104 SANSMIC-Predicted Radial Growth since 2018 Sonar (exaggerated horizontal scale).

2.1.4. BH-105

2.1.4.1. Leaching History

Sonars taken in the A well of BH-105 in 1999 and 2013 are shown in Figure 2-10. Significant floor rise occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical cross sections. There was 8.4 MMB of water injected into this cavern between sonars to create this change in cavern shape. Leaching was asymmetric from 1999 to 2013 suggesting asymmetric leaching should be expected for the 0.6 MMB of water that has been injected since the 2013 sonar.

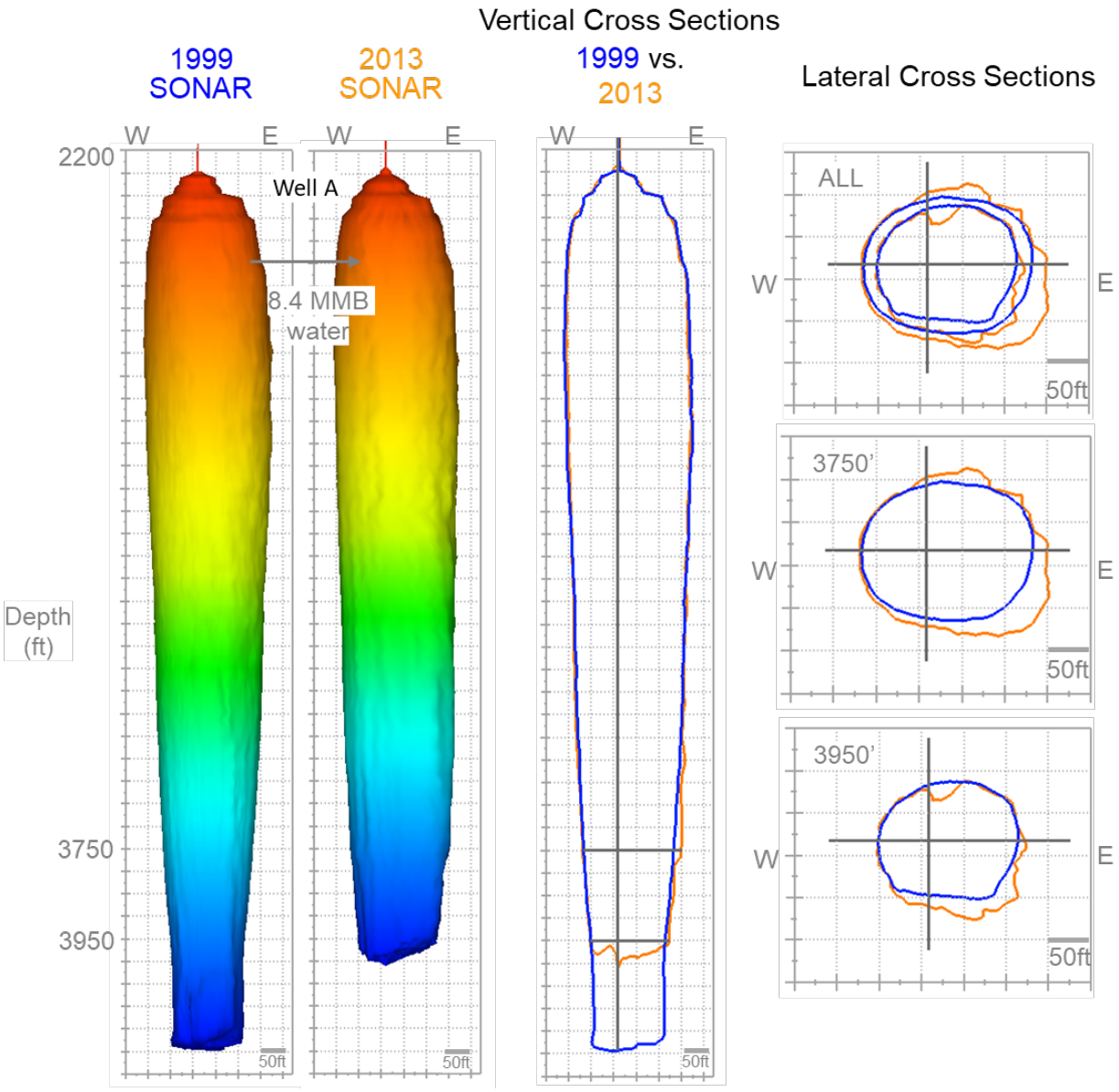

Figure 2-10. Leaching history in BH-105 from 1999 (blue) to 2013 (orange) via sonars in well A.

2.1.4.2. Simulated Leaching Between 2013 Sonar and End of CY20

The last sonar taken in BH-105 was in 2013. Since that sonar, over 0.6 MMB of water have been injected into the cavern in 2013 and 2017-2020 (see Table 2-8). Injection values in 2013 and 2017 were combined to enhance the performance of SANSMIC; for small injection rates and durations, SANSMIC may generate anomalously high efficiencies due to the precision of cavern volume output by the code. The injection history was modeled as 4 different phases of leaching each with an EP of 60 days. To represent CY20 water injection, a single phase was added to the three phases modeled for the CY18-19 report [8]. This cavern has had two Mod EOT rises. The initial OBI in phases 2 and 3 were automatically selected by SANSMIC, based on the final OBI of the previous leaching phase.

Table 2-8. Summary of Simulation Input for BH-105

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	10/30/13-12/02/17	4045	18	10	770	770	8,151	6	48,906
2	04/19/18-12/22/18	4045	18	10	Auto	780	37,468	7	262,276
3	04/23/19-05/13/19	4045	18	10	Auto	810	25,906	12	310,872
4	08/23/20-09/08/20	4047	94	90	323	320	8,828	2	17,656
ALL	N/A	N/A	N/A	N/A	N/A	N/A	N/A	27	639,710

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of the EP. As summarized in Table 2-9, the leaching efficiency for this cavern was 15.8%.

Table 2-9. Summary of Simulation Output for BH-105

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	780	1.2019	8,000	16.4
2	810	1.2007	39,000	14.9
3	840	1.2005	51,000	16.4
4	330	1.2019	3,000	17.0
ALL	330	1.2019	101,000	15.8

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2013 sonar and the end of CY20 (see Figure 2-11). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.6 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which include the very slight radial spread of the cavern floor. The spread can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-12) that is about 800 ft tall and reflects the large distance between OBI and EOT. The radial growth over this depth is predicted to be only about 1 ft. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

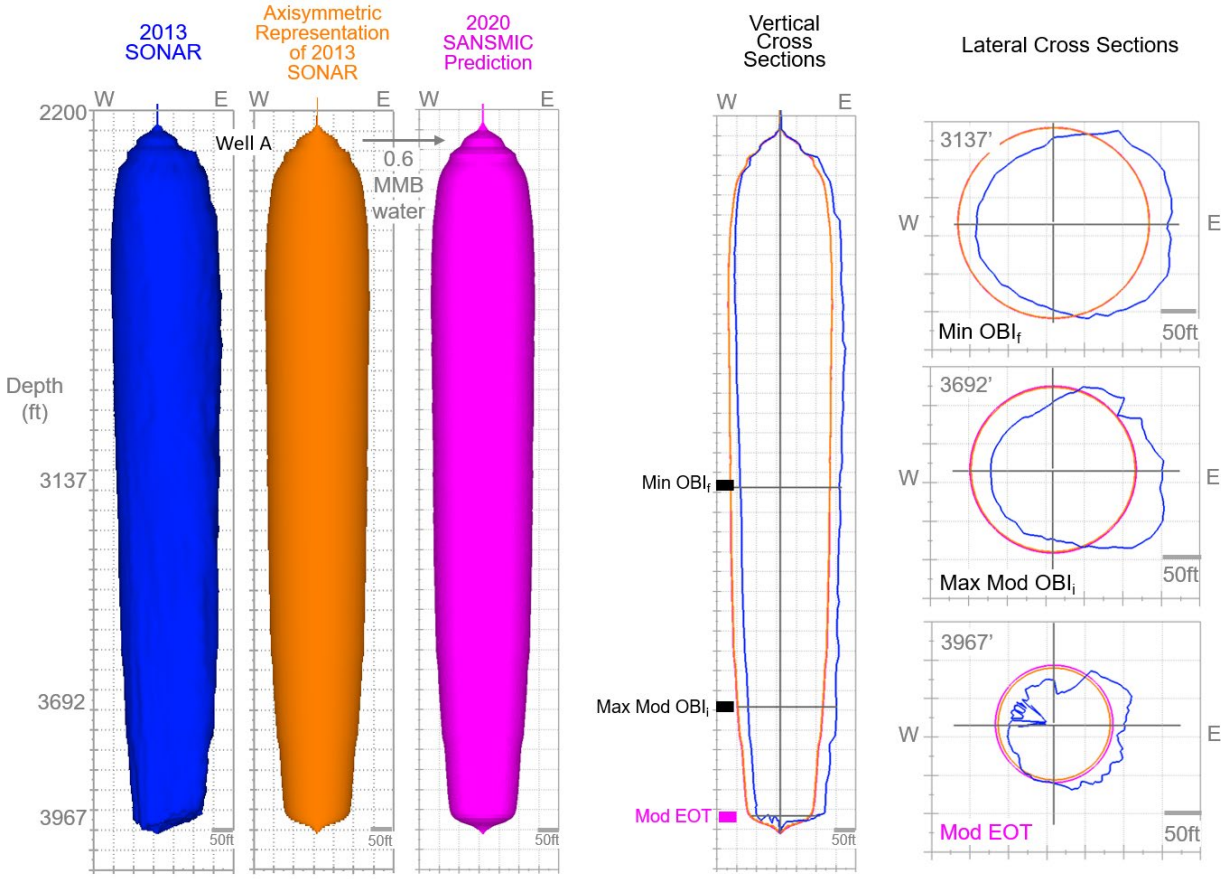

Figure 2-11. BH-105 Modeling Results for Leaching Between 2013 Sonar and End of CY20.

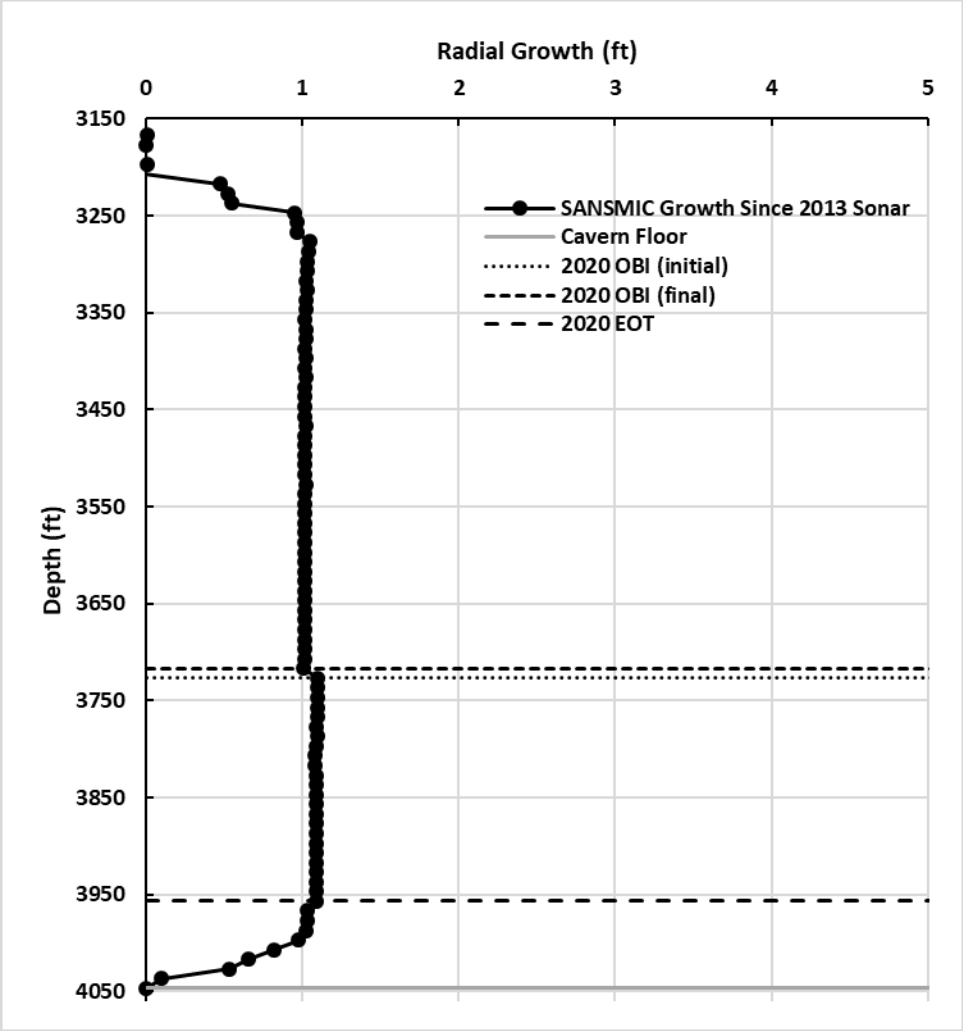

Figure 2-12. BH-105 SANSMIC-Predicted Radial Growth since 2013 Sonar (exaggerated horizontal scale).

2.1.5. BH-107

2.1.5.1. Leaching History

Sonars taken in the A well of BH-107 in 2010 and 2019 are shown in Figure 2-13. Floor rise and spread occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical cross sections. There was 2.9 MMB of water injected into this cavern between sonars which contributed to this change in cavern shape. Leaching was primarily radial from 2010 to 2019, but it concentrated in a small zone near 4020 ft depth. Continued growth of that feature could be geomechanically unfavorable.

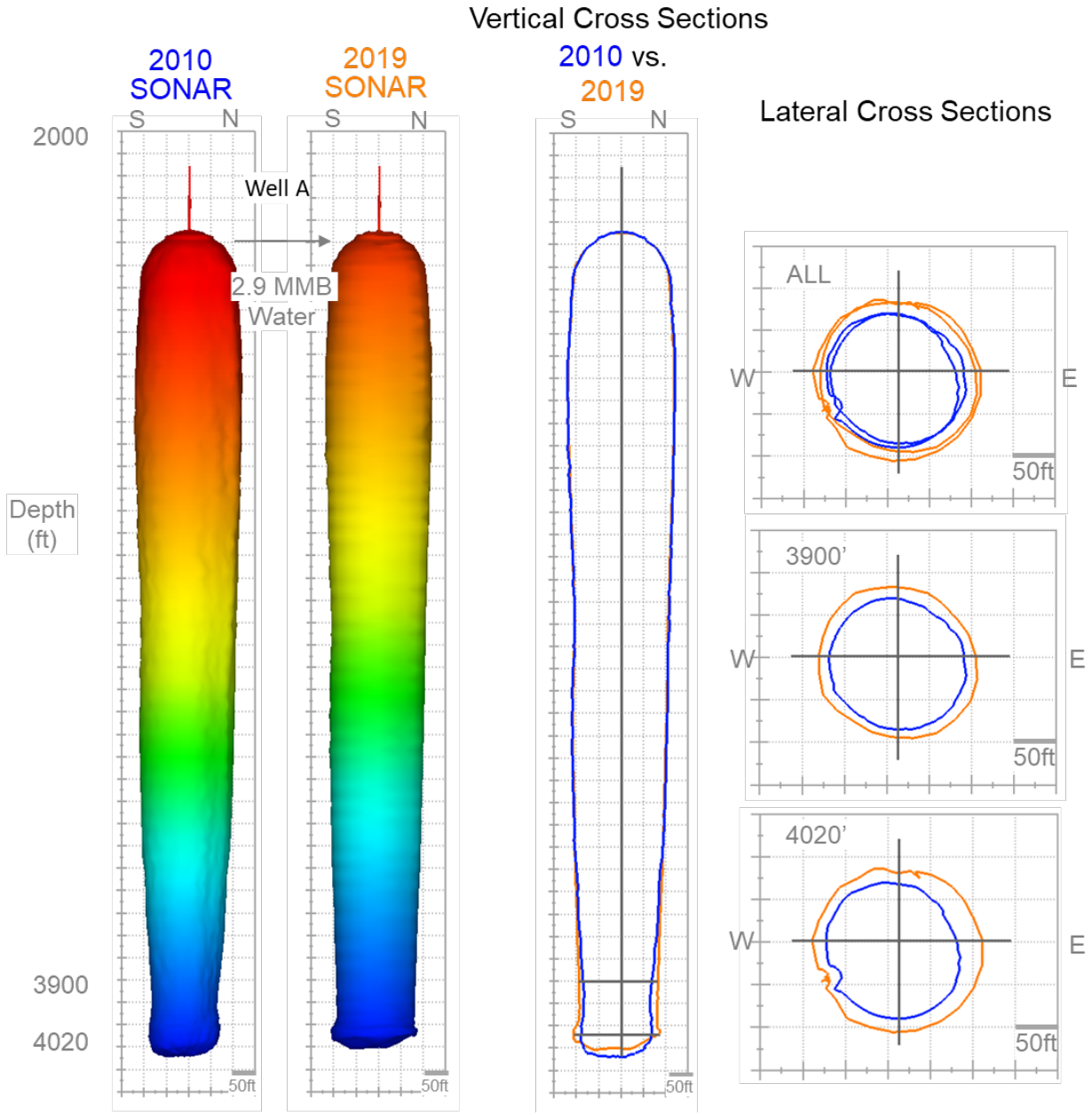

Figure 2-13. Leaching history in BH-107 from 2010 (blue) to 2019 (orange) via sonars in well A.

2.1.5.2. Simulated Leaching Between 2019 Sonar and End of CY20

The last sonar taken in BH-107 was in 2019. Since that sonar, over 0.4 MMB of water was injected into the cavern. The injections occurred over 14 days in 2020 (see Table 2-10). The injection history was modeled using a single leaching phase with an EP of 60 days.

Table 2-10. Summary of Simulation Input for BH-107

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	09/04/20-10/05/20	4090	20	10	598	600	31,981	14	447,734

The final outlet SG was 1.2000, suggesting that leaching was near completion at the end of the EP. As summarized in Table 2-11, the leaching efficiency for this cavern was 15.0%.

Table 2-11. Summary of Simulation Output for BH-107

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	670	1.200	67,000	15.0

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2019 sonar and the end of CY20 (see Figure 2-14). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.4 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which include the slight radial spread of the cavern floor. The spread can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-6) that is about 350 ft tall and reflects the large distance between OBI and EOT. The radial growth over this depth is predicted to be only about 1 ft. Monitoring of the flare feature observed near the floor in the 2019 sonar has been previously recommended [8]. The observed features have grown in size with the modeled CY20 leaching, with the flare being the larger feature. Continued monitoring of the flare is recommended.

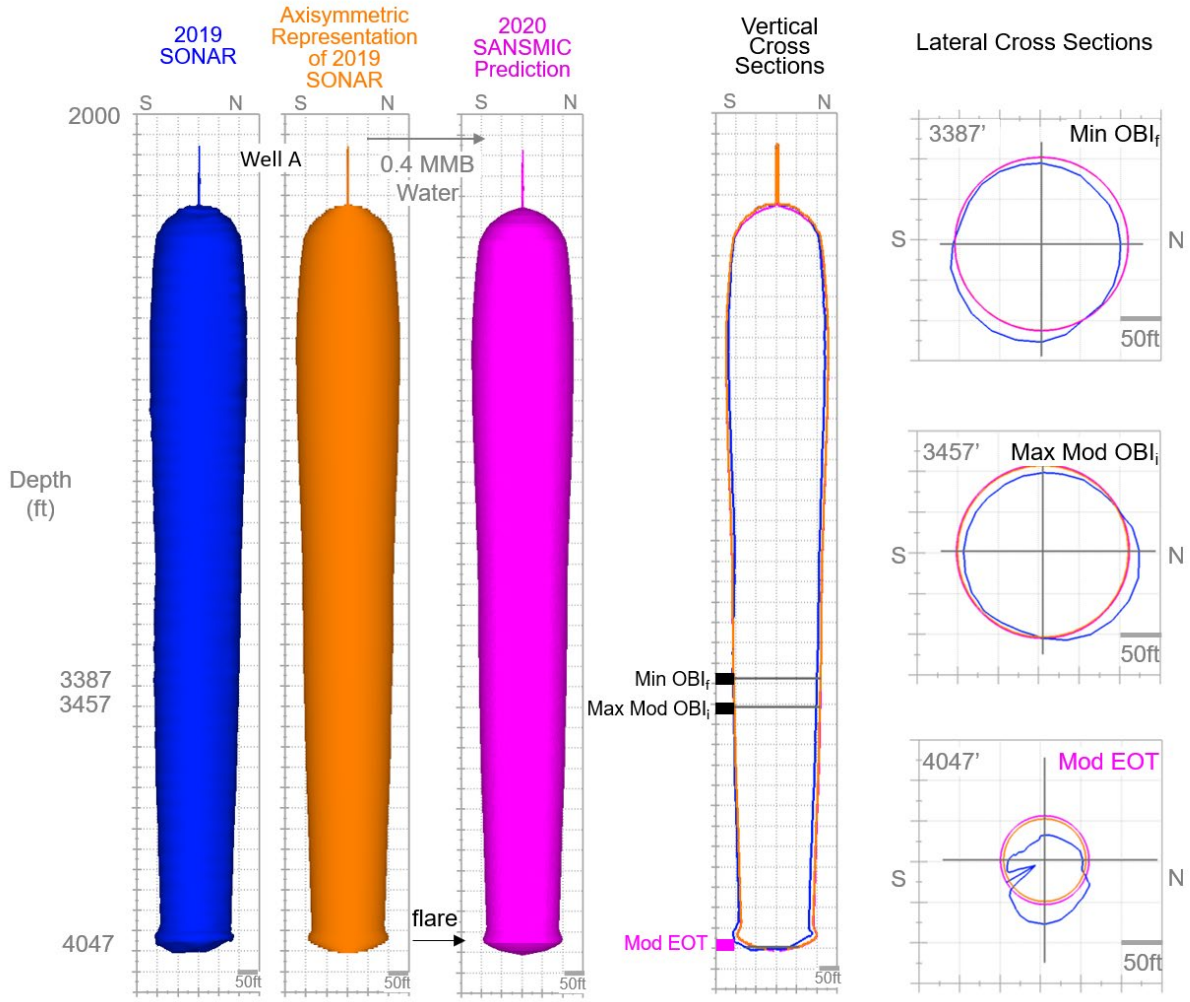

Figure 2-14. BH-107 Modeling Results for Leaching Between 2019 Sonar and End of CY20.

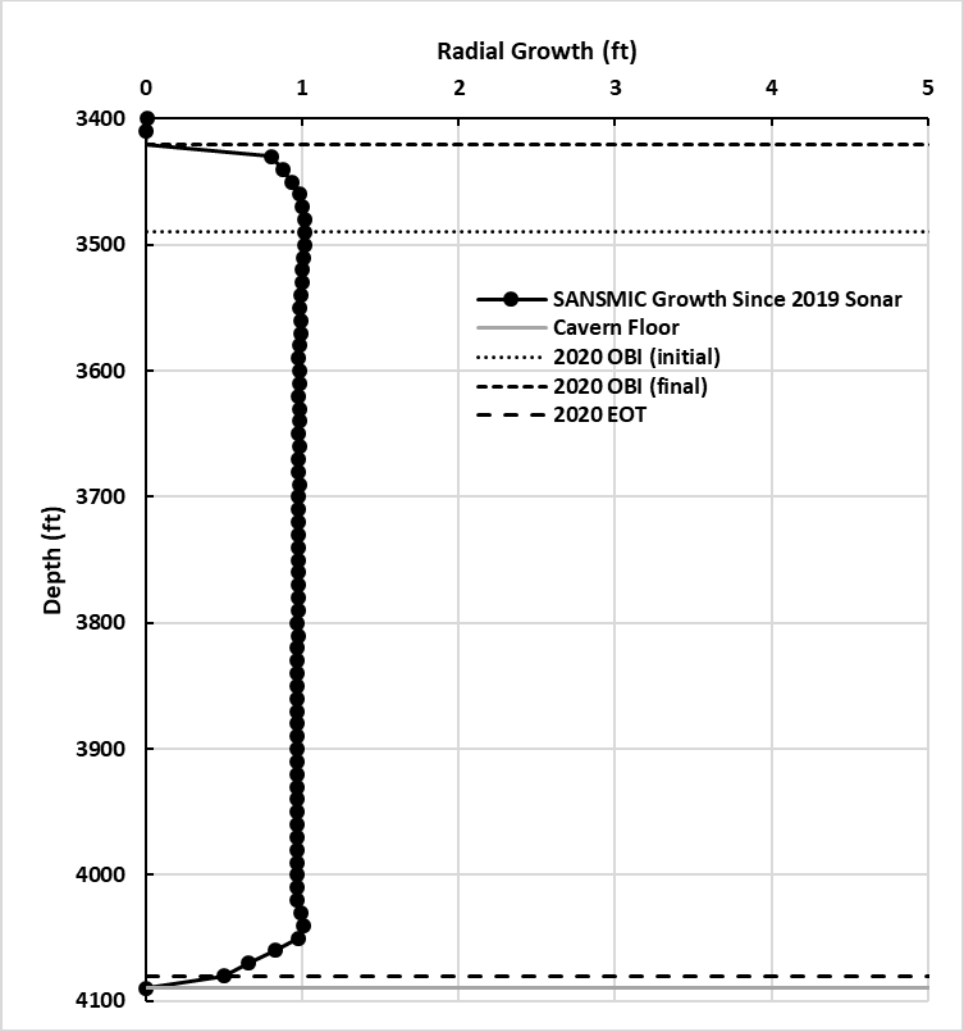

Figure 2-15. BH-107 SANSMIC-Predicted Radial Growth since 2019 Sonar (exaggerated horizontal scale).

2.1.6. BH-108

2.1.6.1. Leaching History

Sonars taken in the A well of BH-108 in 2015 and 2019 are shown in Figure 2-16. Floor rise occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 3.9 MMB of water injected into this cavern between sonars which contributed to some change in cavern shape. One notable feature in the lateral cross section at 4000 ft depth is the presence of two notches in the cavern wall in the northeast and southwest. These notches were not in the lateral cavern profile at 4000 ft depth in 2015 and may represent a geologic control on cavern leaching. That same feature is evident in both the 2015 and 2019 lateral cross sections at 3050 ft, suggesting that geologic control extends vertically along the cavern. Despite that feature, leaching was primarily radial from 2015 to 2019 suggesting radial leaching should be expected for the 0.8 MMB of water that was injected since the 2019 sonar.

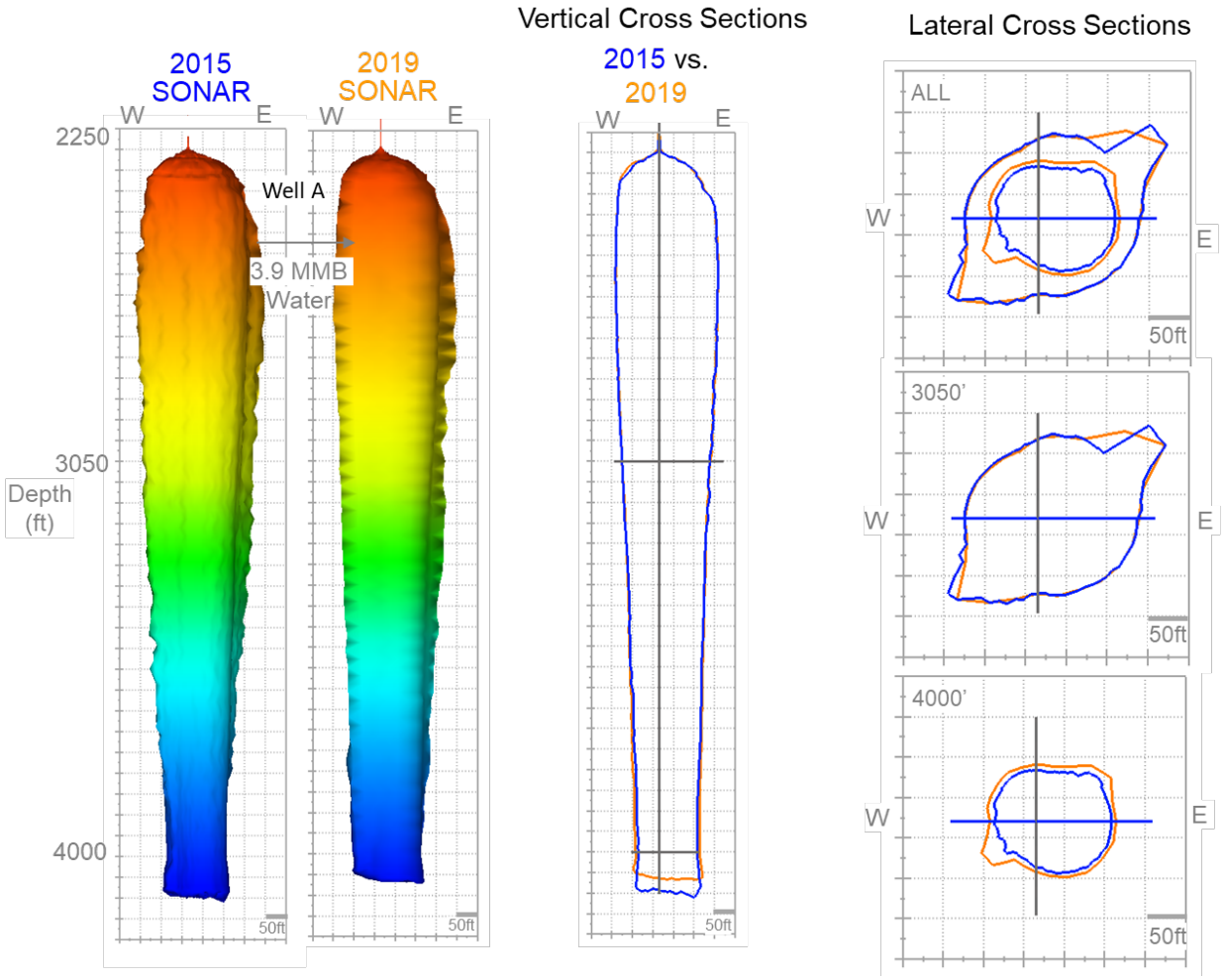

Figure 2-16. Leaching history in BH-108 from 2015 (blue) to 2019 (orange) via sonars in well A.

2.1.6.2. Simulated Leaching Between 2019 Sonar and End of CY20

The last sonar taken in BH-108 was in 2019. Since that sonar, around 0.8 MMB of water have been injected into the cavern in 2020 (see Table 2-12). The injection history was modeled using two separate leaching phases with an EP of 60 days following each injection phase. A single Mod EOT rise was used for both phases, but in the second phase, the OBI was selected to reflect oil entering the cavern between the two leaching time periods.

Table 2-12. Summary of Simulation Input for BH-108

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	01/23/20-01/30/20	4105	116	110	913	910	63,287	6	379,722
2	09/04/20-10/07/20	4105	116	110	959	960	30,415	15	456,225
ALL	N/A	N/A	N/A	N/A	N/A	N/A	N/A	21	835,947

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of the final EP. As summarized in Table 2-13, the leaching efficiency for this cavern was 15.1%.

Table 2-13. Summary of Simulation Output for BH-108

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	970	1.2003	57,000	15.0
2	1020	1.2003	69,000	15.1
ALL	1020	1.2003	126,000	15.1

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2019 sonar and the end of CY20 (see Figure 2-17). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.8 MMB.

Vertical cross sections from each of the cavern geometries reveal only slight changes from leaching. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-18) that is about 800 ft tall and reflects the large distance between OBI and EOT. The radial growth over this depth is predicted to be only about 1 ft. The development of a shelf in addition to a flare near the cavern floor when considering the SANSMIC results have been noted previously [8]; however, the 2019 sonar showed no shelf and only a slight flare (the likely difference is due to floor rise, which SANSMIC does not predict). Monitoring the features observed in the CY18-19 SANSMIC results has been recommended [8], but the 2019 sonar and CY20 SANSMIC results do not indicate any leaching-induced features which may be of concern for this cavern at this time.

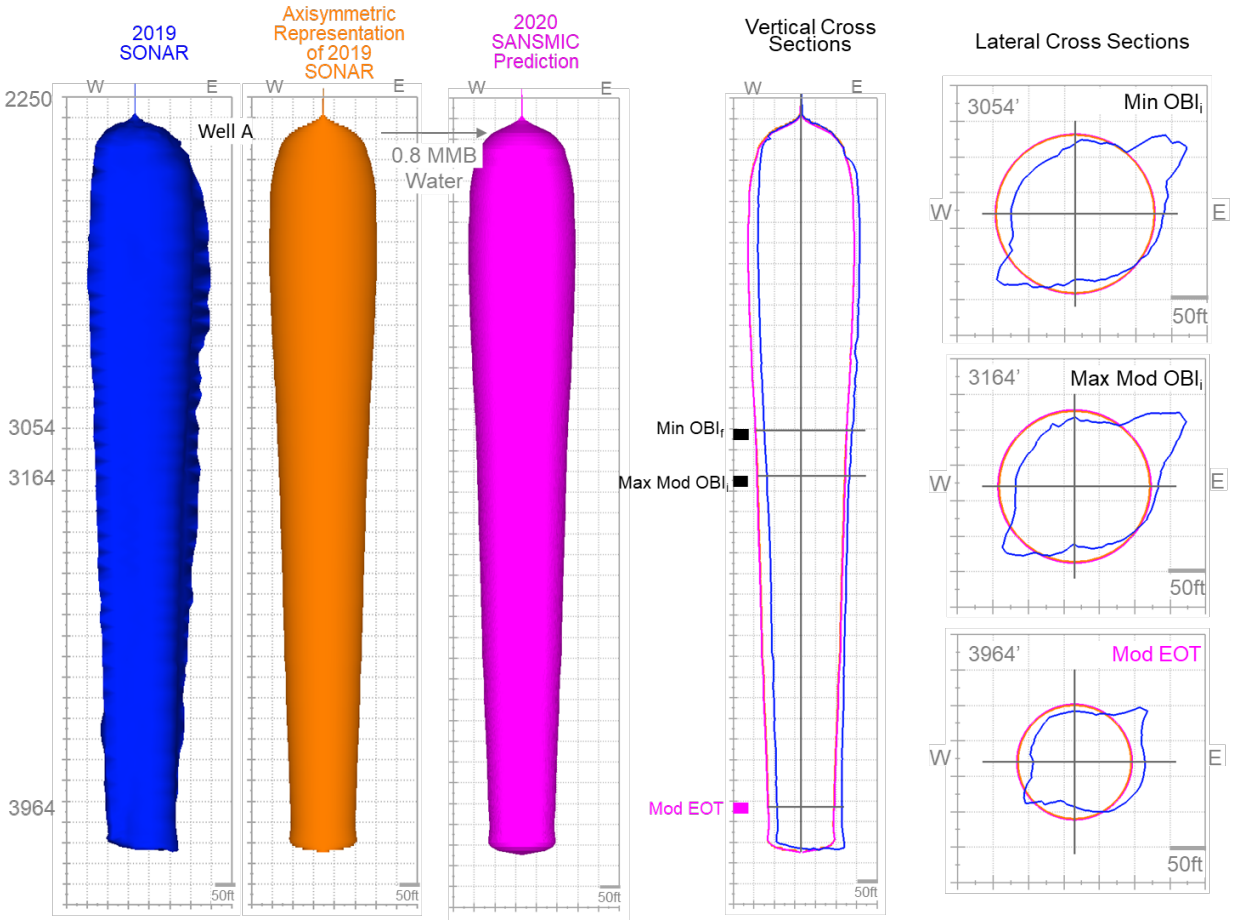

Figure 2-17. BH-108 Modeling Results for Leaching Between 2019 Sonar and End of CY20.

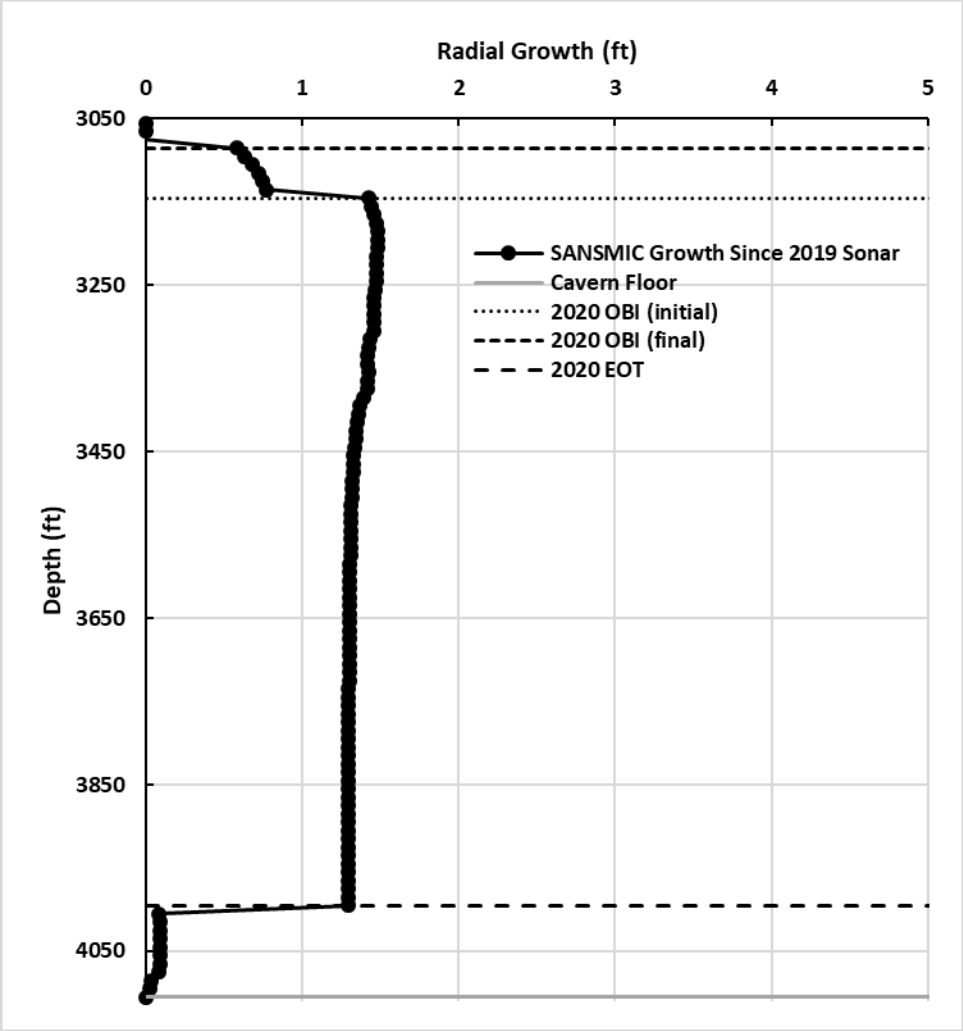

Figure 2-18. BH-108 SANSMIC-Predicted Radial Growth since 2019 Sonar (exaggerated horizontal scale).

2.1.7. BH-109

2.1.7.1. Leaching History

Sonars taken in the A well of BH-109 in 2015 and 2020 are shown in Figure 2-19. Floor rise occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 3.2 MMB of water injected into this cavern between sonars which contributed to the observed change in cavern shape. Leaching was primarily radial from 2015 to 2020, suggesting that radial leaching should be expected for the 0.08 MMB of water that has been injected since the 2020 sonar.

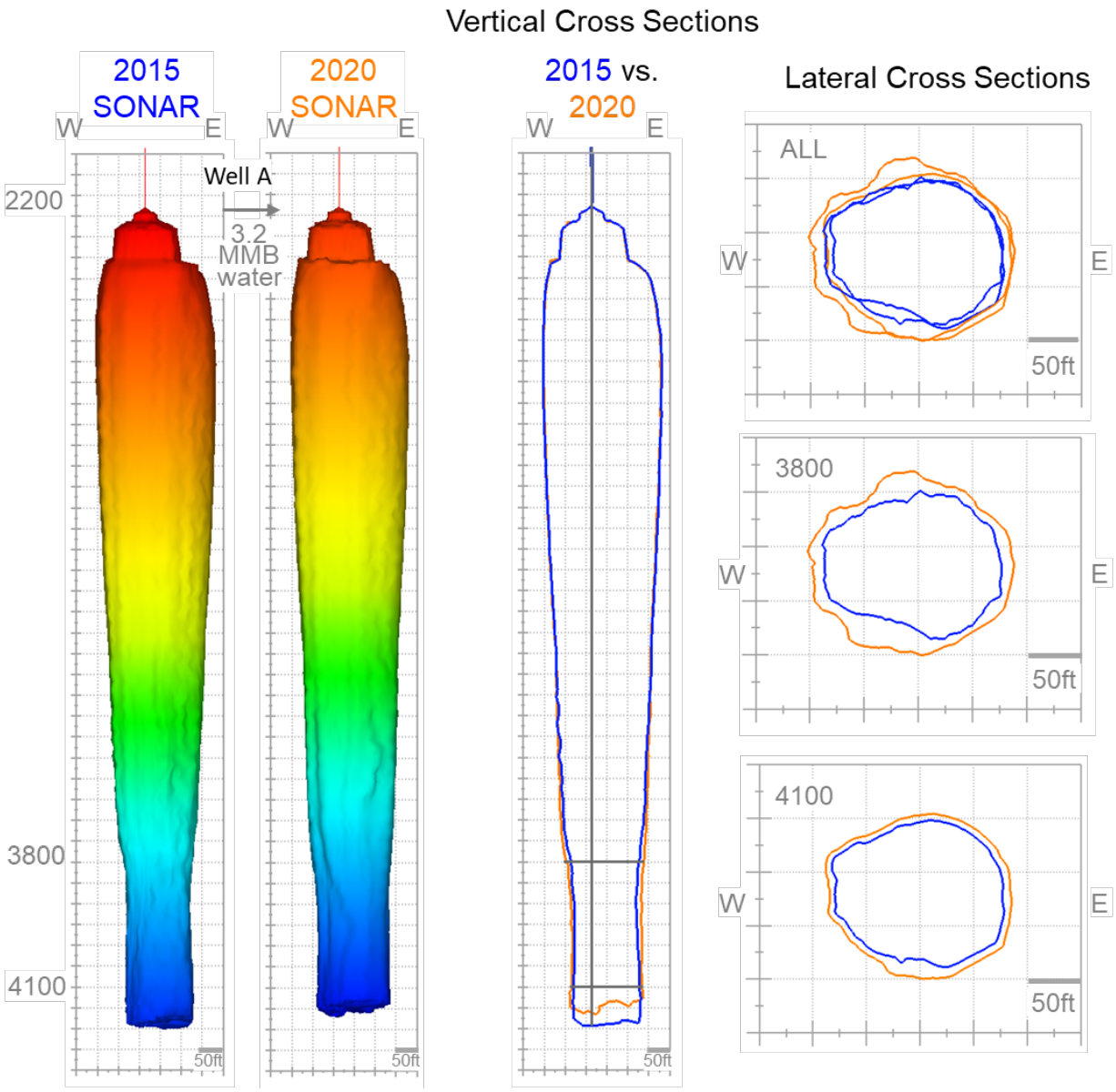

Figure 2-19. Leaching history in BH-109 from 2015 (blue) to 2020 (orange) via sonars in well A.

2.1.7.2. Simulated Leaching Between 2020 Sonar and End of CY20

The last sonar taken in BH-109 was in 2020. Since that sonar, around 84 MB of water has been injected into the cavern over two days in 2020 (see Table 2-14). The injection history was modeled using a single leaching phase with an EP of 60 days.

Table 2-14. Summary of Simulation Input for BH-109

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	09/04/20-09/05/20	4205	426	420	767	770	42,190	2	84,380

The final outlet SG was close to the value of 1.2, suggesting that leaching was near completion at the end of the EP. As summarized in Table 2-15, the leaching efficiency for this cavern was 15.4%.

Table 2-15. Summary of Simulation Output for BH-109

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	780	1.2012	13,000	15.4

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2020 sonar and the end of CY20 (see Figure 2-20). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.1 MMB.

Vertical cross sections from each of the cavern geometries reveal only slight changes from leaching. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-21) that is about 700 ft tall and reflects the large distance between OBI and EOT. The radial growth over this depth is predicted to be only about 1 ft. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time. A comparison of the 2020 sonar with 2019 SANSMIC results from [8] can be found in Section 3.1.

