**SANDIA REPORT**

SAND2018-11419
Unlimited Release
Printed October 5, 2018

# An Analysis of Possible Salt Fall Events in Historical Pressure Data from the U.S. Strategic Petroleum Reserve

David B. Hart

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

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.



Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology and Engineering Solutions of Sandia, LLC.



Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

| | |
|---|---|
| Telephone: | (865) 576-8401 |
| Facsimile: | (865) 576-5728 |
| E-Mail: | reports@adonis.osti.gov |
| Online ordering: | http://www.osti.gov/bridge |

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd
Springfield, VA 22161

| | |
|---|---|
| Telephone: | (800) 553-6847 |
| Facsimile: | (703) 605-6900 |
| E-Mail: | orders@ntis.fedworld.gov |
| Online ordering: | http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online |

SAND2018-11419
Unlimited Release
Printed October 5, 2018

# An Analysis of Possible Salt Fall Events in Historical Pressure Data from the U.S. Strategic Petroleum Reserve

David B. Hart
Geochemistry Department
Sandia National Laboratories
P.O. Box 5800 MS 0751
Albuquerque, NM 87185-0751
dbhart@sandia.gov

**Abstract**

The U.S. Strategic Petroleum Reserve (SPR) stores crude oil in underground storage caverns that have been solution mined from salt domes. Salt falls from the sides or top of a cavern pose a potential threat to cavern and well integrity and to operational readiness. Underground storage caverns require a suspended casing, or hanging string, to extend into the bottom part of the cavern for brine injection in order to remove oil from the top of the cavern; salt falls can break hanging strings, leaving the cavern inaccessible until a well workover is performed to replace or extend the string. Detecting salt falls is difficult, as string breaks may not occur and surface pressure signals are similar to operationally induced signals. SONAR based detection is possible, but SONAR surveys are expensive and conducted infrequently. Historical records from the SPR were examined to look for possible correlations to geographic or operational causes. A library of salt fall and operational signals was developed and three case studies are presented.

# Acknowledgment

The author would like to thank the following people: Bryan Bellevue of Fluor Federal Petroleum Operations (FFPO) for providing dates of salt falls for pressure analysis; Barry Roberts for the salt contour maps and sonar image; Michelle Williams for generating the plots in the appendix; Kirsten Chojnicki for reviewing and providing essential feedback; and the SPR cavern and well integrity group with members from SNL, FFPO, and DOE.

# Contents



## Appendix



# Figures

# Tables

# Nomenclature

| **Notation** | **Description** |
|---|---|
| BC | Bayou Choctaw |
| BH | Big Hill |
| BM | Bryan Mound |
| DCS | Distributed Control System |
| FFPO | Fluor Federal Petroleum Operations |
| MIT | mechanical integrity test |
| MOV | motor operated valve |
| OBI | oil/brine interface |
| SMRI | Solution Mining Research Institute |
| SPR | U.S. Strategic Petroleum Reserve |
| WH | West Hackberry |

# Introduction

The United States U.S. Strategic Petroleum Reserve (SPR) consists of underground storage caverns for crude oil at four sites along the Gulf Coast. These caverns are voids that are solution mined out of salt domes that are then filled with oil. Solution mining is performed by injecting fresh water that dissolves the salt, and then pumping the resulting brine back out. Salt falls occur when large chunks of rock salt break off from the side or roof of a cavern and fall to the bottom of the cavern. These falls are of concern for two primary reasons: first, because salt falls could adversely affect the structure of the cavern [Ward, 1999]; second, falls can damage the well infrastructure that allows the cavern to move fluids in and out [Munson, 2005, Munson et al., 1998b].

Others have previously examined possible geologic and interior cavern conditions that may contribute to salt falls in storage caverns (see the literature review that follows). This report re-examines historical salt fall events at the SPR to ascertain if there are trends relating salt falls to operational conditions. Additionally, the surface wellhead pressure signals are examined for various salt fall and operational events in an effort to help find salt falls through pressure monitoring. Several specific events are presented in detail to demonstrate different salt fall behaviors. This report also contains two appendices that provide: a list of identified salt falls and a set of pressure graphs showing different events.

## Existing literature

This report is focusing on salt fall events, rather than on the mechanics of rock fracture and salt stability. While there is a great deal of journal published academic research regarding rock mechanics, these articles generally focus on falls within traditional mines or on open rock faces. As a result, the majority of research into salt falls in liquid or gas hydrocarbon storage caverns has been presented at the Solution Mining Research Institute (SMRI) technical conferences or as technical reports from engineering firms. SMRI is the primary industry group for solution mining and cavern storage, and has two meetings per year.

Because the SPR is the largest underground crude oil storage facility in the world, and because, as a government facility, more information is made available than can be obtained from private industry, much of the research on salt falls focuses on SPR caverns. Linn [1986] performed one of the first analyses looking for correlation between salt falls and operational actions. Linn looked at the correlation between salt falls and depressurization. The small sample size indicated that, in the cases examined, there was equal chance of a salt fall occurring or not occurring within 80 days post depressurization. The short study also looked at the much larger number of salt falls reported at Bryan Mound than at other sites, and conjectured that the three-well method might be to blame and that further time might demonstrate this. Such a conclusion was not borne out, however, as Bryan Mound has continued to have more salt falls than any other site for three decades after cavern completion, including in the four two-well Phase III caverns.

Loof and Loof [1999] looked at possible geologic influences on the numerous salt falls at the Bryan Mound site. There are several fault zones at Bryan Mound and the salt is less pure with more anhydrite Looff [2017], Munson [2008]. The conclusions from these later research efforts seem to indicate that the salt dome properties have played a larger role in salt falls at Bryan Mound than the leaching method or depressurizations. Research reports on specific salt fall events have been the most common research relating to SPR caverns, particularly a large fall in Big Hill 103 and a suspected fall Bayou Choctaw 20 Munson et al. [2003], Munson [2001], Munson et al. [2004]. There have been two previous updates on casing damage prior to this report Munson [2005], Munson et al. [1998b]. Other work regarding salt fall causes and detection include investigations into spall formation Munson [2000], effects of rapid depressurization Bérest et al. [2013], and salt fall detection through pressure signals Bérest et al. [2017], Hart et al. [2017].

## Ongoing research

Salt falls are a small research area, but there is active academic and industry research being performed. The author is aware of ongoing research being performed at Sandia and in France regarding salt fall detection in liquid hydrocarbon storage caverns. There is also research being performed by private companies regarding the use of other technologies, such as acoustic and seismic monitoring; however, the data and results of such private work is seldom made available to outside groups and could not be incorporated in this report. General rock mechanics research, particularly with respect to traditional mines and within bedded salt, is expected to continue within that community. At the 2018 World Salt Symposium, preliminary work regarding the effects of thermal shock on the walls of gas caverns was presented; thermal shock can create fractures on the surface of the salt, increasing the likelihood of salt falls [Bérest et al., 2013], and that research is continuing in Europe.

# Salt Fall History at the SPR

Records from the solution mining of the purchased caverns are hard to find, and a history of salt falls that may have occurred prior to the acquisition of caverns by the SPR is not available. The only documented structural failure of a cavern prior to the establishment of the SPR was not a salt fall, but the collapse of Bayou Choctaw 7 which created Cavern Lake on the northern edge of the Bayou Choctaw dome. Thus, all the salt fall information available for SPR caverns comes from the last four decades.

Salt falls have historically been detected – and documented – only when there is an overwhelming indication that one has occurred. These indications have traditionally been a broken hanging string, significant and rapid floor rise, or major discrepancies in SONAR surveys. Figure 1 shows evidence of a salt fall that occurred between 2016 and 2018 at Bryan Mound Cavern 111. Unfortunately for the analysis of salt falls, not all salt falls will produce an indicator, and even those that do produce a sonar discrepancy may take years to detect due to the infrequency of sonar surveys (the example in Figure 1 is exceptional due to the short time frame between the sonars). This means that the best historical analysis rests with looking at broken hanging strings.

Analyses of casing damage was performed by Munson [2005], Munson et al. [1998b]; these reports were primarily just documentation that the salt falls occurred. The SPR M&O contractor in 2007 compiled a list of casing string damage, and that record was maintained through 2009, but there has not been a consistent, single database of occurrences maintained since that point. This report provides a list of all casing failures and damage reports that the author could find through the different sources in the Appendix.

## Summary of salt fall occurrences

Phase I caverns – caverns that were purchased by the SPR rather than purposely constructed for oil storage – are typically at relatively shallow depths and are larger and more irregularly shaped than SPR mined caverns. The Phase II and III caverns – caverns developed by the SPR – are of relatively uniform shape, size, and depth. The only difference between Phase II and III caverns is the date of their construction and the design of the wells, not the caverns, so for ease of reading all SPR developed caverns will be referred to hereafter as Phase II caverns. Because of these major geotechnical differences, salt falls within the Phase I caverns should not be compared to those within Phase II caverns. This does not imply any difference in the mechanics or causes of salt falls between the types of cavern, merely that comparing the two populations statistically is inappropriate.

Salt falls do not occur with the same frequency between sites or even within a site, even when looking only at the more uniform Phase II caverns. Some of this is clearly due to differences between the salt domes. As discussed by Loof in 1999 and 2017, anomalous salt and salt shear zones contribute to an increase in salt falls in certain caverns. At the Bryan Mound (BM) site in particular, the salt is more heterogeneous and has more impurities than at the other three sites. The

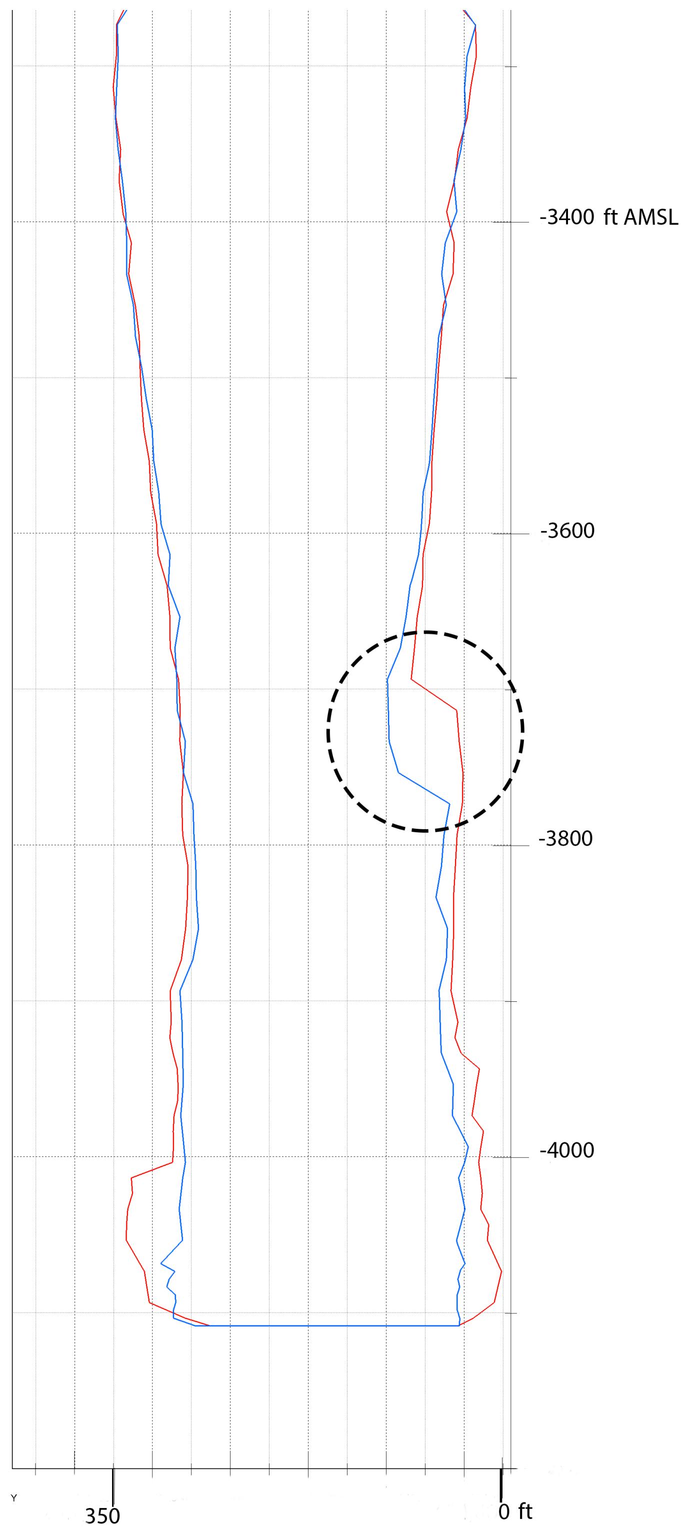



**Figure 1.** Example salt fall evidence by comparing two sonar surveys. Blue (inner) line is from 2016, red (outer) line is from 2018. The circled area indicates where the salt fall occurred. The differences below 3800 ft are due to leaching.

constructed caverns are more irregularly shaped than at any of the other sites, as can be seen in the cavern footprints shown in Figure 2. As would be expected from having the most inconsistent salt, BM has had the most salt falls of any site. There have been 80 recorded salt falls in BM's 16 Phase II caverns, where there have only been 22 recorded salt falls at the 14-cavern Big Hill (BH) site – see Figure 3 – and 33 among West Hackberry (WH)'s 17 Phase II caverns — Figure 4. Bayou Choctaw (BC) is not a useful site for analysis, as there is only one Phase II cavern that is comparable to those at the other sites, although it has had six recorded salt falls in its lifetime — see Figure 5.

Most Phase I caverns are significantly wider than Phase II caverns – with a diameter two to three times larger than a Phase II cavern on average – and there are very few salt falls that have been detected in these caverns, with one exception. Bryan Mound Cavern 5 has a very narrow neck between two large lobes, and hanging strings frequently break within the neck. BM-5 has had nine string failures during its operation by the SPR; however, it is unclear if these breaks are all caused due to salt falls, as casing movement during flow could easily damage the string passing through this narrow neck over time. The remaining Phase I caverns have had at most two string failures in the past forty years of operation, and over half have experienced no salt fall that has been detected. The number of salt falls for each cavern is shown in maps which follow.

The Phase II caverns have seen overwhelmingly more salt falls and casing failures. Phase II caverns were designed to be more geomechanically stable, with a typical radius of 200 ft and height of 2000 ft. This is good for the stability of the cavern, writ large, but it also means that the walls are much closer to the hanging string, increasing the likelihood that a salt fall will cause damage to a string and be detected. Ehgartner [1997] described the kinetics of a salt falling through a cavern, and discusses how the salt could hit and move around a cavern during the fall; in Phase II caverns, the increased height provides for a longer possible fall also increasing the likelihood of a string break.

Overall, the rate of salt falls has been fairly stable through time, as shown in Figure 6. There are a few outlier years with significantly more or less than the average, but there is no significant correlation of known string breaks with sales, raw water injection, or other operational activities. The lack of correlation should not be over interpreted, however, given that salt falls that do not break strings are not included. There were no recorded string breaks at Big Hill between 1991 and 2002; while the early 2000's corresponds to the start of regular fluid movements – exchanges, sales, and releases – there is still not enough data to say that there is any strong correlation between salt falls and oil drawdowns.

## String break characteristics

String breaks are significant events given the impact on cavern operations. Breaks that occur above the oil/brine interface (OBI) can impact the operational readiness of a cavern, as emulsification can occur if raw water is injected into the oil instead of into the brine. String breaks are also expensive, as performing a workover to extend a hanging string requires the cavern to be depressurized and a workover rig must be brought in to perform the work. Depressurization brings

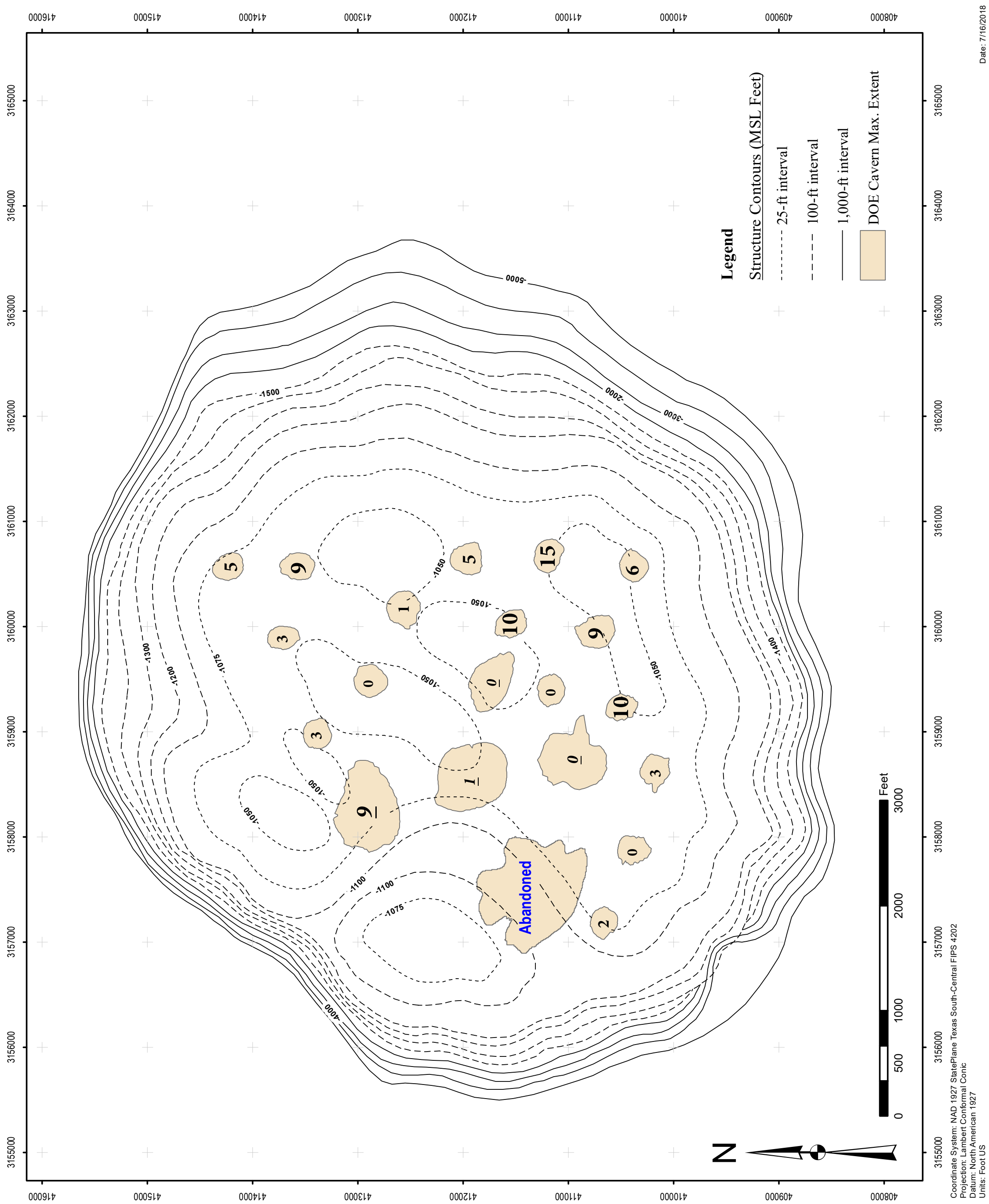



**Figure 2.** Casing failures due to salt falls, cavern footprints and salt contours for the Bryan Mound dome. The number of recorded string breaks is listed inside the cavern footprint. Underlined numbers are Phase I caverns.

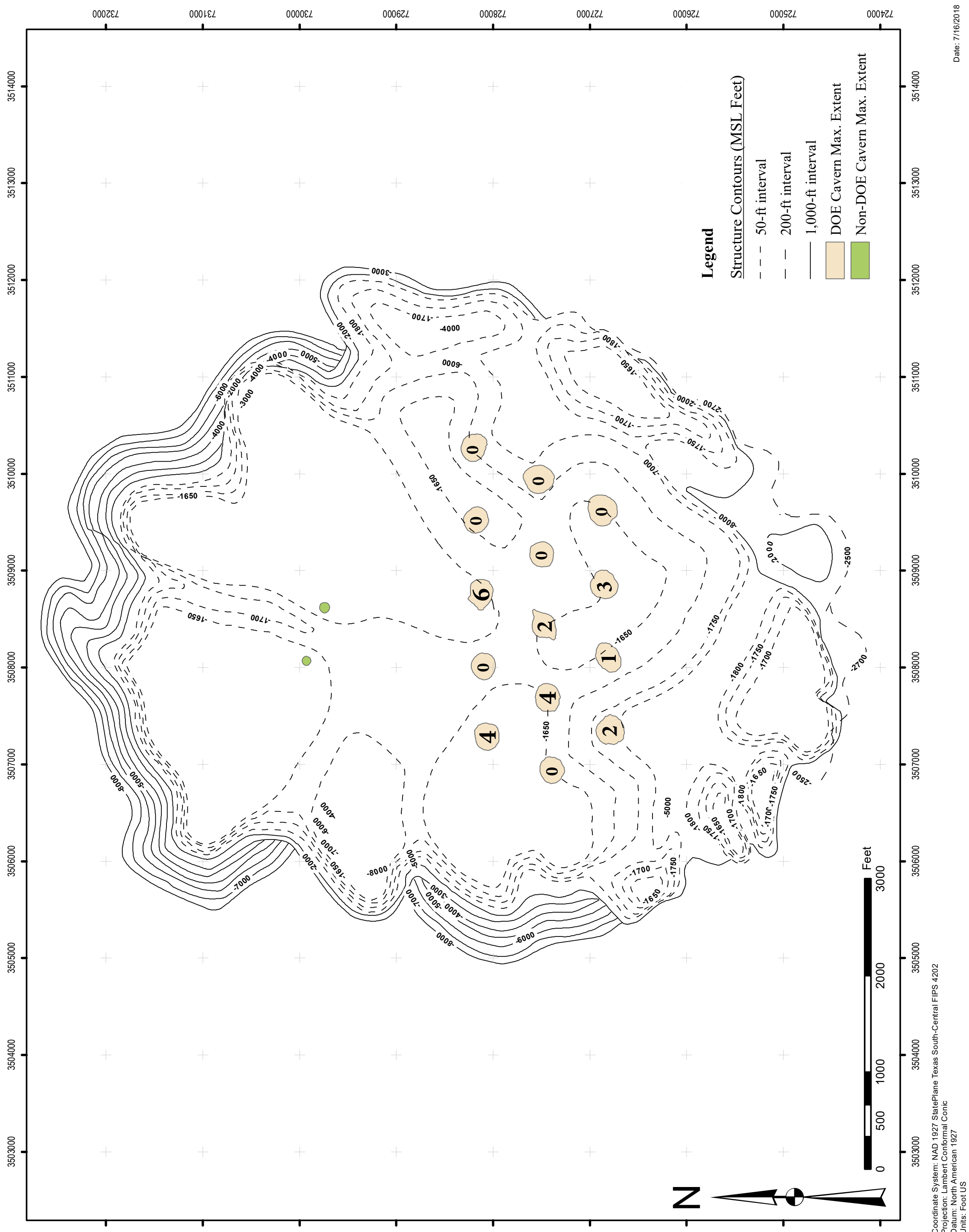



**Figure 3.** Casing failures due to salt falls, cavern footprints and salt contours for the Big Hill dome. The number of recorded string breaks is listed inside the cavern footprint. All caverns are Phase II caverns.

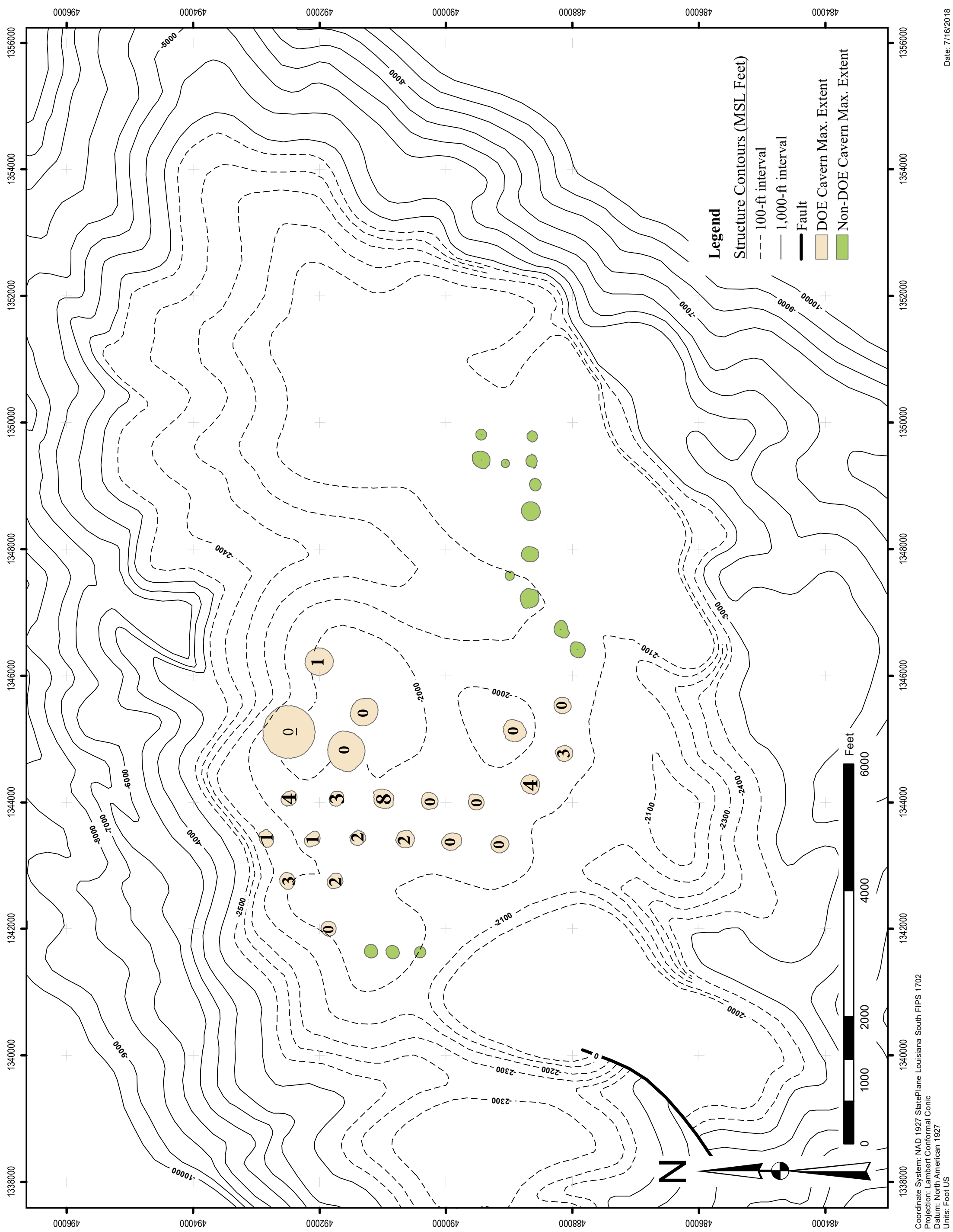



**Figure 4.** Casing failures due to salt falls, cavern footprints and salt contours for the West Hackberry dome. The number of recorded string breaks is listed inside the cavern footprint. The underlined cavern has been decommissioned.

