DET NORSKE VERITAS

NPS 20 Rainbow Pipeline Reinstatement Case Support

Plains Midstream Canada

Project No.: PP016985

July 27th 2011

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Executive Summary

On April 28th 2011, the NPS 20 Rainbow pipeline operated by Plains Midstream Canada ULC (Plains) suffered a failure due to cracking at the toe region of a fillet weld associated with a Type B (pressure containing) repair sleeve at MP188. By a letter dated June 3rd 2011, the Energy Resources Conservation Board (ERCB) informed Plains that it was not prepared to authorize resumption of operation of the pipeline, and directed Plains to engage an independent third party to conduct a comprehensive engineering assessment as to whether or not the pipeline is safe to restart. DNV Canada Ltd (DNV) was subsequently retained by Plains to perform the independent third-party assessment. The ERCB letter included the Terms of Reference for Third Party Engineering Assessment (EA), which set out the project objectives and deliverables. The objectives of the project were twofold:

1. To provide engineering evidence that supports whether or not the pipeline is safe to restart, and

2. To determine whether a failure at another fillet weld is likely to occur.

The Scope section contained a number of specific requirements for further assessments on aspects of repair sleeve safety. Each requirement is addressed under a specific task within the workscope of the EA. Also, a number of tasks additional to the ERCB's stated deliverables were included, with the approval of the ERCB and Plains, to enable DNV to conduct an assessment of the factors that may have contributed to the failure and the actions necessary to manage risk as the pipeline is returned to service.

Summary of Work Performed

The workscope comprised of the following tasks:

- **Task 1: Review of Plains' Proposed Approach to Pipeline Reinstatement**
  A general review of the cause of the failure, the loads that would have been required for failure to occur, the potential sources of such loads and the source of the weld defect that led to the failure.

- **Task 2: Methods for Assessment of Integrity of Fillet Welds on Weld-on Sleeves**
  A review of appropriate inspection methods to detect and size fillet weld cracking, and methodologies for assessing the structural significance of such cracks. Details of cracks reported on other welded sleeves on the pipeline were compiled and their significance assessed.

- **Task 3: Pre-Restart Weld Assessment Program**
  Review of Plains' proposed dig sampling approach to inspecting additional weld-on sleeves to increase confidence that no further fillet weld failures will occur prior to complete inspection (and repair as necessary) of the remaining sleeves.

- **Task 4: Weld Defect Remediation**
  Review of fillet weld defect remediation methods.

- **Task 5: Sleeve-on-Sleeve Repair Method**
  Review of the suitability and effectiveness of the proposed sleeve-on-sleeve repair methodology.

- **Task 6: Pipe Support, Compaction and Backfill Procedures**
  Assessment of the adequacy of Plains' pipe support, compaction and backfill procedures.

- **Task 7: Leak Alarm Response**
  Assessment of the effectiveness of Plains' proposed improvements to leak alarm response.

- **Task 8: Pipeline Operations**
  Identification of any other actions to minimize the probability or consequences of another failure from a sleeve fillet weld.

Conclusions

1. The failure occurred as a result of a crack in the circumferential fillet weld of a pressure-containing repair sleeve in the presence of an axially aligned stress.

2. The initiating defect was formed at the time of installation of the repair sleeve (1980) by a mechanism known as delayed hydrogen cracking. It was caused as a result of the use of a welding procedure that employed cellulosic electrodes.

3. The crack was 30 mm long and 2 mm deep and appears to be limited to the extent of the brittle heat affected zone. The crack showed no evidence of growth into the more ductile pipe body material before the April 28th, 2011 rupture.

4. DNV has identified two analytical approaches for assessing the criticality of cracks in fillet welds; namely, the CorLAS™ and NASGRO 3.0.19 software programs. Based on calculations using CorLAS™, an axial stress of at least 370MPa (85% of the actual yield strength or 103% of SMYS) would have been required to cause the defect to fail.

5. The source of the high axial stress that led to the failure of the defective weld has not been conclusively established. The stress could not have been caused solely by internal pressure or lack of support due to inadequate compaction of the back fill in April 2010. It is possible that the cumulative effect of sub-critical loads from various sources could have caused the weld failure.

6. In the 11 excavations of Type B sleeves completed by Plains since acquisition of the pipeline, 10 have been found to have cracks in association with the fillet welds. The

cracks ranged in length from 1 mm to 53 mm and depths from 0.4 mm to 2.12 mm. The axial tensile stress required to cause failure of these flaws varied from 109% SMYS to 113% SMYS. These values all exceed the stress that caused the MP 188 incident (103% SMYS). It is expected that a similar percentage of the remaining welded repair sleeves on the NPS 20 Rainbow pipeline will have delayed hydrogen cracking associated with their fillet welds since they would all have been welded using cellulosic electrodes.

7. It is likely that the extent of delayed hydrogen cracking would be limited to the extent of the of the weld heat affected zone. On this basis, the maximum crack depth in the fillet welds of the un-inspected sleeves is not expected to exceed 3.1mm (maximum depth of measured heat affected zone).

8. Provided their circumferential length is less than 10% of pipe circumference (152 mm), fillet weld cracks less than 3.70 mm in depth are not predicted to fail at axial stresses ≤ 100% SMYS in both 5.56 and 7.14 mm nominal wall thickness pipe. At axial stresses ≤ 110% SMYS, the equivalent depths are 1.5 mm in 7.14 mm wall thickness pipe and 1.1 mm in 5.56 mm wall thickness pipe. These depths increase to 2 mm and 1.9 mm respectively, provided the circumferential length is ≤ 80 mm, (i.e. the maximum length of cracking detected to date), see Figures 29 and 30.

9. Industry experience indicates that the best approach for detecting and sizing repair sleeve fillet weld cracks once the pipeline has been excavated is through magnetic particle inspection (MPI) and successive grinding followed by ultrasonic measurement of the remaining wall thickness.

10. In discussions with in-line inspection vendors there is presently not a viable in-line inspection technology for detecting fillet weld cracks in welded repair sleeves.

11. Although the actual source(s) of the axial stresses that caused the MP 188 failure are still unknown, it is postulated that a significant change in the local ground conditions (e.g. the sleeve being recently excavated or in proximity to a geotechnical hazard) would be required to cause the failure of another sleeve. Since none of the remaining sleeves have been recently excavated nor are located in close proximity to a geotechnical hazard and assuming the local geotechnical conditions don’t change between now and the time Plains excavates and assesses them, there is no reason to believe they will fail and thus the NPS 20 Rainbow pipeline should be allowed to return to service.

12. DNV has evaluated four potential options for the repair of cracks in sleeve fillet welds. The two most practical options are grinding and, if necessary, sleeve on sleeve. DNV has developed a proposed grinding acceptance criterion.

13. The sleeve on sleeve repair method is a valid approach for the repair of defective sleeves. DNV recommends using this type of repair only if cracks are present and can not be fully removed by grinding and not for those repair sleeves that are found to be defect free.

14. Plains' existing backfill procedures meet standard industry practice for excavations in flat ground away from water courses. They should be enhanced to address compaction requirements.

15. DNV agrees with the conclusion of Plains' internal investigation that the control centre operator's response to the leak alarms raised at the time of the MP188 failure was inadequate. Recommendations for additional improvements to the written leak alarm procedures, the utilization of the leak detection systems and the training and roles of key staff have been identified by DNV and agreed with Plains. DNV has reviewed the enhancements being implemented by Plains to improve the effectiveness of alarm response and leak detection and believes that they help reduce the likelihood of incorrect response to future events, provided that they are implemented within the context of the recommendations made in Section 10 (Task 7) of the report.

16. The NPS 20 Rainbow Pipeline can be returned to service based on the understanding that none of the remaining sleeves have been recently excavated nor are located in proximity to a geotechnical hazard.

Recommendations

1. All welded sleeves on the pipeline need to be excavated and examined for cracks by the end of the year 2012. Based on a risk assessment, DNV has identified 9 sleeves in 7 joints (6 in the Zuma – Rainbow section, and 1 in the Cadotte-Utikuma section) within ± 12 metres of a previous excavation which should be investigated as a higher priority.

2. Plains should monitor the sites of all the remaining investigation sites for Type B sleeves (Inspection Plan C) on a regular basis. It is understood that Plains conduct weekly aerial patrols using fixed wing aircraft to monitor activities which could potentially affect the integrity of the pipeline, and the scope of these patrols should be extended to monitor for changes in ground conditions which could cause additional axial stresses. Plains are recommended to engage the services of BGC Engineering to assist in training pilots regarding "tell tale" indications of ground movement.

3. All welds found to contain cracks should be repaired by grinding in accordance with the proposed grinding acceptance criterion developed by DNV. Those ground areas that are deemed to be acceptable should be recoated while those that exceed the acceptance criteria should be repaired using a sleeve on sleeve repair.

4. Within 60 days of the Rainbow pipeline's return to service, an audit of the enhanced suite of leak alarm response and pipeline re-start procedures should be conducted.

1 INTRODUCTION

The NPS 20 Rainbow pipeline was designed and constructed by Rainbow Pipe Line Company Ltd. in 1967. The pipeline has a licensed maximum operating pressure (MOP) of 7260 kPa, a predominant wall thickness of 7.14 mm and a Grade of 359 MPa. The MOP therefore equates to a hoop stress of 72% specified minimum yield strength (SMYS). Rainbow Pipe Line Company Ltd. subsequently sold the pipeline to Imperial Oil, who in turn sold the pipeline to Plains Midstream Canada ULC ("Plains") in 2008.

Based on data collected during the 2011 magnetic flux leakage (MFL) in-line inspection runs, conducted by Plains on the NPS 20 Rainbow pipeline, there are 95 Type B sleeves on 85 different pipe joints at various locations along the pipeline. The sleeves are thought to have been installed predominately in the 1980's. The circumferential fillet welds associated with all 95 sleeves were re-inspected in 1990 following a directive that was issued by the National Energy Board (NEB) to companies under its jurisdiction relating to a failure experienced by another operator involving a Type B sleeve fillet weld. Although the NPS 20 Rainbow Pipeline was not under NEB jurisdiction, it is assumed that the pipeline operator prudently elected to follow the NEB directive.

Since taking over the operation of the pipeline, Plains has conducted numerous excavations to investigate anomalies reported by various in-line inspection tools; six of those investigations involved excavations which exposed adjacent Type B welded sleeve repairs. The excavations were conducted between 2009 and 2011.

One such excavation was conducted in April 2010 at Milepost (MP) 188 on joint number 55310 which contained a Type B sleeve that was previously installed in 1980. Images taken during the 2010 excavation are shown in Figure 1 to Figure 4. As can be seen in these Figures the site was located on a minor slope (2% grade) and the soil in contact with the pipe was clay till.

That sleeve subsequently failed in a circumferential orientation (transverse to the pipe axis) at the upstream circumferential fillet weld on April 28th, 2011 (the failure location is illustrated in the pipeline schematic at Figure 5). The pressure at the location of the failure was 3105 kPa at the time of the failure which corresponds to a hoop stress of 31% SMYS. Plains estimated that 28,000 barrels of sweet crude oil was released from the pipeline. Plains reported the pipeline failure to the Energy Resources Conservation Board (ERCB), isolated the section and excavated the area. The failed section of pipe was removed from the line and replaced with a section of pre-tested pipe of similar wall thickness and Grade. The failed section was subsequently sent to Acuren Group Inc. (Acuren) for metallurgical examination.

Subsequent to the completion of the repair, Plains sought approval from the ERCB to re-start the NPS 20 Rainbow pipeline. By a letter dated June 3rd, 2011, the ERCB informed Plains that it was not prepared to authorize resumption of operation of the pipeline, and directed Plains to engage an independent third party to conduct a comprehensive engineering assessment as to whether or not the pipeline is safe to restart. The ERCB letter included the Terms of Reference for the Third Party Engineering Assessment (EA) which, amongst other items, included a Scope of Work (Project Deliverables).

Plains subsequently contracted Det Norske Veritas (Canada) Ltd. (DNV) to conduct the independent third-party engineering assessment. DNV prepared a comprehensive Scope of Work which was based on the Terms of Reference included in the ERCB's letter to Plains of June 3rd, 2011. Before commencing the study, the Scope of Work was approved by both Plains and the ERCB on June 27th, 2011 and the final version of the Scope of Work was issued to Plains and the ERCB on June 28th, 2011. The Scope of Work is summarized in Section 3 of this report.

This report details the engineering assessment performed, the findings on the cause of the failure and recommendations for mitigating the risk of similar failures.

2 OBJECTIVES

In accordance with the ERCB's June 3rd letter, the objectives of this project are:

1. To provide engineering evidence that supports whether or not the pipeline is safe to restart, and
2. To determine whether a failure at another fillet weld is likely to occur.

3 SCOPE OF WORK TO ADDRESS ERCB CONCERNS

The agreed Scope of Work to address the ERCB's Terms of Reference was divided into 8 Tasks as indicated below; in addition, several additional factors relevant to the safe reinstatement of the pipeline (although not required in the ERCB letter of June 3rd, 2011) will be investigated and reported separately. Those factors relate to:

- The development and qualification of welding procedures and welders;
- The development of a sleeve installation procedure;
- A geotechnical investigation of all sites with Type B sleeve installations on the NPS 20 Rainbow pipeline; and
- A review of valve spacing/pipeline isolation methods.

The 8 Tasks agreed to with Plains and the ERCB are summarized as follows:

Task 1: Review of Plains' Proposed Approach to Pipeline Reinstatement

DNV will review Plains' technical submission to the ERCB dated May 20th, 2011. Although this task was not specifically requested by the ERCB in their letter of June 3rd, 2011, it was agreed that an independent assessment of the failure and the documents submitted by Plains in relation to the failure was necessary in order to assess the validity of the path forward proposed by Plains.

Task 2: Methods for Assessment of Integrity of Fillet Welds on Weld-on Sleeves

The aim of this task is to review appropriate inspection methods to detect and size fillet weld cracking, and methodologies for assessing the structural significance of such cracks.

Task 3: Pre-Restart Weld Assessment Program

The aim of this task is to review Plains' proposed sampling approach to inspecting additional weld-on sleeves to increase confidence that no further fillet weld failures will occur prior to the complete inspection (and repair as necessary) of the remaining sleeves.

Task 4: Weld Defect Remediation

The aim of this task is to assess fillet weld defect remediation methods such as local grinding, sleeve-on-sleeve repairs, etc., and determine which ones are appropriate.

Task 5: Sleeve-on-Sleeve Repair Method

The aim of this task is to assess the suitability and effectiveness of the sleeve-on-sleeve repair methodology proposed by Plains.

Task 6: Pipe Support, Compaction and Backfill Procedures

The aim of this task is to assess the adequacy of Plains' pipe support, compaction and backfill procedures.

Task 7: Leak Alarm Response

The aim of this task is to assess the effectiveness of Plains' proposed improvements to leak alarm response, and to examine whether alternative methods may be appropriate for the NPS 20 Rainbow pipeline.

Task 8: Pipeline Operations

Having conducted the above tasks, the final task is to identify any other mitigative actions which Plains could take to minimize the probability or consequences of another failure from a sleeve fillet weld.

4 TASK 1: REVIEW OF PLAINS PROPOSED APPROACH TO PIPELINE REINSTATEMENT

The purpose of Task 1 is to evaluate the engineering assessments provided by Plains to the ERCB. To facilitate this evaluation and to thoroughly investigate all the factors which contributed to the failure at MP 188, the following Sub-Tasks were identified:

1. Calculate the "critical stress" required to fail the cracked fillet weld at MP 188 (Sub-Task 1),
2. Calculate the loads that could be generated at the fillet weld location by the adjacent excavation (Sub-Task 2),
3. Summarize the results of an on-site investigation of the topography and ground conditions at the location of the MP 188 failure (Sub-Task 3),
4. Review potential sources of additional loading (frost heave, thaw unloading, thermal expansion, stresses from construction etc.) and model possible load transfer to the pipe (Sub-Task 4),
5. Review the Acuren metallurgical report into the cause of the failure (Sub-Task 5),
6. Conduct a metallurgical examination of the fracture face (Sub-Task 6),
7. Conduct a literature search of similar pipeline failures (Sub-Task 7), and
8. Review potential issues related to the welding procedure utilized during the original sleeve installation (Sub-Task 8).

4.1 Sub-Task 1: Determination of Critical Stress to Cause Failure

For the assessment of a defect in an engineering structure, three key inputs are required; an applied stress, defect dimensions and material properties. If any two of the above are known, then the third can be calculated. The Acuren metallurgical investigation report[1] (reviewed in Sub-Task 5) provides the crack dimensions and the material properties associated with joint 55310 which failed at MP 188; the aim of this Sub-Task is therefore to use fracture mechanics techniques to calculate the stress level necessary to cause the failure of the defect.

The technical approach taken was to apply fracture mechanics and model the flaw as a circumferential surface crack in a cylinder. This model takes no credit for any reinforcement from the sleeve but seeks to quantify the stress level required to cause failure of the crack. However, it should be noted that the presence of the repair sleeve could influence the axial stress in the pipeline and needs to be included in any model that computes estimates of stress from the loads on the pipeline (to be conducted under Sub-Task 2). Since the failure occurred in an orientation transverse to the pipe axis, the anomaly which failed is subjected to axial rather than hoop stresses. This is known as Mode 1 loading in fracture mechanics. The model used is considered to be a reasonable approximation of the reported crack location and configuration.

The CorLAS™ model has been shown to provide very good predictions of burst pressure in pipelines with axially orientated crack-like flaws[2]. Thus, it was chosen for application to the current task. CorLAS™ computes values of the applied J integral and compares them with estimates of J fracture toughness to predict failure pressures. The toughness is a material property and can be estimated from values of Charpy impact energy for full-size specimens, so it does not depend on the crack and stress orientation. However, the applied J integral does depend on the crack and stress orientation. Specifically, the CorLAS™ model includes a Folias factor to account for the local stress magnification that occurs from bulging of a pressurized pipeline containing an axially orientated crack. The Folias factor is not needed for circumferential flaws, so a spreadsheet was developed and used in this task to carry out the calculation of applied J without the Folias factor.

In addition, NASGRO 3.0.19 software was used to compute values of the linear elastic stress intensity factor for Mode I loading (K_I). Since the fracture was reported to be brittle in nature, application of this linear elastic model is reasonable and provides an independent method of validation of the CorLAS™ model.

The calculations were conducted based on the nominal external pipe diameter, measured wall thickness of pipe joint 55310 and the flaw dimensions (assuming a semi-elliptical profile) and material properties measured by Acuren. The significant parameters input into the calculations are as follows:

- Crack depth 2 mm
- Crack length 30 mm
- Pipe OD of 20 inches (508 mm)
- Pipe wall thickness 6.9 mm (minimum measured at failure site)
- Operating pressure of 450 psig (3105 kPa) (this was the internal pressure estimated by Plains at the failure location immediately before failure)
- Yield strength of 62.8 ksi (433 MPa)
- Tensile strength of 85.3 ksi (588 MPa)
- Flow strength of 74.05 ksi (511 MPa) computed as (yield strength + tensile strength)/2
- Charpy impact energy (CVN) of 7.38 ft-lb (10 J) based on lower shelf data

- Gives a **typical** J fracture toughness (J_c) of 714 lb/in based on CorLAS™ model
- Gives a **lower-bound** J fracture toughness (J_c) of 74 lb/in based on CorLAS™ model
- Gives **lower-bound** K fracture toughness (K_{Ic}) of 32.9 ksi√in based on Equation F.67 in API 579-1/ASME FFS-1

The lower-shelf CVN value was used for the calculations because the fracture was reported to be brittle, which is consistent with lower-shelf toughness.

The CorLAS™ model predicted critical axial stress values that would result in brittle failure of the 2 mm deep x 30 mm long fillet weld crack of 69.9 ksi (482 MPa, 111% of the actual yield strength) for the typical J_c and 53.6 ksi (370 MPa, 85% of the actual yield strength) for the lower-bound J_c. NASGRO predicted a critical axial stress value of 53.8 ksi (371 MPa, 86% of the actual yield strength) for lower-bound K_{Ic}. It can be seen that there is very close agreement between the CorLAS™ and NASGRO lower-bound predictions.

The CorLAS™ and NASGRO predicted failure stress levels vary between 85% and 111% of actual pipe yield strength depending on assumed J_c or K_{Ic} values. These values are significantly higher than the maximum level of axial stress that can arise due solely to the internal pressure in the pipeline (34.3 MPa, or 8% of the actual yield strength). It is therefore concluded that a significant level of additional axial stress was required to cause failure. Task 1, Sub-Task 3 discusses a number of potential sources of this additional stress.

4.2 Sub-Task 2: Estimated Loads due to Potential Inadequate Support After 2010 Excavation

4.2.1 Background

The aim of this Sub-Task is to calculate potential loads and stresses which could be generated at the sleeve location adjacent to the weld toe due to the self weight of the pipe and sleeve and the soil overburden. Such loads can then be compared with those stresses required to cause failure (Sub-Task 1) to assist in the evaluation of the cause of the April 2011 rupture.

DNV has modelled the potential loading **during the excavation** based on the pipe geometry and the dimensions of the excavation as provided by Plains (see Figure 6). It is noted that during the excavation approximately 7.3 m of pipe, which included the sleeve which subsequently failed, was excavated and unsupported, whilst the total length of pipe exposed was approximately 13 metres.

The pipe has been modelled in two ways:

1. Pipe self weight with pipe full of product, the stiffening effect of the sleeve and a fillet weld between the carrier pipe and the sleeve, and

2. As above but including the effect of maximum soil loading (i.e. full overburden with no fill under the 7.3 metre span as if the backfill under this span was loose and settled).

The above models have been created using the commercially available finite element software ABAQUS. The models are based on solid elements so that axial stress variations along the pipe can be obtained. The ABAQUS outputs are shown in Figure 7 and Figure 8 respectively. The results generated by ABAQUS show the maximum (bending) stress values only for the respective models; the axial stress due to internal pressure was not included but can be accounted for separately using the following method.

The pressure-induced axial stress for an infinitely long uncapped pipe is given by the formula:

$$\sigma_a = \frac{\nu PD}{2000t}$$

where υ is Poisson's ratio for steel (0.3)

P is the estimated pipeline internal pressure at MP 188 at the time of failure (3105 kPa)

D is the nominal pipeline diameter (508 mm)

t is the pipe wall thickness (6.9 mm)

The axial tensile stress, σ_a, due to internal pressure therefore equates to 34.3 MPa (8% of actual yield strength, or 9.5% of SMYS).

4.2.2 Discussion

The maximum stress values near to the failed fillet weld (with and without the effects of the soil overburden) are 16.0 MPa and 51.3 MPa respectively (see Figure 7 and Figure 8). Taking into account the additional stress that results from the internal pressure, the failed weld location would have experienced a maximum axial stress of 85.7 MPa due to self weight and internal pressure.

This stress is 23.2% of the minimum stress calculated (370 MPa) in Sub-Task 1 required to cause the failure. It is therefore concluded that significant additional loading must have occurred to cause the failure.

4.3 Sub-Task 3: Summary of Geotechnical Site Investigation At MP 188, June 29th 2011

On June 29th 2011, representatives of BGC Engineering completed a geotechnical site reconnaissance at the location of the MP 188 failure. This visit consisted of a visual inspection undertaken near the failure site. The following tasks were completed during the site visit:

- Recording of visual ground-surface observations, documented photographically,

- Excavation of shallow test pits (to a maximum depth of 15 cm) for physical examination of the near-surface soils,

- Collection of soil samples from an area of soil used to backfill the excavated area associated with the repair of the failure, near surface test pits and soil stockpiles, and

- Measurement of soil consistency using a pocket penetrometer or field vane.

The findings of the site visit are summarized below:

1. The soil from a distance of approximately 120 metres South of the excavation to the North of the failure site comprised clay till. Its strength varied from hard to soft, the softer areas being nearer to the repair location,

2. The soil used to backfill the repair area was new and was of a soft to firm consistency,

3. Near to the transition between higher ground and the softer area to the South of the excavation, the ground was relatively soft and could at one time have been associated with muskeg. There was some evidence of freeze/thaw action in the soil as witnessed by cubic, blocky fill structures, and some evidence of water pooling but any area formerly associated with muskeg has 'dried out", and

4. The surface of the current backfill was not compacted according to normal Plains procedures because of special restrictions placed on traffic crossing the right of way at the failure site by the ERCB.

Further details regarding the condition of the backfill are detailed in Section 9 (Task 6). Subsequent to this visit, BGC Engineering also made a three day visit between Monday July 15th and Wednesday July 17th, 2011 to the locations of the remaining 94 Type B sleeves. The details of that visit are described in Section 6 (Task 3).

4.4 Sub-Task 4: Potential Sources of Additional Loading and Their Magnitude

Sub–Task 2 has identified that the stress induced at the upstream end of the sleeve due to the combination of self weight of the pipe, the sleeve and the product, a soil overburden, and internal pressure is insufficient to cause the axial stress necessary for failure. The aim of this sub-Task is therefore to:

1. Identify the potential sources of additional loading which could have contributed to the pipeline failure at MP 188, and

2. Determine their magnitude.

4.4.1 Potential Sources of Additional Axial Loading

Two generic sources of axial loading have been identified, namely those due to pipeline construction and operation, and those resulting from geotechnical effects. The following sources of axial stress due to pipeline construction /operation have been considered:

- Internal pressure, and thermal expansion and contraction resulting from temperatures changes in the line.
- Construction practise of "roping" the pipeline into the original trench possibly leading to the introduction of axial bending stresses at the time of installation.
- Stresses introduced as a result of an attempt to remove, during the 2010 excavation, a warning sign that was attached to the sleeve.
- Stresses introduced as a result of heavy equipment traversing the pipeline as part of the restoration of the excavation site in April 2010.

Prior to making the site visit to the failure location at MP 188 on June 29th 2011, BGC Engineering postulated the following sources of geotechnical loading:

- Frost heave of the fill placed as part of the 2010 excavation. A hypothesis was originally proposed by BGC Engineering (prior to their site visit) that water concentrated in the backfill from the 2010 excavation could have frozen under the pipe during the winter months and introduced stress into the pipe as the water expanded during freezing, a phenomenon known as 'frost heave'. The effect would have been concentrated at the recently exposed section, where the failure occurred, due to the non-permeable clay soils in the surrounding area.
- Tension induced by settlement of the pipeline into the assumed adjacent muskeg[*] area. The pipe located within the muskeg could have sunk; thereby tending to pull adjacent pipe towards it and causing tensile stress in the excavated area. This is shown schematically in Figure 9.
- Strong and weak fill placed on either side of the pipeline, again causing tensile stress within the sleeved area. As a result of the site visit, BGC Engineering discounted this possibility as the ground conditions were not indicative of areas of strong and weak backfill.

[*] The area approximately 100 metres downstream of the excavation was assumed to be characteristic of muskeg on the basis of a "desk top study". However, the site visit (sub-Task #3) indicated that the area was not muskeg

- Vertical loading from fill above the pipeline in conjunction with poor compaction underneath the pipeline. This was investigated within Sub-Task 2 and shown to result in loading insufficient to cause failure.

With respect to frost heave, this theory was subsequently discounted based on records and discussions with Plains' excavation contractors. A preliminary analysis performed by BGC Engineering showed that penetration of frost below the pipeline could not occur if the line remained above 0ºC. An assessment of the product temperature records for the Cadotte to Nipisi section (Figure 10) showed that the mean temperature of the pipeline is maintained above 0ºC throughout the year, whilst Figure 11 shows frost would not penetrate to a sufficient depth into the ground to affect a pipeline operating at 5ºC and 10ºC. These analytical conclusions were supported during interviews held on July 13th, 2011 with excavation contractors who have worked extensively on the NPS 20 Rainbow pipeline. They confirmed that the soils above the pipeline remain unfrozen throughout the year.

4.4.2 Magnitude of Potential Axial Loading

Based on the findings of Section 4.4.1, the magnitude of possible loads associated with the following scenarios were determined:

- Internal pressure/thermal expansion and contraction as a result of different temperatures at the time of pipeline tie-in and during operation.

- Settlement of the pipeline into the area downstream from MP 188, originally assumed to be muskeg area (a sensitivity study was conducted to consider the effects of both muskeg and "old' backfill – see Section 4.4.4.2).

- Possible bending loads introduced during original construction.

- Attempting to remove (during the 2010 excavation) the warning sign attached to the sleeve.

- Heavy equipment used during site restoration of the 2010 excavation at MP 188.

It is possible that several of these factors could have combined to generate the substantial axial stresses (370 MPa) that were shown to be necessary to have caused the failure at MP188.

4.4.3 PIPLIN Software

The commercially available software known as PIPLIN-PC [3,4] was used to determine the possible stresses that could have been generated for the above scenarios. PIPLIN-PC is a special purpose PC based computer program for stress and deformation analysis of buried, cross country pipelines. PIPLIN has been utilized by pipeline designers and engineers for more than 20 years throughout North America. The program considers several non-linear aspects of pipeline behaviour, including pipe yield, large displacement effects and nonlinear soil support. PIPLIN-PC output includes pipe displacement; anchor and soil support deformations and reactions; pipe axial forces, bending moments and curvatures; axial and hoop stresses and strains in the pipe.

4.4.3.1 PIPLIN Model

The pipeline around MP 188 was modelled according to its vertical profile based on the GPS references provided by recent in-line inspection runs [5]. GPS co-ordinates were provided at each of the girth welds, from which it was possible to model the profile (see Figure 12). Plains subsequently provided [6] a profile of the line section upstream and downstream of the failure location (see Figure 13), and the profiles obtained from the two measurement methods were in close agreement.

Some axial load can be introduced if a pipeline is “roped in” during construction to align to the ground topography. Common practice is to make field bends when a minimum radius of curvature is exceeded, but not necessarily when the minimum radius of curvature is not exceeded. The modelled geometry therefore accommodates the natural profile of the line after construction including any potential areas of bending; it also accommodates the natural 2º profile of the slope in a downstream direction, levelling out at a distance of 50 metres into an area originally suspected to be muskeg.

PIPLIN requires the input of both pipe and soil properties. Nominal pipe properties (508 mm diameter and 7.14 mm wall thickness, Grade 359, were input into the model, which also took account of the additional thickness (12.7 mm) of the sleeve. The sleeve length was taken from the Plains’ dig report and was confirmed from the in-line inspection report. The soil properties were provided by BGC Engineering [7]. Soil properties were provided for:

1. Intact, undisturbed soil below the pipeline,
2. “Old backfill” (original backfill material when the pipeline was constructed which has not been disturbed since),
3. “New” backfill, which is the material used to backfill the excavation at MP 188, and
4. Muskeg, which was assumed to be present approximately 50 metres downstream of the (downstream end of the) excavation. Although it was subsequently determined that the area was not characteristic of muskeg, it was assumed for conservatism.

The soil properties for the above materials were incorporated into the model so that loads and bending moments could be developed.

4.4.4 Calculations Performed

Different models and load cases were developed within PIPLIN to simulate all the considered sources of axial loading. The first model considered "straight pipe" without the presence of the sleeve subjected to internal pressure (450 psig, or 3105 kPa) and thermal expansion/contraction (see Section 4.4.4.1). Subsequent models then included the loadings due to internal pressure and thermal contraction and also accommodated the effects of the sleeve self weight, the line profile and the line settling into muskeg/"old" backfill. Using this model as a "base case", models were developed to in turn investigate and add the additional stresses associated with the attempt to remove the sign and heavy equipment traversing the pipeline. The final model developed (Section 4.4.4.5) investigated the effect of an adjacent excavation on the stress profile at a Type B sleeve. The models and the resultant maximum axial stress levels at the bottom of the pipe at the upstream (failure site) end of the sleeve location are summarized in Table 1.

4.4.4.1 Thermal Expansion and Contraction

Axial stresses were calculated firstly to determine the effects of internal pressure and thermal expansion/contraction in nominally straight pipe. The axial stress due to internal pressure is a function of Poisson's ratio and hoop stress as demonstrated in Sub-Task 1.

As the temperature of the pipeline changes, it will expand or contract. This has the potential to introduce significant axial loads on the line because the buried pipe is restrained and cannot accommodate the expansion/contraction freely. The changes in temperature of the transported product are known, but the total thermal stress could be higher than those from just the product, for example, if the pipeline was constructed at a time of high ambient temperature and then operates at lower temperatures. To account for all credible thermal effects, an assessment was performed on the magnitude of stresses that would result from an overall temperature change of 46ºC.

A more detailed assessment using the PIPLIN software was performed assuming cases where the pipe was 'tied in' during the summer and the winter. The total (tensile) axial stress generated in the fully restrained pipe from both internal pressure and thermal effects was calculated for product temperatures of 5ºC and 20ºC (the approximate range of temperatures recorded over a typical year [8]. The results are shown in Figure 14.

If the pipeline was tied-in in the winter, the thermal expansion of the material during operation would impose a compressive axial stress and thus would not be a contributing factor to the failure of sleeve fillet welds. However, if the tie-in occurred in the summer, the pipeline would contract when operating under normal conditions and, assuming a temperature difference of -41.4 F (-23ºC) between construction and operation at 5ºC, would produce a combined (internal pressure and thermal contraction) axial stress of up to 11.4 ksi/78.9 MPa (22% SMYS).

4.4.4.2 Settlement Into Assumed Adjacent Muskeg / "Old" Backfill Area

The first "base" model developed assumed that the pipeline settled into an area of muskeg 50 metres downstream of the excavation to repair the pipe at MP 188 (CASE 1 in Table 2). Therefore, the soil above the pipeline is modelled as "new" backfill above the excavation, 'old" backfill for 50 metres downstream of the excavation and then muskeg; the soil under the pipe is all designated as intact bearing, except under the sleeve and in the muskeg. The results are shown in Figure 15. The tensile stress at the bottom of the pipe (6 o'clock position) at the sleeve failure site (upstream end of the sleeve) is computed as 14.8 ksi/102 MPa (28.5% SMYS). Note that the stress level between the sleeve ends reduces considerably due to the additional thickness of the sleeve.

An additional model (CASE 2, Table 2) was developed; the only change to the above being that the area downstream of the "new" backfill was continuous "old" backfill, i.e. there is no muskeg. The results are shown in Figure 16. The tensile stress at the bottom of the pipe (6 o'clock position) at the sleeve failure site is computed as 14.9 ksi/103 MPa (28.6% SMYS). Therefore the effect of the pipeline settling on "old" backfill or into muskeg is trivial.

4.4.4.3 Attempt to Remove Warning Sign Attached to Sleeve

Before the April 2010 excavation adjacent to the MP188 sleeve, the excavation contractors found a pipeline warning sign on the right of way and attempted to remove it by attaching a chain to the sign and pulling with a back-hoe. The sign did not pull out of the ground so the pipe was excavated and the sign was found to be welded to the repair sleeve in the location shown in Figure 6. The sign was then cut off and an MPI inspection made of the attachment point. No cracks were found.

An assessment has been made of the loads that could have been applied during the original attempt to pull the sign out of the ground. This model (CASE 3) was based on CASE 2 but included the application of a point load to simulate the attempted sign removal. Plains provided information [9] indicating that a load of 15,000 lbf could have occurred during the sign removal attempt, and to add a factor of conservatism, a load of magnitude 20,000 lbf (89 kN) was applied to the downstream end of the sleeve where the sign was attached. The stress profile is shown in Figure 17. The stress profile is very similar to the "base" model, although it can be seen that at the upstream end of the sleeve, the maximum stress at the bottom of the pipe (6 o'clock position) is slightly reduced from that of the base model to a value of 13.9 ksi/96 MPa (26.7% SMYS). The reason for the small reduction in maximum stress is that the pulling action on the sleeve is actually causing a small amount of compression at the upstream end of the sleeve.

4.4.4.4 Bending Loads Caused by Heavy Equipment Used During Site Restoration of April 2010 Excavation

During the site restoration following repair of the failed sleeve, it is conceivable that heavy equipment such as a bulldozer could traverse the line to effect compaction, for example. This action could cause additional axial loading to the pipeline, which is investigated in this section. This model (CASE 4) is again based on CASE 2 but then adding the loading due to heavy equipment. Plains [10] supplied DNV with the weight and ground pressure associated with typical excavation equipment. The maximum weight of vehicle which could conceivably have crossed the line was associated with a Caterpillar 320. The Caterpillar weight was 20,720 kg, the ground pressure was 5 psig with a track length of 175 inches. The ground pressure was converted to a continuous load of 1200 lbf per linear foot and input into PIPLIN, assuming the ground pressure of 5 psig acted over an area of the pipe diameter (20 inches) load and an axial length of 12 inches. The load was then applied over the full length of unsupported pipe (7.3 metres). This loading is considered to be a conservative approximation since the ground pressure will dissipate through the depth of soil cover above the pipeline; however, the full ground pressure is assumed to act directly on the pipeline. The results of the analysis are shown in Figure 18. The tensile stress at the bottom of the pipe (6 o'clock position) at the sleeve failure site (upstream end of the sleeve) is computed as 15.6 ksi/108 MPa (30% SMYS).

4.4.4.5 Effect of Adjacent Excavations

As detailed under Section 6 (Task 3), a number of the Type B welded sleeves have adjacent excavations conducted since Plains acquired the pipeline. It is conceivable that the effect of these adjacent excavations could have imposed axial stresses on the remaining Type B sleeves, and therefore a study has been conducted in this section to investigate the potential effects.

The study (CASE 5) has been conducted by considering the "base" model (CASE 2) and then simulating an excavation, removing the soil around the pipe. The results of the analysis from this study are shown in Figure 19, where it can be observed that blue curve (the operating state) and the red curve (after excavation) deviate from approximately 10 ft upstream to 70 ft downstream of the reference weld. Since the excavation was modelled from 6.5 ft to 50 ft downstream of the reference girth weld, it is concluded that the excavation can influence the stress pattern for a distance of approximately ± 20ft (6 metres) upstream and downstream of the extremities of the excavation. It should be noted that this model may not encompass all cases since other excavations could be associated with different line profiles, soil properties and excavation lengths and so, when prioritizing additional sleeves for investigation, a safety factor should be applied to the above value. DNV has therefore applied a safety factor of 2 on distance (see Section 6.4).

4.4.5 Summary

A series of different loading scenarios have been modelled using the PIPLIN software to try to ascertain if the various loading scenarios identified could have acted independently or in combination to cause the axial stress level necessary (370 MPa). A model was firstly developed to determine the combined stress associated with the effects of internal pressure, thermal contraction, possible bending stresses induced during pipeline construction and the pipeline settling into muskeg downstream of the failure site. Using this model as a "base case", models were developed to in turn investigate and add the additional stresses associated with the attempt to remove the sign and heavy equipment traversing the pipeline.

The combined axial stresses for the different load cases are summarised in Table 1, where it can be seen that the maximum axial stress generated at the bottom of the pipe at the location of the upstream end of the failed sleeve is 14.9 ksi/102.7 MPa (28.6% SMYS) for CASE 2 (internal pressure/thermal contraction/line profile and pipeline settling into "old backfill). This value increases to a maximum of 15.6 ksi/108 MPa (30% SMYS) for CASE 4 (as CASE 2, but including the effects of heavy equipment traversing the pipeline). The increase in stress resulting from the additional loading due to attempted sign removal or heavy equipment is therefore "negligible" (0.7 ksi, or 5 MPa). Although the axial stress values are some 3.6 ksi/ 25 MPa higher than those determined from the ABAQUS calculations, the stress levels generated are significantly below those calculated to have caused the failure.

CASE 5 has shown that the stress influence effects extend ± 20 ft (6 metres) upstream and downstream of an excavation, but this value has been obtained from a specific set of conditions (i.e. line profile, excavation length and soil conditions). If this condition is to be applied to the prioritization of additional sleeves for investigation, then a safety factor should be applied.

4.5 Sub-Task 5: Review of Acuren Metallurgical Report

The aim of Sub-Task 5 is to review the findings of Acuren's metallurgical investigation into the failure. DNV has completed its review, and is generally in agreement with the conclusions stated by Acuren into the cause of the failure. In addition, DNV offers the following comments relating to specific statements in Acuren's report.

Acuren's conclusions were as follows:

"It is our (Acuren's) opinion that failure of the NPS 20 Rainbow pipeline occurred as a result of the combination of:

1. *Failure to follow the prescribed weld procedure during welding of the sleeve to the carrier pipe.*
2. *A very high carbon equivalent of the carrier pipe.*
3. *Failure to detect a small crack during two separate inspections of the weld attaching the sleeve to the pipe.*
4. *The development of a sufficient bending stress in the pipe as a result of local sagging of the pipe.*
5. *The poor toughness of the pipe resulted in a wide open brittle fracture".*

Based on DNV's analysis of the macro-photographs of the welds in the Acuren report, it is DNV's view that the welds were made using cellulosic electrodes. This was not specifically mentioned by Acuren.

DNV's comments with respect to these conclusions are as follows:

1. Without having access to the prescribed procedure, DNV is unable to determine whether either an inadequate procedure was followed, or the procedure was adequate but it was not followed. However, it is known that the actual procedure produced a hardened microstructure that was susceptible to hydrogen cracking. Although not mentioned in the Acuren report, the appearance of the fillet weld is consistent with one made using cellulosic electrodes. Cellulosic electrodes produce large volumes of hydrogen, in comparison with a low hydrogen electrode, which would have been more than sufficient to cause the cracking. Further details are provided in Section 4.8 (Sub-Task 8 of Task 1).

2. Based on the analysis performed, DNV is in agreement.

3. DNV's opinion is that the initiating crack may not have been present at the time of the original inspection based on an assumption that the original inspection would have been completed immediately upon completion of the weld. Acuren states that… "*This feature* (the initiating crack) *was covered with a black iron oxide scale that was readily and uniformly removed with inhibited acid. … It is suspected that the scale on the crack surface formed while the surrounding material was still very hot at the completion of welding".* DNV respectfully disagrees with this statement; it is our view that the most likely cause of the pre-existing crack is a hydrogen assisted crack. This type of crack occurs after the pipe cools to ambient temperature as a result of the trapping of hydrogen in the weld pool.