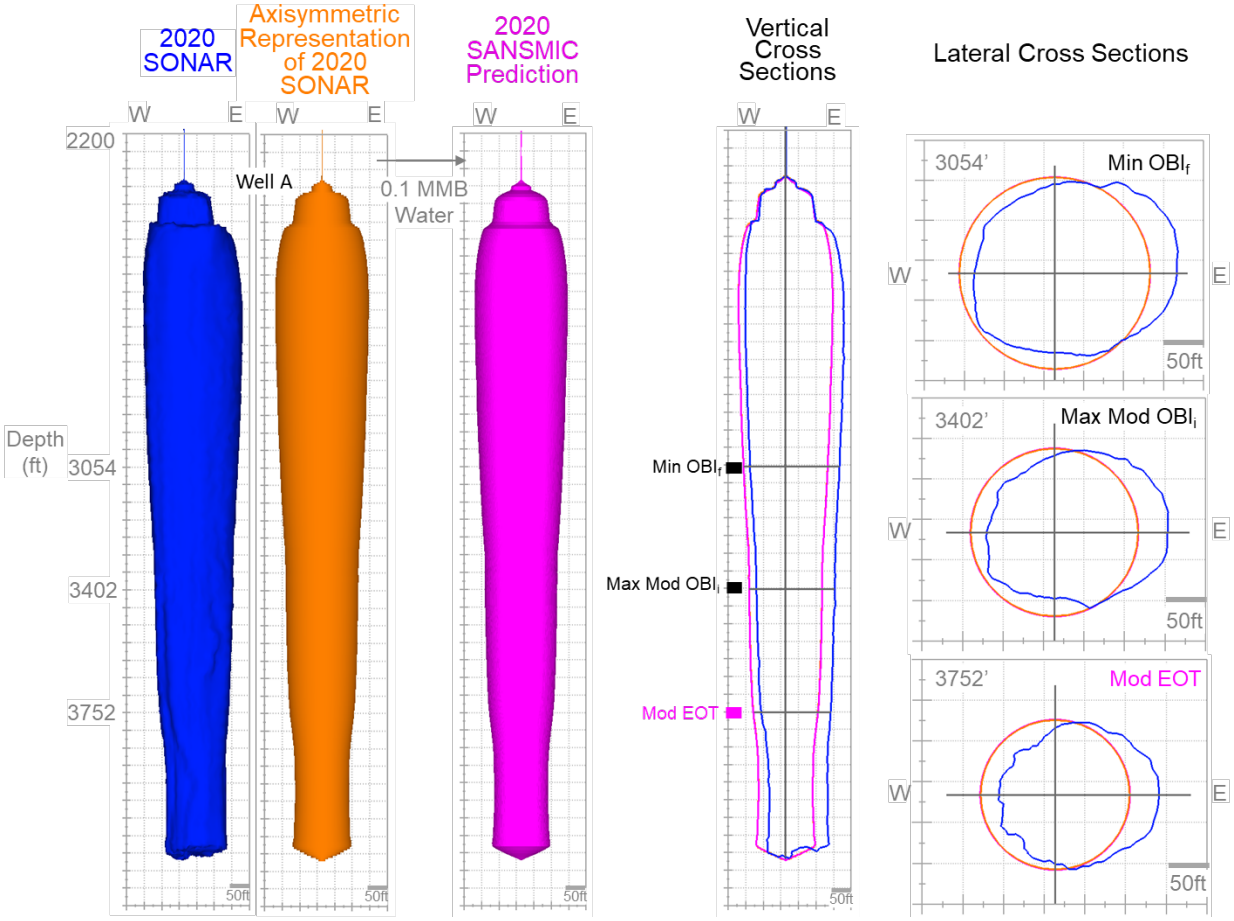

Figure 2-20. BH-109 Modeling Results for Leaching Between 2020 Sonar and End of CY20.

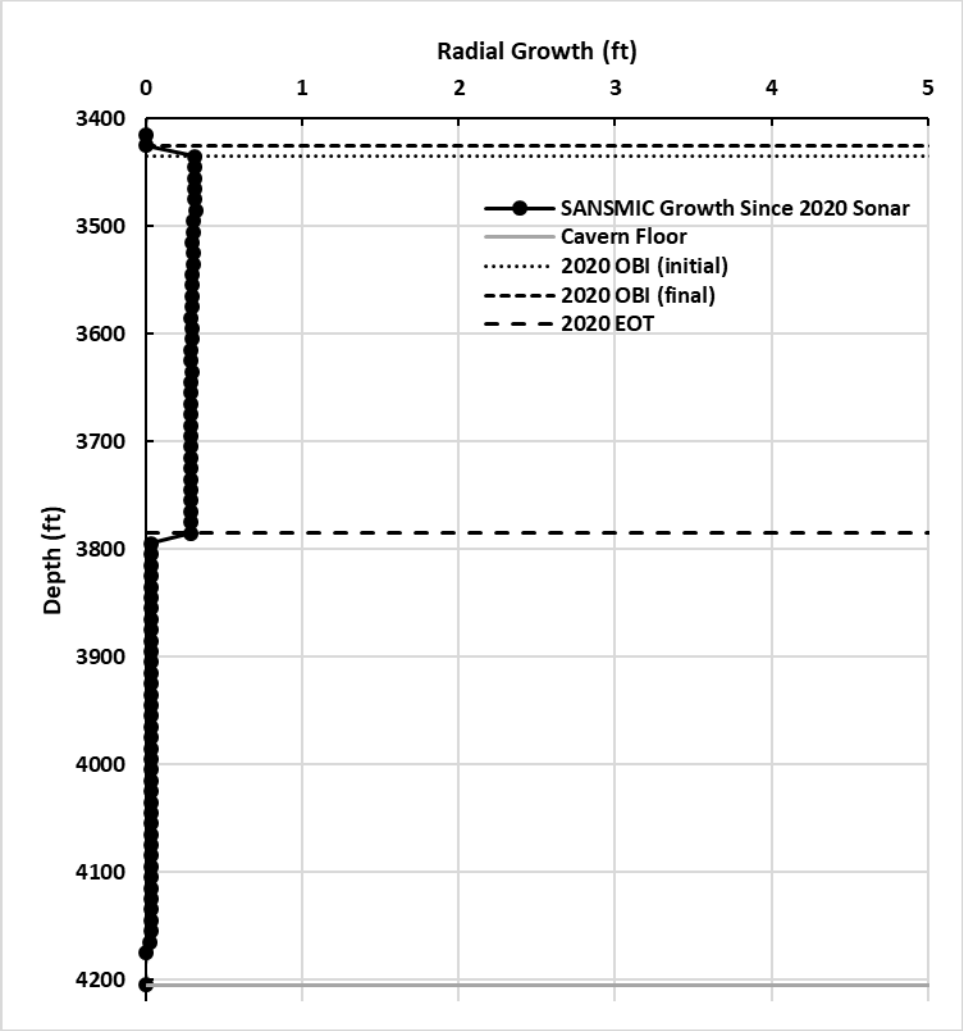

Figure 2-21. BH-109 SANSMIC-Predicted Radial Growth since 2020 Sonar (exaggerated horizontal scale).

2.1.8. BH-110

2.1.8.1. Leaching History

Sonars taken in the A well of BH-110 in 2015 and 2020 are shown in Figure 2-22. Some floor rise and floor spread occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 1.1 MMB of water injected into this cavern between sonars which may have contributed to the change in cavern shape. Leaching was primarily radial from 2015 to 2020, suggesting that radial leaching should be expected for the 0.5 MMB of water that has been injected since the 2020 sonar.

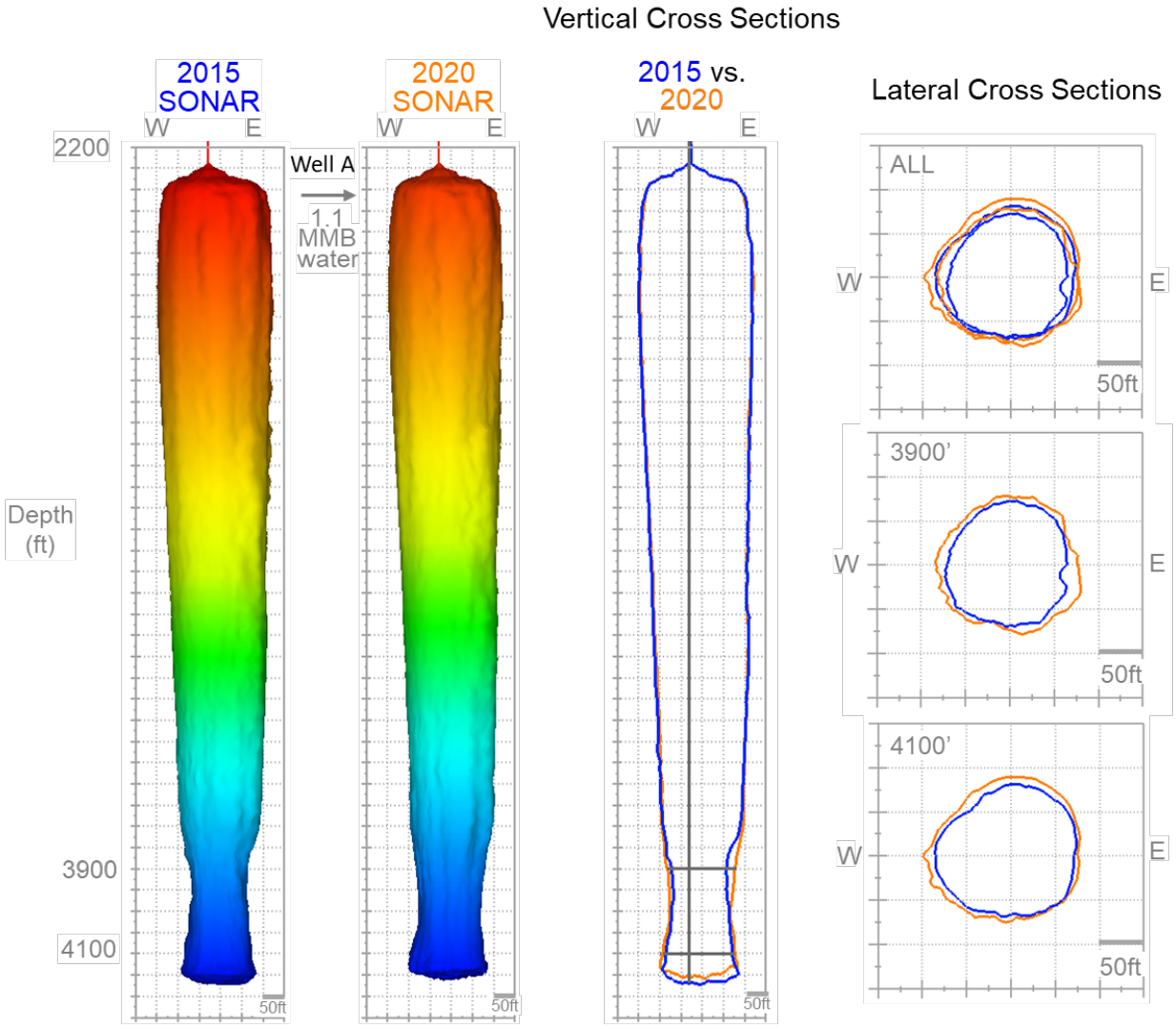

Figure 2-22. Leaching history in BH-110 from 2015 (blue) to 2020 (orange) via sonars in well A.

2.1.8.2. Simulated Leaching Between 2020 Sonar and End of CY20

The last sonar taken in BH-110 was in 2020. Since that sonar, about 0.54 MMB of water have been injected into the cavern over 21 days in 2020 (see Table 2-16). The injection history was modeled using a single leaching phase with an EP of 60 days.

Table 2-16. Summary of Simulation Input for BH-110

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	05/14/20-10/09/20	4197	23	20	481	480	25,651	21	538,671

The final outlet SG was close to the value of 1.2, suggesting that leaching was near completion at the end of the EP. As summarized in Table 2-17, the leaching efficiency for this cavern was 15.6%.

Table 2-17. Summary of Simulation Output for BH-110

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	580	1.2001	84,000	15.6

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2020 sonar and the end of CY20 (see Figure 2-23). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.5 MMB.

Vertical cross sections from each of the cavern geometries reveal only slight changes from leaching. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-24) that is about 500 ft tall and reflects the large distance between OBI and EOT. The radial growth over this depth is predicted to be only about 1 ft. A small growth of the flare near the cavern floor was observed in CY19 leaching work (see Section 3.2). The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time. A comparison of the 2020 sonar with 2019 SANSMIC results from [8] can be found in Section 3.2.

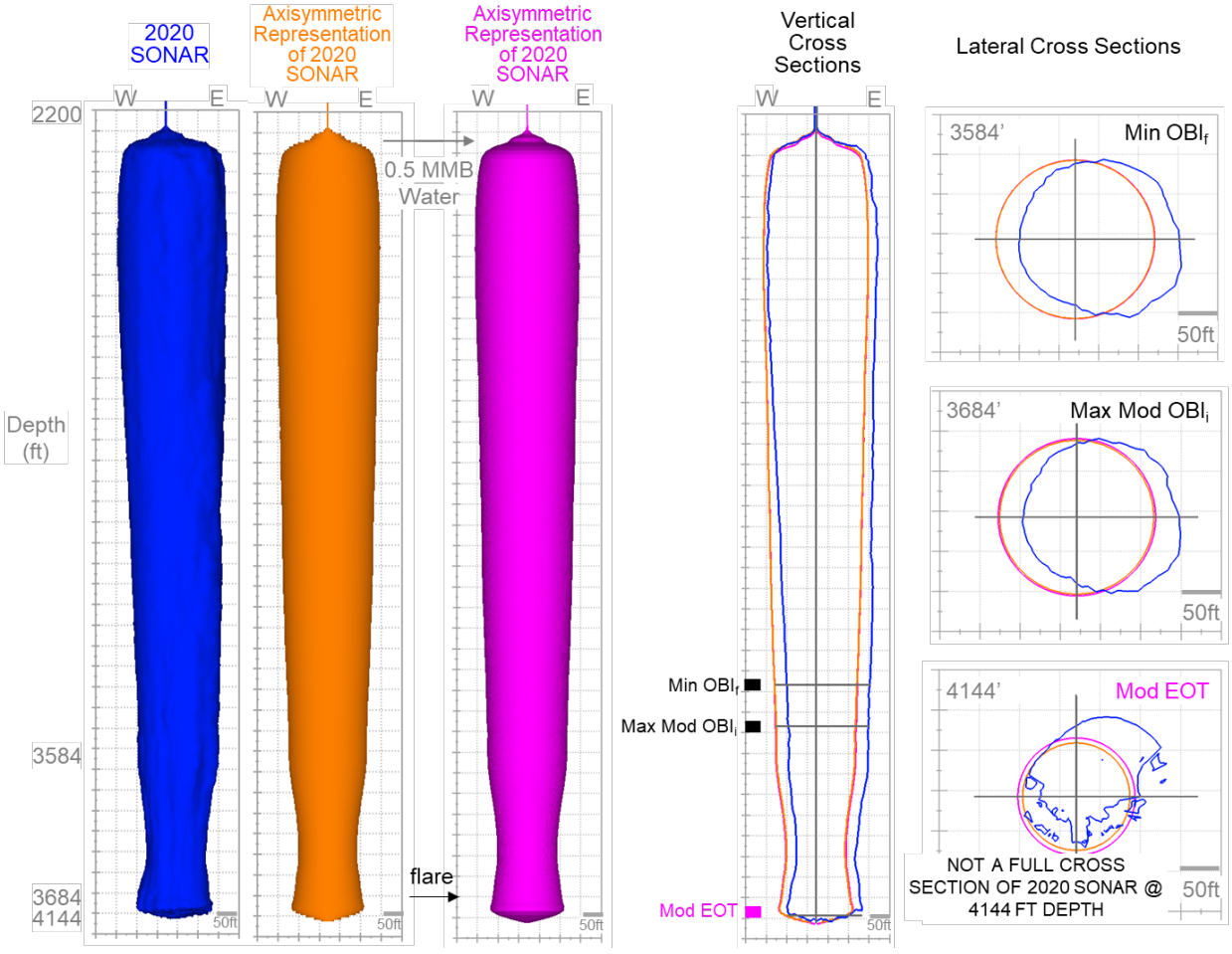

Figure 2-23. BH-110 Modeling Results for Leaching Between 2020 Sonar and End of CY20.

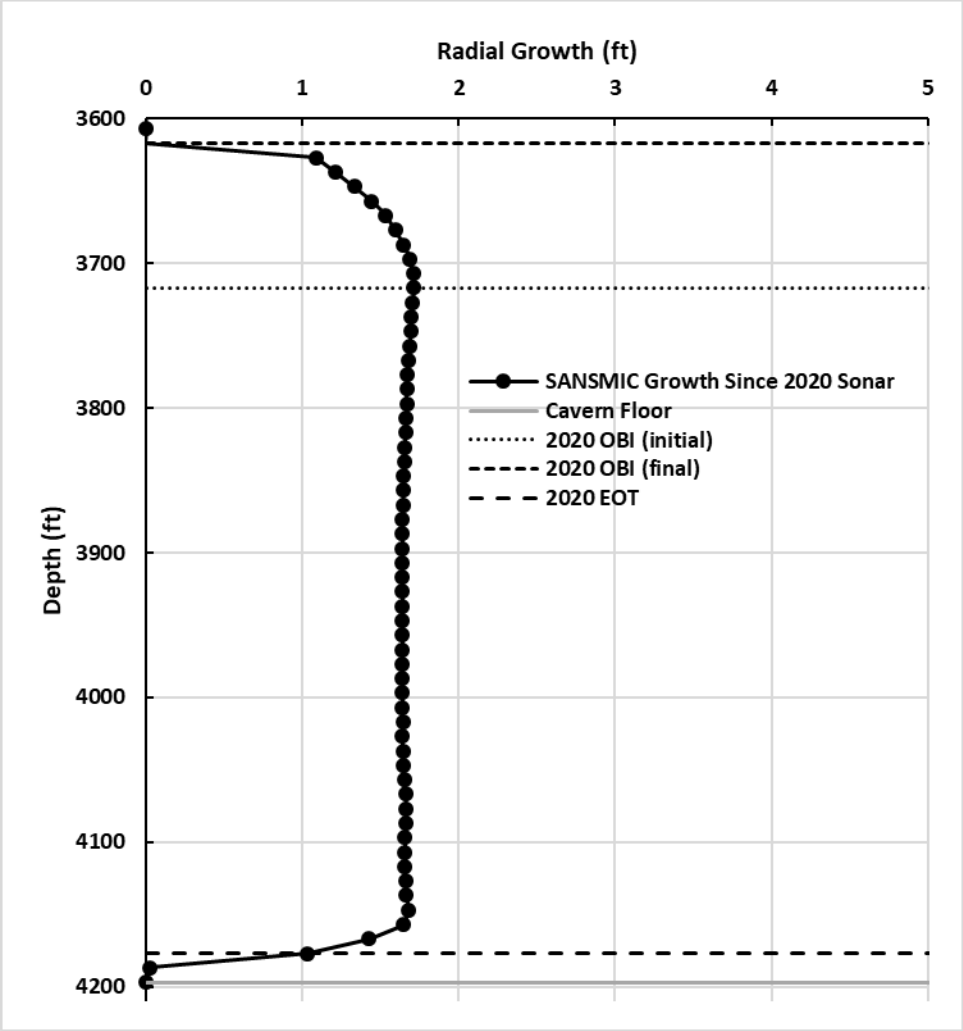

Figure 2-24. BH-110 SANSMIC-Predicted Radial Growth since 2020 Sonar (exaggerated horizontal scale).

2.1.9. BH-113

2.1.9.1. Leaching History

Sonars taken in the A well of BH-113 in 2003 and 2015 are shown in Figure 2-25. No floor rise was observed in this cavern between sonars as evidenced in the lack of change in cavern wall positions near the floor in the vertical and lateral cross sections. Only 0.2 MMB of water was injected into this cavern between sonars and so very little change in cavern shape is observed, but the change is relatively radial, suggesting that radial leaching should be expected for the 0.3 MMB of water that has been injected since the 2015 sonar.

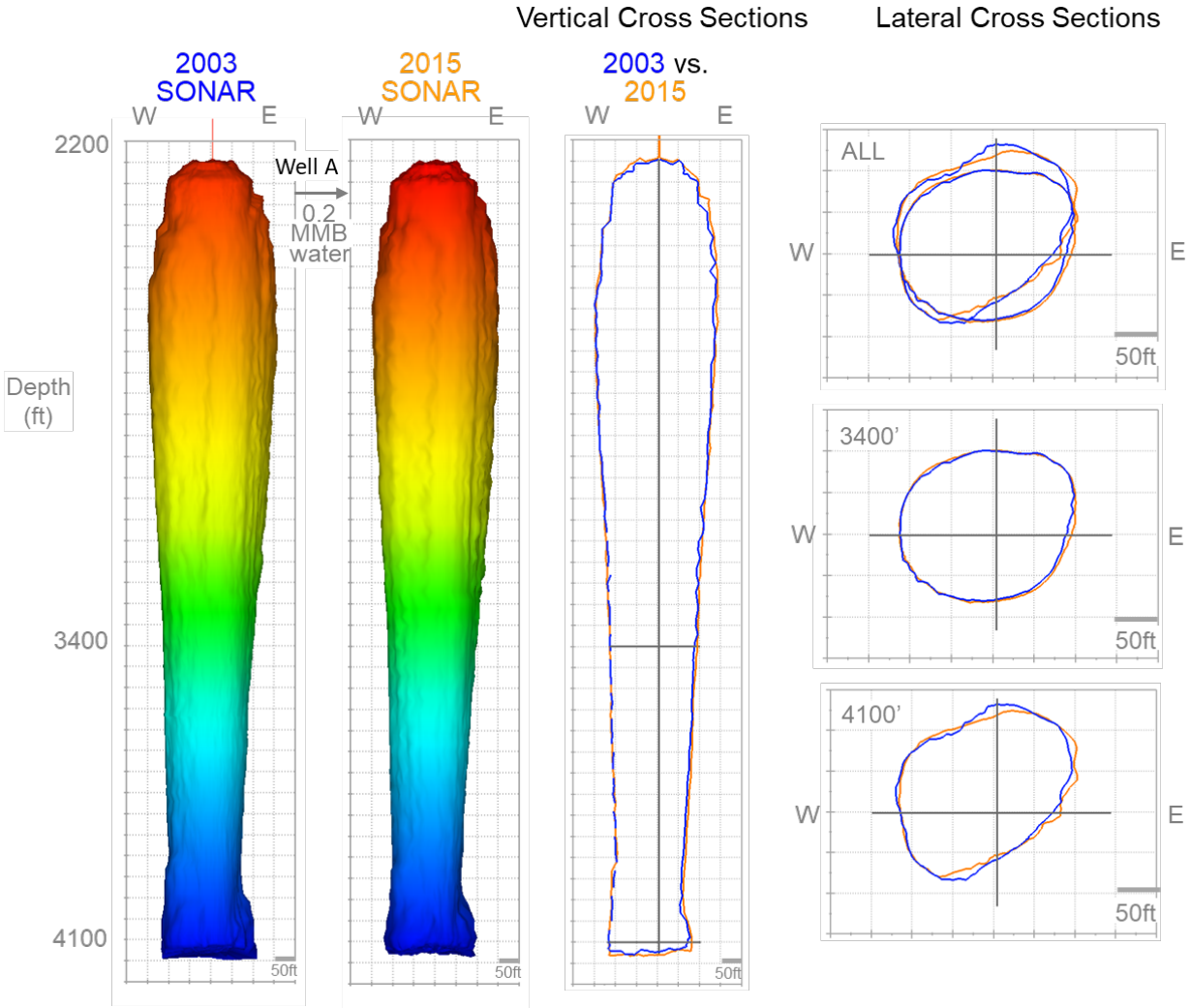

Figure 2-25. Leaching history in BH-113 from 2003 (blue) to 2015 (orange) via sonars in well A.

2.1.9.2. Simulated Leaching Between 2015 Sonar and End of CY20

The last sonar taken in BH-113 was in 2015. Since that sonar, around 0.31 MMB of water have been injected into the cavern over 10 days in 2020 (see Table 2-18) (additionally, less than 3 MB were injected on one day in 2017, but that small amount is not included in the modeling here). The injection history was modeled using a single phase of leaching with an EP of 60 days. Leaching in this cavern was not modeled for the CY17 [6] or CY18/19 [8] leaching reports.

Table 2-18. Summary of Simulation Input for BH-113

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	09/08/20-10/09/20	4167	17	10	49	50	31,173	10	311,730

The final outlet SG was close to the value of 1.2, suggesting that leaching was near completion at the end of the EP. As summarized in Table 2-19, the leaching efficiency for this cavern was 15.1%.

Table 2-19. Summary of Simulation Output for BH-113

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	100	1.1968	47,000	15.1

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2015 sonar and the end of CY20 (see Figure 2-26). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.3 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which include the slight radial spread of the cavern floor. The spread can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-27) that is about 100 ft tall. The maximum radial growth over this depth is predicted to be about 5 ft. The 2015 sonar shows a flare near the floor that could potentially grow with additional small leaches. Continued monitoring of the flare is recommended.

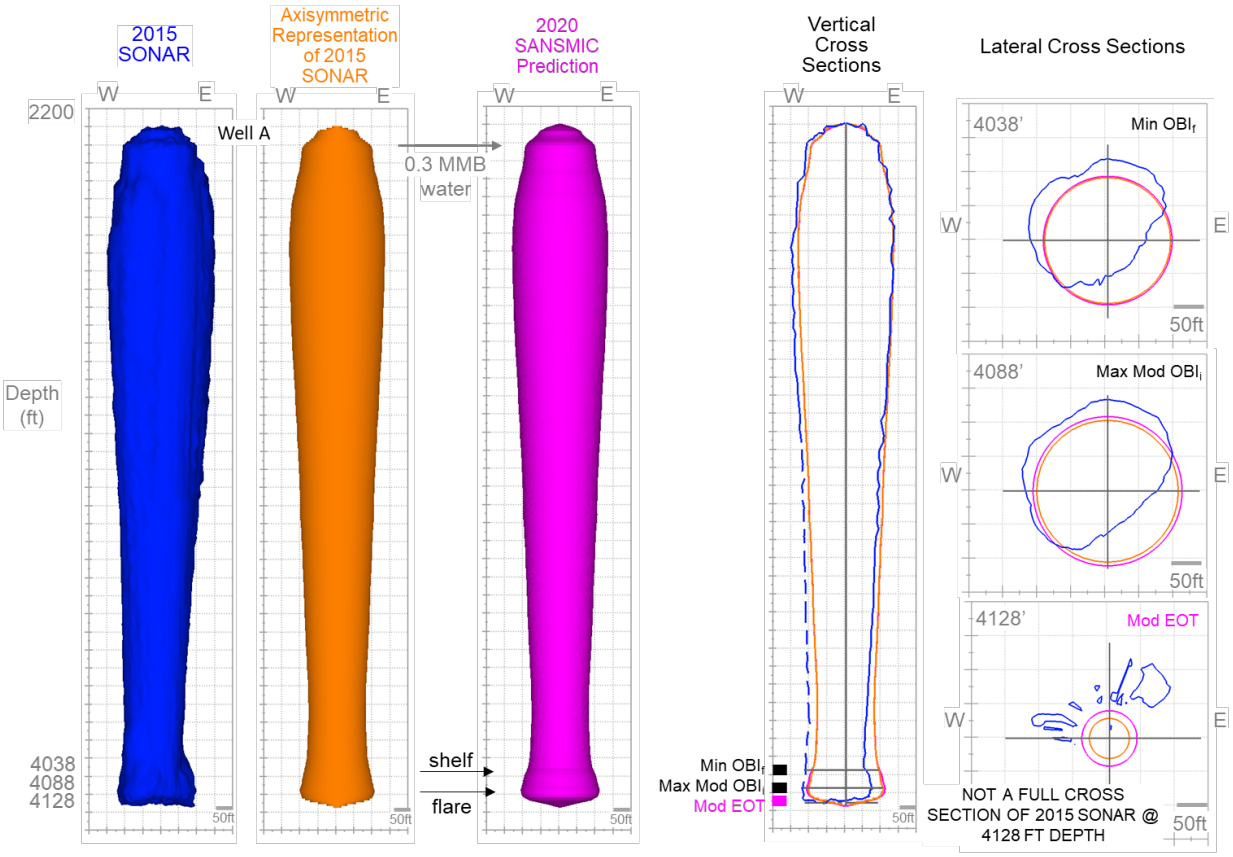

Figure 2-26. BH-113 Modeling Results for Leaching Between 2015 Sonar and End of CY20.

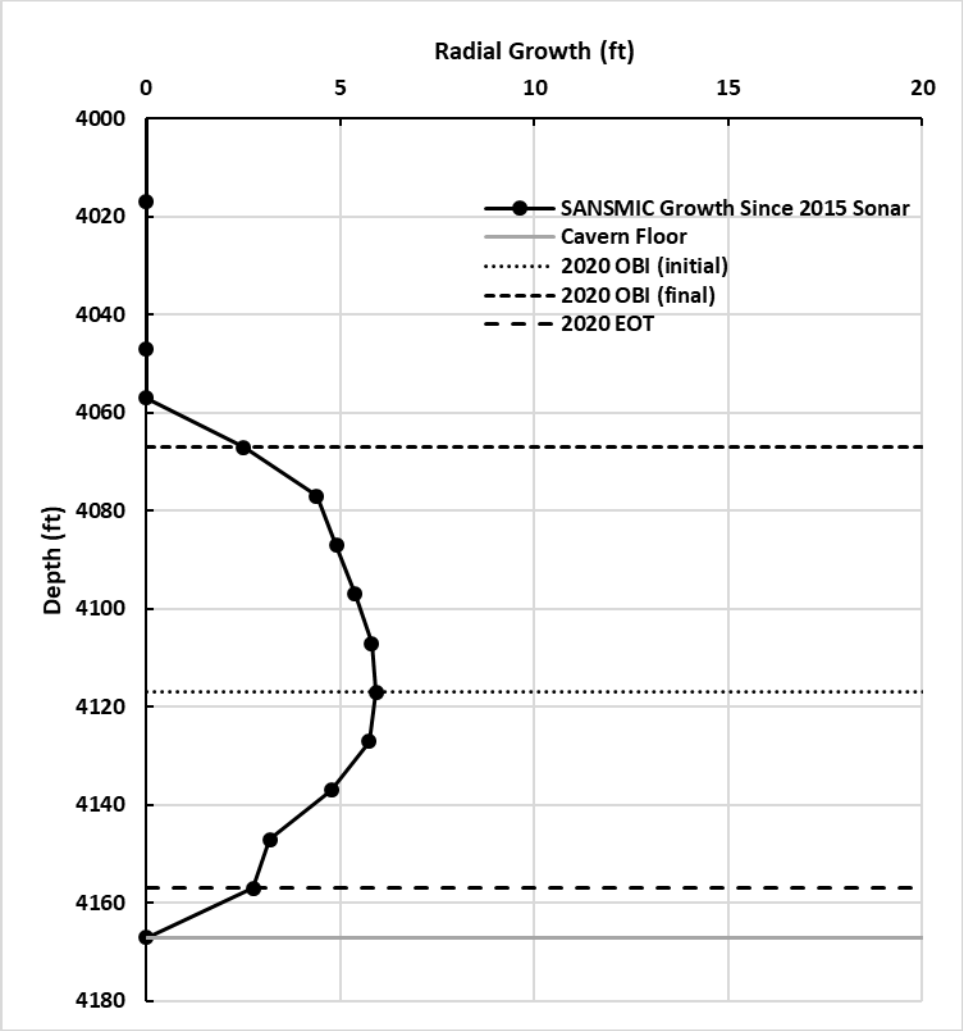

Figure 2-27. BH-113 SANSMIC-Predicted Radial Growth since 2015 Sonar (exaggerated horizontal scale).

2.1.10. BH-114

2.1.10.1. Leaching History

Sonars taken in the A well of BH-114 in 2003 and 2013 are shown in Figure 2-28. Very little change occurred in this cavern between sonars as evidenced by the lack of changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 0.2 MMB of water injected into this cavern between sonars which is why leaching may not have contributed to a change in cavern shape. Without leaching from 2003 to 2013, there is no data to inform the leaching pattern associated with the 3.6 MMB of water that has been injected since the 2013 sonar.

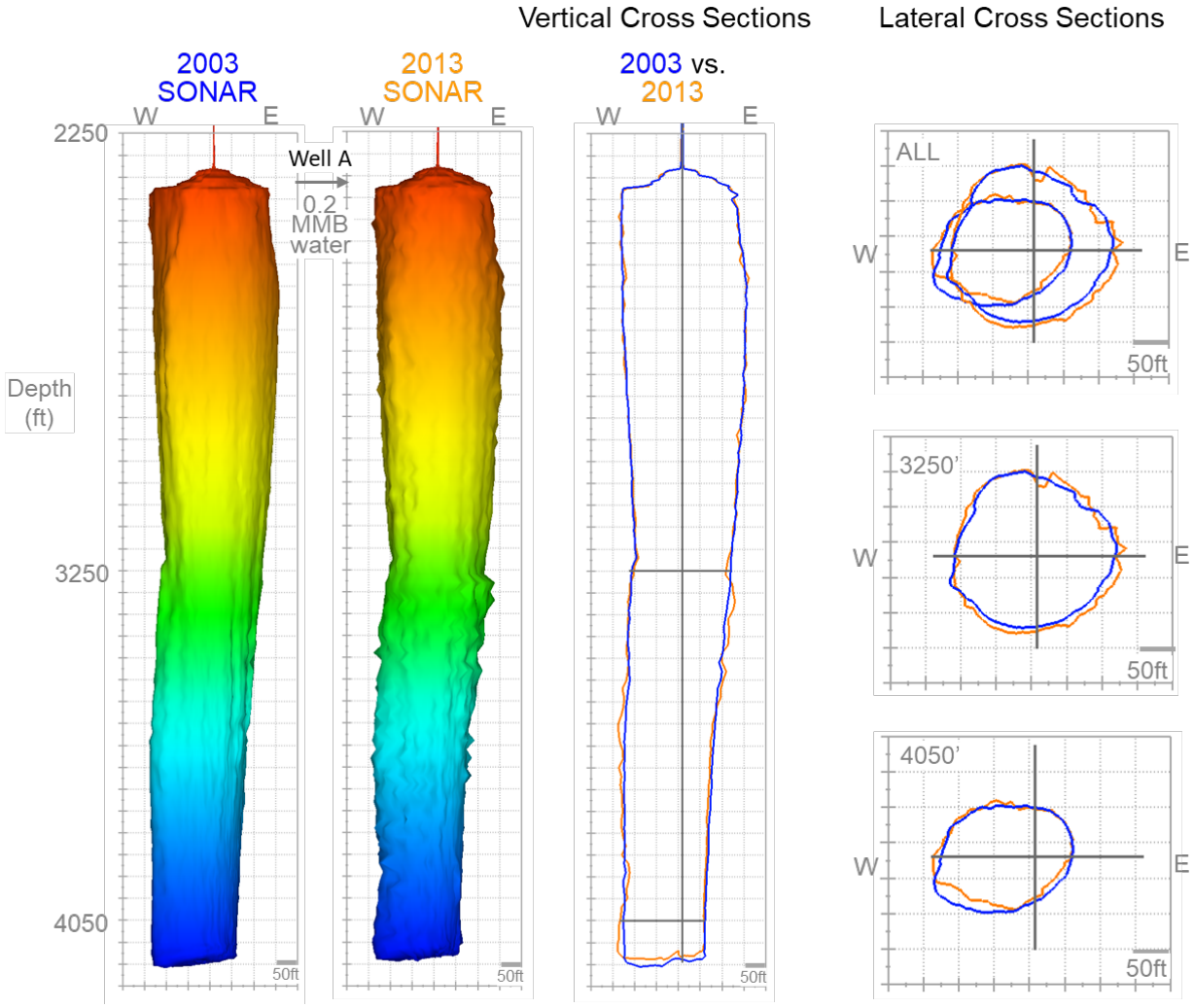

Figure 2-28. Leaching history in BH-114 from 2003 (blue) to 2013 (orange) via sonars in well A.

2.1.10.2. Simulated Leaching Between 2013 Sonar and End of CY20

The last sonar taken in BH-114 was in 2013. Since that sonar, around 3.6 MMB of water have been injected into the cavern in 2016-2020 (see Table 2-20). The injection history was modeled using seven separate leaching phases with an EP of 60 days following each injection phase. To represent CY20 water injection, a single phase was added to the six phases modeled for the CY18-19 report [8]. The initial OBI rises for phases 2, 3, 4, and 6 were automatically selected by SANSMIC based on the final OBI rises in the previous leaching stages. This cavern has had two Mod EOT rises.

Table 2-20. Summary of Simulation Input for BH-114

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	01/11/16-01/14/16	4146	17	10	36	40	45,281	4	181,124
2	02/25/17-05/07/17	4146	17	10	Auto	80	12,398	72	892,656
3	11/29/17-11/30/17	4146	17	10	Auto	310	24,500	2	49,000
4	04/19/18-05/30/18	4146	17	10	Auto	320	27,748	22	610,456
5	09/15/18-12/23/18	4146	49	40	468	470	7,103	3	21,309
6	05/03/19-05/13/19	4146	49	40	Auto	470	33,220	8	265,760
7	08/01/20-10/09/20	4146	49	40	217	220	39,396	41	1,615,236
ALL	N/A	N/A	N/A	N/A	N/A	N/A	N/A	152	3,635,541

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of the final EP. As summarized in Table 2-21, the leaching efficiency for this cavern was 16.2%.

Table 2-21. Summary of Simulation Output for BH-114

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	80	1.9760	31,000	17.1
2	310	1.1997	148,000	16.6
3	320	1.2012	10,000	20.4
4	460	1.1994	100,000	16.4
5	470	1.2019	3,000	14.1
6	530	1.2004	42,000	15.8
7	550	1.1988	256,000	15.8
ALL	550	1.1988	590,000	16.2

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2013 sonar and the end of CY20 (see Figure 2-29). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 3.6 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which include the slight radial spread of the cavern floor. The spread can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-30) that is about 400 ft tall and reflects the variation in OBI since the 2013 sonar, as well as a relatively large distance between OBI and EOT. The maximum radial growth is near the EOT and predicted to be more than 20 ft. Monitoring of the shelf and flare features observed near the floor in the 2019 SANSMIC results has been previously recommended [8]. Continued monitoring of the flare is recommended.

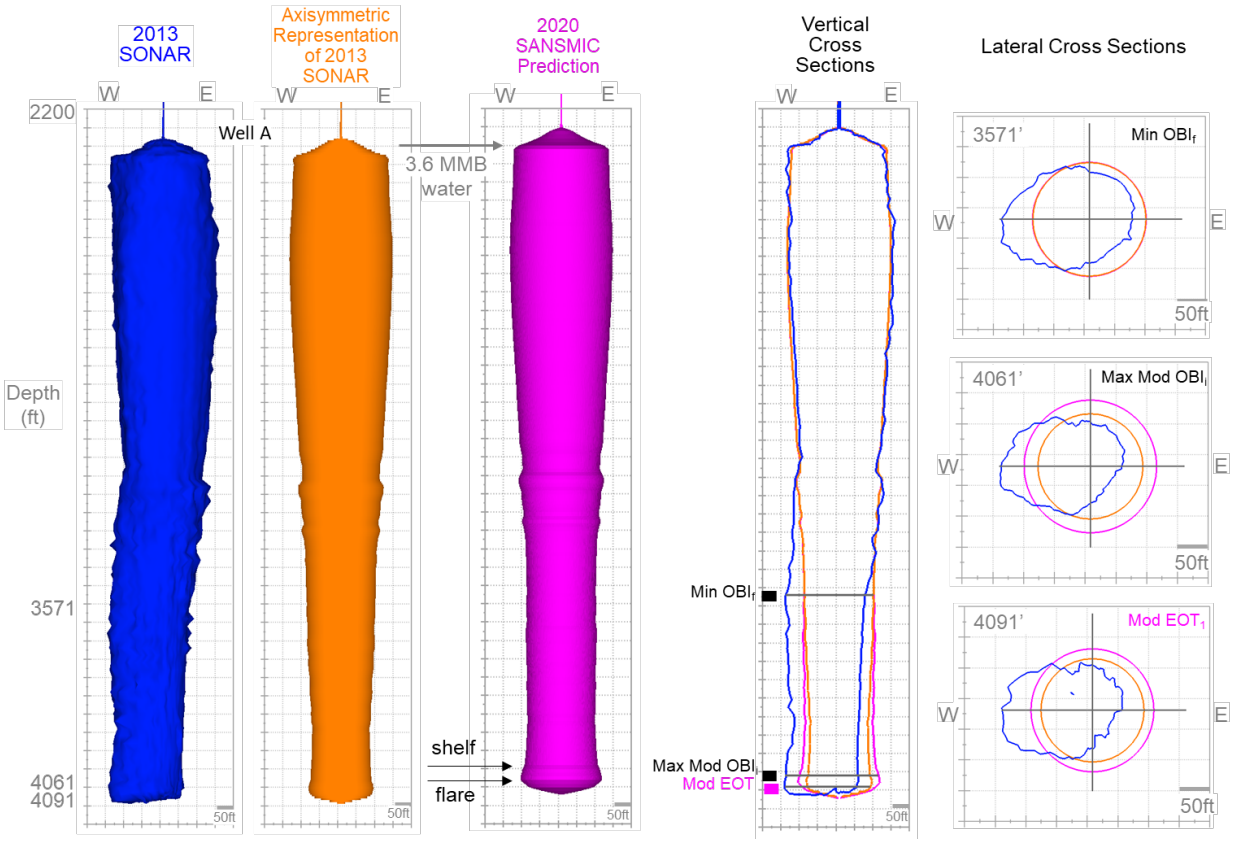

Figure 2-29. BH-114 Modeling Results for Leaching Between 2013 Sonar and End of CY20.

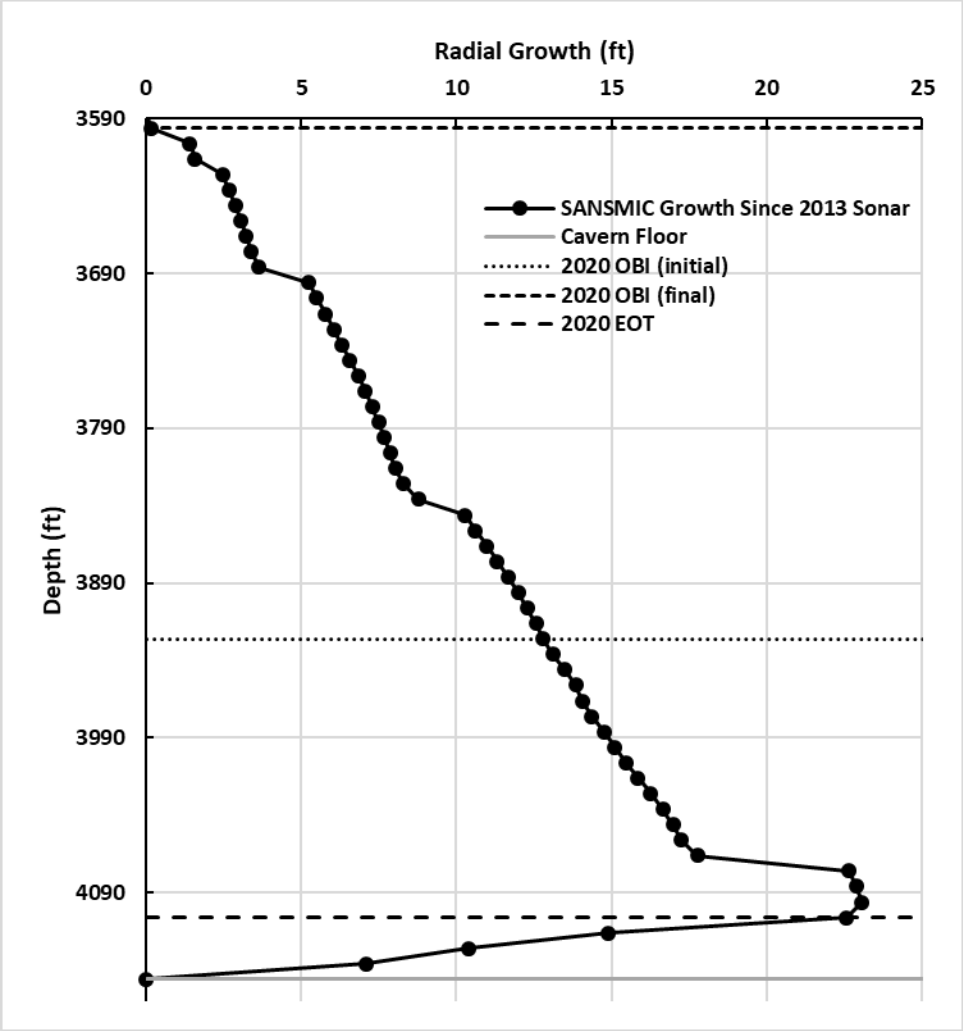

Figure 2-30. BH-114 SANSMIC-Predicted Radial Growth since 2013 Sonar (exaggerated horizontal scale).