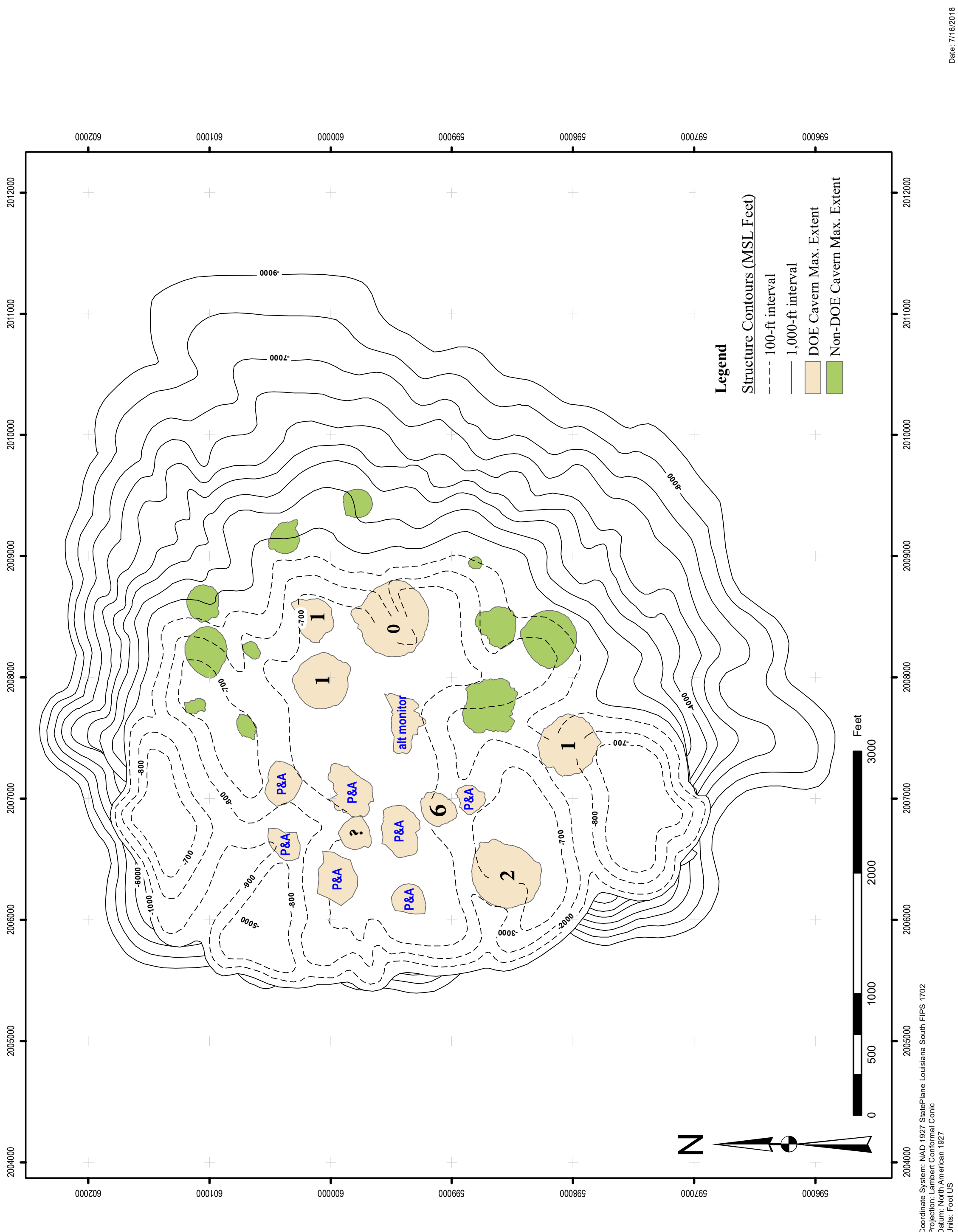



**Figure 5.** Casing failures due to salt falls, cavern footprints and salt contours for the Bayou Choctaw dome. The number of recorded string breaks is listed inside the cavern footprint. Caverns 101 and 102 (with 6 and "?" string breaks, respectively) are the only Phase II caverns at the site. Cavern 102's history is unknown prior to 2012.

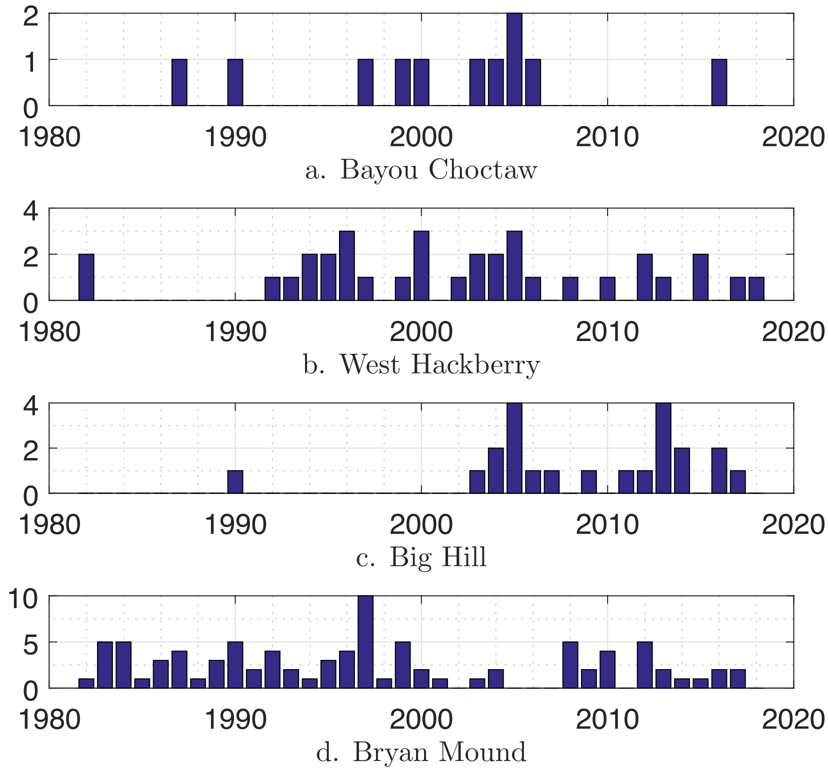



**Figure 6.** String breaks and salt falls per site by year.

its own risks, as described in Bérest et al. [2013], and also results in a permanent loss of a certain amount of cavern volume, as described in Hart et al. [2017].

When a string breaks at a position in the oil-filled part of the cavern, the heavier brine "falls out" of the hanging string and is replaced by oil. This leads to the brine-side pressure rising to equal the oil-side pressure, which is simple to detect in the control room. The impact itself results in significant vibration in the brine string which can also be seen at the wellhead as oscillation in the brine pressure. It can even result in seeing oscillations in the oil pressure, and both these characteristics can be seen in Figure 7. When a break occurs below the OBI, there is not a similar rise in wellhead brine pressure; however, such a break is unlikely to stop the cavern from operating as needed, and is a less serious issue. String breaks are typically verified by running a wireline measurement to find the end of tubing (EOT), and checking if there has been a loss of casing. Occasionally, a string does not break, but there is casing damage that stops a tool from finding the end but leaves the hanging string operational; this is typically referred to as a damaged string. If damage creates a leak path, then oil can start to enter the brine string, as is shown in Figure 8. A zoomed view is available in the appendix.

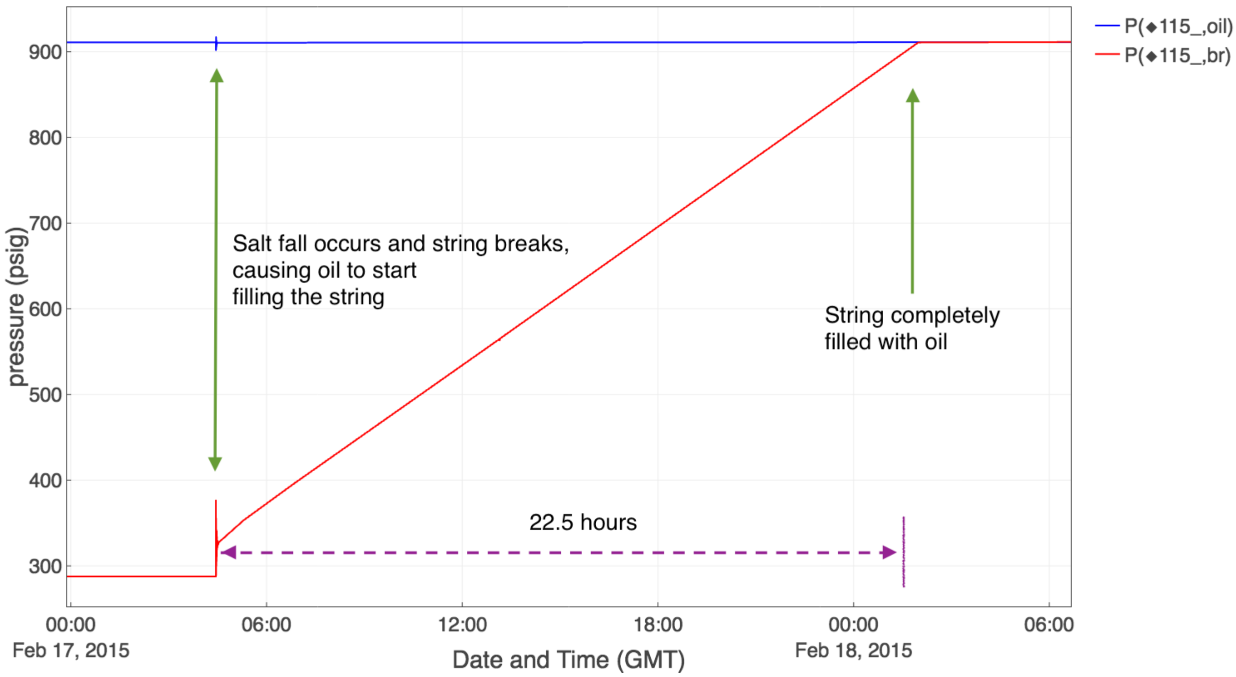



**Figure 7.** String break wellhead pressure response in West Hackberry 115. Initial break occurs at 04:30 on the February 17. By 02:00 on February 18, the oil and brine pressures have equalized, indicating the string has completely filled with oil. Note that the oil pressure also shows the impact of the salt hitting the hanging string.
A diamond indicates wellhead measurement, "br" indicates brine.

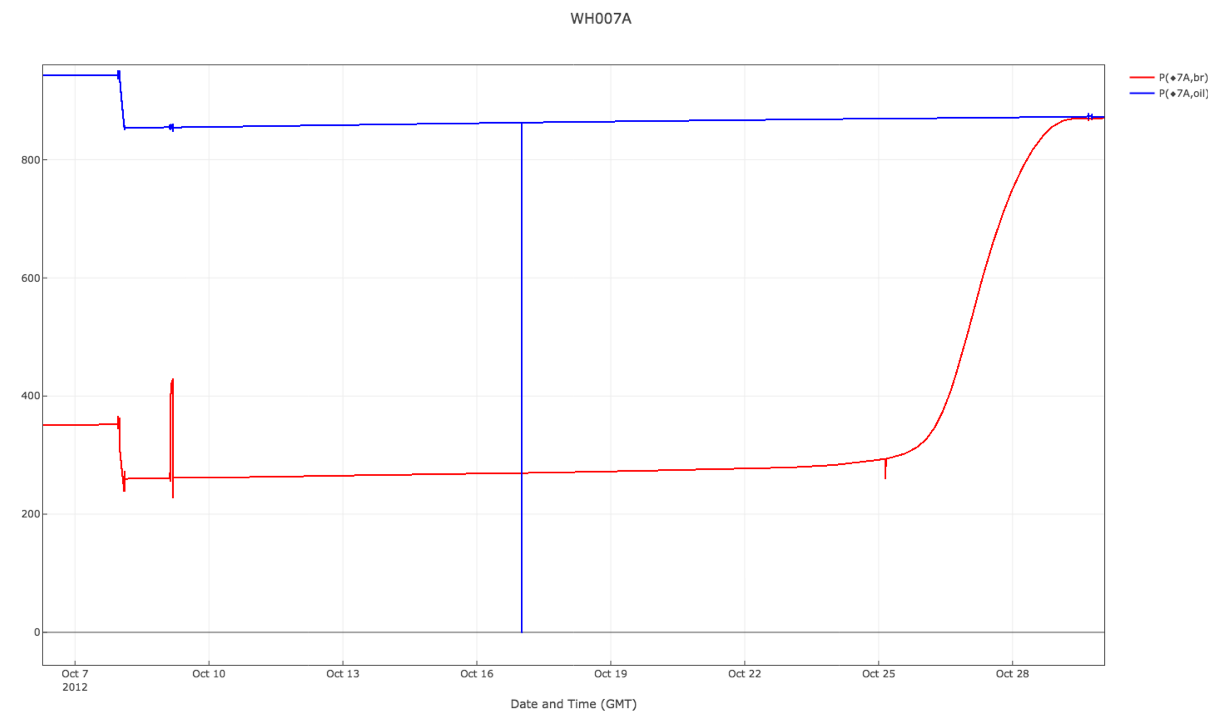



**Figure 8.** String damage causing oil to enter brine string in West Hackberry 7. Compare pressure trend to previous figure, noting the very different shapes, with the string leak slowing down when the in-string OBI reaches the break point.

The last category of string break is not technically a break – it is when a salt fall buries the end of the hanging string with rubble. This stops the string from performing correctly and would cause significant damage should debris be pulled up the string when trying to remove brine. This is effectively a string break due to the loss of operational readiness and because the string will generally need to be cut above the debris to make it operational again.

In the event of a string that breaks while fluid is flowing, the wellhead pressure measurements are not very useful. The wellhead pressure instruments in use at the SPR were designed for static pressure monitoring, and dynamic fluid movements change some of the assumptions that can be made when the wellhead is static. A string break during injection will affect the pump performance, as a change in the string length will change the headloss curve (and therefore change the pump performance). When injecting oil while removing brine, a string break above the OBI will result in oil entering the brine system, but will also change the performance characteristics of the oil pumps.

When a string break occurs above the OBI and the cavern is in a static state, it may be possible to determine the depth where the break occurred. As is shown in Figure 9, when the string breaks there is change in the wellhead. Immediately after the break, the string will still be full of brine and the pressure between the oil and brine will be equal at the new end of tubing. This change in pressure can be used to estimate the length of the remaining hanging string – if the brine and oil densities are sufficiently well known.

The equation that can be used to calculate the new length of tubing is

$$z_{break} = \frac{P_{oil} - P_{brine}}{\gamma_{\mathrm{H_2O}}(SG_{brine} - SG_{oil})} \tag{1}$$

where

$z_{break}$ = depth of the break and new EOT,
$P_{oil}$ = wellhead oil pressure immediately after impact,
$P_{brine}$ = wellhead brine-string pressure immediately after impact,
$\gamma_{\mathrm{H_2O}}$ = specific weight of pure water (approximately 0.4335 $\mathrm{psi/ft_{\langle z \rangle}}$),
$SG_{oil}$ = specific gravity of the oil within the cavern,
$SG_{brine}$ = specific gravity of the brine or raw water within the hanging string.

When the cavern is in static mode, calculating a new EOT this way may not be very important, as getting a wireline measurement can be done relatively quickly. However, if a string break is detected during raw water injection through a change in the pump curve, this provides a method to calculate a new end of tubing using the pressures immediately after the injection stops. Knowing the approximate depth of a string break in a cavern with emulsifying oil can be important piece of information for operators.

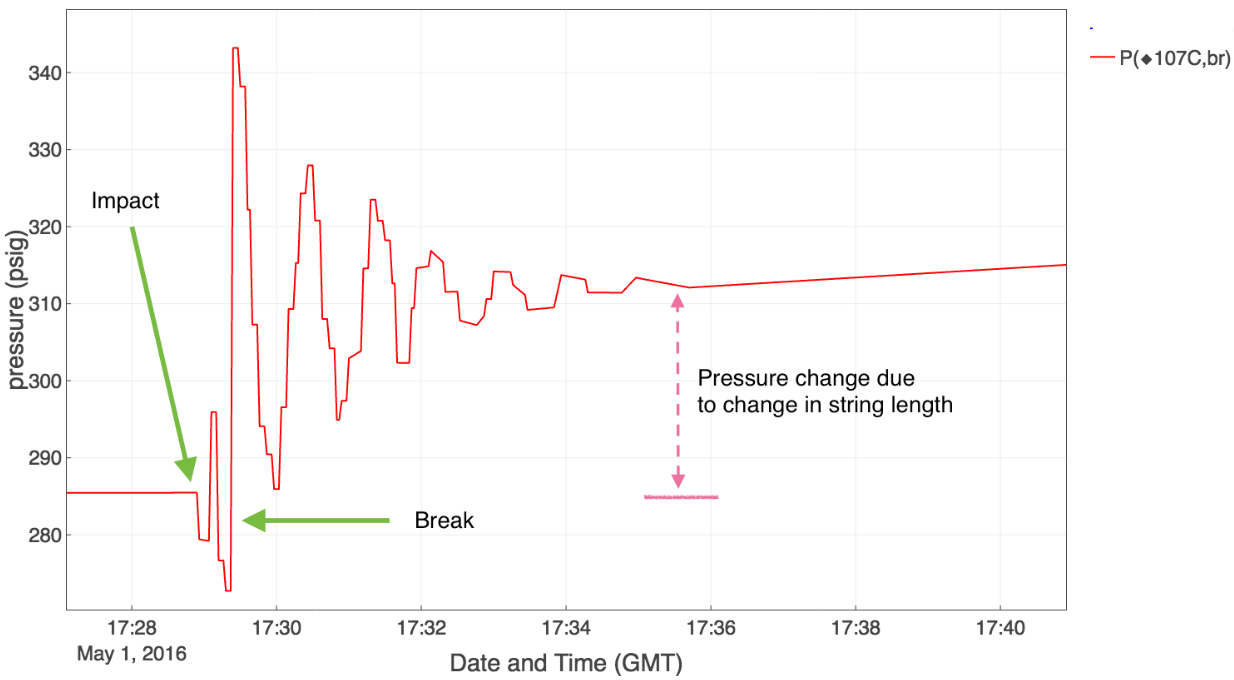
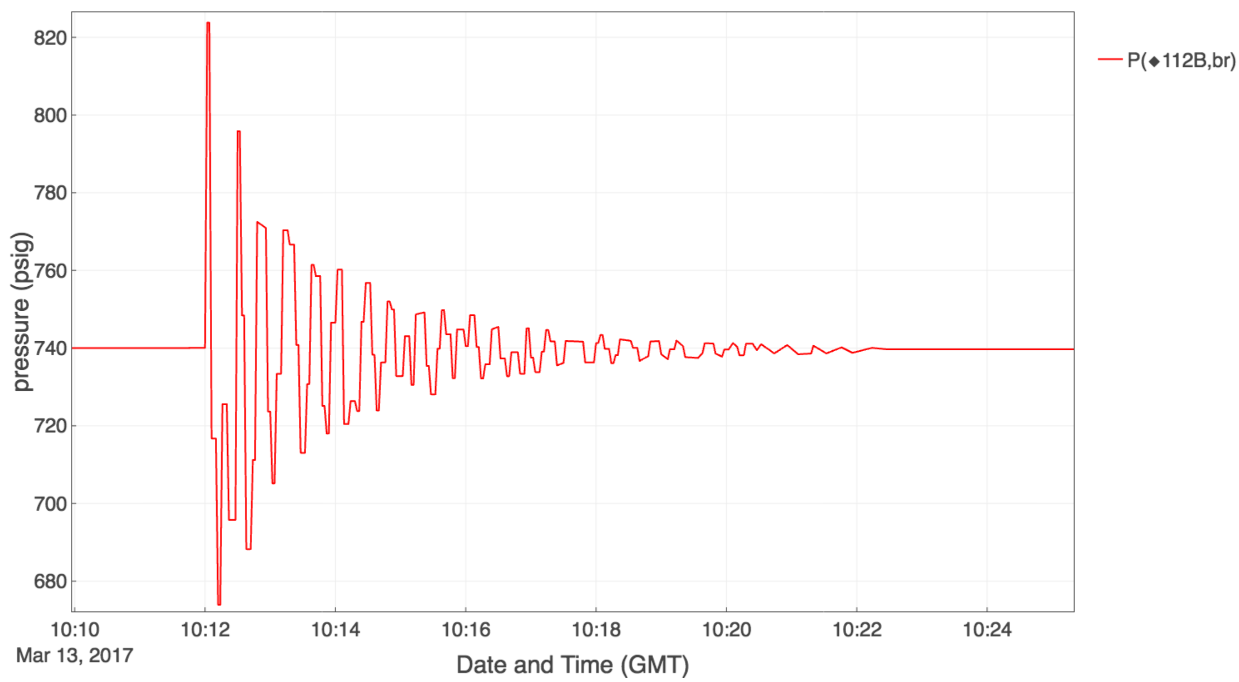



**Figure 9.** String break wellhead pressure response – first ten minutes, in Bryan Mound 107.

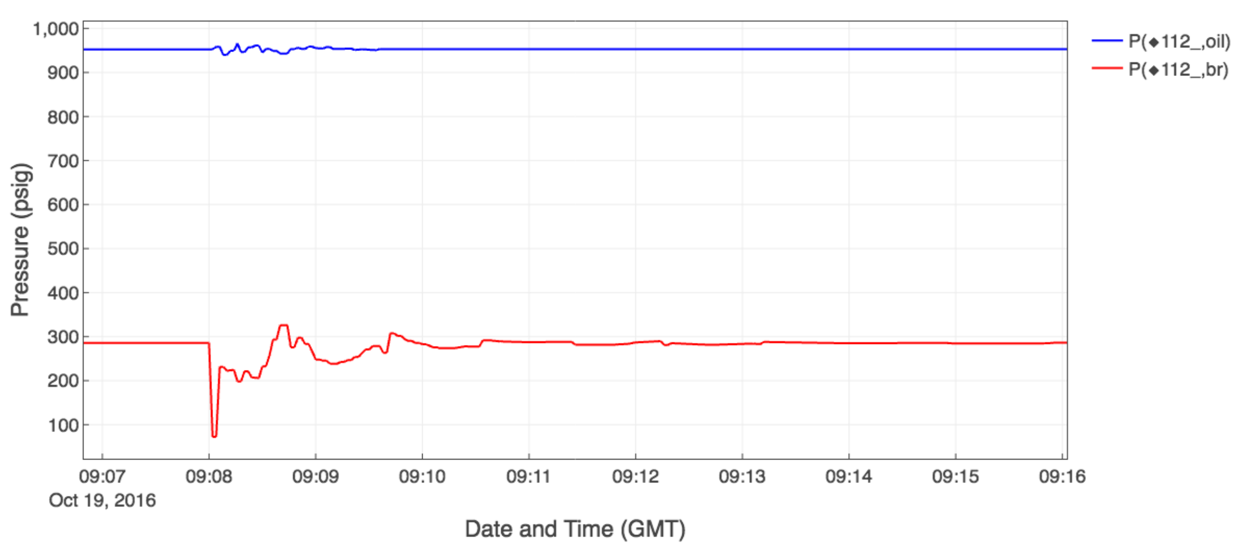
## Salt falls without string breaks

Salt falls that do not cause string breaks are more difficult to describe. There are reports from workers in the field of feeling salt falls when they happen to be on the wellpad when one occurs. Unfortunately, the pressure response from these events is seldom captured, and prior to 2012, data was collected at a maximum rate of one sample per 30 seconds (the Distributed Control System (DCS) now has a maximum storage rate of one data point per two seconds). Given that the examples of salt falls from string breaks show a waveform that has a lifetime of five to ten minutes and a frequency of less than one minute, the old, 30-second sample rate simply does not have the resolution to help describe salt falls.

Work by Bérest et al. [2017] has described the waves that form in the OBI when a large salt fall passes through it. There is a pressure response that can – sometimes – be observed at the wellhead. Bérest et al. found that the amplitude of these waves, as seen at the wellhead, depends on how far off center the brine string is located and where the fall occurred. If the brine string is located near a node of the waveform, no pressure response will be seen. Figure 10a, also a figure in Hart et al. [2017], shows a wellhead response from a suspected salt fall that did not impact the string. This response is a clean oscillatory response that looks like the responses after a string break. There is a marked difference in a suspected salt fall in WH-111, Figure 10b, where oscillations are much larger, but also die out much more quickly.




**(a)** Suspected salt fall without string break in Big Hill 112, March 2017.




**(b)** Suspected salt fall without string break in West Hackberry 111, October 2016.

**Figure 10.** Example salt fall signals

# Salt Fall Detection

Because the pressure responses are so clear, as described in the previous section, it might seem that detecting salt falls would be straightforward. Detecting string breaks is, and with their characteristic jump in pressure followed by a rise to the oil pressure an algorithm for detecting string breaks in static caverns has been implemented with success in the SPR DCS. Detecting non-string break falls is not as simple. As described in Bérest et al. [2017] and discussed previously, if the waves are small or the string is in the center – at a oscillation pole, there may not be a significant pressure response at the surface. But the greater difficulty is that many surface operations can cause the similar looking signals.

## False positives due to site operations

There are many operations that occur daily at the SPR sites. Even when there are no fluid movements or well activities, normal maintenance includes valves opening and closing, pumps being tested, and heavy machinery being used on the surface such as dropping off frac tanks for mechanical integrity tests (MITs). The current static salt fall detection algorithm in use at the sites involves checking for a rapid change in pressure, i.e., the initial impulse response, followed by a waiting period to cancel the detection if a nearby operational signal is received by the DCS. Unfortunately, many pieces of equipment are not instrumented, and other signals, like the status of motor operated valves (MOVs), are notoriously slow to register in the system. The end result is that the operators must be aware of all field activities in real-time to be able to manually ignore salt fall alarms that could have come from a different source.

Some examples of the operational causes are presented in Figures 11 through 16. These figures show both the brine or oil pressure response along with the operational cause, if it can be determined. In many cases, the cause must be inferred from surrogate data streams such as header pressures or flow – though at low rates and during maintenance, flow meters can be an unreliable indicator.

### False positive due to lack of instrumentation

The first example shows a pressure signal that was indicated as a suspected salt fall at cavern BM-111 on May 6, 2017, as shown in Figure 11. The signal that appears in the brine looks like other detected salt falls, and there are no signals from any MOVs that would have caused the response. After fifteen minutes of waiting to make sure there was no operational changes, the salt fall status goes to 1 (active); after an hour, it turns back off. Figure 12 shows a closer view of the pressure signal, which looks like the distinctive salt fall response.

However, there is an additional check that can be made. The cavern oil and brine pipes between the MOVs and the wellheads are instrumented with pressure and temperature sensors. When the line pressure is overlaid on the wellhead pressures, the cause of the impulse becomes clear. As is

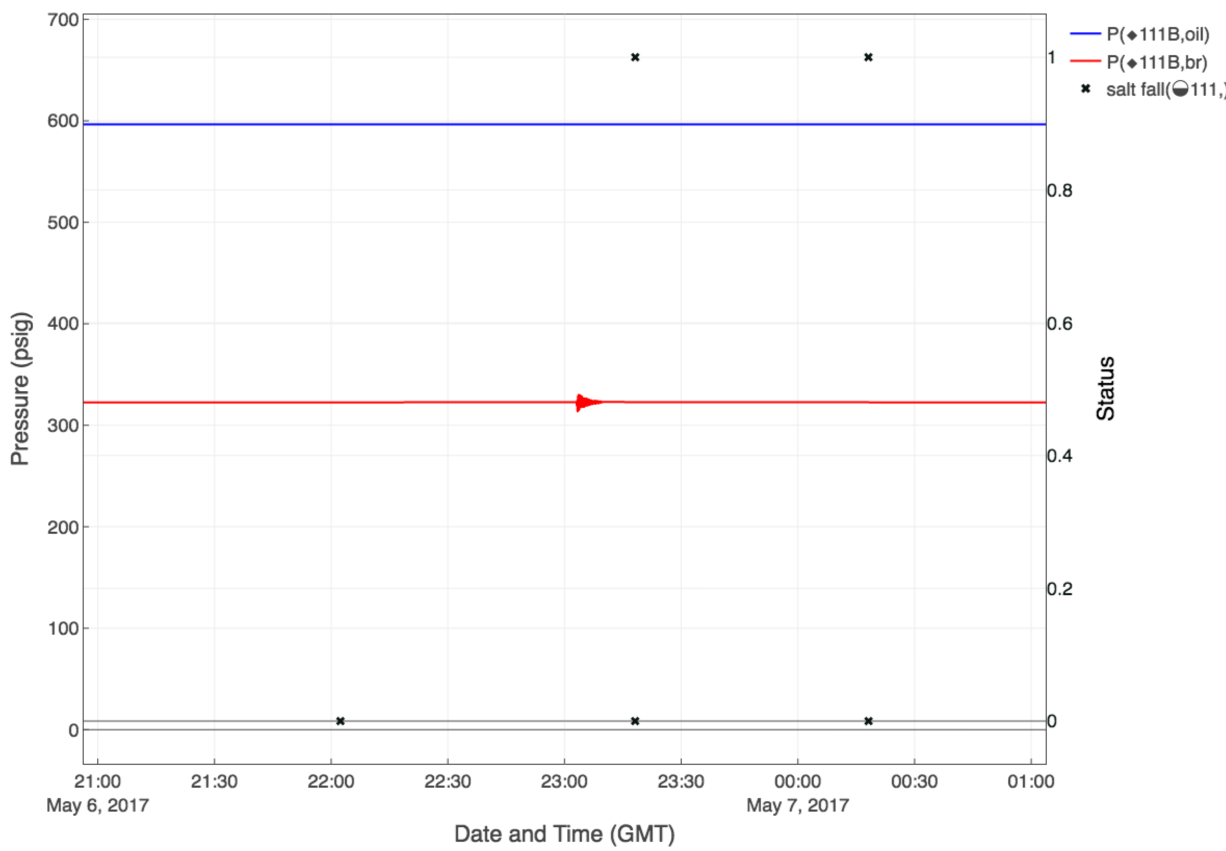



**Figure 11.** Salt fall detection at BM-111. Salt fall alarm as black cross; oil pressure blue, top line; brine pressure red, middle line. Diamond indicates wellhead measurement, half filled circle indicates a cavern measurement.