4. DNV's view is that further analysis is required before this conclusion can be confirmed or refuted.

5. Based on the analysis performed, DNV is in agreement.

In addition to the above comments regarding Acuren's conclusions, DNV has the following comments on the body of the Acuren report (Acuren statements in italics, followed by DNV comment in plain text):

"Examination of the section of failed pipe from the NPS 20 Rainbow pipeline has found that the pipe fractured in a brittle manner",

This is correct. The fracture surface is primarily cleavage, even in the base metal away from the heat affected zone of the weld.

"*…, with the fracture initiating at the location of a small pre-existing crack at the toe of the fillet weld joining a sleeve to the pipe body".*

This is correct. The chevron markings point to an initiation site at the toe of the fillet weld, at the 6:00 o'clock orientation.

"*It is our* (Acuren's) *opinion that the crack formed very soon after completion of the fillet weld and remained dormant until such time as the longitudinal stress on the crack reached some critical value".*

It is DNV's opinion that the pre-existing crack formed soon after completion of the fillet weld, although DNV has a different view regarding the cause and timing of the crack; see DNV's response to Acuren's 3rd conclusion. However, it is true that the crack remained dormant until such time as the total longitudinal stress on the crack reached some critical value. There was no evidence of in-service growth of the flaw. Therefore, failure must have resulted from an increase in the axial stress acting on the flaw. This stress could be a bending stress or an axial tensile stress or a combination of both.

"Once this stress was achieved, the pipe fractured in a one time catastrophic event".

This is correct. The fracture surface was primarily brittle, except for a narrow ligament near the ID surface of the pipe. There was no fractographic evidence of intermediate events.

"The amount of opening at the bottom of the pipe with the fracture running up either side indicates that the stress at the bottom of the pipe resulted from a sag in the pipe".

Whilst this is the most plausible explanation for the initiation at the bottom of the pipe, a uniaxial tensile stress on the pipe could have produced the same result.

Summarizing, DNV agrees with Acuren that the failure initiated at the 6 o'clock position in a brittle manner with no evidence of in-service growth. However, DNV respectfully disagrees with Acuren's assessment of the cause of the initiating crack; DNV's view is that the most likely cause of the initiating crack is delayed hydrogen cracking. This type of crack occurs after the pipe cools to ambient temperature as a result of the trapping of hydrogen in the weld pool. The most likely source of hydrogen was decomposition of the cellulosic coating on the welding rods. Further details are presented under Task 1, Sub-Task 8.

4.6 Sub-Task 6: Investigation of Failed Pipe Samples

The purpose of this Sub-Task is to independently confirm Acuren's conclusions regarding the nature of the crack (i.e. that the initiation was brittle and that there is no evidence of in-service crack growth). DNV has examined the fracture surfaces in its Dublin, OH, laboratory and confirmed the following:

1. The Acuren report correctly identified the failure origin,
2. There is no evidence of in-service fatigue on the fracture surface,
3. The Acuren report appears to be accurate with respect to the maximum depth of the pre-existing crack (2 mm), and
4. The Acuren report accurately reflects the morphology of the fracture surface, i.e. the initiation was brittle and the majority of the fracture appearance outside the initiating flaw was characteristic of cleavage (refer to Figure 20 and Figure 21).

4.7 Sub-Task 7: Literature Review of Similar Pipeline Failures

DNV has reviewed the published literature to identify the causes of pipeline sleeve failures similar to that which occurred at MP 188 in order to establish if additional factors were involved outside those under consideration.

4.7.1 Interprovincial Pipeline Ltd (IPL) – Camrose, AB

In February 1985, a rupture occurred on an Interprovincial Pipe Line Limited (IPL) pipeline near Camrose, Alberta in Canada [11]. The cause of the rupture was due to the sudden propagation of a crack in a fillet weld of a full-encirclement repair sleeve that had been installed in 1973 on IPL's NPS 16 LPG line.

The pipeline consisted of API 5L Grade X52 line pipe that was manufactured in the 1950's. The carbon equivalent (CEIIW) of the pipe material was 0.49%. The previously-installed full-encirclement repair sleeve was fillet welded to the pipeline using cellulosic-coated electrodes while the pipeline was in-service. The rupture was determined to have resulted from a HAZ hydrogen crack at the toe of one of the full-encirclement fillet welds.

The incident resulted in a National Energy Board inquiry [3] that resulted in changes to the Canadian standard for Oil Pipeline Transportation Systems – CSA Z183, which at the time covered pipeline design, construction, operation and maintenance. CSA Z183 later became part of CSA Z662 – Oil and Gas Pipeline Systems.

The NEB required that all operators of pipelines under its jurisdiction conduct examinations for hydrogen cracking at fillet welds made onto the pipe while in a liquid-filled state. Although the NPS 20 Rainbow pipeline was not under NEB jurisdiction, it is assumed that the pipeline operator prudently elected to follow this requirement and thus excavated and inspected, in 1990, the sleeves that had been previously installed on the NPS 20 Rainbow pipeline. Plains do not have the results of those inspections.

4.7.2 British Gas – Palaceknowe, UK

In December 1993, a NPS 36 natural gas pipeline ruptured at the location where a new heavy-wall section had been attached to the line to provide additional protection under a major road crossing. The pipeline was constructed in 1978 and the modification to accommodate the new road was performed earlier in 1993.

The failure investigation that followed concluded that the weld failed due to deficiencies in the backfilling that was performed at the time of the installation of the new section of pipe, combined with additional loading above the pipe from a protective concrete slab and the stress concentration affect of the heavy-wall to standard-wall transition. These factors combined to generate axial stresses at the weld sufficient to cause the weld to fail. The quality of the weld itself was not found to be a factor.

4.7.3 Discussion

The Camrose and Palaceknowe incidents both appear to have parallels with the MP188 failure of the NPS 20 Rainbow pipeline.

The Camrose failure was caused by hydrogen cracking of a fillet weld made onto a liquid-filled pipeline. On the NPS 20 Rainbow pipeline hydrogen cracking of a fillet weld made onto a liquid filled pipeline is also the most likely cause of the failure.

At Palaceknowe, the failure occurred at a tie-in butt weld rather than an external fillet weld. Nevertheless, the combination of stress concentration at the weld location and the possible effect of settlement of the recently completed backfill operation may be similar to some of the contributory factors in the NPS 20 Rainbow pipeline failure.

4.8 Sub-Task 8: Susceptibility of Welding Procedure Utilized During Original Sleeve Installation to Delayed Hydrogen Cracking

4.8.1 Mechanism and Susceptibility to Delayed Hydrogen Cracking

In Sub-Task 5, DNV has identified the cause of the initiating defect which resulted in the failure at MP 188 as delayed hydrogen cracking associated with a fillet weld. For delayed hydrogen cracking to occur in welded joints, three factors have to simultaneously exist:

1. A source of hydrogen,
2. A susceptible microstructure, and
3. A source of tensile stress.

This Sub-Task evaluates the propensity for the fillet welds associated with the sleeve which failed to contain hydrogen cracks (and by implication the fillet welds associated with all Type B welded sleeves on the pipeline).

4.8.1.1 Source of Hydrogen

All arc welding processes introduce hydrogen into the weld to some extent. Hydrogen can originate from moisture in electrode coatings, in the atmosphere (humidity) or on the pipe surface (condensation). Hydrogen can also originate from hydrocarbons, grease, or other organic contaminants on the pipe or on the welding consumables. From the Acuren failure analysis report[1], it is apparent from the shape of the weld ripples that the weld that failed at MP188 – as well as the three other welds that were included in the Acuren analysis - was made using cellulosic-coated electrodes, which are known to emit hydrogen when they decompose. Since little attention was paid at the time to minimizing levels of hydrogen, a source of hydrogen would have been readily available. The evidence of the welding process implicit in the Acuren report is entirely consistent with typical practice at the time.

4.8.1.2 Susceptible Microstructure

Welds made onto in-service pipelines tend to cool at an accelerated rate as the result of the ability of the flowing product to remove heat from the pipe wall. The accelerated cooling rates (a function of weld heat input, product type and flow rate, ambient temperature and pipe wall thickness) can promote the formation of hard heat affected zone (HAZ) microstructures that are susceptible to hydrogen cracking.

Acuren reported very high hardness values in the final weld pass and HAZ (> 500 HV which is consistent with martensitic microstructures) associated with the delayed hydrogen crack that caused the MP 188 failure. Hardness readings taken at three locations around the circumference of the downstream fillet weld (i.e. on the other side of the sleeve from the failure) revealed that the hardness values of the weld and HAZ at the 2:00 and 10:00 o'clock positions were all acceptable (<265 HV); whereas the hardness values of the HAZ associated with the 12:00 o'clock position were slightly >300 HV.

Although there maybe some cases in which the extent of delayed hydrogen cracking exceeds the extent of the hardened HAZ it is likely that the extent of delayed hydrogen cracking will be limited to the depth of the HAZ. The depth of the HAZ depends on the welding parameters (heat input) and the removal of heat by the flowing product; higher heat input and less-severe heat removal tend to result in a deeper HAZ. The hardness of the HAZ, and hence the susceptibility to hydrogen cracking, is just the opposite; lower heat input and more-severe heat removal tend to result in a harder HAZ. It follows that the deeper the HAZ, the less likely the HAZ is to cracking.

Figure 22 to Figure 26† and Table 2 illustrate the range of HAZ depths measured from metallographic sections prepared by Acuren at the 12:00, 2:00, 6:00 (failure location) and 10:00 o'clock positions on the fillet weld that failed and at the 6:00 position of the downstream fillet weld (i.e. on the other side of the sleeve from the failure). The maximum depth of the HAZ seen was 3.15 mm at the 12 o'clock position. The depth of the HAZ associated with the initiating crack at the 6 o'clock position correlated well to the measured depth of the crack which was 2.00 mm. The depths of the HAZ observed from the Acuren work appear to be typical for fillet welds made onto liquid filled pipelines. Even if there are fillet welds elsewhere in the line that have a deeper HAZ, these are going to be less likely to have cracks for the reasons previously discussed above.

Since the sleeves were all installed during the same period (1980's) it is reasonable to assume the welding procedures employed would have been similar. Thus the likely maximum depth of delayed hydrogen cracking that could be anticipated in association with the remaining un-inspected fillet welds is in the order of approximately 3.2 mm based on the observed HAZ depths from the Acuren work.

4.8.1.3 Source of Tensile Stress

The third factor necessary to cause delayed hydrogen cracking is a source of tensile stress. These stresses can be either applied or residual in nature; applied stresses could have resulted from pipe and sleeve self weight or as a result of mishandling shortly after the fillet welds were made. Residual stresses arise from the restraint of the welded connection and strains imposed by the contraction of the weld on cooling. Due to stress concentration effects, the highest stresses will occur at either the toe or the root of the weld.

It is therefore concluded that all three factors necessary to cause delayed hydrogen cracking could have been present in all fillet welds installed using the same welding procedure specification. While such defects may be present, they will not necessarily lead to a failure of the pipeline and could remain safe for many years, unless additional loads are imposed on the pipeline that result in stresses sufficient to cause the failure of the defects.

4.9 Summary of Findings of Task 1

Based on the findings of the individual Sub-Tasks discussed above, DNV's conclusions to date are the following:

1. The failure was caused by a 2 mm deep x 30 mm long delayed hydrogen crack located at the 6 o'clock position in the HAZ of the fillet weld used to connect the type B sleeve to the carrier pipe. The delayed hydrogen crack would have been introduced into the pipe

† Figures are taken from the Acuren Pipeline Failure Examination Report[1]

shortly after the installation of the sleeve (i.e. 30 years ago). The failure occurred in a brittle manner. There was no evidence of in-service growth,

2. The predicted (axial) stress required to cause the delayed hydrogen crack to fail varied due to assumptions regarding material toughness between 370 and 482 MPa (103 to 134% pipe specified minimum yield strength (SMYS), or 85 to 111% actual yield strength of the failed pipe),

3. The maximum calculated axial stress at the failed sleeve location taking account of internal pressure, pipe and sleeve self weight, soil overburden and lack of support beneath the pipe is only 85.7 MPa (i.e. 23.2% of the predicted stress required to cause failure, or 23.9% SMYS). It is thus concluded that the issue of potentially inadequate compaction of the backfill beneath the pipe would not in itself have caused the stress necessary for failure to have occurred; a significant additional source of axial stress was necessary to cause failure,

4. DNV has determined the combined axial stress due to normal operation (internal pressure), pipeline construction (thermal contraction and possible bending stresses induced during construction) and external loading (attempts in April 2010 to pull a sign off the sleeve, heavy equipment traversing the pipeline during site restoration). The maximum combined axial stress was calculated to be 15.6 ksi, or 107.6 MPa (30% SMYS).

5. The additional axial stress resulting from an excavation could extend a distance of 20 feet (6 metres) upstream or downstream.

6. All three factors necessary to cause delayed hydrogen cracking (a source of hydrogen, susceptible microstructure and a form of tensile stress) could have been present in all fillet welds installed using the same welding procedure specification. While such defects may be present, they will not necessarily lead to a failure of the pipeline and could remain safe for many years, unless additional loads are imposed on the pipeline that result in stresses sufficient to cause the failure of the defects, and

7. DNV has reviewed the causes of other failures associated with the fillet welds of other Type B sleeves, but no case matching the exact circumstances of MP 188 has been found.

5 TASK 2: METHODS FOR ASSESSMENT OF INTEGRITY OF FILLET WELDS ON WELD-ON SLEEVES

5.1 Background

The analysis conducted in Section 4 (Task 1) has shown that other fillet welds associated with Type B sleeves installed on the NPS 20 Rainbow pipeline in the 1980's could contain cracks. Consequently, there is a need to ascertain the most appropriate methods of both detecting and sizing such cracks. This Task therefore reviews available inspection methods; both "in-the-ditch" (visual, magnetic particle and ultrasonic) and "in-line".

In addition, the crack-like anomalies identified by Plains in association with the fillet welds of other Type B welded sleeves excavated between May and June 2011 have been catalogued and their structural significance assessed.

The ERCB requirement relating to this Task is as follows:

Consultant to determine assessment methodologies (also considering in-line inspection) that will determine the integrity of fillet welds on weld-on sleeves. Evaluate the results of the assessment methodologies to determine whether or not a failure at a fillet weld on a weld-on sleeve is likely to occur. Explain the criteria used to arrive at this determination.

Within Task 2, the following Sub-Tasks were identified:

1. Review "best industry practice" non-destructive examination (NDE) methods for fillet weld inspection, and compare them with methods utilized "in-the-ditch" by Plains (Sub-Task 1),
2. Review in-line inspection tool capabilities for the detection and sizing of circumferential weld cracking (Sub-Task 2),
3. Develop a methodology for the assessment of all reported circumferential weld flaws (Sub-Task 3),
4. Compile a "catalogue" of anomalies, reported to date, in other Type B fillet welds recently excavated by Plains (Sub-Task 4), and
5. Assess the significance of the other recently reported fillet weld cracks (Sub-Task 5).

5.2 Sub-Task 1: Review of Plains Fillet Weld Inspection Practices

Three basic techniques are available "in the ditch" for the detection and sizing of cracks associated with the toe region of fillet welds:

1. Visual inspection,
2. Magnetic particle inspection (MPI), and
3. Ultrasonic inspection (UT).

5.2.1 Visual Inspection

Visual inspection is by its nature very inexpensive and easy to perform and is normally used during the construction/fabrication phase of a project. Clearly, it can only be utilized to detect and size the length of surface breaking flaws at the toe region of fillet welds such as cracks, undercut and arc strikes, poorly formed beads, (surface breaking) porosity and misalignment. The presence of such flaws can be used as an indicator of either poor welding procedures or poor implementation of welding procedures. Any permanent records of visual inspection can be made by photography.

5.2.2 Magnetic Particle Inspection (MPI)

Magnetic particle inspection (MPI) is a non-destructive testing (NDT) technique for detecting surface and sub-surface discontinuities in ferroelectric materials such as steel. Further details are given in Reference 12.

Prior to conducting MPI, the area to be inspected must first be cleaned ad degreased. The area is then magnetized using an AC yoke. There are three primary media used for MPI, presented below in descending order of resolution:

- Wet fluorescent
- Black on white contrast
- Dry powder

The presence of a surface discontinuity in the material allows the magnetic flux to leak, thus attracting the iron oxide to the flaw and thereby making the presence of the flaw and its associated length recordable.

MPI continues to be the most widely used technique in the pipeline industry to reliably detect external surface breaking defects.

5.2.3 Ultrasonic Inspection

There are two basic forms of ultrasonic inspection; straight beam and angled beam. Straight beam basically involves the transmission of an ultrasound beam at 90 degrees to the pipe surface directly through the pipe wall. Reflections are therefore generated from either three-dimensional anomalies or defects whose primary component is parallel to the pipe surface. Consequently, it is common practice to use this technique to verify the absence of laminations (see Figure 27). However, surface breaking defects such as fillet weld toe cracks are essentially parallel to the 90 degree beam and therefore cannot be detected with straight beam probes. However, angled beam probes convert longitudinal waves to shear waves which progress at an angle to the pipe surface. Reflections can be obtained from cracks which allow them to be detected and sized. The principle of crack detection and sizing is shown in Figure 28. The basic technique has subsequently been refined to involve more complex techniques such as flaw and analysis sizing technique (FAST™), phased array and time of flight diffraction (TOFD).

Generic descriptions of the above techniques are detailed below; their applicability to pipeline fillet welds is discussed in section 5.2.4. Further references to general ultrasonic inspection techniques and their relevance to fillet weld inspection are given in References 13-16.

5.2.3.1 Flaw Analysis and Sizing Technique (FAST™)

The flaw analysis and sizing technique (FAST™) is an innovative way to use a 70° longitudinal wave to both detect and size flaws. The most distinctive feature of FAST™ is the absence of confusing geometric reflections from features such as the root beads of full penetration welds. With FAST™, the entire volume of a weld can be inspected in a single scan with a single transducer, much like a phased array or a multiple transducer system. This attribute allows for reliable inspection of pipeline long seam and girth welds. This attribute makes FAST™ more reliable than phased array UT for accurately characterizing cracks in thin walled piping.

5.2.3.2 Phased Array Inspection[17]

The phased array probe consists of many small ultrasonic elements, each of which can be pulsed individually. By varying the timing by pulsing the elements one by one in sequence along a row, a pattern of constructive interference is set up that results in a beam at a set angle. The beam is swept like a search-light through the object being examined, and the data from multiple beams are combined together to make a visual image showing a slice through the object.

5.2.3.3 Time of Flight Diffraction (TOFD)

Measuring the amplitude of reflected signal is a relatively unreliable method of sizing defects because the amplitude strongly depends on the orientation of the crack. Instead of amplitude, time of flight diffraction (TOFD) uses the time of flight of an ultrasonic pulse to determine the position of a reflector. In a TOFD system, twin probes sit on opposite sides of a weld. One of the probes emits an ultrasonic pulse that is detected by the probe on the other side. In undamaged pipe, the signals detected by the receiver probe are from two waves: one that travels along the surface and one that reflects off the far wall. When a crack is present, there is a diffraction of the ultrasonic wave from the tip(s) of the crack. Using the measured time of flight of the pulse, the depth of a crack tip can be calculated automatically by simple trigonometry.

The system has been shown to be most effective when inspecting thick-walled seam welds where it is typically used, but DNV is unaware of it being utilized to inspect pipeline fillet welds such as those associated with a Type B sleeve.

5.2.4 Applicability of Ultrasonic Inspection to Pipeline Fillet Welds

The ultrasonic methods reported above, when used correctly by a competent operator, can in DNV's experience (and that of others) be very effective in sizing cracks in full penetration welds such as pipeline long and girth weld seams; however, they are ineffective in sizing weld toe cracks associated with fillet welds in pipelines. The reasons are twofold; firstly, there is "built-in" lack of fusion between the carrier pipe and the sleeve material, and secondly the inherent weld geometry makes obtaining reliable results difficult. Consequently, DNV's experience is that ultrasonic inspection is very rarely used in the pipeline industry for the detection and sizing of cracks in the toe region of fillet welds; if UT is performed on fillet welds, the operator should have specific training and experience performing that inspection regardless of the UT method used.

5.2.5 Information Provided By Plains/WAV Inspection Ltd.

Plains have provided DNV with its procedures and other data relating to the various inspections conducted on its fillet welds; namely, visual, MPI and UT. DNV has reviewed the procedures which relate to:

1. Surface preparation,
2. Black and white contrast MPI and calibration of MPI equipment (AC yoke), and
3. Straight and shear wave ultrasonic inspection, together with equipment calibration.

DNV has concluded that all the procedures[20] provided by WAV* Inspection Ltd. meet industry requirements. Plains' NDE contractor, WAV Inspection Ltd., has conducted visual and MPI inspection on all 13 excavated sleeves, and have utilized "straight beam" ultrasonics to measure carrier pipe wall thickness adjacent to the sleeves and confirm the absence of laminations. As anticipated, shear wave ultrasonic inspection has not been utilized to try to measure crack depths.

5.2.6 Discussion

The relative merits of the three different inspection techniques are summarized in Table 3. Based on DNV's knowledge of practices presently being used within the pipeline industry to inspect fillet welds, the most common and reliable methods are visual inspection and MPI. Before conducting such inspections, the surface should firstly be cleaned. Visual inspection should

* Plains NDT contractor

easily detect general poor weld profile and defects such as arc burns and undercut; however, these defects typically are insignificant with respect to structural integrity. The advantage of MPI is that it reliably detects surface breaking defects (two PRCI-AGA[14,19] studies cited a 100% detection rate for weld toe cracks in the laboratory) and provides crack length measurements. However, neither technique can provide crack depth. The most reliable method for determining the depths of cracks associated with fillet welds is successive grinding and MPI to confirm removal of the crack followed by UT of the remaining wall thickness.

DNV has reviewed the visual and MPI procedures provided by Plains and confirmed that in relation to surface preparation, black and white contrast MPI and calibration procedures, Plains' NDE contractor, WAV Inspection Ltd., has used typical, acceptable procedures as specified by both NACE and the Steel Structures Painting Council (SSPC).

5.2.7 Recommendations

- Visual inspection should be performed to detect and measure undercut and arc strikes. MPI can sometimes enhance the examination of these anomalies to facilitate better length measurements.
- Fillet weld inspection by ultrasonic shear wave inspection is not recommended. If ultrasonic shear wave inspection of fillet welds is conducted, then the operator's competence is the most critical factor in both the detection and sizing of flaws, irrespective of the actual technique used.
- The most reliable method for determining the depths of cracks associated with fillet welds is successive grinding and MPI to confirm removal of the crack followed by UT of the remaining wall thickness.

5.3 Sub-Task 2: In-Line Inspection Detection and Sizing Capabilities

5.3.1 Background

This section considers the viability of using currently available in-line inspection technologies to detect circumferential cracks in the fillet welds of Type B repair sleeves.

The information in this section was obtained from telephone interviews with three major ILI vendors with operations in Alberta; namely, Rosen Inspection (Rosen), GE-PII Pipeline Inspection (GE) and BJ Pipeline Services (BJ) (now a subsidiary of Baker-Hughes).

5.3.2 Summary of Commercially Available In-Line Crack Detection Tools

In-line inspection tools classified for crack detection are available from several vendors. They are based on both magnetic flux leakage (MFL) and ultrasonic (UT) technologies. However, as discussed below, all standard crack-detection tools are configured to detect longitudinal cracks and their applicability to circumferentially-orientated cracking is limited.

MFL tools saturate the pipe with magnetic flux as the tool passes along the pipe. They operate on the basis of detecting flux that 'leaks' from the pipe at the locations of anomalies as a result of the reduced capacity of the pipe wall to retain the flux when its cross-sectional area is reduced. To produce a measurable effect, the anomaly has to exceed a minimum volume and must be aligned perpendicular to the direction of the induced magnetic field to create a strong signal. Anomalies aligned parallel to the induced magnetic field create a smaller signal and may not be detected.

MFL is offered by some vendors as a crack detection technology. Such tools are generally designed to detect cracks with significant width (i.e. the crack mouth is open) and orientated perpendicular to the MFL signal, which is typically in the circumferential direction so as to detect axially-orientated cracks. Such tools would be insensitive to tight cracks or circumferentially-orientated cracks.

UT tools operate by transmitting ultrasonic pulses into the pipe wall and detecting reflections from any defects present. They are well suited for crack detection, but are typically configured to detect longitudinally aligned defects.

5.3.3 ILI Vendor Interviews

5.3.3.1 BJ Pipeline Services

BJ Pipeline Services offer a high-resolution tri-axial MFL tool, commercially offered under the 'Vectra' trade name. They do not offer an ultrasonic crack detection tool.

They state that the Vectra tool is capable of detecting circumferential cracks, for example in girth welds, but only where the crack has a significant width. They would not expect their tools to detect sleeve fillet weld cracking of the type associated with the failure at MP188 of the NPS 20 Rainbow pipeline.

5.3.3.2 GE-PII Pipeline Inspection

GE offer several types of high-resolution MFL tools (trade name MagneScan) and ultrasonic crack detection tools (trade name UltraScan). They also have a phased-array ultrasonic technology (DuoScan). The UltraScan tool was run on the NPS 20 Rainbow pipeline in April 2011. No indication of the weld crack at MP188 was reported.

GE's comments on the ability of MFL tools to detect circumferential sleeve fillet weld cracks were in agreement with those of BJ.

For their UltraScan technology, the standard tool will not 'see' circumferential cracks because the sensors are configured to introduce the ultrasonic signal circumferentially around the pipe which will reflect from longitudinal SCC and seam weld cracks (i.e. the types of cracking most commonly of concern in pipelines). This configuration does not allow circumferential cracks to be detected and partially explains why the crack at MP188 was not detected in the recent UltraScan inspection.

GE has built UltraScan tools with the UT sensors rotated 90° to detect circumferential cracks. No such tool exists in the NPS 20 required for the NPS 20 Rainbow pipeline, though theoretically such a tool could be built. However, given the complexity of a fillet weld geometry (versus a standard girth weld) and the small size of the initiating crack at the MP188 sleeve (2 mm deep x 30 mm long), a very high sensor density and extensive testing would be required to achieve a high level of confidence of detecting similar defects.

The DuoScan tool is also configured to detect axially aligned features and conversion to a circumferential defect configuration was not considered to be practical.

5.3.3.3 Rosen Inspection

Rosen offer both MFL and UT tools similar to those of GE. Their 'RoCorr' MFL tool was used for the most recent inspection of the NPS 20 Rainbow pipeline. It did not see any indication of a defect at the MP188 sleeve weld location. This is believed to be due to the same limitations of the MFL technology discussed above.

Rosen's RoCorr-UT ultrasonic crack detection fleet is also configured primarily to detect longitudinal cracking although they have also successfully run a tool configured for circumferential defects, albeit only in a NPS 6 size. The same design could be scaled for a 20-in tool on request. The same technical challenges identified by GE were noted.

5.3.4 Discussion

No in-line tool capable of reliably detecting a circumferential crack in a pipeline fillet weld is available from the standard fleets operated by the major ILI vendors. A special-build tool is possible, but would require a long lead time for design, construction and testing and the technical issues would be significant. For the purposes of re-instatement of the NPS 20 Rainbow pipeline, no in-line option exists that could meet the timescale under consideration. Given the limited number (95) of welded sleeves on the NPS 20 Rainbow pipeline, excavation and detailed NDT of 100% of these welds would be faster, more economical and more reliable than an in-line solution.

For these reasons, the development of an in-line tool to detect cracks in circumferential sleeve fillet welds is not considered to be a practical option.

5.4 Sub-Task 3: Methodology for the Assessment of Circumferential Weld Flaws

As previously stated in Section 4 (Task 1, Sub-Task 1), DNV will utilize either the CorLAS™ or NASGRO 3.0.19 software program to assess the significance of any reported crack-like defects detected in the fillet welds of other Type B sleeves inspected by Plains.

As a simple tool to estimate the severity of any circumferential crack discovered in the line, a series of crack acceptability curves was produced. They show the maximum allowable crack depth as a function of length at assumed axial stresses of 359 MPa (equivalent to 100% SMYS) and 395 MPa (equivalent to 110% of SMYS). A lower bound Charpy impact energy (CVN) of 7.38 ft-lb (10 J) was conservatively assumed based on the toughness of the pipe joint that failed. Curves were calculated for both the 7.14 mm wall thickness and 5.56 mm wall thickness sections of the line (see Figure 29 and Figure 30). It should be recognized that these curves are based on minimum tensile properties for this grade of steel. The actual tensile properties should exceed these values.*

Provided their circumferential length is less than 10% of pipe circumference (152 mm), fillet weld cracks less than 3.70 mm in depth are not predicted to fail at axial stresses ≤ 100% SMYS in both 5.56 and 7.14 mm nominal wall thickness pipe. At axial stresses ≤ 110% SMYS, the equivalent depths are 1.5 mm in 7.14 mm wall thickness pipe and 1.1 mm in 5.56 mm wall thickness pipe. These depths increase to 2 mm and 1.9 mm respectively, provided the circumferential length is ≤ 80 mm, (i.e. the maximum length of cracking detected to date), see Figures 29 and 30.

5.5 Sub-Task 4: Compilation of Crack-Like Flaws Reported by Plains

5.5.1 Summary of Detected Cracks

Eleven excavations involving 13 Type B sleeves have been conducted by Plains since the failure as part of their program to evaluate the safety of the line for reinstatement. The excavated sites are listed in Table 4. Ten of these sleeves were found to have a total of 21 cracks in association with their circumferential fillet welds; the maximum number of cracks reported in an individual fillet weld was 4 (sleeve at GW56510 on the Zama to Rainbow section). A listing of crack-like and other surface-breaking flaws reported by Plains associated with the fillet welds is given in Table 5.

The cracks were identified using visual and black and white contrast magnetic particle inspection. Crack depths were assessed by means of successive grinding resulting in the removal of the majority of the cracks followed by UT measurements of the remaining wall thickness. In

* At the MP 188 failure site, the yield strength and ultimate tensile strength of the pipe body material were found to be 433 MPa and 588 MPa respectively. The minimum permitted properties of CSA Grade 359 steels are 359 MPa yield and 455 MPa tensile.

two cases, a portion of the crack was left in place due to the "crack propagating into the weld material". Available photos of the cracks were reviewed by DNV to confirm their overall length and determine their maximum interlinked crack length.

Provided in Table 6 and Figure 31 to Figure 36 are tabular and graphical depictions of the reported crack depths and lengths of the 21 cracks. The crack depths ranged from 0.4 mm to 2.12 mm (7% to 38% of the pipe wall thickness). The total length of the cracks ranged from 3 mm to 79 mm while the maximum interlinked crack lengths ranged from 1 mm to 53 mm. No crack was found whose depth and length dimensions both exceeded those of the crack that failed at MP 188.

The length and depth of the reported cracks have been plotted on the applicable critical size curves as depicted in Figure 34 and Figure 35. As illustrated in these figures, none of the 21 cracks has dimensions that would be critical at an axial stress <110% SMYS. The actual failure stress of each crack has been calculated and presented in Sub-Task 5 below.

5.6 Sub-Task 5: Assessment of Reported Crack-Like Defects

For each of the reported circumferential cracks referenced in Sub-Task 4 above, an assessment was made of the axial stress that would be required to cause the respective cracks to fail using the CorLAS™ software program described in Section 4 (Task 1, Sub-Task 1). The assessment considered the axial stress only because of the circumferential orientation of the weld cracks. In each case, the mode of failure (brittle fracture or ductile failure) was also calculated. When more than one crack was found in a single location, crack lengths equal to the total length of the colony and equal to the longest interlinking length (or individual crack when no interaction was predicted) were considered.

Since measured material properties are not available for the pipe material at each location, a conservative estimate of the minimum tensile properties for the Grade 359 steel was used (i.e. 359 MPa yield strength and 455 MPa tensile strength). For the fracture toughness, the lower shelf J fracture toughness (J_c) of 74 lb/in (as measured from the pipe joint that failed) was used. The majority of cracks were predicted to fail by ductile tearing with critical stresses in excess of the material SMYS. Three exceptions at GW 55760 (total colony length), GW 57060 (interlinking length) and GW 58280 (interlinking length), were predicted to fail by brittle fracture.

The results of the assessment are shown in Table 6. All the reported cracks from the excavated welds have predicted critical axial stresses that exceed the 370 MPa calculated for the defect at MP 188. The minimum critical stress for an individual (or interlinking) crack was 400.3MPa (112% SMYS) at GW 57060 of the Zama to Rainbow section.

The magnitude of the axial failure stresses predicted to cause failure, based on total length of cracking, for the 18 cracks, for which dimensions are available, varies from 391.3 MPa (109% SMYS) to 406.7 MPa (113% SMYS). These values are greater than the predicted failure stress

(370 MPa, or 103% SMYS) of the crack which caused the MP 188 failure. All these values are significantly greater than values conceivable during normal pipeline operation, from which it is concluded that significant additional loads would need to be imposed to cause failure of any of the detected cracks.

5.7 Summary of Findings of Task 2

Based on the findings of the individual Sub-Tasks discussed above, DNV's conclusions to date are the following:

1. The most suitable "in the ditch" inspection methods for detecting surface-breaking fillet weld anomalies such as weld toe cracks are visual inspection and magnetic particle inspection (MPI). Ultrasonic methods are rarely utilized within the pipeline industry to measure crack depth at fillet welds.

2. The most reliable method for determining the depths of cracks associated with fillet welds is successive grinding and MPI to confirm removal of the crack followed by UT of the remaining wall thickness.

3. Based on currently available tools, in-line inspection is not a practical option to detect and size crack-like defects associated with the fillet welds of other type B sleeves known to be present along the NPS 20 Rainbow pipeline.

4. There are two methodologies available for determining the critical axial stress required to cause a fillet weld crack to fail; namely, the CorLAS™ and NASGRO 3.0.19 software programs. The CorLAS™ software program was used to derive critical length and depth curves at axial stresses equal to 100% and 110% SMYS which can subsequently be used to do a high level assessment of any future fillet welds cracks detected.

5. Since the failure Plains has completed 11 excavations involving 13 Type B sleeves. During those excavations 21 fillet weld cracks were detected. Two welds were found to have cracks deeper than that associated with the failure (2 mm), the deepest crack having a depth of 2.12 mm. Two cracks were found to be longer than that associated with the failure (30 mm) but no cracks were both longer and deeper than that associated with the failure.

6. All the reported cracks were contained within the fillet weld heat affected zone (HAZ), and

7. All the reported cracks have predicted failure stresses greater than 370 MPa, the minimum predicted stress to have caused the failure at MP 188.

6 TASK 3: PRE-RESTART WELD ASSESSMENT PROGRAM

6.1 Background

Prior to re-pressurization of the pipeline, Plains must provide a reasonable level of assurance that a failure similar to the one at MP 188 will not occur whilst Plains is in the process of excavating, assessing and repairing as necessary the remaining Type B sleeves installed in the 1980's.

To meet this requirement, Plains proposed in their submission of May 20th, 2011 to the ERCB, "Request for Leave to Resume Operation of NPS 20 Rainbow Pipeline (License 5592-1)", that a set of sample excavations on sleeves would be performed to gain an understanding of the extent and nature of weld flaws in the remaining population of Type B welded repair sleeves on the pipeline. Plains stated that they would firstly inspect the fillet welds of five sleeves♣ which Plains themselves had excavated since acquiring the pipeline in 2008 (Inspection Plan A). At each excavated weld, they would check for the presence of four coincident factors believed, at the time, to be the cause of the failure at MP188. These coincident factors were:

1. The presence of a stress riser in the form of an increase in relative pipe stiffness from the carrier pipe to the carrier pipe with a full encirclement sleeve.
2. Differential settlement due possibly to inadequate compaction following the re-excavation of a segment of pipeline straddling the location of a stress riser.
3. Excessive stress on the bottom chord of the pipeline likely resulting from soil settlement.
4. The presence of an initiating crack.

Secondly, they would inspect a further 5 sleeves that were selected based on their accessibility (Inspection Plan B). Finally, Plains stated that over a (probable) period of two winters♦, they would excavate and inspect all remaining Type B welded sleeves in the NPS 20 pipeline section between Zama and Utikuma (Inspection Plan C). Plains stated that on completion of Inspection Plans A & B, the line could be safely returned to service at a reduced pressure of 4,000 kPa (55% licensed MOP) with a return to the full licensed MOP on completion of Inspection Plan C.

Plains also stated that, as an additional precaution, they would install an over-sleeve (known as a sleeve-on-sleeve repair) over all the Type B sleeves as they are excavated. The installation would be performed using the welding procedures developed specifically for this pipeline as part of the additional projects referenced in Section 3.0 and the sleeve installation procedures

♣ Two of these had already been excavated at the time of the May 20th, 2011 submission.

♦ This is a conservative estimate. Plains now believe this may be achievable within one winter period.

discussed in Section 8 (Task 5). Plains' intent of installing the oversleeve is to minimize the likelihood of any future failures of the fillet welds associated with the Type B sleeves installed in the 1980's.

The objective of this Task is to assess whether the Plains' proposed program of excavations, weld assessments and pressure reductions will provide the necessary level of assurance that a failure similar to the one which occurred at MP 188 will not occur whilst Plains is the process of addressing the remaining Type B sleeves installed in the 1980's. If this is found not to be the case, a follow-on objective will be to recommend an alternative plan that provides Plains and the ERCB with the required level of assurance.

6.2 Approach for Assessing the Validity of Plains' Proposed Program

In order to evaluate the effectiveness of Plains' current program, DNV has reviewed those factors which could contribute to the probability of another failure of a Type B sleeve. Based on present knowledge that all fillet welds were made with cellulosic electrodes, it is assumed that all fillet welds could contain cracks. The objective then is to estimate the likelihood of another failure of a welded sleeve due to these cracks and to ensure that steps are taken to reduce the likelihood as far as reasonably possible.

In order to assess the potential for a failure in association with the remaining Type B sleeves, DNV and BGC Engineering Inc. have reviewed and assessed data related to the following:

1. Ground conditions associated with the failure at MP 188 to try to determine the source of the axial/bending loads which caused the failure.

2. Ground conditions at the site of the 11 recent excavations to identify any similarities/differences between those sites and the failure site.

3. Geographical/geological factors (soil type, drainage, topography etc.) associated with the location of each of the 95 Type B sleeves, and

4. Proximity and date of subsequent excavations near the location of the Type B sleeves

6.2.1 BGC Engineering Site Visit, July 18th – July 20th 2011

BGC Engineering initially conducted a "desk top" study based on available information to identify those Type B sleeves which could be in the proximity of a geological hazard. A site visit was subsequently scheduled to confirm or revise as necessary the findings of the "desk top study". As previously stated in Section 4 (Task 1 sub-Task 3), BGC Engineering made a visit to the site of the failed type B sleeve, GW 55310 at MP 188 on June 29th, 2011. Between July 18th and July 20th, BGC Engineering made a site visit to the locations of all the remaining Type B sleeves. An inspection at each sleeve site was completed, although it was not possible to land the helicopter at all sites due to the presence of standing water. At all sites, a visual assessment of the site conditions was conducted, photographs were taken and field observations and measurements, where possible, were recorded.

At each site, BGC Engineering noted any areas of possible soil disturbance and (where ground access was possible) measured the undrained shear strength of the soil and made small excavations to examine the soil type. Based on these field observations and measurements, BGC Engineering was able to assess whether or not a geotechnical threat potential existed at given sleeve location. The findings are summarised in Table 7

BGC Engineering recorded at the following data at each sleeve location:

1. The soil type, (e.g. clay, till, muskeg etc.).
2. The drainage characteristics of the soil (e.g. well drained, poorly drained, standing water etc.).
3. The terrain topography (e.g. flat, slightly sloped etc.).
4. The position of the sleeve relative to a slope as appropriate (e.g. toe, middle, crest).
5. The general soil classification with respect to geotechnical hazard, defined as “good”, “adequate” or “adverse” (“good” is defined as a slope which would need to be steeper than 20º before being regarded as a hazard, “adequate” is defined as a slope which would need to be steeper than 15º before being regarded as a hazard, and “adverse” is defined as a slope which would need to be steeper than 5º before being regarded as a hazard).
6. Geotechnical threat; this is specifically designated as any geotechnical hazard which could cause additional axial /bending stresses at the sleeve fillet weld toe.

6.3 Sleeve Locations and Collation of Associated Parameters

DNV has utilized information supplied by Plains, particularly the 2011 MFL in-line inspection data, to determine the location of all remaining Type B sleeves in the NPS 20 Rainbow pipeline. The pipeline was inspected in three sections; namely, from Zama to Rainbow, from Rainbow to Cadotte and from Cadotte to Utikuma sections.

Provided in Table 8 is a listing of the locations of each of the 95 Type B sleeves together with all the following relevant data:

1. Sleeve identifier and length.
2. Soil characteristics as obtained by BGC Engineering during their site visits, including proximity to organic soils.

3. BGC Engineering's assessment as to whether the sleeve location is impacted by a geotechnical threat as determined during their site visits.

4. The proximity to the nearest previous excavation

5. The volume of product which could be lost.

Provided in Figures 37 to 40 are graphical depictions as to the locations of the 95 Type B sleeves (including which ones have been excavated and the date they were excavated), previous excavations resulting in the installation of a Petroline Type A sleeve or a recoat and valves in each of the three in-line inspection sections.

Provided in Figures 41 to 52 are graphical depictions of each individual sleeve location complete with the information provided with in Figures 53 to 125.