2.2. Bryan Mound

Simulation results for Bryan Mound are summarized in Table 2-22, including the volume of raw water injection simulated with SANSMIC modeling and any potential concerns observed. Six caverns had at least 10 MB water injected in CY20. One of those caverns (BM-116) has had at least 3 MMB of water injected since the last sonar. While all caverns do not have a leaching induced feature of concern at this time, two caverns, BM-4 and BM-106, have features which should be monitored as leaching continues in those caverns. A brief leaching history and the results of SANSMIC modeling of leaching since the last sonar are discussed below for each cavern.

Table 2-22. Caverns at Bryan Mound with water injected in CY18 and/or CY19.

Cavern	Last Sonar	Injected Water Volume* (MMB)	Concerns
BM-4	2012	2.4	Monitor flare near cavern floor
BM-105	2012	0.11	No
BM-106	2016	2.7	Monitor shelf ~200 ft from cavern floor
BM-113	2012	0.76	No
BM-114	2012	2.0	No
BM-116	2011	3.8	No

* Since last sonar

2.2.1. BM-4

2.2.1.1. Leaching History

Sonars taken in the A well of BM-4 in 2001 and 2012 are shown in Figure 2-31. Floor rise occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 4.5 MMB of water injected into this cavern between sonars to create this change in cavern shape along with the floor rise. Little net volume change is observed, so there is little data to inform the leaching pattern associated with the 2.4 MMB of water that has been injected since the 2012 sonar.

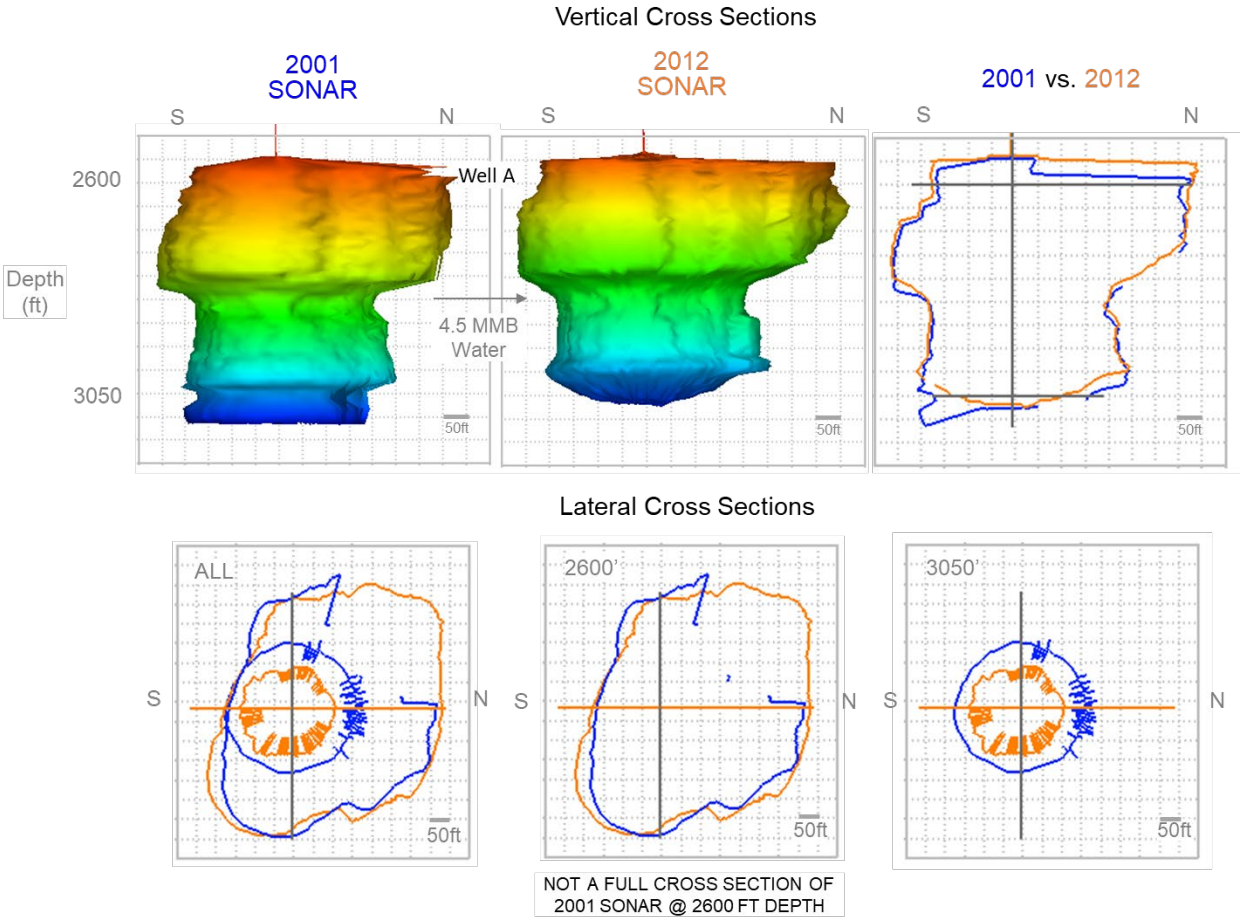

Figure 2-31. Leaching history in BM-4 from 2001 (blue) to 2012 (orange) via sonars.

2.2.1.2. Simulated Leaching Between 2012 Sonar and End of CY20

The last sonar taken in BM-4 was in 2012. Since that sonar, around 2.4 MMB of water have been injected into the cavern in 2014, 2016, and 2020 (see Table 2-23). Leaching in the BM-4 cavern was not modeled in 2017-19 due to no raw water injections in that time period, so the BM-4 SANSMIC modeled was newly created for 2020 leaching. The injection history was modeled as four phases of leaching each with an EP of 60 days. The CY20 injection history was modeled using two separate leaching phases with an EP of 60 days following each injection phase. A single Mod EOT rise was used for both phases, but in the second phase, the OBI was selected to reflect oil entering the cavern between the two leaching time periods. The initial OBI in phase 2 was automatically selected by SANSMIC, based on the final OBI of the previous leaching phase. Leaching in this cavern was not modeled for the CY17 [6] or CY18/19 [8] leaching reports.

Table 2-23. Summary of Simulation Input for BM-4

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	06/12/14-08/15/14	3087	6	10	66	70	4,652	4	18,608
2	08/10/16-10/28/16	3087	6	10	Auto	70	4,865	3	14,595
3	03/17/20-05/06/20	3087	20	10	52	50	58,554	14	819,756
4	07/08/20-09/25/20	3087	19	10	33	30	74,187	21	1,557,927
ALL	N/A	N/A	N/A	N/A	N/A	N/A	N/A	42	2,410,886

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of the final EP. As summarized in Table 2-24, the leaching efficiency for this cavern was 14.0%.

Table 2-24. Summary of Simulation Output for BM-4

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	70	1.1979	5,000	26.9
2	70	1.1977	5,000	34.3
3	90	1.1809	112,000	13.7
4	100	1.1790	216,000	13.9
ALL	100	1.1790	338,000	14.0

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2012 sonar and the end of CY20 (see Figure 2-32). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 2.4 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which include the slight radial spread of the cavern floor. The spread can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-33) that is about 100 ft tall. The maximum radial growth over this depth is predicted to be over 20 ft. The 2012 sonar shows a flare near the floor and that flare is predicted to have grown due to the leaches since the sonar. Continued monitoring of the flare is recommended.

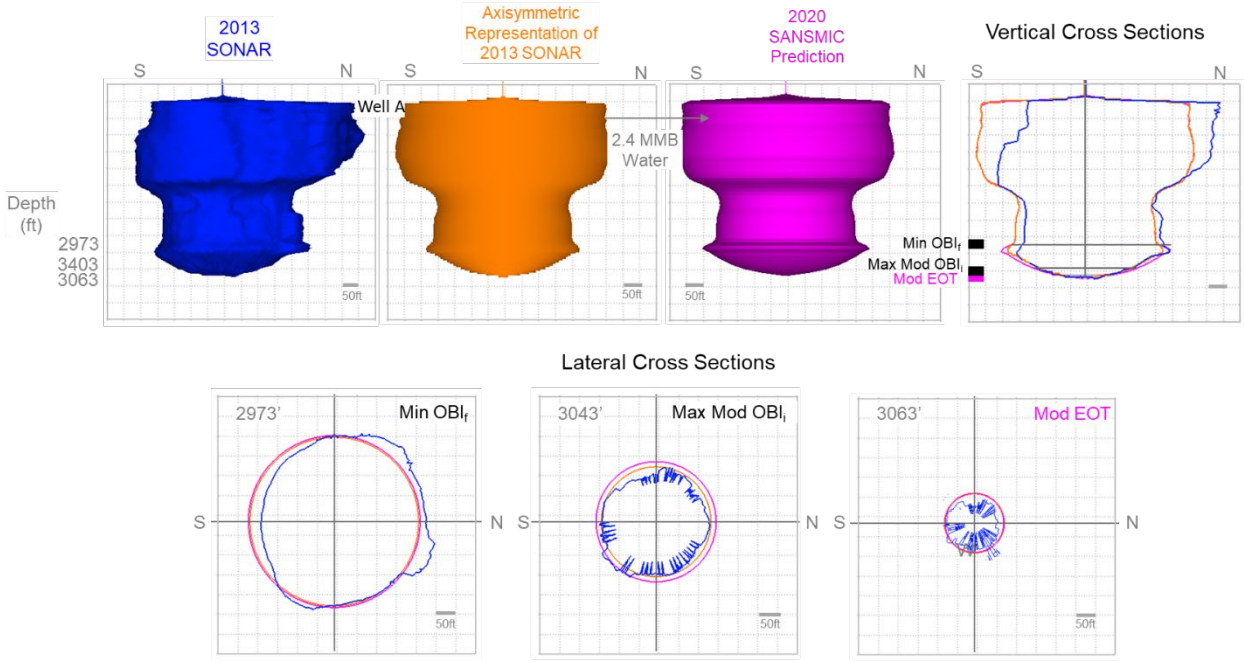

Figure 2-32. BM-4 Modeling Results for Leaching Between 2012 Sonar and End of CY20.

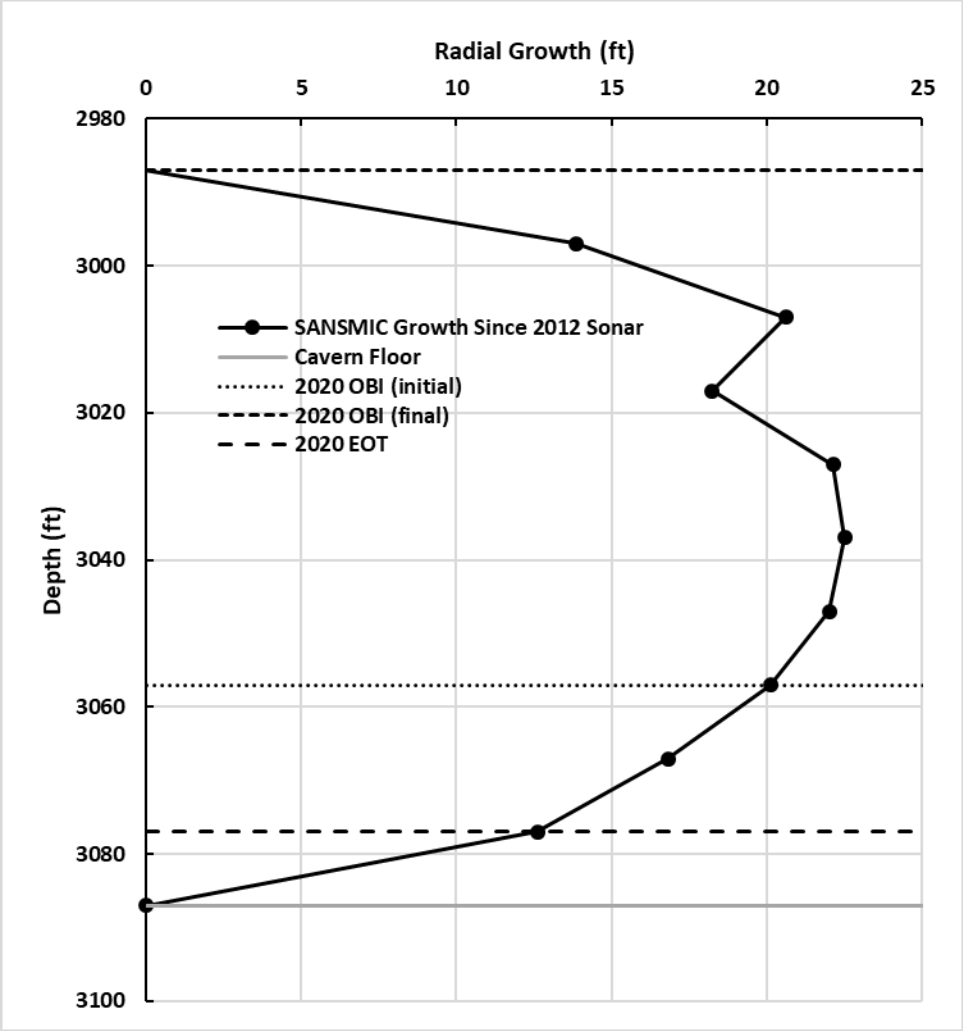

Figure 2-33. BM-4 SANSMIC-Predicted Radial Growth since 2012 Sonar (exaggerated horizontal scale).

2.2.2. *BM-105*

2.2.2.1. Leaching History

Sonars taken in BM-105 in 1998 (B well) and 2012 (C well) are shown in Figure 2-34. The combination of the sonars indicate the existence of a salt bridge. Comparison between the two sonars is difficult, but some floor rise is indicated by the changes in the cavern wall positions near the floor in the vertical cross sections. There was 0.5 MMB of water injected into this cavern between sonars which may have contributed to a change in cavern shape. From the differences in the two sonars, it is unclear how the leaching pattern will evolve for the 0.1 MMB of water that has been injected since the 2012 sonar.

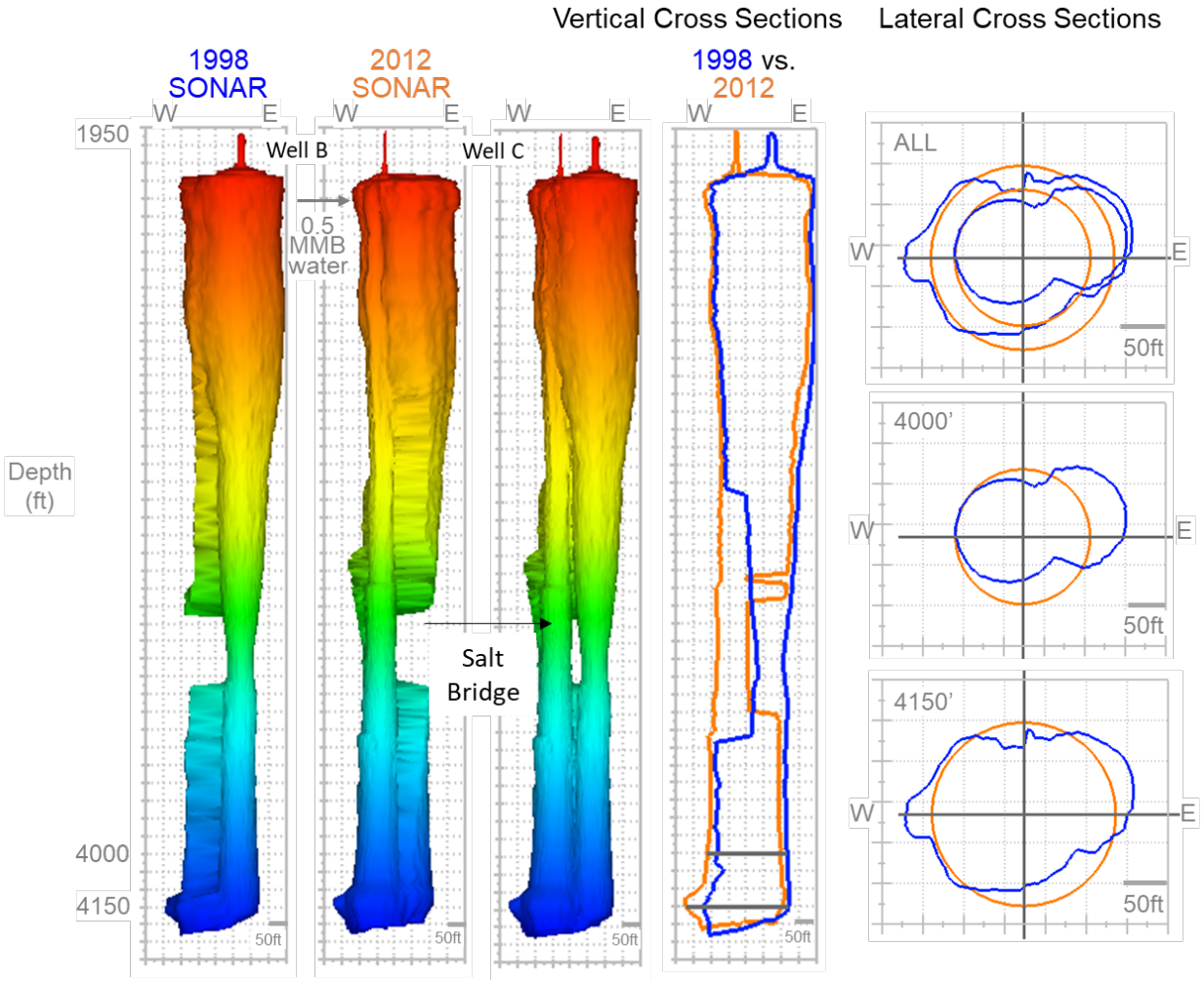

Figure 2-34. Leaching history in BM-105 from 1998 (blue) to 2012 (orange) via sonars.

2.2.2.2. Simulated Leaching Between 2012 Sonar and End of CY20

The last sonar taken in BM-105 was in 2012. Since that sonar, around 0.10 MMB of water have been injected into the cavern in 2012 and 2020 (see Table 2-25). Leaching in the BM-105 cavern was not modeled in 2017-19 due to no raw water injections in that time period, so the BM-105 SANSMIC modeled was newly created for 2020 leaching. The injection history was modeled as 2 phases of leaching each with an EP of 60 days. A single Mod EOT rise was used for both phases. Leaching in this cavern was not modeled for the CY17 [6] or CY18/19 [8] leaching reports.

Table 2-25. Summary of Simulation Input for BM-105

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	09/19/12-09/19/12	4239	15	10	56	60	49,942	1	49,942
2	01/24/20-01/26/20	4239	18	10	35	40	18,704	3	56,112
All	N/A	N/A	N/A	N/A	N/A	N/A	N/A	4	106,054

The final outlet SG for each phase was close to the value of 1.2, that leaching was near completion at the end of the final EP. As summarized in Table 2-26, the leaching efficiency for this cavern was 21.7%, which is higher than expected and may be attributed to the uncertainty associated with modeling relatively small injection volumes with SANSMIC.

Table 2-26. Summary of Simulation Output for BM-105

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	60	1.1962	9,000	18.0
2	50	1.1974	14,000	25.0
All	50	1.1974	23,000	21.7

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2012 sonar and the end of CY20 (see Figure 2-35). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.1 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which include the slight radial spread of the cavern floor. The spread can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-36) that is about 50 ft tall. The maximum radial growth over this depth is predicted to be a little over 5 ft. With leaching initiating at two different OBI depths near the EOT, the development of two small shelves is evident from the SANSMIC results. However, the simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

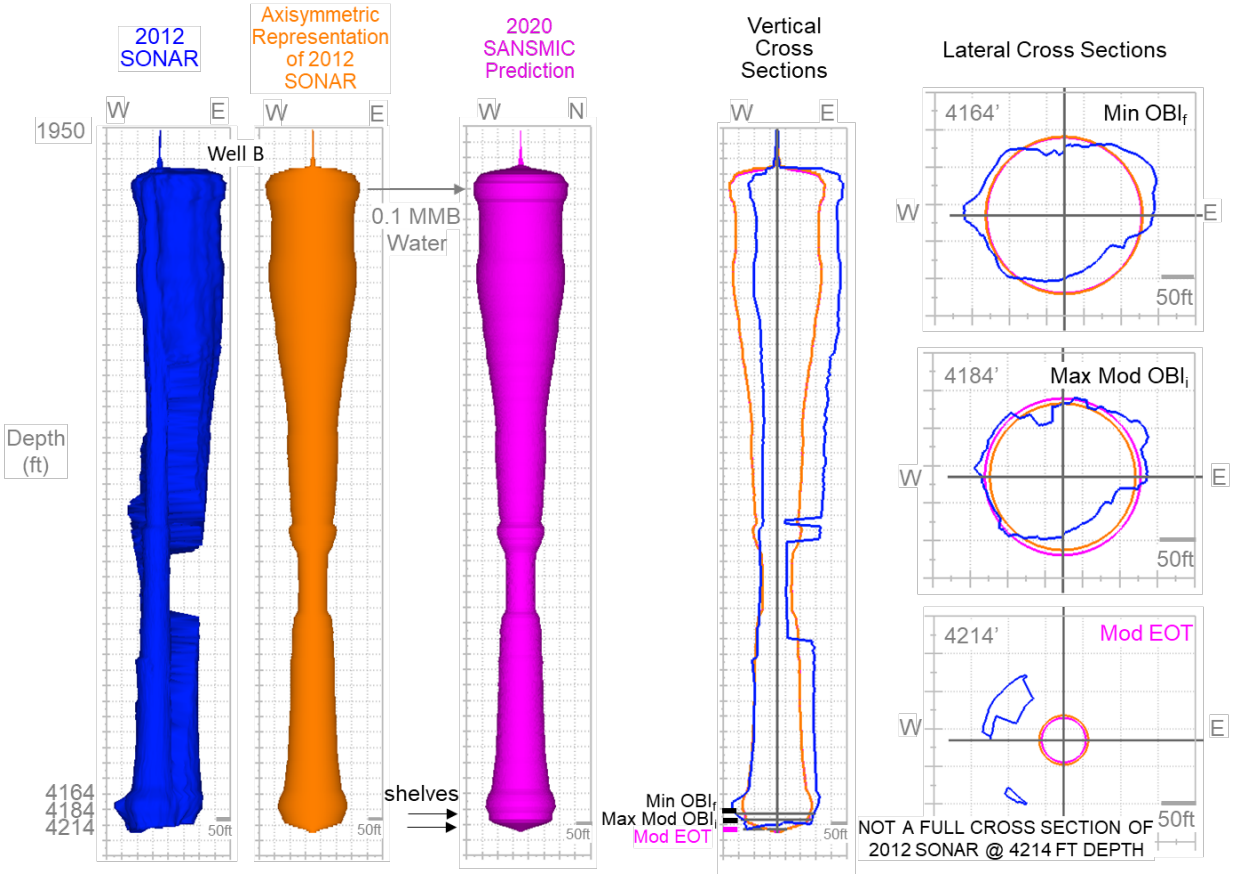

Figure 2-35. BM-105 Modeling Results for Leaching Between 2012 Sonar and End of CY20.

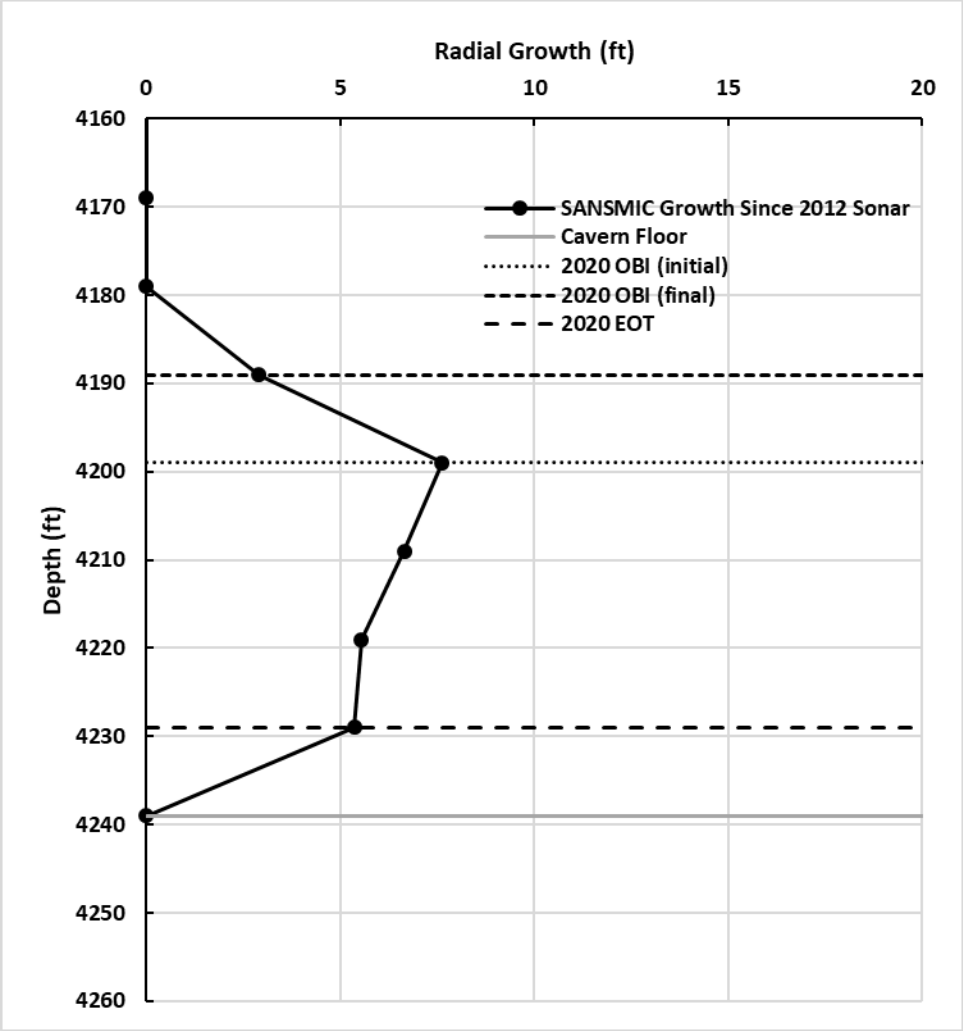

Figure 2-36. BM-105 SANSMIC-Predicted Radial Growth since 2012 Sonar (exaggerated horizontal scale).

2.2.3. BM-106

2.2.3.1. Leaching History

Sonars taken in the B well of BM-106 in 2000 and 2016 are shown in Figure 2-37. Floor rise occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 0.7 MMB of water injected into this cavern between sonars which may have contributed to a change in cavern shape. From the 2000 to 2016 evolution it is unclear how the leaching pattern will evolve that was associated with the much greater volume of 2.7 MMB of water that has been injected since the 2016 sonar.

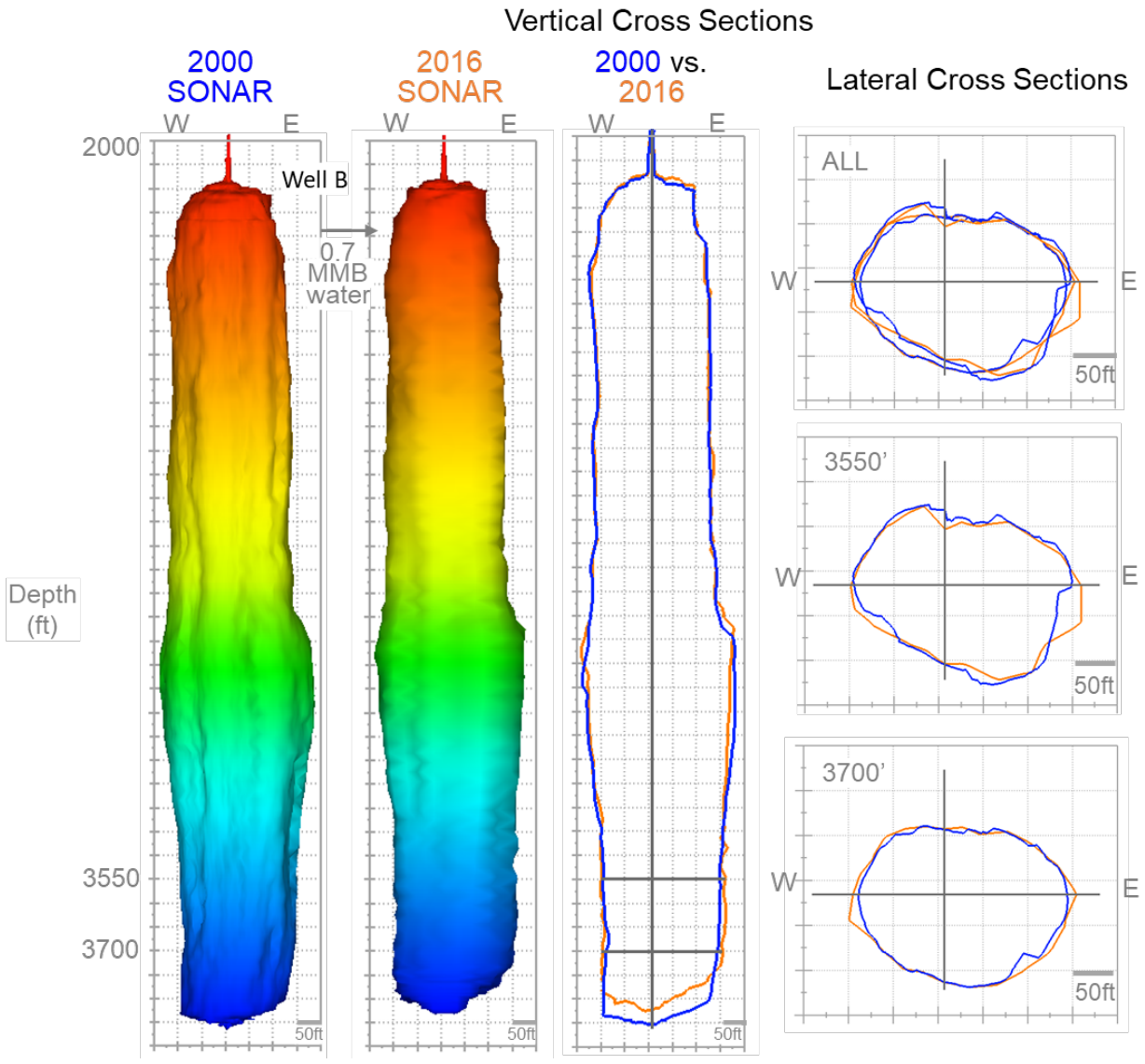

Figure 2-37. Leaching history in BM-106 from 2000 (blue) to 2016 (orange) via sonars in well B.

2.2.3.2. Simulated Leaching Between 2016 Sonar and End of CY20

The last sonar taken in BM-106 was in the B well in 2016. Since that sonar, around 2.7 MMB of water have been injected into the cavern in 2018-2020 (see Table 2-27). The injection history was modeled as three phases of leaching each with an EP of 60 days. To represent CY20 water injection, a single phase was added to the two phases modeled for the CY18-19 report [8]. This cavern has had two Mod EOT rises due to loss of hanging string length between the 2019 and 2020 raw water injections. The initial OBI in phase 2 was automatically selected by SANSMIC based on the final OBI of the previous phase.

Table 2-27. Summary of Simulation Input for BM-106

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	04/18/18-06/11/18	3848	17	10	66	70	72,443	12	869,316
2	05/07/19-05/17/19	3848	17	10	Auto	210	64,706	4	258,824
3	07/14/20-09/19/20	3848	176	170	192	190	59,288	27	1,600,776
All	N/A	N/A	N/A	N/A	N/A	N/A	137,149	43	2,728,916

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of the final EP. As summarized in Table 2-28, the leaching efficiency for this cavern was 15.8%.

Table 2-28. Summary of Simulation Output for BM-106

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	210	1.1958	144,000	16.6
2	250	1.1983	43,000	16.6
3	430	1.1962	245,000	15.3
All	430	1.1962	432,000	15.8

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2016 sonar and the end of CY20 (see Figure 2-38). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 2.7 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which include the slight radial spread of the cavern floor. The spread can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-39) that is about 400 ft tall and reflects the variation of EOT and OBI depths since the last sonar. The radial growth was greatest at around 200 ft the EOT, with over 20 ft of radial growth predicted over a narrow depth range, extending the size of the shelf noted in the CY18-19 SANSMIC leaching report [8]. The observed shelf feature has grown in size with the modeled CY20 leaching. Continued monitoring of the shelf is recommended.

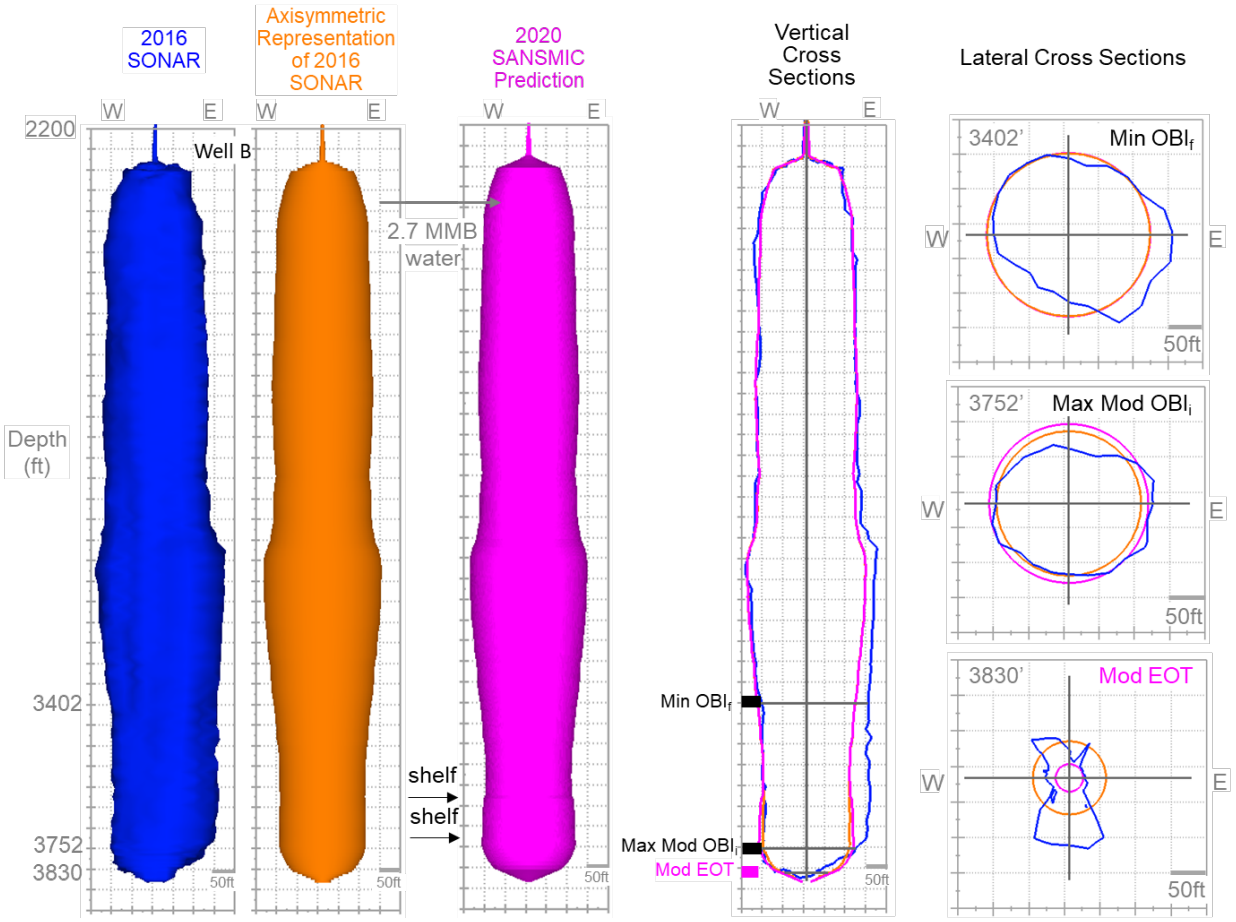

Figure 2-38. BM-106 Modeling Results for Leaching Between 2016 Sonar and End of CY20.

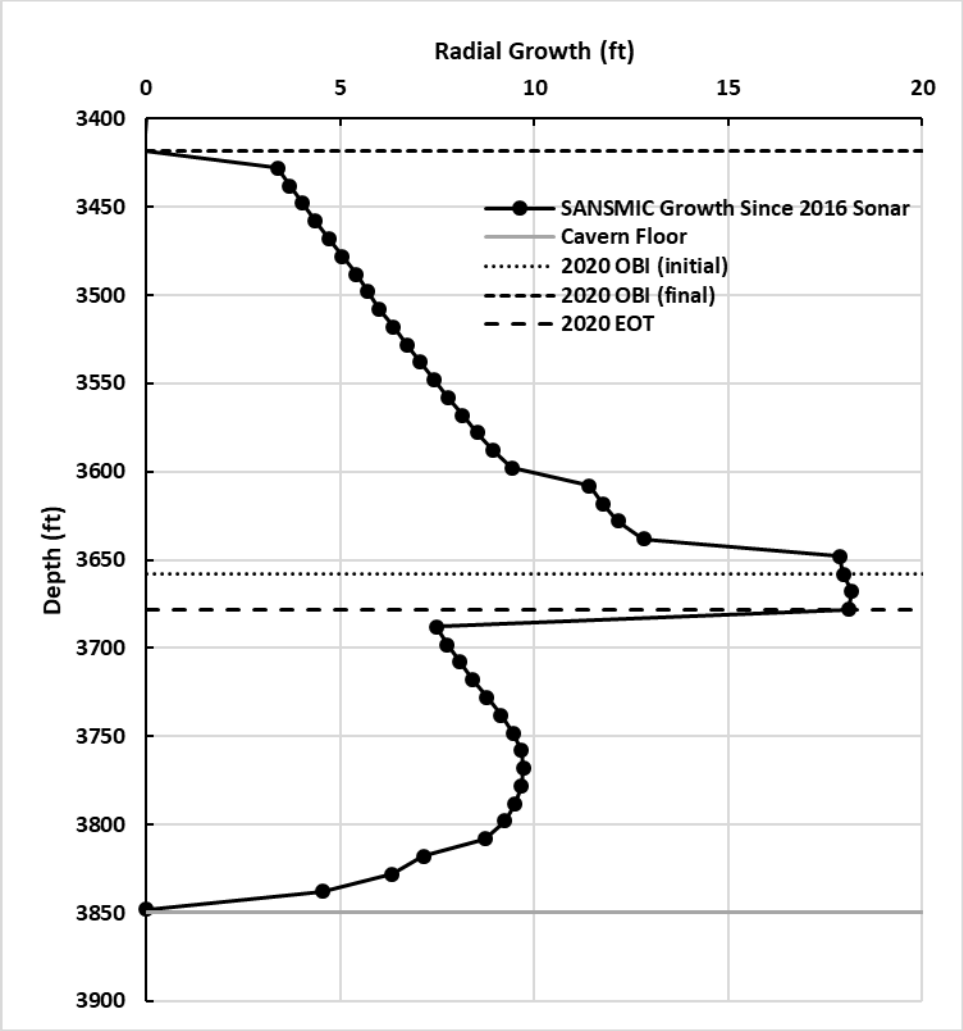

Figure 2-39. BM-106 SANSMIC-Predicted Radial Growth since 2016 Sonar (exaggerated horizontal scale).

2.2.4. BM-113

2.2.4.1. Leaching History

Sonars taken in the A well of BM-113 in 2005 and 2012 are shown in Figure 2-40. Floor rise and spread occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 14.2 MMB of water injected into this cavern between sonars (the volume was reported as 3.4 MMB in [8]). Leaching was primarily radial from 2000 to 2012, suggesting that radial leaching should be expected for the 0.8 MMB of water that has been injected since the 2012 sonar.

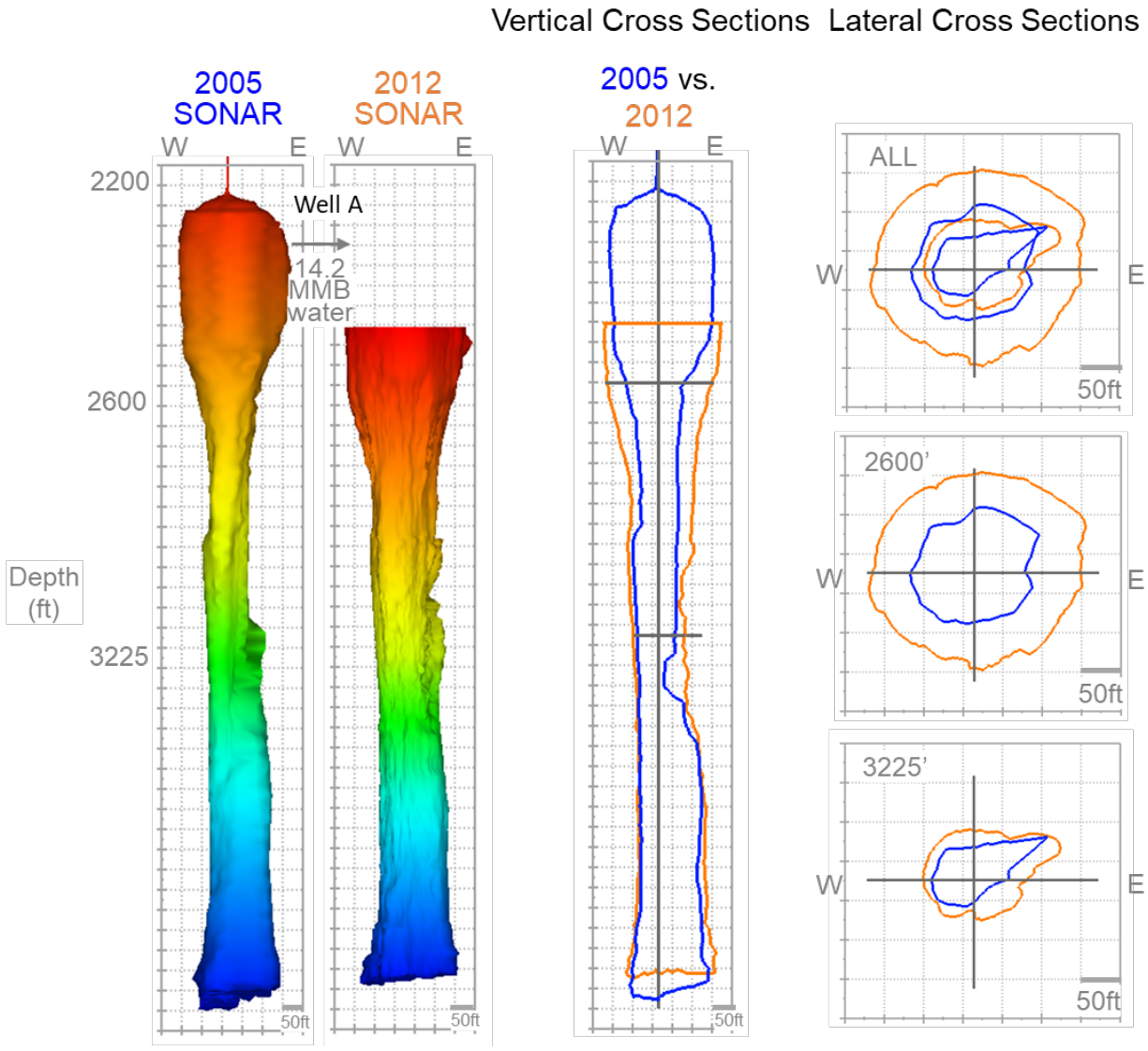

Figure 2-40. Leaching history in BM-113 from 2005 (blue) to 2012 (orange) via sonars in well A.

2.2.4.2. Simulated Leaching Between 2012 Sonar and End of CY20

The last sonar taken in BM-113 was in 2012. Since that sonar, around 0.76 MMB of water have been injected into the cavern in 2017-2020 (see Table 2-29). The injection history was modeled using four separate leaching phases with an EP of 60 days following each injection phase. To represent CY20 water injection, a single phase was added to the three phases modeled for the CY18-19 report [8]. This cavern has had a single Mod EOT rise.