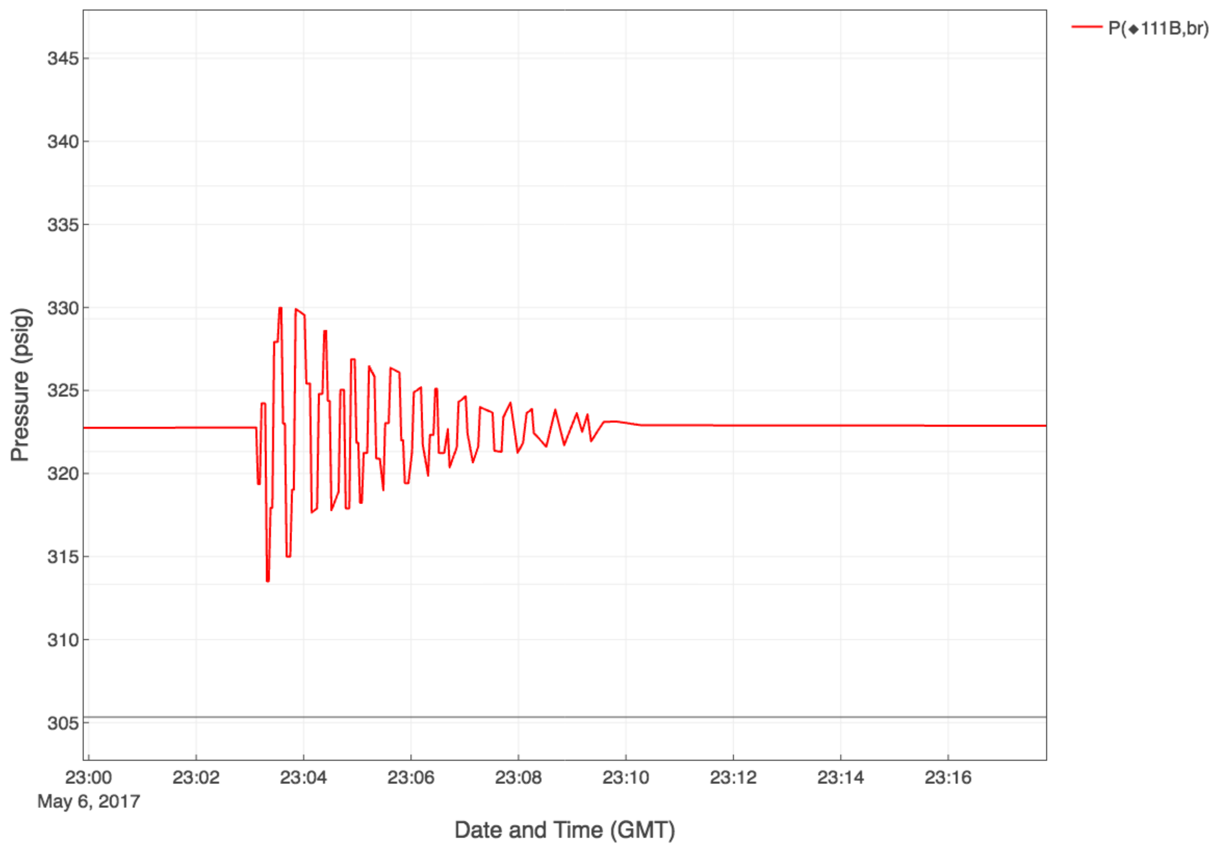



**Figure 12.** Salt fall detection at BM-111 – closeup. Note oscillation lasts approximately five minutes, roughly the same as in string breaks shown in previous chapter.

shown in Figure 13, the line pressures are fluctuating in the days prior to the salt fall alarm. The oscillations are due to solar radiance heating the lines during the day, causing the pressure reading to increase at the gauge. The impulse response seen in Figures 11 and 12 occurs because the line pressure suddenly equalizes to the wellhead pressure. The author assumes that this is due to an uninstrumented valve being opened – but this type of operation does not get logged, and there is no way to check.

When the entire month of May is examined with both line and wellhead pressures, as in Figure 14, it becomes clear that all the salt fall warnings for the month occurred due to a sudden equalization between the wellhead and the line pressures.

### False positives due to unknown surface activities

Another example of an alarm that is likely surface based occurred at Big Hill in June of 2016. Caverns 101 to 103, in a line from east two west, equally spaced, saw a signal that looked like a salt fall one after the other. The "falls" each occurred twenty minutes apart, and the signal diminished much more quickly that those seen during string breaks or other salt falls, as seen in Figure 15. It is possible that this was a series of falls; however, it seems more likely that a series of operational actions moved in an orderly fashion down the row of caverns. Making it more unlikely that these were salt falls, Caverns 101 and 102 have never seen a string break or sonar-detected salt fall. This example shows the importance of knowing surface operations in order to interpret pressure signals at the wellhead.

### False positives due to MOV sensor delays

Figure 16 shows the difficulties with using valve movements to eliminate false positive salt fall detections. In Figure 16a, the start of the transfer is shown. The green line with circles represents the valve status changing from closed to opening to fully open; however, the pressure changes do not occur until several minutes after the valve is opened (16:42 vs 16:46). The flow does not start right away, although in this case, it is unlikely to be mistaken for a salt fall. Figure 16b shows the end of the transfer, when the valve is closed. The signal here looks closer to a salt fall event, and the valve "closed" signal is not received until several minutes after the event occurs. However, when the sign of the instantaneous flow rate is examined (the shaded area on the bottom of the plots, down is flow out, up is flow in to the cavern), the changes in flow line up much more accurately than the MOV status codes.

## Proposed algorithmic improvements

The examples shown above provide a means for possible improvements to the current detection algorithm for the purpose of decreasing false positives. Using the controller to create a new

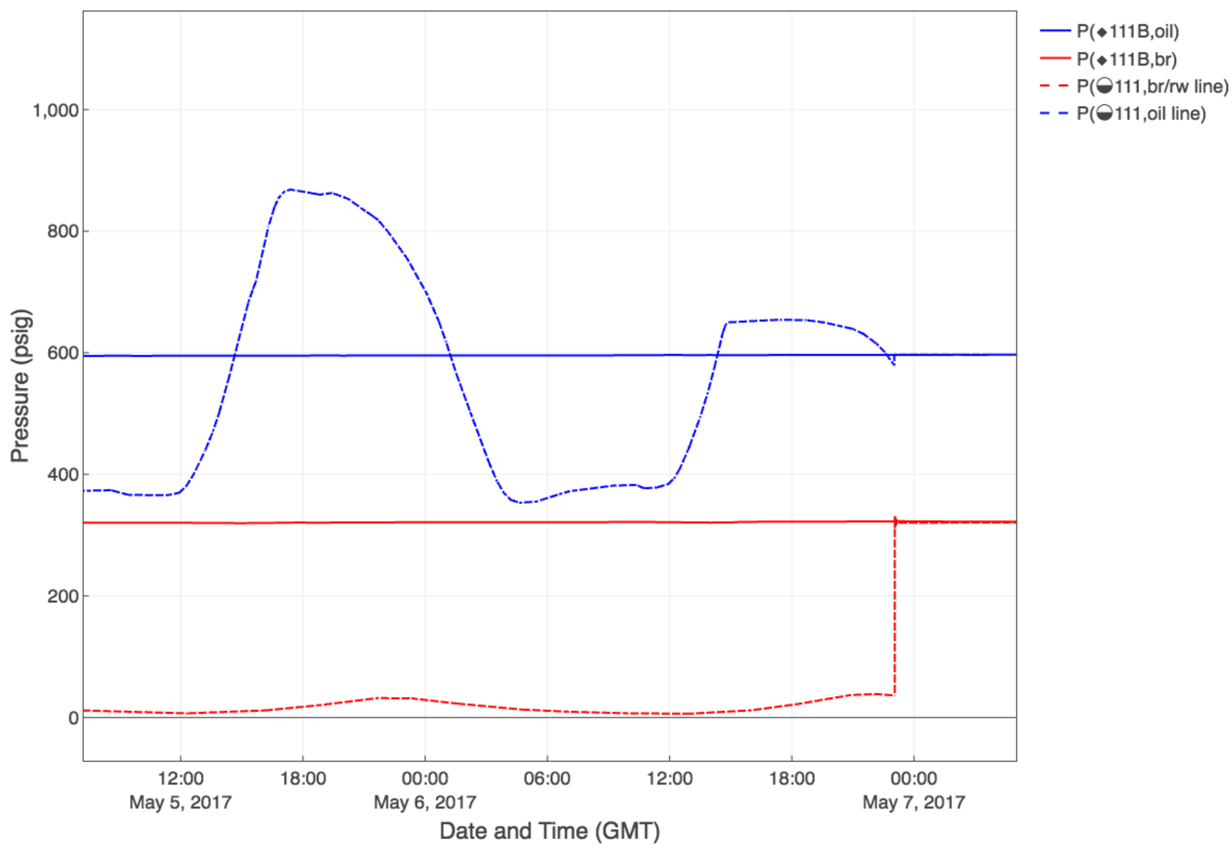



**Figure 13.** Salt fall detection at BM-111 – adding line pressures. Oil pressures in blue, on top, with dashed line representing cavern oil-line pressure. Brine pressures in red, bottom two lines, with dashed line representing cavern brine-line pressure.
Diamond indicates wellhead, half filled circle indicates a cavern measurement. “br/rw” is brine/raw water.

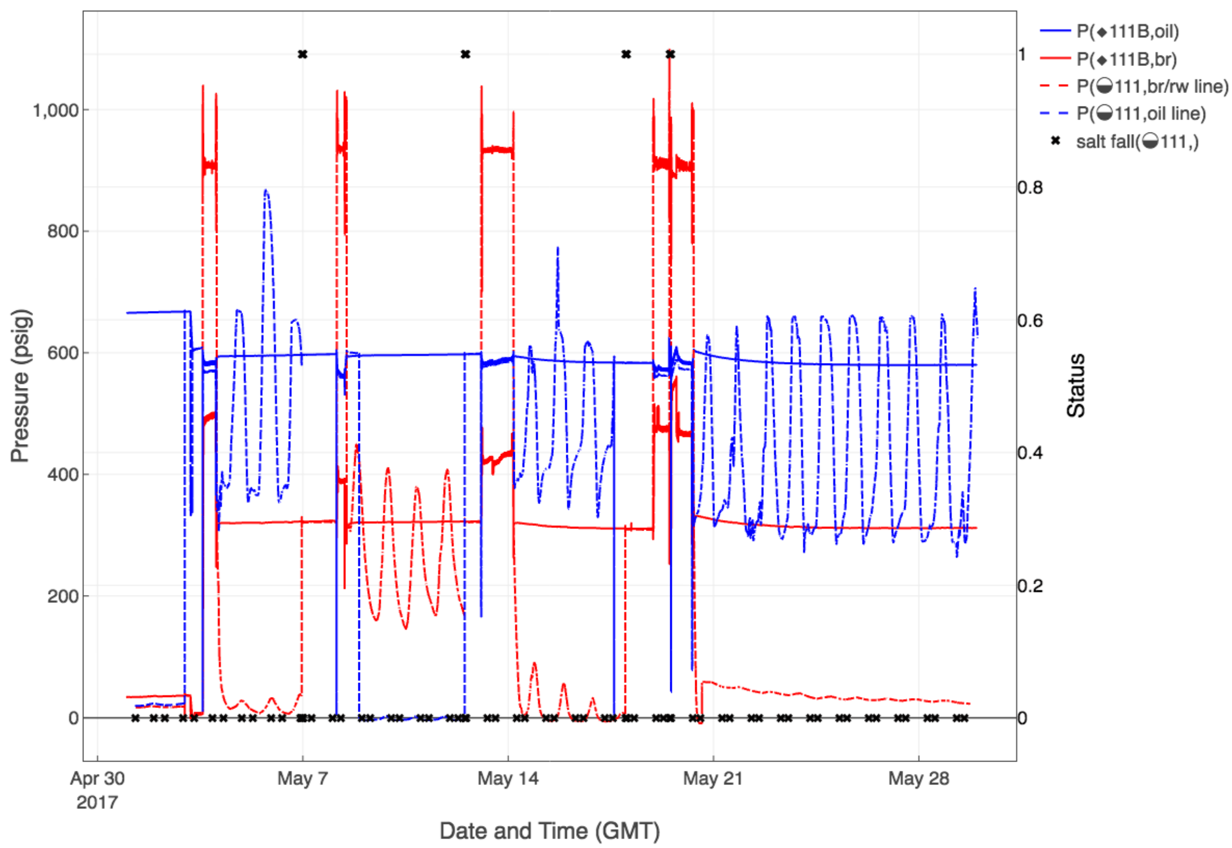



**Figure 14.** BM-111 wellhead and cavern line pressures, May 2017. Note how the salt fall detections – black "x" at a value of 1 – occur at the same time the line pressures (dashed) jump to match the wellhead pressures (solid).
Diamond indicates wellhead, half filled circle indicates a cavern measurement. "br/rw" is brine/raw water.

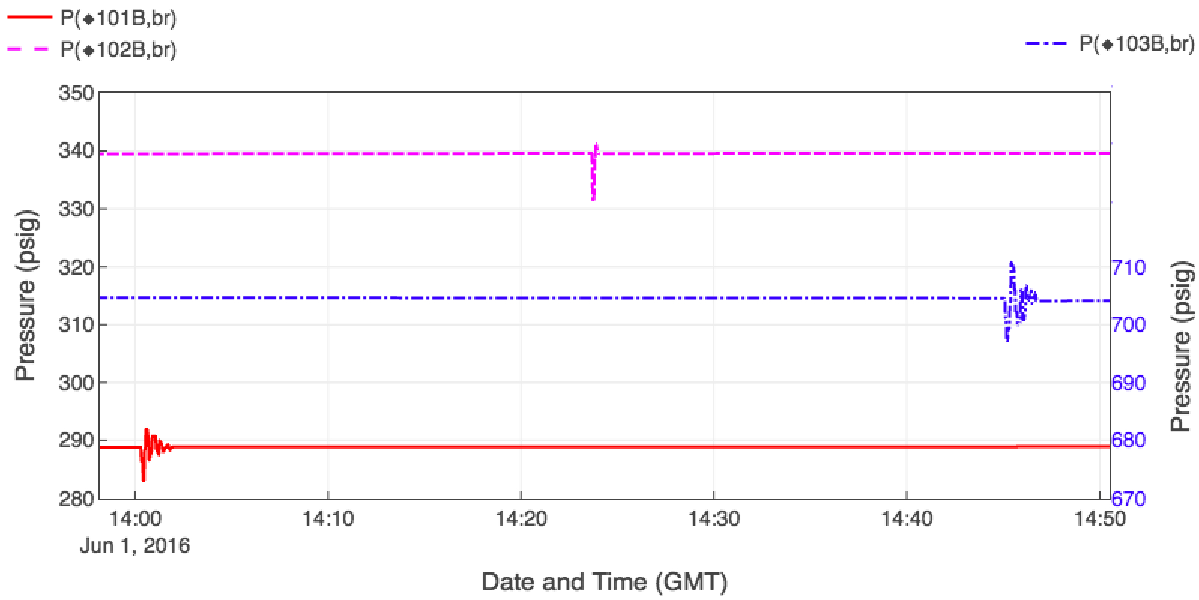
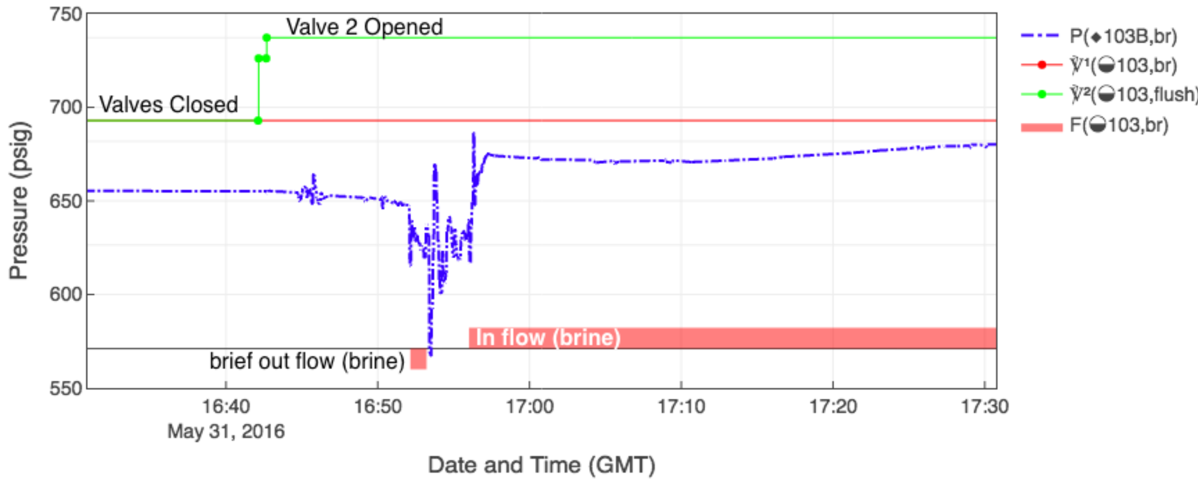
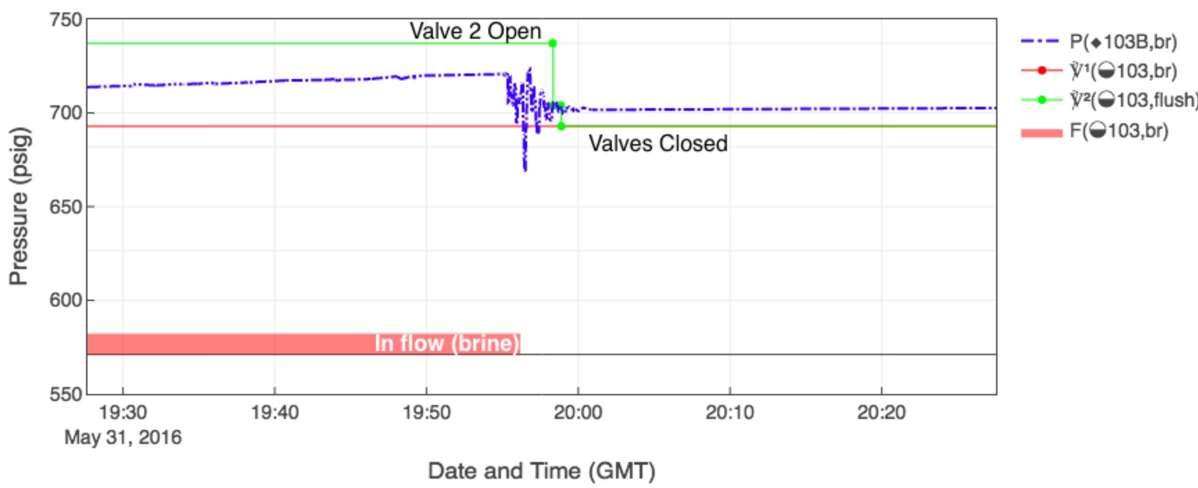



**Figure 15.** Pressure signals that proceed from cavern to cavern in a line. These could be salt falls, or they could be surface activity such as header valves closing or equipment being dropped off from trucks onto well pads.

"pseudo-channel" like the static string break and static salt fall channels on the brine string pressure, two new channels could be created. One channel would look for cases when the cavern line pressure and wellhead pressure suddenly equalize, and put up a signal that would cause the salt fall algorithm to ignore any pressure event at that time. Another channel would look at the actual flow values, setting a value of -1 for negative flow rate and +1 for positive flow rate, and 0 for flow rates within some fence (this fence avoids false flow readings from the flow meter bouncing). The flow direction channel would require appropriate maintenance signals to be used and processed – there have been many cases where a flow meter is disconnected for some reason and the values that come in are non-physical.




**(a)** Start of flush water movement, Big Hill 103, May 2016.




**(b)** End of flush water movement, Big Hill 103, May 2016.

**Figure 16.** Example of valve impacts on pressure.
The versicle symbol (slashed "V") is MOV status signal, the thick line (F) is flow, diamond indicates a wellhead parameter and a half-filled circle indicates a cavern parameter.

# Conclusions

Salt falls can cause significant interruptions to cavern operations due to string breaks. In addition to the cost of repairing the hanging string, breaks above the OBI can make a cavern unavailable for use in sales or releases. The temporal and geographic correlations of salt falls was examined for string breaks occurring since the 1980s. There was no temporal correlation with fluid movements that had any statistical significance. Geologic correlations do seem to exist, as certain caverns and groups of caverns show higher propensity for salt falls resulting in string breaks than others. The Bryan Mound site has had more salt falls and string breaks than all other sites combined.

When salt falls do not impact the hanging string, they can still be problematic by raising the floor, creating instabilities in the wall of the cavern, and changing outcomes during leaching. Detecting salt falls is complicated, as there are no instruments installed that can directly detect a salt fall and therefore surrogates, such as pressure signals, or infrequent sonar surveys must be relied upon.

Detection of string breaks has proven straightforward, and FFPO has already implemented an effective algorithm for detecting these through pressure monitoring. This algorithm and other calculations, such as the break depth calculation described in this report, should be incorporated into the CaveMan Enterprise software to make it even easier to record and provide information regarding these events. This report also provides an updated list of string breaks along with graphics showing recent breaks in the appendices.

Detection of non-string break salt falls is much more difficult. Analysis of the pressure data found that there are too many operations that can impact the wellhead pressure to classify an event as a salt fall without significant manual intervention. One suggestion for how the algorithm that is currently implemented might be made to have fewer false alerts was suggested; equalization between line and wellhead pressure can be used as an exclusionary flag in the same way valve movements are used. However, the lack of instrumentation on certain valves and the uncertainty in flow meters at low rates makes it difficult to algorithmically exclude all well-pad actions; even heavy truck movements could cause visible fluctuations as metering tubing vibrates. While the operations staff will presumably be aware of the activities, there is no way to know to discount an event historically, as this type of information is not recorded in the DCS.

Salt falls that occur when the cavern is active rather than static are even harder to detect. Sonar surveys can find large salt falls after the fact from changes in the cavern geometry or through floor rise. Ongoing research by multiple groups is looking at how salt falls impact pressures within the cavern with the hope that more information can be gleaned from pressure signals. However, if it is important to rapidly detect salt falls that don't impact the string or to detect falls that occur when the cavern is active and wellhead pressures are fluctuating due to flow, other technologies such as acoustic or geophysical monitoring will be necessary.

# References and Further Reading


Pierre Bérest, Hippolyte Djizanne, Benoit Brouard, Grégoire Hévin, et al. Effects of a rapid depressurization in a salt cavern. In *ISRM SINOROCK 2013*. International Society for Rock Mechanics and Rock Engineering, 2013.

Pierre Bérest, Benoit Brouard, Vassily Zakharov, Dean Checkai, and David Hart. Salt-fall detection in oil storage caverns. In *Proc. Fall 2017 Technical Conference, Münster, Germany*, September 2017.

B. L. Ehgartner. Kinetics of a rock slab falling in a cavern. Memo to J. K. Linn (SNL), April 24, 1997. Sandia National Laboratories.

David Hart, Giorgia Bettin, and Bryan Bellevue. Pressure trend analyses for geophysical and integrity investigations. In *Proc. Spring 2017 Technical Conference, Albuquerque, NM*. Solution Mining Research Institute, April 2017.

Brandon Lampe, John Stormont, Tim Lynn, and Stephen Bauer. Potential influence of granular salt on cavern stability. In *Proc. Spring 2017 Technical Conference, Albuquerque, NM*. Solution Mining Research Institute, 2017.

J. K. Linn. Investigation into apparent salt falls at SPR storage caverns. Memo to E. E. Chapple (DOE SPR PMO), August 11, 1986. Sandia National Laboratories.

Karl M. Loof and Kurt M. Loof. Possible geologic influence on salt falls associated with the storage caverns at Bryan Mound, Brazoria County, Texas. In *Proc. Spring 1999 Meeting, Las Vegas, Nevada*. Solution Mining Research Institute, April 1999.

Kurt Looff. The impact of anomalous salt and boundary shear zones on salt cavern geometry, cavern operations and cavern integrity. In *Proc. Spring 2017 Technical Conference, Albuquerque, NM*. Solution Mining Research Institute, April 2017.

Darrel Munson. Update of casing damage survey - 2004. Memo to Robert Myers (DOE SPR PMO), April 14, 2005. Sandia National Laboratories.

Darrell Munson, Stephen Bauer, Christopher Rautman, Brian Ehgartner, and Allan Sattler. Analysis of the massive salt fall in Big Hill cavern 103. SAND 2003-0703, Sandia National Laboratories, Albuquerque, NM, 2003.

Darrell E. Munson. Propensity for spall formation in salt storage caverns using a creep and fracture analysis. In *North American US Rock Mechanics Symposium; Seattle, WA*, February 2000. Also as SAND99-2026C, Sandia National Laboratories.

Darrell E. Munson. Apparent discrepancy in Bayou Choctaw cavern 20 sonar volumes. Memo to Robert Myers (DOE SPR PMO), February 15, 2001. Sandia National Laboratories.

Darrell E. Munson. Bryan Mound storage caverns features and the internal structure of the dome. In *Proc. Fall 2008 Technical Conference, Galveston, Texas*. Solution Mining Research Institute, 2008.

Darrell E. Munson, Martin A. Molecke, and Robert E. Meyers. Interior cavern conditions and salt fall potential. In *Proc. Spring 1998 Meeting, New Orleans, Louisiana*. Solution Mining Research Institute, April 1998a.

Darrell E. Munson, Martin A. Molecke, James T. Neal, Allan R. Sattler, and Robert E. Myers. Strategic Petroleum Reserve caverns casing damage update 1997. SAND 98-0090, Sandia National Laboratories, Albuquerque, NM, 1998b.

Darrell E. Munson, Kwai S. Chan, and Arlo F. Fossum. Fracture and healing of rock salt related to salt caverns. In *Proc. Spring 1999 Meeting, Las Vegas, Nevada*. Solution Mining Research Institute, 1999.

Darrell E. Munson, Brian Ehgartner, Stephen Bauer, Christopher Rautman, and Robert Meyers. Analysis of a salt fall in Big Hill Cavern 103, and a preliminary concept of salt dome structure. In *Proc. Spring 2004 Meeting, Wichita, Kansas*, April 2004.

Steven R. Sobolik and Brian L. Ehgartner. Analysis of cavern stability at the West Hackberry SPR site. SAND 2009-2194, Sandia National Laboratories, Albuquerque, NM, 2009.

SOCON. BM 111-A Bryan Mound, Texas. ECHO-LOG 183028, SOCON Sonar Well Services, Inc., Stafford, Texas, April 2018.

Joe A. Ward. Safety concerns in hydrocarbon storage. In *Proc. Spring 1999 Meeting, Las Vegas, Nevada*. Solution Mining Research Institute, 1999.

# A List of Salt Falls

The following four tables present the known and suspected salt falls. When information is available regarding the depth of the fall or the length of casing lost, this is provided. Comments are given to describe the any extra information that can be provided, such as if there was floor rise or if the detection was due to a sonar survey. The vast majority of the records come from a spreadsheet created by the SPR M&O contractor in 2009, Dyn McDermott. Events are listed in chronological order.