6.4 Risk Ranking Approach to Pipeline Reinstatement

As previously discussed in Section 4 (Task 1), calculations have determined that the sleeve weld cracks present in the NPS 20 Rainbow pipeline would require an axial stress in excess of 110% SMYS in order to fail. Also in Section 4 (Task 1) an assessment was done to evaluate the axial stress levels which could be generated as a result of different conceivable sources of loading. That assessment concluded that none of the modelled sources would result in stress levels significantly greater than those anticipated during normal pipeline operation and none would result in the stress levels required to cause failure of the fillet weld cracks that have been detected to date on the NPS 20 Rainbow pipeline.

Consequently, the source of the significant loading necessary to cause the failure at MP 188 is still unknown but it is postulated that the previous excavation played some, as yet undefined role, in the creation of the additional stresses required to cause failure. The reason for this postulation is that given the failure site isn't in proximity to a geotechnical hazard the only thing that has changed at that site since it was installed in the1980's is the fact that it was excavated in 2010. BGC Engineering has stated that following an excavation soil normally regains its full strength within approximately 2 years.

Since Plains has confirmed that they have now excavated all Type B sleeves on the NPS 20 Rainbow pipeline that have been exposed within the last 2 years for other reasons and since BGC Engineering has determined that none of the remaining Type B sleeves are situated near a geotechnical hazard there is no reason to believe that the remaining sleeves will be subjected to higher axial stresses than they have been since they were originally installed.

Thus although the actual source(s) of the axial stresses that caused the MP 188 failure are still unknown and assuming the local conditions associated with the remaining sleeves do not change between now and the time Plains excavates and assesses them there is no reason to believe they will fail and thus the NPS 20 Rainbow pipeline should be allowed to return to service. Since a reduction in internal pressure has a minimal impact on the magnitude of axial stress acting on the toe region of a fillet weld imposing a pressure restriction will have limited benefit in reducing the likelihood of a fillet weld failure on the NPS 20 Rainbow pipeline.

As mentioned above it is postulated that the 2010 excavation played some role in the MP 188 failure and thus the remaining sleeves were ranked based on their proximity to an excavation that has occurred within the last 2 years. As discussed previously in Section 4 (Task 1), the PIPLIN software was used to determine that the additional stress resulting from an excavation could extend ± 6 m upstream and downstream of the excavation. However, it was noted that this value was based on a particular pipeline profile, excavation length and soil characteristics and therefore a safety factor should be applied when making a generic case. On this basis, DNV has incorporated a safety factor of 2 on this length, and therefore recommends the following risk ranking for the remaining Type B sleeves:

1. All Type B sleeves which are >12 m upstream or downstream of an excavation that has occurred within the last 2 years are designated a "Low" risk, and

2. All Type B sleeves which are <12 m upstream or downstream of an excavation that has occurred within the last 2 years are designated a "Medium" risk. These sleeves should be excavated as a first priority by Plains. It should be noted that 3 Type B sleeves are located within ± 12 metres of previous excavation but they were installed before Plains acquired the pipeline (i.e. > 2 years).

Table 9 shows that a total of 9 Type B sleeves in 7 joints (6 in the Zuma – Rainbow section and 1 within the Cadotte to Utikuma section) fall within the "Medium" risk category and should be investigated as a higher priority ahead of those sleeves falling within the "Low" risk category.

Plains should investigate all remaining Type B sleeve inspections (Inspection Plan C) before the end of the year 2012 as stated in Section 6, Task 3. However, Plains should monitor these sites on a regular basis. It is understood that Plains conduct weekly aerial patrols using fixed wing aircraft to monitor activities which could potentially affect the integrity of the pipeline, and the scope of these patrols should be extended to monitor for changes in ground conditions which could cause additional axial stresses. Plains are recommended to engage the services of BGC Engineering to assist in training pilots regarding "tell tale" indications of ground movement.

7 TASK 4: WELD DEFECT REMEDIATION

The purpose of this section is to respond to the following ERCB requirement:

Assess and determine appropriate remediation measures to manage the integrity of fillet welds on weld-on sleeves. This work should focus on weld-on sleeves, pipe support and backfill.

In order to achieve this objective, DNV has reviewed all the available methods for remediating defective fillet welds similar to the one at the MP 188 failure site, and the actions to take (if any) for non-defective welds. The work scope included the following:

- A review of the various options for remediation of defective fillet welds. The options considered range from a fitness-for-service assessment without defect removal to replacement of the existing weld or sleeve with new pre-tested pipe. The review considered both technically related issues and regulatory acceptability.
- Development of recommended measures when sleeve fillet welds are found to be in good condition.
- An assessment of Plains' currently proposed plan to install over-sleeves on all repair sleeves excavated in the pipeline remediation program.

7.1 Remediation Options

During the evaluation of the remediation options, it was assumed that the fillet weld defects would be discovered during the planned inspection program and that the welds would be exposed and accessible by excavating the pipeline. Four different options, allowed by CSA Z662, were evaluated for applicability to defective fillet welds having characteristics similar to the one at the MP188 failure site. Those options included:

1. Fitness-for-service assessment without defect removal.
2. Defect removal by grinding.
3. Encapsulation of defective weld using sleeve-on-sleeve approach.
4. Replacement of defective sleeved pipeline segment with new pre-tested pipe.

7.1.1 Fitness-For-Service Assessment Without Grinding

Various fitness-for-service ("FFS") approaches, known as "engineering critical assessments" or ECA, have been validated for the assessment of cracked welds. The methodologies rely upon good estimates of pipe and weld mechanical properties as well as the applied and residual stresses acting on the weld. The primary application of FFS is to avoid the costly repair or removal of defective welds that can be shown to have adequate resistance to failure for the anticipated service conditions. It is most often applied to girth welds involved in the construction of new pipelines in which, if flaws are discovered during the post-weld inspection, information is readily available regarding the mechanical properties and flaw dimensions.

In order to conduct an ECA, two critical inputs are required; namely, well-characterized weld material properties and reliable crack depth measurements. Weld material properties can only be obtained from destructive testing. As mentioned previously in Section 5, the only method to reliably obtain the depth of cracks associated with the toe region of sleeve fillet welds is by successive grinding and MPI (to confirm complete removal of the crack), which requires the sleeve to be excavated. Therefore, an ECA without grinding is impractical.

It is also worth noting that the cost associated with actually excavating the pipeline accounts for the most significant portion of the total cost of a permanent repair to the sleeve and hence it would only make sense to repair any fillet weld defects detected during an excavation using one of the approaches discussed in the following sub-sections.

7.1.2 Defect Removal By Grinding

Grinding is an effective and accepted method for the repair of defects in buried pipelines provided that the following two conditions result from the grinding:

1. The stress concentrating effect of the defect is completely removed, and
2. The amount of metal removed by grinding does not adversely affect the integrity of the pipeline.

It is recommended that the weld toe should be dressed by the careful use of a disc grinder or preferably with a fine rotary burr as shown in Figure 126 and Figure 127. Complete defect removal is easily verified by conducting repeat MPI as grinding proceeds.

DNV is recommending the following acceptance criterion for ground areas created during the removal of defects associated with the fillet welds of sleeves:

- **7.14 mm Wall Thickness Pipe - Allowable Grind Dimensions**
    - ≤ 1.75 mm (25%) in depth for lengths ≤ 80 mm (maximum length of cracking found to date on the NPS 20 Rainbow pipeline)
    - ≤ 1.0 mm (14%) in depth for lengths between 80 mm and 120 mm

  - Cracks longer ≥120 mm shall be repaired using a sleeve on sleeve repair or by replacing the portion of pipe containing the sleeve with new pre-tested pipe

- **5.56 mm Wall Thickness Pipe - Allowable Grind Dimensions**
  - ≤ 1.4 mm (25%) in depth for lengths ≤ 80 mm (maximum length of cracking found to date on the NPS 20 Rainbow pipeline)
  - ≤ 0.75 mm (14%) in depth for lengths between 80 mm and 120 mm
  - Cracks longer ≥120 mm shall be repaired using a sleeve on sleeve repair or by replacing the portion of pipe containing the sleeve with new pre-tested pipe

The above criterion was developed by taking into account the dimensions of volumetric defects (i.e. ground areas and/or metal loss) that would be expected to be critical, assuming failure would be governed by flow strength, at axial stresses equal to 110% SMYS (refer to Figure 128 and Figure 129). The actual allowable grind depths are then set to be more conservative than those dimensions by a minimum of 0.7 mm (13% of the pipe wall thickness) for the 5.56 mm wall thickness pipe and 0.8 mm (11% of the pipe wall thickness) for the 7.14 mm wall thickness pipe. The step change in the allowable grind depth was introduced at a length of 80 mm because this is the maximum length of cracking found to date and to ensure that the required level of conservatism is maintained for lengths between 80 mm and 120 mm. Although using the above approach would facilitate the establishment of allowable grind depths for defects longer than 120 mm it was arbitrarily decided to limit the extent of grinding to lengths ≤ 120 mm for conservatism.

7.1.3 Encapsulation of Defective Weld Using Sleeve-on-Sleeve Approach

A sleeve-on-sleeve assembly is fabricated from rolled pipe or rolled plate (see Figure 130). It can be easily fabricated to accommodate almost any length, and requires only one fillet weld to either end of the carrier pipe. To DNV’s knowledge, the encapsulation of a defective weld using a “sleeve-on-sleeve” approach is utilized by at least one other major Canadian operator. Further details are provided in Section 8.

7.1.4 Replacement of Defective Sleeved Pipeline Segment With New Pre-Tested Pipe

Replacement of the defective sleeve with new pre-tested pipe is always an option but it involves a significant disruption in service.

7.2 Assessment of Plains' Plan To Over-Sleeve All Welds

DNV has considered Plains' plan to repair all Type B fillet welds, irrespective of whether or not they are defective. DNV's opinion is that there is no benefit in "repairing" welds which are found to be non-defective based on workmanship standards. The technical justification for this opinion is that since any welding operation carries some risk that weld flaws can be introduced; there is little or no benefit in using a welded repair on welds that have no evidence of cracking. That is particularly true if the potential effect of the additional residual stresses and added weight of the new sleeve are considered.

In addition:

- DNV is unaware of any examples of transmission pipeline fillet welds that eventually cracked in service if the welds had no workmanship defects when they were subjected to a pre-service inspection following a suitable delay time after the weld had cooled, and

- The use of an oversleeve only when deemed necessary is consistent with an NEB report where their belief was that the need for remediation should not be based on "…*assessment of susceptibility* to cracking. Rather, such measures should be triggered by the *actual condition* of the welds…" (emphasis added by DNV).

DNV's recommendation is therefore only to over-sleeve defect welds when shown to be technically necessary.

7.3 Summary

This Task has addressed the available fillet weld remediation methods from a fitness-for-service assessment through to replacement of the affected sleeve with new pre-tested pipe. All the methods are well proven although in Plains' particular case a fitness-for-service assessment of any fillet welds cracks detected during an excavation is deemed to be impractical.

With respect to the original Type B fillet welds which are found to be acceptable to workmanship standards and show no evidence of delayed hydrogen cracking, it is DNV's opinion that no further repair actions should be taken.

8 TASK 5: SLEEVE-ON-SLEEVE REPAIR

The purpose of this section is to respond to the following ERCB requirement:

Assess and determine the suitability and effectiveness of the sleeve-on-sleeve method proposed by Plains to repair fillet welds on sleeves.

In order to achieve this objective, DNV has assessed the suitability and effectiveness of "sleeve-on-sleeve" assemblies to repair defective full encirclement sleeve fillet welds. The design was originally developed by Interprovincial Pipeline Limited (IPL) in response to a failure during the repair of their pipeline near Camrose, Alberta in February 1985.

The "sleeve-on-sleeve" repair configuration (shown in Figure 130) consists of two rings, or "shoes", installed outboard to the ends of the defective sleeve. In the case of a sleeve having only one defective end, only one shoe is installed. Each shoe is fillet welded to the carrier pipe on the end facing the defective end of the sleeve.

The final step consists of installing two outer half-sleeves to bridge the gaps between the shoes and the defective sleeve. These outer half-sleeves are fillet welded to both the shoes and the defective sleeve to make a leak-tight repair in case the toe crack grows through the wall of the carrier pipe. If an unanticipated toe crack were to form at the fillet weld of one or both of the shoes, the cracking and potential leakage will be contained within the space between the shoes, the new outer sleeve and the pre-existing sleeve.

For the sleeve-on-sleeve repair to perform adequately:

- The pressure carrying capacity of the repair should exceed the pressure corresponding to 100% of the carrier pipe SMYS,
- The shoe-to-carrier pipe fillet welds and the shoe to outer sleeve fillet welds must not leak, and
- The sleeve assembly must be capable of carrying all of the longitudinal stress on the pipeline, including any additional stress imposed by the added weight of the sleeve-on-sleeve assembly.

There are pros and cons for which end of the shoe should be fillet welded to the pipe but DNV's preference is to weld the inboard end for the following reasons:

1. Any leak through a crack at an inboard weld will be contained within the original sleeve, the shoe and the over-sleeve. An outboard fillet weld can always be inspected, but it is more highly stressed and if it does fail, then a leak path exists, and
2. Any perceived risk of fluid ingress causing crevice corrosion if welding inboard can be overcome by sealing the outboard end of the repair with a variety of effective sealers (either elastomeric caulk-like compounds or thermosetting epoxies).

In some cases, separate full encirclement sleeves may be in close proximity to each other and at least one of the inboard fillet welds between the two sleeves may be defective. In that case, it is permissible to eliminate the use of shoes and attach an overlapping sleeve that bridges across the gap between the two sleeves. The overlapping sleeve is fillet welded to the outer surface of each defective sleeve and any leakage is contained within the annular space between the carrier pipe and the overlapping sleeve. Additional benefits include the fact that the overlapping sleeve prevents the need for making any new welds directly to the carrier pipe and the overlapping sleeve stiffens the sleeved area and minimizes bending stresses on the defective fillet welds.

8.1 Sleeve-on-Sleeve Validation

In 1989, Kiefner and Maxey[21]conducted validation testing of the sleeve-on-sleeve repair design. The testing included the application of pressure and bending to repaired sleeves that had full circumferential separation (two loose ends), and a fully circumferential 50% deep flaw.

The test samples were subjected to a bending moment equivalent to 100% SMYS and an internal pressure giving a hoop stress of 72% SMYS. No leakage was observed, and the authors concluded that the sleeve-on-sleeve repair technique "…can be used to repair sleeves and prevent fluid leakage resulting from failure of cracked fillet welds at the ends of existing single sleeves without adversely affecting the integrity of a pipeline."

Kiefner and Maxey also referred to validation work performed by others in which the shoe fillet weld was located on the side of the shoe furthest from the defective sleeve (i.e. not under the outer sleeve) and the pipes were internally pressurized without an applied bending stress. In one case the test was terminated without failure when an axial strain of 7% was attained in the carrier pipe. In the second case, the pipe burst outside the sleeve when the pressure was equivalent to 50% of the SMYS of the grade X52 carrier pipe. Kiefner and Maxey concluded that "These tests provide enhanced confidence that the pressure carrying capacity of a properly fabricated sleeve-on-sleeve repair can be expected to exceed that corresponding to a stress level of 100% of SMYS."

8.2 National Energy Board (NEB) Approval

As part of its investigation into the Camrose incident experienced by Interprovincial Pipe Line Ltd. (IPL), the NEB reviewed and agreed to the use of certain repair techniques including the "sleeve-on-sleeve" repair methodology. The relevant part of their report is reproduced as Figure 131.

9 TASK 6: PIPE SUPPORT, COMPACTION AND BACKFILL PROCEDURES

The purpose of this Task is to address the following ERCB requirement:

Assess Plains' pipe support compaction and backfill procedures and make recommendations for improvement to ensure that improper backfilling and compaction at excavated weld-on sleeve sites is no longer a hazard to the fillet welds.

In order to achieve this objective, DNV reviewed the pipeline backfill procedures supplied by Plains and BGC Engineering made some preliminary observations regarding the actual backfill quality associated with the repair of MP 188.

9.1 Sub-Task 1: Review Plains' Backfill Procedures

DNV has reviewed the latest version of Plains' "Pipeline Backfill Procedure" for backfilling a typical pipeline excavation where the supporting earth underneath the pipeline has been removed for inspection of the pipe or, in this case, installation of a Type B welded repair sleeve. Maximum span lengths are given for a range of pipe diameters with instructions to determine the necessity to install additional supports if fixtures are installed or encountered (sleeves, fittings, tap valves, etc.).

The document reflects industry standard practice in avoiding inadequate support underneath a pipeline in conditions of flat ground away from slopes or ditches. However, the procedure could be enhanced by considering the following:

1. Specifying limits for the use of heavy equipment to traverse back and forth over the freshly backfilled excavation to effect soil compaction by utilizing the stress calculation methodology in API 1102[22].

2. Ensuring that the effect of any fixtures that are installed or encountered that create additional weight or anchor points to the pipeline are considered.

3. Adding the instructions for "crowning" the backfill to allow for possible ground settlement and other guidelines that are in Plains Document 6.28[23] "Ground Disturbance Conducted by Plains Midstream Canada (PMC) (specifically the section entitled "Guidelines for Backfilling Excavations").

4. Including guidelines for the use of "padding" materials when the backfill contains rock or other material that could damage the external coating. Specify acceptable rock shield materials.

5. Considering the inclusion of guidelines for utilizing breakers or trench plugs which provide protection against padding or backfill material washout and changes in natural drainage patterns.

6. Considering the inclusion of guidelines for keeping the excavated pipe from floating and creating undue external stresses if the open ditch is subject to flooding due to rain, high water tables, or being near waterways or swamps.

7. Including guidelines for restoring high banks at stream or river crossings or terraces by creating cross drains or diversion terraces that help avoid erosion of the backfill material.

8. Considering the inclusion of instructions for examining the external coating of the pipeline before and during backfilling to assure that holidays are minimized.

9.2 Sub-Task 2: Observation of Plains' Backfill Operation

BGC Engineering personnel visited the site of the incident at MP 188 on June 29th and 30th 2011. During their visit, they were able to observe the backfill above the new pipe section installed as part of the repair to the failed sleeve.

They observed that the backfill area is currently fenced off and no traffic goes over the pipeline. This is not normal practice, but the restrictions have been implemented as a result of a requirement from the ERCB. Therefore, there is little to no compaction of the soil at the surface. Plains have confirmed that their normal compaction procedures were followed for the sub-surface material adjacent to the pipe. The backfill encountered appears to consist of the same till encountered throughout the site.

At a time mutually convenient to Plains, a visit will be made to observe a "typical" backfill operation.

9.3 Summary

Plains' backfill procedures have been reviewed and have been found to meet standard industry practice with respect to excavations in conditions of flat ground away from water courses. However, the procedures do not mention compaction and/or other factors which can come into play when more complex soil conditions are encountered.

10 TASK 7: LEAK ALARM RESPONSE

The purpose of this Task is to address the ERCB requirement:

Assess the effectiveness of Plains' proposed improvements to leak alarm response, and make recommendations for improvements to minimize possible consequences of failure.

DNV has conducted a review of Plains' response to the MP 188 incident based on information supplied to DNV by Plains. The documentation provided by Plains included interviews held between the staff involved at the time of the incident and senior management, procedures in effect at the time of the incident, documents of roles and responsibilities for operations personnel, and flow diagrams and written procedures for the proposed enhanced leak alarm response.

10.1 Significant Information from Plains' Documentation Relevant to DNV's Assessment

The following summarizes some of the key information received from Plains that is relevant for DNV's assessment of Plains' proposed improvements:

i) Plains has two leak detection systems in place, apart from SCADA information. The first system is based on mass balance (PLM) and historically has given rise to many alarms not associated with pipeline leaks; while the second system which is entitled SimSuite™ is a dynamic system which is perceived by Plains to be more accurate in terms of leak detection

ii) Plains has supplied comprehensive information relating to the leak alarm response and pipeline re-start procedures in place at the time of the incident. Furthermore, DNV has received revised flow diagrams and written procedures for the enhanced leak detection and pipeline restart procedures, which take account of lessons learned from the incident.

iii) The Plains assessment of the MP-188 incident (ref. Plains document "MP-188 Incident April 28-29th, 2011) contains the following conclusions that are of relevance to DNV's assessment:

- "_________'s (The console operator's) *actions indicate he was convinced he was experiencing mechanical or PLC failure and not a leak situation."*
- *"Both PLM and SimSuite were giving accurate information. The frequency of changes to flow rates, pressure setpoints and pump starts caused SimSuite's dynamic alarm thresholds to remain higher than normal and may have caused some of the misinterpretation of leak data although there were other indicators that corroborated the alarms."*
- "(The console operator) *focused too much attention on first event – control valve, pressure transmitter, and metering….There seems to have been very little followup on PLM or SimSuite alarms."*
- "(The console operator) *showed an apparent lack of confidence in leak detection system."*

- *"The Rainbow Pipeline should NOT have been restarted following the shutdown of the line at approx. 20:09 hours."*

10.2 Synopsis of the Procedures in Place at the Time of the MP-188 Incident

The Rainbow Pipeline procedures manual (Ref. "Rainbow Pipeline Procedures for Pipeline Operations," Revised May 2011) includes procedures for Line Balance (pages 91-94) and Mainline Emergency Shutdown (pages 94-97). The introduction to the Line Balance procedure describes the challenges of leak detection and response as follows:

"The Rainbow System is somewhat unique to many Pipe Lines due to the fact that there are so many producers injecting product into the Pipe line and the System is capable of delivering product into tankage while lifting different products from the same place, as well the System takes advantage of breakout tankage at key locations on the line. Its dynamic nature makes Leak Detection and Over & Short calculations critical and somewhat challenging. It is necessary for the Control Centre Operator to monitor and understand the Leak detection program and the variables that influence its readings if he/she is to be able to respond to Line leaks / breaks accurately and with the least amount of environmental impact. Understanding the data being displayed by SCADA will also help direct field operators to the correct area of concern."

This description of the complexity of leak detection for the Rainbow pipeline implies that special care should be taken in developing and implementing enhancements to the Plains' pipeline alarm response system and procedures to give confidence that similar events will be prevented in the future.

The procedure also describes how to respond to possible meter failures at injection or terminal locations, and directs the operator to request *"…meter swings…to see if that solves the problem."* DNV recommends that steps are taken to ensure that console operators, when investigating possible meter failures, do not become predisposed to ignore other possible failure modes such as a line break. In the MP-188 incident it appears that the operator continued to focus on the possibility of hardware or instrument failures even when there was ample evidence for a pipeline leak.

The procedure next addresses the possibility of a line break if there is a line balance problem on the mainline, and actions to take to isolate the cause of the problem. Then it states that … *"If the problem has not been found at this point, the Operator will report the concern to the OCC supervisor and begin shutting down the line until further inspection (Line Patrol etc.) can verify condition in the suspect area. When the Operator experiences a large pressure drop on the mainline and a large minus on the over & short, it is important that the operator takes the proper steps in shutting in the system and reporting the problem."* DNV therefore concludes that in the existing procedure the operator has authority to shutdown the pipeline if such conditions are experienced.

The operator is then directed to a flow diagram with additional details to support the process in deciding to shut down the pipeline and notify the relevant individuals. The operator is also directed to *"…reference the Leak Detection Manual in the Control Centre."* DNV has not received or reviewed this Leak Detection Manual.

The Line Balance procedure will be replaced by the enhanced Leak Detection Procedure described below.

10.3 Summary of Plains' Enhancements to Control Centre Operator Response to a Potential Leak Situation

The following is a summary of Plains' enhancements in relation to leak alarm response, based directly on the information provided by Plains (Ref. Plains Document "Information Request").

10.3.1 Develop and review procedures for response calls for supervisor

Two new flow diagram procedures have been provided by Plains – one for "Leak Detection Alarm or Warning" (Figure 132) and another for "Pipeline Restart" from a shutdown condition (Figure 133). The basic premise behind the development of the flow diagrams is to better define and formalise the relevant steps to follow for alarm response and leak detection. They provide the "backbone" of the thought processes that will be used to evaluate alarms and parameters that indicate a potential leak situation. The flow diagrams will be combined with text-based procedures to form the complete system of procedures for alarm response and leak detection.

10.3.1.1 Leak Alarm Flow Diagram

The leak detection procedure provides a "leak trigger list" to alert the operator to conditions that may be indicative of a pipeline leak. The leak trigger list includes:

- Sudden drop in upstream discharge pressure
- Sudden change in upstream control valve throttling
- Sudden drop in downstream suction pressure
- Sudden change in downstream control valve throttling

- Sudden drop in holding pressure at delivery location

An additional step created in the enhanced procedure flow chart is that there are maximum time intervals specified for a console operator to investigate the source of alarms before deferring to a supervisor so that potential consequences can be minimised. If an alarm is triggered, the operator is then instructed to investigate the pertinent meters and pumps. If this assessment results in an "All Clear" evaluation, i.e. the cause of the alarm is explained, within a specified time period (determined by pipeline flow rate), the operator is allowed to return to normal operations. If an "All Clear" determination is not reached within the specified time frame, the operator is instructed to call a supervisor.

The next step in the proposed alarm response procedure is to look for "subsequent and supporting alarms" from PLM, SCADA, and/or SimSuite. If these alarms are present, the operator is instructed to shut down the pipeline and to issue an outage notification. Then further investigation is to be initiated in the form of field visits to suspected problem locations, aerial surveys of pipeline sections, or other balances to evaluate the conditions that could indicate a leak. If this investigation indicates a leak situation then an official notification is issued and emergency response actions are initiated. If a leak situation is not indicated by the investigation then the operator is directed to the restart procedure to perform the actions to bring the pipeline back online.

If the review of "subsequent and supporting alarms" results in no additional indications, the operator is asked to evaluate the presence of additional anomalies. If there are indications of additional anomalies, the operator is directed to the flow chart branch for shutting down the pipeline. If additional anomalies are not indicated the operator is directed to review PLM, SCADA, and SimSuite to determine if the situation has returned to normal. If not, the procedure returns to the "Call to Supervisor" step and the assessment of alarms and anomalies is initiated again. If the review of PLM, SCADA, and SimSuite indicates that conditions have returned to normal, the operator is directed to conduct "high priority monitoring" for a period of two hours from the time of the initial alarm. If at the end of this period the situation remains in the "normal" condition, the operator is authorized to return to normal operations. If there is deviation from normal, the operator is instructed to notify the supervisor once again and the assessment process is started again.

10.3.1.2 Supervisor to Authorize any System Re-start

The new pipeline startup procedure requires the supervisor to be present and to authorize the restart. In addition, he or she is required to obtain "all clear" concurrence from senior sources representing major operations functions – the Control Centre Manager, the District Superintendent and the Area Supervisor. Once the "all clear" has been obtained from these sources, the site-specific startup procedure is followed. The operator is instructed to monitor the system for eight hours to ensure that stable conditions have been established. If so, normal operations are re-established under the direction of the normal operating procedures. If steady-state operations cannot be verified, then the operator is directed to return to the Leak Detection Alarm or Warning Procedure.

10.3.2 On call supervisor to monitor events remotely and call in throughout the shift to monitor leak detection status

Plains has advised that as part of their enhanced procedures, they will institute 24/7 supervision instead of the 40 hours per week, which was in place at the time of the failure. While they are recruiting staff to fill these additional supervisory roles, Plains has put in place after hours on-call supervisory coverage such that supervisors can respond to the control centre to participate fully in all potential line loss alerts and shutdowns. Any Abnormal Operating Conditions (as defined in the Plains document with that title) must be reported to the supervisor, who will then be required to travel to the operations centre to participate in the incident response and to authorize and supervise any re-start operations.

10.3.3 Review Abnormal Operating Conditions with control centre staff

Ongoing training will reinforce the concepts of Abnormal Operating Conditions and the authority of the on-shift operator to shutdown the pipeline if there is a question of integrity based on balance concerns, pressure problems, etc.

10.4 Summary of Industry Regulation and Standards for Alarm Response and Leak Detection

10.4.1 Canadian requirements

Clause 10.3.6 of CSA Z662-07 sets out requirements for leak detection for liquid hydrocarbon pipeline systems, as follows:

> ***10.3.6 Leak detection for liquid hydrocarbon pipeline systems***
>
> ***10.3.6.1***
>
> *Operating companies shall make periodic line balance measurements for system integrity.*
>
> ***10.3.6.2***
>
> *Operating companies shall periodically review their leak detection programs to confirm their adequacy and effectiveness.*

10.3.6.3

Installed devices or operating practices, or both, shall be capable of early detection of leaks.

10.3.6.4

Measuring equipment shall be calibrated regularly to facilitate proper measurement.

10.3.6.5

Evidence of leaks shall be investigated promptly.

Further, Annex E of the standard contains a recommended practice for liquid hydrocarbon pipeline system leak detection. The Annex focuses on material balance methods that provide leak detection capability in keeping with industry practice and commonly used technology, but is not intended to exclude other equally effective leak detection methods. Regardless of the method of leak detection used, the Annex states that operating companies shall comply as thoroughly as practical with the record retention, maintenance, auditing, testing, and training requirements of the Annex. The Annex also sets out measurement requirements and operational considerations for material balance calculations.

For liquid hydrocarbon pipelines under the jurisdiction of the Province of Alberta, the Pipeline Regulations (Alberta Regulation 91/2005) state that the leak detection requirements contained in Annex E of CSA Z662 are mandatory.

10.4.2 US Federal Regulations

The US Pipeline and Hazardous Materials Safety Administration (PHMSA) has published regulations for the transportation of hazardous liquids by pipeline in 49 CFR Part 195. These regulations set the high level requirements for operating safely, while the detailed recommendations are covered by industry documents such as the American Petroleum Institute (API) Recommended Practices. The most relevant PHMSA regulations from 49 CFR 195 include the following:

a. **195.402** Procedural manual for operations, maintenance, and emergencies

This section describes the requirements for a written procedures manual for conducting normal operations and handling abnormal operations and emergencies. For abnormal operations, procedures must be provided to maintain safety when operating design limits have been exceeded. In particular, a procedure is required for “taking necessary action, such as emergency shutdown or pressure reduction, to minimize the volume of hazardous liquid … that is released from any section of a pipeline system in the event of a failure.” In addition, the pipeline operator is required to perform a post accident review to determine whether the procedures were effective, and to correct any deficiencies that are found.

b. **195.403** Emergency response training

This section covers the training requirements for responding to emergencies, for example to develop and maintain competence to "recognize conditions that are likely to cause emergencies, predict the consequences of facility malfunctions or failures and hazardous liquids or carbon dioxide spills, and take appropriate corrective action."

c. **195.444** Computational pipeline monitoring (CPM) leak detection

This section requires that all CPM leak detection systems must comply with the requirements of API Recommended Practice 1130 "Computational Pipeline Monitoring for Liquids," described in more detail in Section 1.3.5 below.

d. **195.446** Control room management

This section is a comprehensive summary of the requirements for control room management procedures governing the control rooms where controllers use a SCADA system to monitor and control all or part of a pipeline facility. Some of the most relevant requirements for evaluating the adequacy of Plains' response to the MP-188 pipeline incident include:

- Each operator must define the roles and responsibilities of controllers during normal, abnormal, and emergency operating conditions, including the controller's responsibility to take specific actions and communicate with others.

- Each operator must provide its controllers with the information, tools, processes and procedures necessary to carry out their roles and responsibilities.

- Operators must implement API RP 1165 Recommended Practice for Pipeline SCADA Displays whenever a SCADA system is added, expanded, or replaced.

- Each operator using a SCADA system must have a written alarm management plan to provide for effective controller response to alarms.

- Each operator must assure that lessons learned from operating experience are incorporated into control room management procedures.

- Each operator must establish a controller training program that covers responding to abnormal operating conditions, use of a computerized simulator or a tabletop method for training controllers to recognize abnormal operating conditions, and responsibility for communication during emergency response conditions.

All the written control room management procedures must be developed by August 1, 2011. Some of the procedures must be implemented October 1, 2011 and others by August 1, 2012.

10.4.3 API RP 1168 Pipeline control room management

This recommended practice is invoked by 49 CFR 195 and addresses four elements of pipeline safety:

- Control room personnel roles, authorities, and responsibilities
- Guidelines for shift turnover
- Control room fatigue management
- Control room management of change

Within the topic of roles and responsibilities the RP specifies that pipeline operators should establish guidelines for responsibilities associated with responding to alarms, investigating abnormal conditions, notifying other personnel, and ensuring that the system returns to normal operating conditions. It also specifies that roles and responsibilities should be defined for supervisors during abnormal or emergency conditions, including ensuring necessary actions are taken, operator and external personnel are notified, adjusting alarm priorities/thresholds, and providing authorization to restart the pipeline.

10.4.4 API RP 1167 Pipeline SCADA alarm management

API RP 1167 contains comprehensive guidance for designing and operating an effective SCADA alarm management system. The recommended practice provides specific definition of an alarm – "A visible and/or audible means of indicating to the controller an equipment malfunction, an analogue or accumulation process deviation, or other condition requiring a controller's response." Please note that the definition specifies that an alarm should require a response by the controller.

On a related point, the RP defines a nuisance alarm as "an alarm that annunciates excessively, unnecessarily, or does not return to normal after the correct response is taken (e.g. chattering, fleeting, false, or stale alarms.)"

The recommended practice also prescribes that operators should develop a written Alarm Philosophy document "that covers the proper ways to define, design, implement, maintain, monitor, and test an alarm system."

10.4.5 API RP 1165 Pipeline SCADA displays

This recommended practice provides detailed guidance for the design of SCADA displays, including those for alarm management.

10.4.6 API RP 1130 Computational pipeline monitoring for liquids

This recommended practice provides comprehensive guidance for the use of computational pipeline monitoring (CPM) systems for pipeline operation, including for leak detection and alarm response. It also provides guidance for the integration of CPM and SCADA systems.

Regarding response to CPM alarms, the following factors should be taken into consideration:

- All CPM alarms have a cause.
- CPM alarms will be probabilistic, and need to be assessed in light of the current sensitivity threshold.
- Past instances of alarm causes can be a useful guide in alarm evaluation but every alarm should be evaluated individually and assumptions of previous causes should not be readily made.

10.5 Assessment of Enhancements Proposed by Plains

The following are the main ingredients for effective response to diagnose and respond to indications of a pipeline leak situation:

- Availability of qualified personnel
- Availability of relevant information
- Availability of effective tools to support situation assessment and decision making
- Supportive organizational environment

The following sections describe DNV's assessment of the effectiveness of the proposed enhancements in each of these categories. The comparison is based on the draft flow charts and written procedures, and Plains' description of the enhancements in their response to ERCB "Requests for Information".

10.5.1 Availability of qualified personnel

- Training

Plains' past and future training programs will be reviewed as part of a planned "point by point" review of the new procedures for alarm response and leak detection. In the meantime, it is recommended that Plains review its revised training program to ensure compliance with the requirements of CSA Z662 Annex E, Clause E.5 Employee Training. It is further recommended that the training include a means of evaluating that operators comprehend and are capable of following the procedures.

- Staffing level

The addition of full-time supervisory coverage on a 24/7 basis will enhance the on-site availability of a "second set of eyes" to support the assessment of the alarm situation and the formulation of a response plan. As part of their enhanced procedures, Plains has reviewed roles and responsibilities documentation from other business units within Plains. DNV's impression of the existing documents is that they are relatively generic and that they should be tailored specifically to leak alarm response. Plains has stated that they will tailor the roles and responsibilities of the console operator and the Shift Supervisor so that the supervisor effectively provides an independent and complementary perspective to that of the console operator. The draft documents provided by Plains describing roles and responsibilities for the Shift Supervisor include the following items:

  - Ensures all procedures are followed during emergency or AOC conditions
  - Liaison between field and control centre on follow up on emergencies, AOC's and near misses
  - Provide advice on alarm management
  - Review PLM over/short spreadsheet every 2 hours
  - Review and troubleshoot alarm conditions on 70 PLM segments
  - Leak Detection (PLM) testing – 70 segments
  - Review and document PLM alarm limit configuration – 70 segments

Additional description will be provided by Plains in the final documents to clarify how the supervisor is to oversee and complement the operator's role so that both can work in a complementary fashion for alarm response and leak detection.

10.5.2 Availability of relevant information

As before the incident, many sources of information including SCADA, PLM, and SimSuite will be available to the operator and the supervisor to support assessment and decision making during an alarm response situation. Plains are recommended to ensure that the information from all these sources is effectively integrated to facilitate making the distinction between "systemic" and real alarms that indicate an actual leak condition.

10.5.3 Availability of effective procedures to support situation assessment and decision making

The draft flow diagram procedures reviewed by DNV provide a valid framework for guiding situation assessment and response during off-normal conditions. However, in the draft flow diagrams there was some ambiguity regarding the authority of the console operator to shutdown the pipeline unilaterally based on indications from the "Leak Trigger List," or whether the supervisor must be consulted first. In addition, some of the terms and decision criteria contained in the draft flow charts were ambiguous. For example, one of the decision points asks the operators to assess "Subsequent and Supporting Alarms" without specifying clear criteria for determining whether this condition is satisfied.

In the final procedures that will be implemented, Plains has stated that they will clarify that the console operator does indeed have authority to shutdown the pipeline without first receiving authorization from the supervisor, and will provide notes on the flow diagram itself or in the written procedure to clarify the ambiguous terms.

In response to comments from DNV on the draft flow diagram "Leak Detection and Warning" and the accompanying draft written procedure "Leak Detection Procedure," Plains has informed DNV that they have made the following modifications:

- Added a comment at the beginning of the written procedure to clarify that the console operator has authority to shut down the pipeline unilaterally if leak alarms or SCADA parameters meet any of the criteria for Abnormal Operating Conditions and the integrity of the pipeline is in question. (Under most circumstances it is expected that such a decision would be made jointly by the operator and shift supervisor since the latter will now be co-located in the control centre on a 24/7 basis.)

- Added a note to the written procedure to describe the criteria by which "subsequent and supporting alarms" would be used to make a decision to shut down the pipeline.

- Added a note to the written procedure to summarize the meaning of the time constraints based on flow rates contained in the "Type of Flow on Pipeline" box on the flow diagram.

- Added the "Leak Trigger List" and the definition of Abnormal Operating Conditions to the written procedure.

In addition, Plains has stated their intent to add the following additional modifications prior to release of the new written and flow diagram procedures for alarm response and leak detection:

- Add a comment to the flow diagram to indicate that the console operator has authority to shut down the pipeline unilaterally if leak alarms or SCADA parameters meet any of the criteria for Abnormal Operating Conditions and the integrity of the pipeline is in question.

- Modify the description of the roles and responsibility for the shift supervisor to emphasize that the shift supervisor is expected to provide independent and complementary perspectives to the role of the console operator for the processes of alarm response and leak detection. That is, the supervisor should provide a higher level, oversight function to challenge (when warranted), support, and validate the console operator's decision processes to ensure that all relevant information is taken into account and reduce the likelihood of an incorrect assessment and response.

- Implement a written procedure to accompany the new flow diagram for restarting the pipeline, and to clarify the number and organizational functions of the personnel whose concurrence must be obtained to restart the pipeline following its shutdown under the direction of the leak detection procedure.

While DNV believes that the new procedures are adequate assuming that they are implemented as described by Plains, a complete "point by point" comparison of the original and the enhanced procedures would be needed to demonstrate the degree of improvement afforded by the new procedures.

10.5.4 Supportive organizational environment

The information provided by Plains to ERCB (Ref. Plains document "Information Request") states that, "Training for new operators and frequent discussions at the Control Centre have re-enforced that the on-shift operator has the authority to shut down a pipeline if there is ever a question of integrity (balance concerns, pressure problems, etc.)." It is recommended that along with the "point by point" comparison of the original and the enhanced procedures that an assessment should be made of how the organizational environment at the Plains operation centre will support operators in choosing to shut down the pipeline as opposed to keeping the pipeline in operation to achieve production and financial goals.

10.6 Conclusions and Recommendations

Based on the documents received to date and information received from Plains regarding additional changes that will be made prior to full implementation of the new procedures, DNV believes that the suite of enhancements proposed by Plains Midstream Canada could significantly improve alarm assessment and leak response if implemented within the context of the recommendations contained in Sections 10.6.1 and 10.6.2 below. The new flow diagram and written procedures relating to "Leak Alarm Response" and "Pipeline Re-Start" provide an improved framework when compared to the previous procedures for guiding situation assessment and response during off-normal conditions.

10.6.1 Near-Term Recommendations to Enhance Alarm Response and Leak Detection

- The enhancements for alarm response and leak detection proposed by Plains should be confirmed by an on-site audit of their implementation.

- The new procedures, roles and responsibilities, and lessons learned from the MP-188 incident should be formally introduced in controlled documents and focused training sessions with the affected personnel. In addition, Plains' senior management should attend the training sessions and clearly convey the message that the organization will support a console operator's decision to shut down a pipeline.

- The degree of improvement afforded by the new alarm response procedures relative to the old procedures should be demonstrated by a "point-by-point" comparison of the old and new procedures, accompanied by a systematic assessment of the number and adequacy of the barriers to pipeline leaks that are provided by the two systems. An effective way to accomplish this would be to develop formal "Bow Tie" diagrams to graphically illustrate the number of barriers provided by the original and the enhanced procedures. (Bow Tie diagrams are a systematic approach used to graphically illustrate the hardware, human, and procedural barriers that are present to prevent the occurrence of an accident and to mitigate its consequences.)

- The availability of a powerful tool such as SimSuite should be a very helpful resource to diagnose and respond to pipeline leak situations. Unfortunately, in the MP188 event, it did not serve this role effectively and may have inadvertently aggravated the situation because its alarms were outnumbered and masked by the PLM alarms. Therefore, it is recommended that Plains systematically review the desired role of SimSuite in alarm response, and then evaluate whether there is a need to revise the dynamic alarm thresholds to provide the degree of information consistent with this role.

- The relative sensitivity and accuracy of SimSuite and PLM for leak detection and diagnosis should be evaluated. The most effective modes for the use of both tools in an integrated, complementary fashion for leak detection and response should be identified. The availability of information on SCADA, PLM, and SimSuite display screens should be evaluated to ensure that they can be used efficiently and consistently to support leak detection and response tasks. Information contained in API Recommended Practices 1130, 1165, and 1167 can be used to support these assessments.