Table 2-29. Summary of Simulation Input for BM-113

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	04/16/17-04/27/17	4100	395	390	915	920	30,854	8	246,832
2	04/18/18-06/11/18	4100	400	390	660	660	23,209	13	301,717
3	05/07/19-05/17/19	4100	398	390	621	620	42,453	4	169,812
4	03/24/20-05/06/20	4101	398	390	556	560	7,852	5	39,260
All	N/A	N/A	N/A	N/A	N/A	N/A	N/A	30	757,621

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of each EP. As summarized in Table 2-30, the leaching efficiency for this cavern was 17.0%.

Table 2-30. Summary of Simulation Output for BM-113

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	1010	1.2012	41,800	16.9
2	790	1.2007	50,800	16.8
3	680	1.2006	28,700	16.9
4	570	1.2006	7,400	18.8
All	570	1.2006	128,700	17.0

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2012 sonar and the end of CY20 (see Figure 2-41). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.8 MMB.

Vertical cross sections from each of the cavern geometries reveal the general changes from leaching, which include the slight radial spread of the cavern floor. The spread can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-42) that is about 600 ft tall and reflects the large distance between OBI and EOT, as well as variation in initial OBI depths for different injections. The maximum radial growth over this depth is predicted to be only about 4 ft. The development of a small shelf (previously shown in [8]), which has grown taller, but not much wider, with CY20 leaching. However, the simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

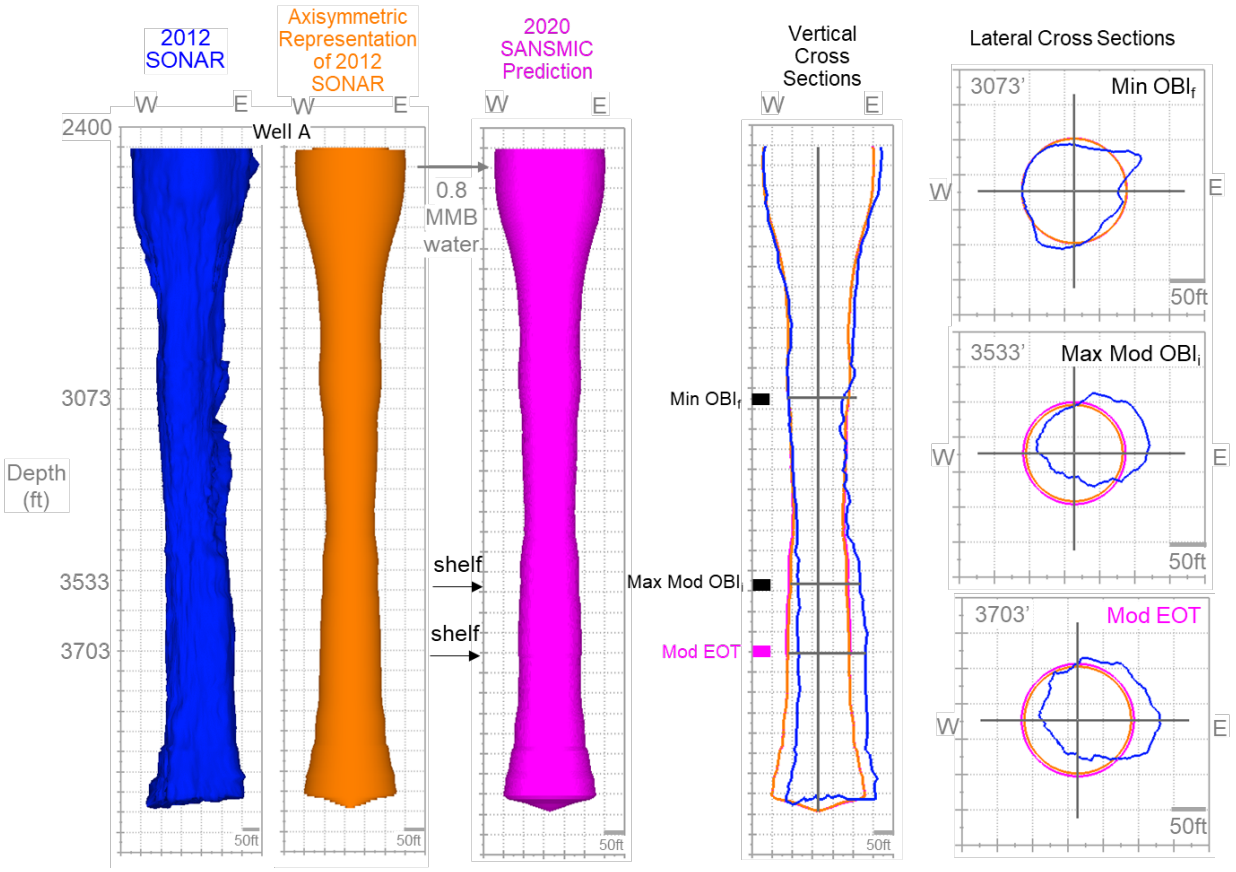

Figure 2-41. BM-113 Modeling Results for Leaching Between 2012 Sonar and End of CY20.

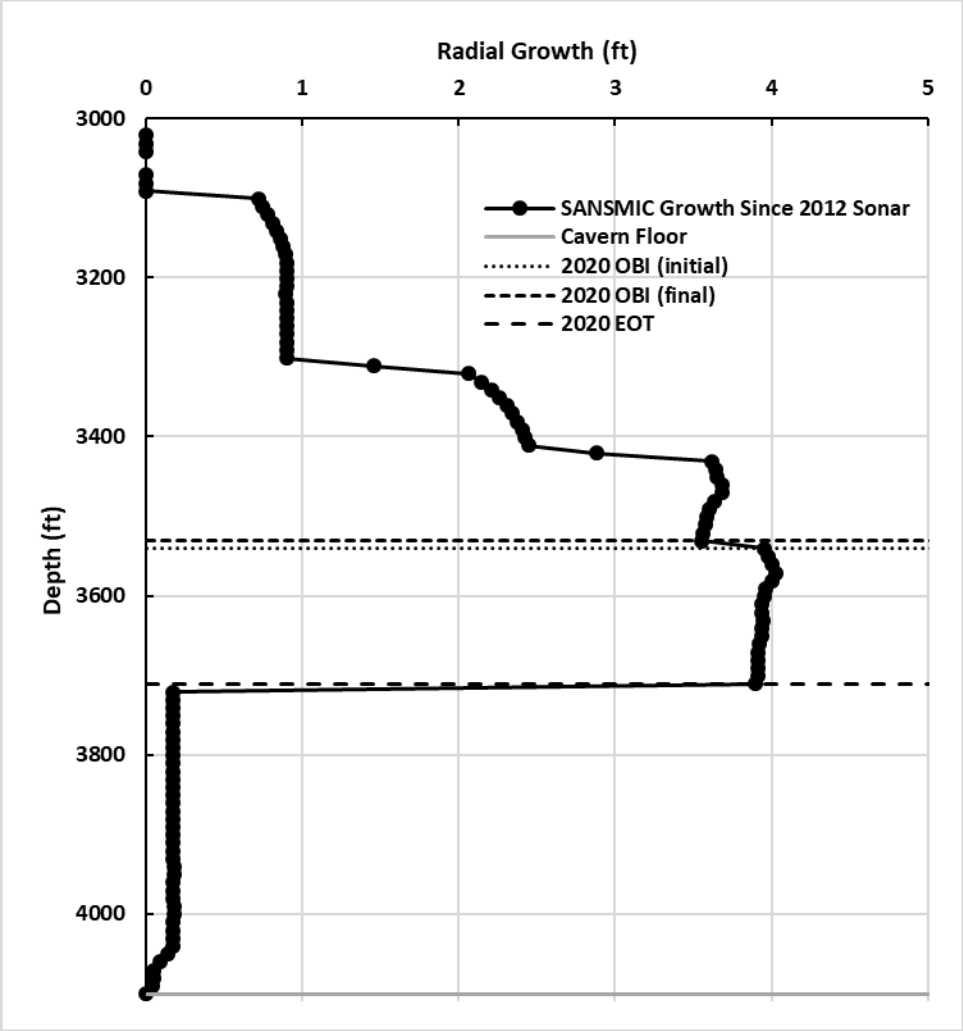

Figure 2-42. BM-113 SANSMIC-Predicted Radial Growth since 2012 Sonar (exaggerated horizontal scale).

2.2.5. BM-114

2.2.5.1. Leaching History

Sonars taken in the A well of BM-114 in 2006 and 2012 are shown in Figure 2-43. Floor rise and spread occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 6.8 MMB of water injected into this cavern between sonars. From the 2006 to 2012 evolution, it is possible that a symmetric leaching pattern will evolve from the 2.0 MMB of water that has been injected since the 2012 sonar.

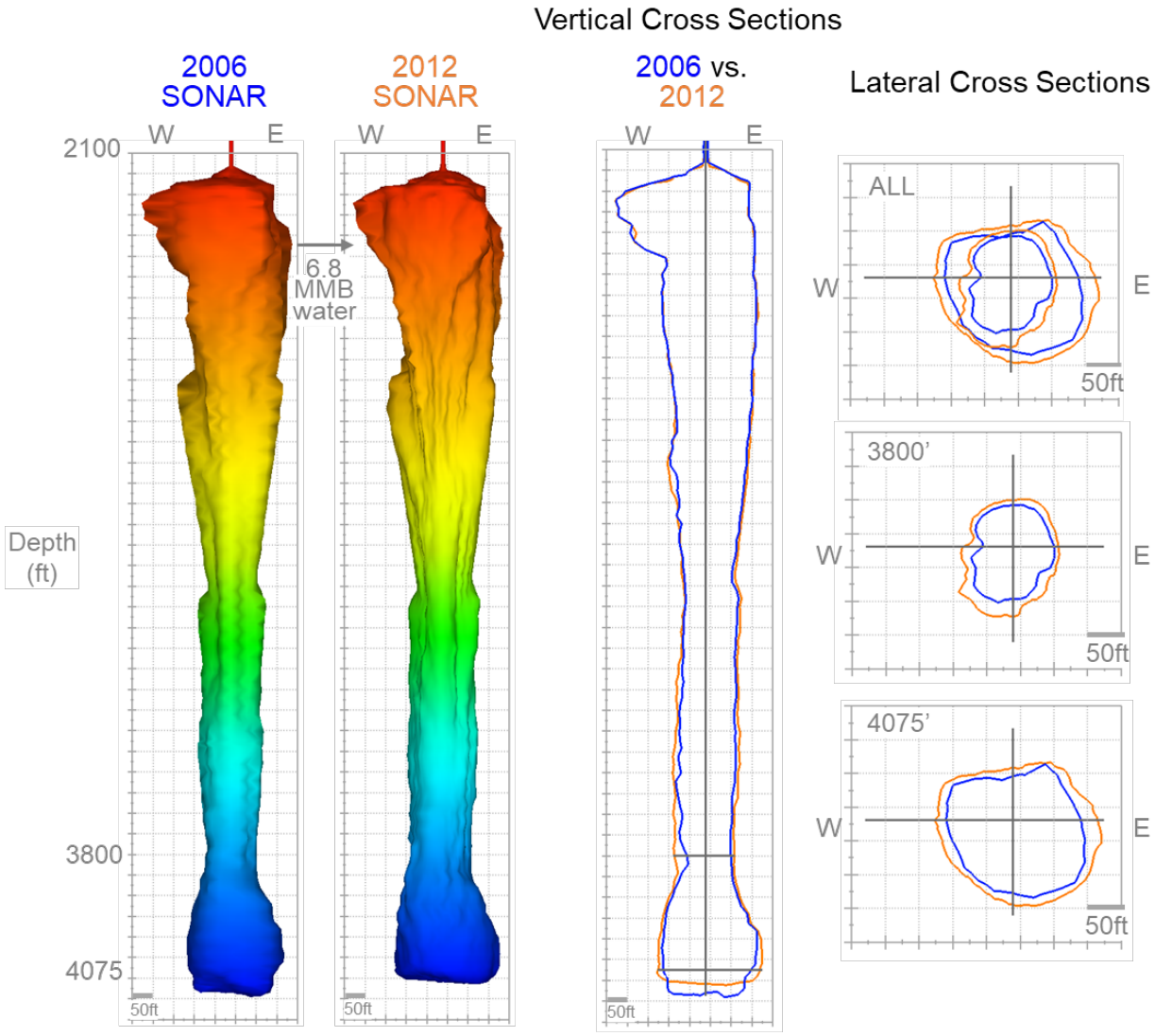

Figure 2-43. Leaching history in BM-114 from 2006 (blue) to 2012 (orange) via sonars in well A.

2.2.5.2. Simulated Leaching Between 2012 Sonar and End of CY20

The last sonar taken in BM-114 was in 2012. Since that sonar, around 2.0 MMB of water have been injected into the cavern in 2012 and 2017-2020 (see Table 2-31). The injection history was modeled using six separate leaching phases with an EP of 60 days following each injection phase. To represent CY20 water injection, a single phase was added to the five phases modeled for the CY18-19 report [8]. This cavern has had a single Mod EOT rise. This cavern has had three Mod EOT rises.

Table 2-31. Summary of Simulation Input for BM-114

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	01/19/12-01/27/12	4115	11	0	1455	1460	91,315	9	821,835
2	04/16/17-04/27/17	4115	6	10	123	120	29,441	9	264,969
3	11/26/17-06/11/18	4115	6	10	198	200	27,238	14	381,332
4	11/18/18-12/12/18	4115	6	10	195	200	5,387	2	10,774
5	03/16/19-05/17/19	4115	6	10	Auto	200	46,333	7	324,331
6	08/02/20-09/25/20	4115	23	20	76	80	34,992	5	174,960
All	N/A	N/A	N/A	N/A	N/A	N/A	N/A	46	1,978,201

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of each EP. As summarized in Table 2-32, the leaching efficiency for this cavern was 15.4%.

Table 2-32. Summary of Simulation Output for BM-114

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	1590	1.2002	131,300	16.0
2	160	1.1973	41,100	15.5
3	270	1.1982	58,900	15.4
4	200	1.2019	1,400	13.0
5	250	1.1981	47,500	14.6
6	90	1.1955	24,800	14.2
All	90	1.1955	305,000	15.4

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2012 sonar and the end of CY20 (see Figure 2-44). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 2.0 MMB.

Vertical cross sections from each of the cavern geometries reveal only slight changes from leaching. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-45) that is about 1500 ft tall and reflects the large distance between OBI and EOT, as well as changing EOT depth. The maximum radial growth over this depth is predicted to be about 10 ft in the region just above the EOT and cavern floor. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

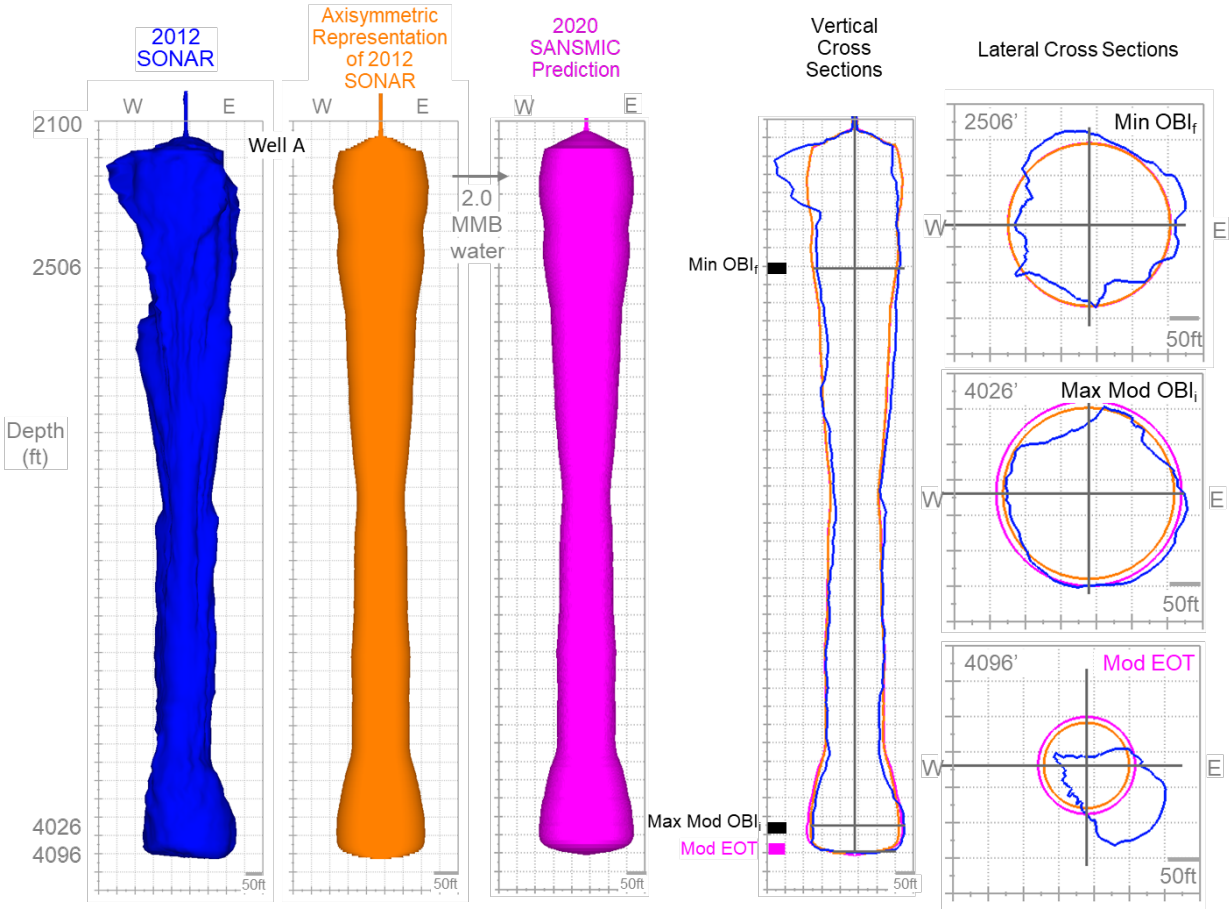

Figure 2-44. BM-114 Modeling Results for Leaching Between 2012 Sonar and End of CY20.

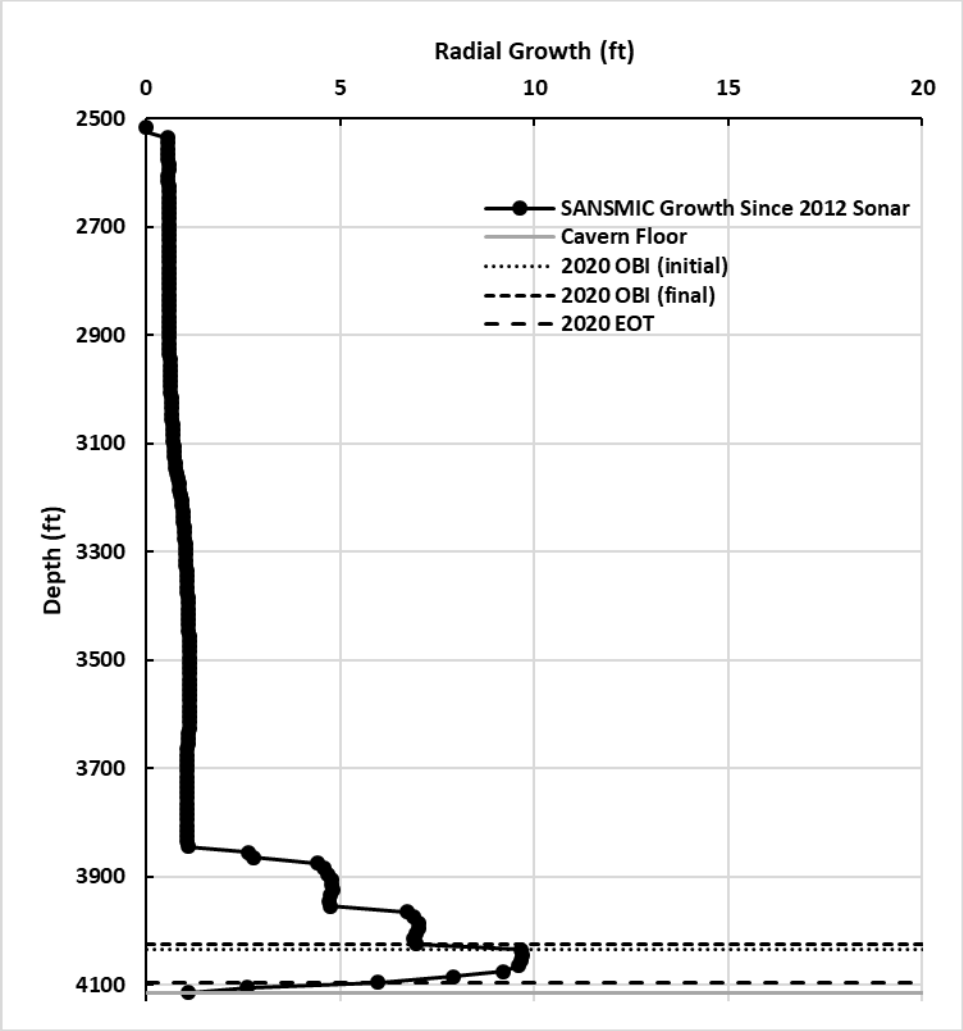

Figure 2-45. BM-114 SANSMIC-Predicted Radial Growth since 2012 Sonar (exaggerated horizontal scale).

2.2.6. BM-116

2.2.6.1. Leaching History

Sonars taken in the A well of BM-116 in 2004 and 2011 are shown in Figure 2-46. Floor rise and spread occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 5.1 MMB of water injected into this cavern between sonars. From the 2004 to 2011 evolution, it is possible that a symmetric leaching pattern will evolve from the 3.8 MMB of water that has been injected since the 2011 sonar.

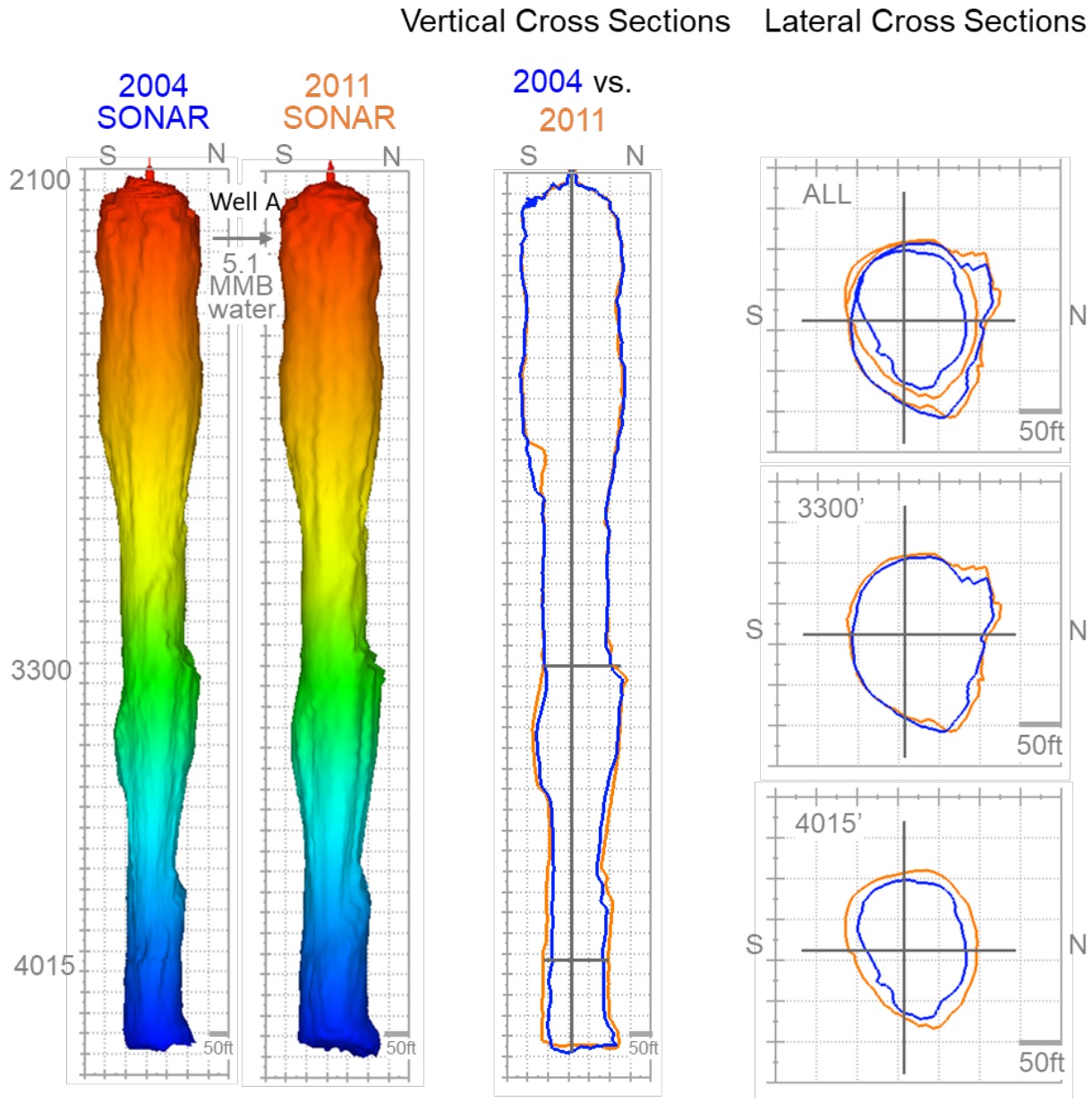

Figure 2-46. Leaching history in BM-116 from 2004 (blue) to 2011 (orange) via sonars in well A.

2.2.6.2. Simulated Leaching Between 2011 Sonar and End of CY20

The last sonar taken in BM-116 was in 2011. Since that sonar, around 3.8 MMB of water have been injected into the cavern in 2012, 2013, and 2017 - 2020 (see Table 2-33). The injection history was modeled using seven separate leaching phases with an EP of 60 days following each injection phase. To represent CY20 water injection, a single phase was added to the six phases modeled for the CY18-19 report [8]. This cavern has had two EOT depths. The initial OBI in phases 2 and 6 were automatically selected by SANSMIC based on the final OBI of the previous phase.

Table 2-33. Summary of Simulation Input for BM-116

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	08/30/12-12/31/12	4260	18	10	1135	1140	34,227	34	1,163,718
2	01/01/13-12/19/13	4260	18	10	Auto	1400	25,936	5	129,680
3	04/16/17-04/27/17	4260	15	10	628	630	39,591	8	316,728
4	04/18/18-06/11/18	4260	17	10	697	700	30,469	13	396,097
5	11/18/18-12/12/18	4260	17	10	504	500	6,439	2	12,878
6	05/07/19-05/17/19	4260	17	10	Auto	510	69,543	4	278,172
7	08/02/20-09/25/20	4261	14	0	178	180	73,164	20	1,463,280
All	N/A	N/A	N/A	N/A	N/A	N/A	N/A	86	3,760,553

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of each EP. The leaching efficiency was anomalously high for phase 2, as observed in the 2018-19 leaching study [8]. As summarized in Table 2-34, the overall leaching efficiency for this cavern was 16.1%.

Table 2-34. Summary of Simulation Output for BM-116

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	1400	1.2005	189,000	16.2
2	1420	1.2017	28,000	21.6
3	690	1.2004	51,000	16.1
4	760	1.2003	63,000	15.9
5	510	1.2019	2,000	15.5
6	570	1.2004	44,000	15.8
7	540	1.1985	230,000	15.7
All	540	1.1985	607,000	16.1

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2011 sonar and the end of CY20 (see Figure 2-47). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 3.8 MMB.

Vertical cross sections from each of the cavern geometries reveal only slight changes from leaching. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-48) that is about 1500 ft tall and reflects the large distance between OBI and EOT, as well as the variation in OBI over time since the sonar. The maximum radial growth over this depth is predicted to be about 8 ft. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

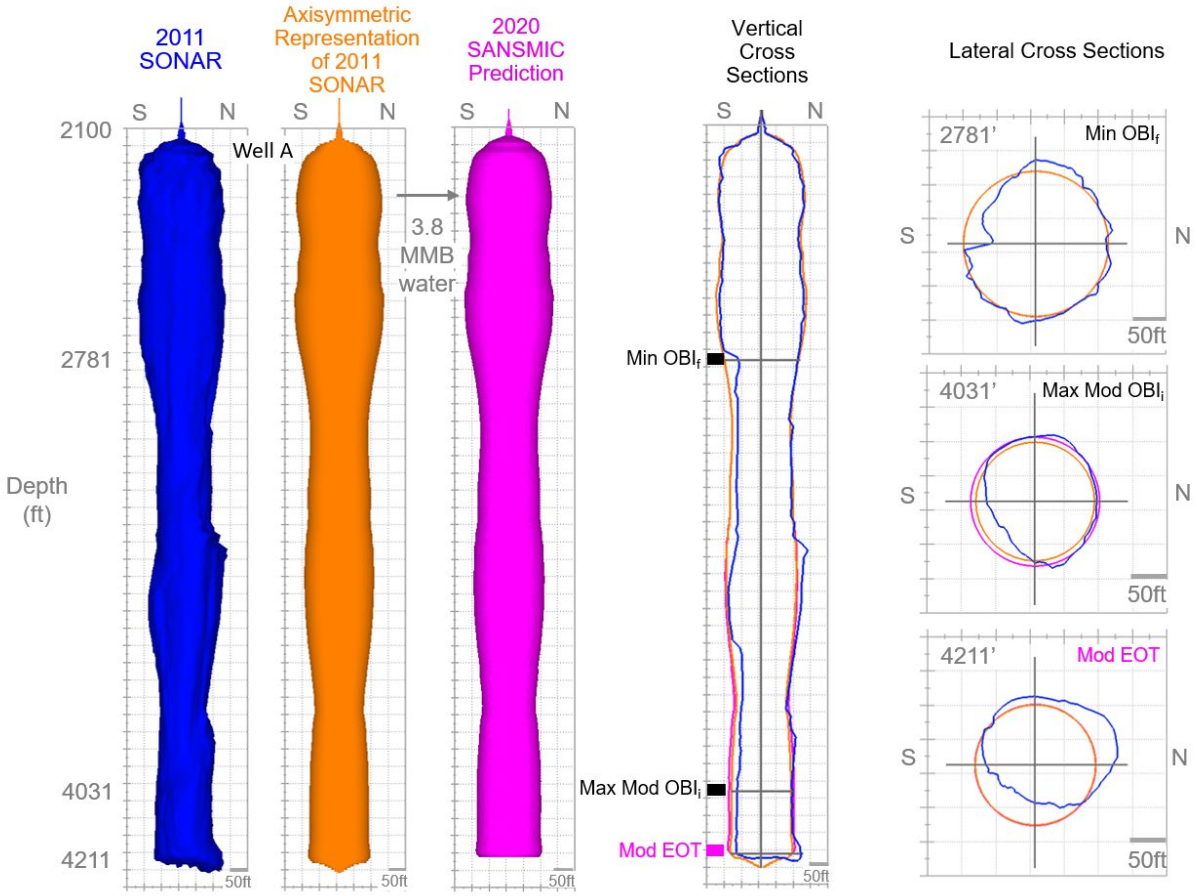

Figure 2-47. BM-116 Modeling Results for Leaching Between 2011 Sonar and End of CY20.

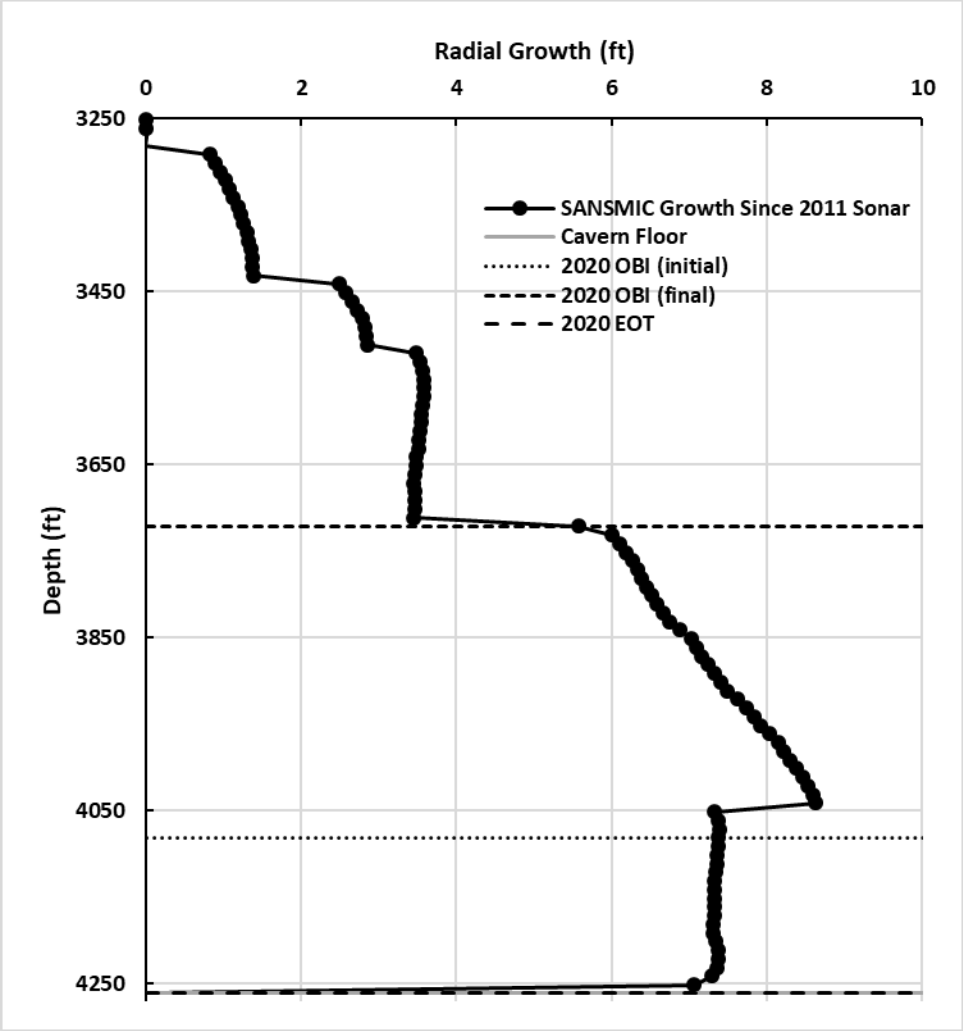

Figure 2-48. BM-116 SANSMIC-Predicted Radial Growth since 2011 Sonar (exaggerated horizontal scale).

2.3. West Hackberry

Simulation results for West Hackberry are summarized in Table 2-35, including the volume of raw water injection simulated with SANSMIC modeling and any potential concerns observed. Seven caverns had at least 10 MB of raw water injected in CY20. One of those caverns (WH-111) has had at least 3 MMB of water injected since the last sonar. While most of the caverns do not have leaching induced features of concern at this time, WH114 has a leaching induced feature near 4215' which should be monitored with continued leaching in that cavern. A brief leaching history and the results of SANSMIC modeling of leaching since the last sonar are discussed below for each cavern.

Table 2-35. Caverns at West Hackberry with water injected in CY20.

Cavern	Last Sonar	Injected Water Volume* (MMB)	Concerns
WH-11	2020	0.50	No
WH-109	2019	0.23	No
WH-111	2015	4.5	No
WH-112	2018	0.99	No
WH-114	2020	0.50	Monitor feature near 4215'
WH-115	2020	0.53	No
WH-117	2019	1.6	No

* Since last sonar

2.3.1. WH-11

2.3.1.1. Leaching History

Sonars taken in the S well of WH-11 in 2018 and 2020 are shown in Figure 2-49. The 1.3 MMB of water injected between sonars resulted in small radial growth above the existing flaring of the cavern floor (i.e., the "flipper" feature described in [8]), but no growth of the existing flare. Additionally, some small floor rise is observed. Based on leaching from 2018 to 2020, the leaching pattern may be symmetric that was associated with the 0.5 MMB of water that has been injected since the 2020 sonar.

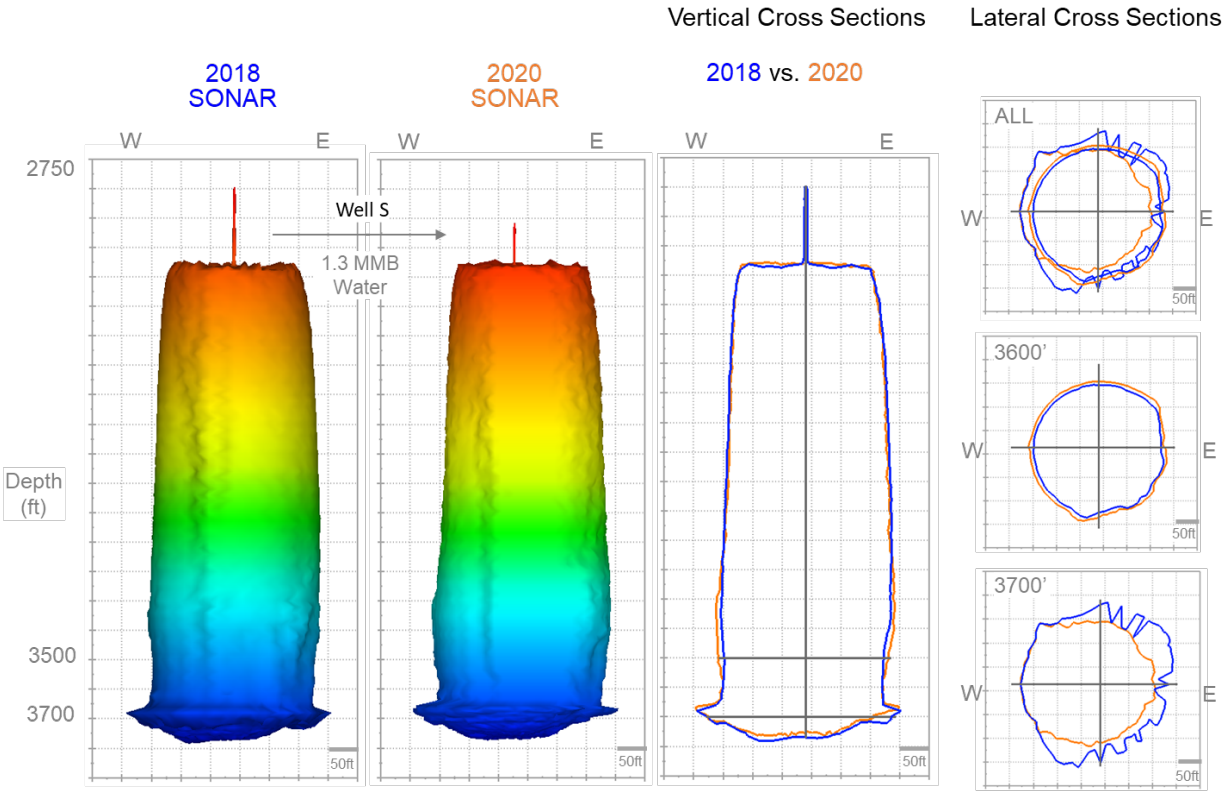

Figure 2-49. Leaching history in WH-11 from 2018 (blue) to 2020 (orange) via sonars in well S.

2.3.1.2. Simulated Leaching Between 2020 Sonar and End of CY20

The last sonar taken in WH-11 was in 2020. Since that sonar, around 0.5 MMB of water have been injected into the cavern in 2020 (see Table 2-36). The injection history was modeled using a single phase of leaching with an EP of 60 days.

Table 2-36. Summary of Simulation Input for WH-11

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	08/02/20-08/22/20	3750	111	100	156	160	83,396	6	500,376

The final outlet SG was close to the value of 1.2, suggesting that leaching was near completion at the end of the EP. As summarized in Table 2-37, the overall leaching efficiency for this cavern was 14.5%.

Table 2-37. Summary of Simulation Output for WH-11

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	200	1.194	72,500	14.5

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2020 sonar and the end of CY20 (see Figure 2-50). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.5 MMB.

Vertical cross sections from each of the cavern geometries reveal only slight changes from leaching. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-51) that is about 100 ft tall and reflects the large distance between OBI and EOT. The maximum radial growth over this depth is predicted to be only about 4 ft. The SANSMIC-predicted growth of a sharp flare feature near the cavern floor was noted in [8]. Later, the EOT was moved higher in the cavern to avoid further growth of the flare. With the current EOT depth, [8] noted that there was no concern related to further flare growth and we draw the same conclusion: the simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time. A comparison of the 2020 sonar with 2019 SANSMIC results from [8] can be found in Section 3.5.

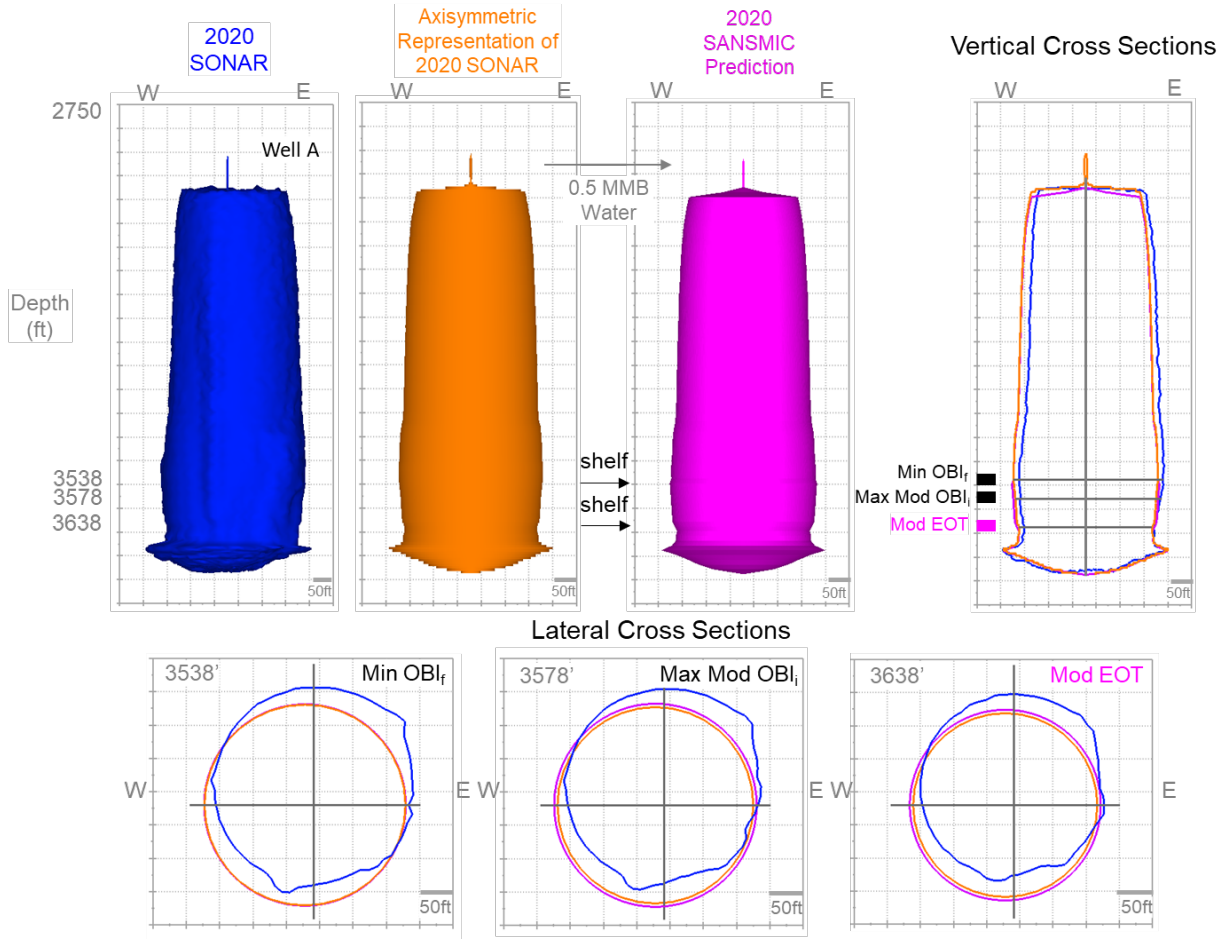

Figure 2-50. WH-11 Modeling Results for Leaching Between 2020 Sonar and End of CY20.