Table A.1: List of salt falls and casing failures at Bayou Choctaw

| Site | Cavern | Well | Yr-Mo | Depth | Feet Lost | Comments |
|---|---|---|---|---|---|---|
| BC | 101 | B | 1987-12 | 4838 | 118 | |
| BC | 101 | A | 1990-03 | 3874 | 1445 | |
| BC | 15 | A | 1997-12 | | | |
| BC | 101 | A | 1999-06 | | | |
| BC | 19 | _ | 2000-06 | | | |
| BC | 101 | A | 2003-03 | | | |
| BC | 17 | A | 2004-06 | | | |
| BC | 20 | _ | 2005-06 | | | |
| BC | 20 | _ | 2005-06 | | | |
| BC | 101 | A | 2006-11 | | | |
| BC | 101 | A | 2016-11 | | | |

Table A.2: List of salt falls and casing failures at Big Hill

| Site | Cavern | Well | Yr-Mo | Depth | Feet Lost | Comments |
|---|---|---|---|---|---|---|
| BH | 114 | A | 1990-06 | 3006 | 620 | |
| BH | 114 | B | 2003-06 | | 162 | |
| BH | 103 | B | 2004-04 | | 50 | |
| BH | 105 | B | 2004-04 | | 488 | |
| BH | 113 | B | 2005-02 | | 237 | |
| BH | 109 | B | 2005-03 | | 77 | |
| BH | 112 | B | 2005-06 | | 292 | |
| BH | 112 | B | 2005-07 | | 359 | |
| BH | 108 | B | 2006-05 | | 125 | |
| BH | 105 | B | 2007-06 | 4046 | 119 | |
| BH | 109 | B | 2009-01 | 3864 | 374 | |
| BH | 103 | B | 2011-04 | | | |
| BH | 109 | B | 2012-06 | | | |
| BH | 103 | B | 2013-03 | | | |
| BH | 105 | B | 2013-03 | | 80 | During leaching |
| BH | 103 | B | 2013-03 | | 700 | OIBS |
| BH | 105 | B | 2013-03 | | 200 | During leaching |
| BH | 108 | B | 2014-05 | | | |
| BH | 103 | B | 2014-07 | | 734 | |
| BH | 109 | B | 2016-09 | | | Floor rise 16 ft |
| BH | 112 | B | 2016-11 | | | Plug set above OBI |
| BH | 103 | B | 2017-08 | | | |

Table A.3: List of salt falls and casing failures at Bryan Mound

| Site | Cavern | Well | Yr-Mo | Depth | Feet Lost | Comments |
|---|---|---|---|---|---|---|
| BM | 5 | _ | 1978-10 | 2817 | 456 | |
| BM | 103 | C | 1982-10 | | 4202 | |
| BM | 105 | B | 1983-03 | | 2377 | |
| BM | 102 | B | 1983-07 | | 817 | |
| BM | 109 | C | 1983-07 | | 97 | |
| BM | 101 | C | 1983-10 | | 226 | |
| BM | 103 | C | 1983-12 | | 3802 | |
| BM | 108 | A | 1984-04 | | 767 | |
| BM | 108 | B | 1984-04 | | 41 | |
| BM | 107 | C | 1984-08 | | 1232 | |
| BM | 107 | B | 1984-09 | | DAMAGE | |
| BM | 109 | A | 1984-11 | | 305 | |
| BM | 112 | A | 1985-08 | | 769 | |
| BM | 106 | A | 1986-05 | | 1027 | |
| BM | 107 | A | 1986-06 | | 297 | |
| BM | 112 | A | 1986-12 | | 1371 | |
| BM | 108 | B | 1987-01 | | 620 | |
| BM | 103 | C | 1987-08 | | 156 | |
| BM | 103 | C | 1987-11 | | 343 | |
| BM | 109 | B | 1987-11 | | 268 | |
| BM | 106 | C | 1988-01 | 3340 | DAMAGED | |
| BM | 107 | A | 1989-04 | | 3174 | |
| BM | 112 | A | 1989-06 | | 1304 | |
| BM | 5 | _ | 1989-08 | | 204 | |
| BM | 5 | _ | 1990-06 | | 458 | |
| BM | 102 | B | 1990-07 | | 747 | |
| BM | 106 | A | 1990-07 | 3400 | DAMAGED | |
| BM | 103 | C | 1990-10 | | 284 | |
| BM | 112 | A | 1990-11 | | 992 | |
| BM | 106 | A | 1991-03 | | 1080 | |
| BM | 106 | C | 1991-04 | | 1238 | |
| BM | 106 | A | 1992-05 | | 561 | |
| BM | 106 | C | 1992-05 | | 431 | |
| BM | 107 | A | 1992-06 | | 1125 | |
| BM | 5 | C | 1992-07 | | 530 | |
| BM | 112 | A | 1993-01 | | 1563 | |
| BM | 106 | C | 1993-05 | | 896 | |
| BM | 111 | B | 1994-06 | | 584 | |
| BM | 116 | B | 1995-04 | | 1243 | |

*Continued on next page*

Table A.3 – *Continued from previous page*

| Site | Cavern | Well | Yr-Mo | Depth | Feet Lost | Comments |
|---|---|---|---|---|---|---|
| BM | 109 | B | 1995-07 | 3620 | 988 | |
| BM | 106 | C | 1995-11 | 3670 | damaged | |
| BM | 103 | C | 1996-08 | | 624 | |
| BM | 108 | A | 1996-10 | 3720 | damaged | |
| BM | 113 | B | 1996-10 | | 89 | |
| BM | 109 | A | 1996-11 | | 130 | |
| BM | 103 | C | 1997-03 | | 300 | |
| BM | 109 | A | 1997-03 | | 694 | |
| BM | 109 | B | 1997-03 | | 1464 | |
| BM | 113 | B | 1997-03 | 3751 | damaged | |
| BM | 106 | A | 1997-07 | | 74 | |
| BM | 107 | C | 1997-07 | | 623 | |
| BM | 101 | A | 1997-08 | 3713 | damaged | |
| BM | 107 | A | 1997-08 | 3904 | damaged | |
| BM | 112 | A | 1997-10 | | 1228 | |
| BM | 114 | B | 1997-11 | | 112 | |
| BM | 5 | _ | 1998-05 | | 271 damaged | |
| BM | 113 | B | 1999-01 | 2184 | 488 sand cut | |
| BM | 5 | _ | 1999-06 | | 553 | |
| BM | 5 | C | 1999-07 | | 381 | |
| BM | 102 | B | 1999-07 | 4071 | damaged | |
| BM | 107 | C | 1999-10 | 2668 | 1345 | |
| BM | 106 | A | 2000-01 | 3140 | 1355 | |
| BM | 106 | C | 2000-01 | 3222 | 659 | |
| BM | 113 | B | 2001-06 | 227 | lost | |
| BM | 113 | B | 2003-02 | 71 | | |
| BM | 112 | C | 2004-01 | 603 | lost | |
| BM | 107 | C | 2004-12 | 1642 | | |
| BM | 108 | B | 2008-02 | 4054 | damaged | |
| BM | 106 | C | 2008-03 | 3565 | 270 | |
| BM | 111 | B | 2008-03 | | | |
| BM | 116 | B | 2008-07 | 726 | | |
| BM | 106 | A | 2008-08 | 3564 | damaged | |
| BM | 114 | B | 2009-01 | 4063 | 39 | |
| BM | 5 | C | 2009-07 | 2704 | damaged | |
| BM | 103 | C | 2010-01 | | | |
| BM | 111 | B | 2010-03 | | | |
| BM | 114 | B | 2010-03 | | | |
| BM | 112 | C | 2010-06 | | | |
| BM | 112 | C | 2012-02 | | | |

*Continued on next page*

Table A.3 – *Continued from previous page*

| Site | Cavern | Well | Yr-Mo | Depth | Feet Lost | Comments |
|---|---|---|---|---|---|---|
| BM | 4 | _ | 2012-07 | | | |
| BM | 103 | C | 2012-07 | | | |
| BM | 109 | A | 2012-10 | | | |
| BM | 5 | _ | 2012-12 | | | |
| BM | 113 | B | 2013-01 | | | Pre 2013 |
| BM | 111 | B | 2013-08 | | | |
| BM | 109 | A | 2014-09 | | | |
| BM | 101 | C | 2015-09 | | | |
| BM | 107 | C | 2016-05 | | | |
| BM | 106 | C | 2016-07 | | | |
| BM | 112 | C | 2017-02 | | | |
| BM | 111 | B | 2017-06 | | | From SONAR |

Table A.4: List of salt falls and casing failures at West Hackberry

| Site | Cavern | Well | Yr-Mo | Depth | Feet Lost | Comments |
|---|---|---|---|---|---|---|
| WH | 103 | _ | 1982-07 | 4215 | 188 | |
| WH | 107 | _ | 1982-11 | 4234 | 300 | |
| WH | 113 | _ | 1992-11 | 4630 | 40 | |
| WH | 109 | _ | 1993-10 | 4573 | 40 | |
| WH | 108 | _ | 1994-05 | 3573 | 860 | |
| WH | 108 | _ | 1994-09 | 4290 | 143 | |
| WH | 103 | _ | 1995-05 | 3927 | 476 | |
| WH | 102 | _ | 1995-09 | 4433 | damaged | |
| WH | 110 | _ | 1996-03 | 4425 | damaged | |
| WH | 109 | _ | 1996-12 | 4396 | 217 | |
| WH | 114 | _ | 1996-12 | 4396 | damaged | |
| WH | 103 | _ | 1997-05 | 4242 | 161 | |
| WH | 107 | _ | 1999-11 | Jt.#107 | damaged | |
| WH | 114 | _ | 2000-07 | 3655 | 740 | |
| WH | 103 | _ | 2000-09 | 3481 | damaged | |
| WH | 113 | _ | 2000-11 | Last Jt. | damaged | |
| WH | 113 | _ | 2002-07 | | 367 | |
| WH | 110 | _ | 2003-05 | | damaged | |
| WH | 103 | _ | 2003-11 | 3896 | 470 | |
| WH | 110 | _ | 2004-04 | | 207 | |
| WH | 103 | _ | 2004-09 | | 422 | |
| WH | 102 | _ | 2005-05 | 4233 | damaged | |
| WH | 108 | _ | 2005-05 | | 896 | |
| WH | 111 | _ | 2005-11 | 4200 | damaged | |
| WH | 103 | _ | 2006-09 | 3327 | 1000? | |
| WH | 103 | _ | 2008-01 | 3170 | 1158 | |
| WH | 117 | B | 2010-02 | | | |
| WH | 7 | A | 2012-10 | | | |
| WH | 117 | B | 2012-12 | | | |
| WH | 117 | B | 2013-09 | | | |
| WH | 115 | _ | 2015-02 | | | |
| WH | 117 | B | 2015-02 | | | |
| WH | 109 | _ | 2017-10 | | | Below OBI |
| WH | 110 | _ | 2018-02 | | | |

# B String Break Pressure Signals

This appendix provides examples of string breaks, string damage, a string cut, and one case where the OBI is moved beyond the end of tubing, resulting in something that looks like a salt fall, but is not. This is not a comprehensive library of all the most recent salt falls, nor of all the most recent string breaks. It is intended to be representative of the different sites, with the majority coming from Bryan Mound, as would be expected. When possible, a zoomed view of the impact/cut is provided; zoomed graphs will still have a legend entry for pressure signals that are no longer visible.