- The new procedures should be regularly covered in training for new operators and refresher training should be conducted to ensure that the concepts are retained and kept fresh. Operator and supervisory training is critical to ensure that appropriate knowledge is conveyed and retained so that it can be effectively used under upset or abnormal conditions. The overall training program should be reviewed to ensure that these goals are achieved, and periodic refresher training and exercises should be conducted to ensure that knowledge and skills are maintained current. The proper use of SCADA/SimSuite/PLM in alarm response should be incorporated in the operator and supervisor training programs. Finally, consideration should be given to the use of SimSuite in the role of a dynamic, real time simulator to conduct realistic exercises of crew response to potential pipeline leak situations.

10.6.2 Longer term recommendations to ensure effective alarm response and leak detection for the Rainbow Pipeline

In the longer term, Plains should implement a program to evaluate the compliance of their alarm response, leak detection, and leak response systems and processes to the expectations of the relevant industry standards. In particular, Plains should:

- Review the proposed amendments to Plains' leak detection procedures to ensure compliance with the requirements of CSA Z662-07 Annex E.

- Develop and implement a pipeline control room management plan that takes into consideration the guidance contained in API RP 1168 "Pipeline Control Room Management."

- Ensure that the performance and usage of SimSuite (in harmony with SCADA and PLM) are consistent with the guidance of API RP 1130 "Computational Pipeline Monitoring for Liquids"

- Ensure that the PLM and SimSuite alarm displays are consistent with the guidance of API RP 1165 "Recommended Practice for Pipeline SCADA Displays"

- Develop an alarm philosophy and ensure that SCADA, PLM, and SimSuite alarms that is consistent with the guidance of API RP 1167 "Pipeline SCADA Alarm Management," and that the three sources of alarms are integrated to effectively support alarm response and leak detection.

- If not already in place, Plains should ensure that the organizational environment and culture effectively supports console operators and other personnel in making conservative decisions when evaluating potential leak conditions and choosing to shut down the pipeline. Critical values should be reinforced to all operations staff, for example:

  - Making conservative decisions (e.g. to shut down the pipeline) when confronted by ambiguous information that cannot be quickly resolved.

  - Providing an environment so that operators and other personnel can make conservative decisions without fear of reprisal.

  - Encourage console operators to ask for help when faced with ambiguous or challenging situations.

  - Freedom to speak up and voice concerns when a fellow worker is proceeding down a potentially dangerous pathway.

  - The importance of stopping for reflection rather than pressing ahead when conditions are uncertain or poorly understood.

These values should be reinforced through consistent modelling, behaviour, and communication by all levels of Plains management.

DNV's preliminary conclusions and recommendations regarding the new, enhanced alarm response procedures and processes are summarized as follows:

Based on the information received to date, DNV believes that the suite of enhancements proposed by Plains Midstream Canada could significantly improve alarm assessment and leak response if implemented within the context of the recommendations contained in Sections 1.6.1, 1.6.2, and 1.6.3 below. The new flow diagram procedures relating to "Leak Alarm Response" and "Pipeline Re-Start" provide an improved framework when compared to the previous procedures for guiding situation assessment and response during off-normal conditions, which will be confirmed by the "point by point" procedures review.

10.6.1 Near Term Recommendations Prior to Pipeline Restart

- The new procedures should clearly define the criteria (based on the "leak trigger list" and the definition of Abnormal Operating Conditions) and the authority of the console operator for shutting down the pipeline if alarm conditions cannot be resolved within the prescribed time limits. These criteria should be defined to ensure that the pipeline will be shutdown with a high degree of confidence in those situations when an actual leak has occurred, including conditions where information coming from SCADA, PLM, and SimSuite may seem inconsistent. In addition, the new procedures should be designed to ensure that operators and supervisors do not focus on initial suspicions of instrument and/or hardware failures to the exclusion of possible indications of a pipeline leak. This can be accomplished by identifying the key parameters that should be constantly monitored even while investigating possible instrumentation or hardware problems.

- The supervisory roles should be specifically defined to ensure independent and complementary perspectives to the role of the console operator. That is, the supervisor should provide a higher level, oversight function to challenge (when warranted), support, and validate the console operator's decision processes to ensure that all relevant information is taken into account and reduce the likelihood of an incorrect assessment and response. The roles and responsibilities of both the console operator and supervisor should be clearly defined and reinforced through training and exercises. API RP 1168 provides guidance on the definition of roles and responsibilities for controllers and supervisors.

- The new procedures, roles and responsibilities, and lessons learned from the MP-188 incident should be formally introduced in controlled documents and focused training sessions with the affected personnel. In addition, Plains' senior management should attend the training sessions and clearly convey the message that the organization will support a console operator's decision to shut down a pipeline.

10.6.2 Additional Near-Term Recommendations to Enhance Alarm Response and Leak Detection

- The degree of improvement afforded by the new alarm response procedures relative to the old procedures will be demonstrated by a systematic assessment of the number and adequacy of the barriers to pipeline leaks that are provided by the two systems. An effective way to accomplish this would be to develop formal "Bow Tie" diagrams to graphically illustrate the number of barriers provided by the original and the enhanced procedures. (Bow Tie diagrams are a systematic approach used to graphically illustrate the hardware, human, and procedural barriers that are present to prevent the occurrence of an accident and to mitigate its consequences.)

- The new procedures should be regularly covered in training for new operators and refresher training to ensure that the concepts are retained and kept fresh by the operators. Operator and supervisory training is critical to ensure that appropriate knowledge is conveyed and retained so that it can be effectively used under upset or abnormal conditions. The overall training program should be reviewed to ensure that these goals are achieved and periodic refresher training and exercises to ensure that knowledge and skills are maintained current. The concepts and philosophy of correct behaviour under Abnormal Operating Conditions should be documented in a written form that is readily available to operators, and training and exercises should regularly reinforce these concepts. Finally, the proper use of SCADA/SimSuite/PLM in alarm response should be incorporated in the operator and supervisor training programs.

- The availability of a powerful tool such as SimSuite should be a very helpful resource to diagnose and respond to pipeline leak situations. Unfortunately, in the MP188 event, it did not serve this role effectively and may have inadvertently aggravated the situation because its alarms were outnumbered and masked by the PLM alarms. Therefore, it is recommended that Plains systematically review the desired role of SimSuite in alarm response, and then evaluate whether there is a need to revise the dynamic alarm thresholds to provide the degree of information consistent with this role.

- The relative sensitivity and accuracy of SimSuite and PLM for leak detection and diagnosis should be evaluated. The most effective modes for the use of both tools in an integrated, complementary fashion for leak detection and response should be identified. The availability of information on SCADA, PLM, and SimSuite display screens should be evaluated to ensure that they can be used efficiently and consistently to support leak detection and response tasks. Information contained in API Recommended Practices 1130, 1165, and 1167 can be used to support these assessments.

10.6.3 Longer term recommendations to ensure effective alarm response and leak detection for the Rainbow Pipeline

In the longer term, Plains should implement a program to evaluate the compliance of their alarm response, leak detection, and leak response systems and processes to the expectations of the relevant industry standards. In particular, Plains should:

- Review the proposed amendments to Plains' leak detection procedures to ensure compliance with the requirements of CSA Z662-07 Annex E.

- Develop and implement a pipeline control room management plan that takes into consideration the guidance contained in API RP 1168 "Pipeline Control Room Management."

- Ensure that the performance and usage of SimSuite (in harmony with SCADA and PLM) consider the guidance of API RP 1130 "Computational Pipeline Monitoring for Liquids"

- Ensure that the PLM and SimSuite alarm displays consider the guidance of API RP 1165 "Recommended Practice for Pipeline SCADA Displays"

- Develop an alarm philosophy and ensure that SCADA, PLM, and SimSuite alarms consider the guidance of API RP 1167 "Pipeline SCADA Alarm Management," and that the three sources of alarms are integrated to effectively support alarm response and leak detection.

- If not already in place, Plains should ensure that the organizational environment and culture effectively supports console operators and other personnel in making conservative decisions when evaluating potential leak conditions and choosing to shut down the pipeline. Critical values should be reinforced to all operations staff, for example:

    - Making conservative decisions (e.g. to shut down the pipeline) when confronted by ambiguous information that cannot be quickly resolved.

    - Providing an environment so that operators and other personnel can make conservative decisions without fear of reprisal.

    - Encourage console operators to ask for help when faced with ambiguous or challenging situations.

    - Freedom to speak up and voice concerns when a fellow worker is proceeding down a potentially dangerous pathway.

    - The importance of stopping for reflection rather than pressing ahead when conditions are uncertain or poorly understood.

These values should be reinforced through consistent modelling, behaviour, and communication by all levels of Plains management.

11 TASK 8 – PIPELINE OPERATIONS

The purpose of this section is to identify any other mitigative actions which Plains could take to minimize the probability or consequences of another failure from a sleeve fillet weld.

Since the failure occurred in the circumferential orientation, axial stresses due to variations in internal pressure are small and are not anticipated to have a significant effect on the integrity of the NPS 20 Rainbow pipeline.

Plains are recommended to complete all remaining Type B sleeve inspections (Inspection Plan C) before the end of the year 2012 as stated in Section 6, Task 3. However, Plains should monitor these sites on a regular basis. It is understood that Plains conduct weekly aerial patrols using fixed wing aircraft to monitor activities which could potentially affect the integrity of the pipeline, and the scope of these patrols should be extended to monitor for changes in ground conditions which could cause additional axial stresses. Plains are recommended to engage the services of BGC Engineering to assist in training pilots regarding "tell tale" indications of ground movement.

Finally, it is understood that Plains are currently evaluating the merits of changing valve operation from manual to automated. DNV supports this evaluation.

12 CONCLUSIONS

1. The failure occurred as a result of a crack in the circumferential fillet weld of a pressure-containing repair sleeve in the presence of an axially aligned stress.

2. The initiating defect was formed at the time of installation of the repair sleeve (1980) by a mechanism known as delayed hydrogen cracking. It was caused as a result of the use of a welding procedure that employed cellulosic electrodes.

3. The crack was 30 mm long and 2 mm deep and appears to be limited to the extent of the brittle heat affected zone. The crack showed no evidence of growth into the more ductile pipe body material before the April 28th, 2011 rupture.

4. DNV has identified two analytical approaches for assessing the criticality of cracks in fillet welds; namely, the CorLAS^{TM} and NASGRO 3.0.19 software programs. Based on calculations using CorLAS^{TM}, an axial stress of at least 370MPa (85% of the actual yield strength or 103% of SMYS) would have been required to cause the defect to fail.

5. The source of the high axial stress that led to the failure of the defective weld has not been conclusively established. The stress could not have been caused solely by internal pressure or lack of support due to inadequate compaction of the back fill in April 2010. It is possible that the cumulative effect of sub-critical loads from various sources could have caused the weld failure.

6. In the 11 excavations of Type B sleeves completed by Plains since acquisition of the pipeline, 10 have been found to have cracks in association with the fillet welds. The cracks ranged in length from 1 mm to 53 mm and depths from 0.4 mm to 2.12 mm. The axial tensile stress required to cause failure of these flaws varied from 109% SMYS to 113% SMYS. These values all exceed the stress that caused the MP 188 incident (103% SMYS). It is expected that a similar percentage of the remaining welded repair sleeves on the NPS 20 Rainbow pipeline will have delayed hydrogen cracking associated with their fillet welds since they would all have been welded using cellulosic electrodes.

7. It is likely that the extent of delayed hydrogen cracking would be limited to the extent of the of the weld heat affected zone. On this basis, the maximum crack depth in the fillet welds of the un-inspected sleeves is not expected to exceed 3.1mm (maximum depth of measured heat affected zone).

8. Provided their circumferential length is less than 10% of pipe circumference (152 mm), fillet weld cracks less than 3.70 mm in depth are not predicted to fail at axial stresses $\leq$ 100% SMYS in both 5.56 and 7.14 mm nominal wall thickness pipe. At axial stresses $\leq$ 110% SMYS, the equivalent depths are 1.5 mm in 7.14 mm wall thickness pipe and 1.1

mm in 5.56 mm wall thickness pipe. These depths increase to 2 mm and 1.9 mm respectively, provided the circumferential length is ≤ 80 mm, (i.e. the maximum length of cracking detected to date), see Figures 29 and 30.

9. Industry experience indicates that the best approach for detecting and sizing repair sleeve fillet weld cracks once the pipeline has been excavated is through magnetic particle inspection (MPI) and successive grinding followed by ultrasonic measurement of the remaining wall thickness.

10. In discussions with in-line inspection vendors there is presently not a viable in-line inspection technology for detecting fillet weld cracks in welded repair sleeves.

11. Although the actual source(s) of the axial stresses that caused the MP 188 failure are still unknown, it is postulated that a significant change in the local ground conditions (e.g. the sleeve being recently excavated or in proximity to a geotechnical hazard) would be required to cause the failure of another sleeve. Since none of the remaining sleeves have been recently excavated nor are located in close proximity to a geotechnical hazard and assuming the local geotechnical conditions don't change between now and the time Plains excavates and assesses them, there is no reason to believe they will fail and thus the NPS 20 Rainbow pipeline should be allowed to return to service.

12. DNV has evaluated four potential options for the repair of cracks in sleeve fillet welds. The two most practical options are grinding and, if necessary, sleeve on sleeve. DNV has developed a proposed grinding acceptance criterion.

13. The sleeve on sleeve repair method is a valid approach for the repair of defective sleeves. DNV recommends using this type of repair only if cracks are present and can not be fully removed by grinding and not for those repair sleeves that are found to be defect free.

14. Plains' existing backfill procedures meet standard industry practice for excavations in flat ground away from water courses. They should be enhanced to address compaction requirements.

15. DNV agrees with the conclusion of Plains' internal investigation that the control centre operator's response to the leak alarms raised at the time of the MP188 failure was inadequate. Recommendations for additional improvements to the written leak alarm procedures, the utilization of the leak detection systems and the training and roles of key staff have been identified by DNV and agreed with Plains. DNV has reviewed the enhancements being implemented by Plains to improve the effectiveness of alarm response and leak detection and believes that they help reduce the likelihood of incorrect response to future events, provided that they are implemented within the context of the recommendations made in Section 10 (Task 7) of the report.

16. The NPS 20 Rainbow Pipeline can be returned to service based on the understanding that none of the remaining sleeves have been recently excavated nor are located in proximity to a geotechnical hazard.

13 RECOMMENDATIONS

1. All welded sleeves on the pipeline need to be excavated and examined for cracks by the end of the year 2012. Based on a risk assessment, DNV has identified 9 sleeves in 7 joints (6 in the Zuma – Rainbow section, and 1 in the Cadotte-Utikuma section) within ± 12 metres of a previous excavation which should be investigated as a higher priority.

2. Plains should monitor the sites of all the remaining investigation sites for Type B sleeves (Inspection Plan C) on a regular basis. It is understood that Plains conduct weekly aerial patrols using fixed wing aircraft to monitor activities which could potentially affect the integrity of the pipeline, and the scope of these patrols should be extended to monitor for changes in ground conditions which could cause additional axial stresses. Plains are recommended to engage the services of BGC Engineering to assist in training pilots regarding "tell tale" indications of ground movement.

3. All welds found to contain cracks should be repaired by grinding in accordance with the proposed grinding acceptance criterion developed by DNV. Those ground areas that are deemed to be acceptable should be recoated while those that exceed the acceptance criteria should be repaired using a sleeve on sleeve repair.

4. Within 60 days of the Rainbow pipeline's return to service, an audit of the enhanced suite of leak alarm response and pipeline re-start procedures should be conducted.

14 REFERENCES

1. Acuren Report No 206-11-05-0059227, “Examination of NPS 20 Rainbow Pipeline Failure”, May 19th, 2011

2. “A Critical Review of Assessment Methods for Axial Planar Surface Flaws in Pipe”, A.B. Rothwell and R.I.Coote, Ostend Pipeline Conference, 2010

3. Hart, J.D., Powell, G.H., and Rinawi, A.K., "*Experimental and Analytical Investigations of Sleeved Pipeline Configurations*", ASME Pipeline Engineering Symposium, Houston, Texas, February, 1995.

4. Rinawi, A.M., Hart, J.D., Powell, G.H., and Khatib, I.F., "*Wrinkling Evaluation of Straight Pipe-Sleeve Configurations*", ASME Pipeline Engineering Symposium, Houston, Texas, February, 1993.

5. “106413_20E PipeListing_GPS”, GE In-Line Inspection Listing Supplied By Plains to DNV

6. “FW: MP188 Pipeline Profile P-0017-11-X-2 (500m U/S and 500m D/S of failure site)”, e-mail forwarded by Minh Ho to DNV, July 19th 2011

7. “G002-Appendix A”, G Ferris (BGC Engineering) e-mail to A. Clyne, July 8th 2011

8. “Peace River Historical Weather Data”, email from S Finneran to J Hart, July 11th 2011

9. “Another Possible Failure Mode”, email from Minh Ho to R Fletcher/G Ferris, July 13th, 2011

10. “FW: Backhoe Weight”, email from R Fletcher to J Hart and S Finneran, July 19th 2011

11. National Energy Board Report, “In the Matter of an Accident on 19 February 1985 near Camrose, Alberta, on the Pipeline System of Interprovincial Pipe Line Limited”, June 1986

12. Programmed Instruction Handbook, “Nondestructive Testing, Magnetic Particle Testing”,

13. Programmed Instruction Handbook, “Nondestructive Testing, Ultrasonic Testing”, PI-4-4, General Dynamics (Corvair Division), Copyright 1977

14. Final Report, “Guide for the Welding, Assessment and Inspection of Fillet and Tee Butt Welds”, Welding Technology Institute of Australia (WTIA), ABN 69 003 696 526A, TGN-RT-05, May 31 2006

15. Final Report Phases I & II to Minerals Management Service, "Appraisal And Development Of Pipeline Defect Assessment Methodologies", MSL Engineering Limited Contract No. 1435-01-CT-99-50001, June 2000

16. BS3923: Part 1: 1986, "Ultrasonic Examination of Welds, Part 1. Methods for Manual Examination of Fusion Welds in Ferritic Steel", British Standards Institution, London England, 1986

17. Handbook, "Advances in Phased Array Ultrasonic Technology Applications", Olympus NDT, Waltham, MA, 2007

18. Final Report to the American Gas Association (AGA), NDT Supervisory Committee, "Evaluation of Nondestructive Inspection Methods For Welds Made Onto In-Service Pipelines – Phases I & II", EWI Project Nos. J7154 and J77182, April 26, 1991

19. Final Report to the American Gas Association (AGA), NDT Supervisory Committee, "Development of Optimized Inspection Methods For Welds Made Onto In-Service Pipelines – Phase III, EWI Project No. J7203, September 2, 1992

20. WAV NDE Manual, Section Two, "Ultrasonic Examination Procedure 2.0" and Section Three, "Magnetic Particle Examination Procedure 3.0", Wav Inspection Ltd., Alberta T1R 1B5

21. Kiefner, J.F., Maxey, W.A., "Tests Validate Pipeline Sleeve Repair Technique", Oil & Gas Journal, August 28, 1989 pg 47-52

22. API RP 1102, "Steel Pipelines Crossing Railroads and Highways, Seventh Edition, includes Errata 1 (2008) and Errata 2 (2010)", 7th Edition, American Petroleum Institute, 01-Dec-2007

23. "Ground Disturbances Conducted by Plains Midstream Canada (PMC)", Document No. 6.28, Plains Midstream Canada Operations Department, July 24th 2006

Table 1 Maximum Axial Stress for Different Pipeline Conditions Based on PIPLIN Model

PIPLIN Model	Maximum Axial Stress at 6 o'clock Position at Upstream End of Sleeve (Failure Location)		
	ksi	MPa	% SMYS
CASE 1: Internal Pressure, thermal contraction, line profile, no support under excavated area, pipe settlement into muskeg	14.8	102	28.5
CASE 2: As above but pipe settlement into "old backfill"	14.9	102.7	28.6
CASE 3: As CASE 2 but adding effects of attempting to remove sign	13.9	95.8	26.7
CASE 4: As CASE 2 but heavy equipment traversing pipeline	15.6	107.6	30.0
CASE 5: Effect of adjacent excavation	14.3	98.6	27.5

Table 2 Depths of HAZ for Welds on Failed Sleeve at MP188

Sample Location	Depth of Heat Affected Zone (mm)
Fillet weld adjacent to fracture at the 2:00 position	2.18
Fillet weld adjacent to fracture at the 10:00 position	2.00
Fillet weld adjacent to fracture at the 12:00 position	3.15
Upstream fillet weld at the 6:00 position	1.33
Fracture location at the 6:00 position	2.00

Table 3 Summary of Merits of Available Inspection Techniques

Inspection Method	Equipment	Detects	Advantages	Limitations	Notes
VT	Magnifying glass, weld gauge, small rulers, company workmanship standards	Surface flaws - cracks, porosity, unfilled craters, slag inclusions warping, underwelding, overwelding, poorly formed beads, misalignments, improper fitup	Low cost. Can be applied while work is in process, permitting correction of faults. Gives indication of incorrect procedures.	Applicable to surface defects only. Provides no permanent record unless photography is used to document.	Should always be the primary method of inspection, no matter what other techniques are required. It is considered a "productive" type of inspection and should be performed from the construction phase
MT	Special commercial equipment. Magnetic powders - dry or wet; may be visible or fluorescent	Excellent for detecting surface discontinuities, especially surface connected cracks.	Simpler to use than radiographic inspection and faster than PT. Permits controlled sensitivity. Relatively low-cost method.	Applicable to ferromagnetic materials only. Requires skill in interpretation of indications and recognition of irrelevant patterns. Difficult to use on rough surfaces.	Linear defects parallel to the magnetic field may not give pattern; for this reason the field should be applied from two directions at or near right angles to each other.
UT	Special commercial equipment, either of the pulse-echo or transmission type. Standard reference patterns for interpretation of defects. Encompasses shear wave, straight beam and advanced techniques	Subsurface and some surface flaws including subsurface flaws too small to be detected by radiography. Commonly used for the detection of lamination-type defects and internal corrosion.	Very sensitive. Permits probing of joints inaccessible to radiography.	Requires high degree of skill. Advanced processes require specialized training. Permanent record is not readily obtained. Not recommended for inspecting fillet welds. Difficult to use on rough surfaces.	Pulse-echo equipment is highly developed for weld inspection purposes. The transmission-type equipment simplifies pattern interpretation where it is applicable.

Table 4 Summary of Welded Sleeve Excavations: April 28th 2011 to July 10th 2011

Dig ID	Date	Pipe Joint #	Inspected Pipe (from U/S Weld)		Measured Wall Thickness (mm)				Comment
			Start (m)	End (m)	0°	90°	180°	270°	
Zama to Rainbow									
120	6-Jun-11	120	1.50	4.00	5.63	5.62	5.63	5.63	U/S of Sleeve
					5.62	5.62	5.64	5.62	D/S of Sleeve
44750	7-Apr-11	44750	N/A	N/A	N/A	N/A	N/A	N/A	No data regarding inspected pipe (l, wt, etc) in report
52700	7-Jun-11	52700	1.10	3.00	5.64	5.64	5.63	5.64	U/S of Sleeve
					5.63	5.62	5.64	5.62	D/S of Sleeve
55580	2-Jun-11	55580	9.70	12.00	5.7	5.75	5.75	5.7	U/S of Sleeve
					5.7	5.75	5.7	5.7	D/S of Sleeve
55760	3-Jun-11	55760	10.30	12.00	5.62	5.62	5.66	5.62	U/S of Sleeve
					5.64	5.62	5.62	5.62	D/S of Sleeve
56510	1-Jun-11	56510	8.50	12.40	5.6	5.65	5.6	5.65	
	1-Jun-11	56520	0.00	2.20	5.9	5.85	5.9	5.9	
57060	2-Jun-11	57060	4.40	6.18	5.7	5.65	5.7	5.7	U/S of Sleeve
					5.7	5.7	5.65	5.65	D/S of Sleeve
57130	2-Jun-11	57130	9.70	12.00	5.7	5.75	5.75	5.7	U/S of Sleeve
					5.7	5.75	5.7	5.7	D/S of Sleeve
58280	2-Jun-11	58280[3]	2.10	5.74	5.7	5.65	5.7	5.7	U/S of Sleeve
					5.7	5.7	5.65	5.65	D/S of Sleeve
58460	8-Mar-11	58460	N/A	N/A	N/A	N/A	N/A	N/A	No data regarding inspected pipe (l, wt, etc) in report
Cadotte to Utikuma									
73430	23-May-11	73430	4.44	6.70	7.3	7.3	7.2	7.3	U/S of Sleeve

[3] The sleeve at this location was fabricated from two sections that were butt welded together before welding to the pipe.

Table 5 Weld Crack Details at Excavated Sleeves

Joint #	GW Log Distance (m)	Defect Type	Axial Distance (m)	Orient. (°)	Local Wall Thick. (mm)	*NDE Method*	*Reported Max.Depth (mm)*	*Reported Max. Depth (%wt)*	Cracking Removed? (Yes/No)	Colony Length[4] (mm)	Interlinking or Longest Crack Length[1] (mm)
Zama to Rainbow											
120	66.78	Cracks	3.3	100	5.63	Grind	0.84	14.9%	Yes	No ruler in photo	Crack not visible in photo
52700	62617.84	Cracks	2.5	208	5.64	Grind	>1.33[5]	23.6%	No	Crack not visible in photo	Crack not visible in photo
55580	65831.32	Cracks	10	150	5.7	Grind	1	17.5%	Yes	11	3
55580	65831.32	Cracks	11.5	150	5.7	Grind	0.6	10.5%	Yes	3	3
55580	65831.32	Cracks	11.5	165	5.7	Grind	>1.80[2]	31.6%	No	5.75	5.75
55760	66036.35	Cracks	11.4	180	5.62	Grind	2.12	37.7%	Yes	33	6.5
55760	66036.35	Cracks	11.4	210	5.62	Grind	2.12	37.7%	Yes	4	4
56510	66916.86	Cracks	9	170	5.65	Grind	>1.50[2]	26.5%	No	No ruler in photo	16
56510	66916.86	Cracks	10	190	5.65	Grind	>1.20[2]	21.2%	No	14.5	2
56510	66916.86	Cracks	11	195	5.65	Grind	0.61	10.8%	Yes	9	3
56510	66916.86	Cracks	11	205	5.65	Grind	0.61	10.8%	Yes	3	1
56520	66916.86	Cracks	1.7	205	5.9	Grind	>0.80[2]	13.6%	No	15	6
57060	67584.79	Cracks	4.9	270	5.7	Grind	0.93	16.3%	Yes	13.5	3
57060	67584.79	Cracks	5.8	200	5.7	Grind	1.64	28.8%	Yes	79	53
57130	67670.83	Cracks	10	120	5.75	Grind	1.03	17.9%	Yes	41	12
57130	67670.83	Cracks	11.5	180	5.75	Grind	0.8	13.9%	Yes	25	4
57130	67670.83	Cracks	11.5	190	5.75	Grind	0.8	13.9%	Yes	19	3
58280	68984.64	Cracks	2.4	100	5.7	Grind	0.4	7.0%	Yes	45.5	37
58280	68984.64	Cracks	2.4	200	5.7	Grind	1.7	29.8%	Yes	74	16
58280	68984.64	Cracks	5.5	200	5.7	Grind	0.4	7.0%	Yes	77	15.5

[1] Estimated by DNV from images supplied by Plains.

[2] Grinding stopped before maximum crack depth was reached.

Table 5 Weld Crack Details at Excavated Sleeves Continued

Joint #	GW Log Distance (m)	Defect Type	Axial Distance (m)	Orient. (°)	Local Wall Thick. (mm)	*NDE Method*	*Reported Max.Depth (mm)*	*Reported Max. Depth (%wt)*	Cracking Removed? (Yes/No)	Colony Length[6] (mm)	Interlinking or Longest Crack Length[1] (mm)
120	66.78	LOF	3.3	170	5.63	N/A					
120	66.78	LOF	3.3	180	5.63	N/A					
120	66.78	LOF	3.3	190	5.63	N/A					
52700	62617.84	LOF	1.58	150	5.64	N/A					
52700	62617.84	LOF	1.58	304	5.64	N/A					
52700	62617.84	LOF	2.5	187	5.64	N/A					
120	66.78	Undercut	N/A	N/A	5.63	N/A	0.89	15.8%			
52700	62617.84	Undercut	N/A	N/A	5.64	N/A	1.2	21.3%			
55580	65831.32	Undercut	10	120	5.7	N/A	0.9	15.8%			
55580	65831.32	Undercut	11.5	60	5.7	N/A	1.2	21.1%			
55580	65831.32	Undercut	11.5	240	5.7	N/A	0.65	11.4%			
55760	66036.35	Undercut	N/A	N/A	5.62	N/A	1.2	21.4%			
56510	66916.86	Undercut	N/A	N/A	5.65	N/A	1.4	24.8%			
57060	67584.79	Undercut	N/A	N/A	5.7	N/A	0.6	10.5%			
57130	67670.83	Undercut	N/A	N/A	5.75	N/A	0.6	10.4%			
58280	68984.64	Undercut	N/A	N/A	5.7	N/A	1.2	21.1%			
44750	53218.47	No defects Detected									
58460	69205.26	No Defects Detected									

Table 5 Weld Crack Details at Excavated Sleeves Continued

Joint #	GW Log Distance (m)	Defect Type	Axial Distance (m)	Orient. (°)	Local Wall Thick. (mm)	*NDE Method*	*Reported Max.Depth (mm)*	*Reported Max. Depth (%wt)*	Cracking Removed? (Yes/No)	Colony Length[7] (mm)	Interlinking or Longest Crack Length[1] (mm)
Cadotte to Utikuma											
73430	84981.37	Cracks	6.56	90	7.3	N/A	N/A		N/A		No photos of Crack
73430	84981.37	Undercut	4.44	300	7.3	N/A	1.6	21.9%			
73430	84981.37	Undercut	6.56	83	7.3	N/A	0.8	11.0%			

Table 6 Critical Axial Stress for Reported Cracks

Joint Number	DNV Feature ID	t	Depth	Maximum Colony Length	Maximum Interlinked Length	Colony Critical Stress*		Interlinked Critical Stress*	
		mm	mm	mm	mm	MPa	% SMYS	MPa	% SMYS
Zama to Rainbow									
120	C1	5.56	0.84	Crack lengths can not be determined from inspection report					
52700	C2	5.56	1.33	Crack lengths can not be determined from inspection report					
55580	C3	5.56	1.00	11.0	3.0	406.0	113	406.6	113
55580	C4	5.56	0.60	3.0	3.0	406.7	113	406.7	113
55580	C5	5.56	1.80	5.8	5.8	406.0	113	406.0	113
55760	C6	5.56	2.12	33.0	6.5	391.3	109	405.8	113
55760	C7	5.56	2.12	4.0	4.0	406.2	113	406.2	113
56510	C8	5.56	1.50	NA	16.0	NA		405.1	113
56510	C9	5.56	1.20	14.5	2.0	405.6	113	406.6	113
56510	C10	5.56	0.61	9.0	3.0	406.4	113	406.7	113
56510	C11	5.56	0.61	3.0	1.0	406.7	113	406.7	113
56520	C12	5.56	0.80	15.0	6.0	406.0	113	406.6	113
57060	C13	5.56	0.93	13.5	3.0	405.9	113	406.6	113
57060	C14	5.56	1.64	79.0	53.0	397.4	111	400.3	112
57130	C15	5.56	1.03	41.0	12.0	403.7	113	405.9	113
57130	C16	5.56	0.80	25.0	4.0	405.4	113	406.6	113
57130	C17	5.56	0.80	19.0	3.0	405.7	113	406.6	113
58280	C18	5.56	0.40	45.5	37.0	405.5	113	405.7	113
58280	C19	5.56	1.70	74.0	16.0	397.8	111	402.5	112
58280	C20	5.56	0.40	77.0	15.5	404.5	113	406.3	113
Cadotte to Utikuma									
73430	C21	7.14	Crack sizes can not be determined from inspection report						

* Highlighted values indicate toughness-dependent failure; all others are flow-strength dependent.

NOTE: No cracks were reported for excavated sleeves at GW 44750, 58460

Table 7 Proximities of Geotechnical Hazards to Sleeves

Pipeline	Joint Number	Distance to Launch	Latitutde	Longitude	Geotechnical Threat	Proximal to Watercourse	Upstream Distance to Organics (m)	Downstream Distance to Organics (m)	Upstream Hazard Distance (m)	Downstream Hazard Distance (m)
ZAM-RAI	120	69	59.072714	-118.648151	No	No	902	923	>1000	>1000
ZAM-RAI	2160	2518	59.051063	-118.655200	No	No	>1000	443	368	>1000
ZAM-RAI	3440	4001	59.037905	-118.659495	No	No	404	519	>1000	>1000
ZAM-RAI	6570	7669	59.005339	-118.670082	No	No	>1000	521	>1000	>1000
ZAM-RAI	7430	8686	58.996289	-118.673018	No	No	Organic Soil	Organic Soil	>1000	>1000
ZAM-RAI	12100	14254	58.946478	-118.681976	No	No	20	>1000	>1000	>1000
ZAM-RAI	28430	33760	58.774601	-118.720811	No	No	Organic Soil	Organic Soil	>1000	>1000
ZAM-RAI	44750	53229	58.631438	-118.900300	No	No	>1000	>1000	600	>1000
ZAM-RAI	45260	53830	58.626724	-118.905455	No	No	>1000	>1000	>1000	>1000
ZAM-RAI	45270	53844	58.626629	-118.905558	No	No	>1000	>1000	>1000	>1000
ZAM-RAI	45800	54490	58.621696	-118.911457	No	No	>1000	>1000	>1000	>1000
ZAM-RAI	46420	55235	58.617358	-118.921295	No	No	>1000	366	>1000	>1000
ZAM-RAI	48050	57190	58.605980	-118.947030	No	No	973	>1000	>1000	>1000
ZAM-RAI	48090	57242	58.605693	-118.947680	No	No	>1000	>1000	>1000	>1000
ZAM-RAI	48370	57567	58.603796	-118.951971	No	No	>1000	>1000	>1000	974
ZAM-RAI	48670	57907	58.601795	-118.956486	No	No	>1000	>1000	>1000	662
ZAM-RAI	49390	58768	58.596780	-118.967826	No	No	>1000	>1000	230	>1000
ZAM-RAI	49560	58975	58.595393	-118.970244	No	No	>1000	>1000	435	>1000
ZAM-RAI	49910	59349	58.592900	-118.974429	No	No	>1000	>1000	787	>1000
ZAM-RAI	50390	59899	58.589193	-118.980662	No	No	>1000	>1000	>1000	1000
ZAM-RAI	51300	60975	58.581893	-118.993002	No	No	>1000	>1000	21	634
ZAM-RAI	51810	61586	58.577764	-118.999993	No	Yes	>1000	>1000	634	13
ZAM-RAI	52330	62178	58.573771	-119.006720	No	No	>1000	>1000	578	573
ZAM-RAI	52330	62182	58.573771	-119.006720	No	No	>1000	>1000	582	569
ZAM-RAI	52340	62188	58.573688	-119.006860	No	No	>1000	>1000	588	563
ZAM-RAI	52340	62191	58.573688	-119.006860	No	No	>1000	>1000	591	560
ZAM-RAI	52700	62619	58.570771	-119.011784	No	No	>1000	>1000	1000	118
ZAM-RAI	52910	62851	58.569222	-119.014389	No	Yes	>1000	>1000	102	19
ZAM-RAI	54730	64863	58.555514	-119.036806	No	No	>1000	>1000	>1000	143
ZAM-RAI	54930	65063	58.554151	-119.039086	No	Yes	>1000	>1000	55	85
ZAM-RAI	54930	65065	58.554151	-119.039086	No	Yes	>1000	>1000	57	83
ZAM-RAI	55000	65151	58.553577	-119.040049	No	Yes	>1000	>1000	132	9
ZAM-RAI	55100	65273	58.552751	-119.041442	No	No	>1000	>1000	103	573
ZAM-RAI	55190	65379	58.552058	-119.042613	No	No	>1000	>1000	208	468
ZAM-RAI	55220	65409	58.551809	-119.043031	No	No	>1000	>1000	244	432
ZAM-RAI	55580	65840	58.548959	-119.047848	No	Yes	>1000	>1000	668	11
ZAM-RAI	55580	65841	58.548959	-119.047848	No	Yes	>1000	>1000	669	10
ZAM-RAI	55760	66047	58.547580	-119.050174	No	No	>1000	>1000	197	903
ZAM-RAI	55870	66180	58.546667	-119.051721	No	No	>1000	>1000	328	772
ZAM-RAI	55880	66185	58.546583	-119.051862	No	No	>1000	>1000	333	767
ZAM-RAI	56510	66926	58.541628	-119.060180	No	Yes	>1000	>1000	>1000	23
ZAM-RAI	56510	66928	58.541628	-119.060180	No	Yes	>1000	>1000	>1000	21
ZAM-RAI	56530	66936	58.541512	-119.060372	No	Yes	>1000	>1000	>1000	13
ZAM-RAI	57060	67590	58.537083	-119.067721	No	No	>1000	>1000	650	147
ZAM-RAI	57130	67681	58.535576	-119.064177	No	Yes	>1000	>1000	744	47
ZAM-RAI	57240	67772	58.535576	-119.064177	No	Yes	>1000	>1000	38	>1000
ZAM-RAI	57310	67833	58.535458	-119.070522	No	No	>1000	>1000	93	>1000
ZAM-RAI	57360	67900	58.535015	-119.071286	No	No	>1000	>1000	157	>1000
ZAM-RAI	57650	68235	58.532733	-119.075063	No	No	>1000	>1000	496	>1000
ZAM-RAI	58280	68987	58.527636	-119.083541	No	No	>1000	>1000	>1000	884
ZAM-RAI	58460	69214	58.526175	-119.086663	No	No	>1000	>1000	>1000	674
ZAM-RAI	60690	71871	58.508175	-119.116368	No	No	>1000	814	>1000	94
ZAM-RAI	60790	71968	58.507487	-119.117524	No	Yes	>1000	740	18	>1000
ZAM-RAI	63750	75516	58.483451	-119.157810	No	No	582	182	>1000	>1000
ZAM-RAI	68560	81193	58.445746	-119.223283	No	No	>1000	>1000	>1000	>1000
ZAM-RAI	68570	81205	58.445663	-119.223423	No	No	>1000	>1000	>1000	>1000
ZAM-RAI	68590	81229	58.445498	-119.223707	No	No	>1000	>1000	>1000	>1000
ZAM-RAI	68630	81281	58.445315	-119.223941	No	No	>1000	>1000	>1000	>1000
ZAM-RAI	68650	81300	58.445315	-119.223941	No	No	>1000	994	>1000	>1000
ZAM-RAI	68670	81322	58.445315	-119.223941	No	No	>1000	972	>1000	>1000
ZAM-RAI	68670	81325	58.445315	-119.223941	No	No	>1000	969	>1000	>1000
ZAM-RAI	68670	81328	58.445315	-119.223941	No	No	>1000	966	>1000	>1000
ZAM-RAI	68690	81339	58.445315	-119.223941	No	No	>1000	955	>1000	>1000
RAI-CAD	115780	172793	57.346057	-117.185047	No	No	>1000	>1000	>1000	>1000
RAI-CAD	152090	216852	57.039336	-116.759796	No	No	>1000	>1000	>1000	>1000
RAI-CAD	166360	233326	56.917428	-116.607290	No	No	Organic Soil	Organic Soil	>1000	>1000
CAD-UTI	5730	6521	56.831262	-116.497211	No	No	Organic Soil	Organic Soil	>1000	>1000
CAD-UTI	19710	22575	56.716670	-116.339361	No	No	949	528	>1000	1000
CAD-UTI	44660	51151	56.518761	-116.043663	No	No	>1000	>1000	>1000	>1000
CAD-UTI	44660	51153	56.518761	-116.043663	No	No	>1000	>1000	>1000	>1000
CAD-UTI	55300	63737	56.429999	-115.917568	No	No	433	244	>1000	>1000
CAD-UTI	55310	63744	56.429911	-115.917446	No	No	440	251	>1000	>1000
CAD-UTI	73430	84986	56.281658	-115.701155	No	No	>1000	270	>1000	961
CAD-UTI	73560	85146	56.280576	-115.699532	No	No	>1000	111	>1000	804
CAD-UTI	73610	85193	56.280261	-115.699054	No	No	>1000	49	>1000	755
CAD-UTI	73920	85581	56.277678	-115.695174	No	No	155	283	>1000	388
CAD-UTI	74130	85833	56.275936	-115.692562	No	Yes	404	20	>1000	142
CAD-UTI	76420	88520	56.257637	-115.665081	No	No	>1000	>1000	>1000	>1000
CAD-UTI	76430	88532	56.257552	-115.664954	No	No	>1000	>1000	>1000	>1000
CAD-UTI	100980	117970	56.054431	-115.365846	No	No	>1000	253	>1000	>1000
CAD-UTI	100980	117972	56.054431	-115.365846	No	No	>1000	253	>1000	>1000
CAD-UTI	107820	126240	56.000590	-115.276373	No	No	738	40	738	>1000
CAD-UTI	111000	130066	55.974326	-115.237538	No	No	818	24	>1000	>1000
CAD-UTI	112560	131947	55.961770	-115.217554	No	No	630	558	>1000	>1000
CAD-UTI	113340	132911	55.955414	-115.207389	No	No	Organic Soil	Organic Soil	>1000	>1000
CAD-UTI	113660	133304	55.952834	-115.203220	No	No	Organic Soil	Organic Soil	>1000	>1000
CAD-UTI	114460	134239	55.946667	-115.193260	No	No	10	>1000	>1000	>1000
CAD-UTI	117020	137355	55.925098	-115.162163	No	No	Organic Soil	Organic Soil	>1000	>1000
CAD-UTI	117650	138129	55.919320	-115.155429	No	No	98	46	>1000	>1000
CAD-UTI	118510	139137	55.911753	-115.146587	No	No	>1000	>1000	>1000	972
CAD-UTI	118920	139640	55.908002	-115.142207	No	No	>1000	>1000	>1000	472
CAD-UTI	118920	139643	55.908002	-115.142207	No	No	>1000	>1000	>1000	469
CAD-UTI	118940	139661	55.907813	-115.141988	No	No	>1000	>1000	>1000	450
CAD-UTI	118970	139681	55.907695	-115.141852	No	No	>1000	>1000	>1000	430
CAD-UTI	118980	139682	55.907623	-115.141765	No	No	>1000	>1000	>1000	429