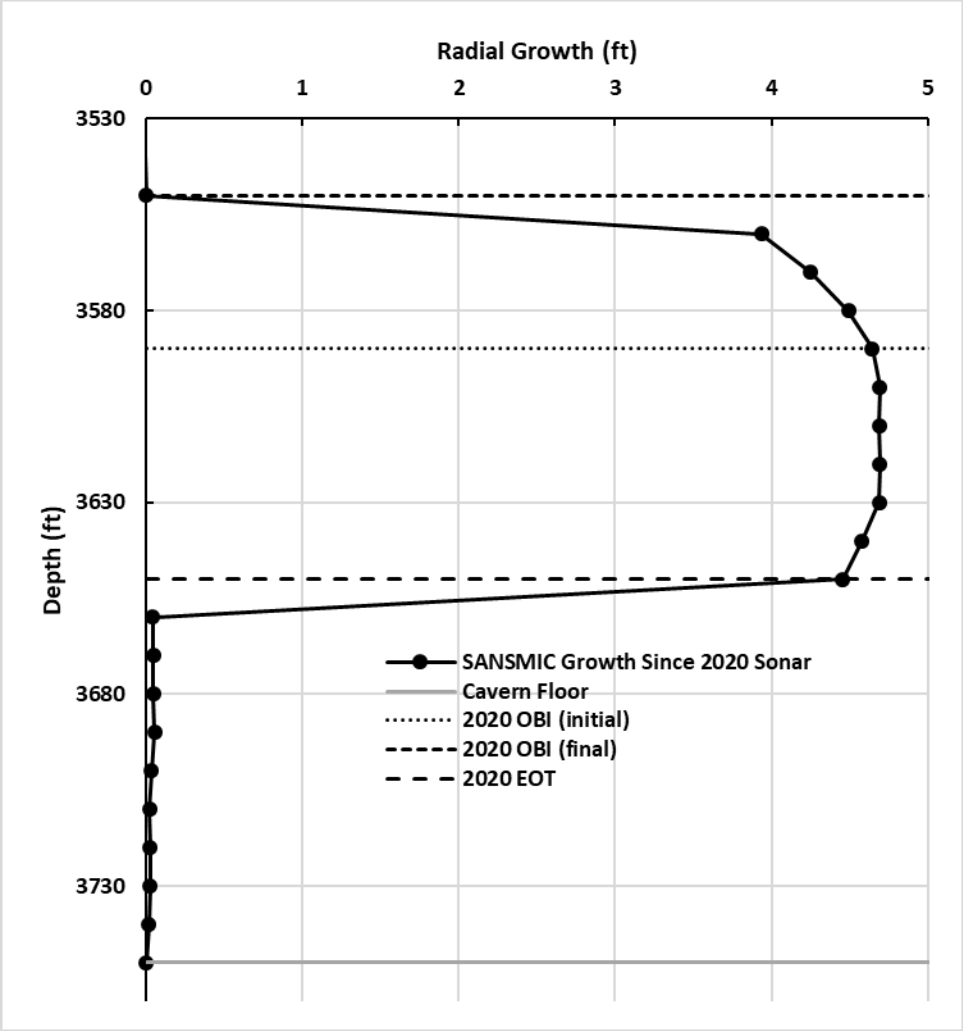

Figure 2-51. WH-11 SANSMIC-Predicted Radial Growth since 2020 Sonar (exaggerated horizontal scale).

2.3.2. WH-109

2.3.2.1. Leaching History (new cavern)

Sonars taken in WH-109 in 2004 and 2019 are shown in Figure 2-52. Floor rise and spread occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 3.4 MMB of water injected into this cavern between sonars. Based on leaching from 2004 to 2019, the leaching pattern may be relatively symmetric (although leaching is observed to be somewhat biased toward east-west rather than north-south) that was associated with the 0.2 MMB of water that has been injected since the 2019 sonar.

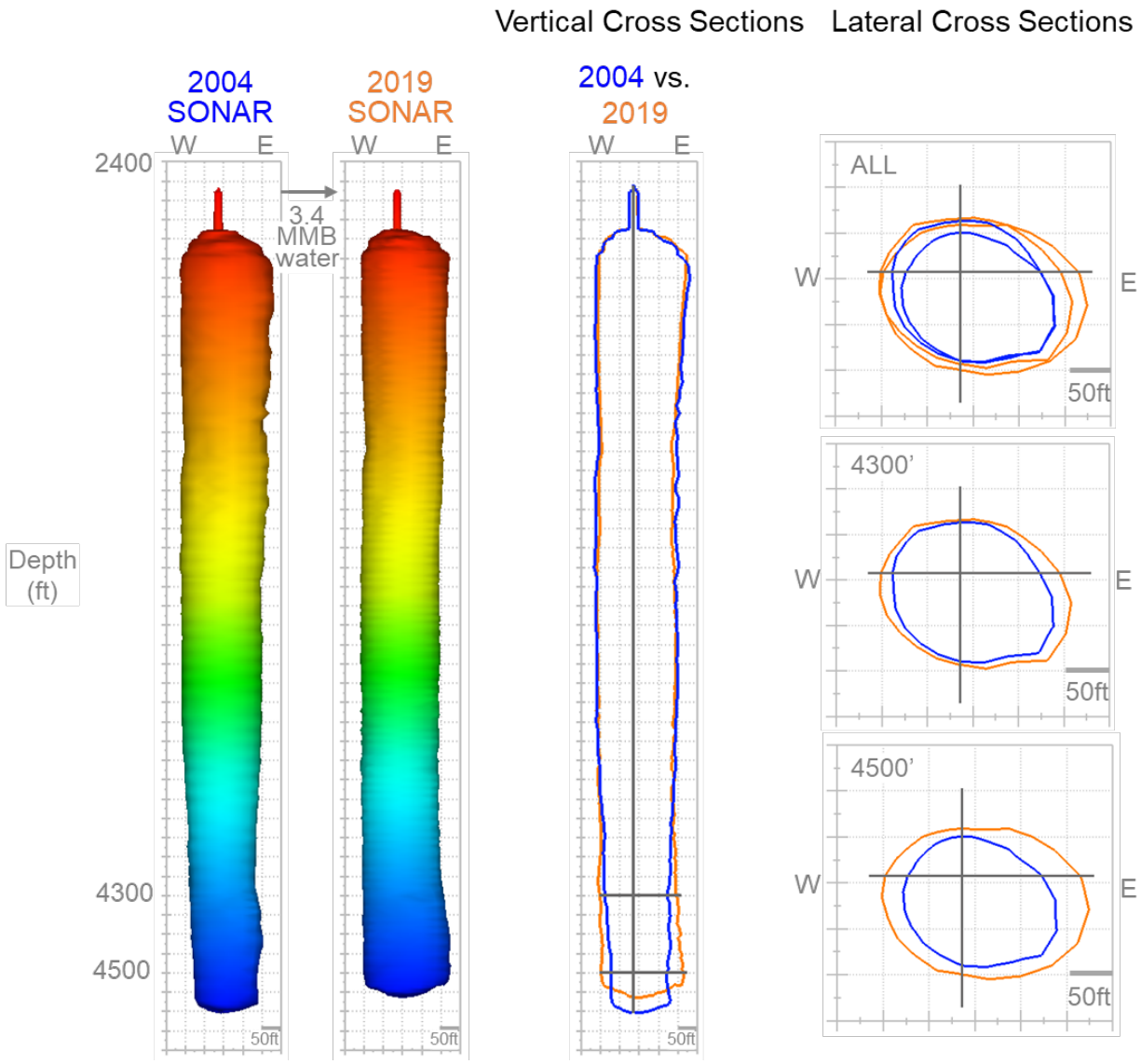

Figure 2-52. Leaching history in WH-109 from 2004 (blue) to 2019 (orange) via sonars.

2.3.2.2. Simulated Leaching Between 2019 Sonar and End of CY20

The last sonar taken in WH-109 was in 2019. Since that sonar, around 0.23 MMB of water was injected into the cavern in 2020 (see Table 2-38). The injection history was modeled as a single phase of leaching with an EP of 60 days.

Table 2-38. Summary of Simulation Input for WH-109

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	10/27/20-11/22/20	4574	22	20	598	600	25,100	9	225,900

The final outlet SG was close to the value of 1.2, suggesting that leaching was near completion at the end of the EP. As summarized in Table 2-39, the overall leaching efficiency for this cavern was 14.6%.

Table 2-39. Summary of Simulation Output for WH-109

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	640	1.2008	33,000	14.6

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2019 sonar and the end of CY20 (see Figure 2-53). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.2 MMB.

Vertical cross sections from each of the cavern geometries reveal only slight changes from leaching. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-54) that is about 600 ft tall and reflects the large distance between OBI and EOT. The radial growth over this depth is predicted to be only about 1 ft. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

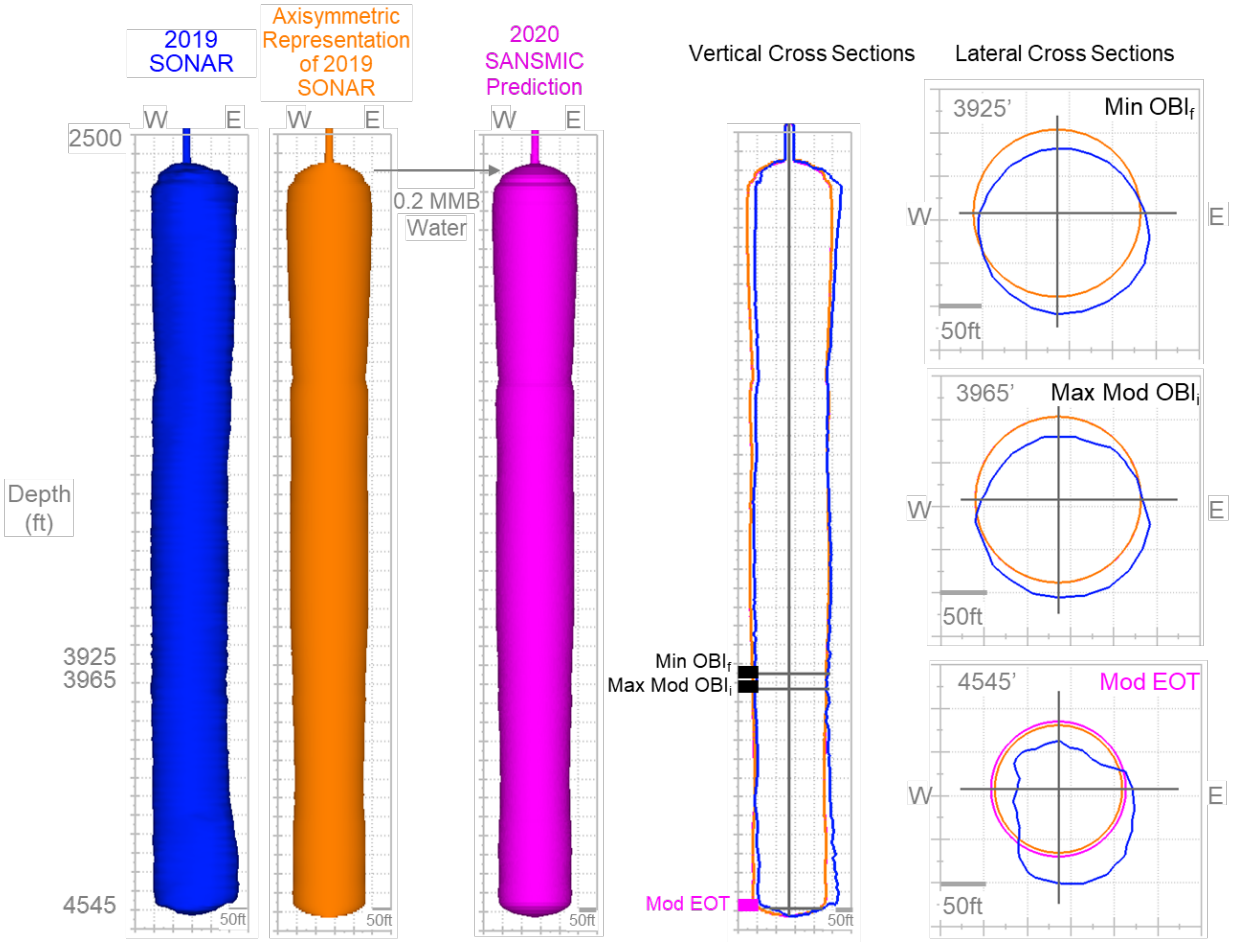

Figure 2-53. WH-109 Modeling Results for Leaching Between 2019 Sonar and End of CY20.

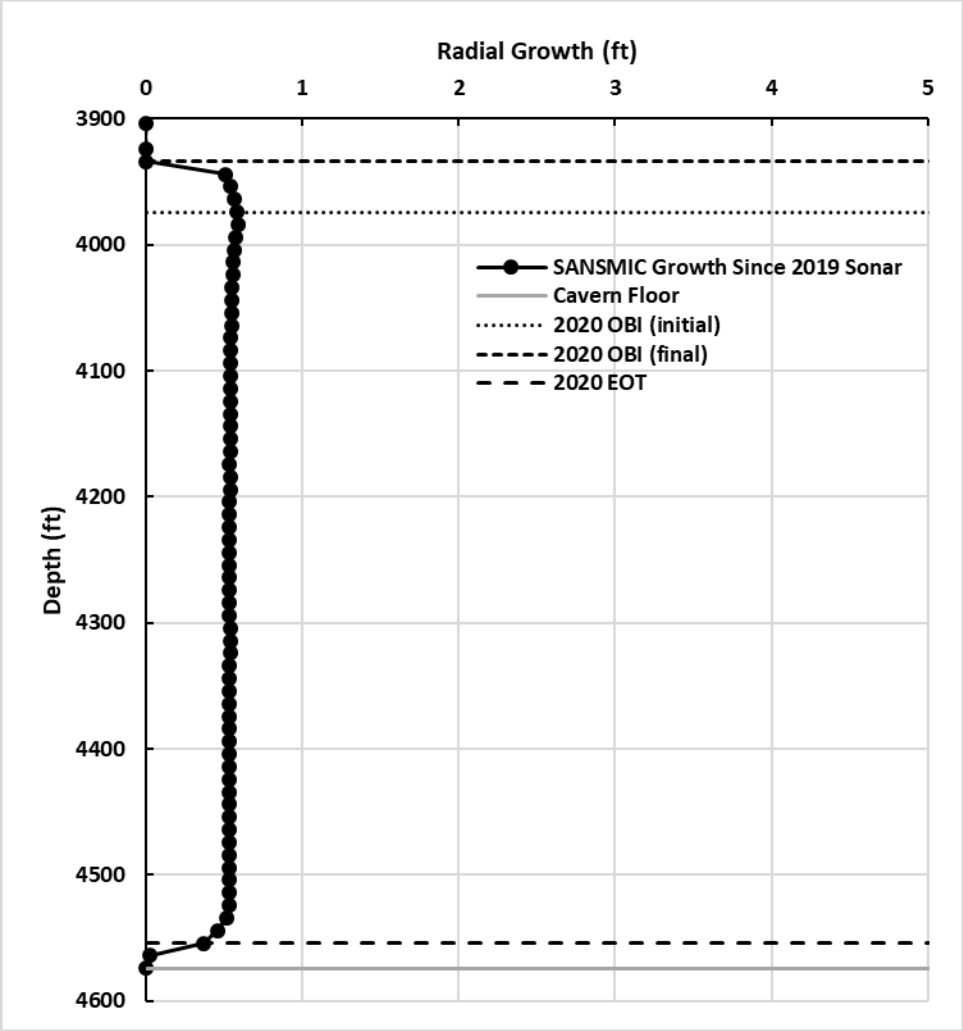

Figure 2-54. WH-109 SANSMIC-Predicted Radial Growth since 2019 Sonar (exaggerated horizontal scale).

2.3.3. WH-111

2.3.3.1. Leaching History

Sonars taken in WH-111 in 2006 and 2015 are shown in Figure 2-55. Floor rise and spread occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 7.3 MMB of water injected into this cavern between sonars. Leaching was primarily radial from 2006 to 2015, suggesting that radial leaching should be expected for the 5 MMB of water that has been injected since the 2015 sonar.

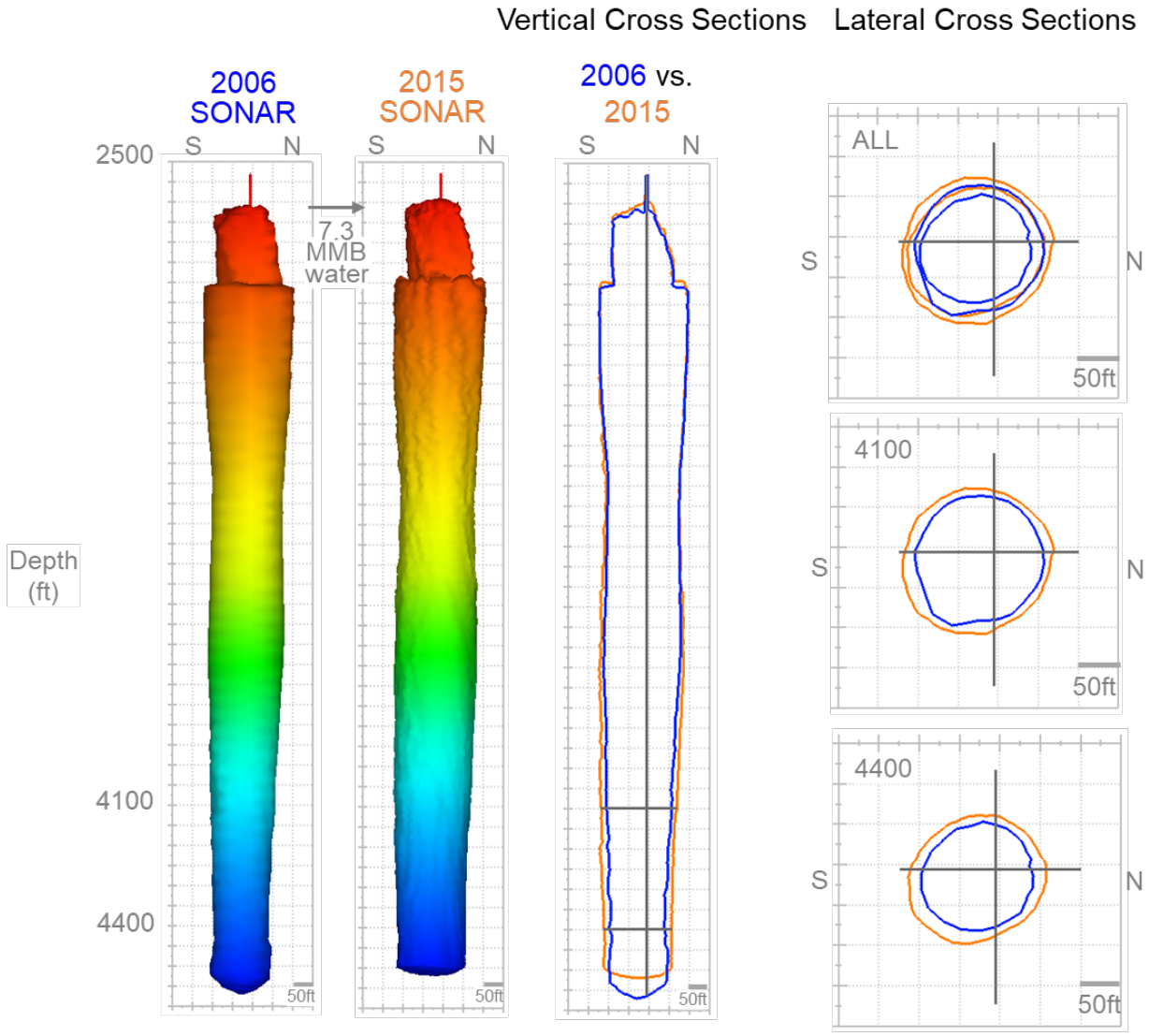

Figure 2-55. Leaching history in WH-111 from 2006 (blue) to 2015 (orange) via sonars.

2.3.3.2. Simulated Leaching Between 2015 Sonar and End of CY20

The last sonar taken in WH-111 was in 2015. Since that sonar, around 4.5 MMB of water have been injected into the cavern in 2017 and 2020 (see Table 2-40). The injection history was modeled using five separate phases of leaching with an EP of 60 days. To represent CY20 water injection, a single phase was added to the four phases modeled for the CY17 report [6]. This cavern has had two Mod EOT rises. The initial OBI in phase 2 was automatically selected by SANSMIC based on the final OBI of the previous phase.

Table 2-40. Summary of Simulation Input for WH-111

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	2017	4527	25	20	1142	1140	75,750	5	378,750
2	2017	4527	25	20	Auto	1220	39,597	44	1,742,268
3	2017	4527	14	10	1402	1400	12,292	95	1,167,740
4	2017	4527	14	20	1551	1550	28,144	42	1,182,048
5	10/26/20-11/22/20	4527	14	20	1575	1580	4,055	4	16,220
All	N/A	N/A	N/A	N/A	N/A	N/A	N/A	190	4,487,026

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of each EP. As summarized in Table 2-41, the overall leaching efficiency for this cavern was 14.9%. The leaching efficiency of phase 5 was anomalously calculated as 43.2%, likely due to the relatively small volumes and the precision of the SANSMIC output.

Table 2-41. Summary of Simulation Output for WH-111

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	1220	1.2009	58,200	15.4
2	1500	1.1979	268,400	15.4
3	1560	1.1957	149,400	12.8
4	1690	1.2003	183,900	15.6
5	1580	1.2019	7,000	43.2
ALL	1580	1.2019	666,900	14.9

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2015 sonar and the end of CY20 (see Figure 2-56). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 4.5 MMB.

Vertical cross sections from each of the cavern geometries reveal only slight changes from leaching. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-57) that is about 1800 ft tall and reflects the large distance between OBI and EOT. The maximum radial growth over this depth is predicted to be only about 5 ft. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

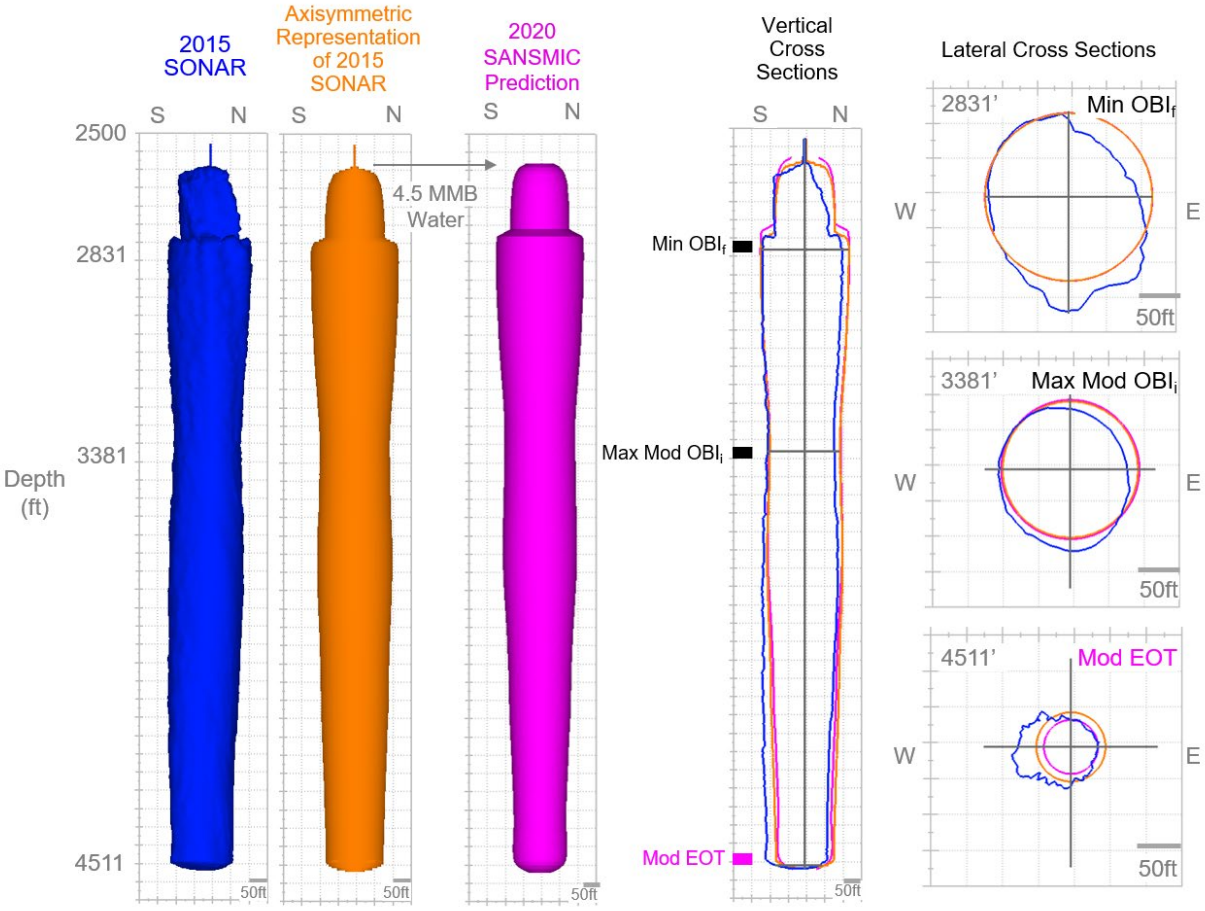

Figure 2-56. WH-111 Modeling Results for Leaching Between 2015 Sonar and End of CY20.

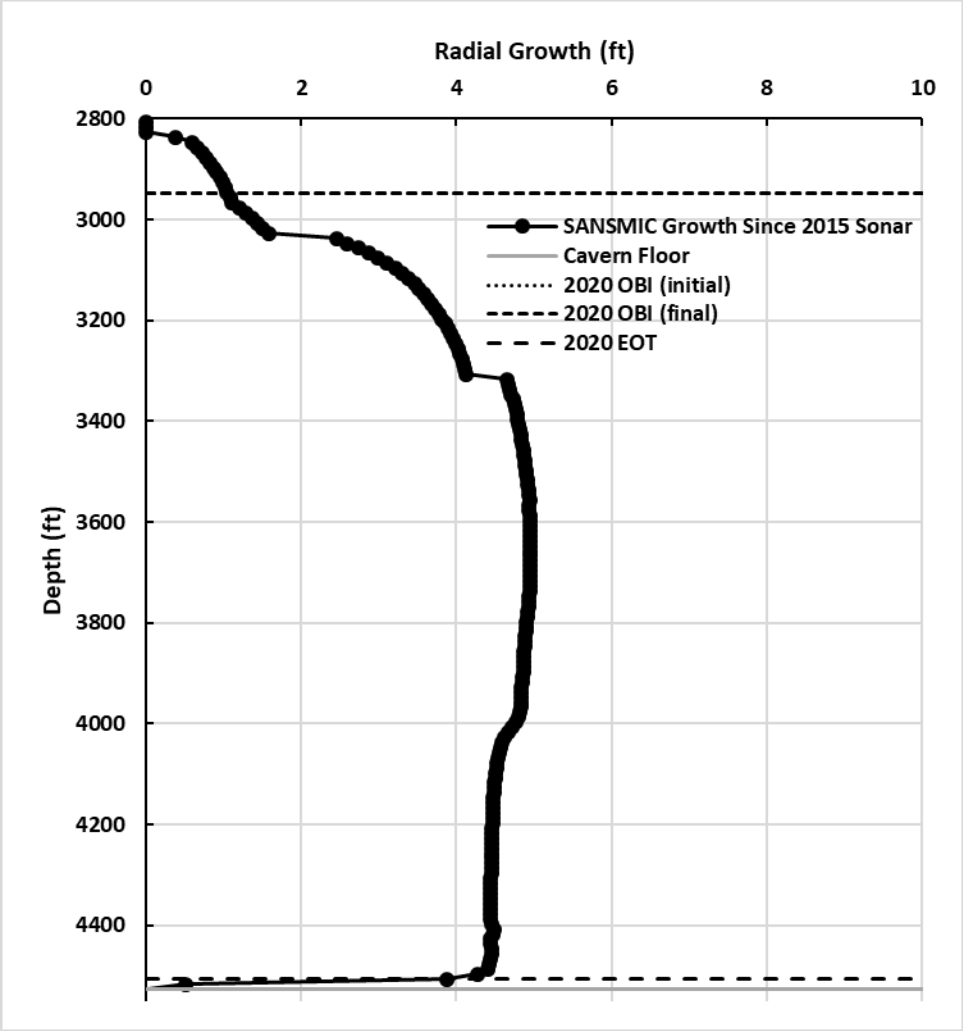

Figure 2-57. WH-111 SANSMIC-Predicted Radial Growth since 2015 Sonar (exaggerated horizontal scale).

2.3.4. WH-112

2.3.4.1. Leaching History

Sonars taken in WH-112 in 2013 and 2018 are shown in Figure 2-58. It appears that contraction has occurred in this cavern between sonars as evidenced by the small changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 0.7 MMB of water injected into this cavern between sonars. Based on the relatively small amount of leaching from 2013 to 2018, it is difficult to estimate the leaching pattern associated with the 1.0 MMB of water that has been injected since the 2018 sonar.

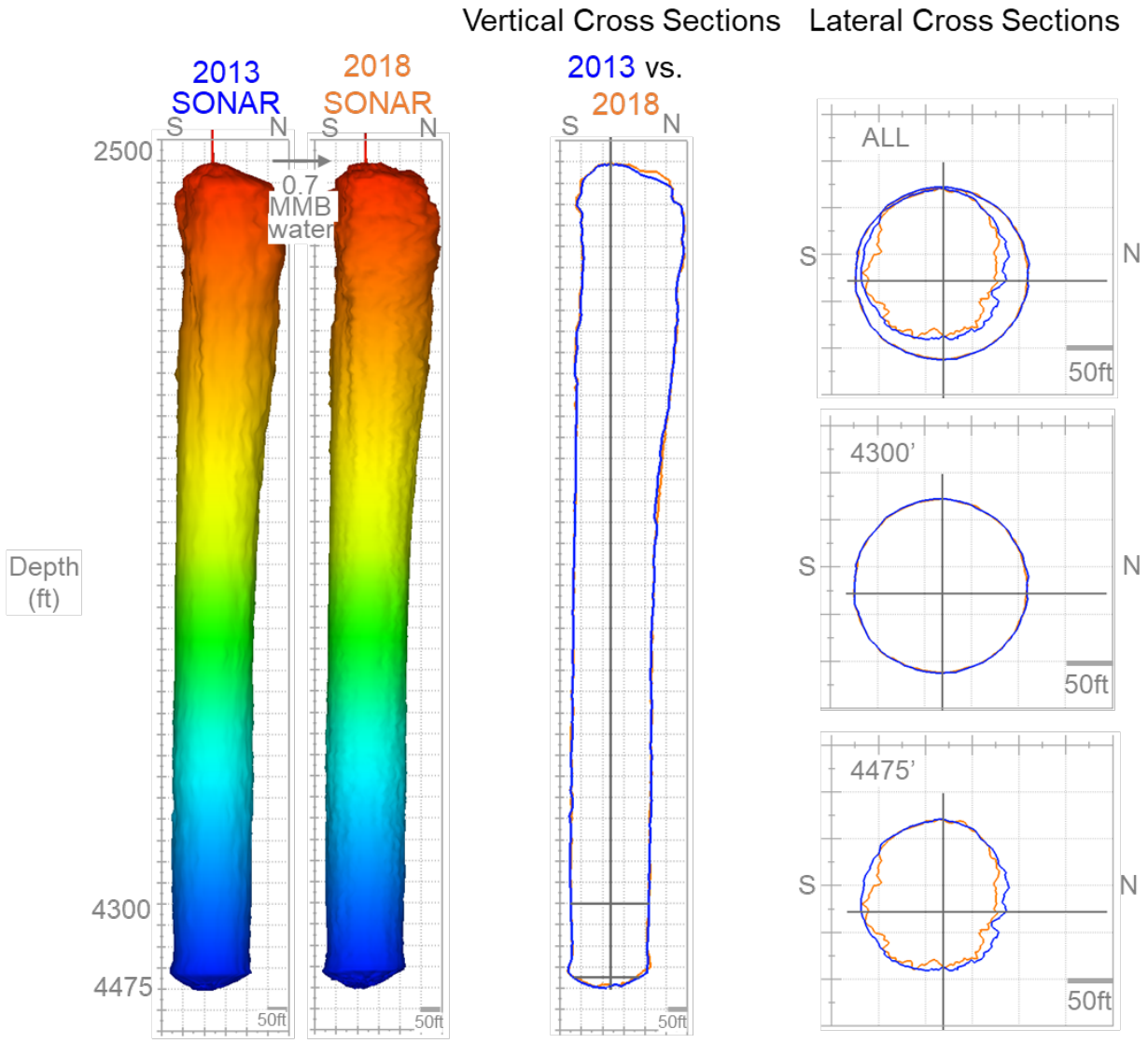

Figure 2-58. Leaching history in WH-112 from 2013 (blue) to 2018 (orange) via sonars.

2.3.4.2. Simulated Leaching Between 2018 Sonar and End of CY20

The last sonar taken in WH-112 was in 2018. Since that sonar, around 1.0 MMB of water have been injected into the cavern in 2018-2020 (see Table 2-42). The injection history was modeled using three separate phases of leaching with an EP of 60 days. To represent CY20 water injection, a single phase was added to the two phases modeled for the CY18-19 report [8]. This cavern has had two Mod EOT rises.

Table 2-42. Summary of Simulation Input for WH-112

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	10/04/18-11/30/18	4513	21	20	55	60	13,657	58	792,106
2	04/30/19-05/15/19	4513	21	10	248	250	31,699	5	158,495
3	08/22/20-08/22/20	4513	21	10	273	270	39,959	1	39,959
All	N/A	N/A	N/A	N/A	N/A	N/A	N/A	64	990,560

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of each EP. As summarized in Table 2-43, the overall leaching efficiency for this cavern was 16.1%.

Table 2-43. Summary of Simulation Output for WH-112

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	220	1.1988	129,000	16.3
2	280	1.1999	24,000	15.1
3	280	1.2014	6,000	15.0
All	280	1.2014	159,000	16.1

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2018 sonar and the end of CY20 (see Figure 2-59). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 1.0 MMB.

Vertical cross sections from each of the cavern geometries reveal only slight changes from leaching. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-60) that is about 250 ft tall and reflects the large distance between OBI and EOT, as well as large variation in OBI. The maximum radial growth over this depth is predicted to be about 10 ft. While the flaring at the bottom of the cavern is predicted to be more pronounced than in [8], the simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

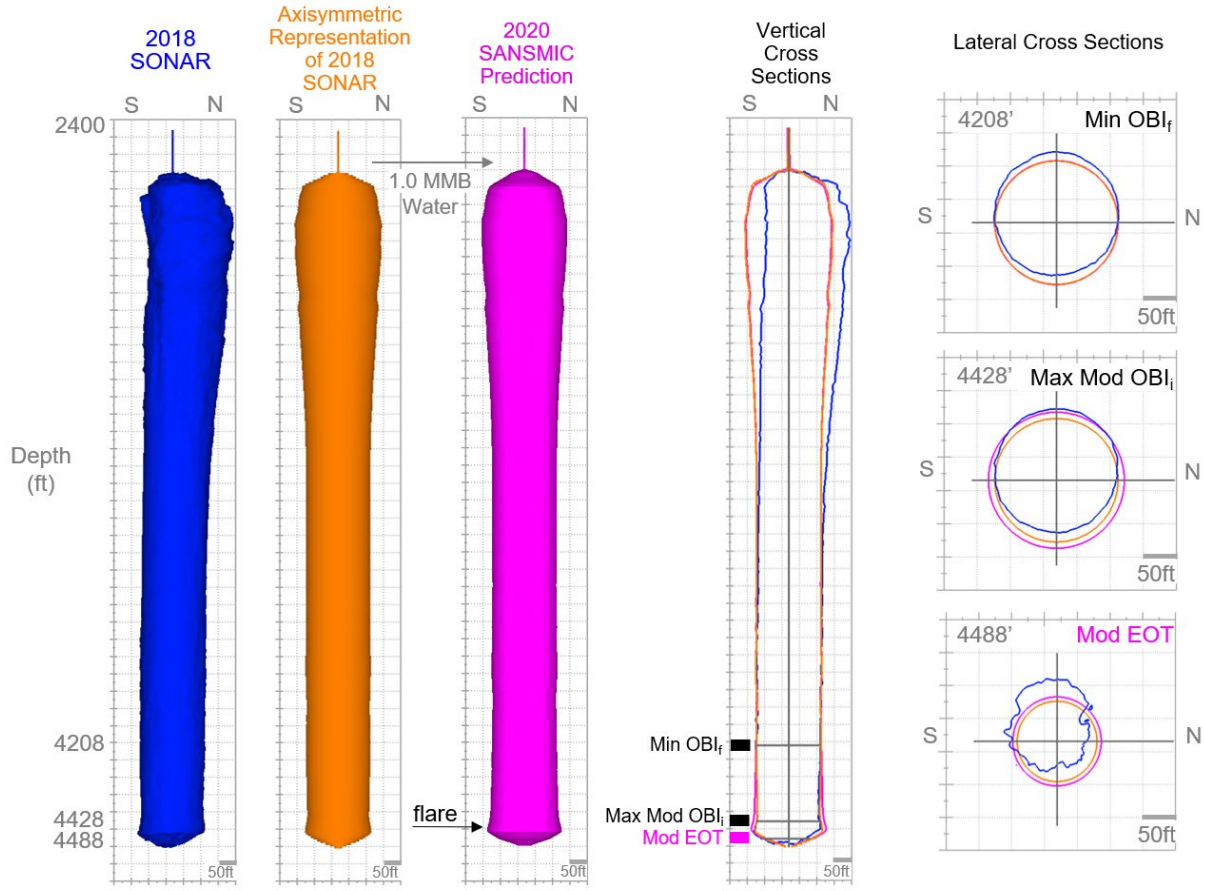

Figure 2-59. WH-112 Modeling Results for Leaching Between 2018 Sonar and End of CY20.

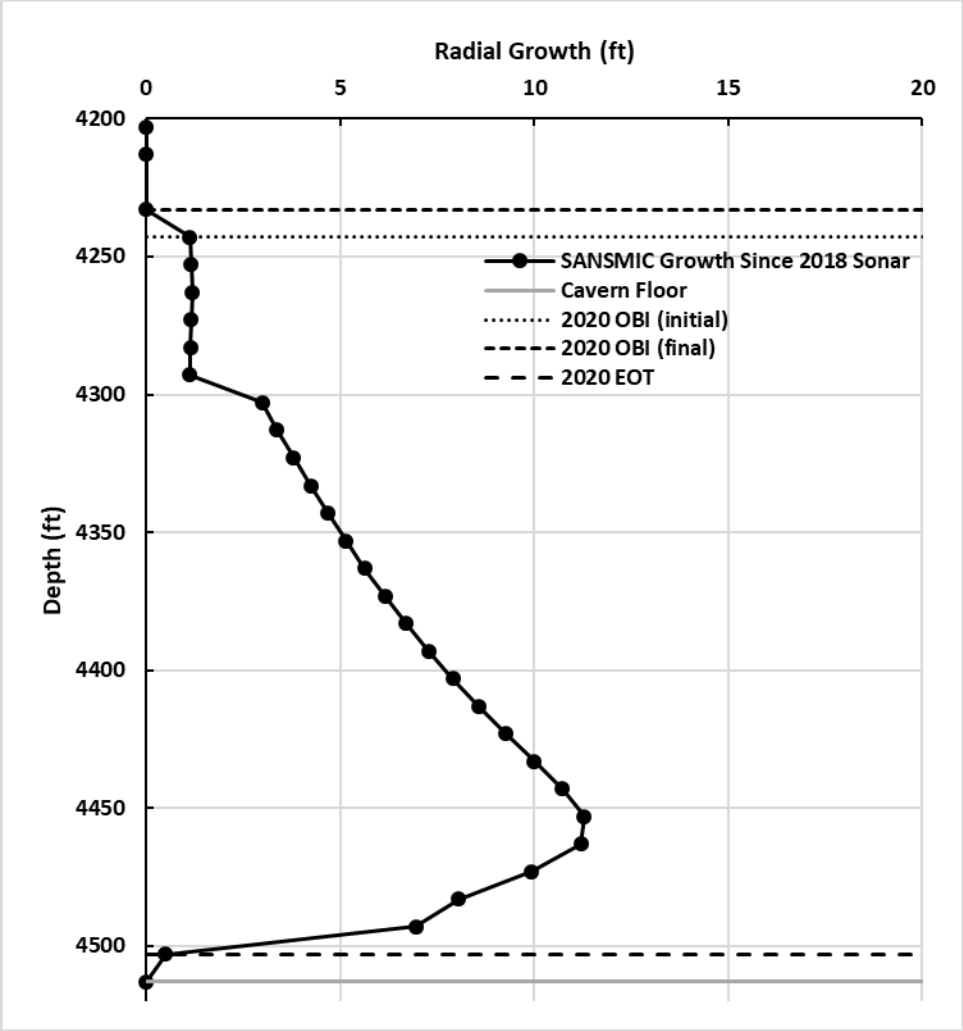

Figure 2-60. WH-112 SANSMIC-Predicted Radial Growth since 2018 Sonar (exaggerated horizontal scale).

2.3.5. WH-114

2.3.5.1. Leaching History

Sonars taken in WH-114 in 2015 and 2020 are shown in Figure 2-61. Floor rise has occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 0.5 MMB of water injected into this cavern between sonars, but at least part of the time, the EOT was approximately 300 ft above the floor, whereas by the time of 2020 leaching, it was only about 10-20 ft from the floor. As a result, an increased cavern radius at about 4200 ft is observed. Based on leaching from 2015 to 2020 and the movement of the EOT, it is not clear what leaching pattern may result from the 0.5 MMB of water that has been injected since the 2020 sonar, but it is likely to be radially symmetric.

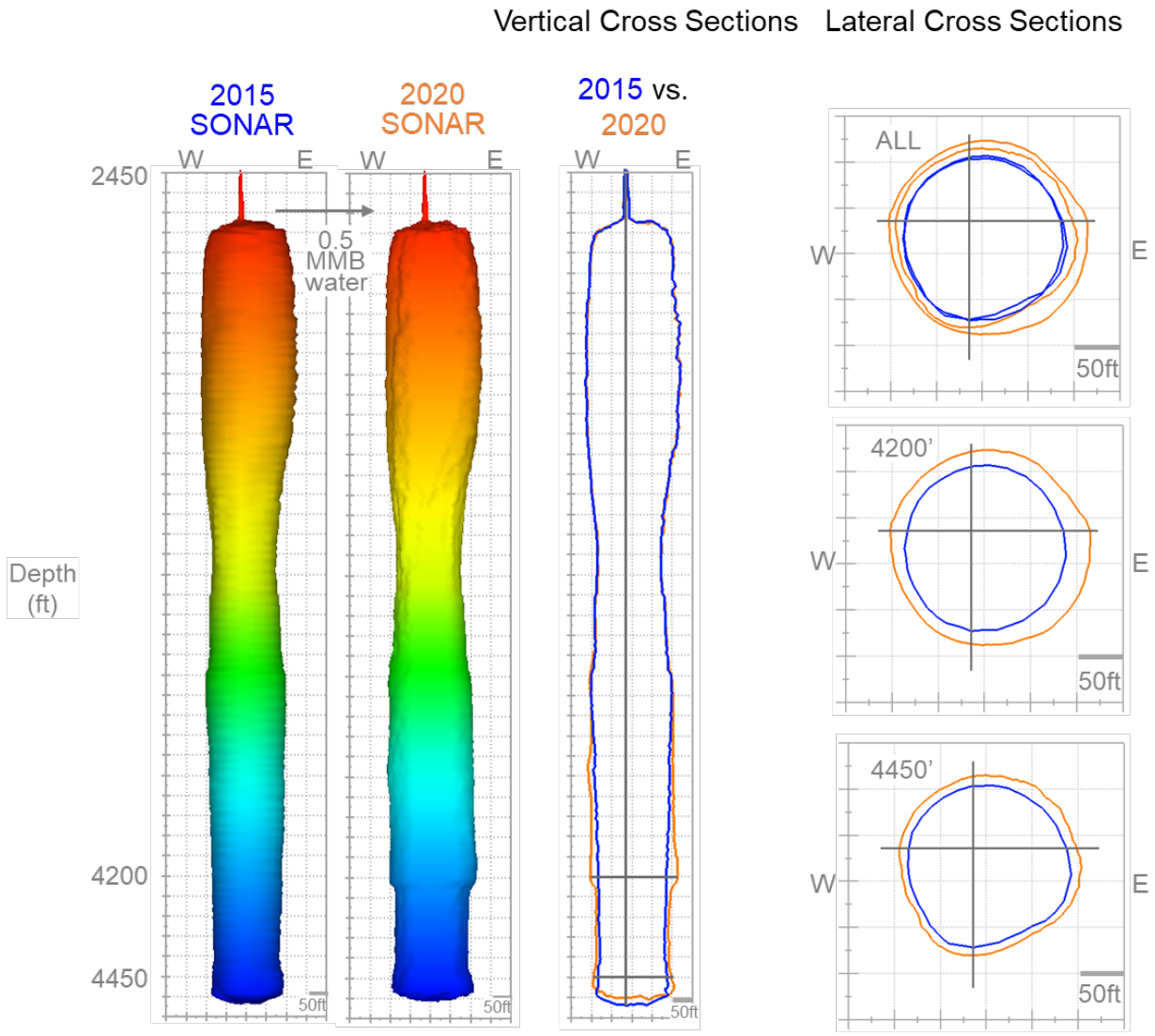

Figure 2-61. Leaching history in WH-114 from 2015 (blue) to 2020 (orange) via sonars.