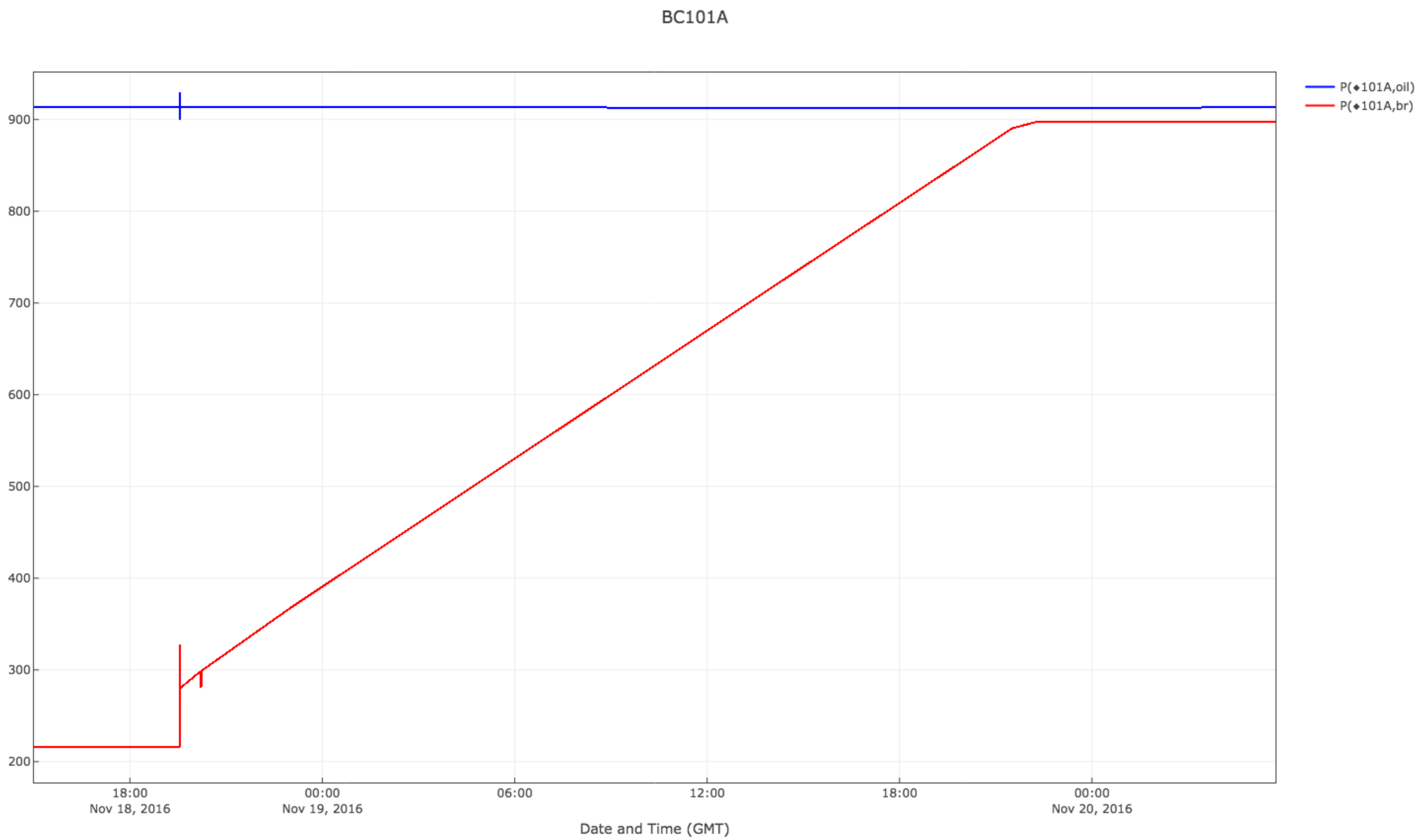



**Figure B.1.** BC-101 November 2016 string break.

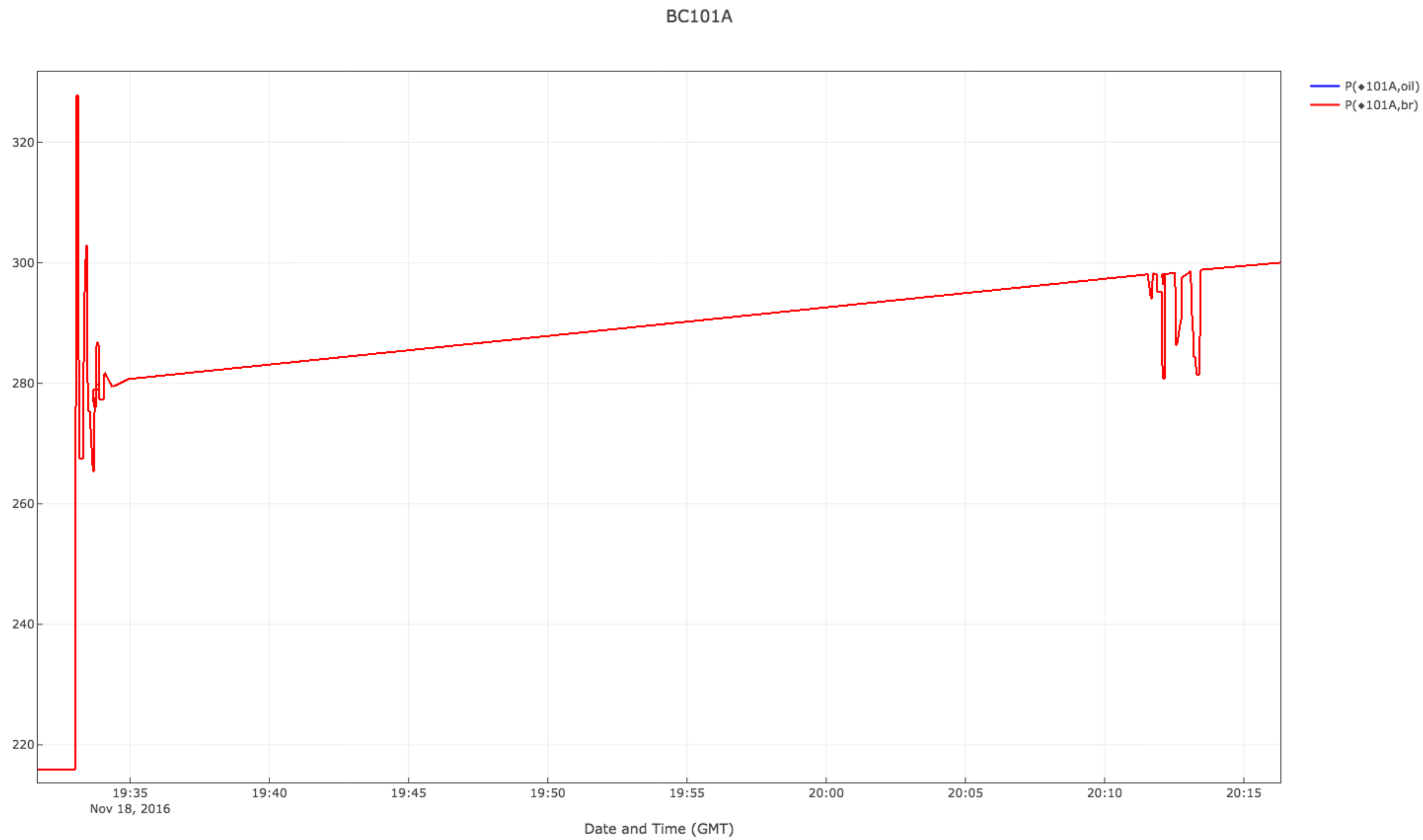



**Figure B.2.** BC-101 November 2016 salt impact with string.

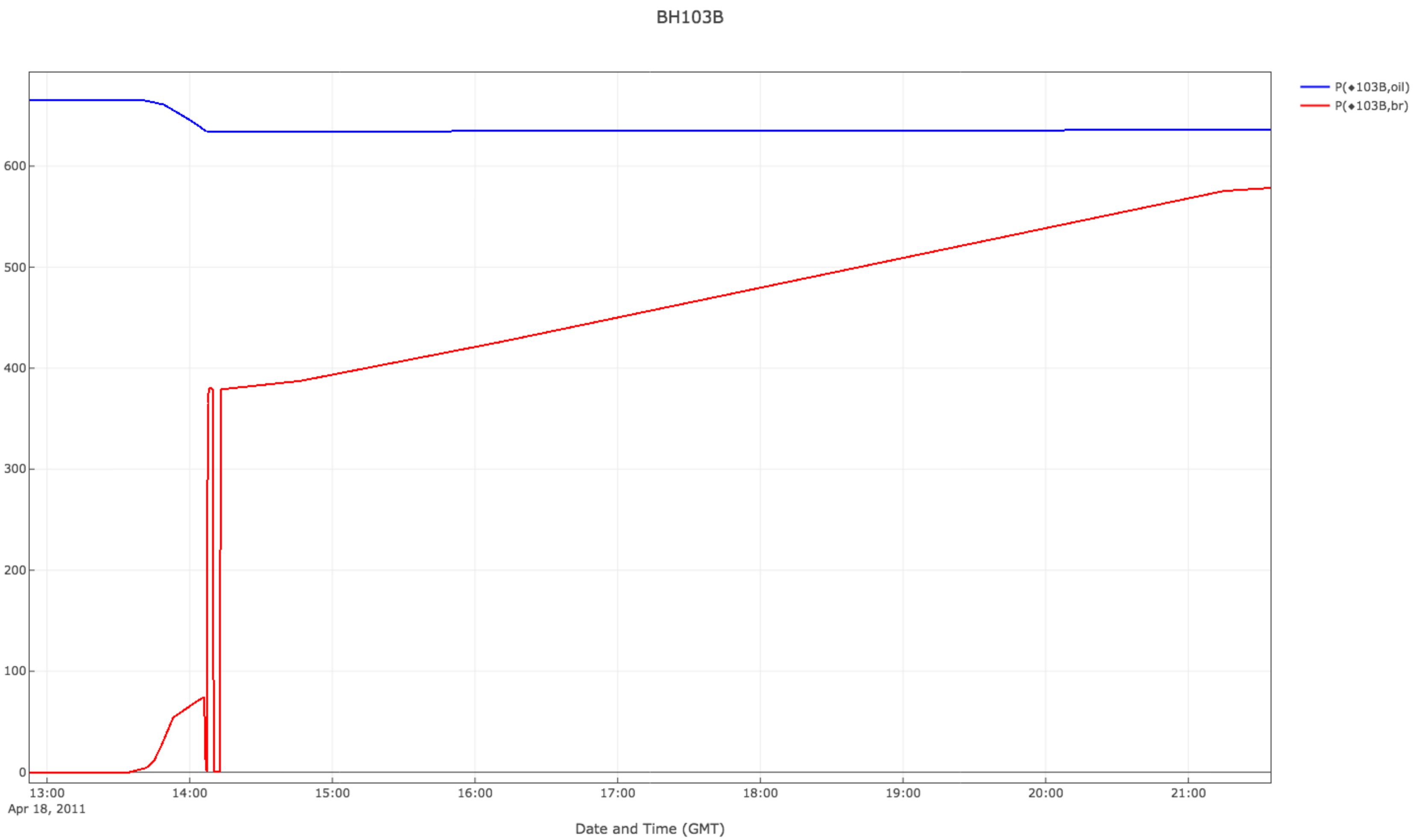



**Figure B.3.** BH-103 April 2011 OBI moved below EOT.

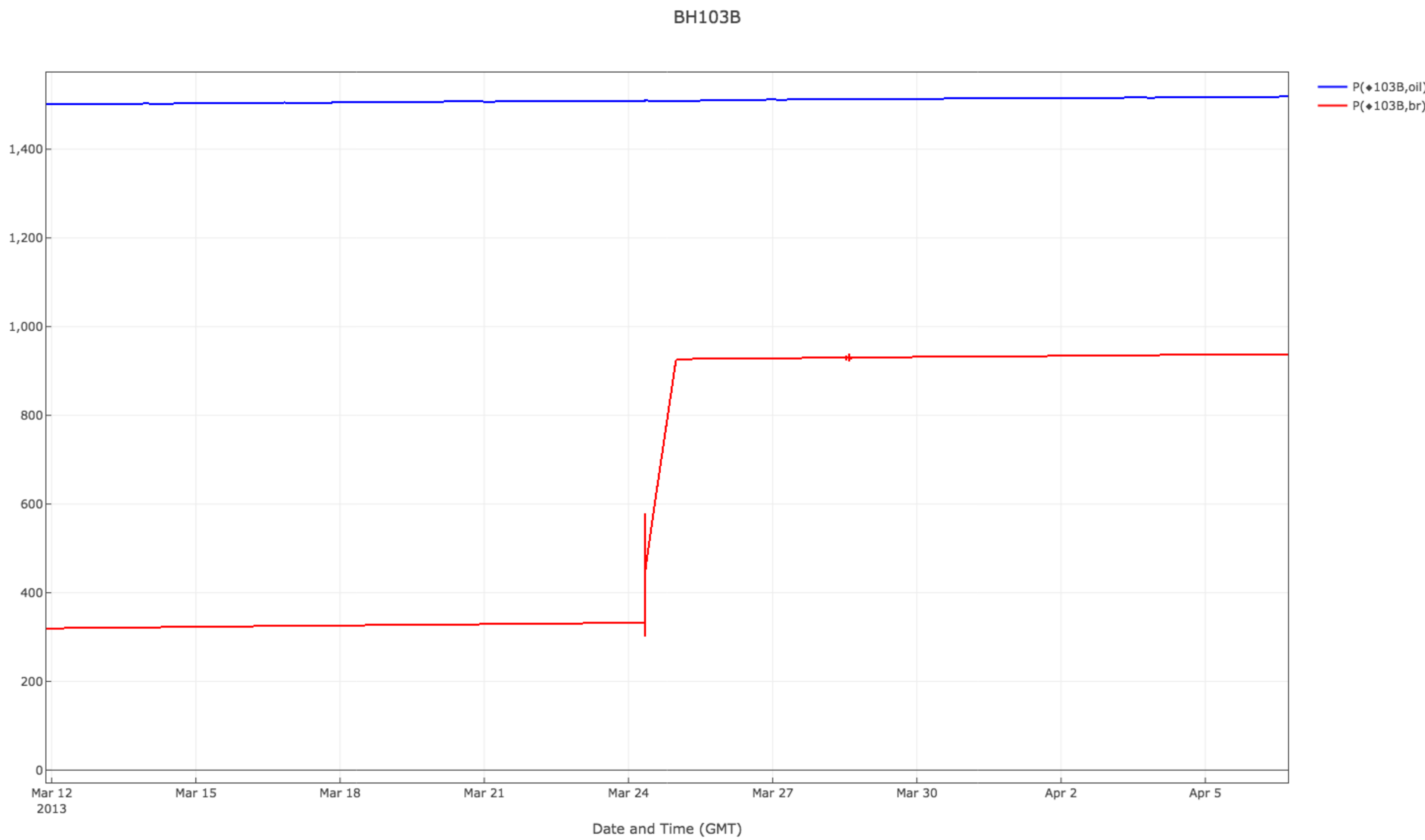



**Figure B.4.** BH-103 March 2013 string break.

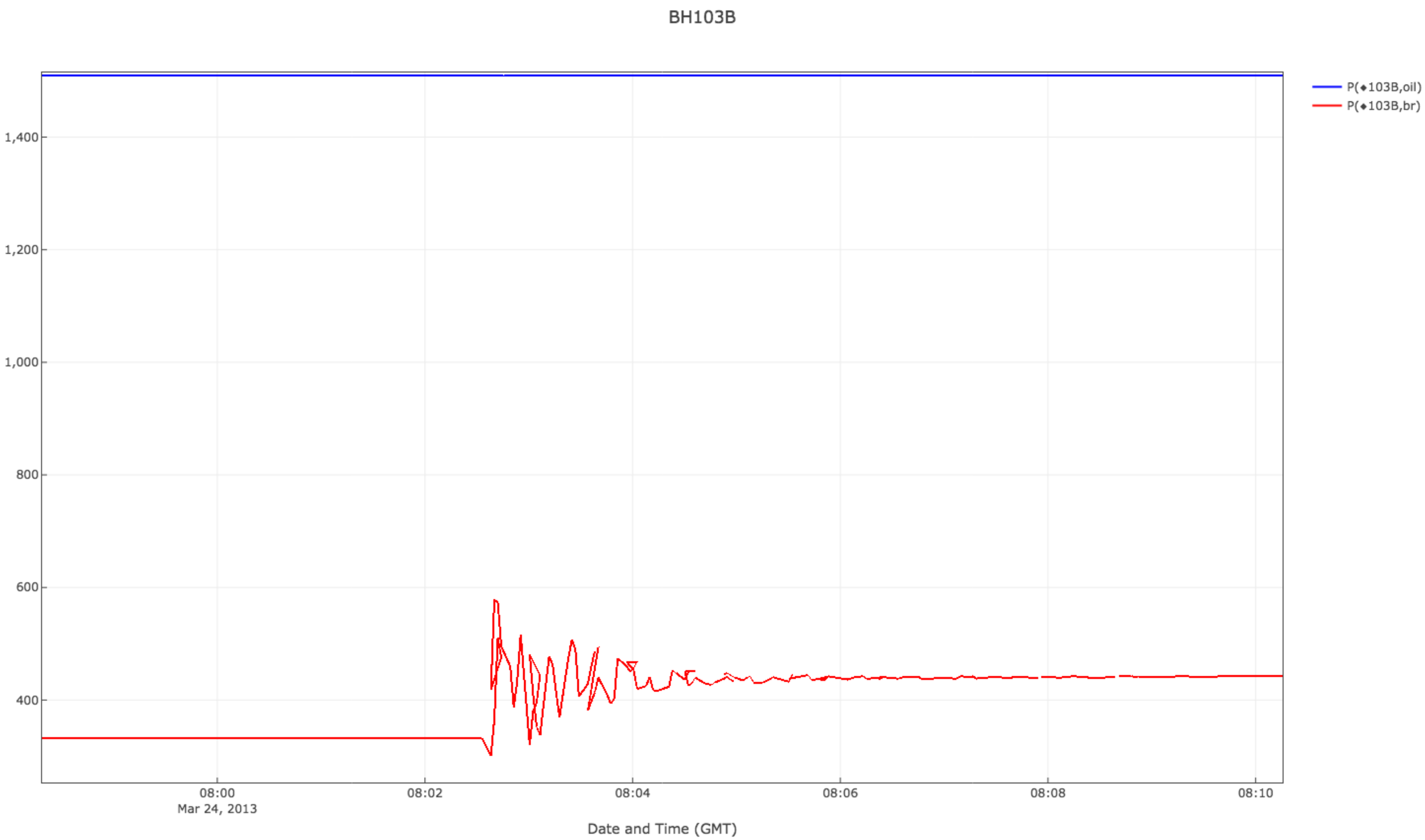



**Figure B.5.** BH-103 March 2013 salt impact with string.

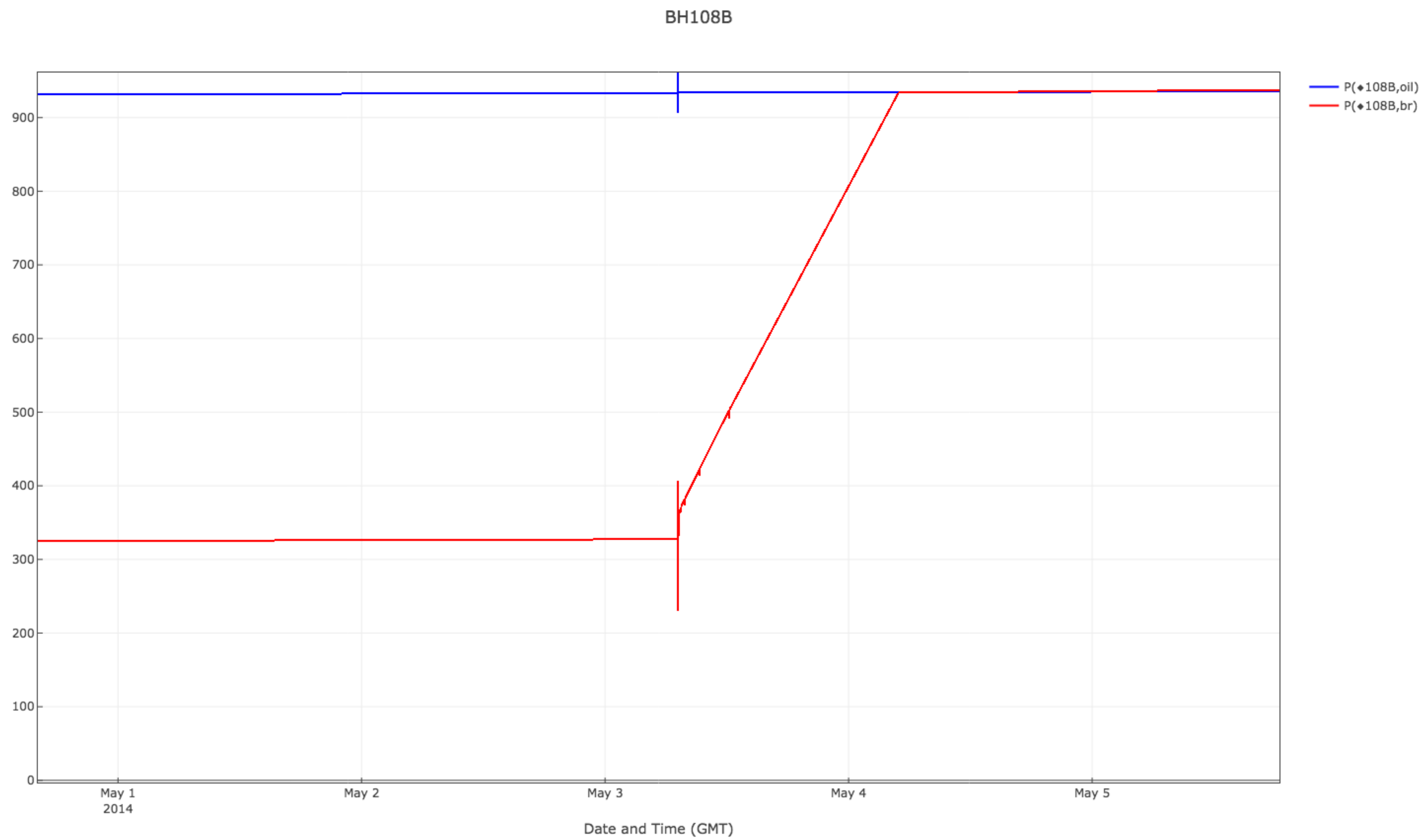



**Figure B.6.** BH-108 May 2014 string break.

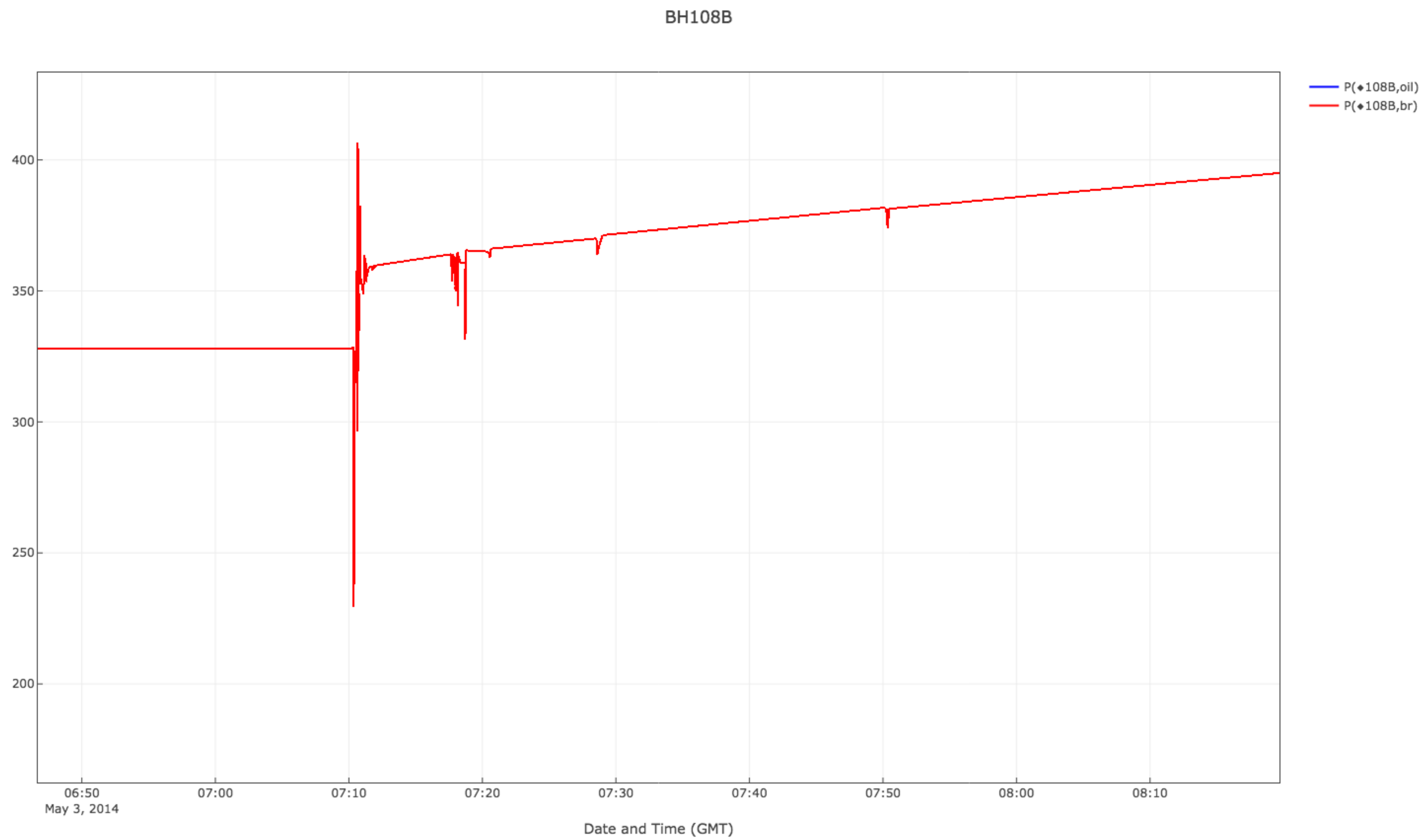



**Figure B.7.** BH-108 May 2014 salt impact with string.

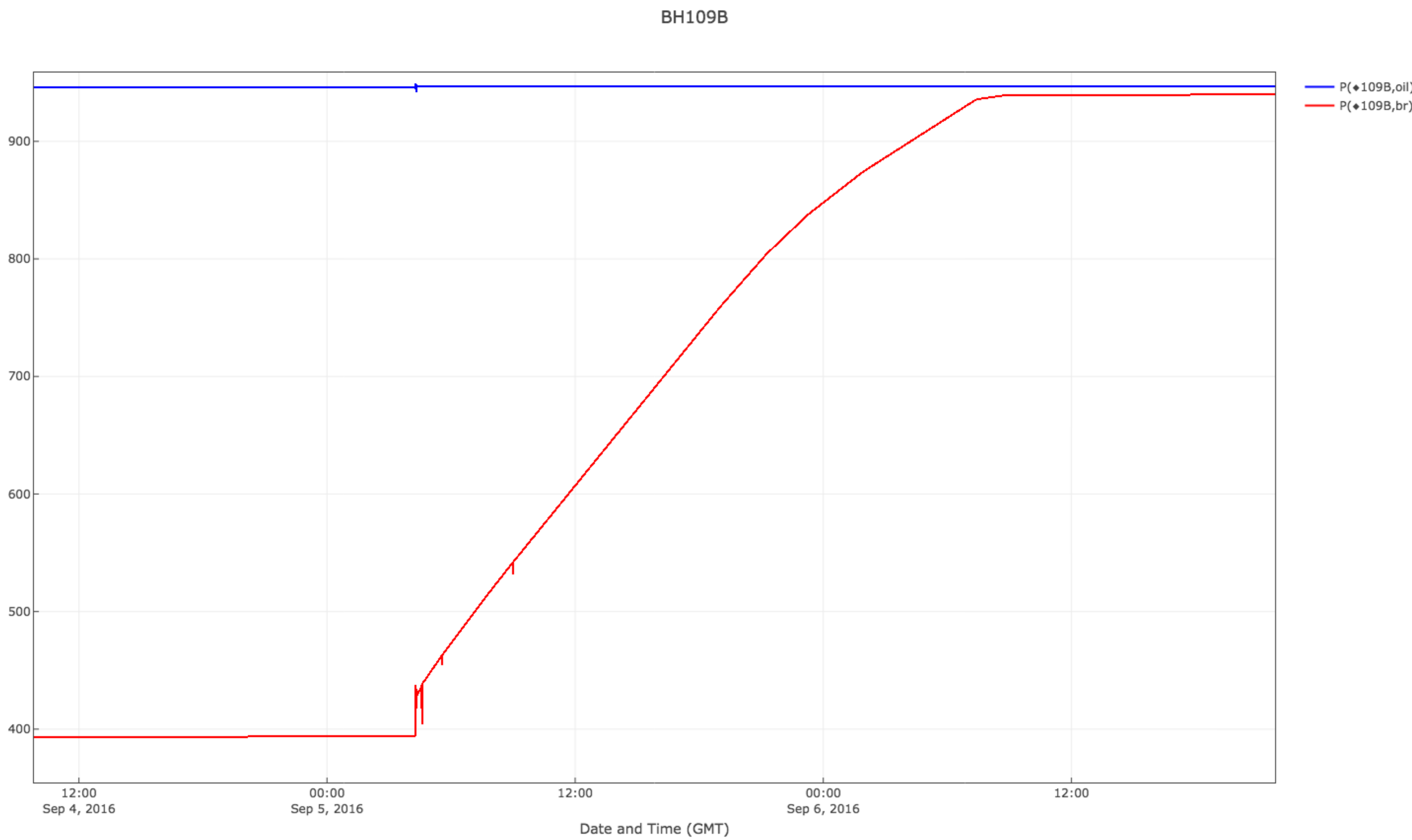



**Figure B.8.** BH-109 September 2016 string break.

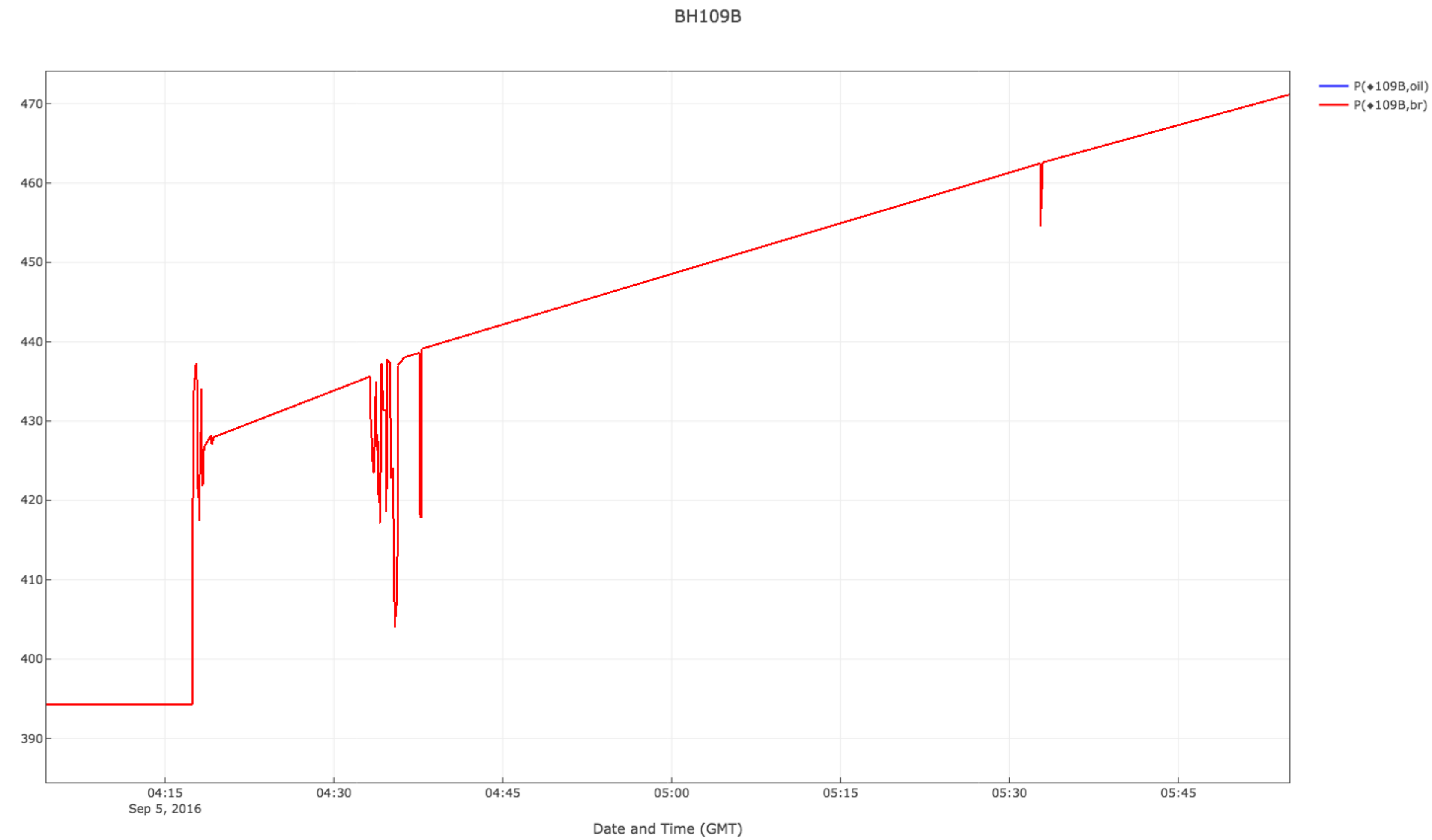



**Figure B.9.** BH-109 September 2016 salt impact with string.

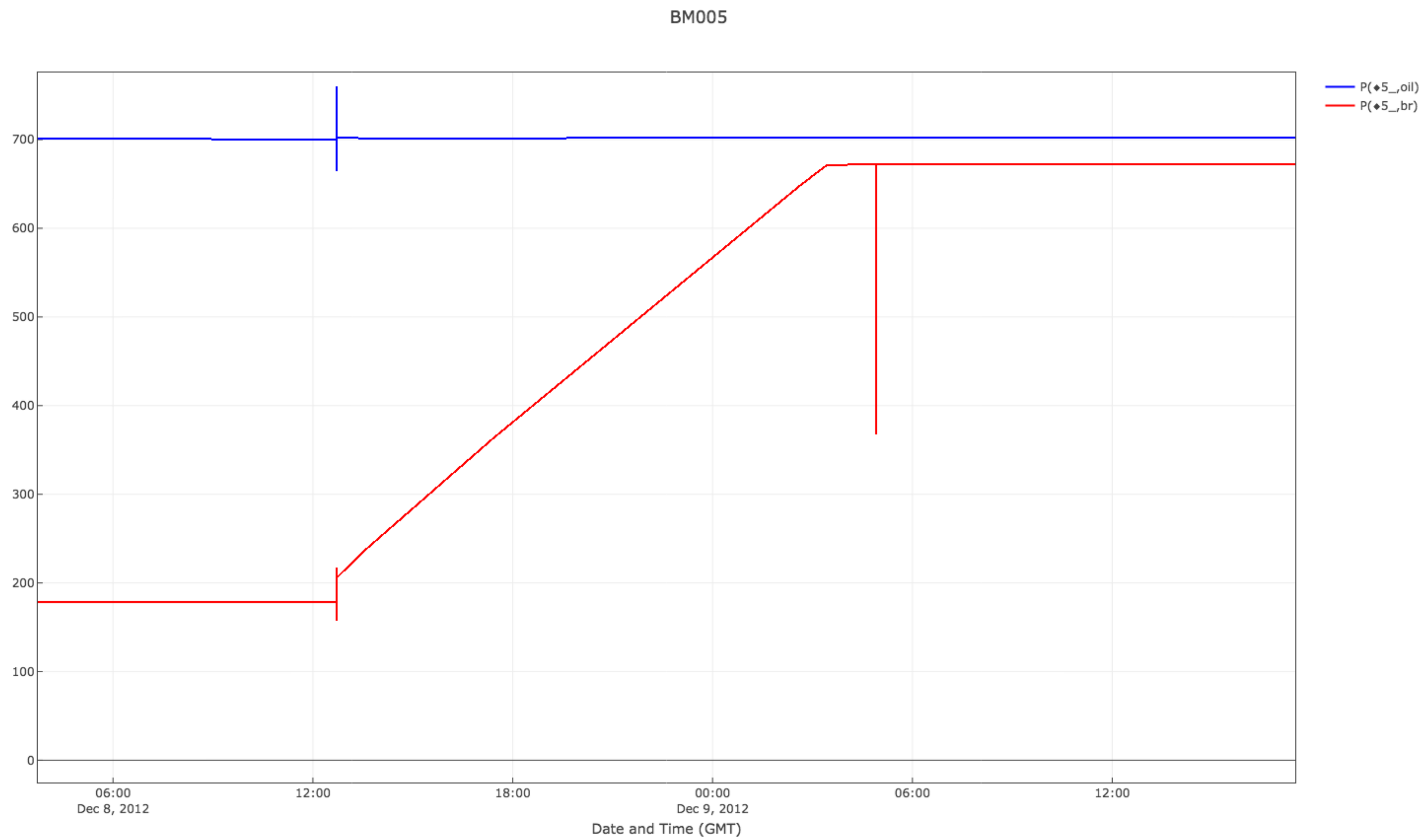



**Figure B.10.** BM-5 December 2012 string break.


**Figure B.11.** BM-5 December 2012 salt impact with string.

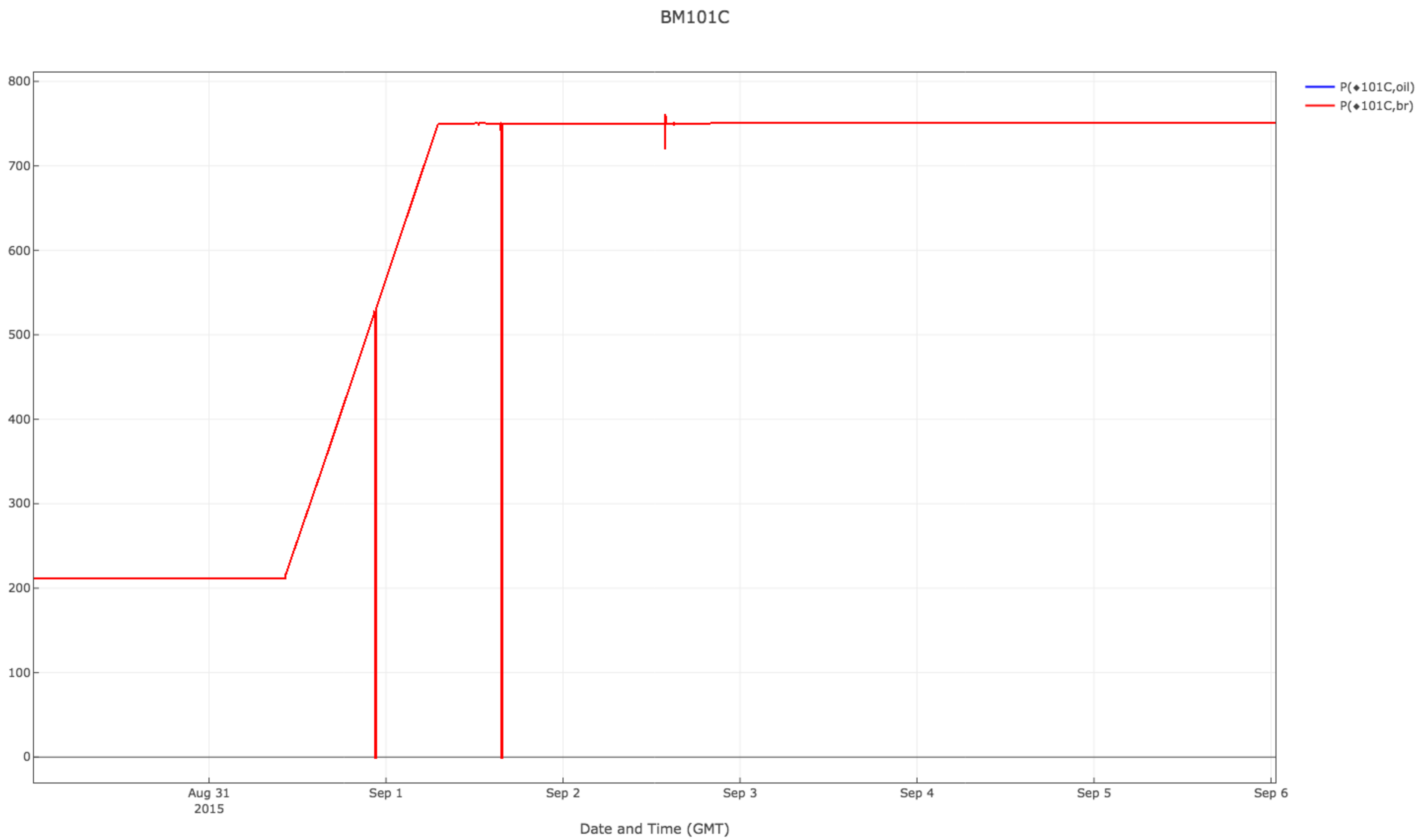