Table 8 Summary of Welded Sleeve Locations and Properties

Zama to Rainbow Location							Soil Data						Elevation Profile Within ±250 m			Sleeves Within ±25 m					Recoats Within ±25 m						
Plains Joint Number	Distance from Launch (m)	Distance from Nearest U/S Valve (m)	Length (m)	Wall Thickness (mm)	Latitude (°)	Longitude (°)	Soil Type	Soil Classification	Drainage	Terrain	Site Position	Geotechnical Threat	Maximum (m)	Minimum (m)	Elevation Change (m)	Number of Petrosleeves	Earliest Year	Number of Type B Sleeves	Closest Upstream (m)	Closest Downstream (m)	Number	Earliest Year	Closest Upstream (m)	Closest Downstream (m)	Total Outflow Volume (Barrels)	Closest Excavation (m)	Risk Ranking
120	69	69	1.24	5.56	59.07271	-118.648	Clay	Good	Seasonal wet	Flat	-	No	343.3	347.2	-3.9	3	2010	0	1	63	0		56	226	3232.05		R
2160	2,518	2,518	0.65	5.56	59.05106	-118.655	Silt	Adequate	Well drained	Flat	-	No	331.8	335.4	-3.6	0		0	2,045	1,484	0		2,223	2,569	6275.7		L
3440	4,001	4,001	0.63	5.56	59.03791	-118.659	Silt	Adequate	Poorly drained	Flat	-	No	328.1	329.7	-1.6	0		0	1,484	930	0		3,707	1,086	8102.3		L
6570	7,669	7,669	0.94	5.56	59.00534	-118.67	Till	Good	Standing water	Flat	-	No	324.2	325.6	-1.4	0		0	1,377	817	0		1,705	2,420	12588.13		L
7430	8,686	8,686	0.94	5.56	58.99629	-118.673	Bog	Adverse	Standing water	Flat	-	No	320.7	321.8	-1.1	0		0	201	5,568	0		2,723	1,402	13828.11		L
12100	14,254	5,027	1.25	5.56	58.94648	-118.682	Bog	Adverse	Standing water	Flat	-	No	315	315.9	-0.9	0		0	5,568	19,505	0		4,165	13,608	9485.27		L
28430	33,760	3,086	0.64	5.56	58.7746	-118.721	Bog	Adverse	Standing water	Flat	-	No	306.8	307.4	-0.6	0		0	19,505	19,470	0		1,629	19,037	12438.31		L
44750	53,229	1,556	0.63	5.56	58.63144	-118.9	Till	Good	Poorly drained	Flat	-	No	439.2	452.8	-13.6	0		0	19,470	130	0		433	69	4987.32		R
45260	53,830	2,158	0.63	5.56	58.62672	-118.905	Till	Good	Seasonal wet	Flat	-	No	455	464.1	-9.1	0		1	471	13	0		275	1,113	3967.53		L
45270	53,844	2,171	1.26	5.56	58.62663	-118.906	Till	Good	Seasonal wet	Flat	-	No	455	464.4	-9.4	0		1	13	634	0		288	1,100	N/A		L
45800	54,490	2,818	0.64	5.56	58.6217	-118.911	Till	Good	Seasonal wet	1% grade	-	No	466.5	472.8	-6.3	1	---	0	13	720	0		935	453	2771.2	Pre-Plains Acquisition	L
46420	55,235	3,562	2.98	5.56	58.61736	-118.921	Till	Good	Seasonal wet	Flat	-	No	470.8	474.6	-3.8	2	2010	0	24	1,955	0		292	3,607	N/A	20.48	L
48050	57,190	5,517	2.95	5.56	58.60598	-118.947	Till	Good	Poorly drained	Flat	-	No	468.3	469.6	-1.3	0		0	1,955	52	0		2,246	1,652	2772.46		L
48090	57,242	5,569	0.93	5.56	58.60569	-118.948	Till	Good	Poorly drained	Flat	-	No	468.3	469.9	-1.6	0		0	52	315	0		2,298	1,601	N/A		L
48370	57,567	5,894	0.92	5.56	58.6038	-118.952	Till	Good	Poorly drained	Flat	-	No	468.3	471.9	-3.6	1	2010	0	10	333	0		2,623	1,276	2865.06	7.47	M
48670	57,907	6,234	0.63	5.56	58.6018	-118.956	Organics over till	Adverse	Standing water	Flat	-	No	469.7	472.7	-3	2	2010	0	7	4	0		2,963	935	3275.07	0.1	M
49390	58,768	7,095	1.23	5.56	58.59678	-118.968	Organics over till	Good	Standing water	Flat	-	No	467.5	469.3	-1.8	0		0	857	53	0		3,825	74	N/A		L
49560	58,975	7,303	0.93	5.56	58.59539	-118.97	Till	Good	Poorly drained	Flat	-	No	466.3	469.3	-3	3	2010	0	154	9	0		121	63	4562.18	2.21	M
49910	59,349	7,676	0.93	5.56	58.5929	-118.974	Till	Good	Poorly drained	Flat	-	No	461.1	467.6	-6.5	0		0	363	551	0		310	620	5011.95		L
50390	59,899	8,227	0.69	5.56	58.58919	-118.981	Till	Good	Poorly drained	Flat	-	No	453.1	460.3	-7.2	0		0	551	297	0		861	69	3363.5		L
51300	60,975	9,302	0.93	5.56	58.58189	-118.993	Till	Good	Standing water	Flat	-	No	445.5	448.4	-2.9	0		0	652	612	0		1,006	3,004	3039.66		L
51810	61,586	9,914	2.21	5.56	58.57776	-119	Till	Good	Standing water	Flat and small bank of river	Toe	No	443.1	452.3	-9.2	0		0	612	591	0		1,618	2,392	4450.06		L
52330	62,178	10,505	3.1	5.56	58.57377	-119.007	Till	Good	Standing water	Flat	-	No	454.1	459.3	-5.2	2	2009	3	591	5	0		2,210	1,801	2857.17	7.41	M
52330	62,182	10,510	0.63	5.56	58.57377	-119.007	Till	Good	Standing water	Flat	-	No	454.1	459.9	-5.8	2	2009	3	5	5	0		2,214	1,796	2862.84	5.18	M
52340	62,188	10,515	2.52	5.56	58.57369	-119.007	Till	Good	Standing water	Flat	-	No	454.1	459.9	-5.8	2	2009	3	5	3	0		2,220	1,791	2869.27		M
52340	62,191	10,518	0.68	5.56	58.57369	-119.007	Till	Good	Standing water	Flat	-	No	454.1	459.9	-5.8	2	2009	3	3	3	0		2,223	1,788	2873.41		M
52700	62,619	10,947	0.94	5.56	58.57077	-119.012	Till	Good	Standing water	Flat	-	No	451.9	461.2	-9.3	9	2009	0	3	4	0		2,651	1,359	2991.99		R
52910	62,851	11,178	1.53	5.56	58.56922	-119.014	Till	Good	Poorly drained	Flat	-	No	451.9	460.4	-8.5	0		0	84	312	0		2,883	1,128	2765.76		L
54730	64,863	51	2.49	5.56	58.55551	-119.037	Till	Good	Poorly drained	Flat	-	No	453.3	463.1	-9.8	0		0	720	199	0		633	230	3882.06		L
54930	65,063	251	0.64	5.56	58.55415	-119.039	Till	Good	Poorly drained	Flat	-	No	453.3	464.4	-11.1	0		1	199	2	0		832	30	3643.46		L
54930	65,065	253	0.63	5.56	58.55415	-119.039	Till	Good	Poorly drained	Flat	-	No	453.3	464.4	-11.1	0		1	2	85	0		834	28	3640.66		L
55000	65,151	339	1.3	5.56	58.55358	-119.04	Till	Good	Poorly drained	Sloped	Toe	No	453.3	465.5	-12.2	2	---	0	1	2	0		58	394	3537.38	Pre-Plains Acquisition	L
55100	65,273	461	2.78	5.56	58.55275	-119.041	Till	Good	Poorly drained	Sloped	Toe	No	453.6	467.5	-13.9	0		0	120	106	0		180	273	3391.63		L
55190	65,379	567	1.24	5.56	58.55206	-119.043	Till	Good	Seasonal wet	Flat	-	No	453.6	467.7	-14.1	0		0	106	30	0		286	167	3264.89		L
55220	65,409	597	0.64	5.56	58.55181	-119.043	Till	Good	Seasonal wet	Flat	-	No	454.9	467.7	-12.8	0		0	30	415	0		316	137	3228.73		L
55580	65,840	1,028	0.69	5.56	58.54896	-119.048	Till	Good	Seasonal wet	Slight slope	Toe	No	460.7	466.5	-5.8	3	2010	1	16	1	0		295	102	2818.69		R
55580	65,841	1,029	0.91	5.56	58.54896	-119.048	Till	Good	Seasonal wet	Slight slope	Toe	No	460.7	466.5	-5.8	3	2010	1	1	11	0		295	102	N/A		R
55760	66,047	1,235	0.64	5.56	58.54758	-119.05	Till	Good	Seasonal wet	Flat	-	No	460.7	467.7	-7	2	2010	0	5	133	0		99	6,017	2777.49		R
55870	66,180	1,368	0.93	5.56	58.54667	-119.052	Till	Good	Well drained	Flat	-	No	465.7	468.7	-3	0		1	133	5	0		232	5,884	2936.39		L
55880	66,185	1,373	0.94	5.56	58.54658	-119.052	Till	Good	Well drained	Flat	-	No	465.7	468.7	-3	0		1	5	741	0		237	5,879	2942.44		L
56510	66,926	2,114	0.95	5.56	58.54163	-119.06	Till	Good	Standing water	Small river valley	Toe	No	462.5	468.2	-5.7	1	---	2	741	2	0		978	5,138	2926.74		R
56510	66,928	2,116	3.14	5.56	58.54163	-119.06	Till	Good	Standing water	Small river valley	Toe	No	462.5	468	-5.5	1	---	2	2	4	0		980	5,136	2929.11		R
56530	66,936	2,124	0.64	5.56	58.54151	-119.06	Till	Good	Standing water	Small river valley	Toe	No	462.5	468	-5.5	1	---	2	5	653	0		989	5,127	2939.36		R
57060	67,590	2,778	0.96	5.56	58.53708	-119.06772	Till	Good	Standing water	Flat	-	No	465	465	0	0		0	653	91	0		1,642	4,474	3579.63		R
57130	67,681	2,869	1.54	5.56	58.53558	-119.06418	Till	Good	Standing water	Flat	-	No	465	465	0	0		0	91	91	0		1,733	4,383	3470.52		R
57240	67,772	2,960	1.25	5.56	58.53558	-119.06418	Till	Good	Well drained	Sloped	Mid	No	465	465	0	7	---	0	91	4	0		1,824	4,292	3361.73	0.96	M
57310	67,833	3,021	0.64	5.56	58.53546	-119.07052	Till	Good	Well drained	Flat	-	No	465	465	0	0		0	51	67	0		1,885	4,231	3288.31		L
57360	67,900	3,088	0.93	5.56	58.53502	-119.07129	Till	Good	Well drained	Flat	-	No	465	465	0	0		0	67	336	0		1,952	4,164	3208.56		L
57650	68,235	3,423	0.92	5.56	58.53273	-119.07506	Organics over till	Good	Standing water	Flat	-	No	465	465	0	0		0	336	752	0		2,288	3,828	N/A		L
58280	68,987	4,175	3.07	5.56	58.52764	-119.08354	Till	Good	Standing water	Flat	-	No	465	465	0	0		0	752	227	0		3,039	3,077	2793.88		R
58460	69,214	4,402	1.25	5.56	58.52618	-119.08666	Till	Good	Standing water	Flat	-	No	465	465	0	0		0	227	2,657	0		3,266	2,849	N/A		R
60690	71,871	7,059	0.94	5.56	58.50818	-119.116	Till	Good	Poorly drained	Flat	-	No	449.8	454.9	-5.1	0		0	2,657	97	0		5,923	193	3548.78		L
60790	71,968	7,156	4.27	5.56	58.50749	-119.118	Till	Good	Standing water	Flat	-	No	448.6	454.3	-5.7	0		0	97	170	0		6,020	96	3438.85		L
63750	75,516	10,704	3.12	5.56	58.48345	-119.158	Till	Good	Standing water	Flat	-	No	447	448.1	-1.1	0		0	161	4,647	0		171	2,158	5006.92		L
68560	81,193	16,381	0.92	5.56	58.44575	-119.223	Silt	Adequate	Poorly drained	Flat	-	No	455.9	457.4	-1.5	0		1	1,030	12	0		926	N/A	3853.57		L
68570	81,205	16,393	0.62	5.56	58.44566	-119.223	Silt	Adequate	Poorly drained	Flat	-	No	455.9	457.4	-1.5	0		2	12	24	0		938	N/A	3832.06		L
68590	81,229	16,417	0.64	5.56	58.4455	-119.224	Silt	Adequate	Poorly drained	Flat	-	No	455.9	457.4	-1.5	0		1	24	52	0		962	N/A	3789.35		L
68630	81,281	16,469	0.63	5.56	58.44532	-119.224	Gravel over silt	Adequate	Poorly drained	Flat	-	No	455.9	457.4	-1.5	0		1	52	19	0		1,014	N/A	3691.72		L
68650	81,300	16,488	0.64	5.56	58.44532	-119.224	Gravel over silt	Adequate	Poorly drained	Flat	-	No	455.9	457.4	-1.5	0		2	19	22	0		1,033	N/A	3651.32		L
68670	81,322	16,510	1.32	5.56	58.44532	-119.224	Gravel over silt	Adequate	Poorly drained	Flat	-	No	455.9	457.4	-1.5	0		4	22	3	0		1,055	N/A	N/A		L
68670	81,325	16,513	2.76	5.56	58.44532	-119.224	Gravel over silt	Adequate	Poorly drained	Flat	-	No	455.9	457.4	-1.5	0		3	3	3	0		1,058	N/A	N/A		L
68670	81,328	16,516	0.69	5.56	58.44532	-119.224	Gravel over silt	Adequate	Poorly drained	Flat	-	No	455.9	457.4	-1.5	0		3	3	10	0		1,062	N/A	3581.8		L
68690	81,339	16,527	0.47	12.7	58.44532	-119.224	Gravel over silt	Adequate	Poorly drained	Flat	-	No	456.1	457.4	-1.3	0		3	10	N/A	0		1,072	N/A	3548.76		L

Table 8 Summary of Welded Sleeve Locations and Properties Continued

Rainbow to Cadotte Location							Soil Data						Elevation Profile Within ±250 m			Sleeves Within ±25 m					Recoats Within ±25 m						
Plains Joint Number	Distance from Launch (m)	Distance from Nearest U/S Valve (m)	Length (m)	Wall Thickness (mm)	Latitude (°)	Longitude (°)	Soil Type	Soil Classification	Drainage	Terrain	Site Position	Geotechnical Threat	Maximum (m)	Minimum (m)	Elevation Change (m)	Number of Petrosleeves	Earliest Year	Number of Type B Sleeves	Closest Upstream (m)	Closest Downstream (m)	Number	Earliest Year	Closest Upstream (m)	Closest Downstream (m)	Total Outflow Volume (Barrels)	Closest Excavation (m)	Risk Ranking
115780	172,793	30,590	2.47	7.14	57.34606	-117.18505	Clay	Good	Seasonal wet	Flat	-	No	420.2	417.49	2.71	0		0	10,813	5,578	0		4,289	22,412	27775.52		L
152090	216,852	37,178	0.95	7.14	57.03934	-116.7598	Till	Good	Well drained	Flat	-	No	601.58	590.1	11.48	0		0	21,771	16,474	0		21,345	20,143	13773.6		L
166360	233,326	7,389	0.93	7.14	56.91743	-116.60729	Muskeg	Adverse	Standing water	Flat	-	No	640.41	633.67	6.74	0		0	16,474	N/A	0		37,819	3,669	13408.55		L

Cadotte to Utikuma Location							Soil Data						Elevation Profile Within ±250 m			Sleeves Within ±25 m					Recoats Within ±25 m						
Plains Joint Number	Distance from Launch (m)	Distance from Nearest U/S Valve (m)	Length (m)	Wall Thickness (mm)	Latitude (°)	Longitude (°)	Soil Type	Soil Classification	Drainage	Terrain	Site Position	Geotechnical Threat	Maximum (m)	Minimum (m)	Elevation Change (m)	Number of Petrosleeves	Earliest Year	Number of Type B Sleeves	Closest Upstream (m)	Closest Downstream (m)	Number	Earliest Year	Closest Upstream (m)	Closest Downstream (m)	Total Outflow Volume (Barrels)	Closest Excavation (m)	Risk Ranking
5730	6,521	6,466	0.93	7.14	56.83126	-116.497	Muskeg	Adverse	Standing water	Flat	-	No	679.4	680	-0.6	0		0	2,034	5,455	0		2,179	6,855	6538.66		L
19710	22,575	22,519	0.96	7.14	56.71667	-116.339	Till	Good	Seasonal wet	Flat	-	No	654.7	669.3	-14.6	0		0	6,401	565	0		2,510	9,760	N/A		L
44660	51,151	20,709	0.6	7.14	56.51876	-116.044	Ogranics over silt	Adverse	Standing water	Flat	-	No	565.4	569.7	-4.3	0		1	4,412	2	0		2,627	9,468	17132.32		L
44660	51,153	20,712	0.63	7.14	56.51876	-116.044	Organics over silt	Adverse	Standing water	Flat	-	No	565.4	569.7	-4.3	0		1	2	5,807	0		2,630	9,466	17135.43		L
55300	63,737	33,296	0.94	7.14	56.43	-115.918	Till	Good	Poorly drained	Flat	-	No	555.1	560.6	-5.5	0		1	329	7	1	2010	23	2	16622.79		R
55310	63,744	33,303	1.55	7.14	56.42991	-115.917	Till	Good	Poorly drained	Flat	-	No	555.1	560.6	-5.5	0		1	7	741	1	2010	5	32	16634.06		R
73430	84,986	54,545	1.85	7.14	56.28166	-115.701	Till	Good	Well drained	Flat	-	No	540.9	544.2	-3.3	0		0	14,535	160	0		14,402	N/A	23829.75		R
73560	85,146	54,705	1.25	7.14	56.28058	-115.7	Till	Good	Well drained	Flat	-	No	539.5	544.2	-4.7	1	---	0	160	19	0		14,561	N/A	23212.18	Pre-Plains Acquisition	L
73610	85,193	54,752	0.64	7.14	56.28026	-115.699	Till	Good	Well drained	Flat	-	No	539.5	544.2	-4.7	0		0	28	203	0		14,609	N/A	23029.64		L
73920	85,581	55,140	0.64	7.14	56.27768	-115.695	Till	Good	Well drained	Slight slope	-	No	536.8	541.8	-5	1	2010	0	103	5	0		14,997	N/A	21526.44	3.19	M
74130	85,833	55,392	0.65	7.14	56.27594	-115.693	Till	Good	Well drained	Flat	-	No	535.6	539.5	-3.9	0		0	247	2,687	0		15,249	N/A	20546.73		L
76420	88,520	58,079	1.57	7.14	56.25764	-115.665	Till	Good	Well drained	Undulating	-	No	552.5	568.5	-16	0		1	2,687	12	0		17,936	N/A	10806.14		L
76430	88,532	58,091	0.95	7.14	56.25755	-115.665	Till	Good	Well drained	Undulating	-	No	553	568.5	-15.5	0		1	12	29,438	0		17,948	N/A	10598.81		L
100980	117,970	14,851	0.34	7.14	56.05443	-115.366	Organics over till	Good	Poorly drained	Flat	-	No	611	621.6	-10.6	0		1	29,438	2	0		47,386	N/A	N/A		L
100980	117,972	14,853	0.3	7.14	56.05443	-115.366	Organics over till	Good	Poorly drained	Flat	-	No	611	621.6	-10.6	0		1	2	8,268	0		47,388	N/A	3448.96		L
107820	126,240	23,121	0.66	7.14	56.00059	-115.276	Till	Good	Well drained	Flat with slight grade	-	No	620.6	624.3	-3.7	0		0	8,268	3,826	0		55,655	N/A	18817.71		L
111000	130,066	26,947	0.65	7.14	55.97433	-115.238	Till	Good	Well drained	Flat	-	No	638.3	640.2	-1.9	0		0	3,826	1,881	0		59,482	N/A	14028.41		L
112560	131,947	28,828	0.64	7.14	55.96177	-115.218	Till	Good	Poorly drained	Flat	-	No	635.6	636.8	-1.2	0		0	1,881	964	0		61,363	N/A	11679.19		L
113340	132,911	29,792	0.64	7.14	55.95541	-115.207	Muskeg	Adverse	Poorly drained	Flat	-	No	635.5	636.7	-1.2	0		0	964	393	0		62,327	N/A	10477.57		L
113660	133,304	30,185	0.65	7.14	55.95283	-115.203	Muskeg	Adverse	Standing water	Flat	-	No	635.7	636.9	-1.2	0		0	393	935	0		62,719	N/A	9988.07		L
114460	134,239	31,119	2.55	7.14	55.94667	-115.193	Till	Good	Standing water	Flat	-	No	636.2	636.8	-0.6	0		0	935	3,117	0		63,654	N/A	8960.34		L
117020	137,355	34,236	0.65	7.14	55.9251	-115.162	Muskeg	Adequate	Standing water	Flat	-	No	624	624.7	-0.7	0		0	3,117	774	0		66,771	N/A	5168.42		L
117650	138,129	35,010	0.64	7.14	55.91932	-115.155	Till	Good	Poorly drained	Flat	-	No	624.6	626.6	-2	0		0	774	1,008	0		67,545	N/A	4213.55		L
118510	139,137	36,018	1.25	7.14	55.91175	-115.147	Till	Good	Poorly drained	Flat	-	No	627.3	629.9	-2.6	0		0	1,008	503	0		68,553	N/A	3071.21		L
118920	139,640	36,521	0.32	7.14	55.908	-115.142	Till	Good	Poorly drained	Flat	-	No	629.6	630.6	-1	0		2	503	2	0		69,056	N/A	2384.6		L
118920	139,643	36,524	0.32	7.14	55.908	-115.142	Till	Good	Poorly drained	Flat	-	No	629.6	630.6	-1	0		2	2	18	0		69,058	N/A	2380.69		L
118940	139,661	36,542	1.87	7.14	55.90781	-115.142	Till	Good	Poorly drained	Flat	-	No	629.7	630.6	-0.9	0		4	18	20	0		69,077	N/A	2351.27		L
118970	139,681	10	0.19	7.14	55.9077	-115.142	Till	Good	Poorly drained	Flat	-	No	629.9	630.6	-0.7	0		2	20	0	0		69,097	N/A	2356.46		L
118980	139,682	11	0.21	7.14	55.90762	-115.142	Till	Good	Poorly drained	Flat	-	No	629.9	630.6	-0.7	0		2	0	N/A	0		69,097	N/A	N/A		L

R	Remediated
M	Medium Risk
L	Low Risk

Yellow Highlight	Joint Exposed and Remediated
Green Highlight	Medium Risk

Table 9 Sleeve Risk Factors

Zama to Rainbow Location					Soil Data						Sleeves Within ±25 m					Recoats Within ±25 m					
Plains Joint Number	Distance from Launch (m)	Distance from Nearest U/S Valve (m)	Length (m)	Wall Thickness (mm)	Soil Type	Soil Classification	Drainage	Terrain	Site Position	Geotechnical Threat	Number of Petrosleeves	Earliest Year	Number of Type B Sleeves	Closest Upstream (m)	Closest Downstream (m)	Number	Earliest Year	Closest Upstream (m)	Closest Downstream (m)	Closest Excavation (m)	Risk Ranking
120	69	69	1.24	5.56	Clay	Good	Seasonal wet	Flat	-	No	3	2010	0	1	63	0		56	226		R
2160	2,518	2,518	0.65	5.56	Silt	Adequate	Well drained	Flat	-	No	0		0	2,045	1,484	0		2,223	2,569		L
3440	4,001	4,001	0.63	5.56	Silt	Adequate	Poorly drained	Flat	-	No	0		0	1,484	930	0		3,707	1,086		L
6570	7,669	7,669	0.94	5.56	Till	Good	Standing water	Flat	-	No	0		0	1,377	817	0		1,705	2,420		L
7430	8,686	8,686	0.94	5.56	Bog	Adverse	Standing water	Flat	-	No	0		0	201	5,568	0		2,723	1,402		L
12100	14,254	5,027	1.25	5.56	Bog	Adverse	Standing water	Flat	-	No	0		0	5,568	19,505	0		4,165	13,608		L
28430	33,760	3,086	0.64	5.56	Bog	Adverse	Standing water	Flat	-	No	0		0	19,505	19,470	0		1,629	19,037		L
44750	53,229	1,556	0.63	5.56	Till	Good	Poorly drained	Flat	-	No	0		0	19,470	130	0		433	69		R
45260	53,830	2,158	0.63	5.56	Till	Good	Seasonal wet	Flat	-	No	0		1	471	13	0		275	1,113		L
45270	53,844	2,171	1.26	5.56	Till	Good	Seasonal wet	Flat	-	No	0		1	13	634	0		288	1,100		L
45800	54,490	2,818	0.64	5.56	Till	Good	Seasonal wet	1% grade	-	No	1	---	0	13	720	0		935	453	Pre-Plains Acquisition	L
46420	55,235	3,562	2.98	5.56	Till	Good	Seasonal wet	Flat	-	No	2	2010	0	24	1,955	0		292	3,607	20.48	L
48050	57,190	5,517	2.95	5.56	Till	Good	Poorly drained	Flat	-	No	0		0	1,955	52	0		2,246	1,652		L
48090	57,242	5,569	0.93	5.56	Till	Good	Poorly drained	Flat	-	No	0		0	52	315	0		2,298	1,601		L
48370	57,567	5,894	0.92	5.56	Till	Good	Poorly drained	Flat	-	No	1	2010	0	10	333	0		2,623	1,276	7.47	M
48670	57,907	6,234	0.63	5.56	Organics over till	Adverse	Standing water	Flat	-	No	2	2010	0	7	4	0		2,963	935	0.1	M
49390	58,768	7,095	1.23	5.56	Organics over till	Good	Standing water	Flat	-	No	0		0	857	53	0		3,825	74		L
49560	58,975	7,303	0.93	5.56	Till	Good	Poorly drained	Flat	-	No	3	2010	0	154	9	0		121	63	2.21	M
49910	59,349	7,676	0.93	5.56	Till	Good	Poorly drained	Flat	-	No	0		0	363	551	0		310	620		L
50390	59,899	8,227	0.69	5.56	Till	Good	Poorly drained	Flat	-	No	0		0	551	297	0		861	69		L
51300	60,975	9,302	0.93	5.56	Till	Good	Standing water	Flat	-	No	0		0	652	612	0		1,006	3,004		L
51810	61,586	9,914	2.21	5.56	Till	Good	Standing water	Flat and small bank of river	Toe	No	0		0	612	591	0		1,618	2,392		L
52330	62,178	10,505	3.1	5.56	Till	Good	Standing water	Flat	-	No	2	2009	3	591	5	0		2,210	1,801	7.41	M
52330	62,182	10,510	0.63	5.56	Till	Good	Standing water	Flat	-	No	2	2009	3	5	5	0		2,214	1,796	5.18	M
52340	62,188	10,515	2.52	5.56	Till	Good	Standing water	Flat	-	No	2	2009	3	5	3	0		2,220	1,791		M
52340	62,191	10,518	0.68	5.56	Till	Good	Standing water	Flat	-	No	2	2009	3	3	3	0		2,223	1,788		M
52700	62,619	10,947	0.94	5.56	Till	Good	Standing water	Flat	-	No	9	2009	0	3	4	0		2,651	1,359		R
52910	62,851	11,178	1.53	5.56	Till	Good	Poorly drained	Flat	-	No	0		0	84	312	0		2,883	1,128		L
54730	64,863	51	2.49	5.56	Till	Good	Poorly drained	Flat	-	No	0		0	720	199	0		633	230		L
54930	65,063	251	0.64	5.56	Till	Good	Poorly drained	Flat	-	No	0		1	199	2	0		832	30		L
54930	65,065	253	0.63	5.56	Till	Good	Poorly drained	Flat	-	No	0		1	2	85	0		834	28		L
55000	65,151	339	1.3	5.56	Till	Good	Poorly drained	Sloped	Toe	No	2	---	0	1	2	0		58	394	Pre-Plains Acquisition	L
55100	65,273	461	2.78	5.56	Till	Good	Poorly drained	Sloped	Toe	No	0		0	120	106	0		180	273		L
55190	65,379	567	1.24	5.56	Till	Good	Seasonal wet	Flat	-	No	0		0	106	30	0		286	167		L
55220	65,409	597	0.64	5.56	Till	Good	Seasonal wet	Flat	-	No	0		0	30	415	0		316	137		L
55580	65,840	1,028	0.69	5.56	Till	Good	Seasonal wet	Slight slope	Toe	No	3	2010	1	16	1	0		295	102		R
55580	65,841	1,029	0.91	5.56	Till	Good	Seasonal wet	Slight slope	Toe	No	3	2010	1	1	11	0		295	102		R
55760	66,047	1,235	0.64	5.56	Till	Good	Seasonal wet	Flat	-	No	2	2010	0	5	133	0		99	6,017		R
55870	66,180	1,368	0.93	5.56	Till	Good	Well drained	Flat	-	No	0		1	133	5	0		232	5,884		L
55880	66,185	1,373	0.94	5.56	Till	Good	Well drained	Flat	-	No	0		1	5	741	0		237	5,879		L
56510	66,926	2,114	0.95	5.56	Till	Good	Standing water	Small river valley	Toe	No	1	---	2	741	2	0		978	5,138		R
56510	66,928	2,116	3.14	5.56	Till	Good	Standing water	Small river valley	Toe	No	1	---	2	2	4	0		980	5,136		R
56530	66,936	2,124	0.64	5.56	Till	Good	Standing water	Small river valley	Toe	No	1	---	2	5	653	0		989	5,127		R
57060	67,590	2,778	0.96	5.56	Till	Good	Standing water	Flat	-	No	0		0	653	91	0		1,642	4,474		R
57130	67,681	2,869	1.54	5.56	Till	Good	Standing water	Flat	-	No	0		0	91	91	0		1,733	4,383		R
57240	67,772	2,960	1.25	5.56	Till	Good	Well drained	Sloped	Mid	No	7	---	0	91	4	0		1,824	4,292	0.96	M
57310	67,833	3,021	0.64	5.56	Till	Good	Well drained	Flat	-	No	0		0	51	67	0		1,885	4,231		L
57360	67,900	3,088	0.93	5.56	Till	Good	Well drained	Flat	-	No	0		0	67	336	0		1,952	4,164		L
57650	68,235	3,423	0.92	5.56	Organics over till	Good	Standing water	Flat	-	No	0		0	336	752	0		2,288	3,828		L
58280	68,987	4,175	3.07	5.56	Till	Good	Standing water	Flat	-	No	0		0	752	227	0		3,039	3,077		R
58460	69,214	4,402	1.25	5.56	Till	Good	Standing water	Flat	-	No	0		0	227	2,657	0		3,266	2,849		R
60690	71,871	7,059	0.94	5.56	Till	Good	Poorly drained	Flat	-	No	0		0	2,657	97	0		5,923	193		L
60790	71,968	7,156	4.27	5.56	Till	Good	Standing water	Flat	-	No	0		0	97	170	0		6,020	96		L
63750	75,516	10,704	3.12	5.56	Till	Good	Standing water	Flat	-	No	0		0	161	4,647	0		171	2,158		L
68560	81,193	16,381	0.92	5.56	Silt	Adequate	Poorly drained	Flat	-	No	0		1	1,030	12	0		926	N/A		L
68570	81,205	16,393	0.62	5.56	Silt	Adequate	Poorly drained	Flat	-	No	0		2	12	24	0		938	N/A		L
68590	81,229	16,417	0.64	5.56	Silt	Adequate	Poorly drained	Flat	-	No	0		1	24	52	0		962	N/A		L
68630	81,281	16,469	0.63	5.56	Gravel over silt	Adequate	Poorly drained	Flat	-	No	0		1	52	19	0		1,014	N/A		L
68650	81,300	16,488	0.64	5.56	Gravel over silt	Adequate	Poorly drained	Flat	-	No	0		2	19	22	0		1,033	N/A		L
68670	81,322	16,510	1.32	5.56	Gravel over silt	Adequate	Poorly drained	Flat	-	No	0		4	22	3	0		1,055	N/A		L
68670	81,325	16,513	2.76	5.56	Gravel over silt	Adequate	Poorly drained	Flat	-	No	0		3	3	3	0		1,058	N/A		L
68670	81,328	16,516	0.69	5.56	Gravel over silt	Adequate	Poorly drained	Flat	-	No	0		3	3	10	0		1,062	N/A		L
68690	81,339	16,527	0.47	12.7	Gravel over silt	Adequate	Poorly drained	Flat	-	No	0		3	10	N/A	0		1,072	N/A		L

Table 9 Sleeve Risk Factors Continued

Rainbow to Cadotte Location					Soil Data						Sleeves Within ±25 m					Recoats Within ±25 m					
Plains Joint Number	Distance from Launch (m)	Distance from Nearest U/S Valve (m)	Length (m)	Wall Thickness (mm)	Soil Type	Soil Classification	Drainage	Terrain	Site Position	Geotechnical Threat	Number of Petrosleeves	Earliest Year	Number of Type B Sleeves	Closest Upstream (m)	Closest Downstream (m)	Number	Earliest Year	Closest Upstream (m)	Closest Downstream (m)	Closest Excavation (m)	Risk Ranking
115780	172,793	30,590	2.47	7.14	Clay	Good	Seasonal wet	Flat	-	No	0		0	10,813	5,578	0		4,289	22,412		L
152090	216,852	37,178	0.95	7.14	Till	Good	Well drained	Flat	-	No	0		0	21,771	16,474	0		21,345	20,143		L
166360	233,326	7,389	0.93	7.14	Muskeg	Adverse	Standing water	Flat	-	No	0		0	16,474	N/A	0		37,819	3,669		L

Cadotte to Utikuma Location					Soil Data						Sleeves Within ±25 m					Recoats Within ±25 m					
Plains Joint Number	Distance from Launch (m)	Distance from Nearest U/S Valve (m)	Length (m)	Wall Thickness (mm)	Soil Type	Soil Classification	Drainage	Terrain	Site Position	Geotechnical Threat	Number of Petrosleeves	Earliest Year	Number of Type B Sleeves	Closest Upstream (m)	Closest Downstream (m)	Number	Earliest Year	Closest Upstream (m)	Closest Downstream (m)	Closest Excavation (m)	Risk Ranking
5730	6,521	6,466	0.93	7.14	Muskeg	Adverse	Standing water	Flat	-	No	0		0	2,034	5,455	0		2,179	6,855		L
19710	22,575	22,519	0.96	7.14	Till	Good	Seasonal wet	Flat	-	No	0		0	6,401	565	0		2,510	9,760		L
44660	51,151	20,709	0.6	7.14	Ogranics over silt	Adverse	Standing water	Flat	-	No	0		1	4,412	2	0		2,627	9,468		L
44660	51,153	20,712	0.63	7.14	Organics over silt	Adverse	Standing water	Flat	-	No	0		1	2	5,807	0		2,630	9,466		L
55300	63,737	33,296	0.94	7.14	Till	Good	Poorly drained	Flat	-	No	0		1	329	7	1	2010	23	2		R
55310	63,744	33,303	1.55	7.14	Till	Good	Poorly drained	Flat	-	No	0		1	7	741	1	2010	5	32		R
73430	84,986	54,545	1.85	7.14	Till	Good	Well drained	Flat	-	No	0		0	14,535	160	0		14,402	N/A		R
73560	85,146	54,705	1.25	7.14	Till	Good	Well drained	Flat	-	No	1	---	0	160	19	0		14,561	N/A	Pre-Plains Acquisition	L
73610	85,193	54,752	0.64	7.14	Till	Good	Well drained	Flat	-	No	0		0	28	203	0		14,609	N/A		L
73920	85,581	55,140	0.64	7.14	Till	Good	Well drained	Slight slope	-	No	1	2010	0	103	5	0		14,997	N/A	3.19	M
74130	85,833	55,392	0.65	7.14	Till	Good	Well drained	Flat	-	No	0		0	247	2,687	0		15,249	N/A		L
76420	88,520	58,079	1.57	7.14	Till	Good	Well drained	Undulating	-	No	0		1	2,687	12	0		17,936	N/A		L
76430	88,532	58,091	0.95	7.14	Till	Good	Well drained	Undulating	-	No	0		1	12	29,438	0		17,948	N/A		L
100980	117,970	14,851	0.34	7.14	Organics over till	Good	Poorly drained	Flat	-	No	0		1	29,438	2	0		47,386	N/A		L
100980	117,972	14,853	0.3	7.14	Organics over till	Good	Poorly drained	Flat	-	No	0		1	2	8,268	0		47,388	N/A		L
107820	126,240	23,121	0.66	7.14	Till	Good	Well drained	Flat with slight grade	-	No	0		0	8,268	3,826	0		55,655	N/A		L
111000	130,066	26,947	0.65	7.14	Till	Good	Well drained	Flat	-	No	0		0	3,826	1,881	0		59,482	N/A		L
112560	131,947	28,828	0.64	7.14	Till	Good	Poorly drained	Flat	-	No	0		0	1,881	964	0		61,363	N/A		L
113340	132,911	29,792	0.64	7.14	Muskeg	Adverse	Poorly drained	Flat	-	No	0		0	964	393	0		62,327	N/A		L
113660	133,304	30,185	0.65	7.14	Muskeg	Adverse	Standing water	Flat	-	No	0		0	393	935	0		62,719	N/A		L
114460	134,239	31,119	2.55	7.14	Till	Good	Standing water	Flat	-	No	0		0	935	3,117	0		63,654	N/A		L
117020	137,355	34,236	0.65	7.14	Muskeg	Adequate	Standing water	Flat	-	No	0		0	3,117	774	0		66,771	N/A		L
117650	138,129	35,010	0.64	7.14	Till	Good	Poorly drained	Flat	-	No	0		0	774	1,008	0		67,545	N/A		L
118510	139,137	36,018	1.25	7.14	Till	Good	Poorly drained	Flat	-	No	0		0	1,008	503	0		68,553	N/A		L
118920	139,640	36,521	0.32	7.14	Till	Good	Poorly drained	Flat	-	No	0		2	503	2	0		69,056	N/A		L
118920	139,643	36,524	0.32	7.14	Till	Good	Poorly drained	Flat	-	No	0		2	2	18	0		69,058	N/A		L
118940	139,661	36,542	1.87	7.14	Till	Good	Poorly drained	Flat	-	No	0		4	18	20	0		69,077	N/A		L
118970	139,681	10	0.19	7.14	Till	Good	Poorly drained	Flat	-	No	0		2	20	0	0		69,097	N/A		L
118980	139,682	11	0.21	7.14	Till	Good	Poorly drained	Flat	-	No	0		2	0	N/A	0		69,097	N/A		L

R	Remediated
M	Medium Risk
L	Low Risk

Yellow Highlight	Joint Exposed and Remediated
Green Highlight	Medium Risk

Figure 1 Site of April 2010 Excavation Involving Joint 55310 (Failure Joint)

Figure 2 Site of April 2010 Excavation Involving Joint 55310 (Failure Joint) (after Recoat)

Figure 3 Topography Downstream of April 2010 Excavation Involving Joint 55310 (Failure Joint) (after Backfill)

Figure 4 Topography Upstream of April 2010 Excavation Involving Joint 55310 (Failure Joint) (after Backfill)