2.3.5.2. Simulated Leaching Between 2020 Sonar and End of CY20

The last sonar taken in WH-114 was in 2020. Since that sonar, around 0.50 MMB of water was injected into the cavern in 2020 (see Table 2-44). The injection history was modeled using a single phase of leaching with an EP of 60 days.

Table 2-44. Summary of Simulation Input for WH-114

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	08/02/20-11/22/20	4515	21	10	815	820	38,703	13	503,139

The final outlet SG was close to the value of 1.2, suggesting that leaching was near completion at the end of the EP. As summarized in Table 2-45, the overall leaching efficiency for this cavern was 14.7%.

Table 2-45. Summary of Simulation Output for WH-114

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	910	1.2003	74,000	14.7

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2020 sonar and the end of CY20 (see Figure 2-62). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.5 MMB.

Vertical cross sections from each of the cavern geometries reveal the minimal changes from leaching. The changes can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-63) that is about 900 ft tall and reflects the large distance between OBI and EOT. The maximum radial growth over this depth is predicted to be only about 1 ft.

Shelf formation at about 300 ft above the cavern floor was previously predicted [8] and that shelf has appeared in the 2020 Sonar. With only minimal growth since the 2020 sonar, the simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time, but it should be monitored if leaching continues in this cavern. A comparison of the 2020 sonar with 2019 SANSMIC results (from [8]) can be found in Section 3.8.

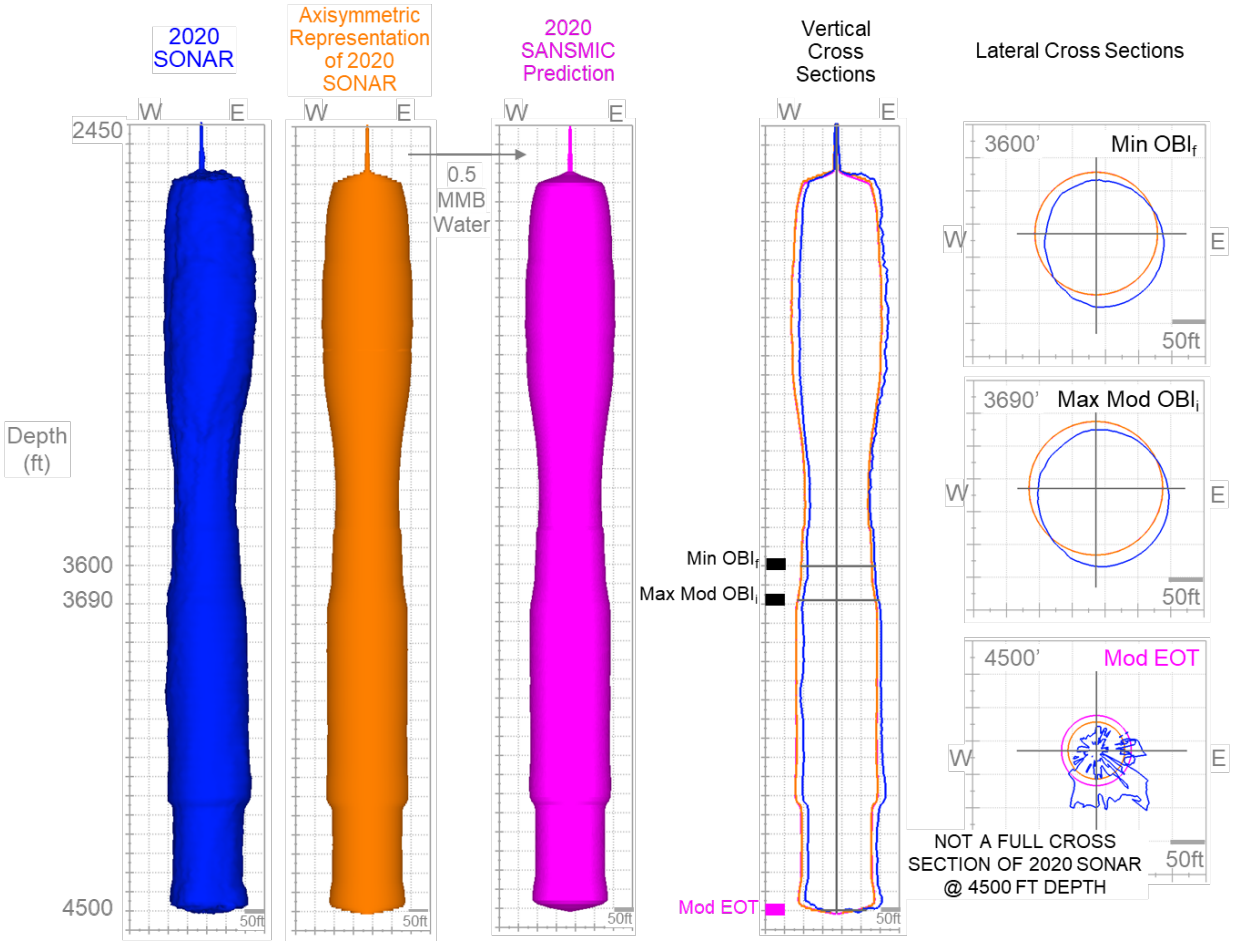

Figure 2-62. WH-114 Modeling Results for Leaching Between 2020 Sonar and End of CY20.

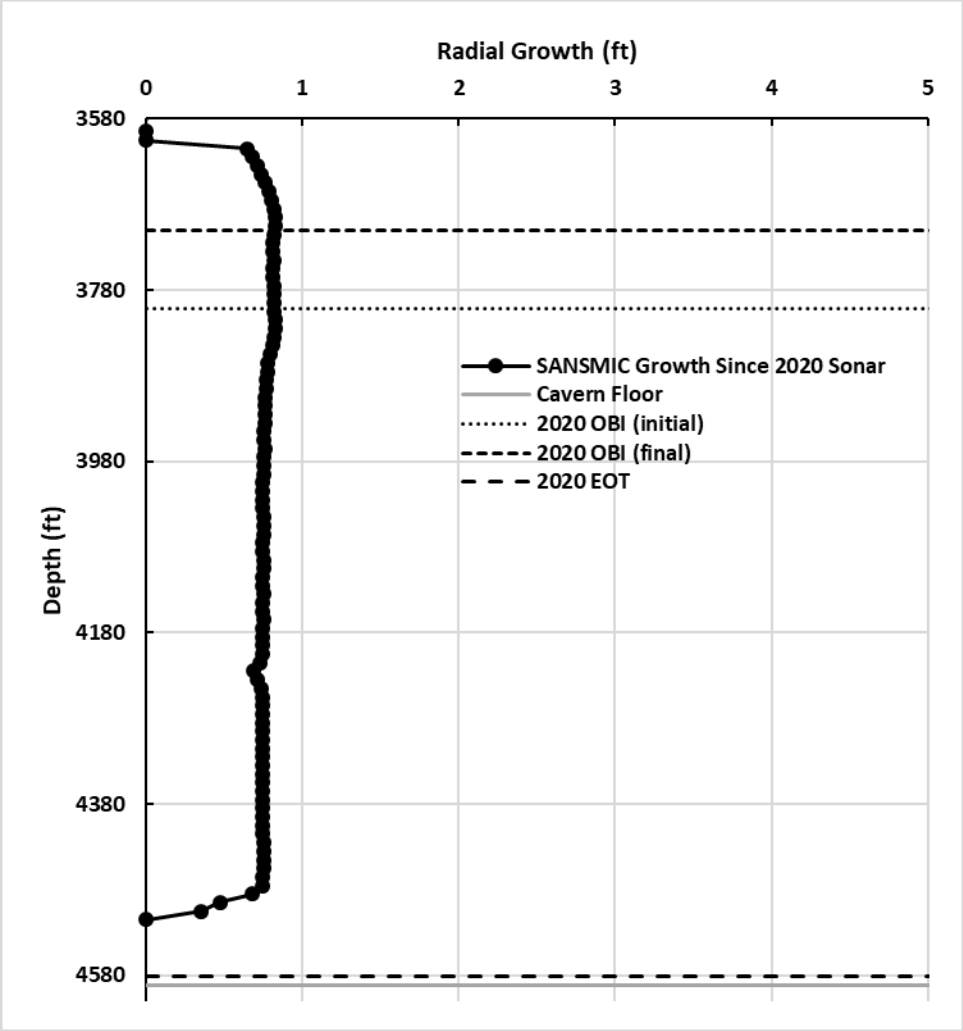

Figure 2-63. WH-114 SANSMIC-Predicted Radial Growth since 2020 Sonar (exaggerated horizontal scale).

2.3.6. WH-115

2.3.6.1. Leaching History

Sonars taken in WH-115 in 2017 and 2020 are shown in Figure 2-64. The 2020 sonar only covered the bottom portion of the cavern (approximately from the floor to the OBI), so the remainder of the cavern sonar plot for 2020 is identical to 2017. Overall, not much change has occurred in this cavern between sonars as evidenced by the lack of changes in the cavern wall positions near the floor in the vertical and lateral cross sections, but some small floor rise is observed. There was 2.5 MMB of water injected into this cavern between sonars. Based on leaching from 2017 to 2020, it is likely that little change to the cavern shape may result from the 0.5 MMB of water that has been injected since the 2020 sonar.

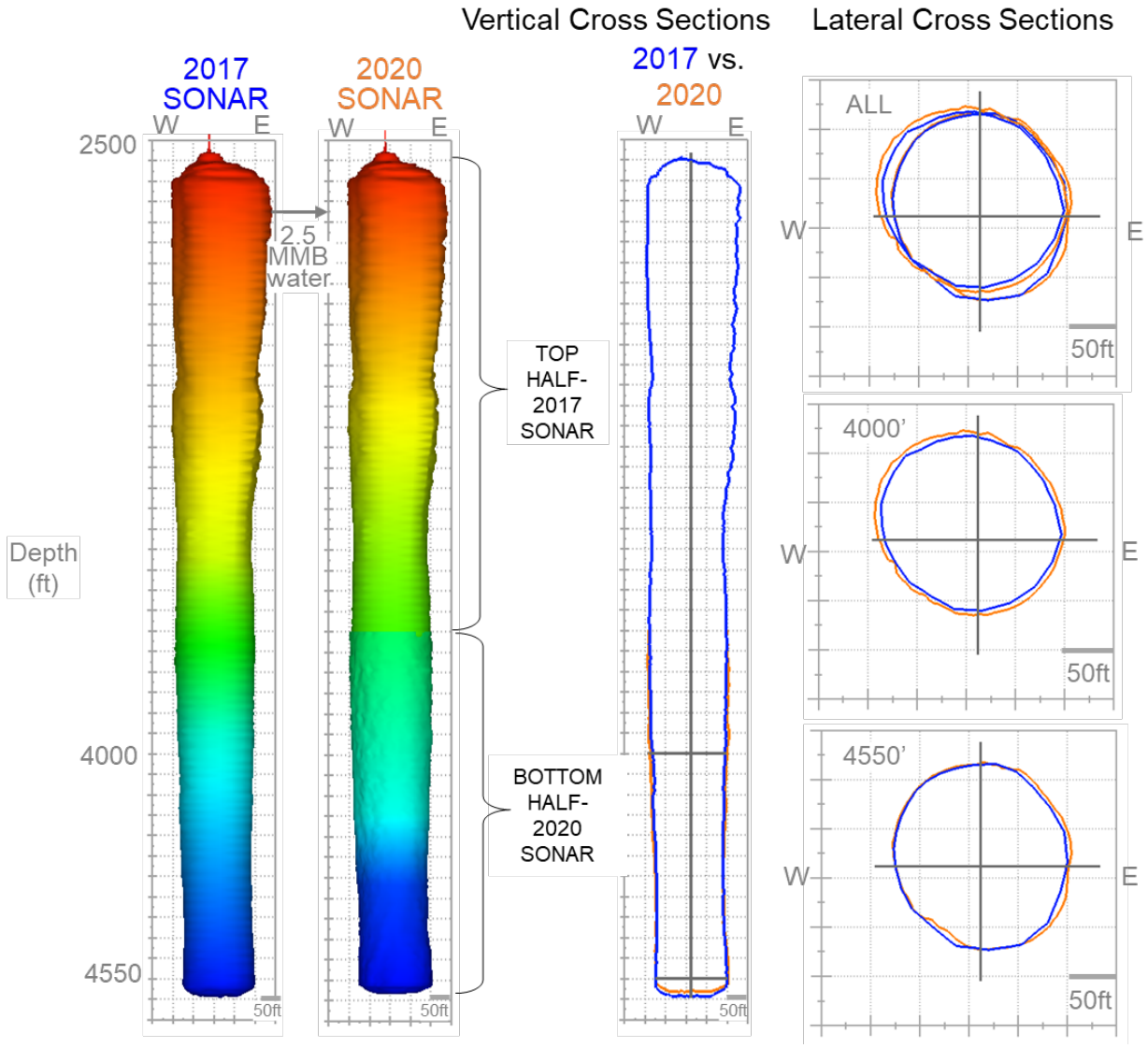

Figure 2-64. Leaching history in WH-115 from 2017 (blue) to 2020 (orange) via sonars.

2.3.6.2. Simulated Leaching Between 2020 Sonar and End of CY20

The last sonar taken in WH-115 was in 2020. Since that sonar, around 0.53 MMB of water was injected into the cavern in 2020 (see Table 2-46). Because the 2020 sonar only covered the bottom portion of the cavern (approximately from the floor to the OBI), the remainder of the cavern sonar plot for 2020 was used in SANSMIC modeling for the top of the cavern. The injection history was modeled as a single phase of leaching with an EP of 60 days.

Table 2-46. Summary of Simulation Input for WH-115

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	08/02/20-11/22/20	4591	21	10	790	790	37,817	14	529,438

The final outlet SG was close to the value of 1.2, suggesting that leaching was near completion at the end of the EP. As summarized in Table 2-47, the overall leaching efficiency for this cavern was 15.1%.

Table 2-47. Summary of Simulation Output for WH-115

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	880	1.2003	80,000	15.1

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2020 sonar and the end of CY20 (see Figure 2-62). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 0.5 MMB.

Vertical cross sections from each of the cavern geometries reveal the minimal changes from leaching. The changes can be seen by the variation between the input (orange) and output (magenta) cavern profiles in the lateral cross sections. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-66) that is about 900 ft tall and reflects the large distance between OBI and EOT. The maximum radial growth over this depth is predicted to be only about 1 ft.

Increased growth of the flare near the cavern floor was previously predicted [8] and that flare growth in apparent from the 2020 sonar. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time, but it should be monitored if leaching continues in this cavern. A comparison of the 2020 sonar with 2019 SANSMIC results (from [8]) can be found in Section 3.9.

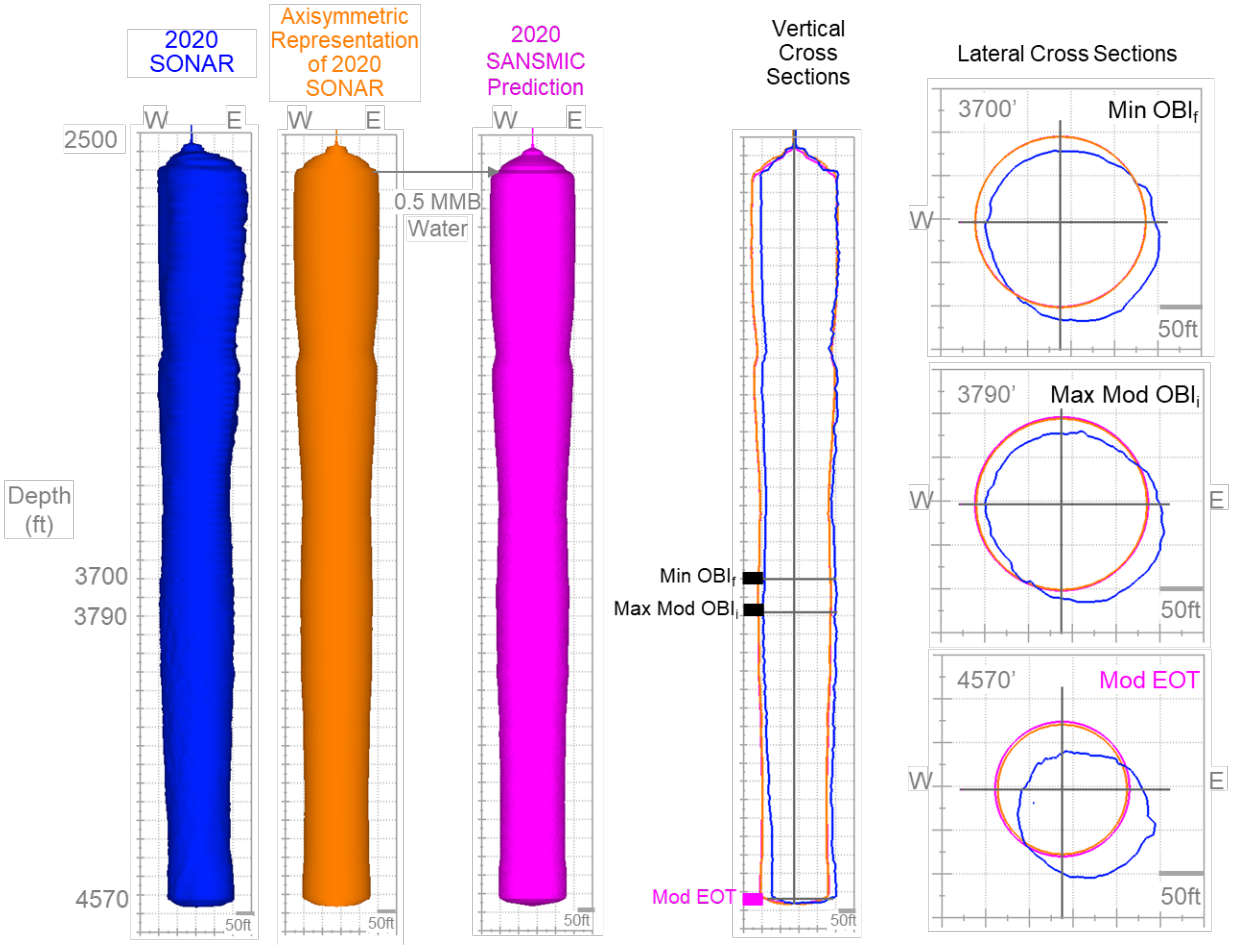

Figure 2-65. WH-115 Modeling Results for Leaching Between 2020 Sonar and End of CY20.

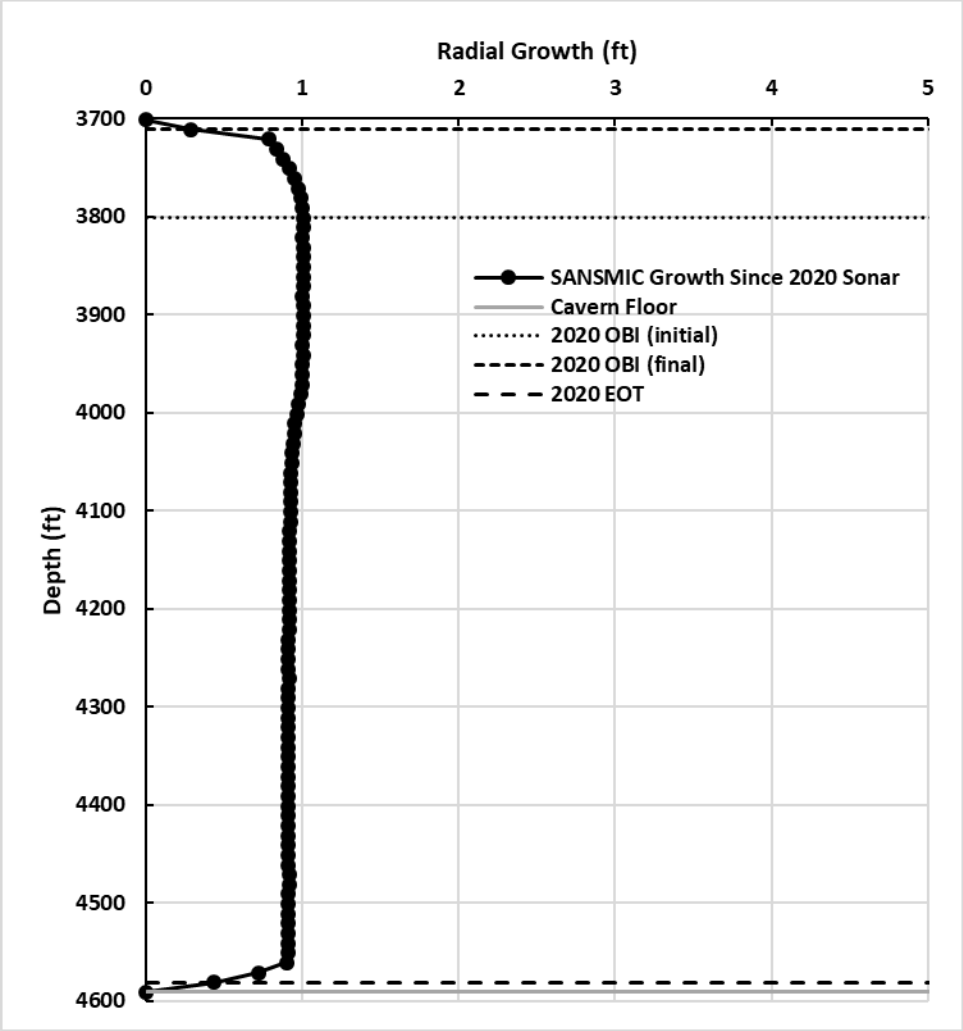

Figure 2-66. WH-115 SANSMIC-Predicted Radial Growth since 2020 Sonar (exaggerated horizontal scale).

2.3.7. WH-117

2.3.7.1. Leaching History

Sonars taken in WH-117 in 2018 and 2019 are shown in Figure 2-67. A very minor amount of floor rise and spread occurred in this cavern between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. There was 0.7 MMB of water injected into this cavern between sonars. Based on leaching from 2018 to 2019, symmetric leaching did occur between 2018 and 2019. Thus, it is also possible that symmetric leaching may result from the 1.6 MMB of water that has been injected since the 2019 sonar. The 2019 sonar in WH117 was taken after water was injected for the spring 2019 sale and before water was injected for the fall 2019 sale. This history covers the cavern geometry changes observed up to the end of the spring 2019 sale but not due to the fall 2019 sale.

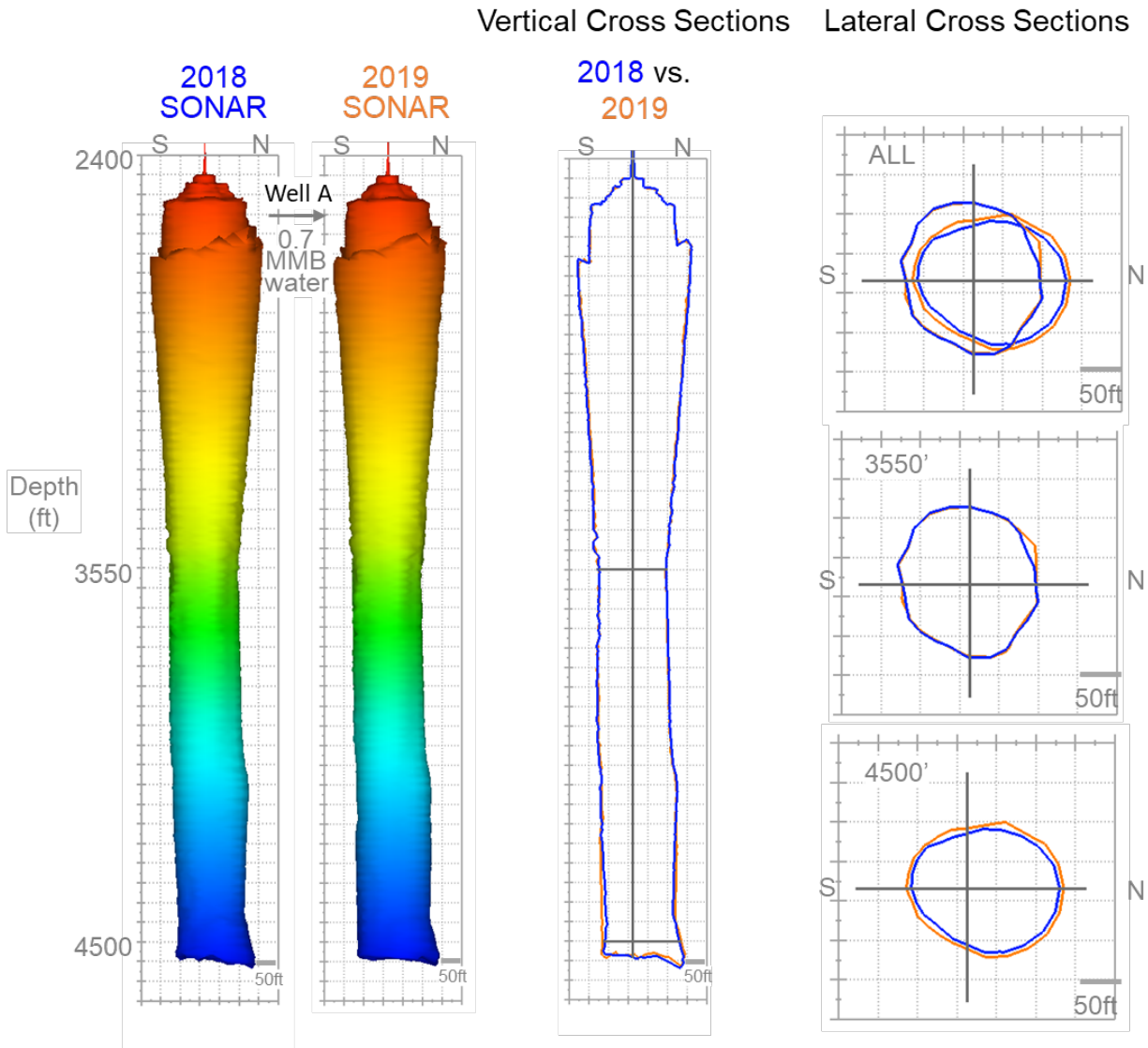

Figure 2-67. Leaching history in WH-117 from 2018 (blue) to 2019 (orange) via sonars.

2.3.7.2. Simulated Leaching Between 2019 Sonar and End of CY20

The last sonar taken in WH-117 was in 2019. Since that 2019 sonar, around 1.6 MMB of water have been injected into the cavern in 2019-2020 (see Table 2-48). The injection history was modeled using two phases of leaching with an EP of 60 days. To represent CY20 water injection, a single phase was added to the one phase modeled for the CY18-19 report [8]. This cavern has had two Mod EOT rises.

Table 2-48. Summary of Simulation Input for WH-117

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	10/07/19-12/04/19	4575	11	0	366	370	37,675	33	1,243,275
2	08/02/20-08/22/20	4576	13	20	187	190	55,620	6	333,720
All	N/A	N/A	N/A	N/A	N/A	N/A	N/A	39	1,576,995

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of each EP. As summarized in Table 2-49, the overall leaching efficiency for this cavern was 16.2%.

Table 2-49. Summary of Simulation Output for WH-117

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	670	1.1995	204,000	16.4
2	260	1.1987	52,000	15.6
All	260	1.1967	256,000	16.2

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2019 sonar and the end of CY20 (see Figure 2-68). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 1.6 MMB.

Vertical cross sections from each of the cavern geometries reveal only slight changes from leaching. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-69) that is about 700 ft tall and reflects the large distance between OBI and EOT. The maximum radial growth over this depth is predicted to be only about 5 ft. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

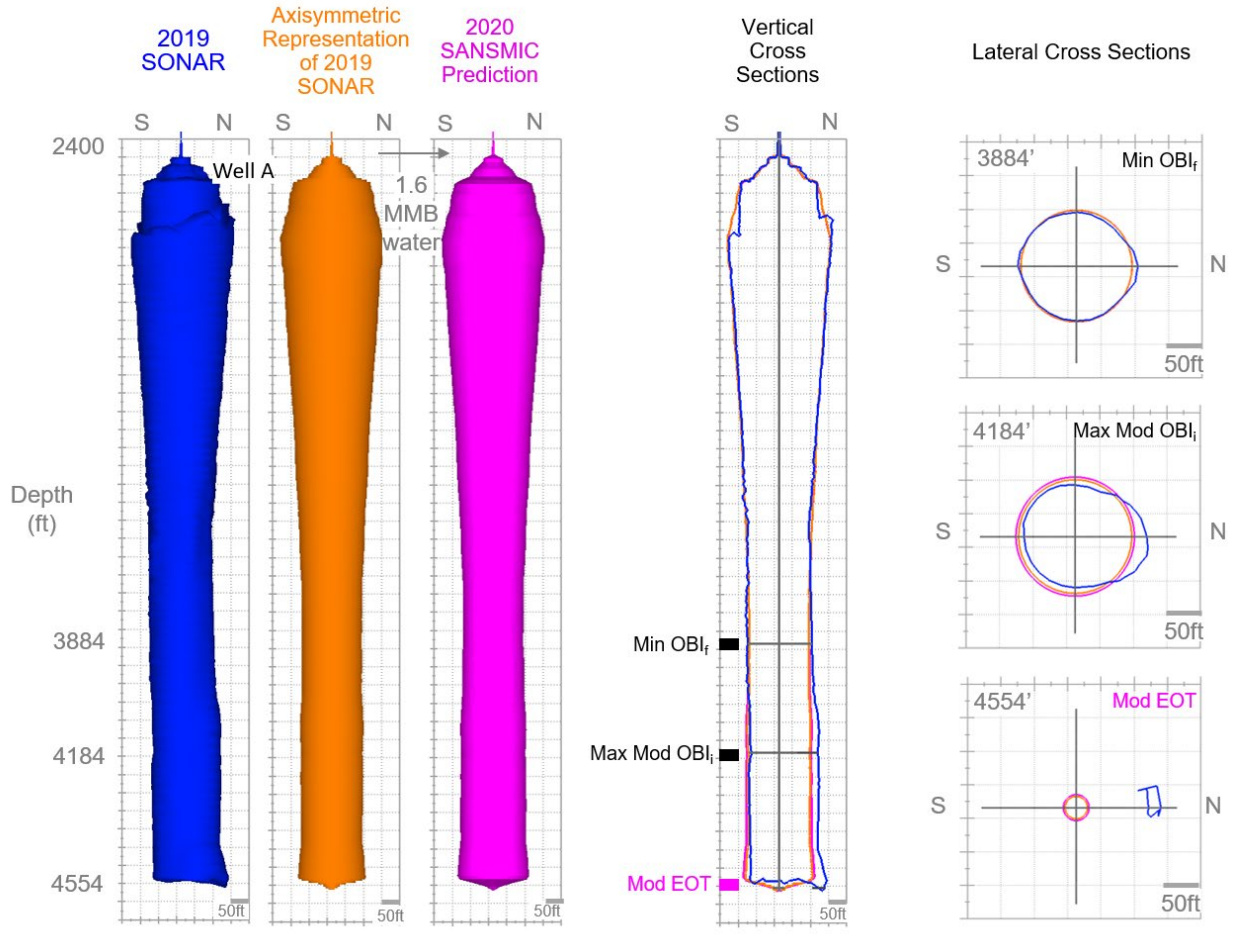

Figure 2-68. WH-117 Modeling Results for Leaching Between 2019 Sonar and End of CY20.

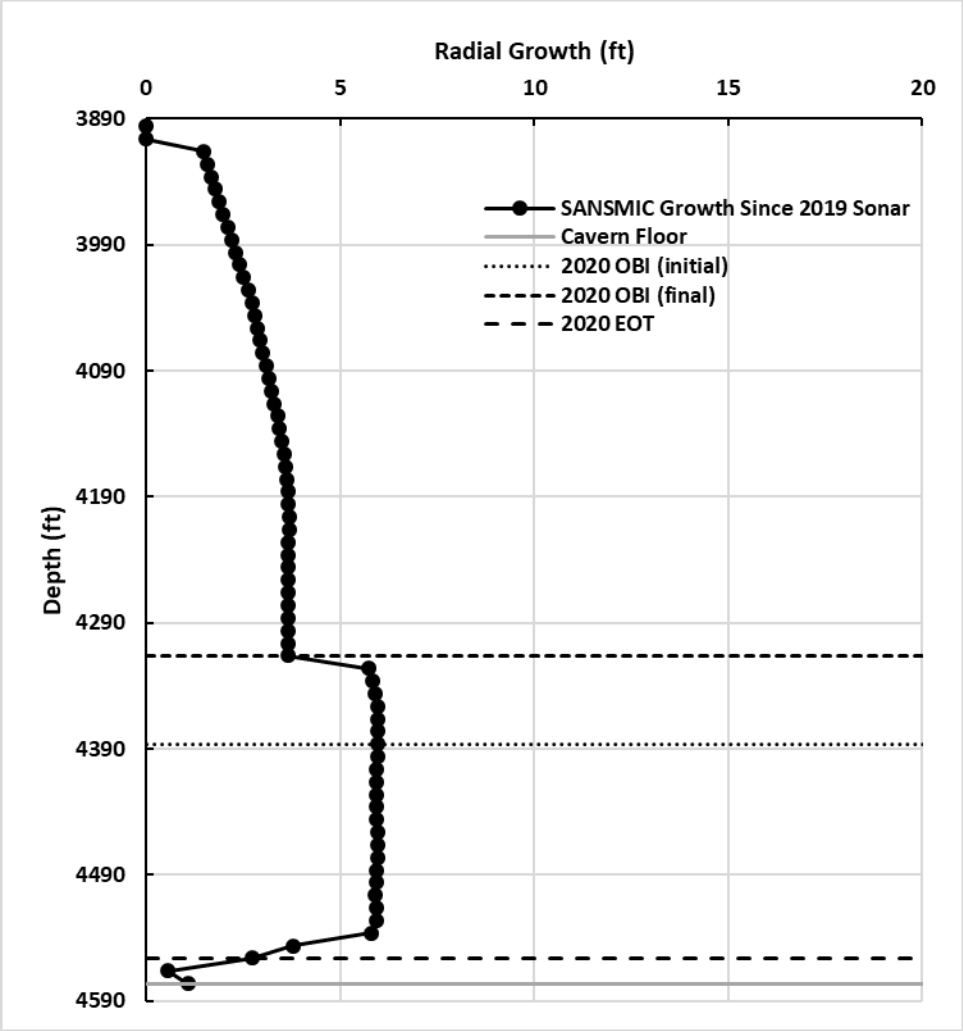

Figure 2-69. WH-117 SANSMIC-Predicted Radial Growth since 2019 Sonar (exaggerated horizontal scale).

2.4. Bayou Choctaw

Simulation results for Bayou Choctaw are summarized in Table 2-50. Two caverns had water injected in CY20, but one (BC-18) had a sonar taken at the end of CY20 and thus no raw water injected subsequent to the sonar. Therefore, only the leaching results for BC-102 are discussed in this section, while a comparison of the leaching results to the 2020 sonar for BC-18 are discussed in Section 3.10. No caverns at Bayou Choctaw have had at least 3.0 MMB of water injected since the last sonar. A brief leaching history and the results of SANSMIC modeling of leaching since the last sonar are discussed below for each cavern.

Table 2-50. Caverns at Bayou Choctaw with Water Injected in CY20

Cavern	Last Sonar	Injected Water Volume* (MMB)	Concerns
BC-18	2020**	0.0	No
BC-102	2017	1.9	No

* Since last sonar
** No raw water injected subsequent to 2020 sonar

2.4.1. BC-102

2.4.1.1. Leaching History

Sonars taken in the A well of BC-102 in 2005 and 2017 are shown in Figure 2-49. Some floor rise is observed between sonars as evidenced by the changes in the cavern wall positions near the floor in the vertical and lateral cross sections. The 5.4 MMB of water injected between sonars resulted in only small changes to cavern geometry. Based on leaching from 2003 to 2018, the leaching pattern may be symmetric that was associated with the 1.9 MMB of water that has been injected since the 2017 sonar.

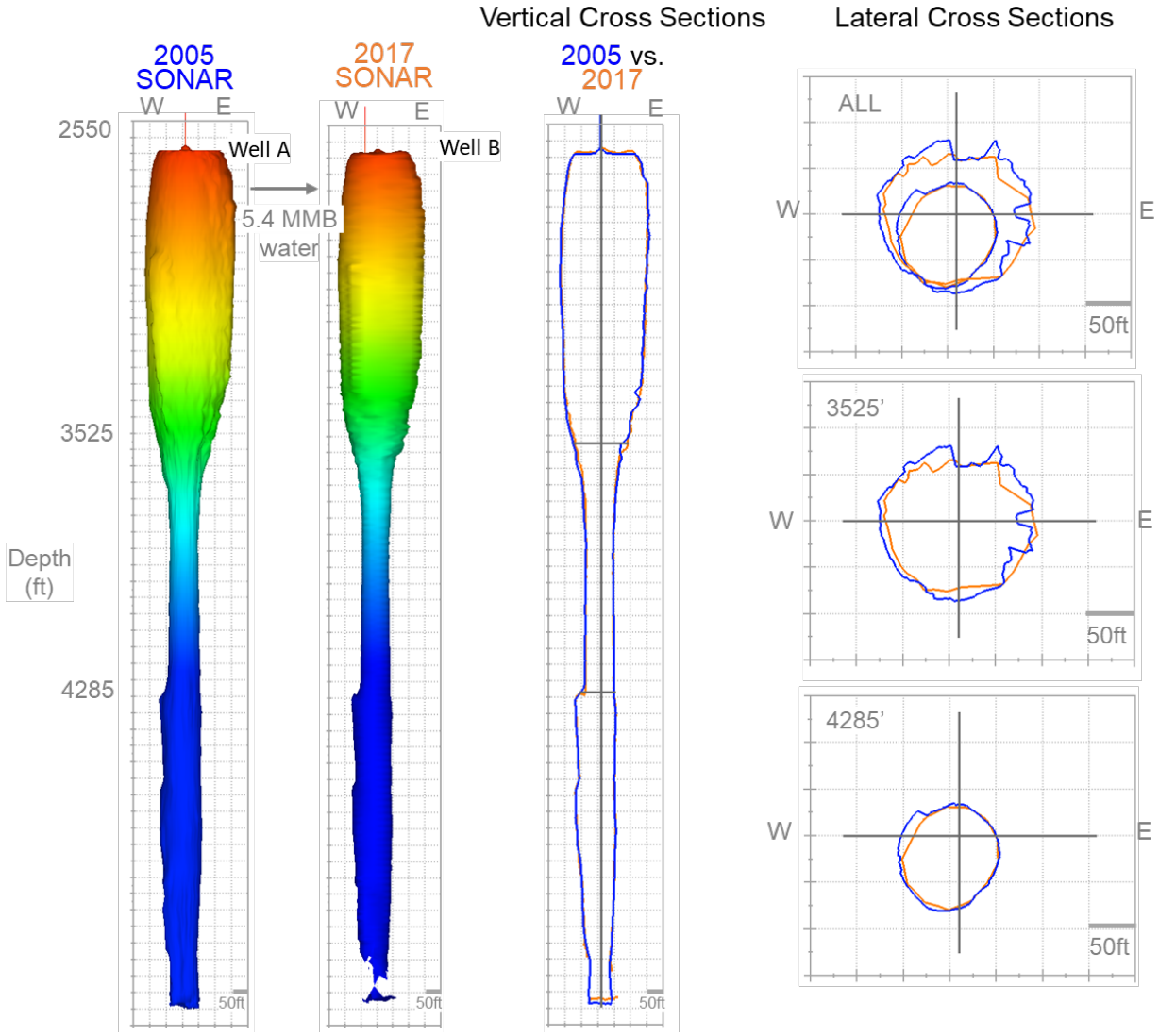

Figure 2-70. Leaching history in BC-102 from 2005 (blue) to 2017 (orange) via sonars.

2.4.1.2. Simulated Leaching Between 2017 Sonar and End of CY20

The last sonar taken in BC-102 was in 2017. Since that sonar, around 1.9 MMB of water have been injected into the cavern in 2017 and 2020 (see Table 2-51). The injection history was modeled using two separate leaching phases with an EP of 60 days following each injection phase. To represent CY20 water injection, a single phase was added to the one phase modeled for the CY17 report [6]. This cavern has had a single Mod EOT rise.

Table 2-51. Summary of Simulation Input for BC-102

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	09/03/17-09/29/17	5243	50	40	1738	1740	38,212	24	917,088
2	10/05/20-10/31/20	5243	50	40	1298	1300	48,600	20	972,000
All	N/A	N/A	N/A	N/A	N/A	N/A	N/A	44	1,889,088

The final outlet SG for each phase was close to the value of 1.2, suggesting that leaching was near completion at the end of each EP. As summarized in Table 2-52, the overall leaching efficiency for this cavern was 16.2%.

Table 2-52. Summary of Simulation Output for BC-102

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	1890	1.2002	148,800	16.2
2	1790	1.2003	156,400	16.1
All	1790	1.2003	305,200	16.2

The resultant cavern geometry after leaching was then computed and compared with the pre-leaching geometry to understand the leaching effects from water injection between the 2019 sonar and the end of CY20 (see Figure 2-50). The most recent sonar is shown in blue, the 2D axisymmetric representation of that sonar – the SANSMIC input – is shown in orange, and the SANSMIC output is shown in magenta and titled '2020 SANSMIC prediction'. The total volume of injected water modeled is shown with a grey arrow, in this case 1.9 MMB.

Vertical cross sections from each of the cavern geometries reveal only slight changes from leaching. Plotting SANSMIC-predicted radial growth reveals a modeled leaching zone (see Figure 2-51) that is about 1700 ft tall and reflects the large distance between OBI and EOT. The maximum radial growth over this depth is predicted to be only about 5 ft. The simulated shape of this cavern does not suggest any leaching-induced features which may be of concern for this cavern at this time.

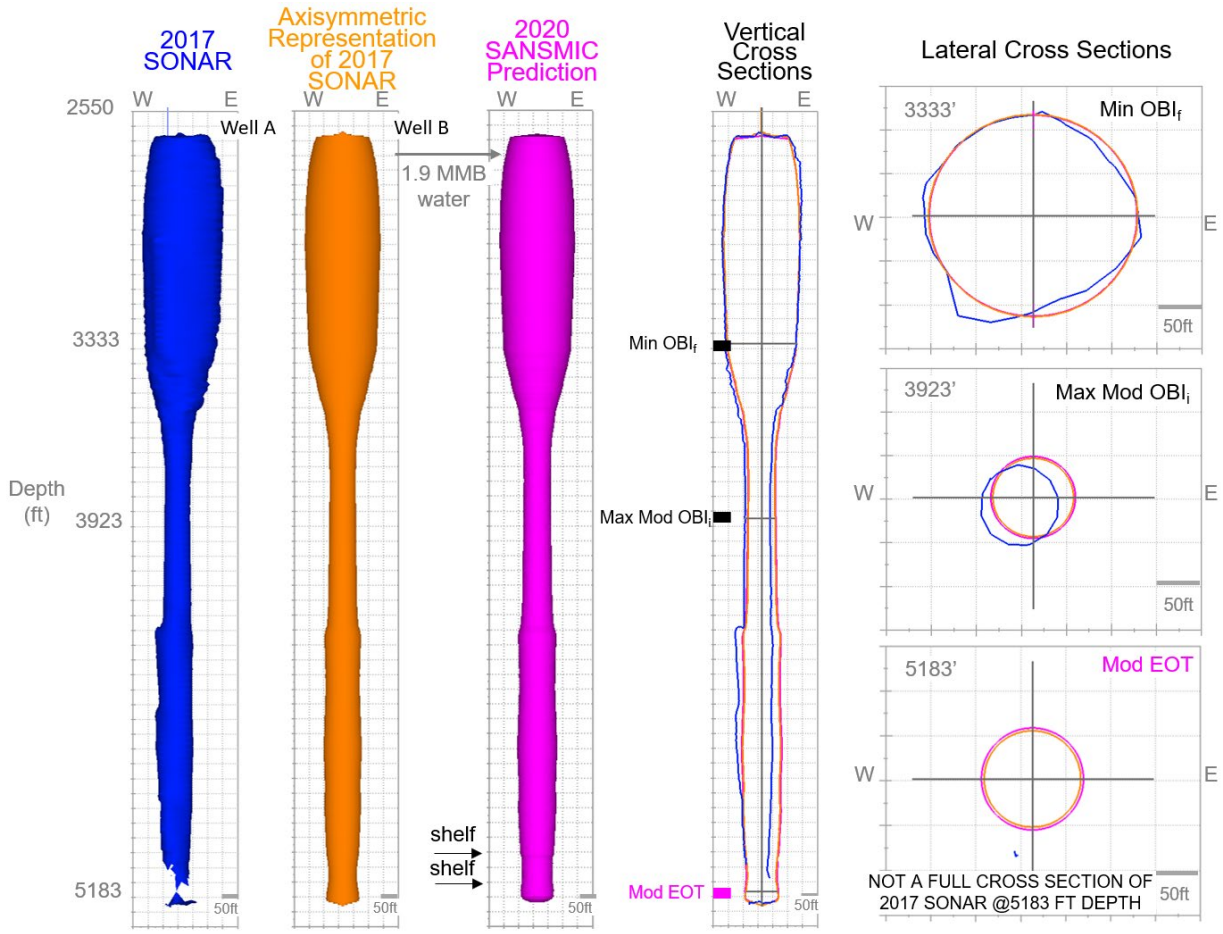

Figure 2-71. BC-102 Modeling Results for Leaching Between 2017 Sonar and End of CY20.