**Figure B.12.** BM-101 August 2015 string break.

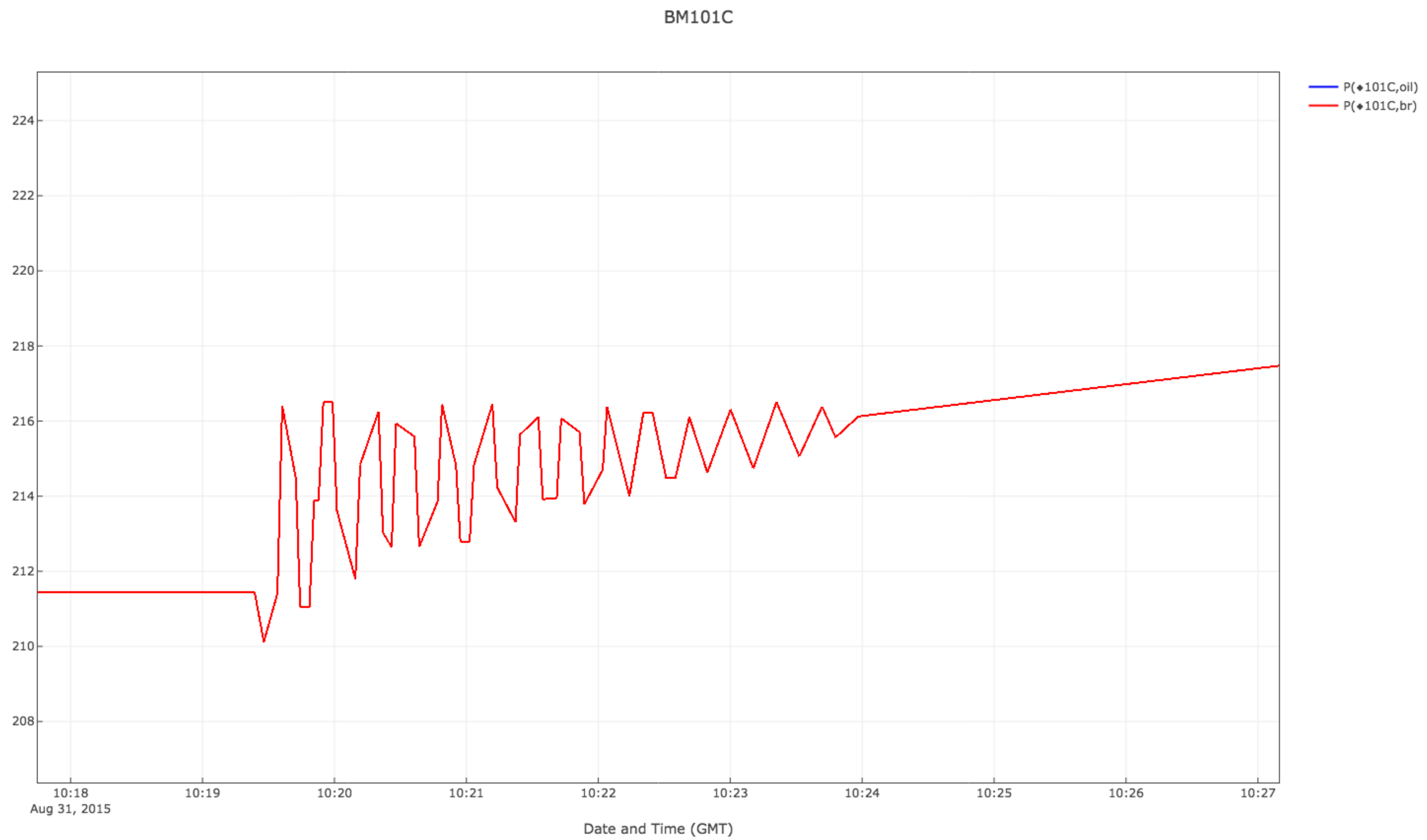



**Figure B.13.** BM-101 August 2015 salt impact with string.

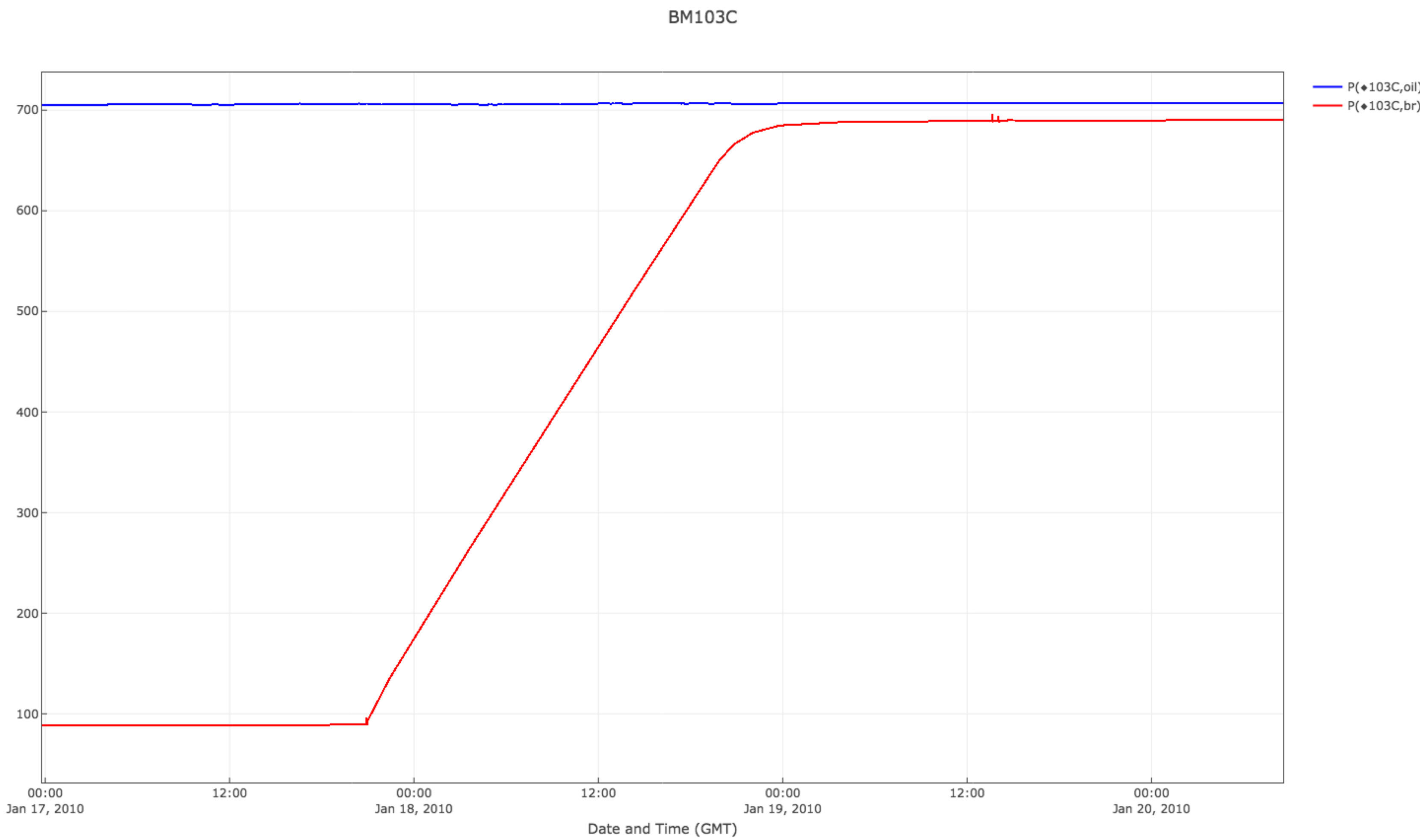



**Figure B.14.** BM-103 January 2010 string break.

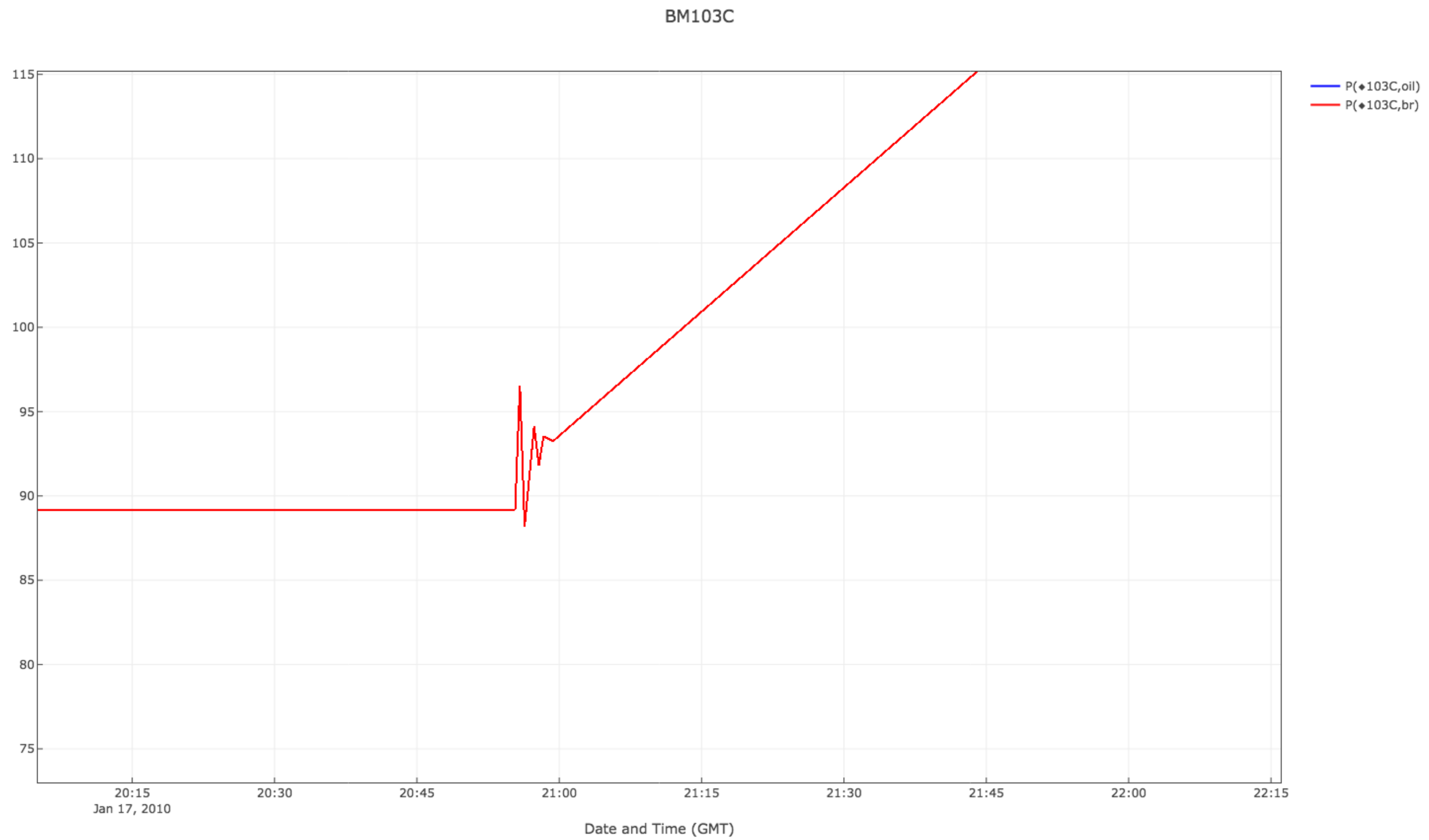



**Figure B.15.** BM-103 January 2010 salt impact with string.

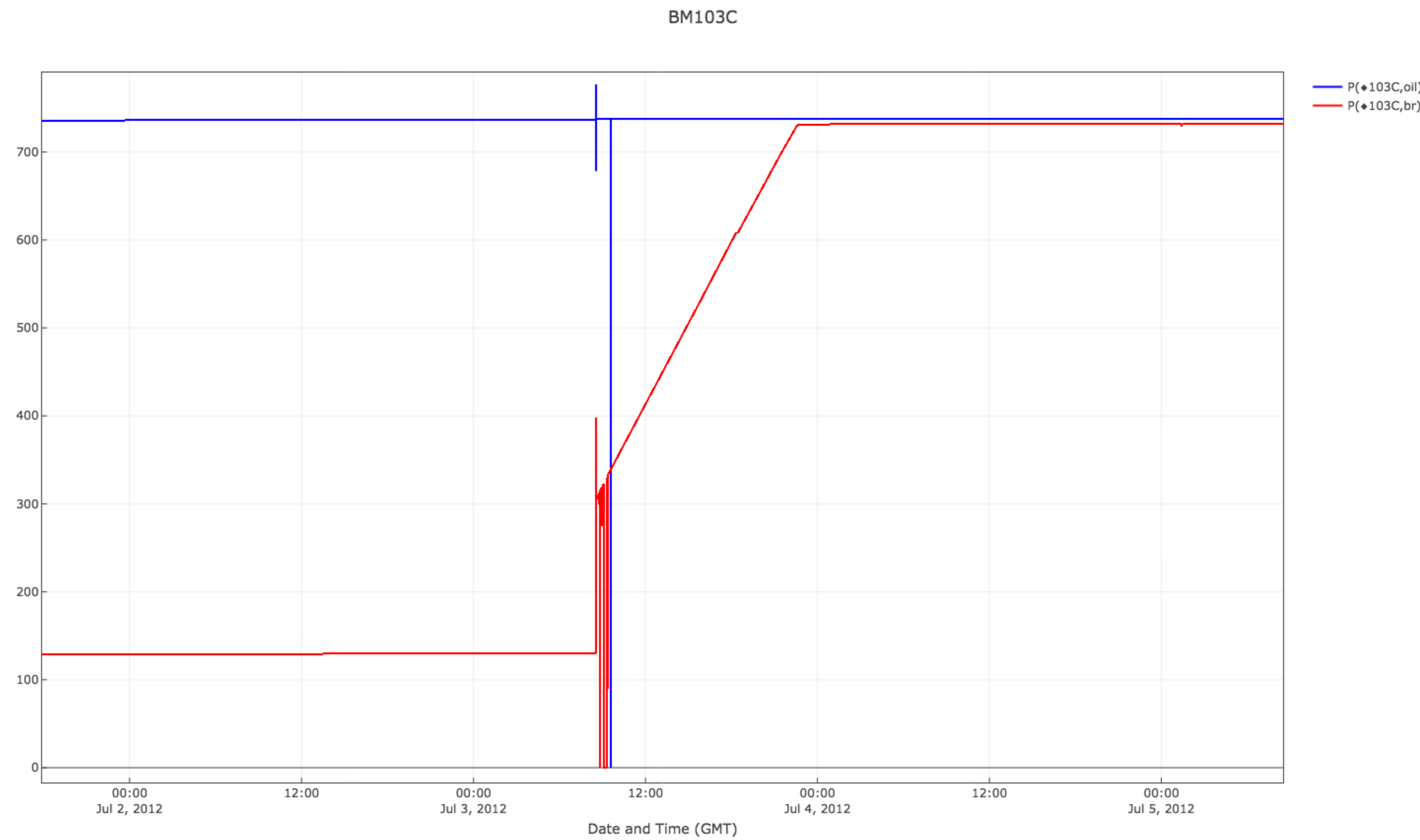



**Figure B.16.** BM-103 July 2012 string break.

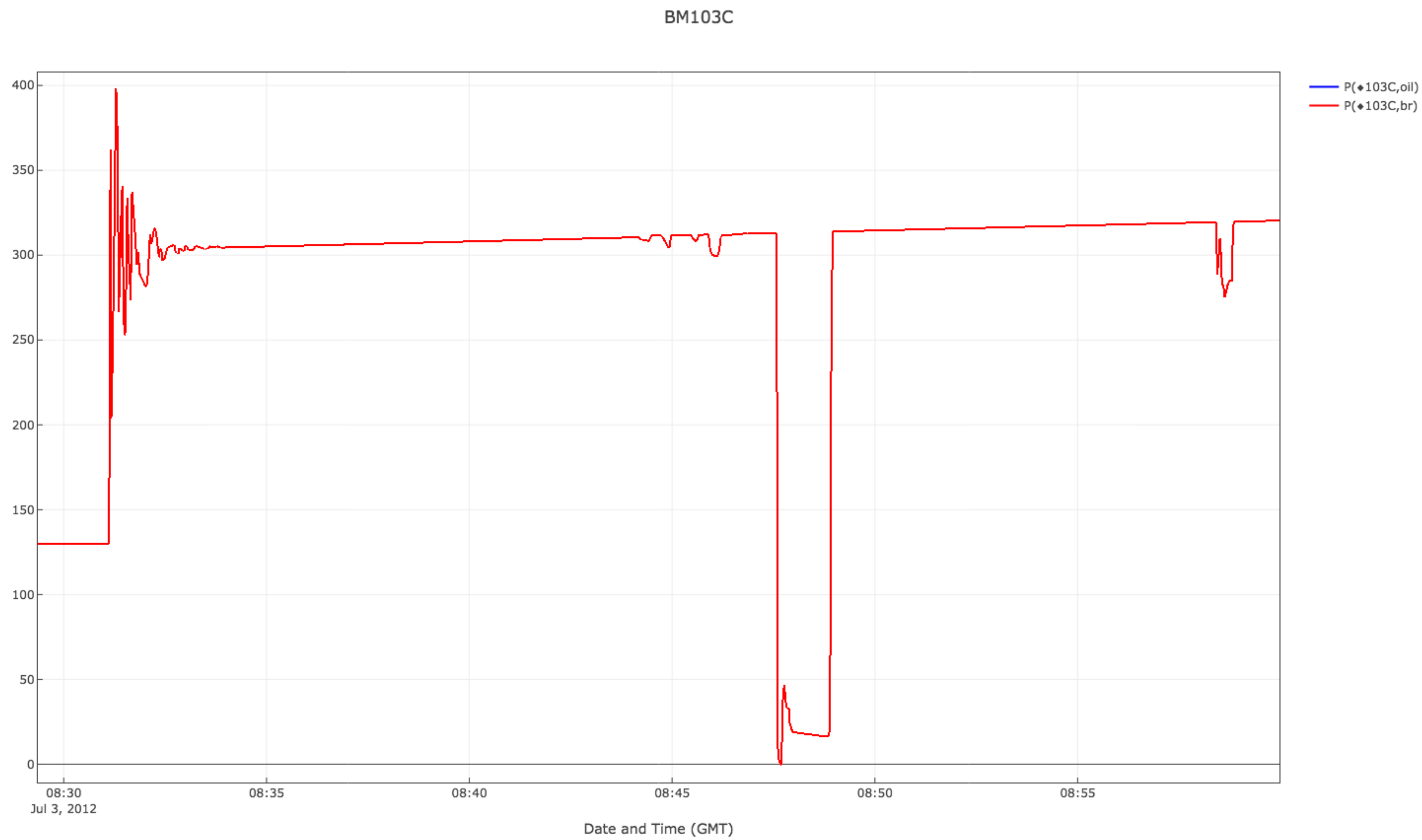



**Figure B.17.** BM-103 July 2012 salt impact with string.

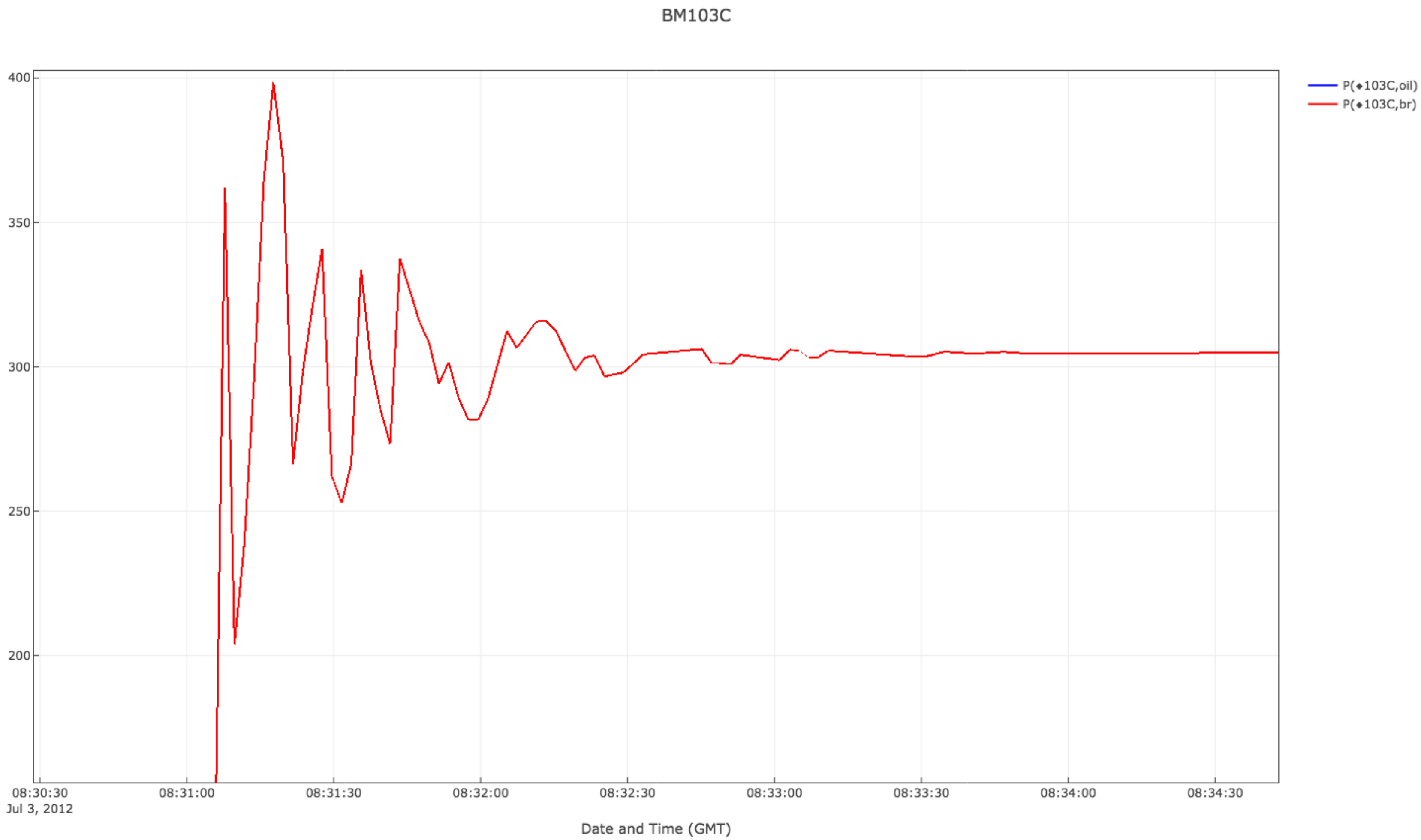



**Figure B.18.** BM-103 July 2012 salt impact with string – additional zoom.

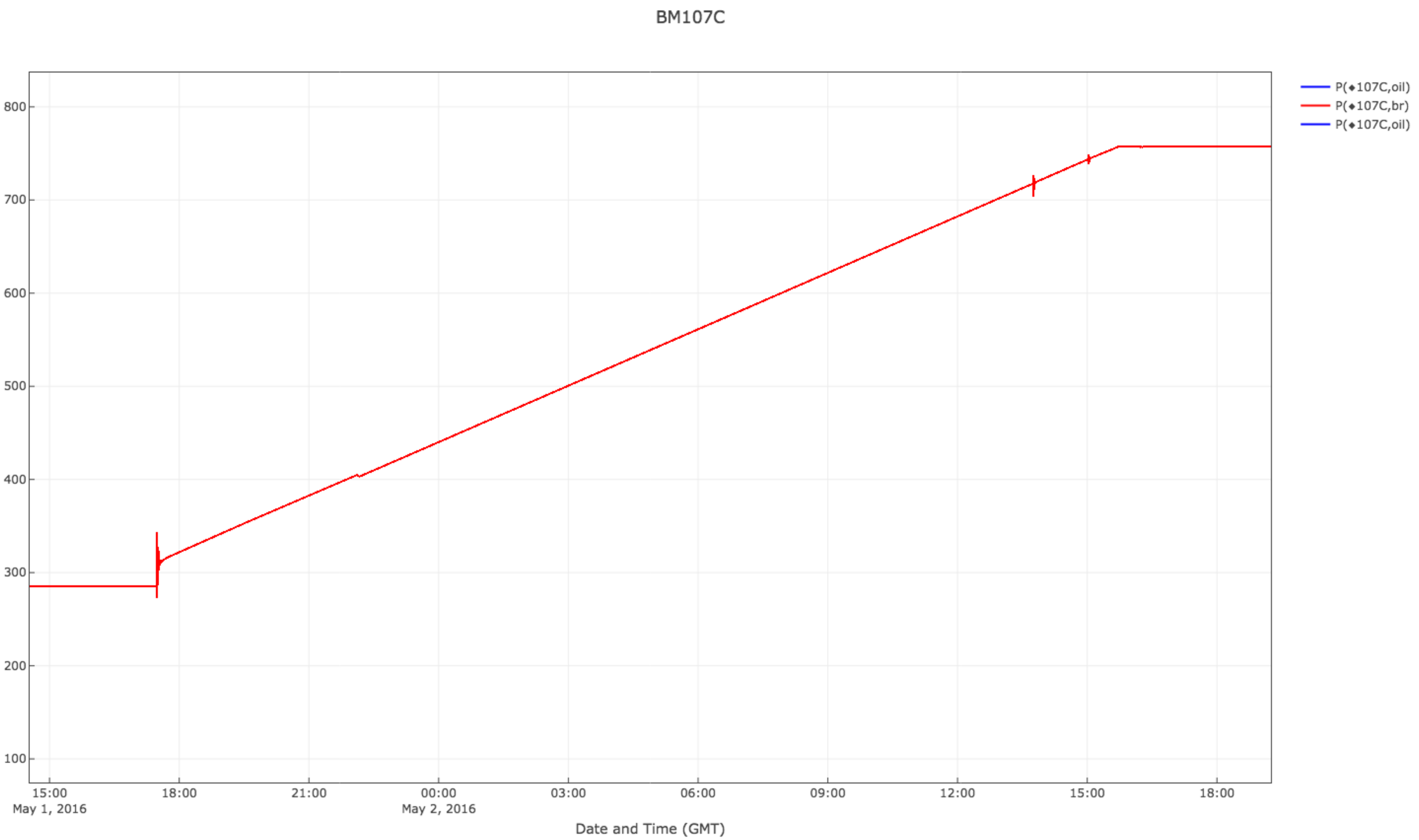



**Figure B.19.** BM-107 May 2016 string break.

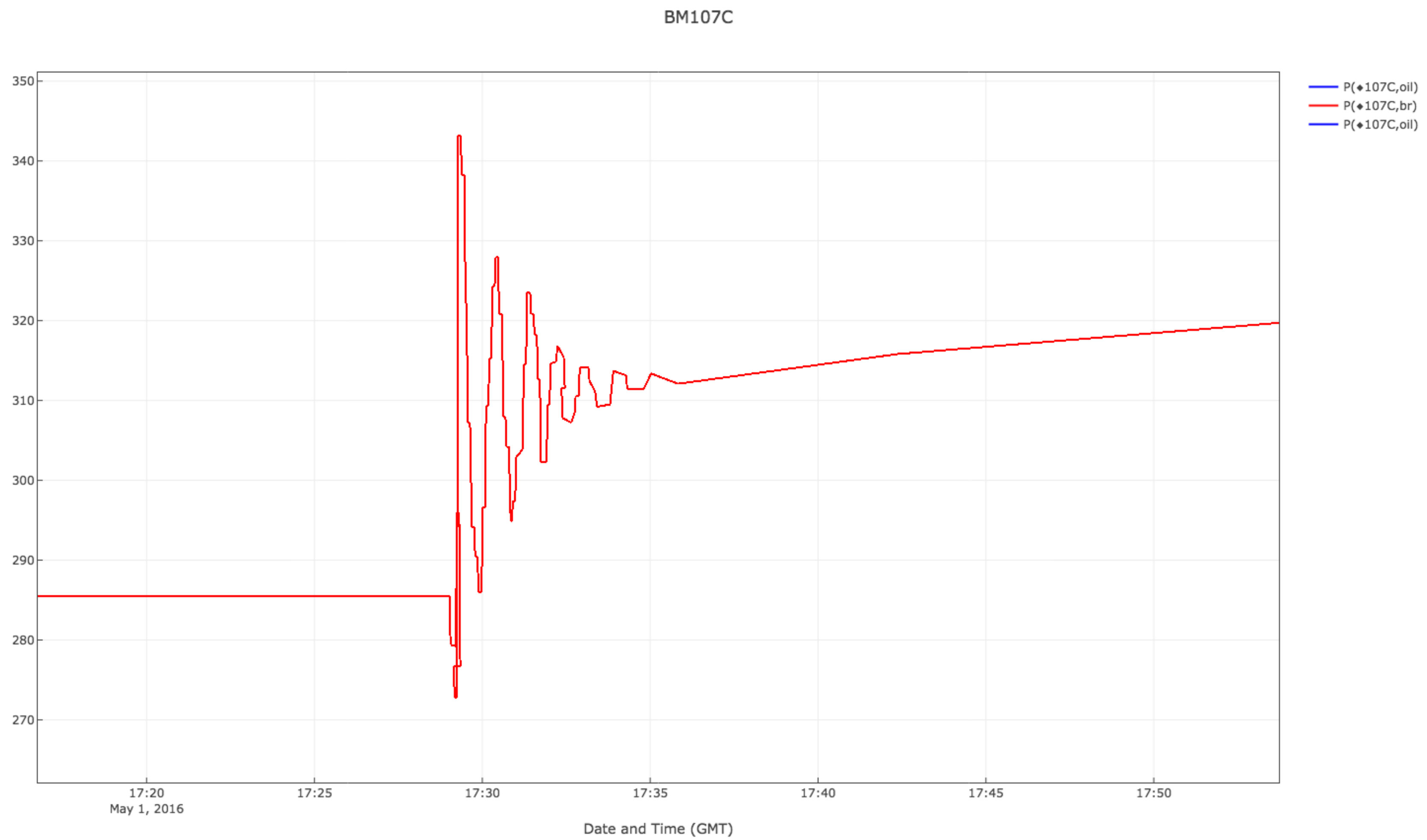



**Figure B.20.** BM-107 May 2016 salt impact with string.

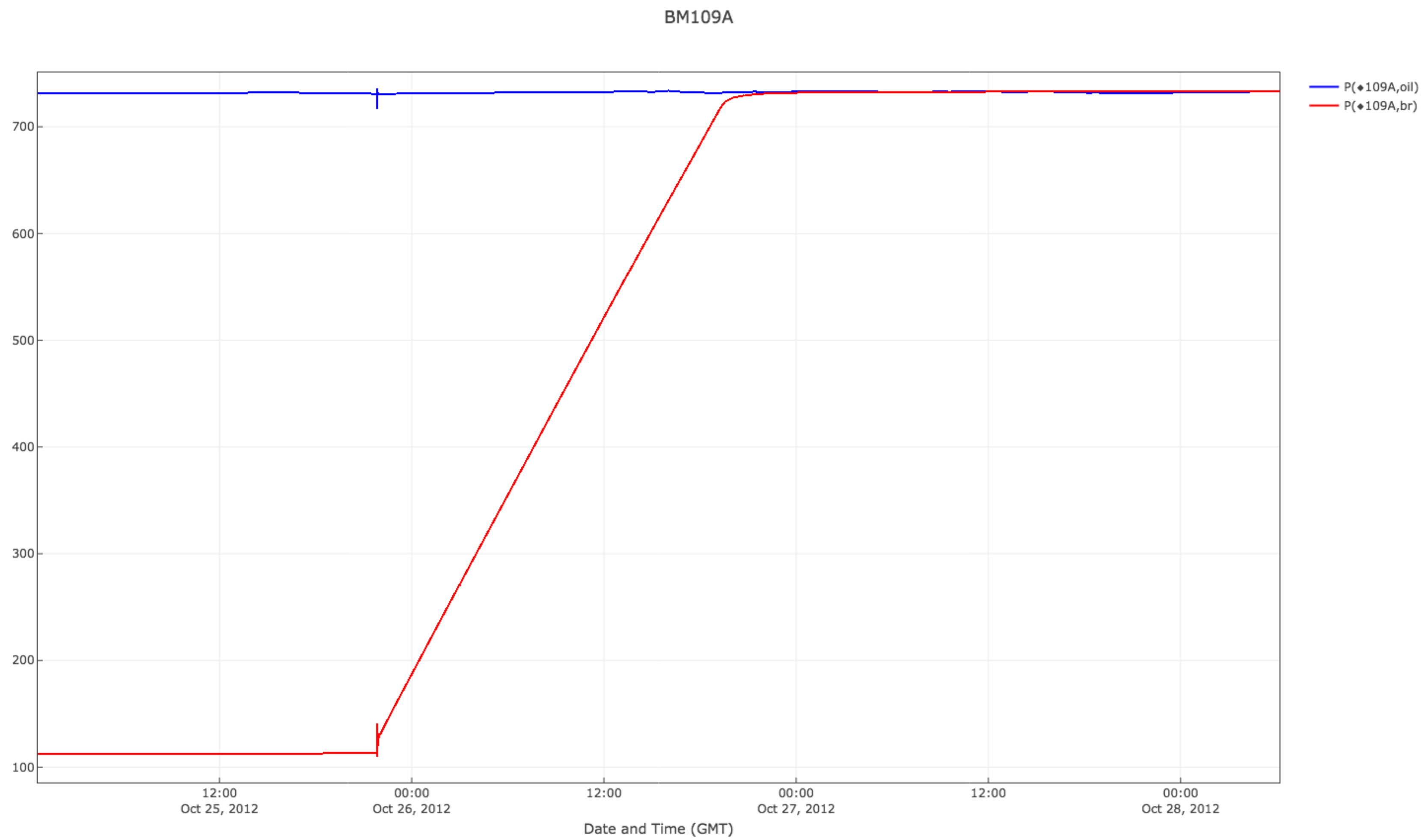



**Figure B.21.** BM-109 October 2012 string break.

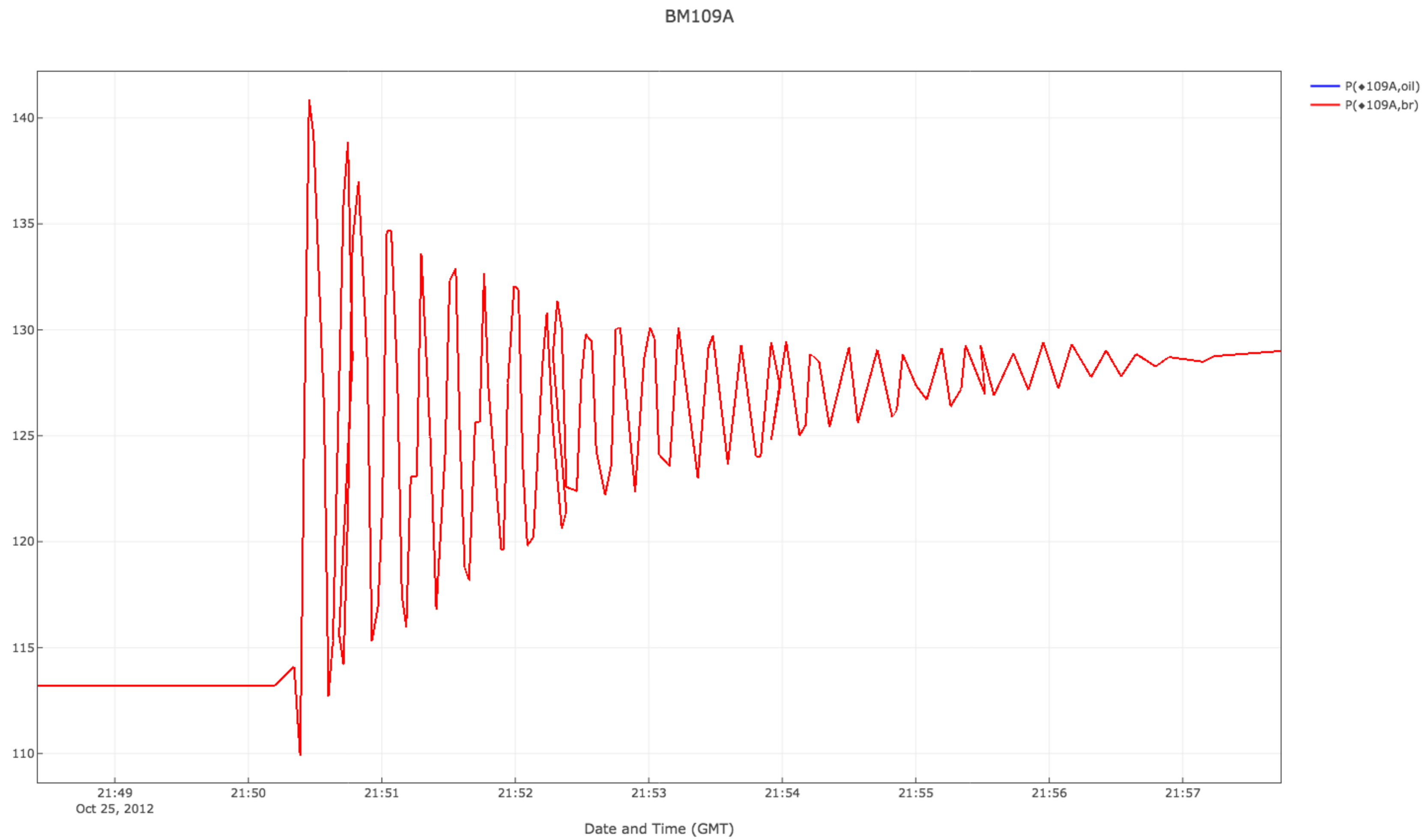



**Figure B.22.** BM-109 October 2012 salt impact with string.

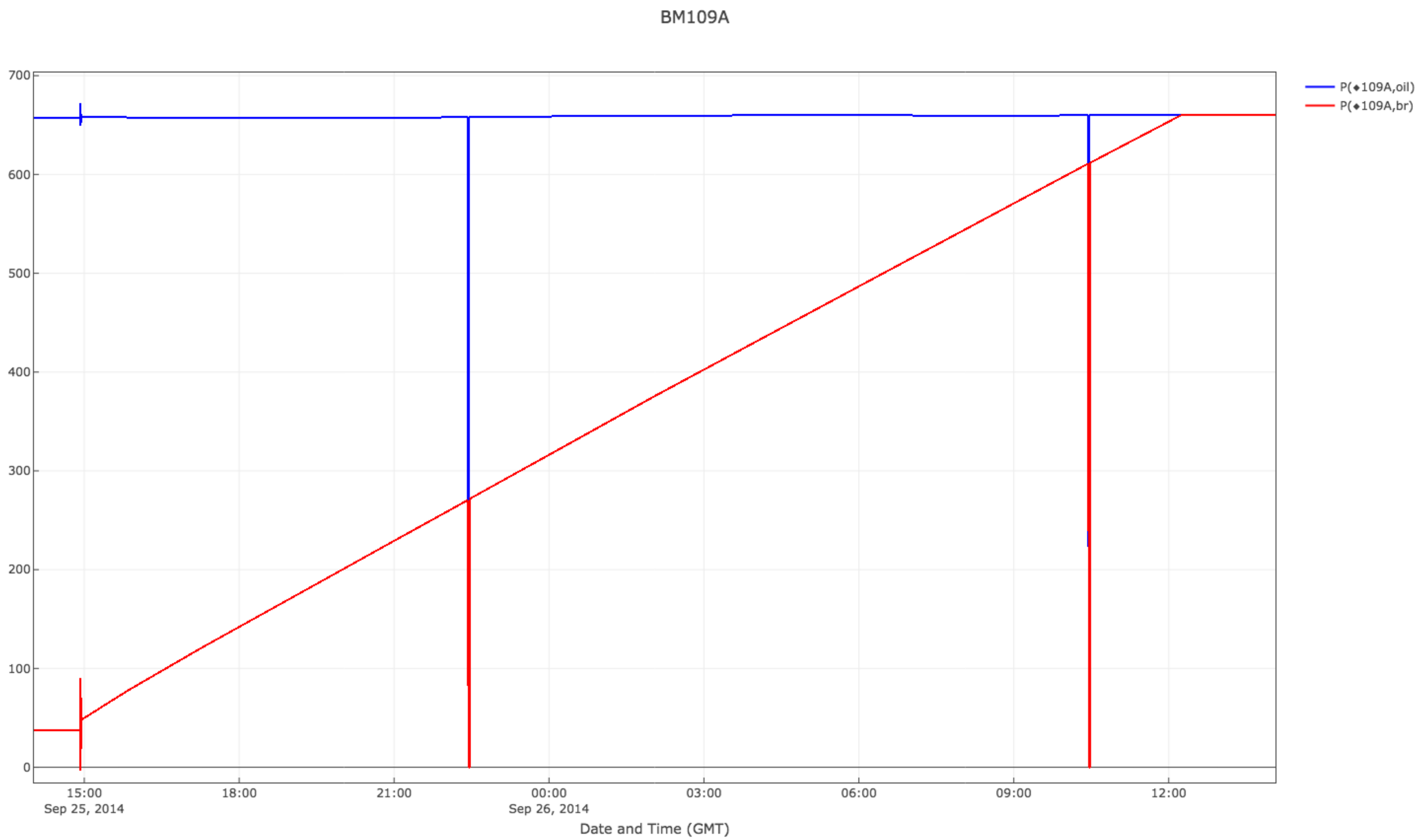