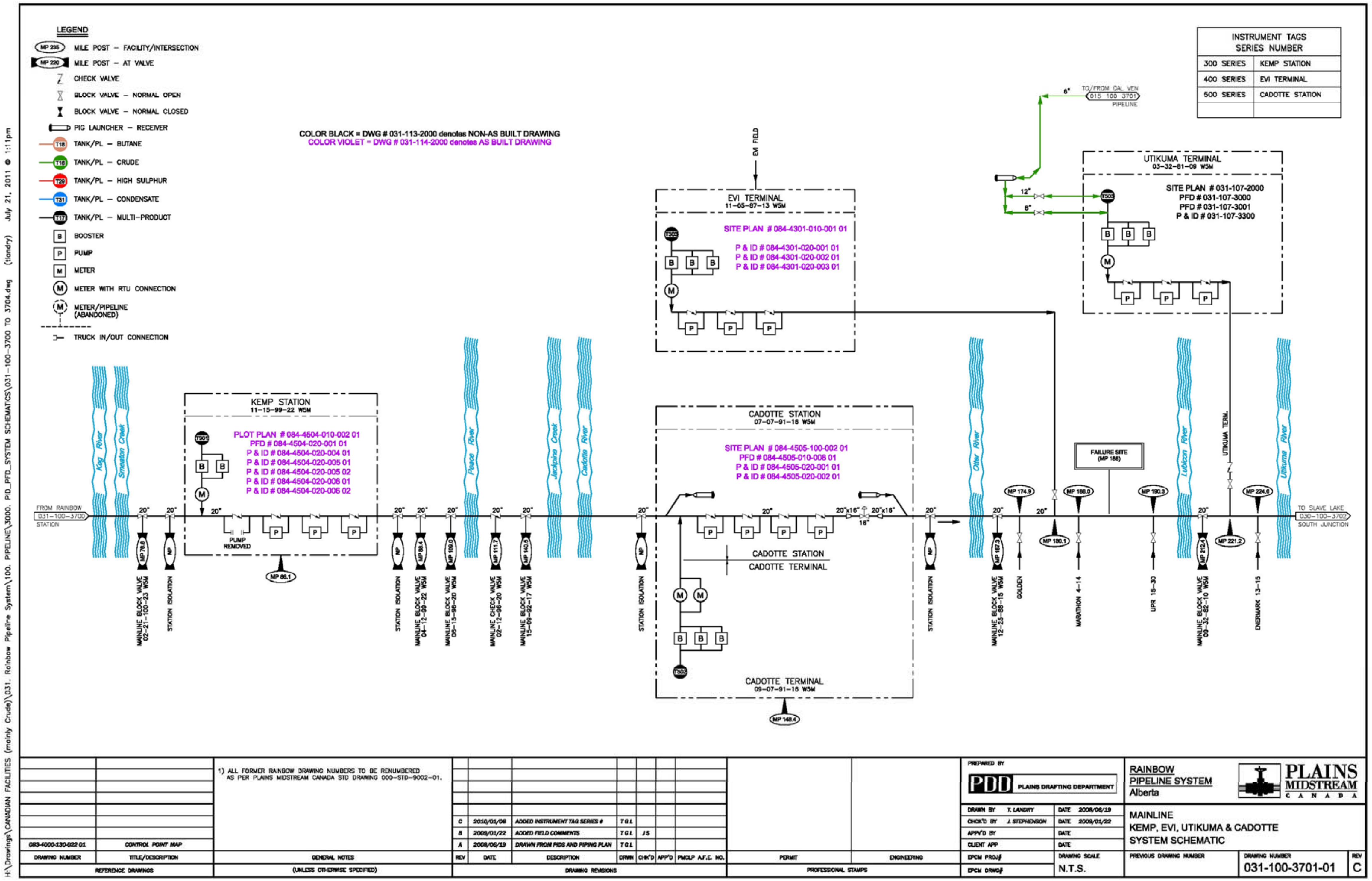


Figure 5 Schematic of Pipeline in Proximity of MP188 Failure

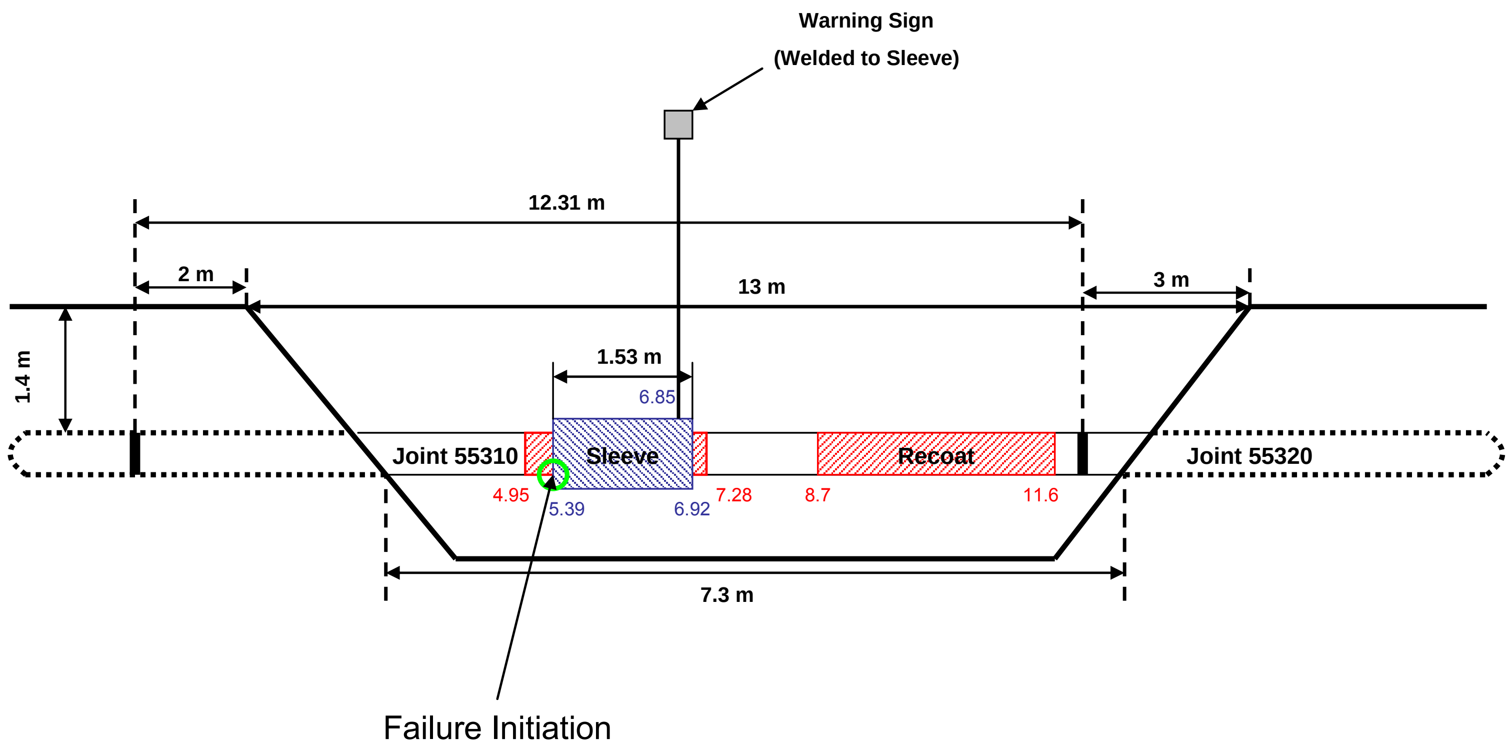


Figure 6 Configuration of April 2010 Excavation

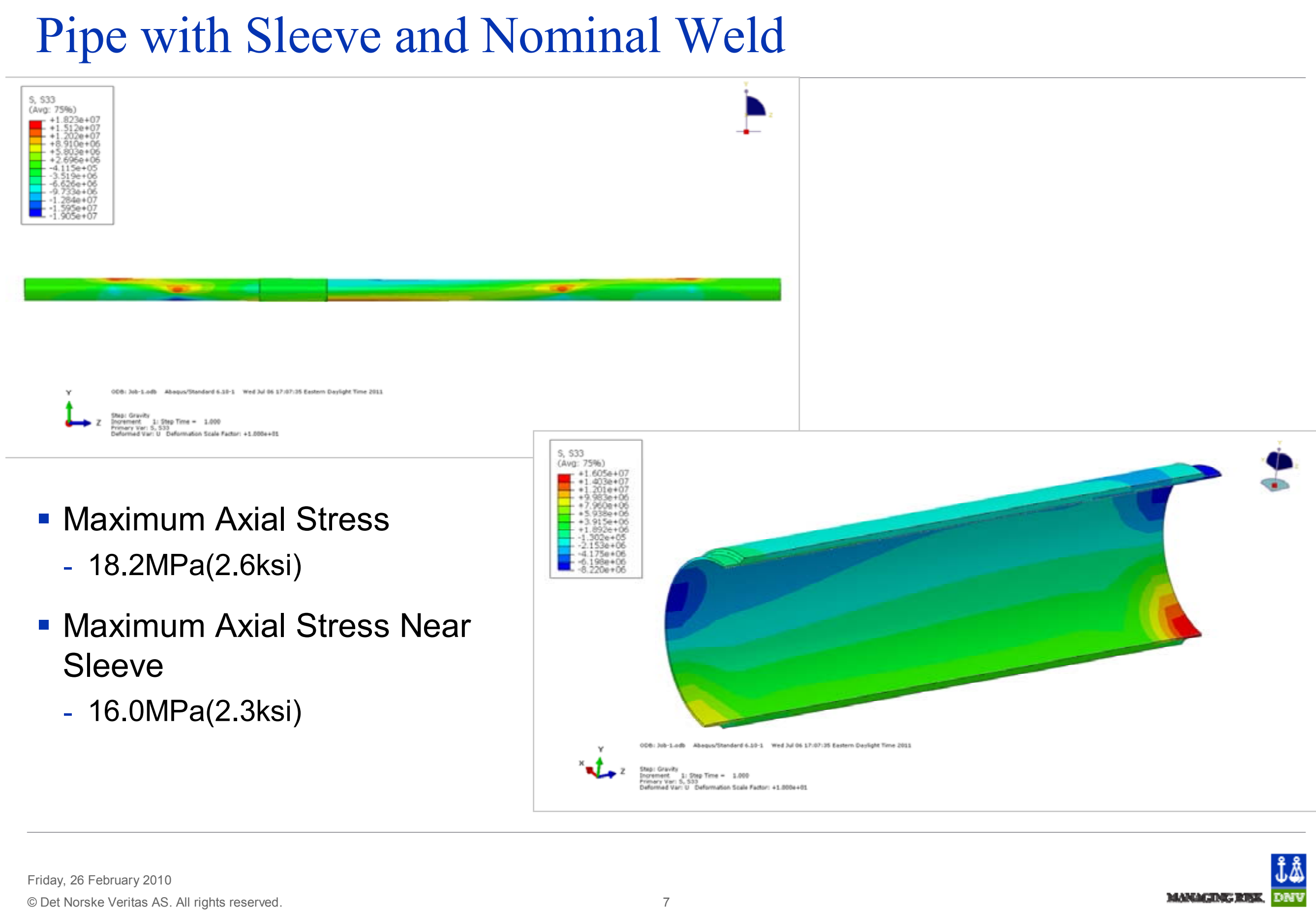
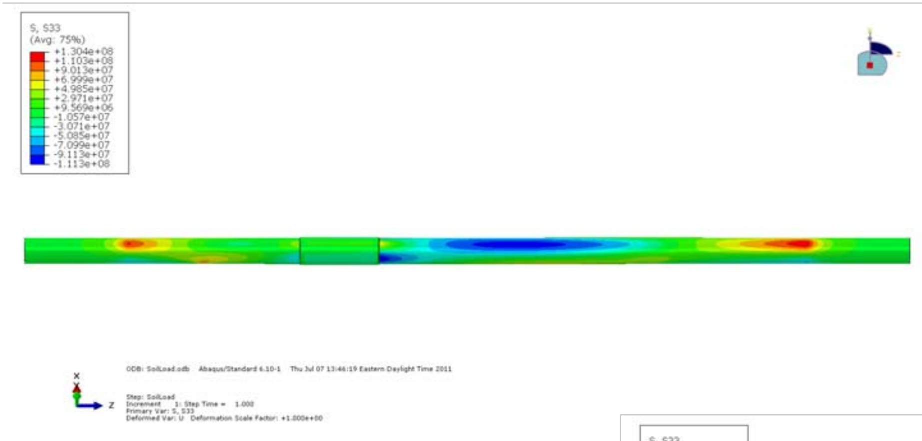


Figure 7 Maximum Stress Value, Self Weight, Pipe with Sleeve and Fillet Weld

Pipe with Sleeve and Nominal Weld



- Maximum Axial Stress
  - 130.4MPa(18.9ksi)
- Maximum Axial Stress Near Sleeve
  - 126.7MPa(18.4ksi)
- Peak Axial Stress Near Failed Weld
  - 51.3MPa(7.4ksi)

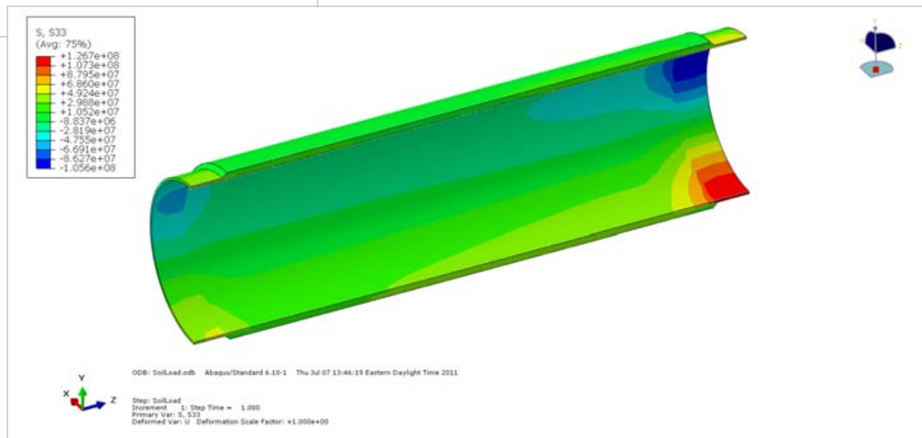


Figure 8 Maximum Stress Value, Self Weight Plus Overburden, Pipe with Sleeve and Fillet Weld

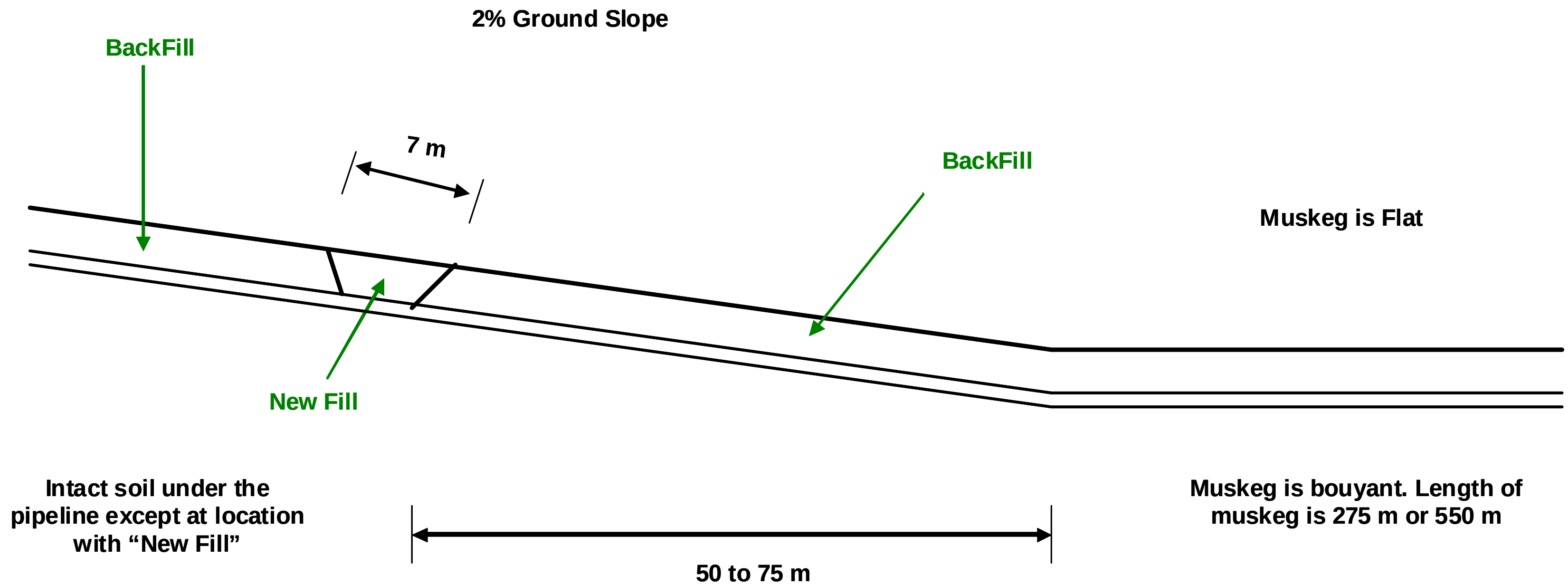


Figure 9 Potential Muskeg Pipe Settlement Scenario

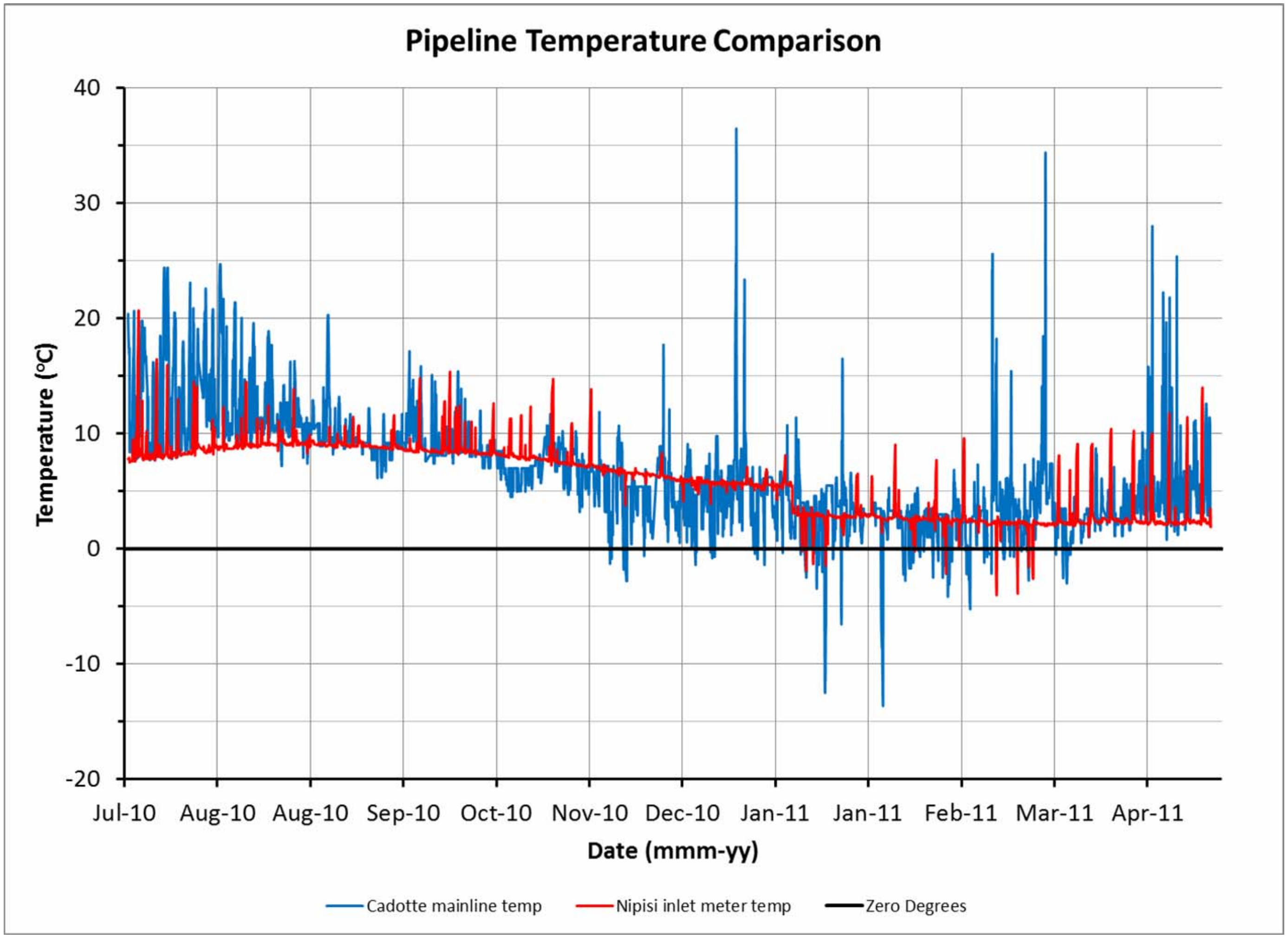


Figure 10 Product Temperature Profile. NPS 20 Rainbow Pipeline. Cadotte to Nipisi

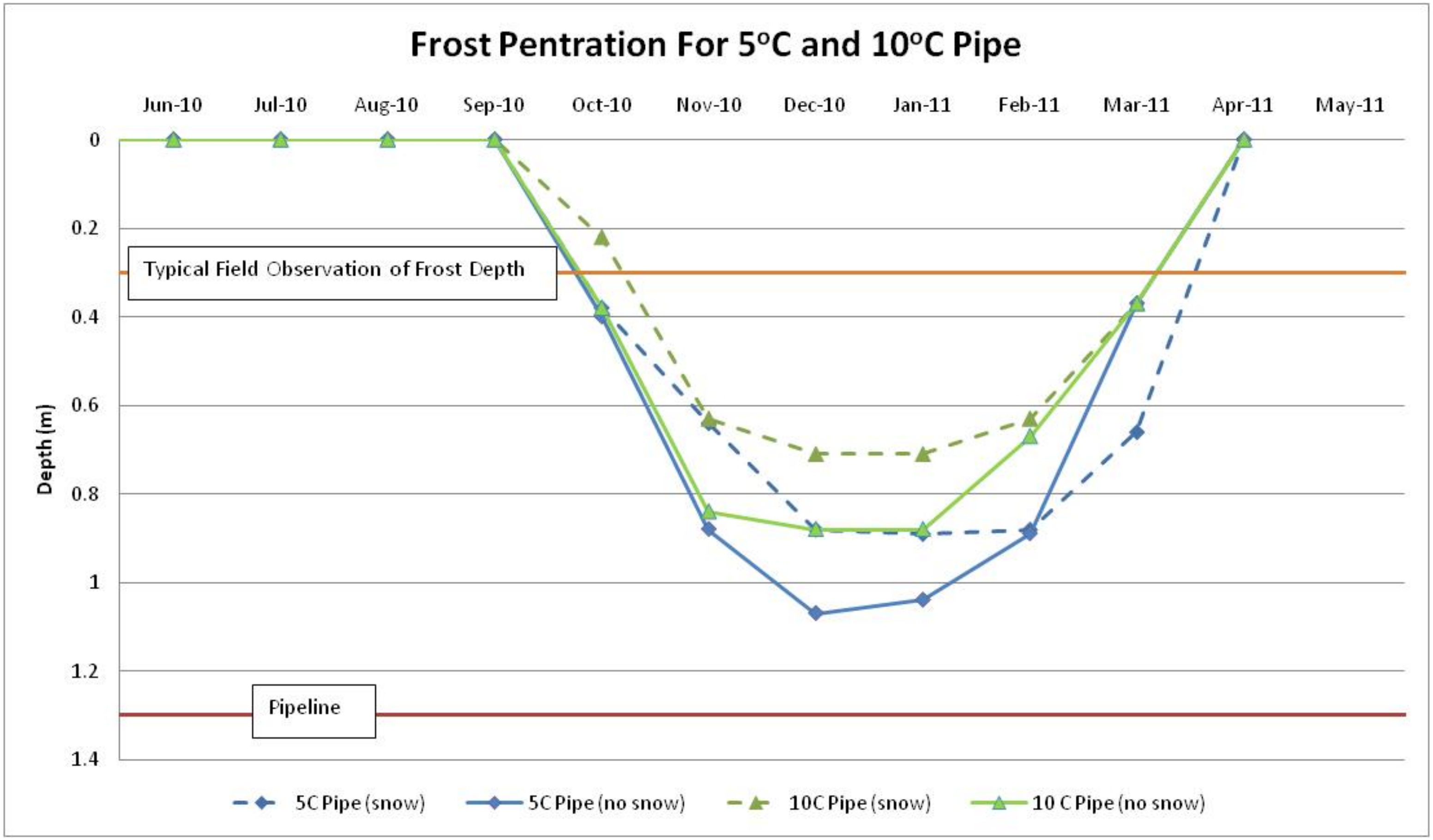


Figure 11 Predicted Frost Penetration Above NPS 20 Rainbow Pipeline Under Ambient Conditions

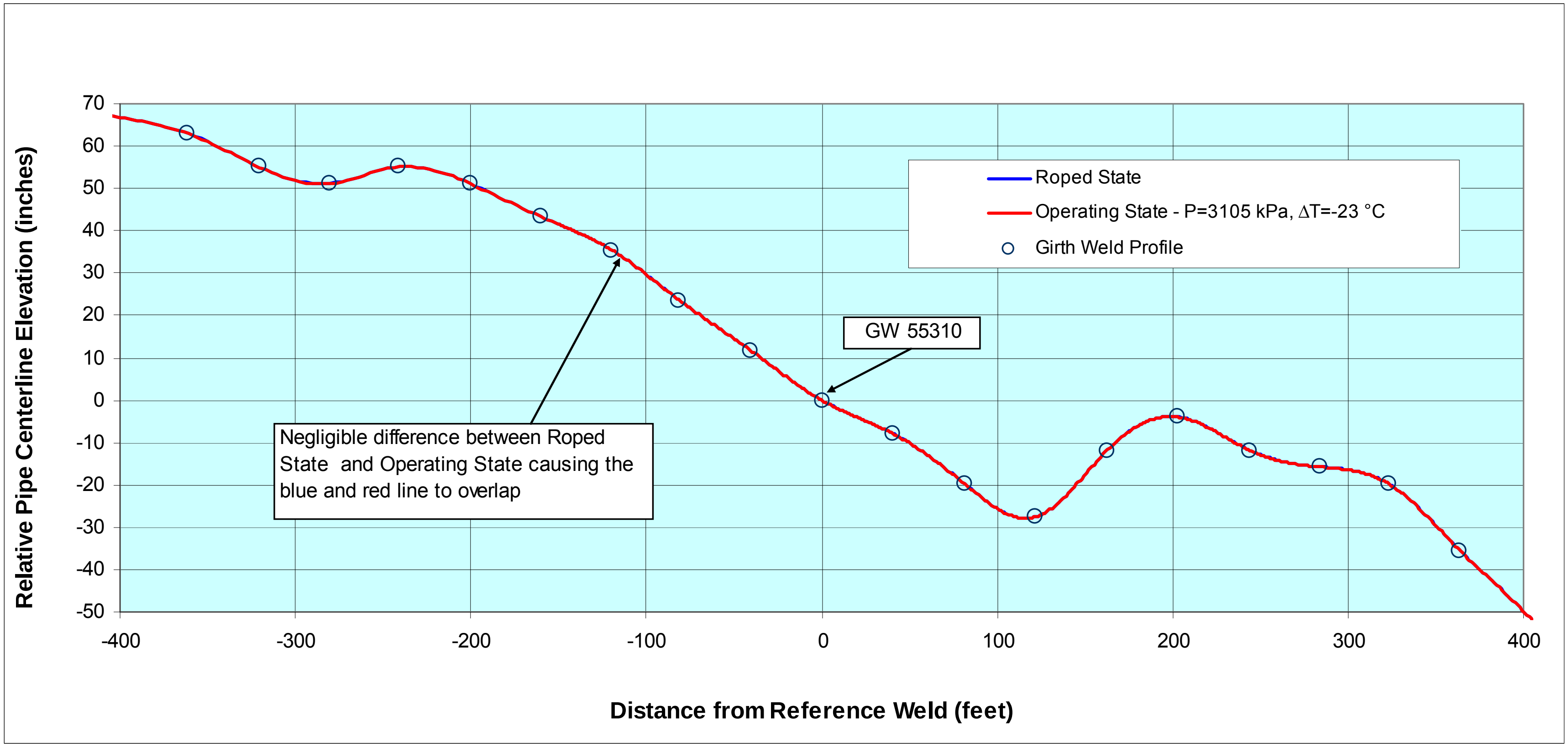


Figure 12 Pipe Elevation Profile Upstream and Downstream of GW 55310

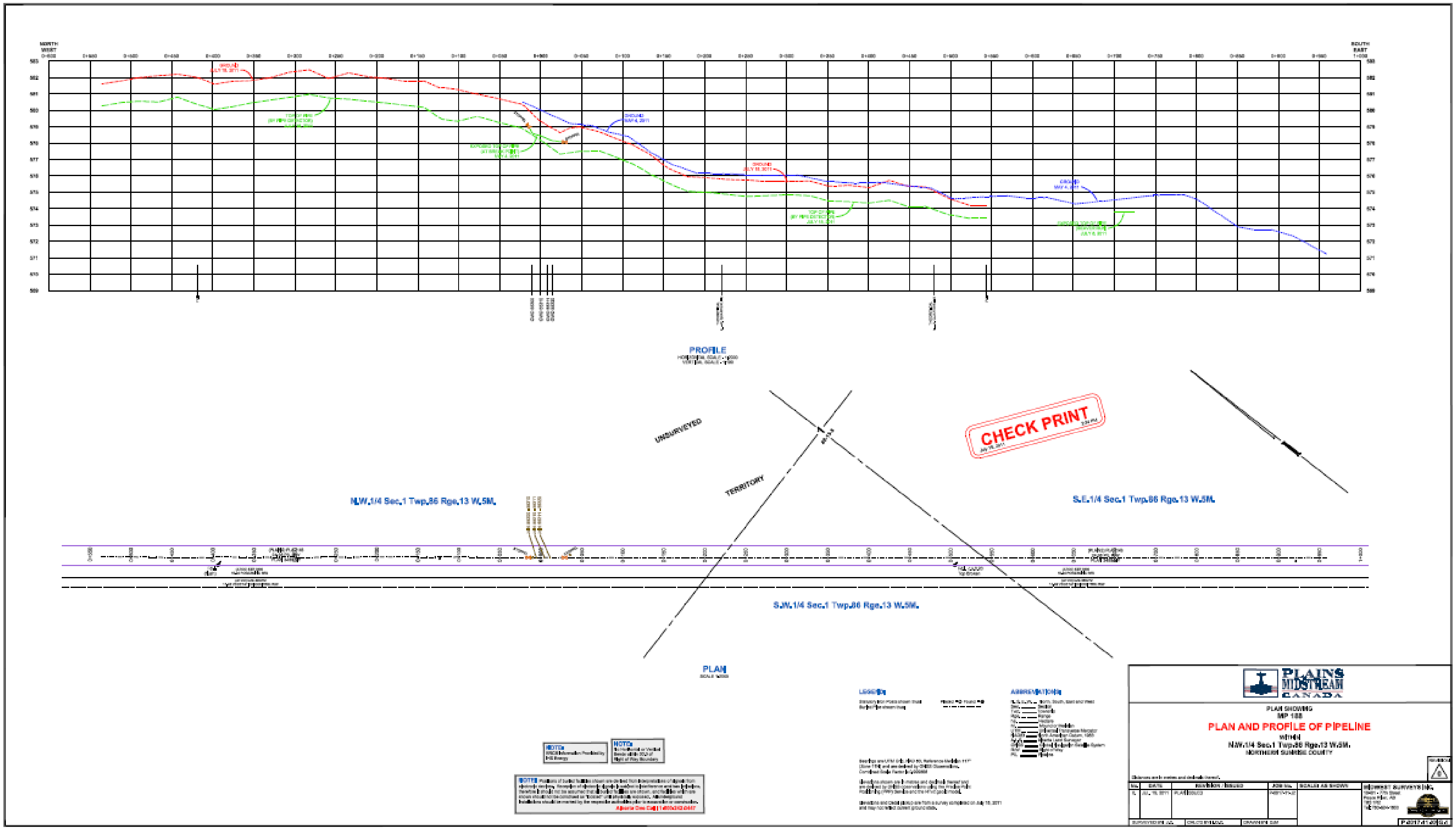


Figure 13 Line Profile Upstream and Downstream of Failure Location (Provided by Midwest Surveys Inc.)

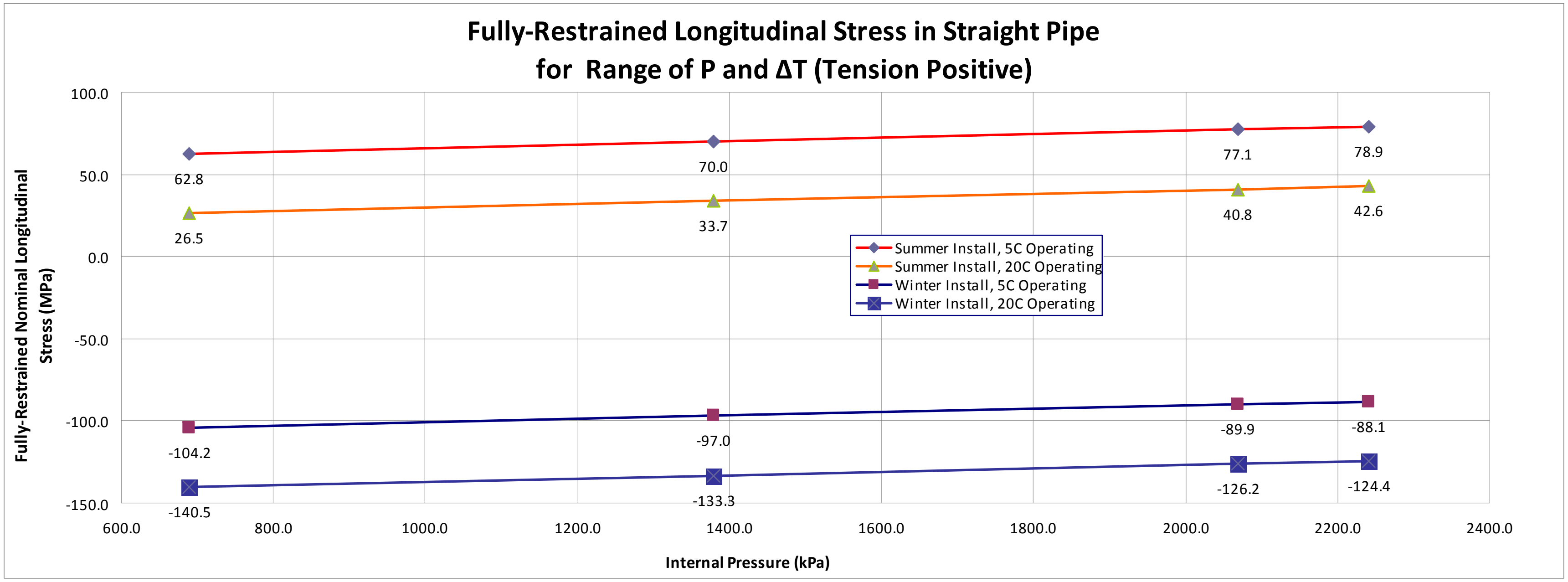


Figure 14 Total Axial Stress due to Combined Thermal Expansion and Internal Pressure

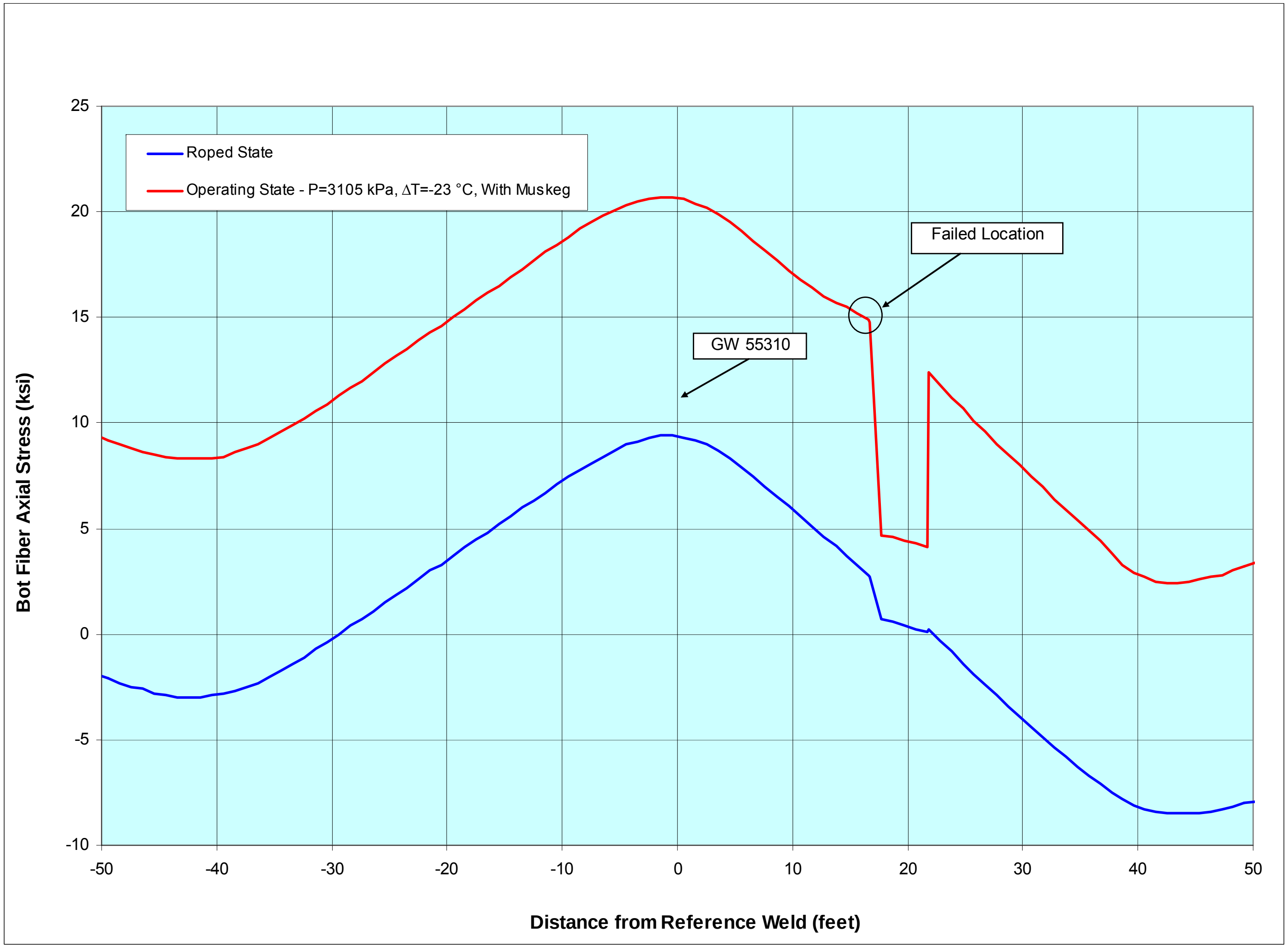


Figure 15 Axial Stress Profile at 6 o'clock Position: Pipe Settlement into Muskeg

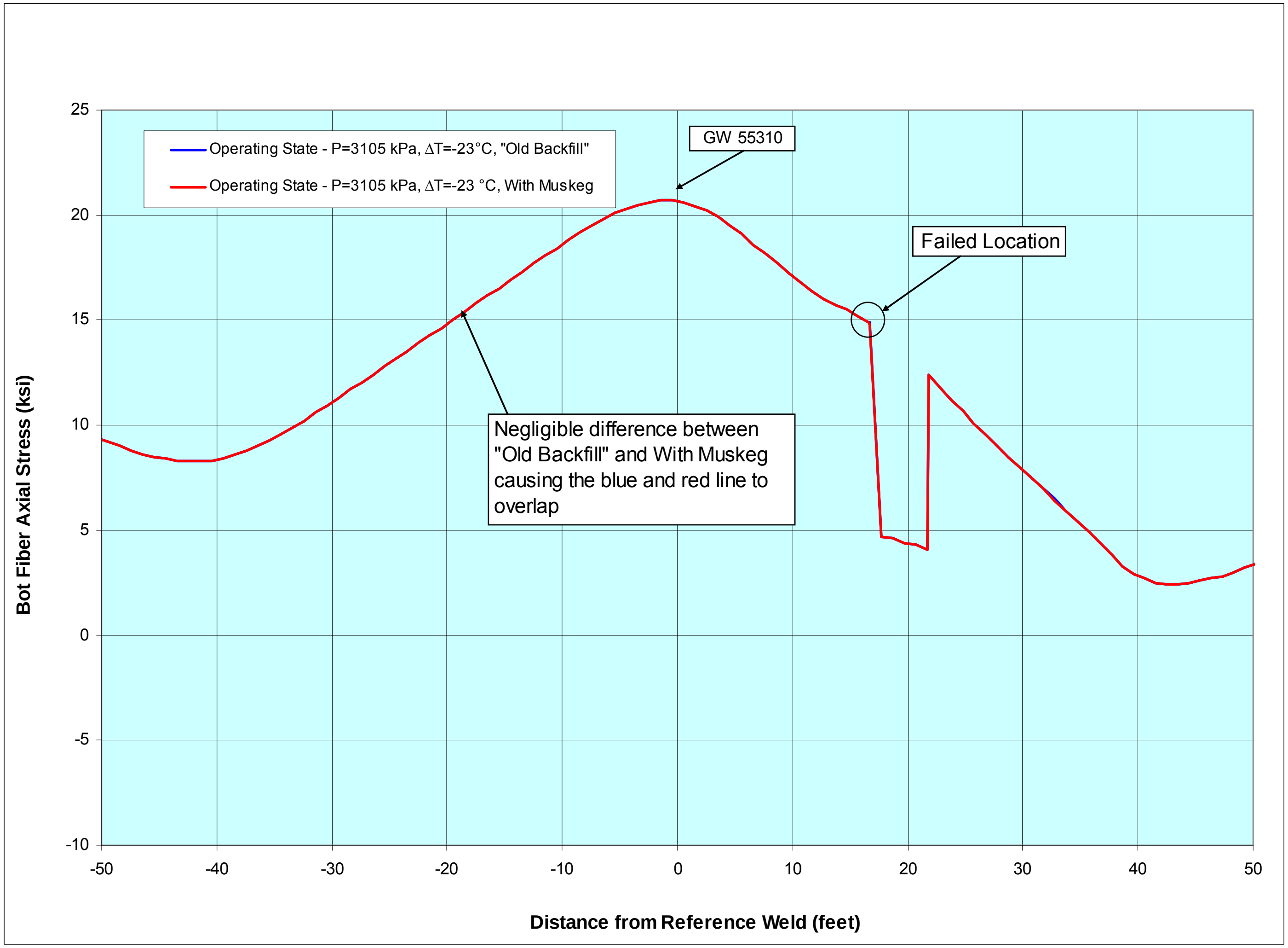


Figure 16 Axial Stress Profile at 6 o'clock Position: Pipe Settlement into "Old Backfill"