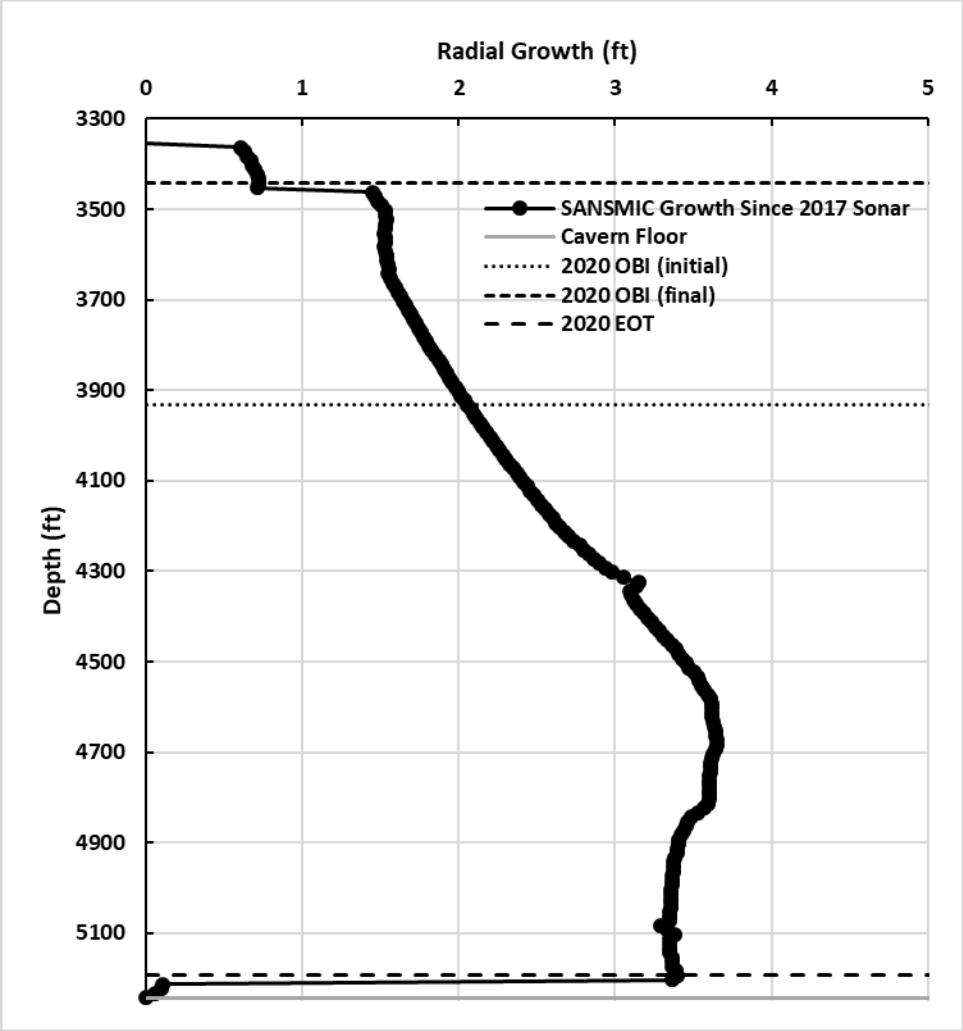

Figure 2-72. BC-102 SANSMIC-Predicted Radial Growth since 2017 Sonar (exaggerated horizontal scale).

3. COMPARISON OF SIMULATED RESULTS WITH SONARS

Results from SANSMIC simulations are compared to the current (post-sales) sonars in this section. In these figures, the latest post-sale sonar is shown in blue, the axisymmetric representation of that sonar is shown in orange, and the SANSMIC predicted geometry is shown in magenta. Vertical and lateral cross sections of each representation are then overlayed and presented to enable comparisons among the data. Comparisons for 10 caverns are included in this section. Raw water injection volumes between the two latest sonars were used as input for SANSMIC calculations. For 9 of the 10 caverns, the SANSMIC results were drawn from previously published cavern leaching reports [6][7]. In these nine cases, each cavern did not have more than 10.000 bbls of raw water injected in 2020, so no new SANSMIC simulations were performed. In the case of BC-18, new SANSMIC calculations were done to include the impact of raw water injection in 2020; the 2020 sonar was performed subsequent to all raw water injection. In general, SANSMIC is reasonably predicting the observed leaching behavior, particularly the formation of flares and shelves.

The error metrics for the sonar comparisons include:

- OBIs and cavern shapes are influenced by cavern creep between sonars, and creep is not a part of the SANSMIC model
- OBIs and cavern shapes are influenced by floor rise between sonars, and floor rise is not a part of the SANSMIC model
- OBIs and EOTs are automatically modified by SANSMIC due to limitations on the number of cells in a SANSMIC simulation, meaning that the Δh_{OBI} is only accurate to $\pm 2.0 \Delta z_{CELL}$.
- Sonar volumes are only accurate to $\pm$1-3% V, meaning that ΔV is only accurate to $\pm$(0.02 to 0.06)(V_{final})

Accounting for some of these errors, OBI over/under prediction is less relevant than the qualitative prediction of changes at the EOT or initial OBI (flares/shelves). Thus, SANSMIC is a useful tool for understanding leaching outcomes in the caverns due to the partial drawdowns associated with sales and exchanges, particularly for caverns with multiple phases of leaching.

3.1. BH-109

The CY18-CY19 SANSMIC modeling report [8] presented results based on leaching since the 2015 sonar in BH-109. When the 2019 SANSMIC results are compared with the 2020 sonar in BH-109, a notable difference in the position of the cavern floor is observed (see vertical cross sections in Figure 3-1 and Figure 3-2). This difference is the result of significant floor rise that occurred prior to the 2020 sonar in BH-109. Floor rise is not a process that is currently included in SANSMIC and thus the change in floor rise cannot be accurately estimated with it. As a result, there is a discrepancy between the modeled OBI and sonar OBI—in this case, the sonar OBI is at a lower depth than the modeled OBI. SANSMIC did capture the leaching behavior well in terms of growth of the flare the bottom of the cavern. SANSMIC has overpredicted the extent of flare growth, in some part due to the extreme floor rise; the lack of floor rise in the SANSMIC model leads to additional leaching closer to the cavern floor. As a result, SANSMIC has also underpredicted leaching further up in the cavern. Overall, SANSMIC did a reasonable job estimating the leaching in this cavern and the resultant flare.

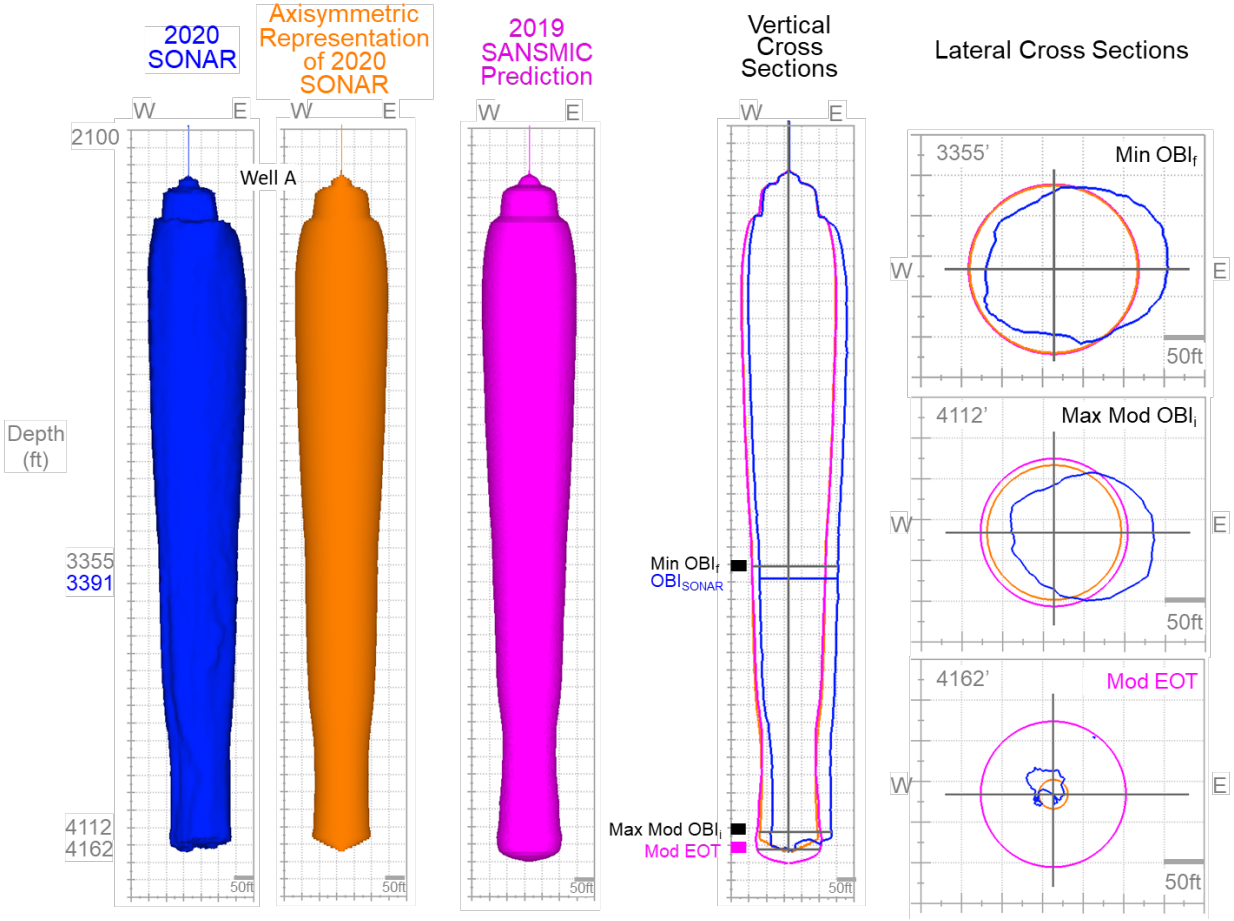

Figure 3-1. Predicted (magenta) and observed (blue, orange) cavern geometries for BH-109.

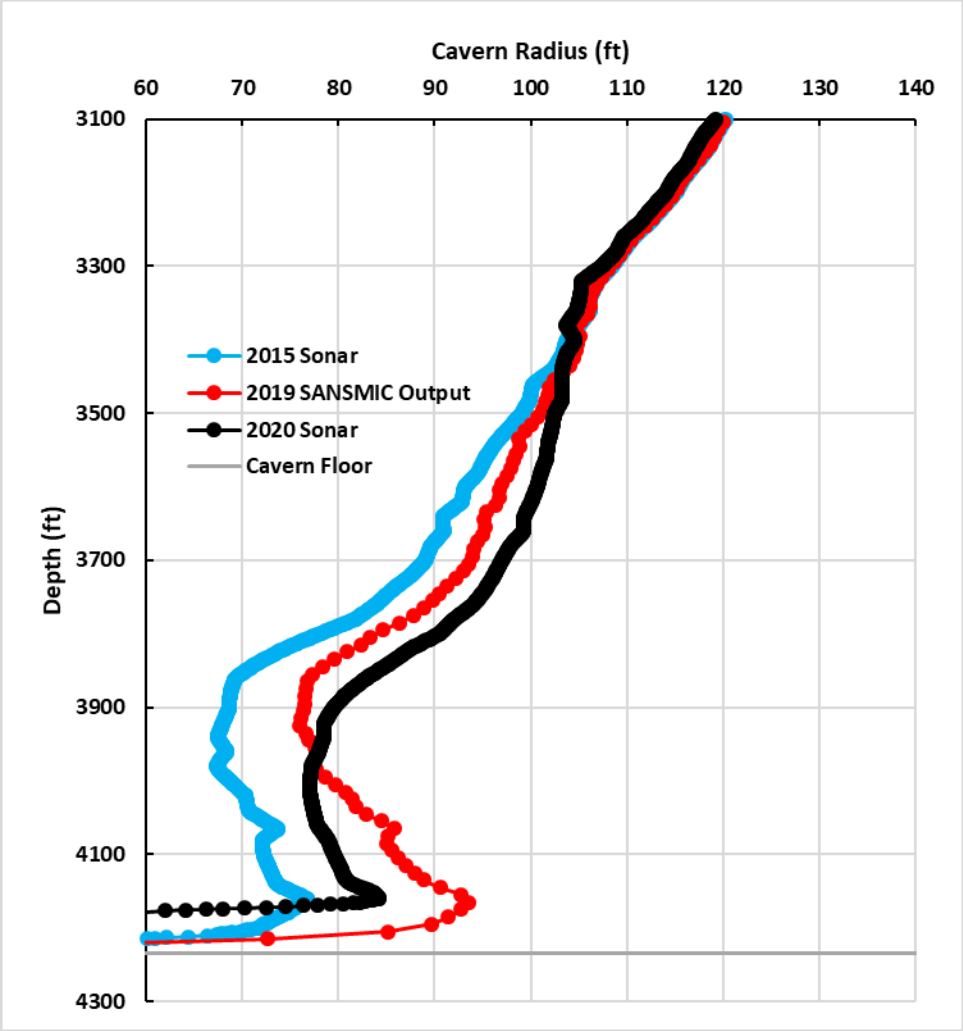

Figure 3-2. Axisymmetric BH-109 cavern profiles for 2015 sonar (blue), 2019 SANSMIC output (red), and 2020 sonar (black) (exaggerated horizontal scale).

3.2. BH-110

The CY18-CY19 SANSMIC modeling report [8] presented results based on leaching since the 2015 sonar in BH-110. When the 2019 SANSMIC results are compared with the 2020 sonar in BH-110, a notable difference in the position of the cavern floor is observed (see vertical cross sections in Figure 3-3 and Figure 3-4). This difference is the result of some floor rise that occurred prior to the 2020 sonar in BH-110. Floor rise is not a process that is currently included in SANSMIC and thus the change in floor rise cannot be accurately estimated with it. SANSMIC did capture the leaching behavior well in terms of growth of the flare the bottom of the cavern.

SANSMIC has slightly overpredicted the extent of flare growth, in some part due to the floor rise; the lack of floor rise in the SANSMIC model leads to additional leaching closer to the cavern floor. As a result, SANSMIC has also underpredicted leaching further up in the cavern. Overall, SANSMIC did a reasonable job estimating the leaching in this cavern and the resultant flare.

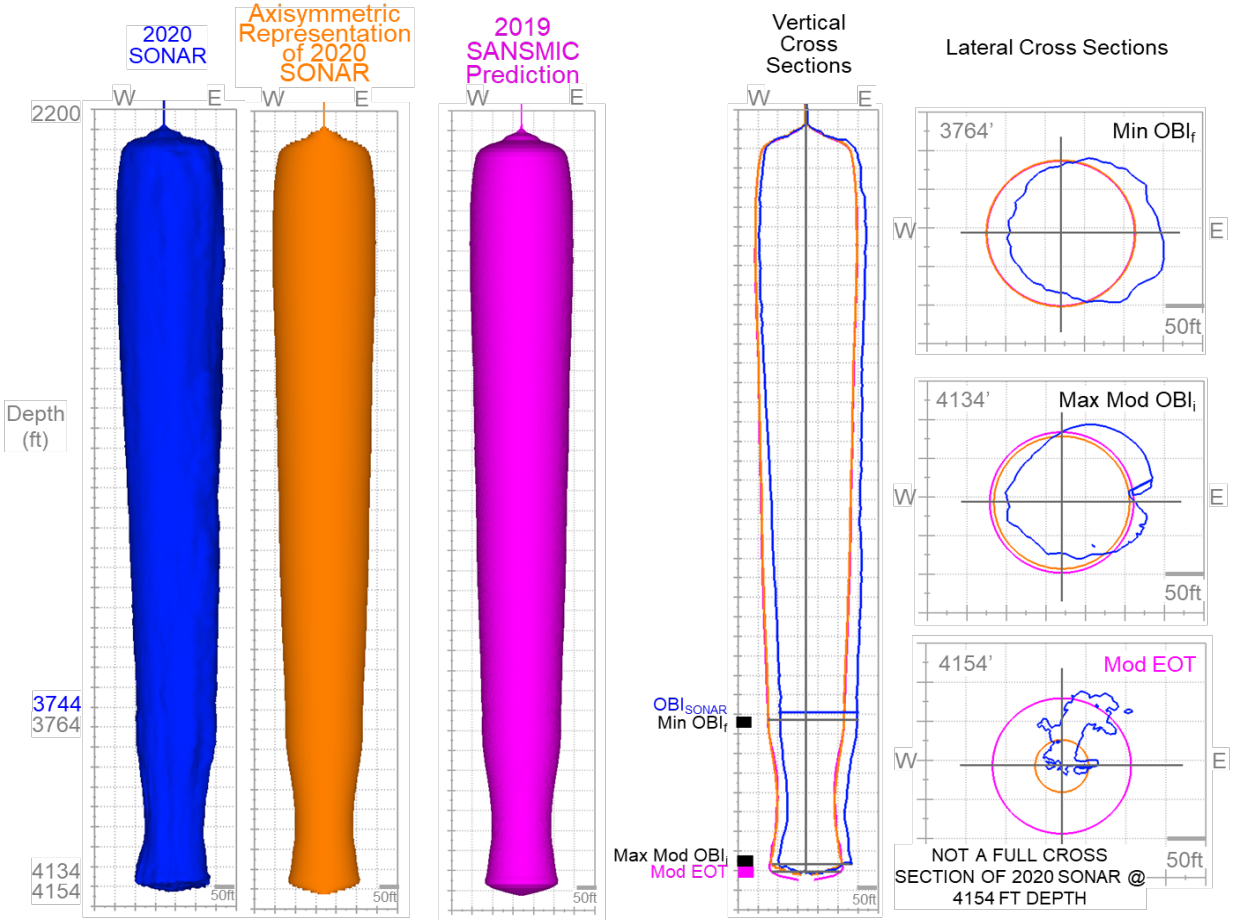

Figure 3-3. Predicted (magenta) and observed (blue, orange) cavern geometries for BH-110.

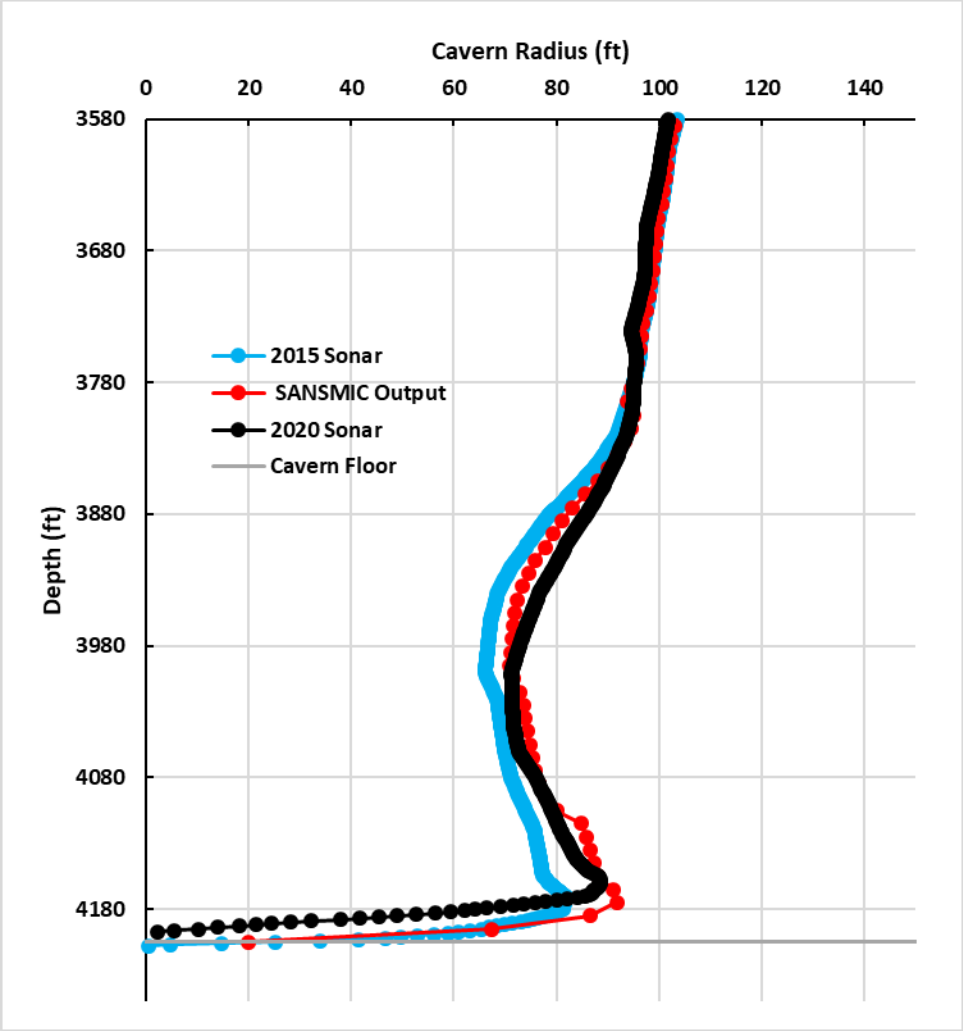

Figure 3-4. Axisymmetric BH-110 cavern profiles for 2015 sonar (blue), 2019 SANSMIC output (red), and 2020 sonar (black) (exaggerated horizontal scale).

3.3. BM-102

The CY18-CY19 SANSMIC modeling report [8] presented results based on leaching since the 2019 sonar in BM-102. When the 2019 SANSMIC results are compared with the 2020 sonar in BM-102, only a slight difference in the position of the cavern floor is observed (see vertical cross sections in Figure 3-5 and Figure 3-6). This difference is likely not the result of floor rise, since there is only ~1 year between sonars, but more attributable to the minor effect of rounding when setting up the SANSMIC model. Overall, SANSMIC did a reasonable job estimating the leaching in this cavern and the resultant flare.

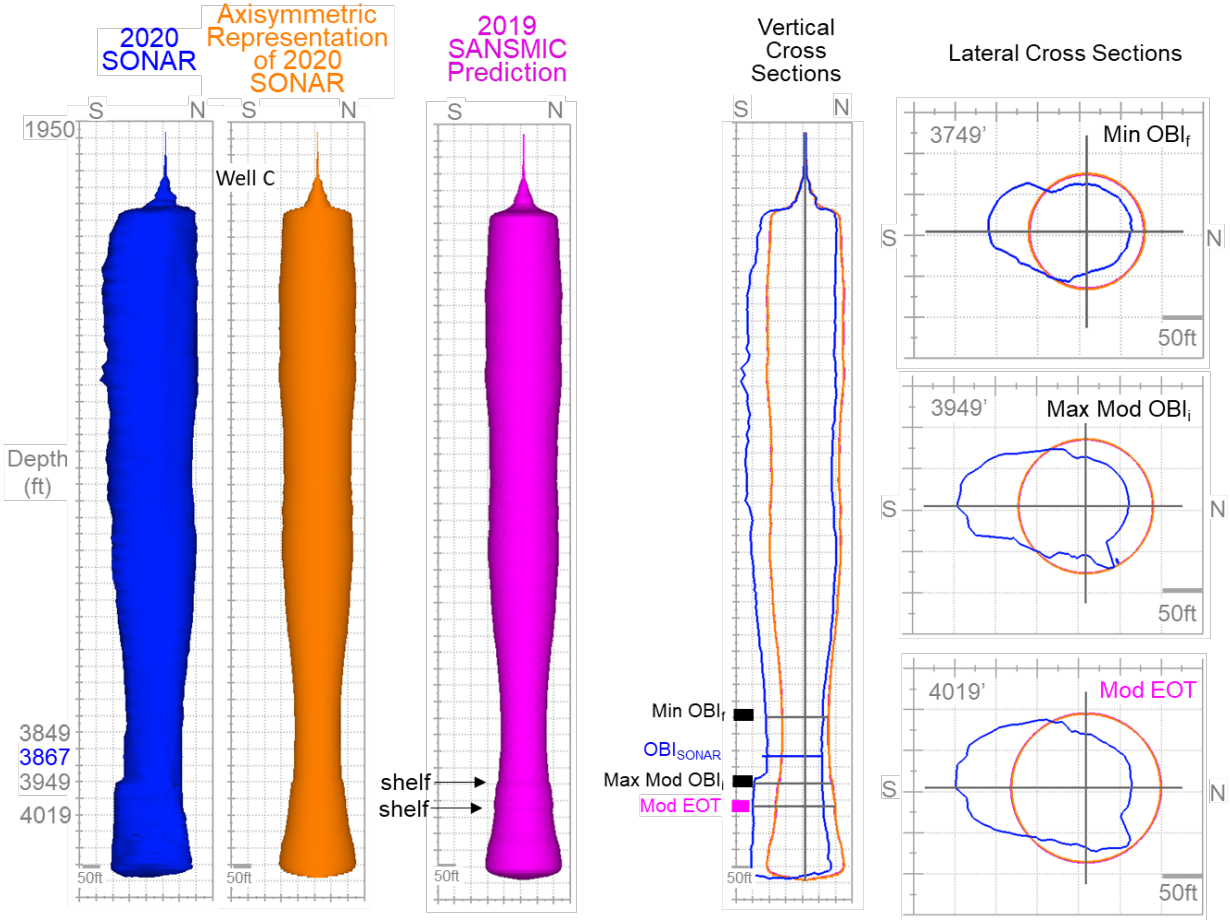

Figure 3-5. Predicted (magenta) and observed (blue, orange) cavern geometries for BM-102.

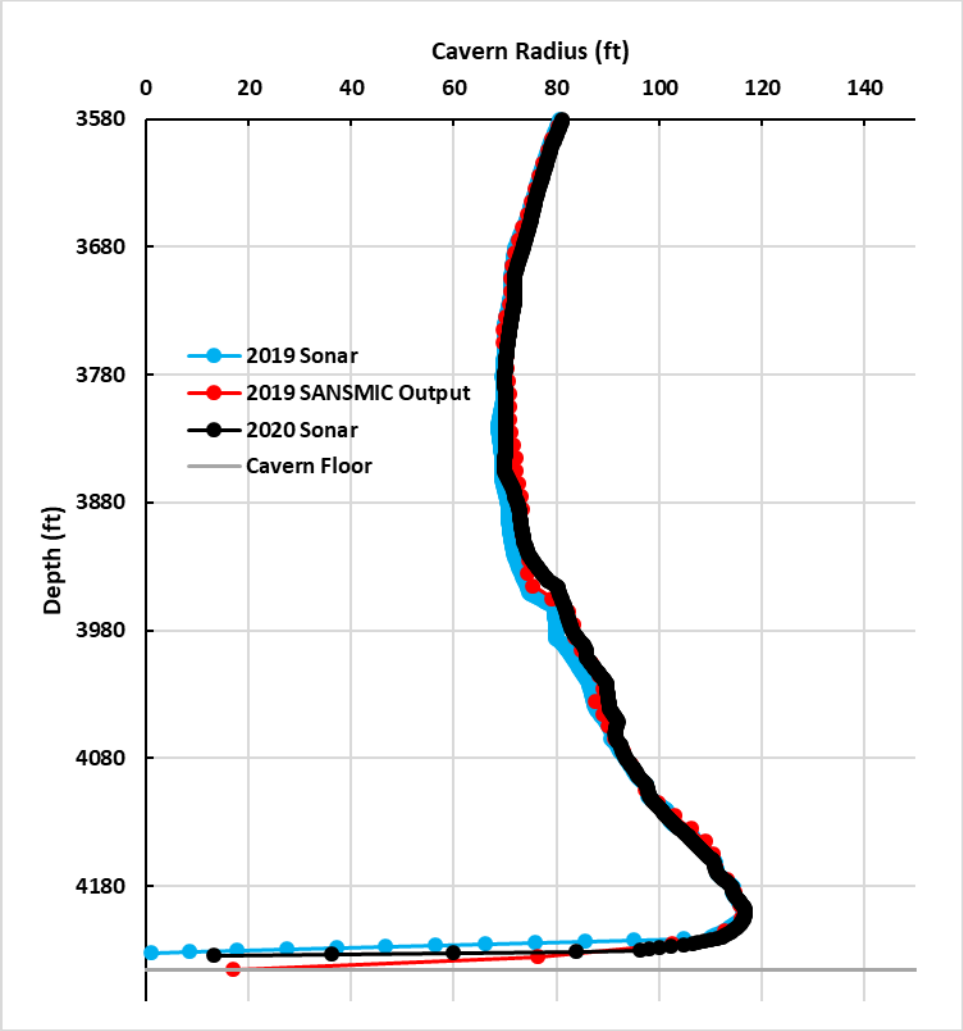

Figure 3-6. Axisymmetric BM-102 cavern profiles for 2019 sonar (blue), 2019 SANSMIC output (red), and 2020 sonar (black) (exaggerated horizontal scale).

3.4. BM-111

The CY18-CY19 SANSMIC modeling report [8] presented results based on leaching since the 2018 sonar in BM-111. When the 2019 SANSMIC results are compared with the 2020 sonar in BM-111, only slight differences in cavern geometry are observed (see vertical cross sections in Figure 3-7 and Figure 3-8). SANSMIC only predicted a maximum of about 2 ft growth at any depth and the lack of change in geometry between sonars is consistent with the SANSMIC results. Overall, SANSMIC did a reasonable job estimating the leaching in this cavern and the resultant flare.

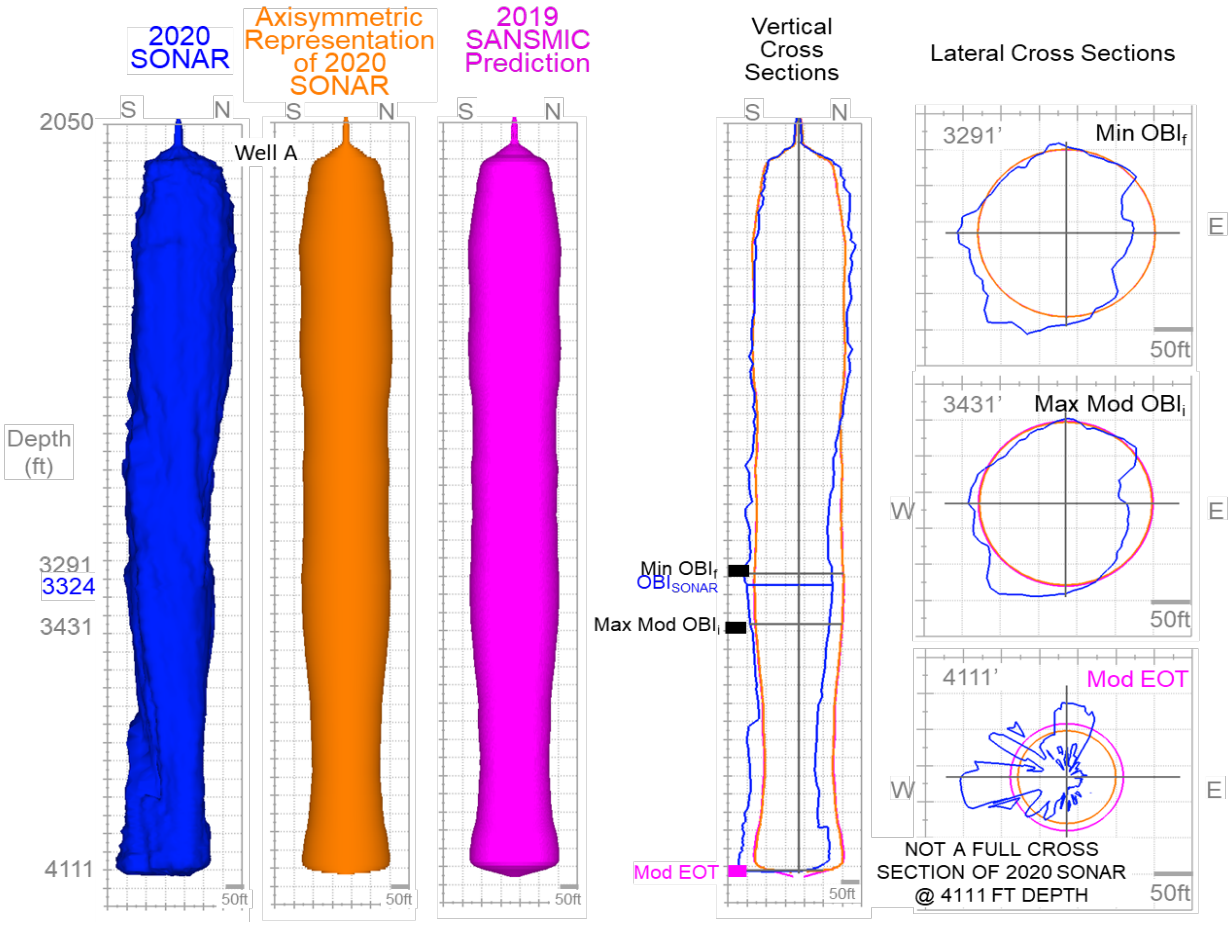

Figure 3-7. Predicted (magenta) and observed (blue, orange) cavern geometries for BM-111.

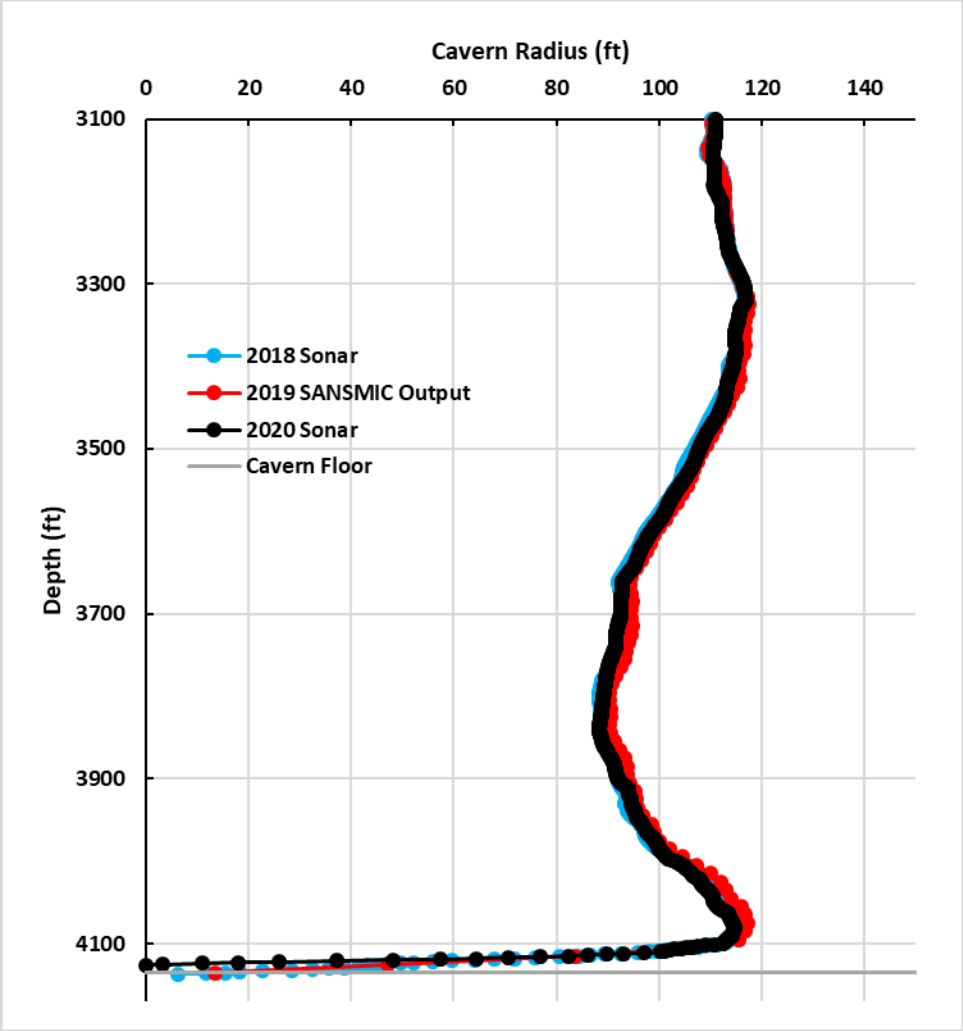

Figure 3-8. Axisymmetric BM-111 cavern profiles for 2018 sonar (blue), 2019 SANSMIC output (red), and 2020 sonar (black) (exaggerated horizontal scale).

3.5. WH-11

The CY18-CY19 SANSMIC modeling report [8] presented results based on leaching since the 2018 sonar in WH-11. When the 2019 SANSMIC results are compared with the 2020 sonar in WH-11, an overall excellent agreement is observed, particularly in the region of growth at depths between 3450-3650 ft (see vertical cross sections in Figure 3-9 and Figure 3-10). The observed lack of growth of the flare feature near the cavern floor confirms that raising the EOT was sufficient to avoid flare growth. Some floor rise, which cannot be captured with SANSMIC, is observed between sonars. Overall, SANSMIC did a reasonable job estimating the leaching in this cavern.

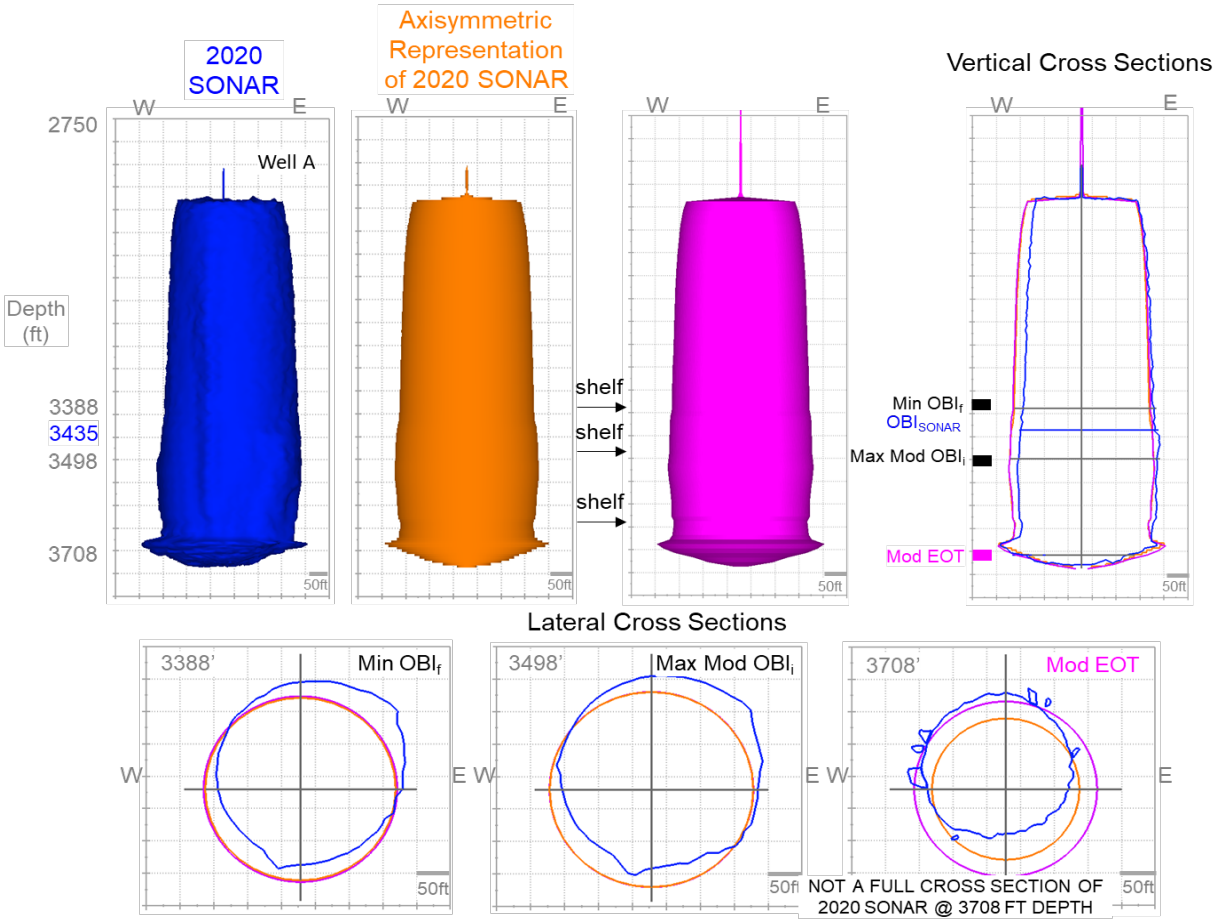

Figure 3-9. Predicted (magenta) and observed (blue, orange) cavern geometries for WH-11.

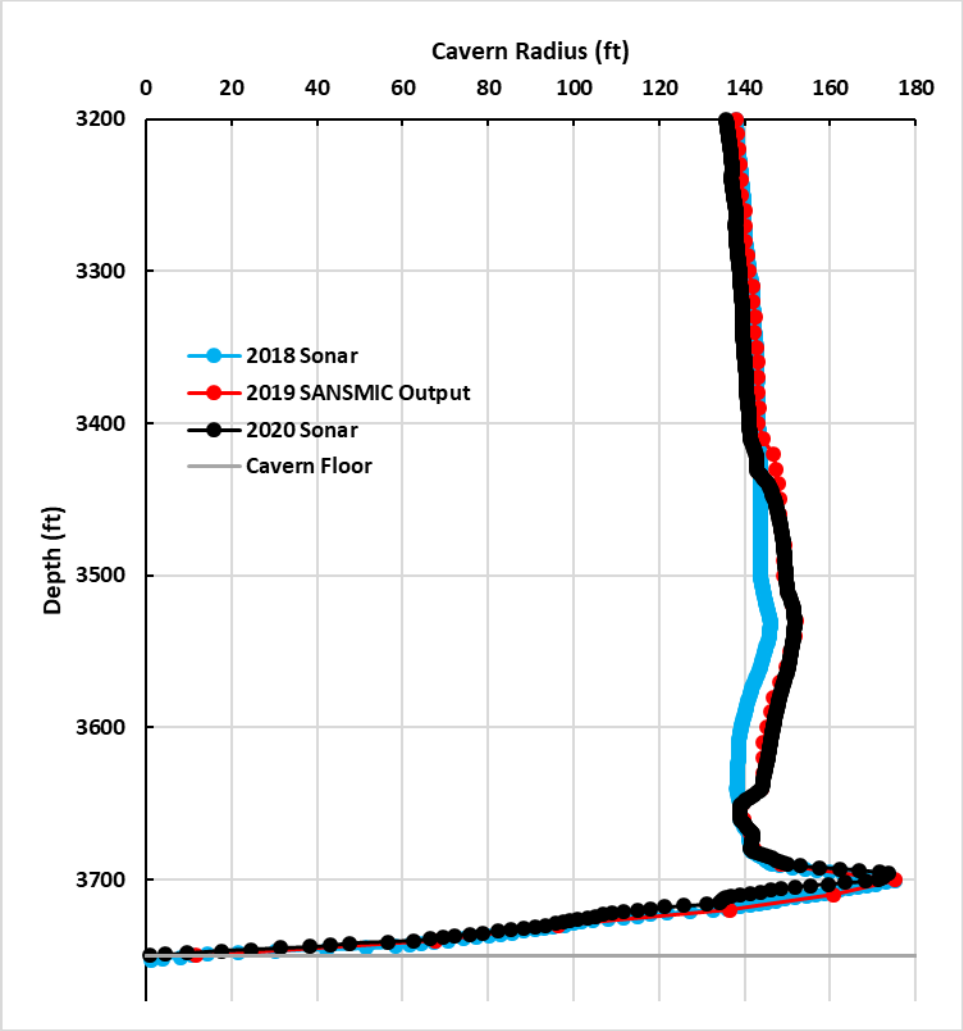

Figure 3-10. Axisymmetric WH-11 cavern profiles for 2018 sonar (blue), 2019 SANSMIC output (red), and 2020 sonar (black) (exaggerated horizontal scale).