**Figure B.23.** BM-109 September 2014 string break.

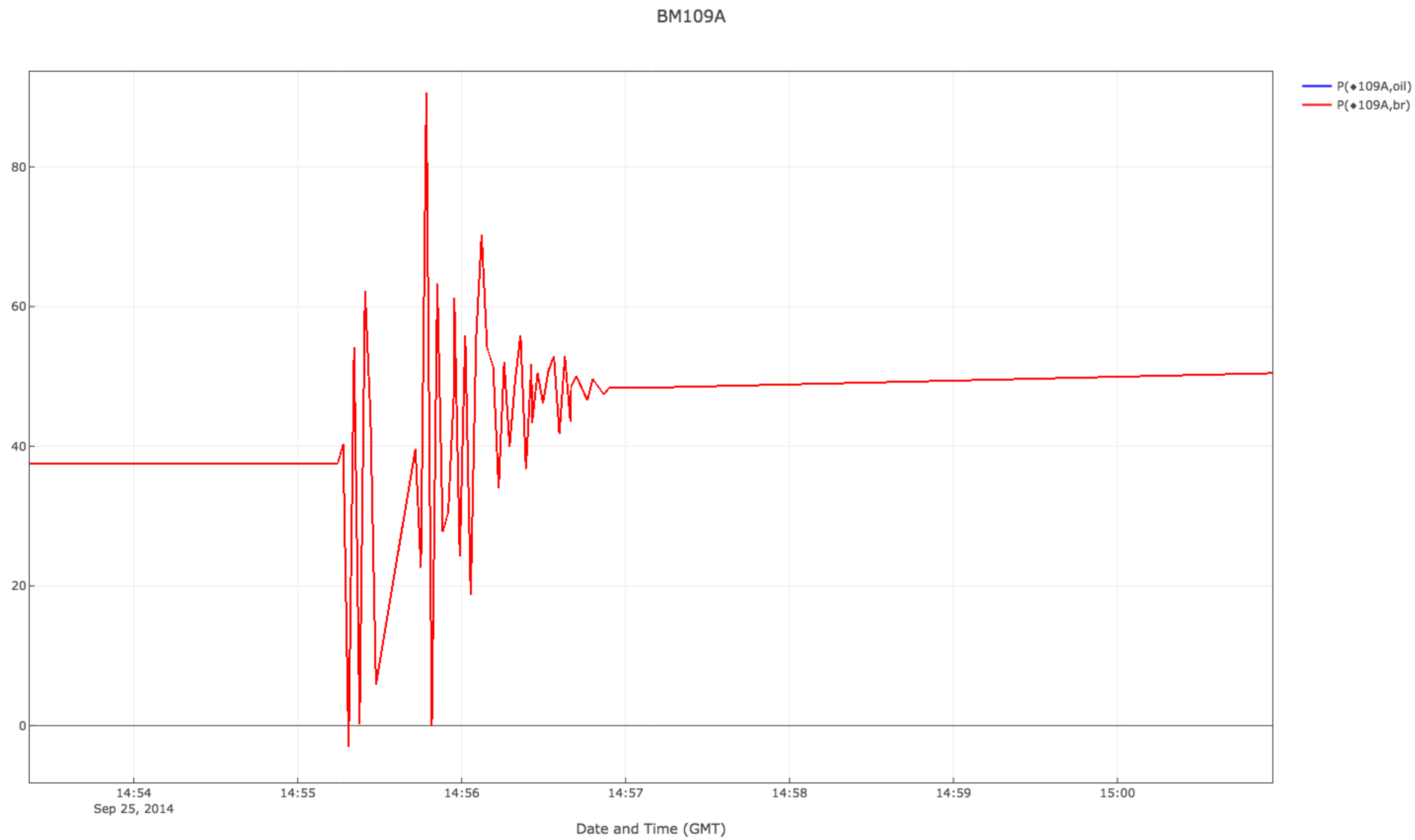



**Figure B.24.** BM-109 September 2014 salt impact with string.

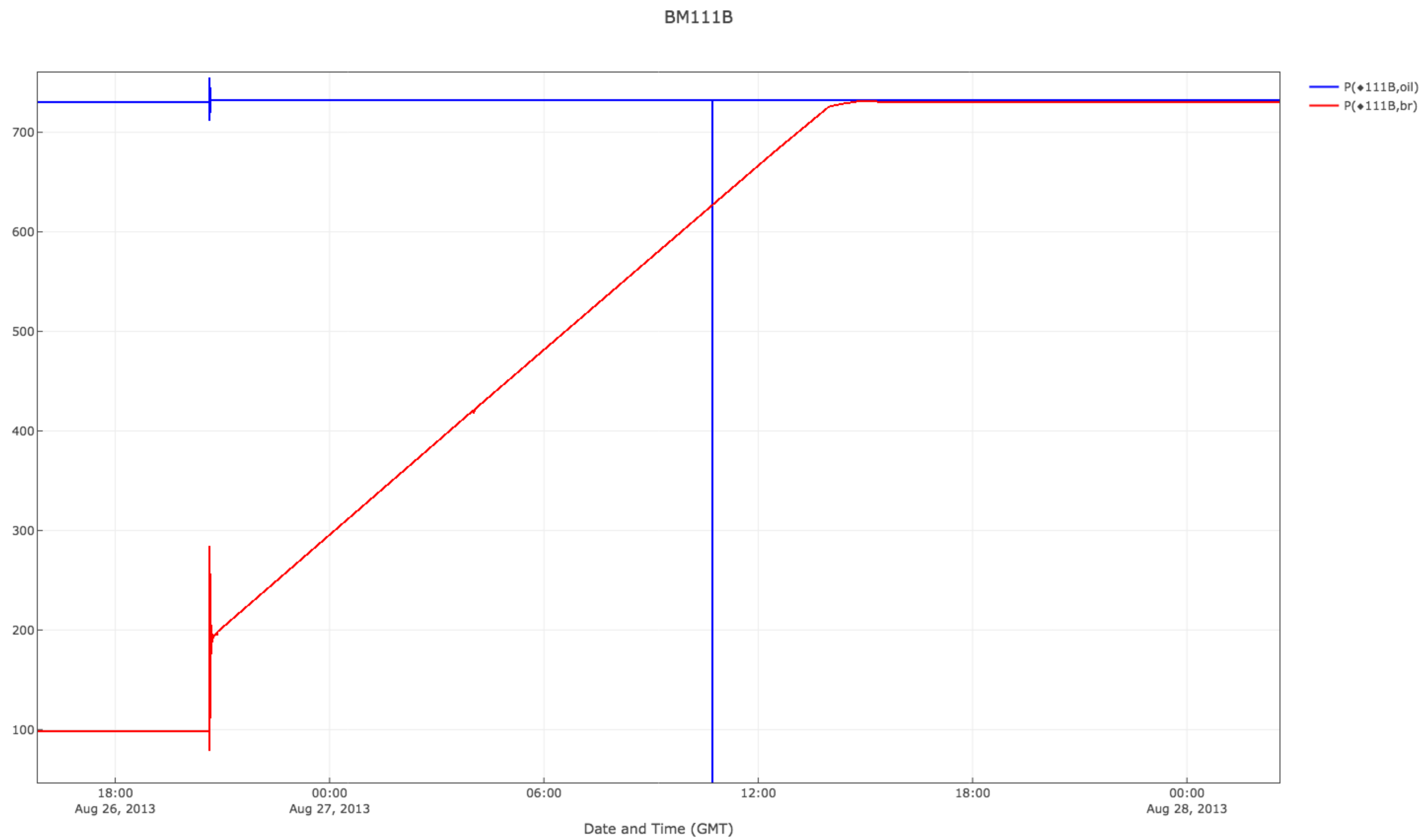



**Figure B.25.** BM-111 August 2013 string break.

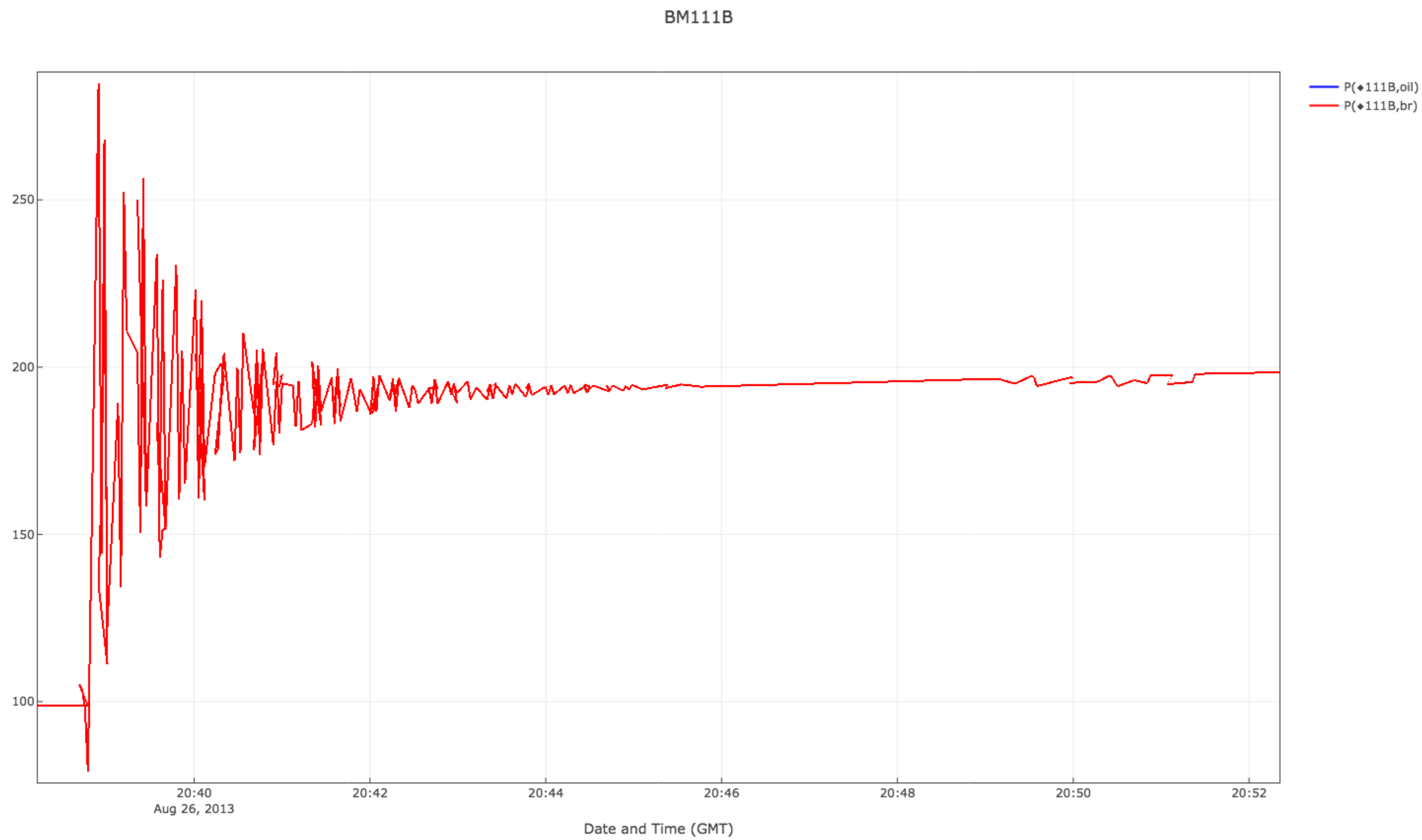



**Figure B.26.** BM-111 August 2013 salt impact with string.

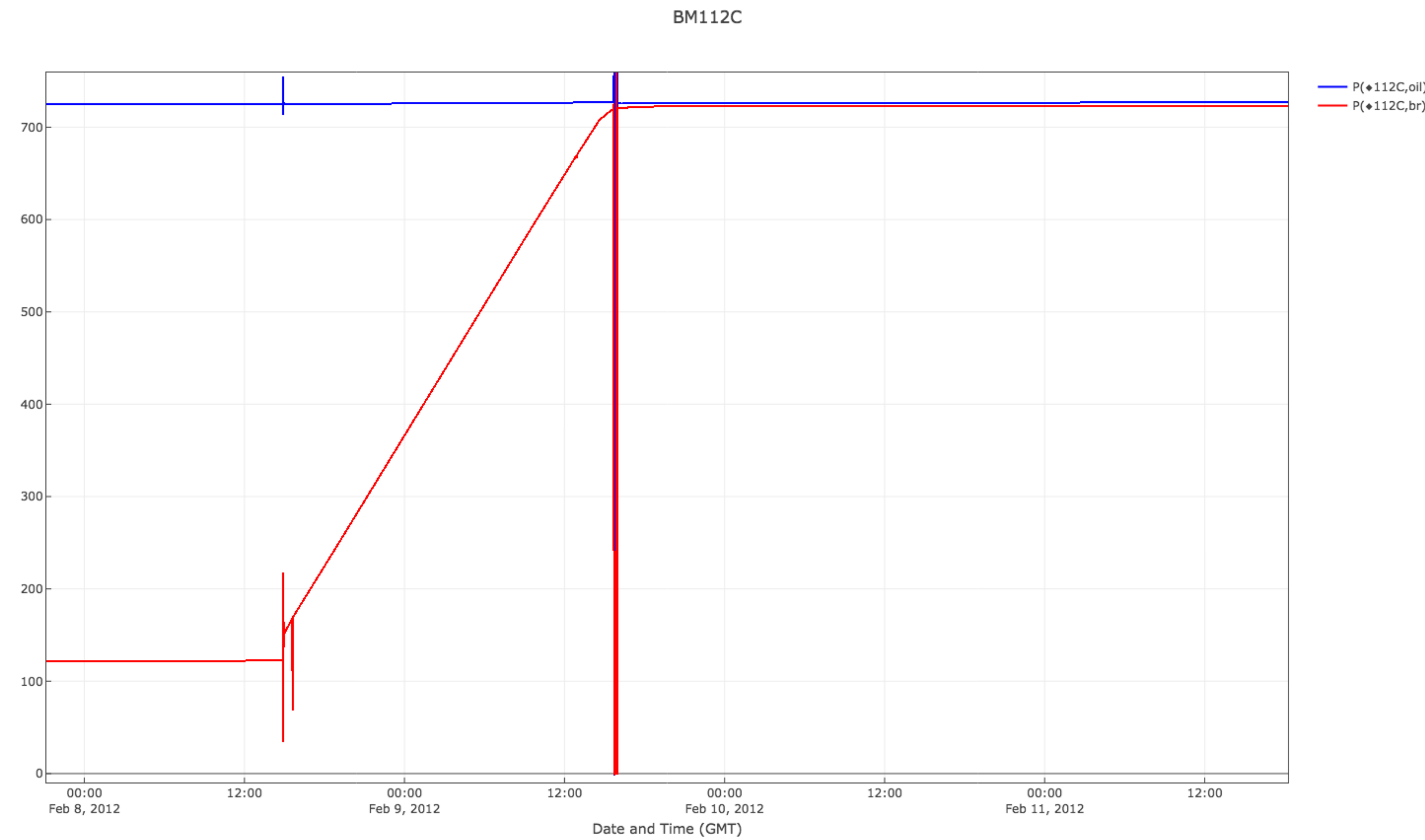



**Figure B.27.** BM-112 February 2012 string break.

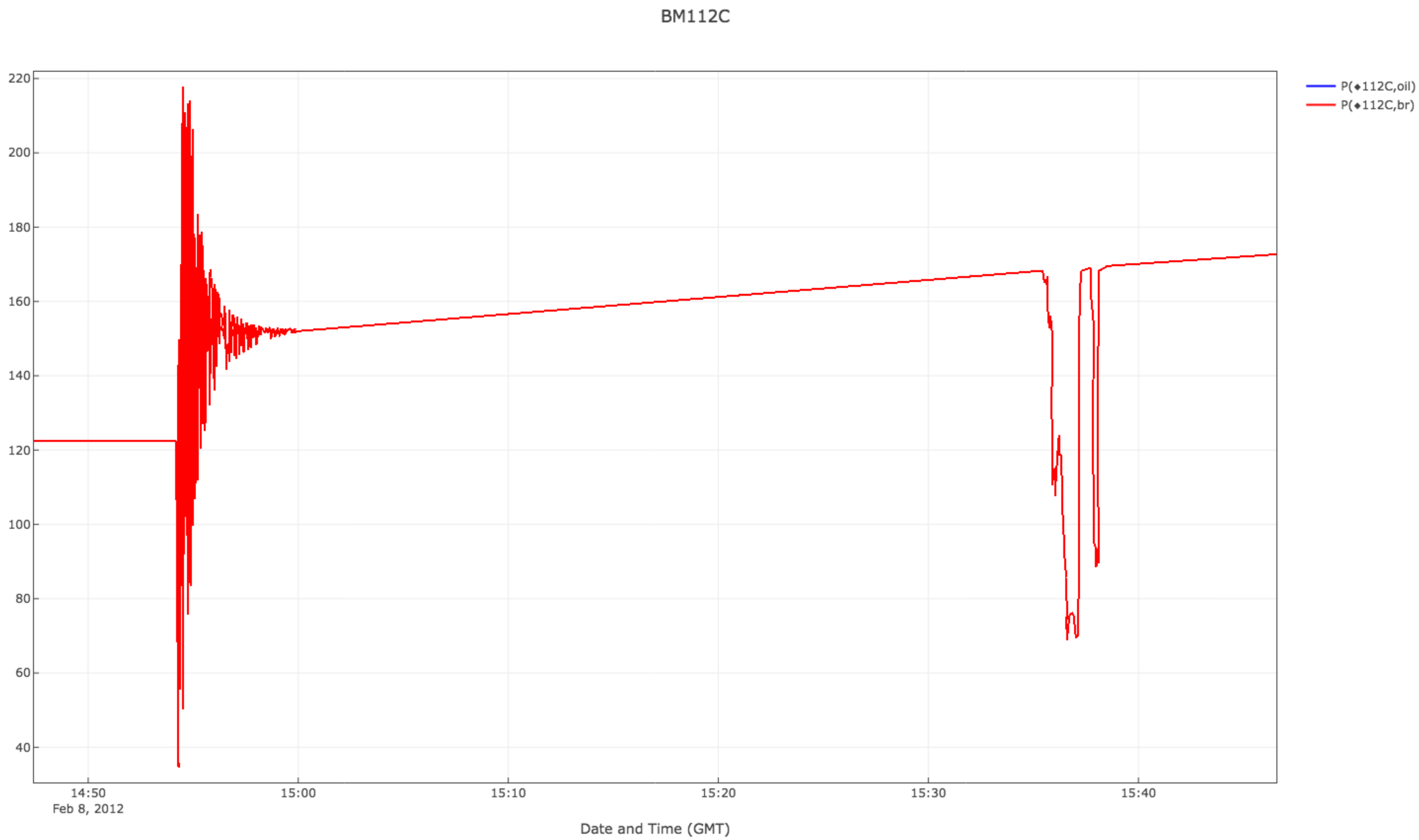



**Figure B.28.** BM-112 February 2012 salt impact with string.

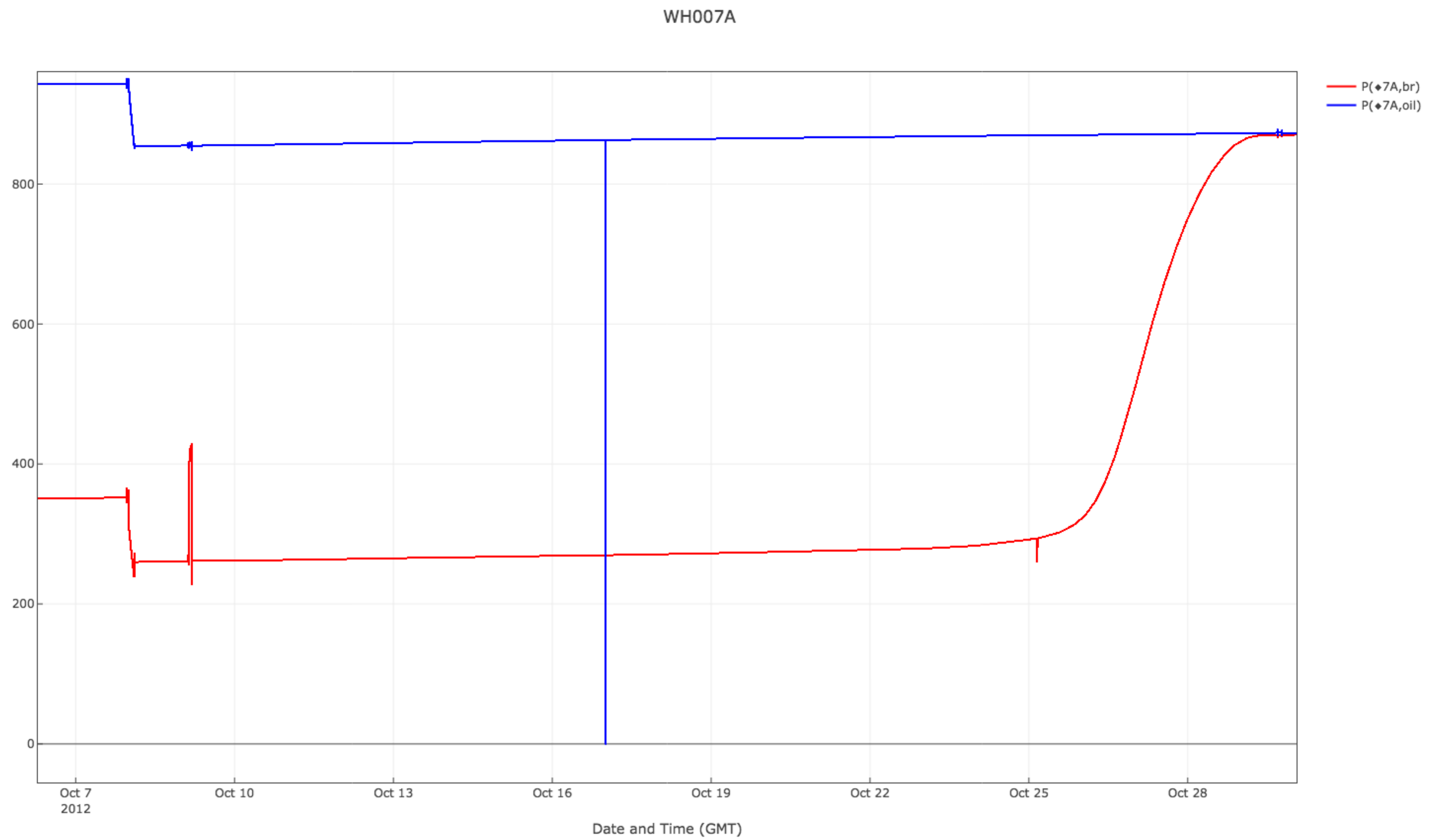



**Figure B.29.** WH-7A October 2012. String damage causing oil to enter brine string. Note the differences compared to full breaks; also included as 8.

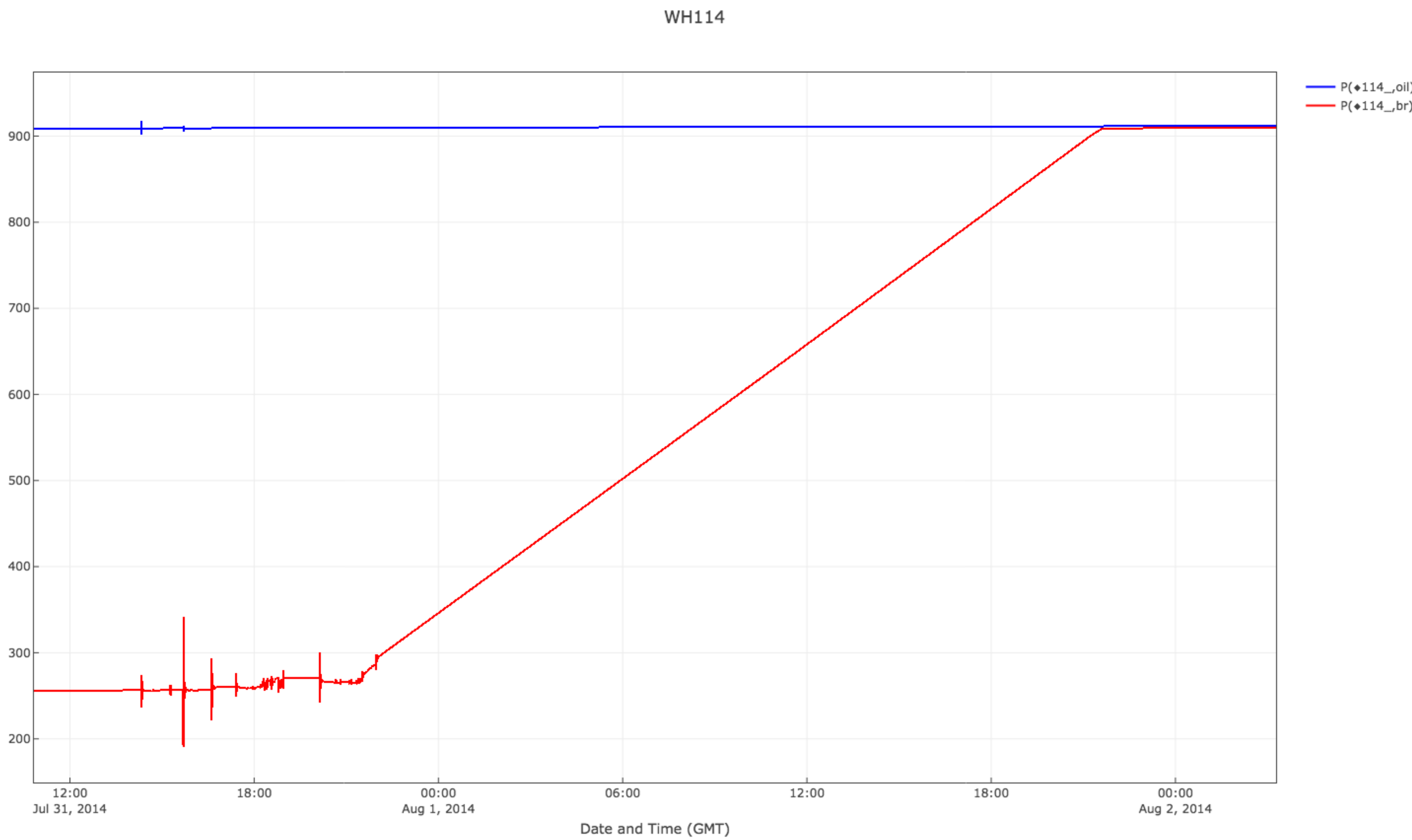



**Figure B.30.** WH-114 August 2014 string cut for degas.

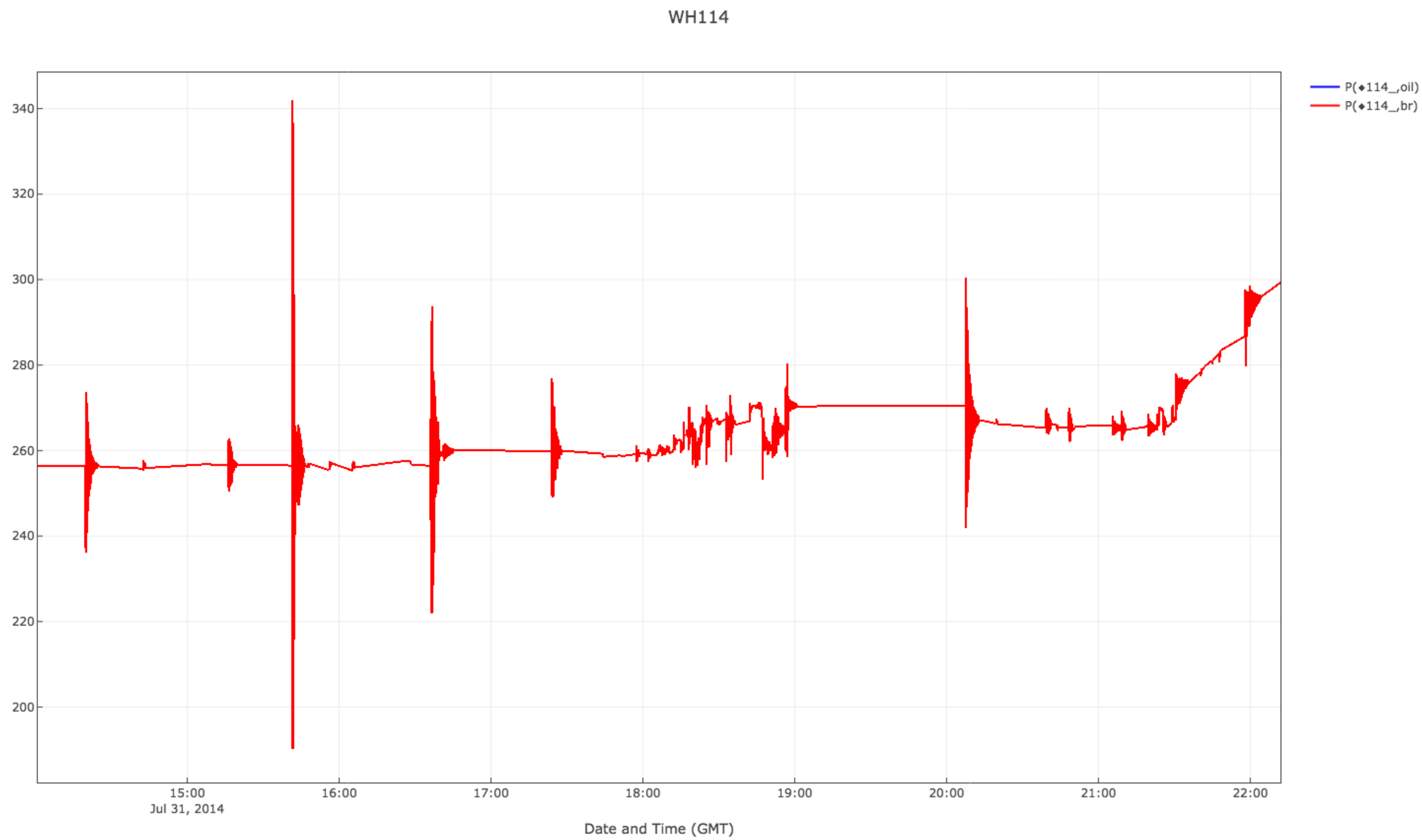



**Figure B.31.** WH-114 August 2014 string cut logging and placement signals.

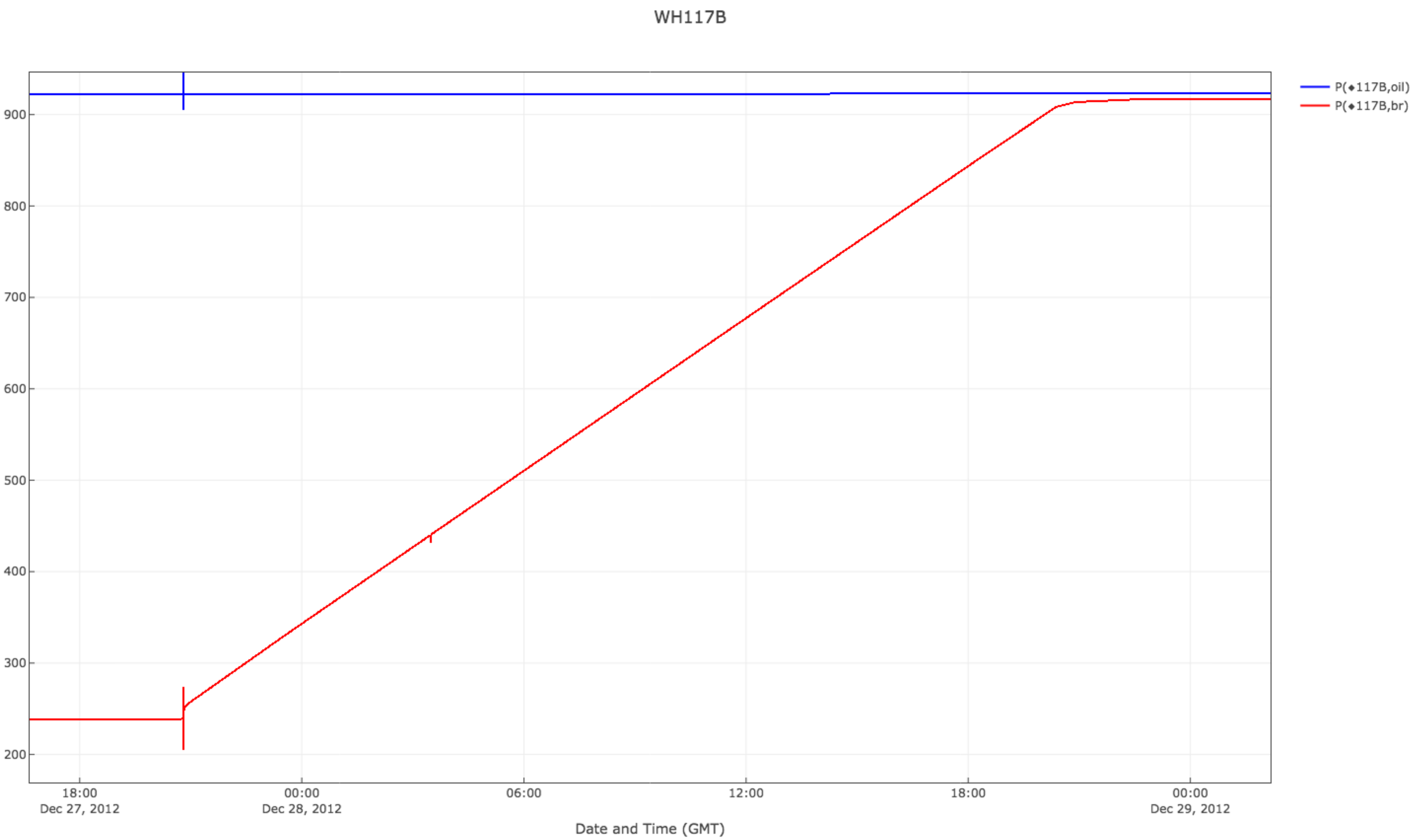