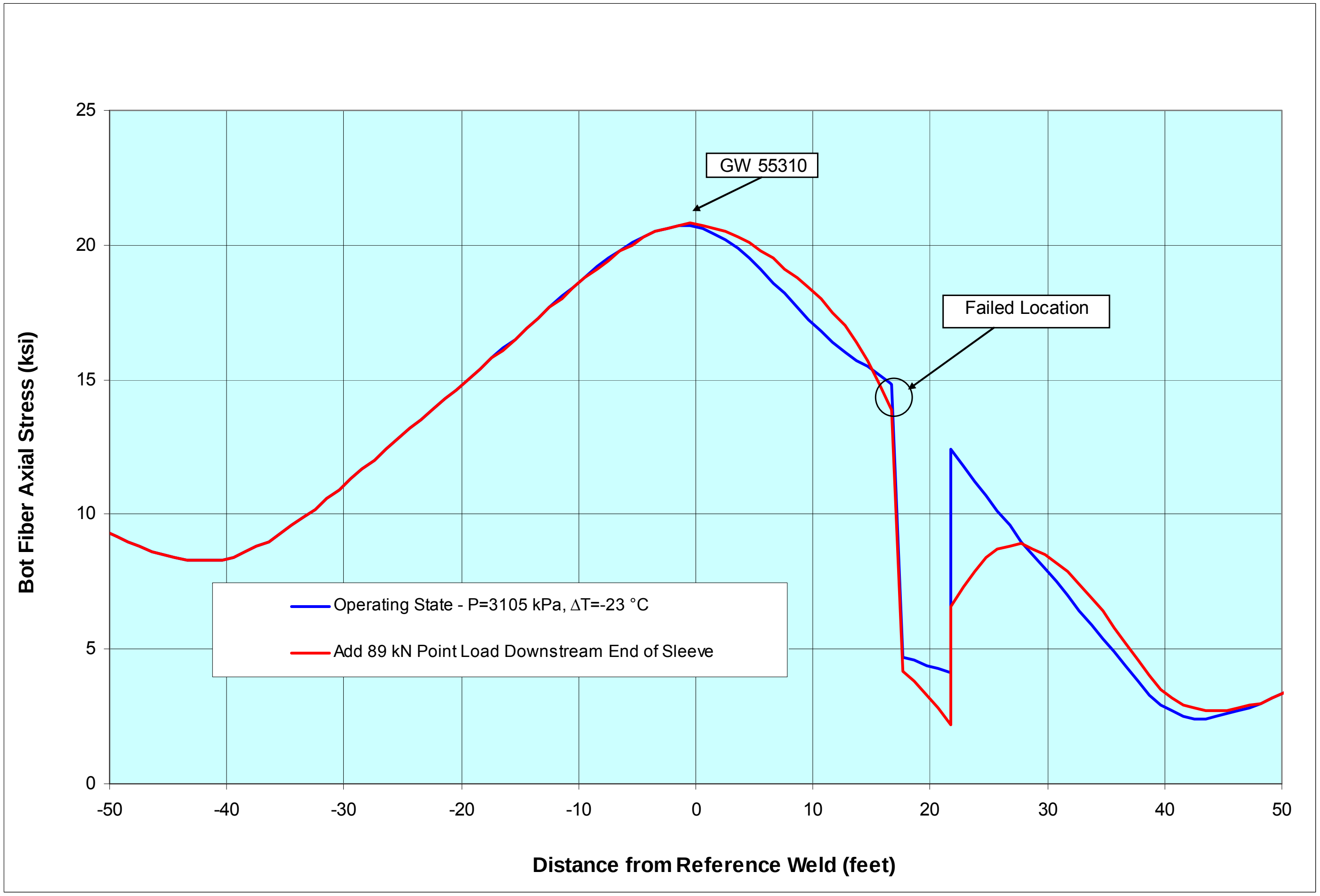


Figure 17 Axial Stress Profile at 6 o'clock Position: Attempting to Remove Sign

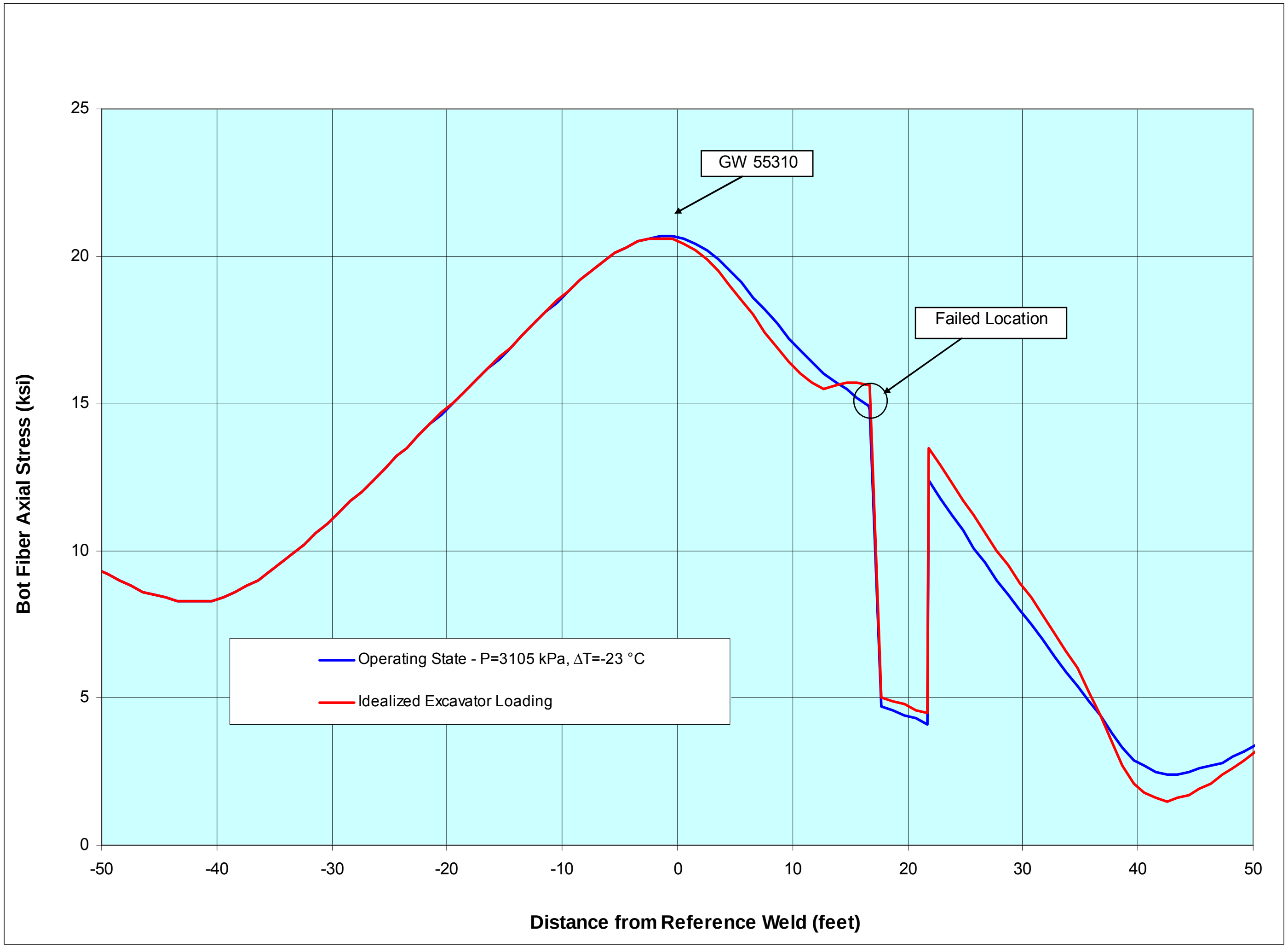


Figure 18 Axial Stress Profile at 6 o'clock Position: Heavy Equipment Traversing Pipeline

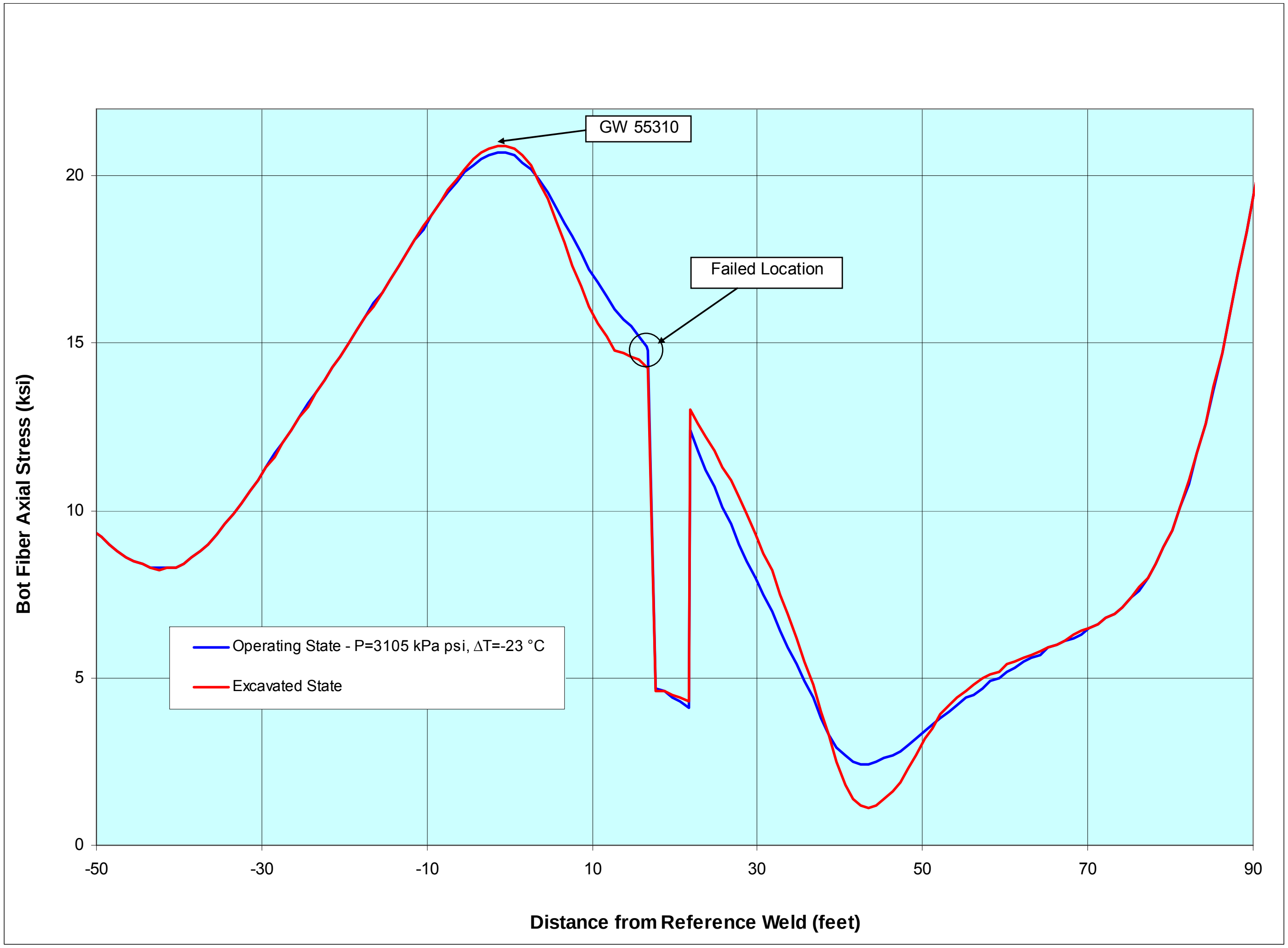


Figure 19 Axial Stress Profile at 6 o'clock Position: Excavation Influence

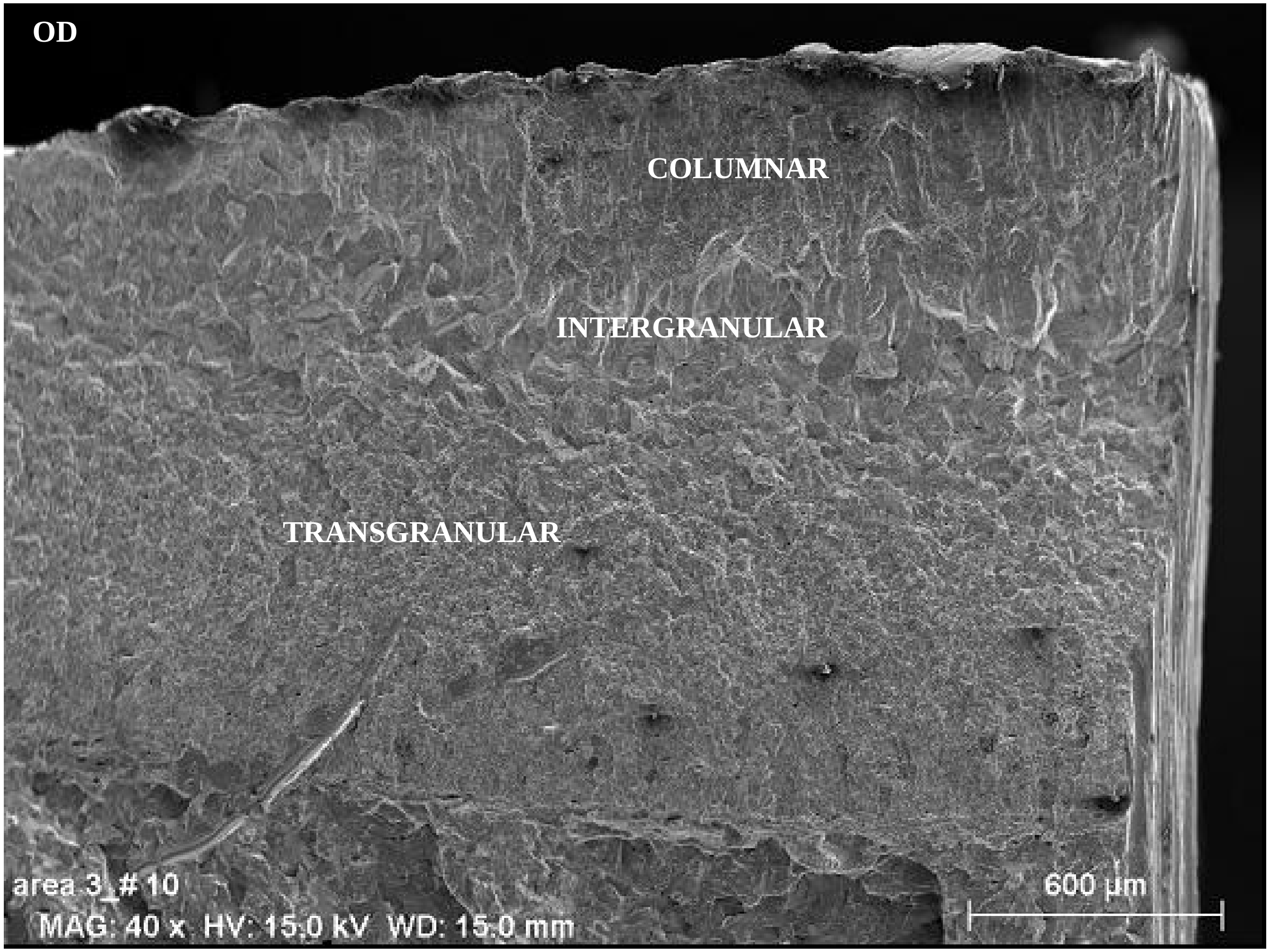


Figure 20 SEM photograph of the pre-existing flaw on the fracture surface of Sample 1677-3, showing the columnar structure near the OD, intergranular features below the columnar structure, and quasi-cleavage below that

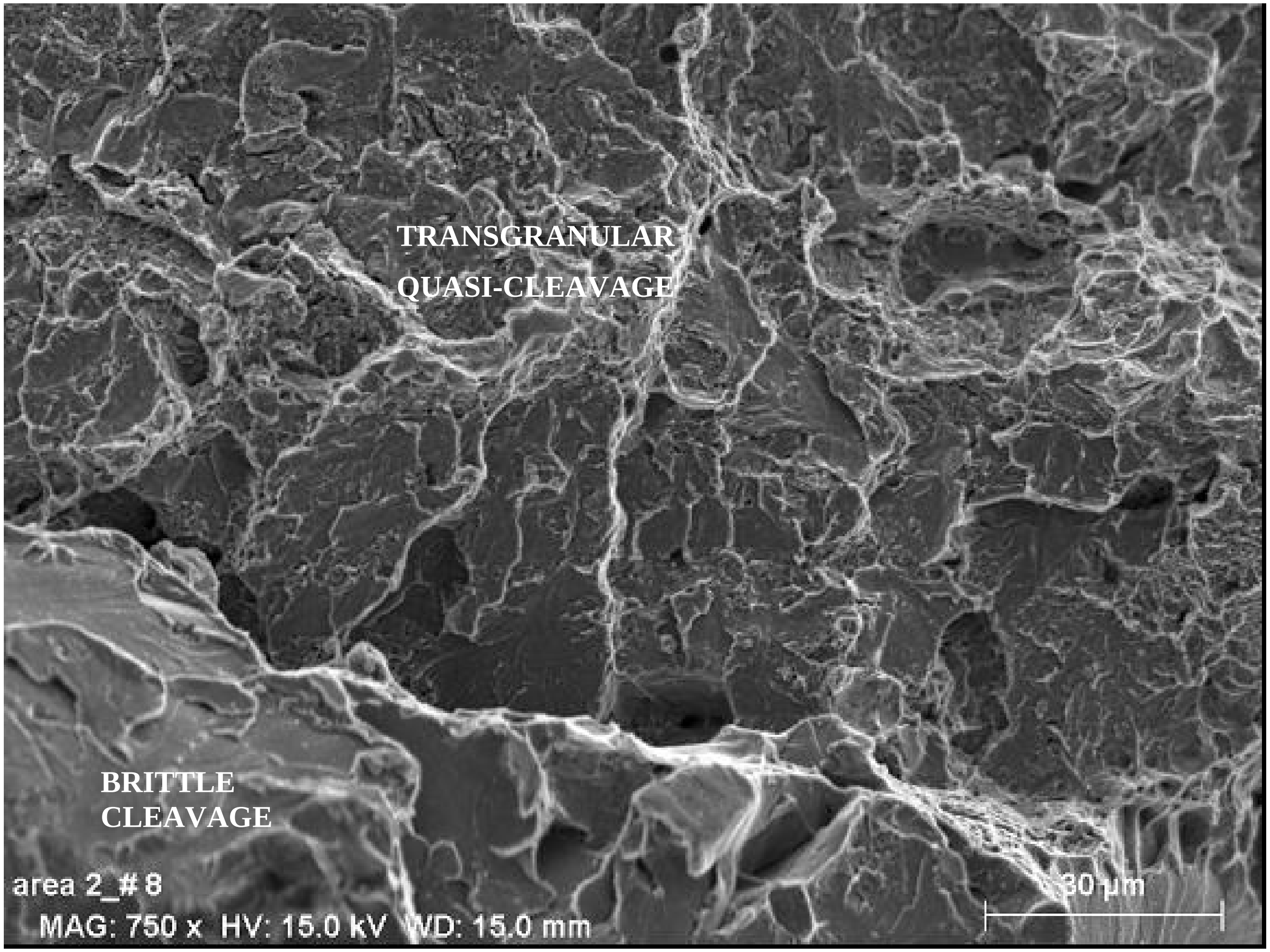


Figure 21 SEM photograph of the fracture surface of Sample 1677-3 showing the interface between the quasi-cleavage in the pre-existing flaw and the brittle cleavage associated with the rapid fracture

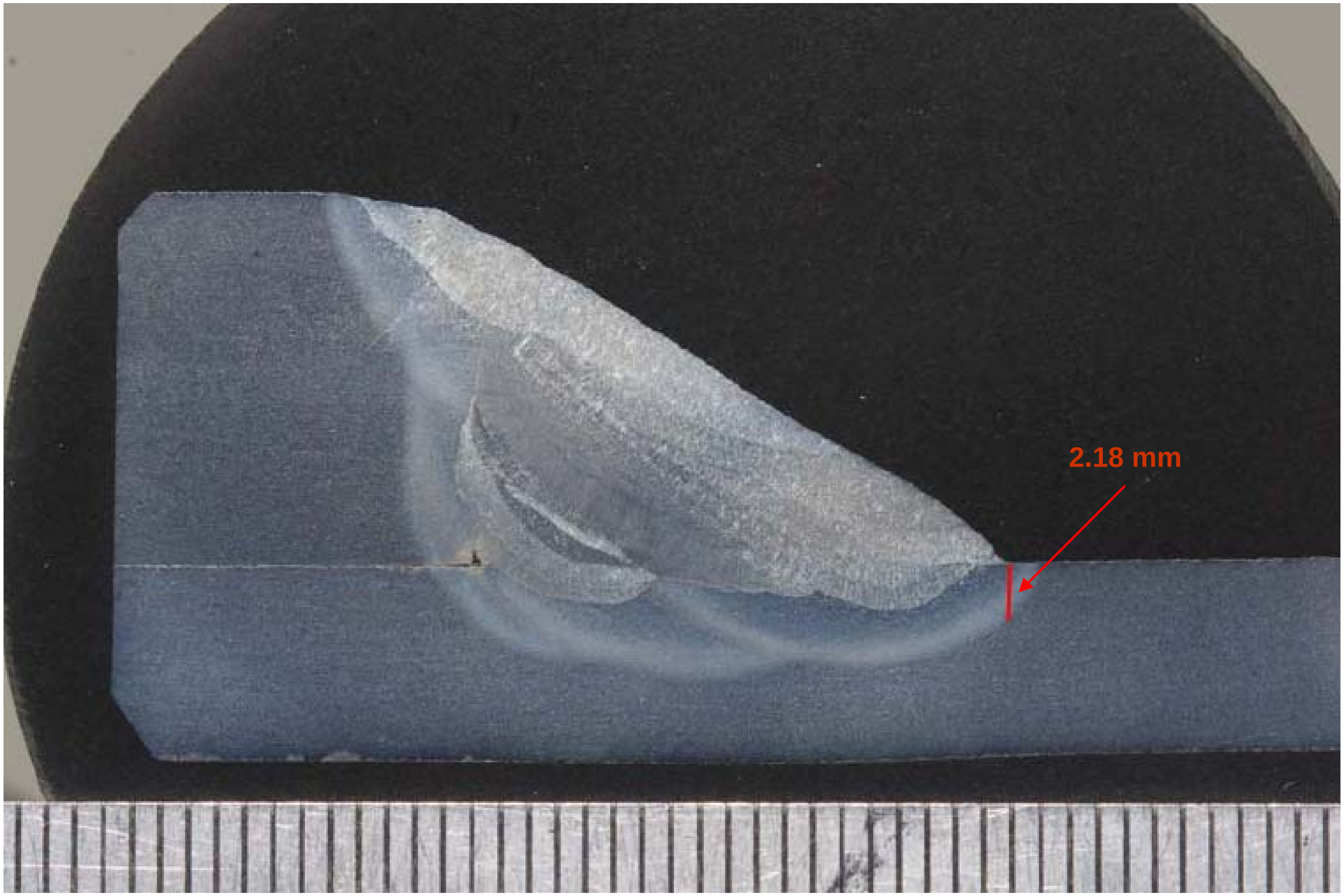


Figure 22 Fillet Weld Section and HAZ Depth at 2:00 Position

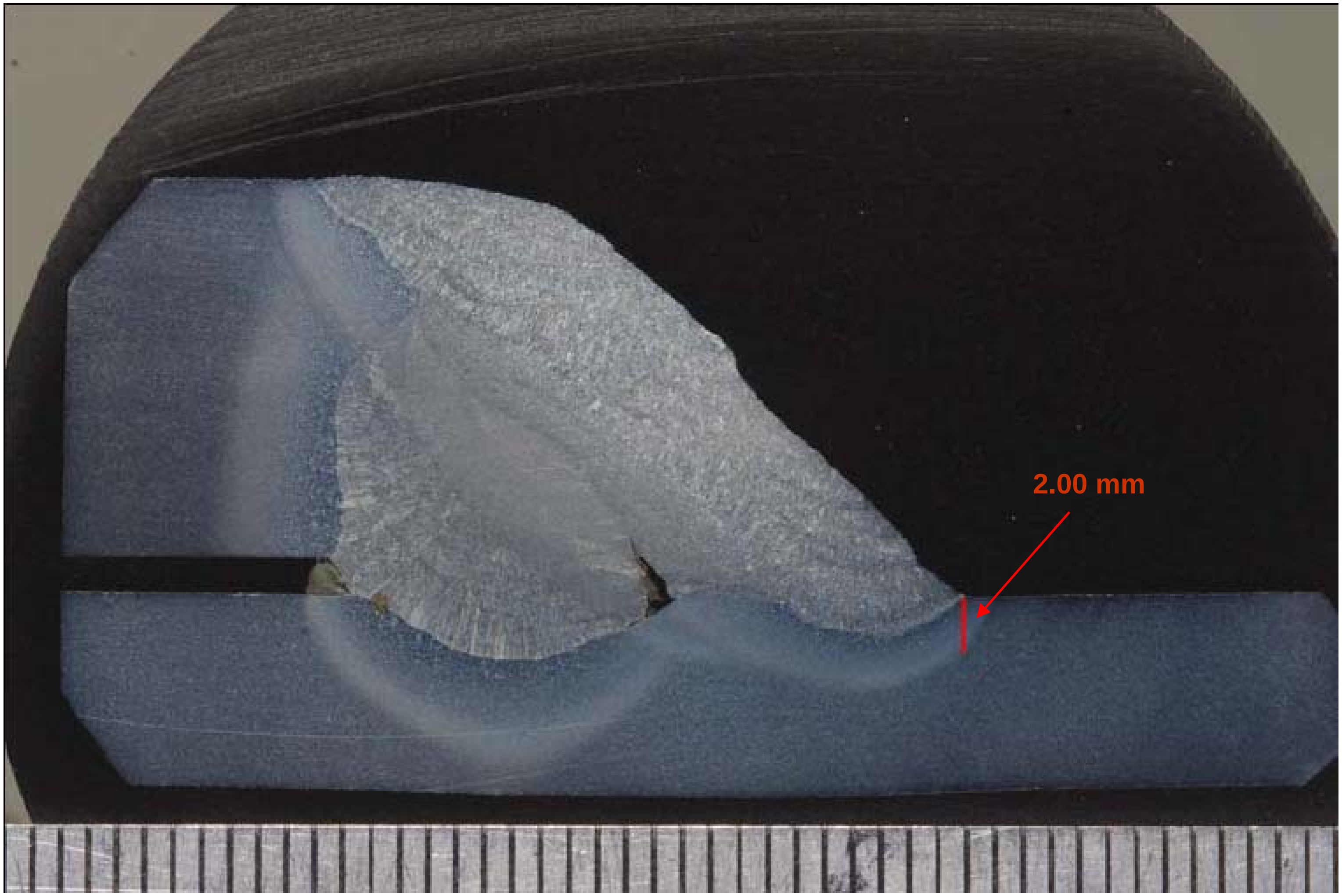


Figure 23 Fillet Weld Section and HAZ Depth at 10:00 Position

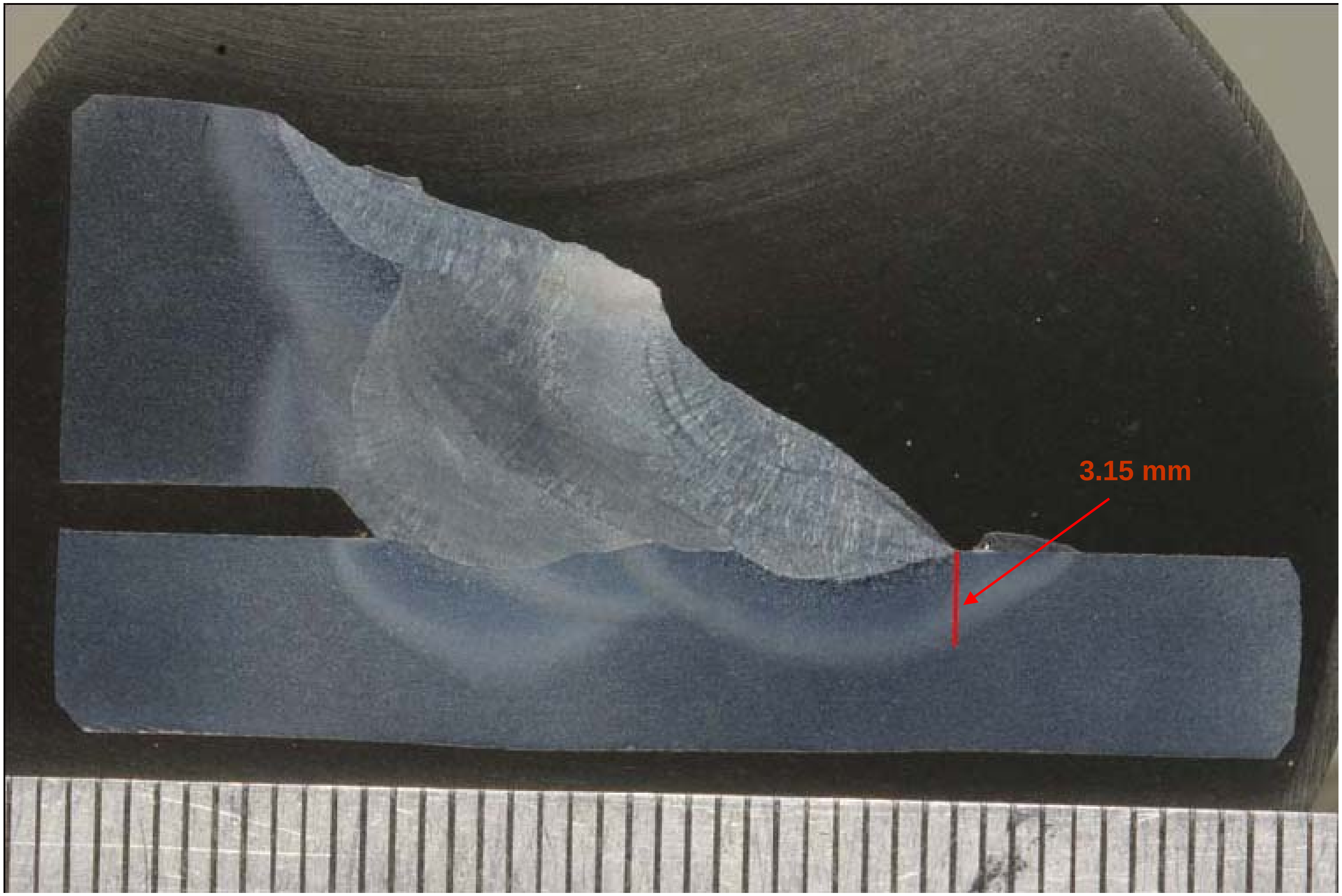


Figure 24 Fillet Weld Section and HAZ Depth at 12:00 Position

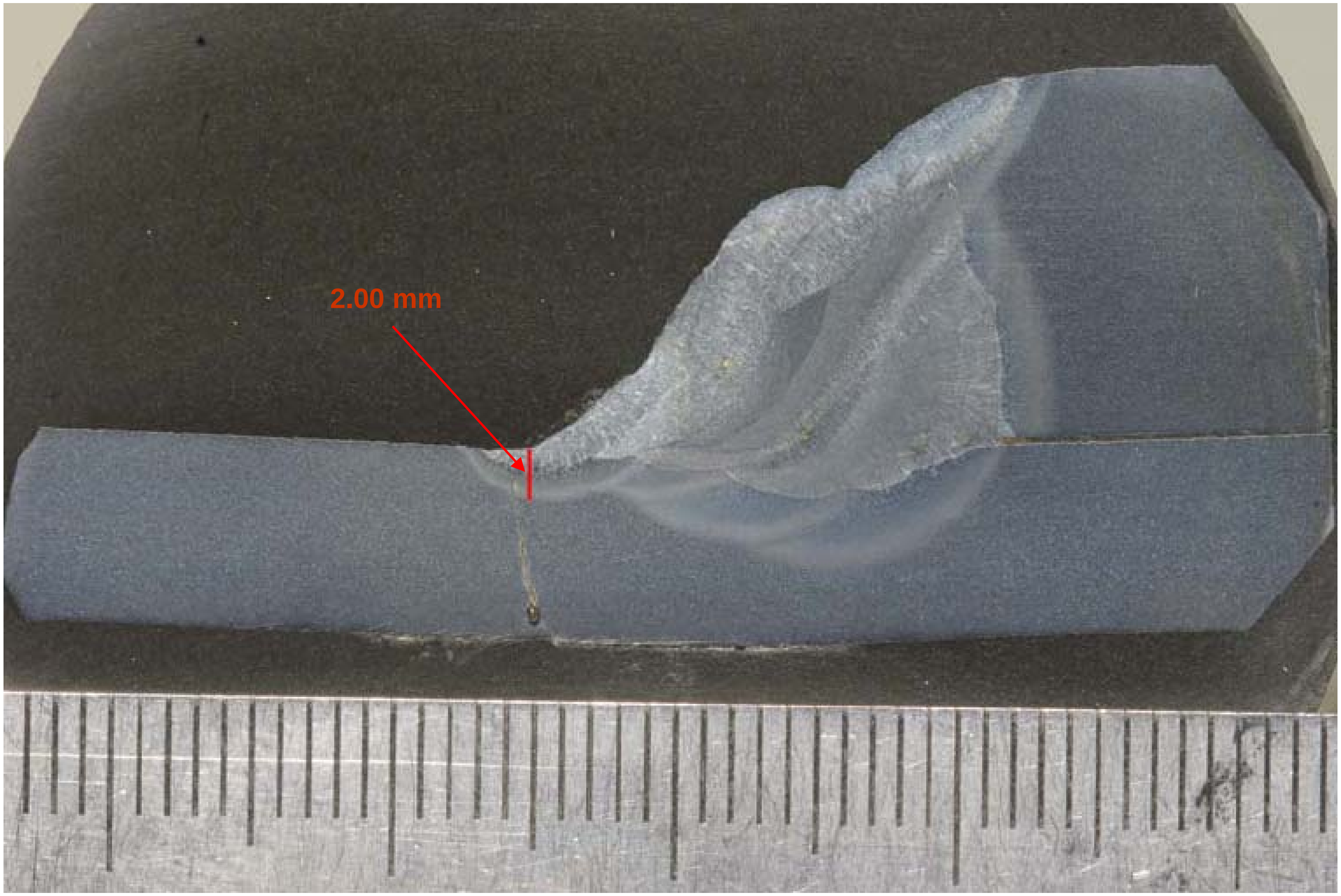


Figure 25 Fillet Weld Section and HAZ Depth at the 6:00 Position (Site of the Initiating Crack in the Pipeline Failure.)

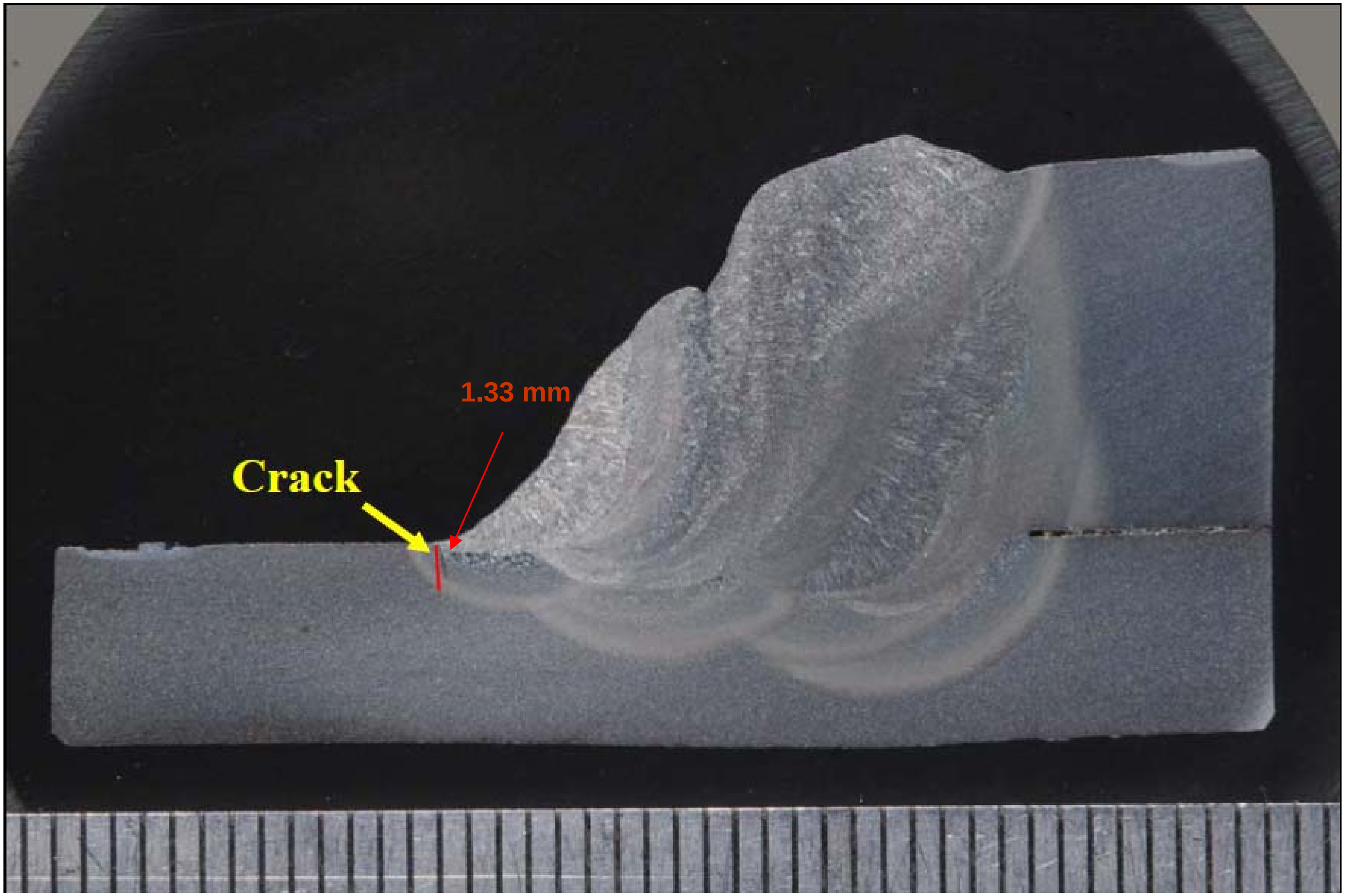


Figure 26 Detail of Fillet Weld Section and HAZ Depth at the 6:00 Position (upstream fillet weld)