3.6. WH-105

The CY18-CY19 SANSMIC modeling report [8] presented results based on leaching since the 2015 sonar in WH-105. When the 2018 SANSMIC results are compared with the 2020 sonar in WH-105, a small difference in the position of the cavern floor is observed (see vertical cross sections in Figure 3-11 and Figure 3-12). This difference is the result of floor rise that occurred prior to the 2020 sonar in WH-105. Floor rise is not a process that is currently included in SANSMIC and thus the change in floor rise cannot be accurately estimated with it. SANSMIC did capture the leaching behavior well in terms of growth of the flare the bottom of the cavern. Overall, SANSMIC did a reasonable job estimating the leaching in this cavern and the resultant flare.

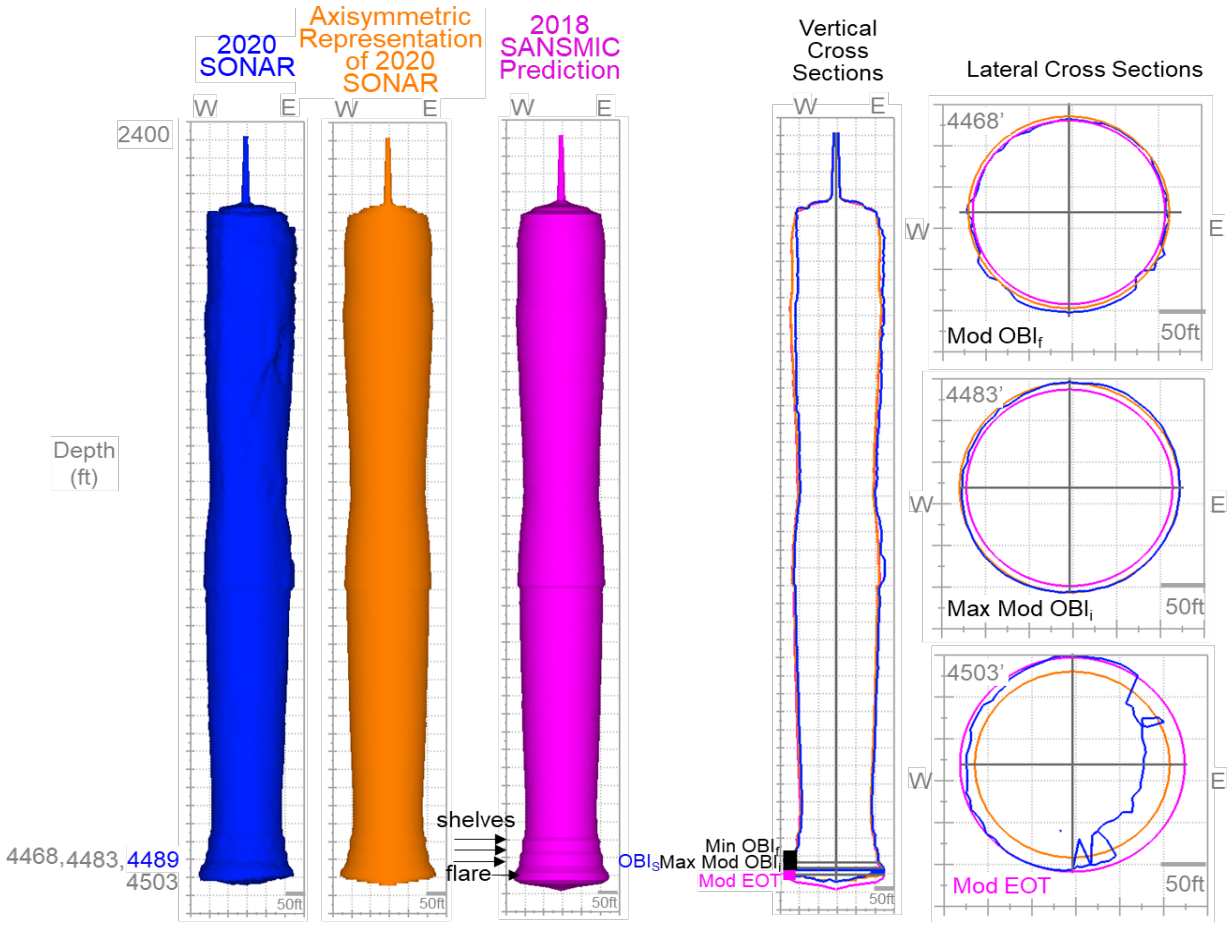

Figure 3-11. Predicted (magenta) and observed (blue, orange) cavern geometries for WH-105.

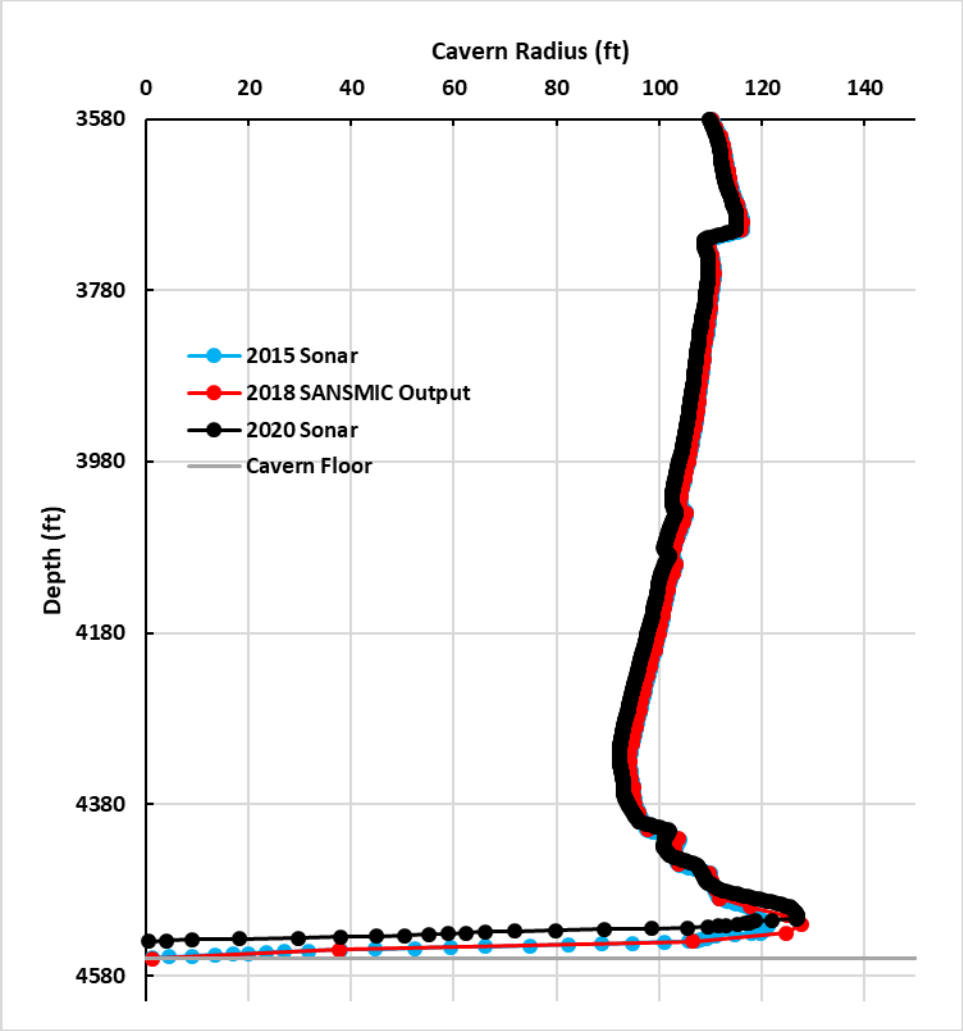

Figure 3-12. Axisymmetric WH-105 cavern profiles for 2015 sonar (blue), 2018 SANSMIC output (red), and 2020 sonar (black) (exaggerated horizontal scale).

3.7. WH-110

The CY18-CY19 SANSMIC modeling report [8] presented results based on leaching since the 2015 sonar in WH-110. When the 2018 SANSMIC results are compared with the 2020 sonar in WH-110, a small difference in the position of the cavern floor is observed (see vertical cross sections in Figure 3-13 and Figure 3-14). This difference is the result of some floor rise that occurred prior to the 2020 sonar in WH-110. Floor rise is not a process that is currently included in SANSMIC and thus the change in floor rise cannot be accurately estimated with it. SANSMIC did capture the leaching behavior well in terms of growth of the flare the bottom of the cavern. Overall, SANSMIC did a reasonable job estimating the leaching in this cavern and the resultant flare.

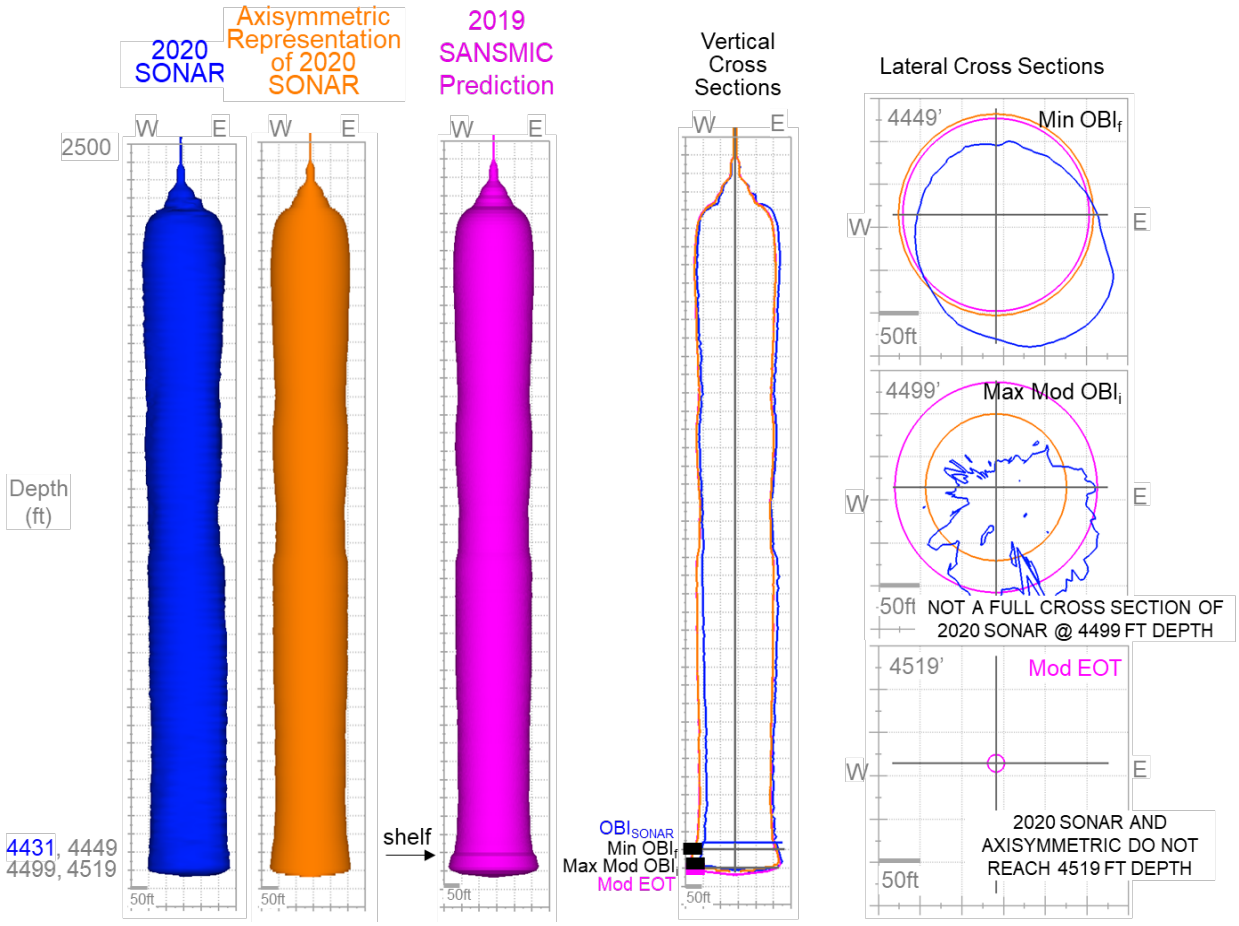

Figure 3-13. Predicted (magenta) and observed (blue, orange) cavern geometries for WH-110.

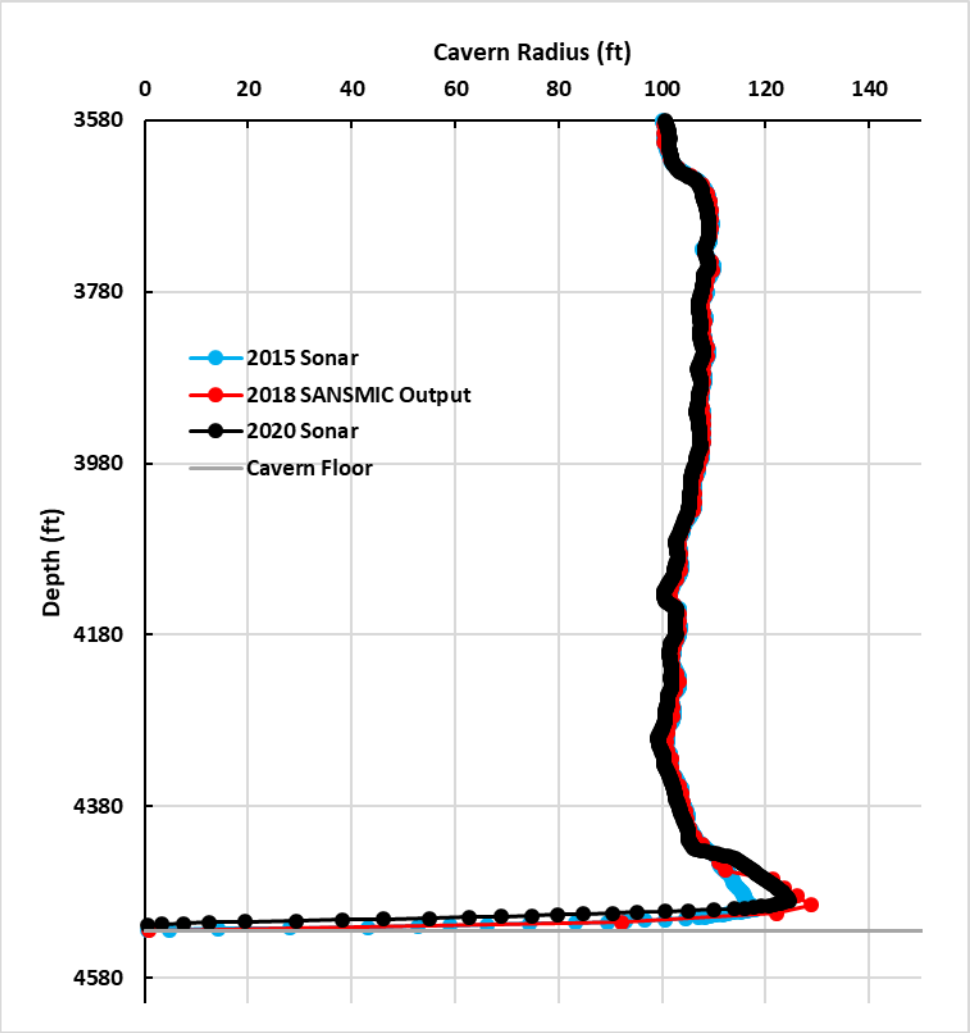

Figure 3-14. Axisymmetric WH-110 cavern profiles for 2015 sonar (blue), 2018 SANSMIC output (red), and 2020 sonar (black) (exaggerated horizontal scale).

3.8. WH-114

The CY18-CY19 SANSMIC modeling report [8] presented results based on leaching since the 2015 sonar in WH-114. When the 2019 SANSMIC results are compared with the 2020 sonar in WH-114, growth of the flare at the cavern floor and the appearance of a shelf feature are apparent (see vertical cross sections in Figure 3-15 and Figure 3-16). SANSMIC has slightly overpredicted the extent of growth of both the flare and the shelf. Overall, SANSMIC did a reasonable job estimating the leaching in this cavern and the resultant flare.

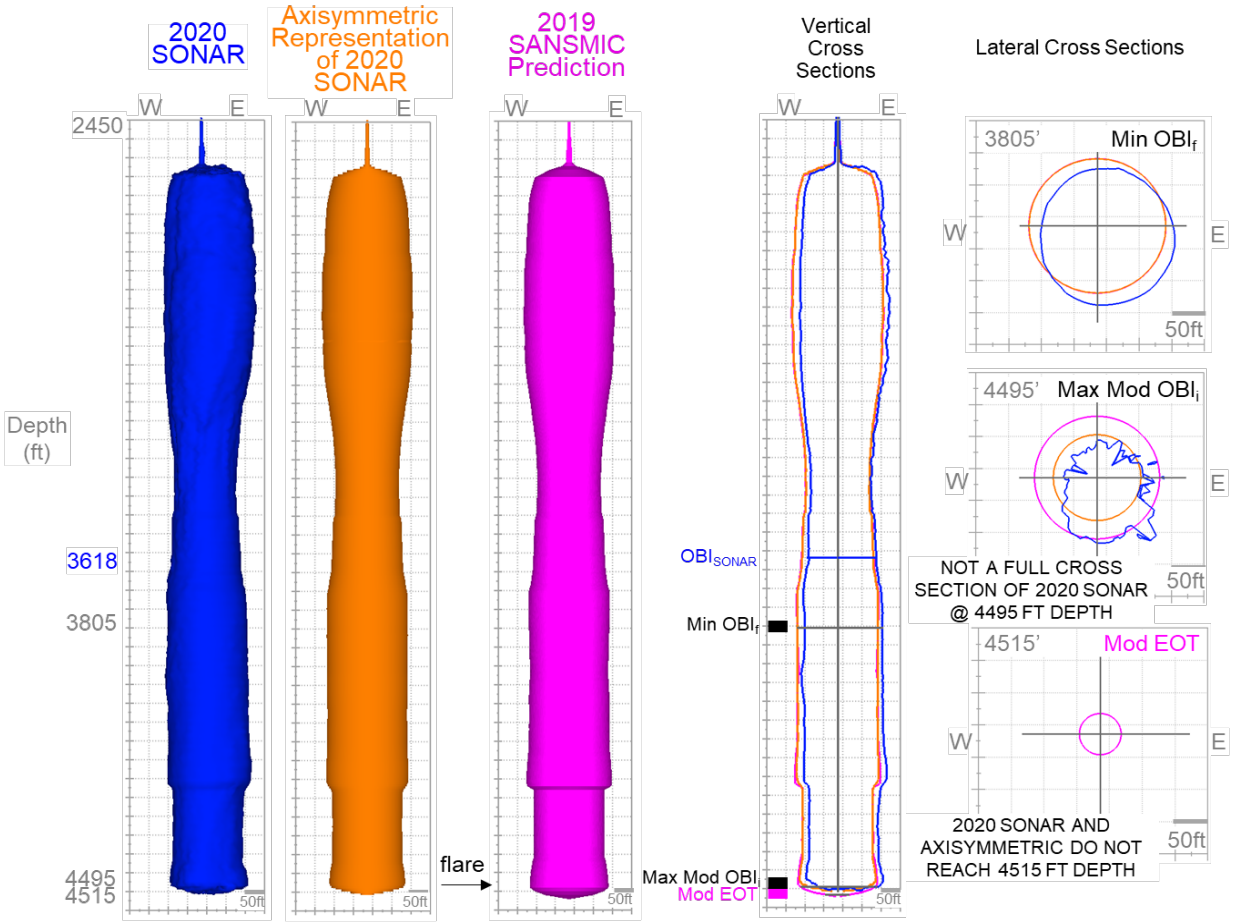

Figure 3-15. Predicted (magenta) and observed (blue, orange) cavern geometries for WH-114.

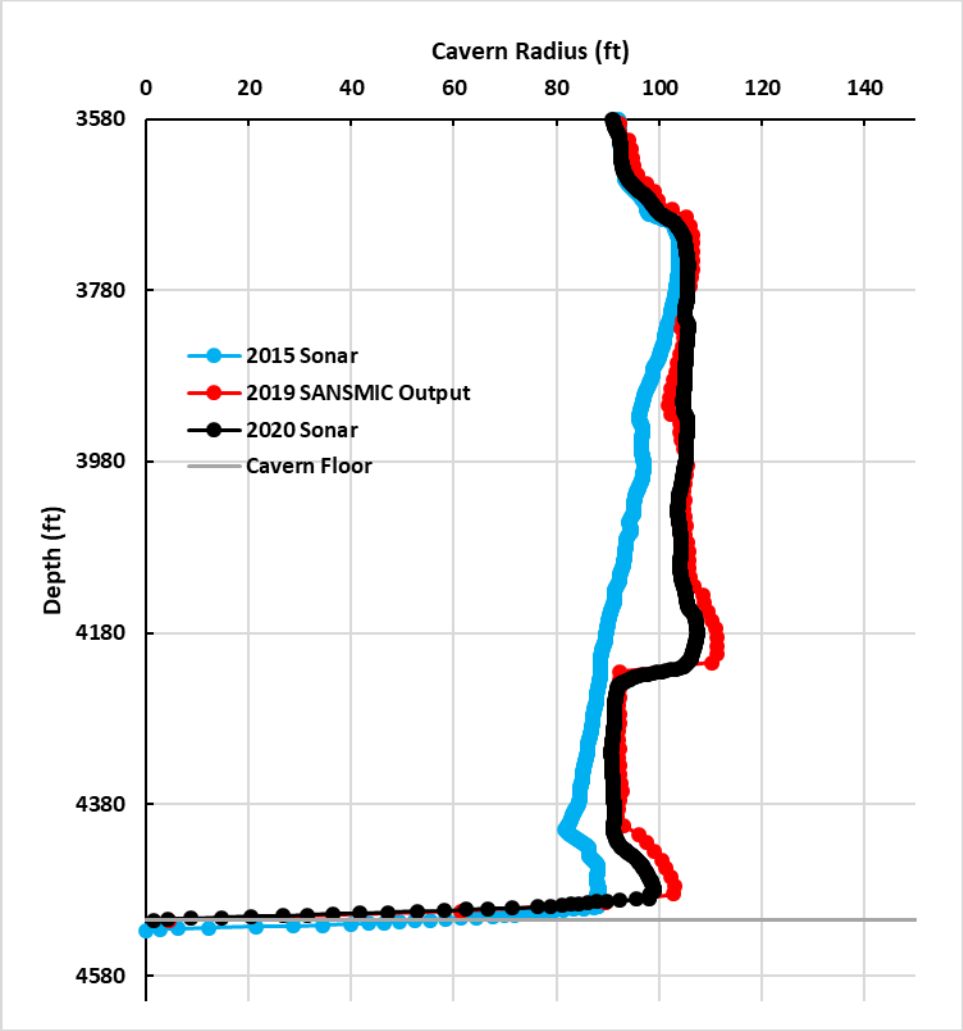

Figure 3-16. Axisymmetric WH-114 cavern profiles for 2015 sonar (blue), 2019 SANSMIC output (red), and 2020 sonar (black) (exaggerated horizontal scale).

3.9. WH-115

The CY18-CY19 SANSMIC modeling report [8] presented results based on leaching since the 2017 sonar in WH-115. When the 2019 SANSMIC results are compared with the 2020 sonar in WH-115, a notable difference in the position of the cavern floor is observed (see vertical cross sections in Figure 3-17 and Figure 3-18), due in part to floor rise and rounding in setting up the SANSMIC model. Floor rise is not a process that is currently included in SANSMIC and thus the change in floor rise cannot be accurately estimated with it. SANSMIC did capture the leaching behavior well in terms of growth of the flare the bottom of the cavern. SANSMIC has overpredicted the extent of flare growth, in some part due to the floor rise; the lack of floor rise in the SANSMIC model leads to additional leaching closer to the cavern floor.. Overall, SANSMIC did a reasonable job estimating the leaching in this cavern and the resultant flare.

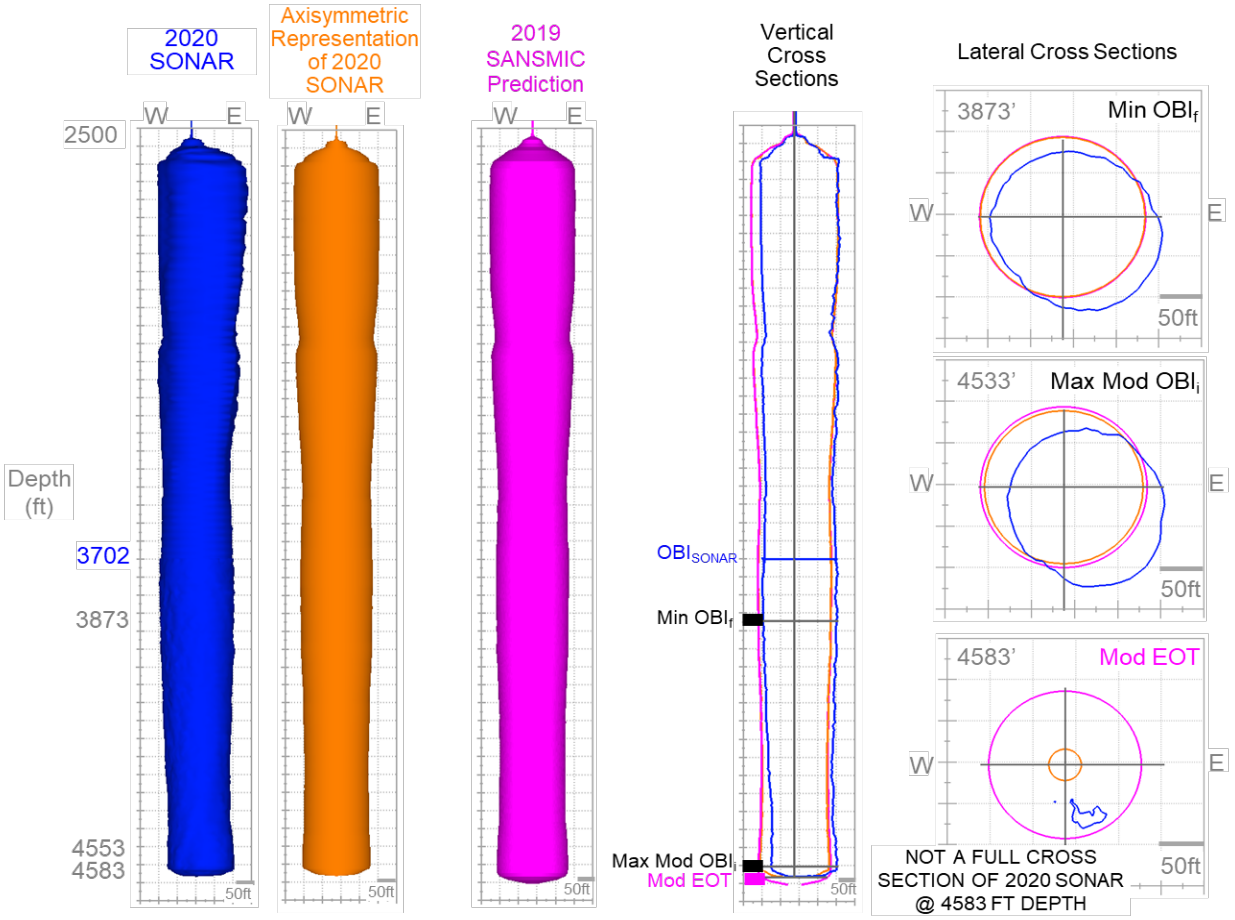

Figure 3-17. Predicted (magenta) and observed (blue, orange) cavern geometries for WH-115.

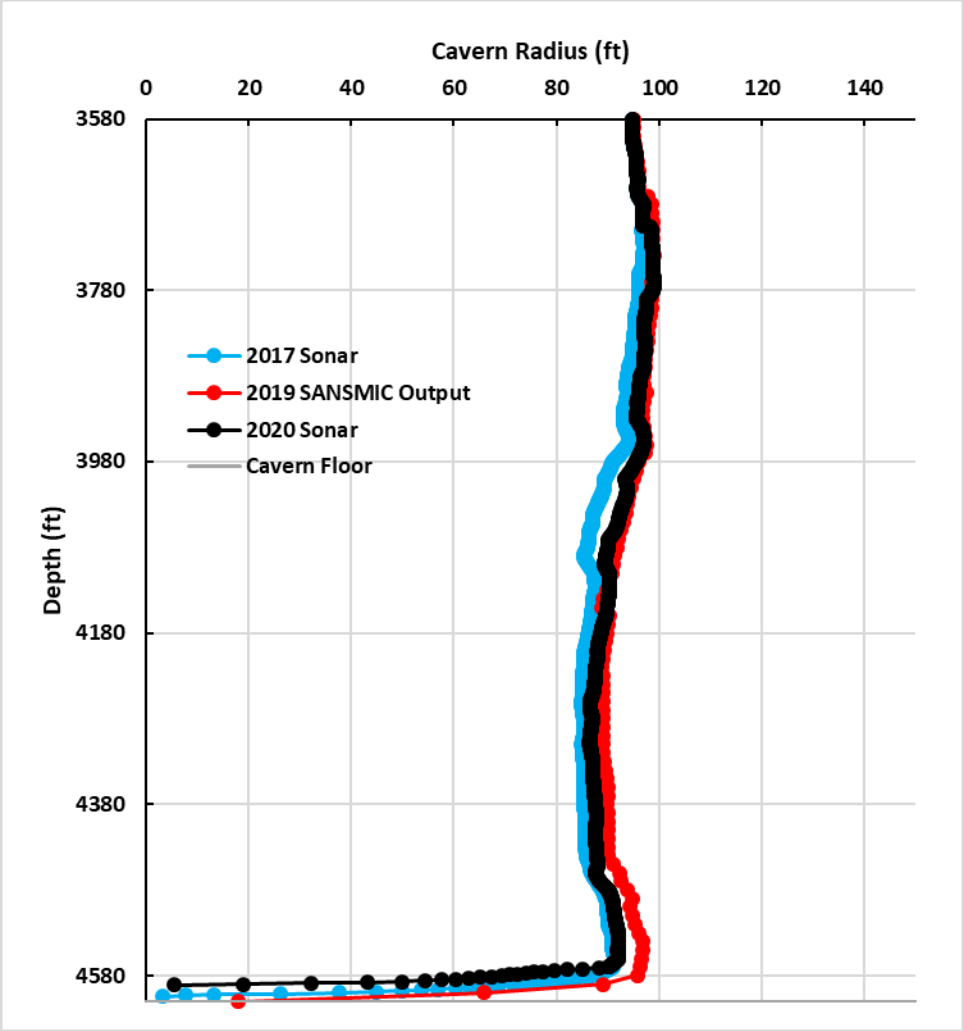

Figure 3-18. Axisymmetric WH-115 cavern profiles for 2017 sonar (blue), 2019 SANSMIC output (red), and 2020 sonar (black) (exaggerated horizontal scale).

3.10. BC-18

A sonar was taken in BC-18 at the end of 2020 subsequent to raw water injections. No additional water was injected subsequent to the sonar. Previous to the 2020 sonar, the last sonar taken in BC-18 was in 2018. Between the two sonars, around 1.6 MMB of water were injected into the cavern (see Table 3-1). The injection history was modeled using a single leaching phases followed by an EP of 60 days.

When the 2020 SANSMIC results are compared with the 2020 sonar in BC-18, very little difference in the cavern geometries is observed (see vertical cross sections in Figure 3-19 and Figure 3-20). SANSMIC only predicts a maximum growth of about 3 ft. (Figure 3-21) which is consistent with the little growth observed between sonars. Overall, SANSMIC did a reasonable job estimating the leaching in this cavern and the resultant flare.

Table 3-1. Summary of Simulation Input for BC-18

Phase	Dates	Cavern Floor Depth (ft)	EOT Rise (ft)	Mod EOT Rise (ft)	OBI Rise (ft)	Mod OBI Rise (ft)	Injection Rate (bbl/day)	Injection Duration (days)	Total Injected Water Volume (bbl)
1	10/05/20-10/31/20	4227	108	100	413	410	77,817	20	1,556,340

The final outlet SG was close to the value of 1.2, suggesting that leaching was near completion at the end of the EP. As summarized in Table 3-2, the overall leaching efficiency for this cavern was 13.9%.

Table 3-2. Summary of Simulation Output for BC-18

Phase	Final OBI Rise (ft)	Outlet SG	Change in Volume (bbl)	Leaching Efficiency (%)
1	580	1.1961	216,000	13.9

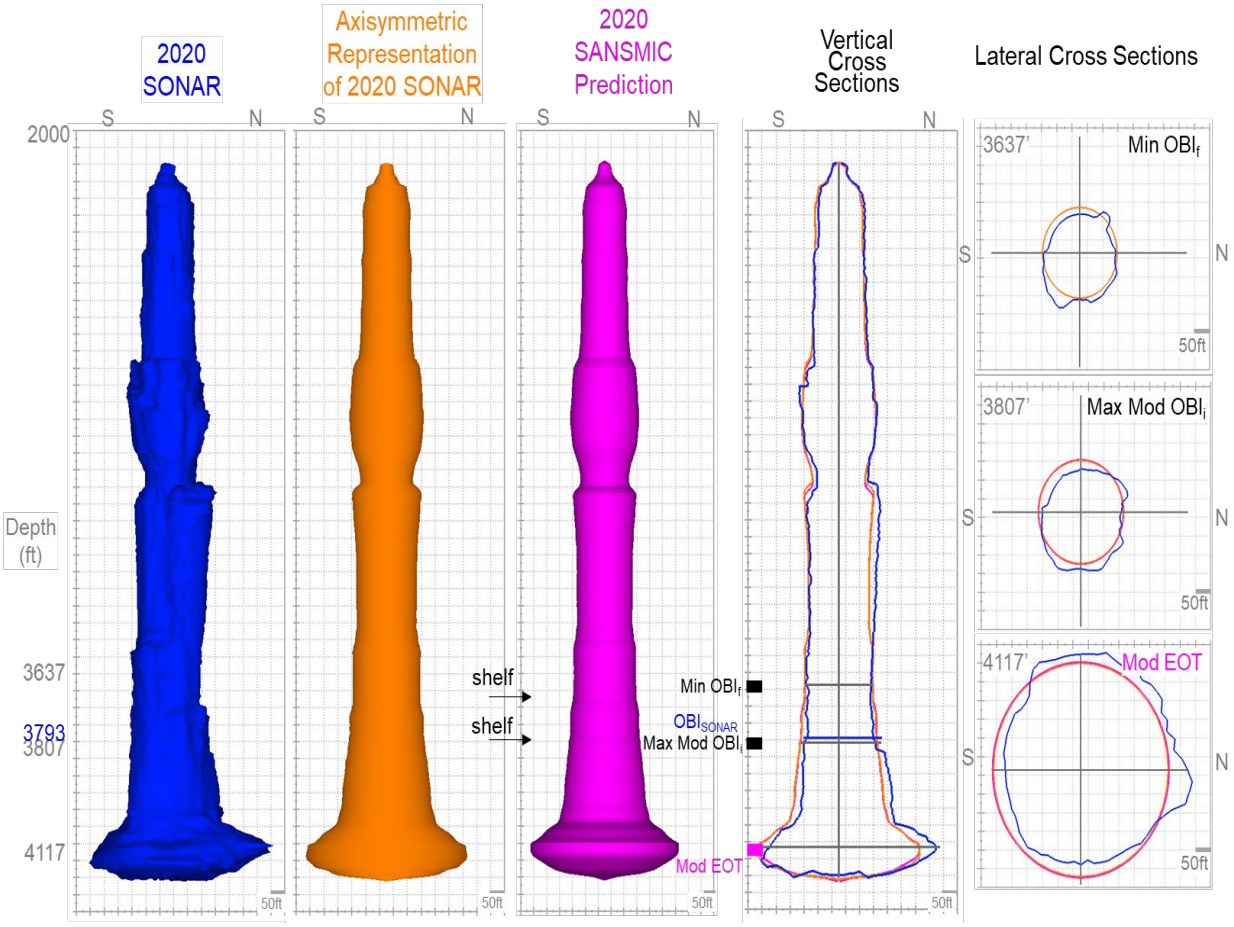

Figure 3-19. Predicted (magenta) and observed (blue, orange) cavern geometries for BC-18.

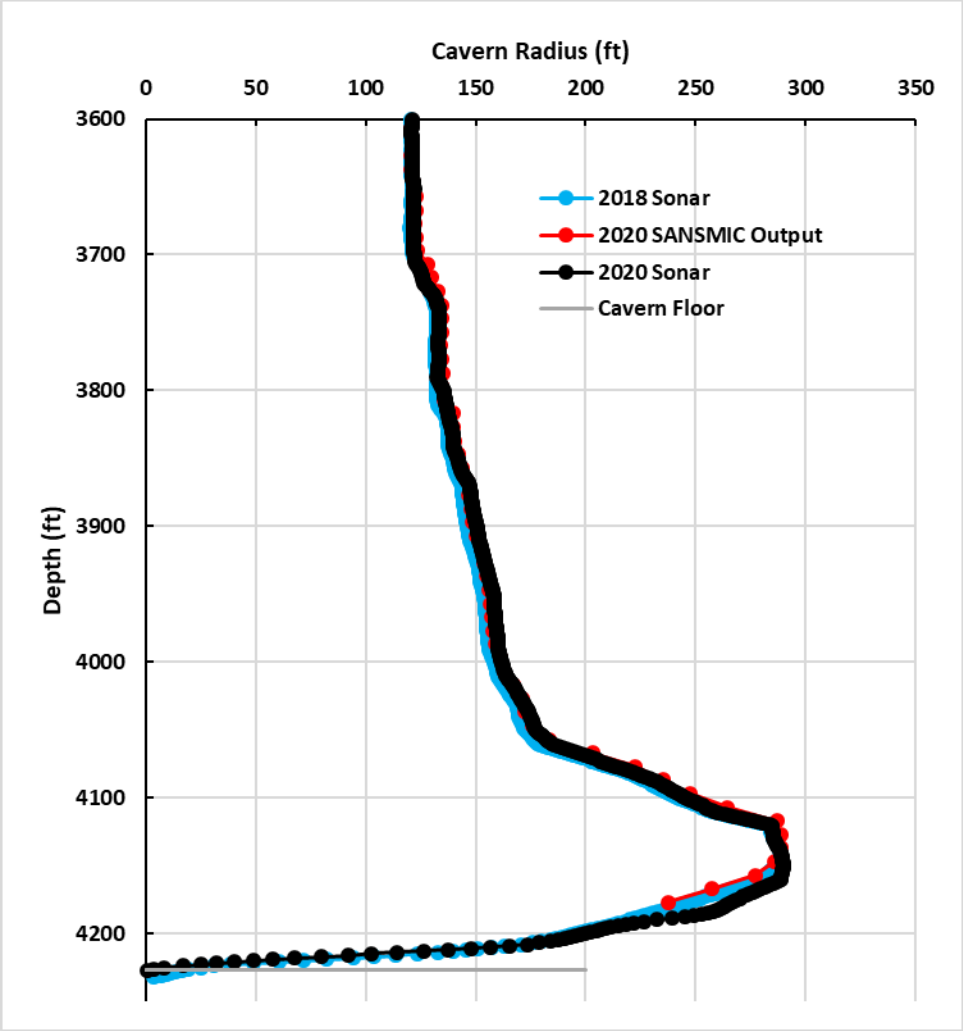

Figure 3-20. Axisymmetric BC-18 cavern profiles for 2018 sonar (blue), 2020 SANSMIC output (red), and 2020 sonar (black) (exaggerated horizontal scale).

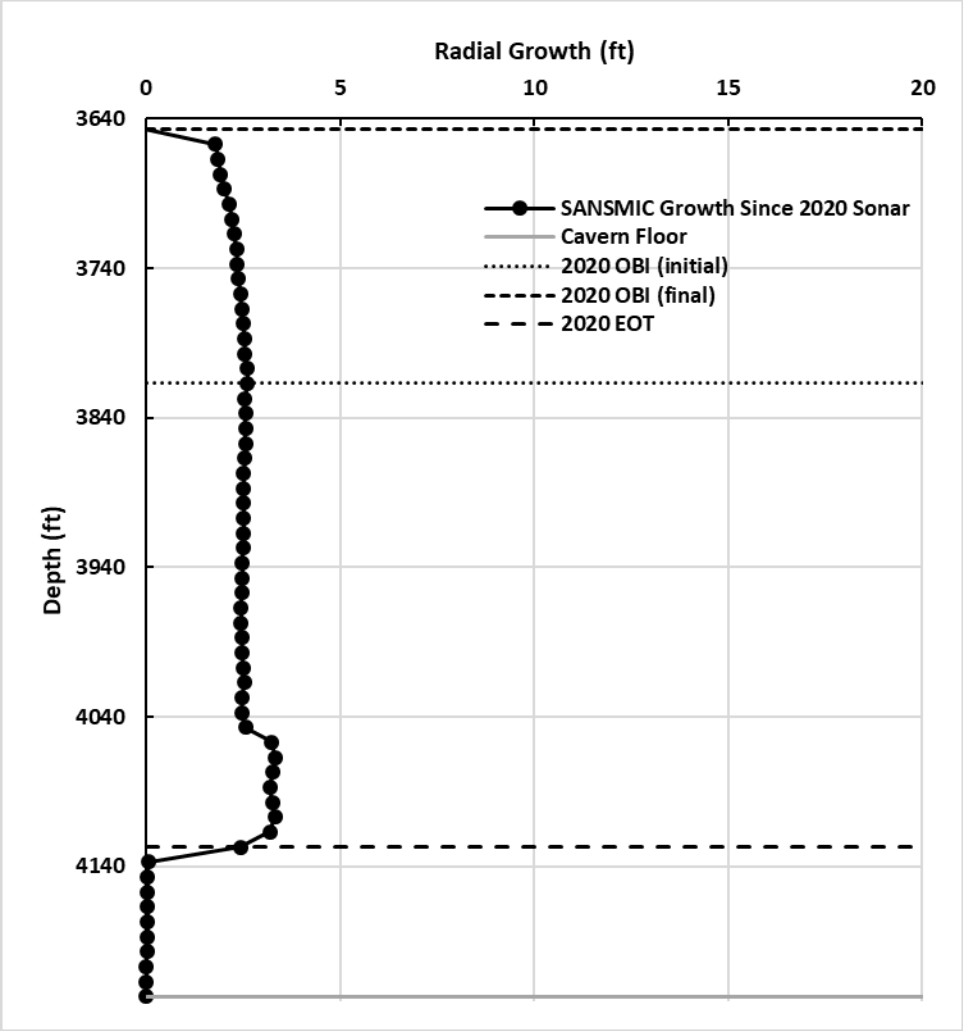

Figure 3-21. BC-18 SANSMIC-Predicted Radial Growth since 2020 Sonar (exaggerated horizontal scale).

4. SUMMARY AND CONCLUSIONS

Twenty-five caverns had over 39 MMB of water injected in CY20 as part of the Exchange for Storage program. Leaching effects were monitored in these caverns to understand how the sales operations may impact the long-term integrity of the caverns. While frequent sonars are the best way to monitor changes in cavern shape, they can be resource intensive for the number of caverns involved in sales and exchanges. An intermediate option is to model the leaching effects and see if any concerning features develop.

The leaching effects were modeled here using the Sandia Solution Mining Code. The results indicate that leaching induced features are not of concern in the majority of the caverns, 19 of 25. Six caverns, BH-107, BH-113, BH-114, BM-4, BM-106, and WH-114 have features that may grow with additional leaching and should be monitored as leaching continues in those caverns.

Ten caverns had post sale sonars that were compared with SANSMIC results. SANSMIC was able to capture the leaching well, particularly the formation of shelves and flares. A deviation in the SANSMIC and sonar cavern shapes was observed near the cavern floor in caverns with significant floor rise, a process not captured by SANSMIC. These results suggest SANSMIC is a useful tool for monitoring changes in cavern shape due to leaching effects related to sales and exchanges.

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