**Figure B.32.** WH-117 December 2012 string break.

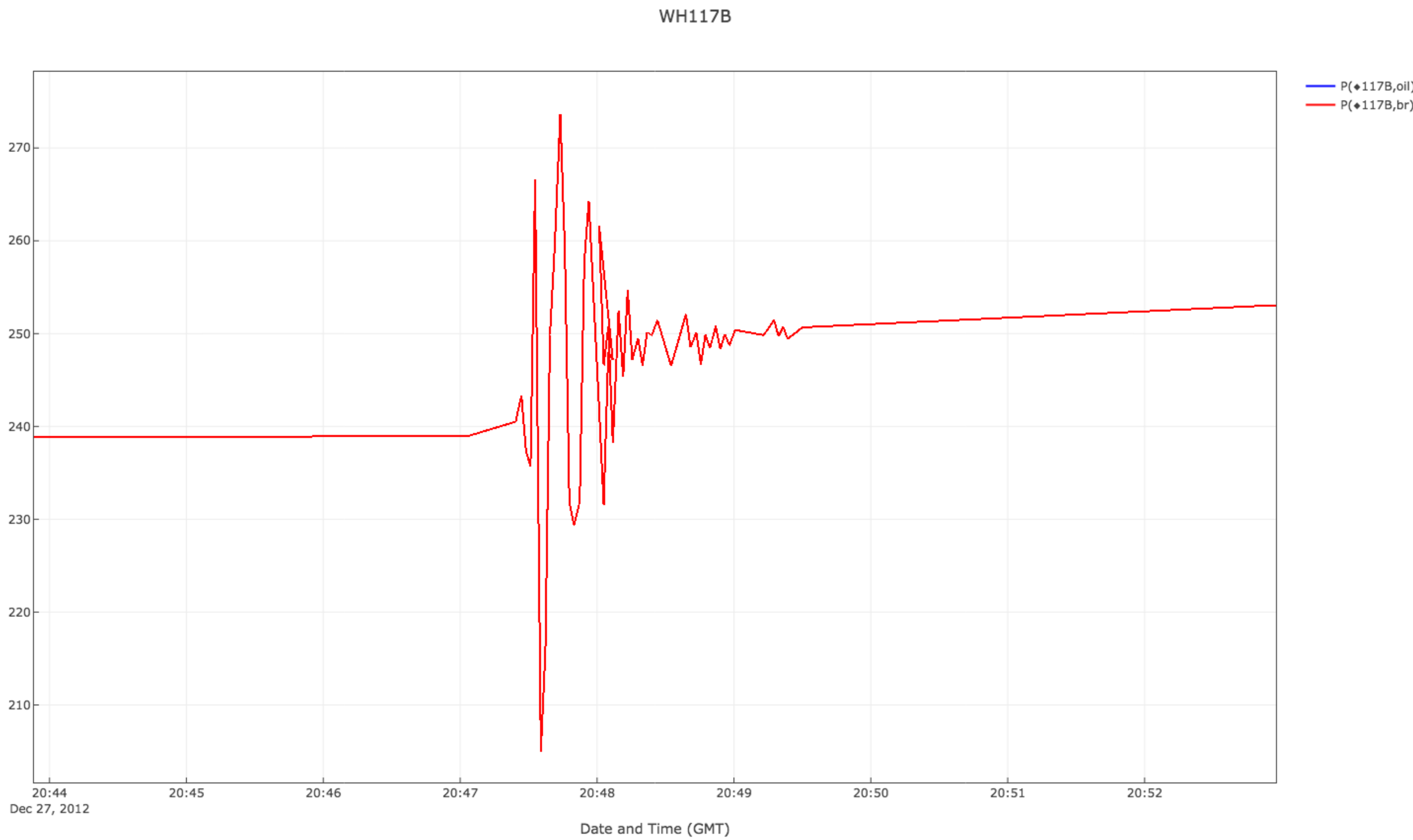



**Figure B.33.** WH-117 December 2012 salt impact with string.

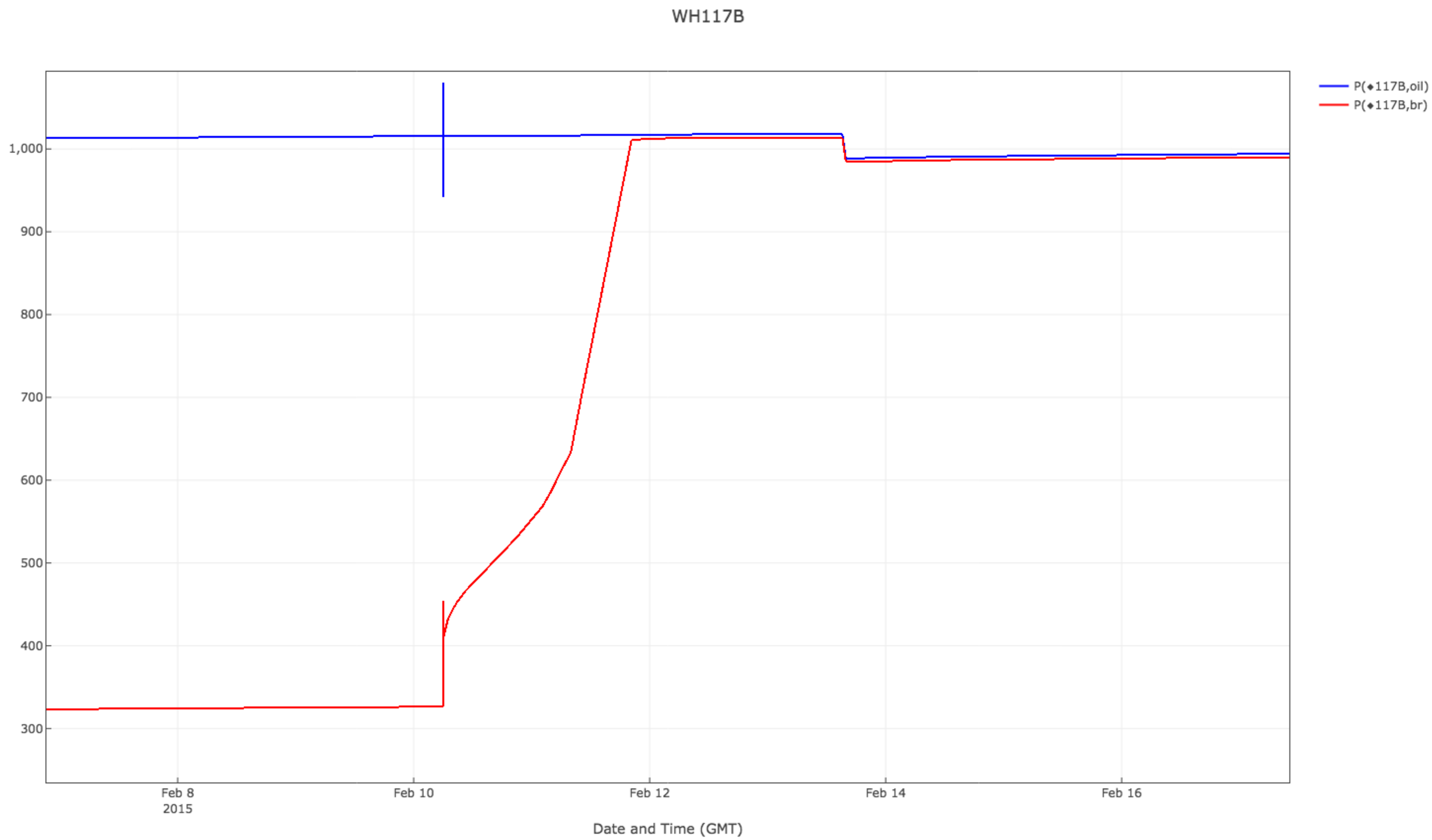



**Figure B.34.** WH-117 Feb 2015. String break with damage.

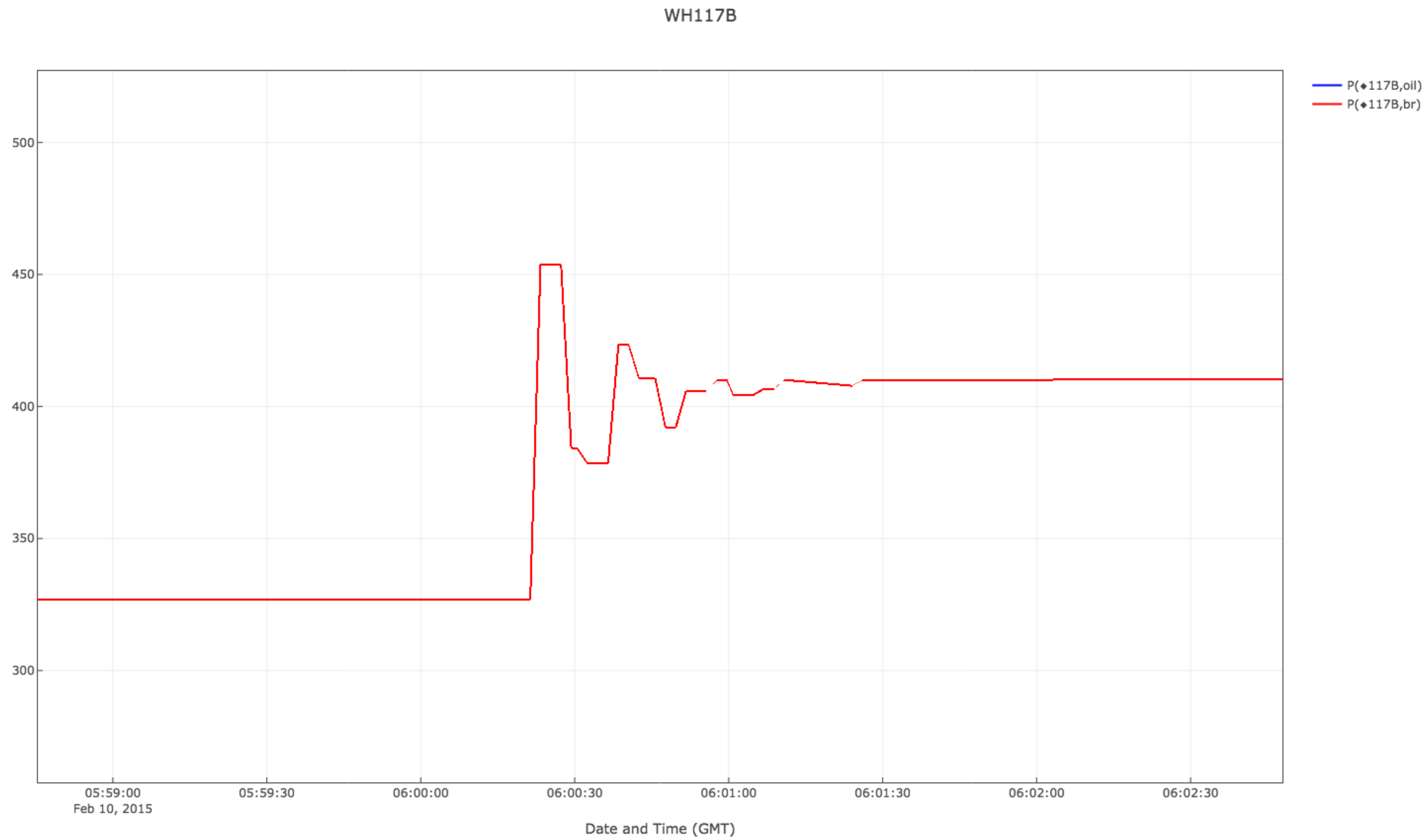



**Figure B.35.** WH-117 Feb 2015. String break with damage – zoomed.

# DISTRIBUTION:

| | | | |
|---|---|---|---|
| Electronic | Diane Willard (diane.willard@spr.doe.gov)<br>U.S. Department of Energy<br>Strategic Petroleum Reserve Project Management Office<br>900 Commerce Road East<br>New Orleans, LA 70123 | | |
| 0 | MS | 0706 | A. C. Snider Lord, 8862 |
| 0 | MS | 0750 | G. Bettin, 8866 |
| 0 | MS | 0750 | K. Chojnicki, 8862 |
| 1 | MS | 0751 | D. B. Hart, 8865 |
| 1 | MS | 0750 | C. L. Kirby, 8862 |
| 0 | MS | 0750 | D. M. Moriarty, 8862 |
| 0 | MS | 0751 | B. Park, 8862 |
| 0 | MS | 0751 | B. L. Roberts, 8862 |
| 0 | MS | 0751 | S. R. Sobolik, 8862 |
| 1 | MS | 0899 | Technical Library, 9536 (electronic copy) |

This page intentionally left blank.

Sandia National Laboratories