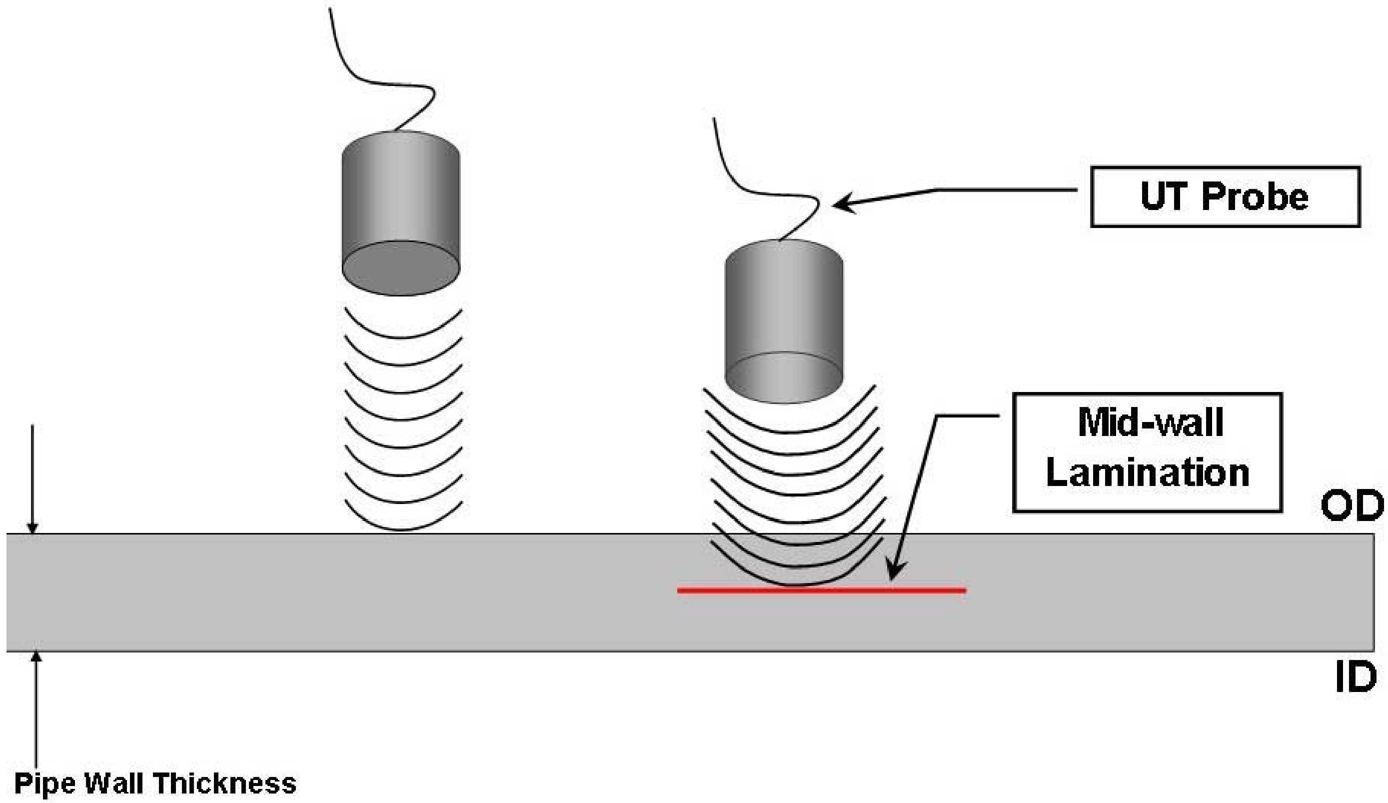


Figure 27 Principle of Lamination Detection and Wall Thickness Measurement

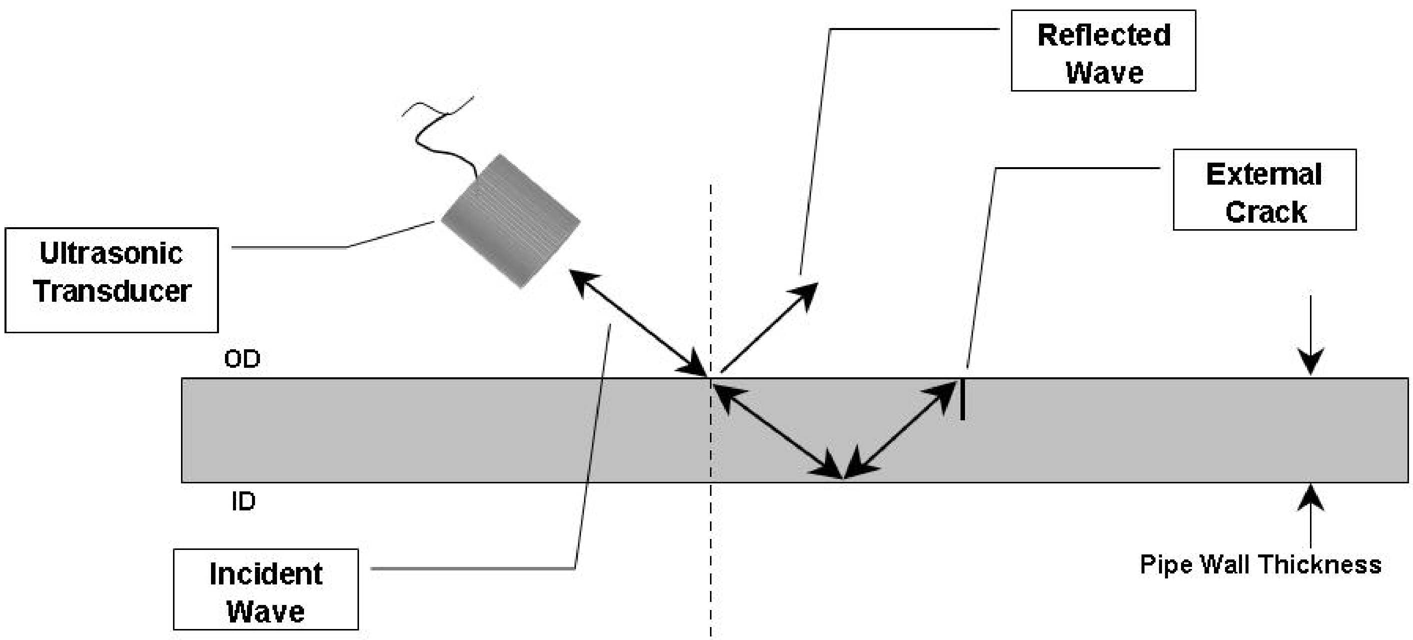


Figure 28 Principle of Crack Detection Using Angled Probe Ultrasonics

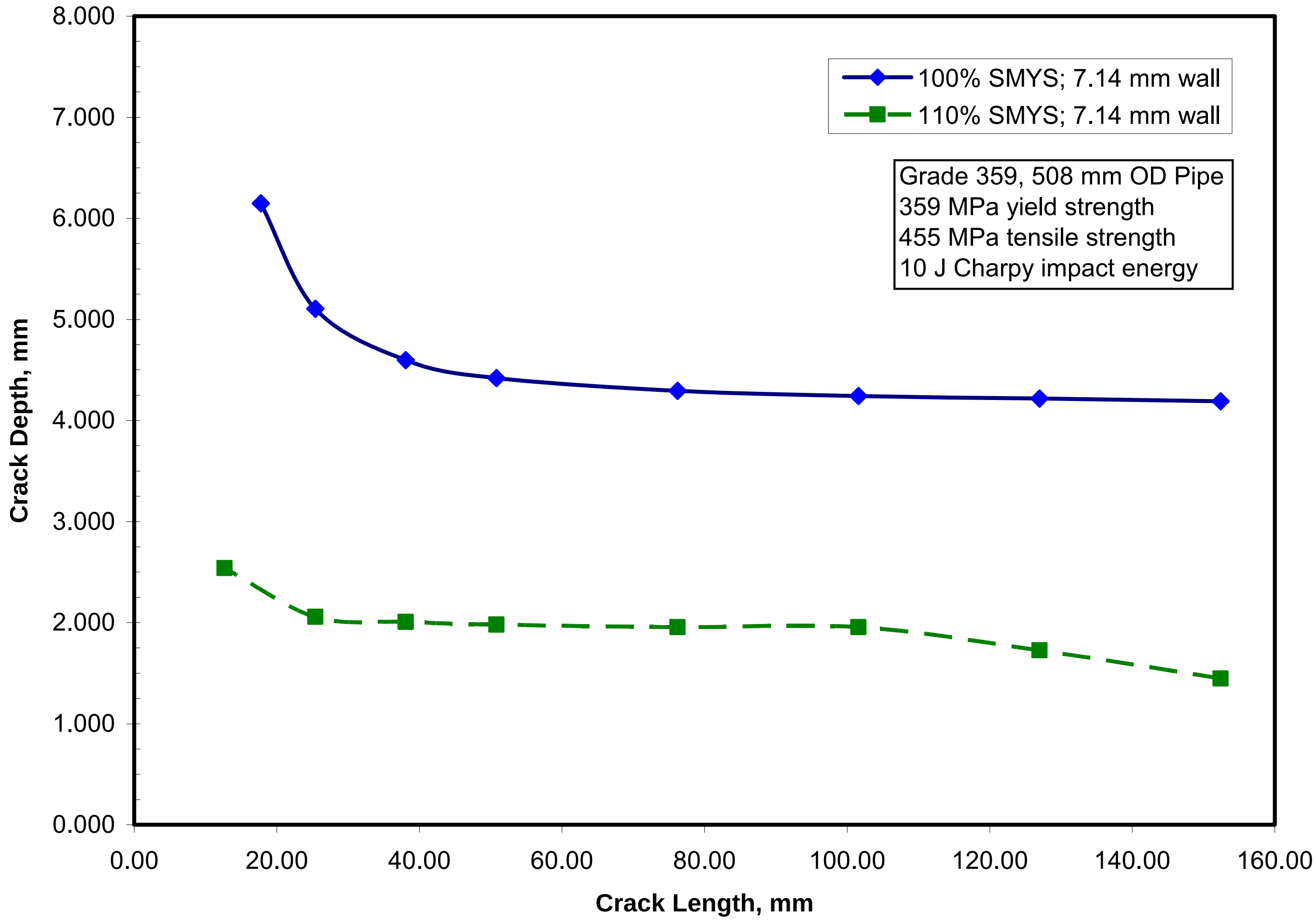


Figure 29 Circumferential Crack Acceptability Curves Specified Minimum Tensile Properties. WT = 7.14mm

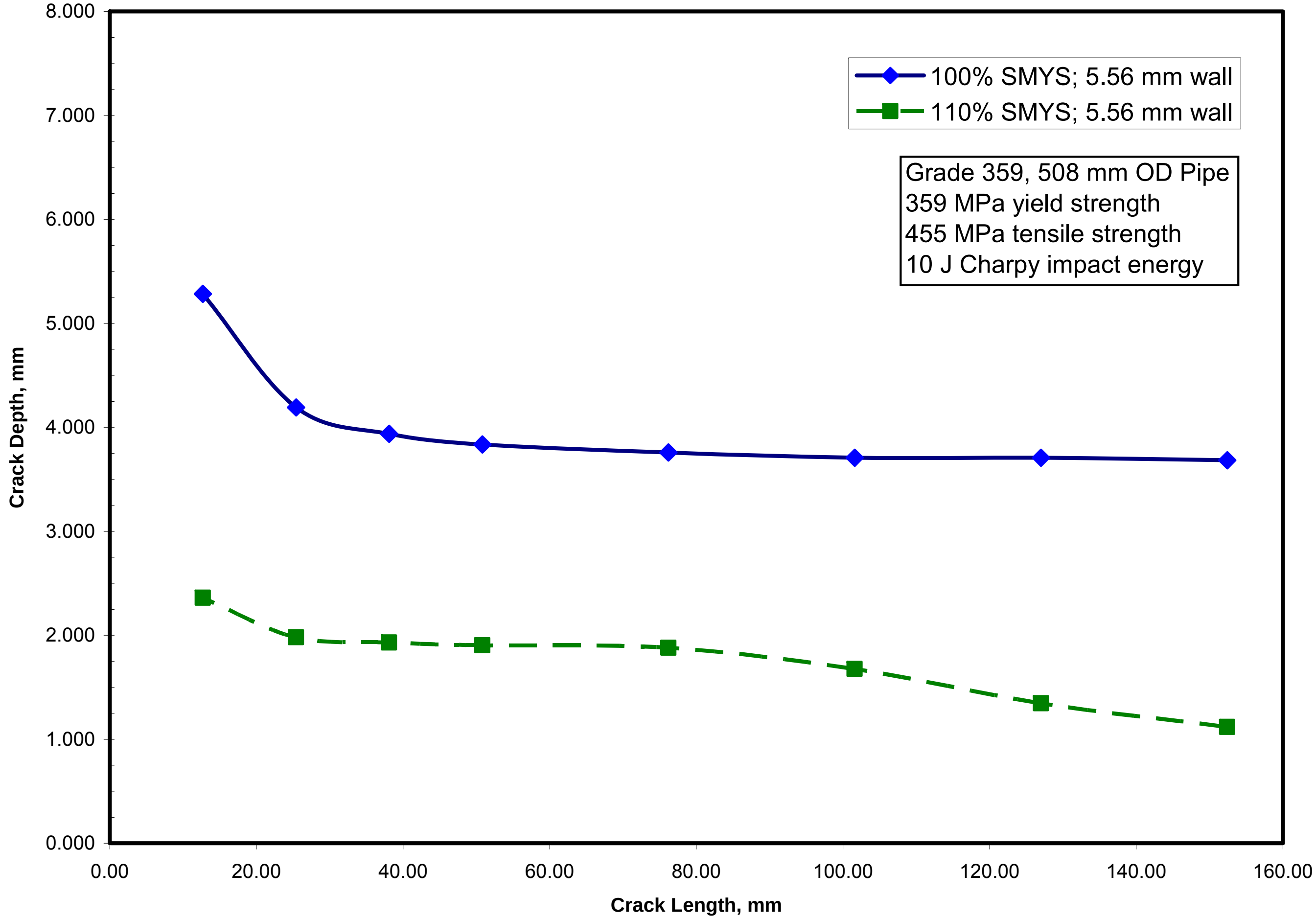


Figure 30 Circumferential Crack Acceptability Curves Specified Minimum Tensile Properties. WT = 5.56mm

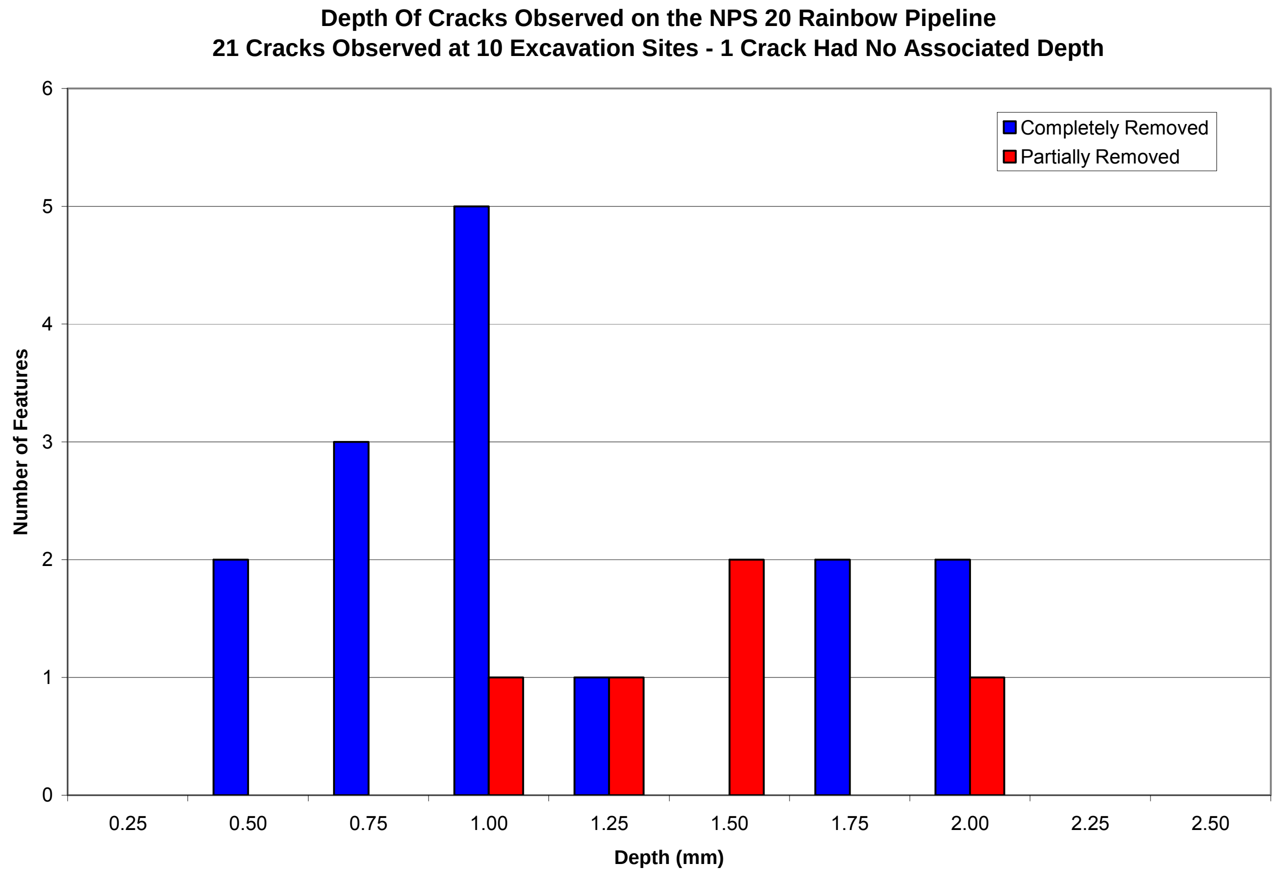


Figure 31 Excavated Crack Depth Summary

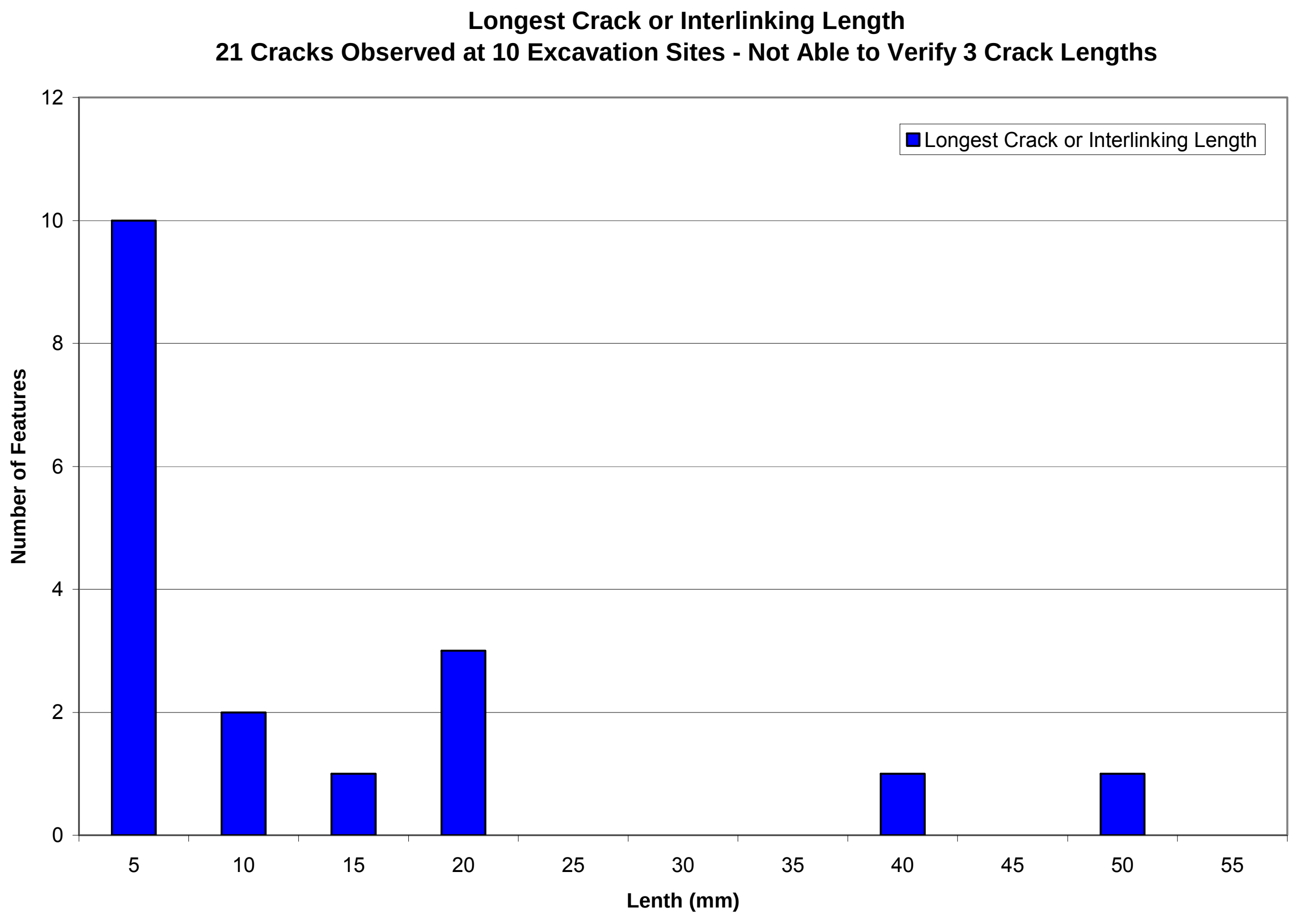


Figure 32 Excavated Crack Length Summary

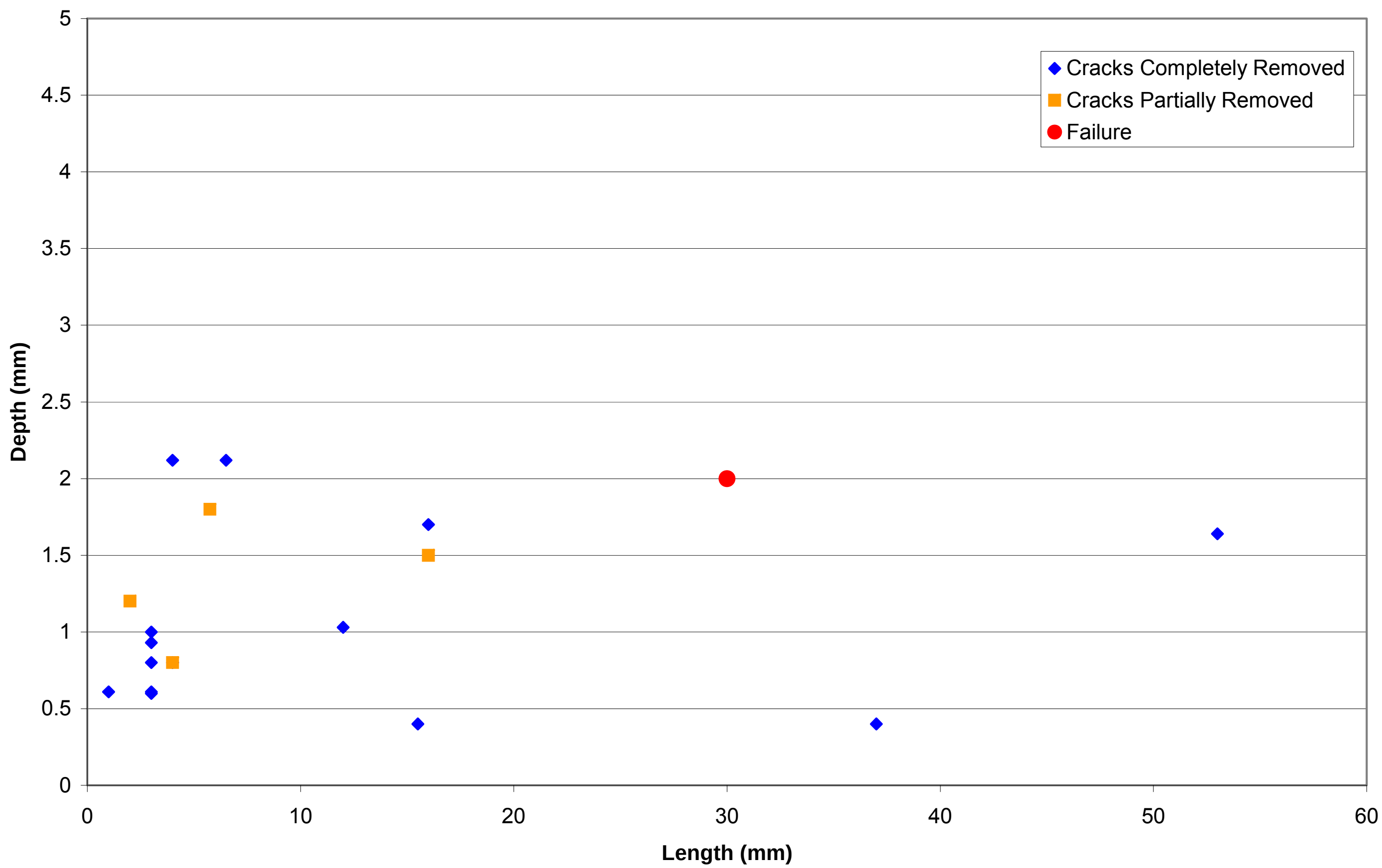


Figure 33 Crack Sizes Reported in Sleeve Welds

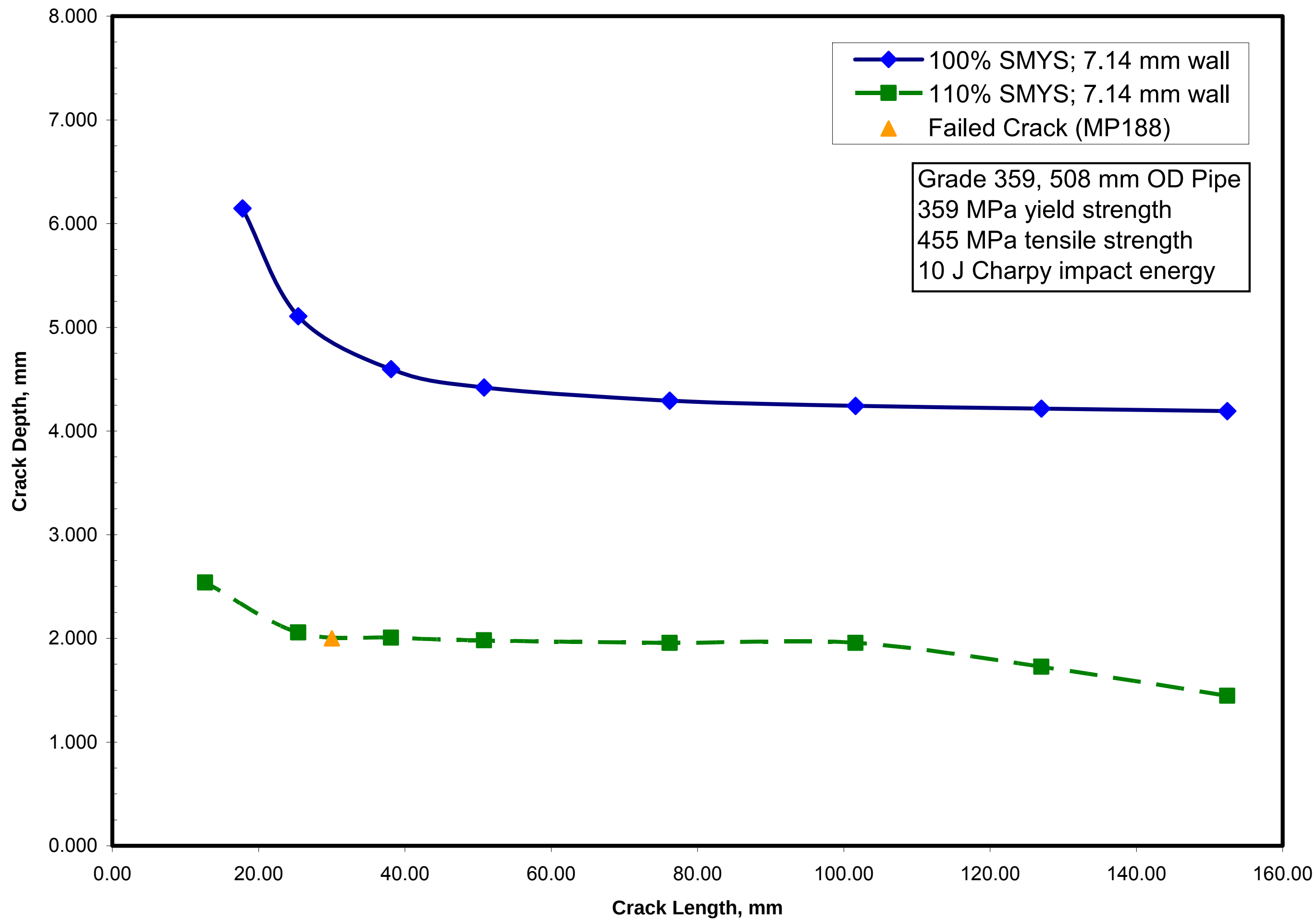


Figure 34 Weld Cracks Detected in 7.14mm WT Sections

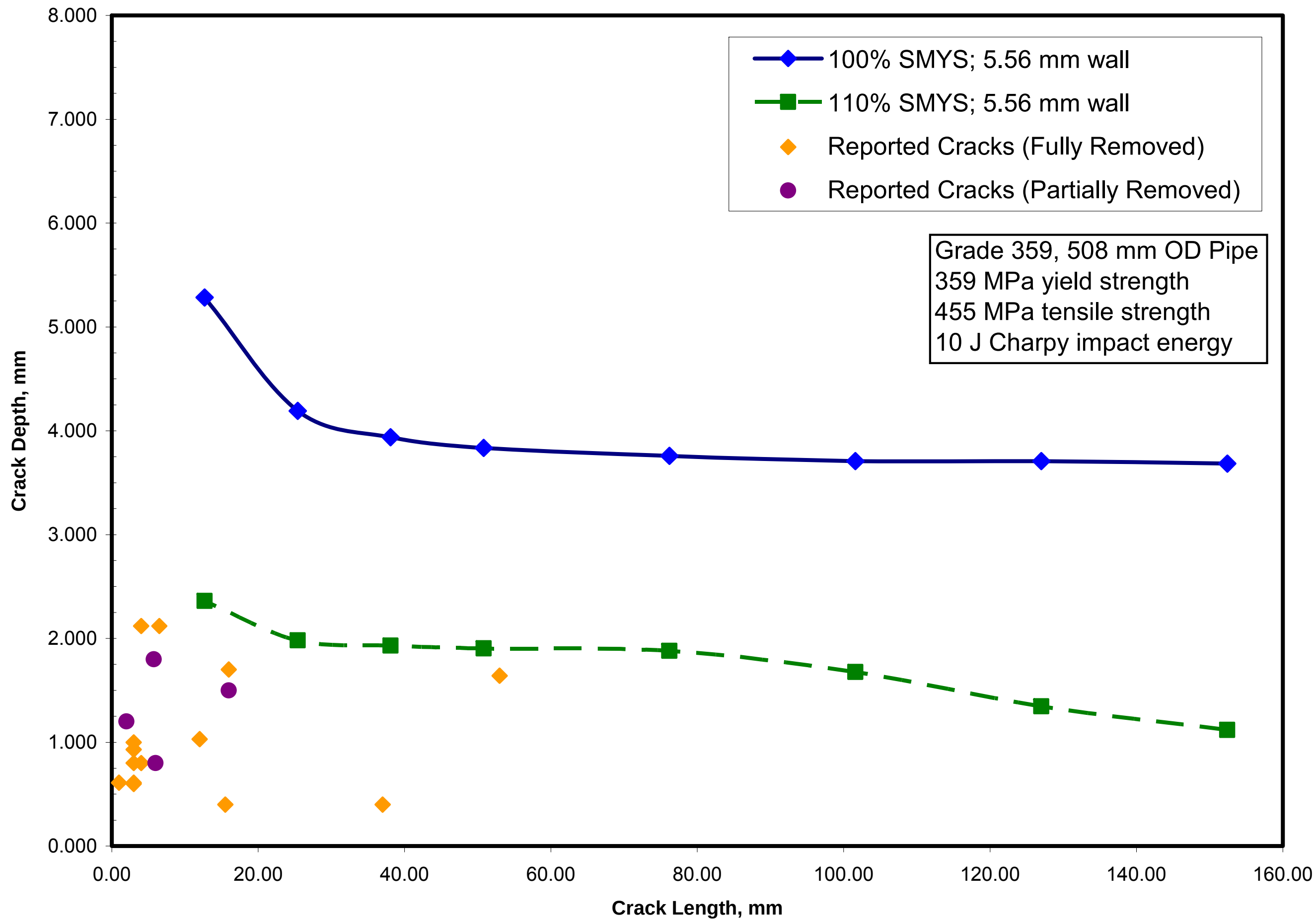


Figure 35 Weld Cracks Detected in 5.56mm WT Sections

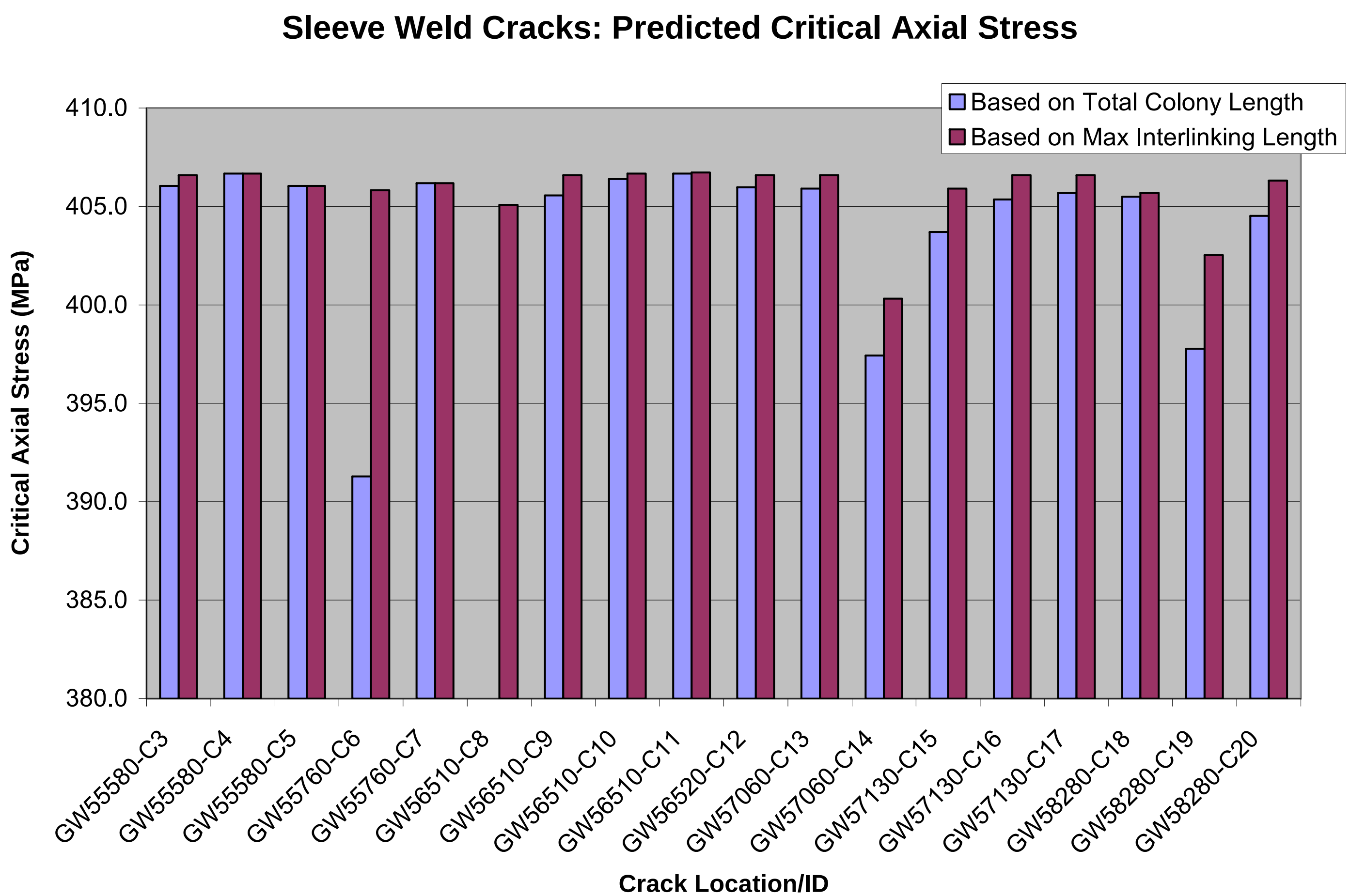


Figure 36 Critical Calculated Stress For Reported Cracks

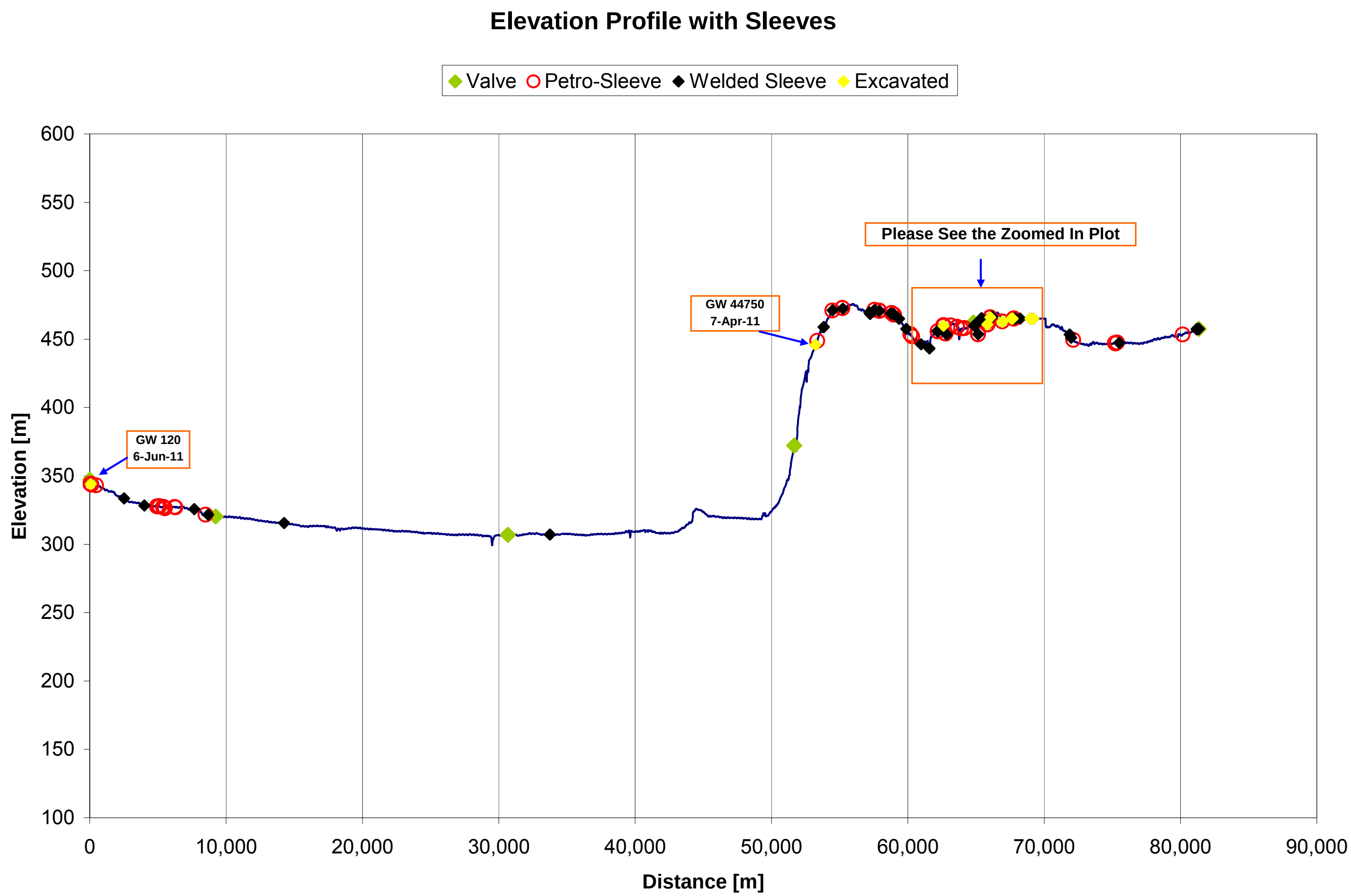


Figure 37 Pipeline Elevation Profile. Zama to Rainbow

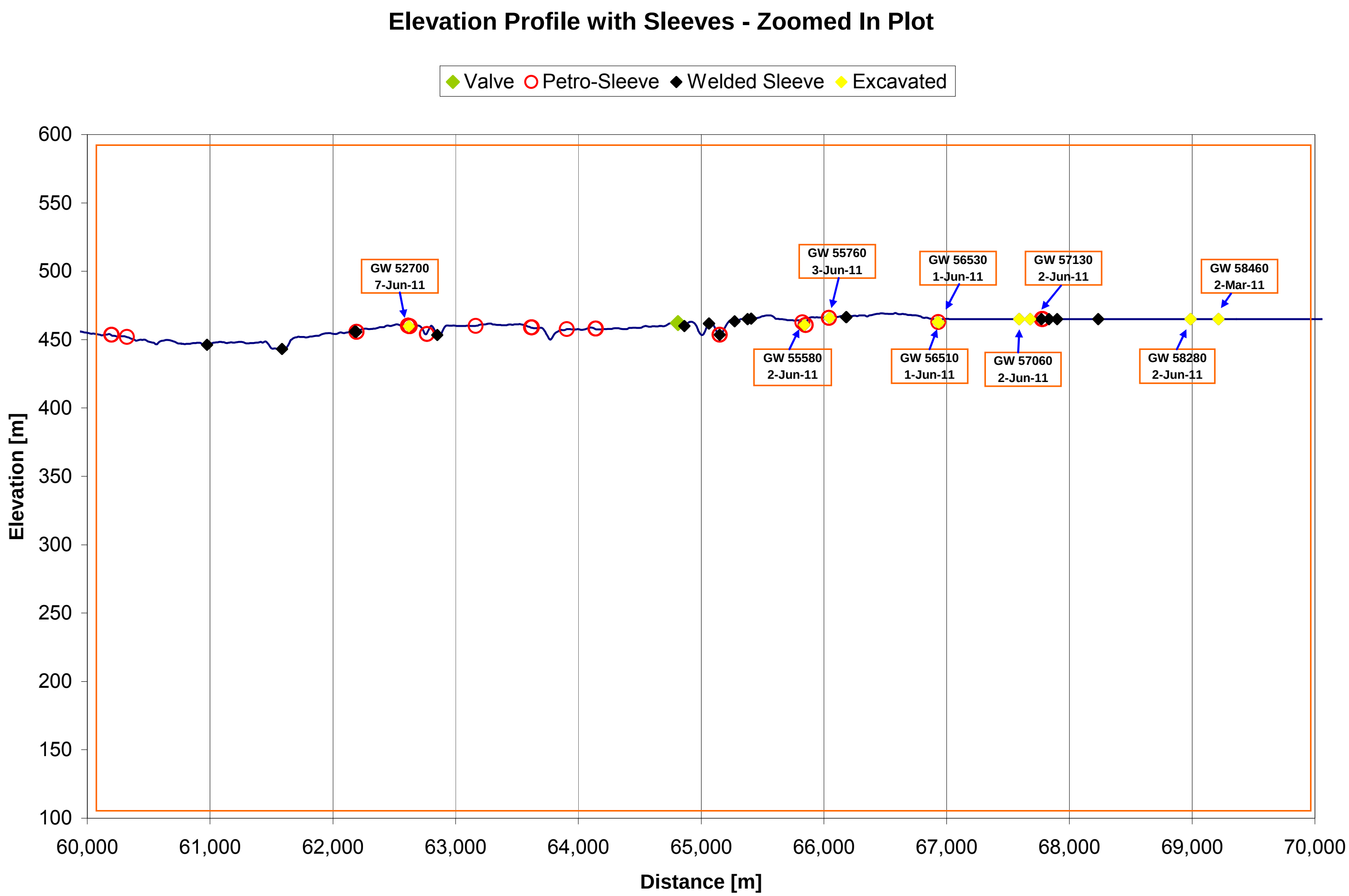


Figure 38 Pipeline Elevation Profile. Zama to Rainbow (Area of High Sleeve Concentration)

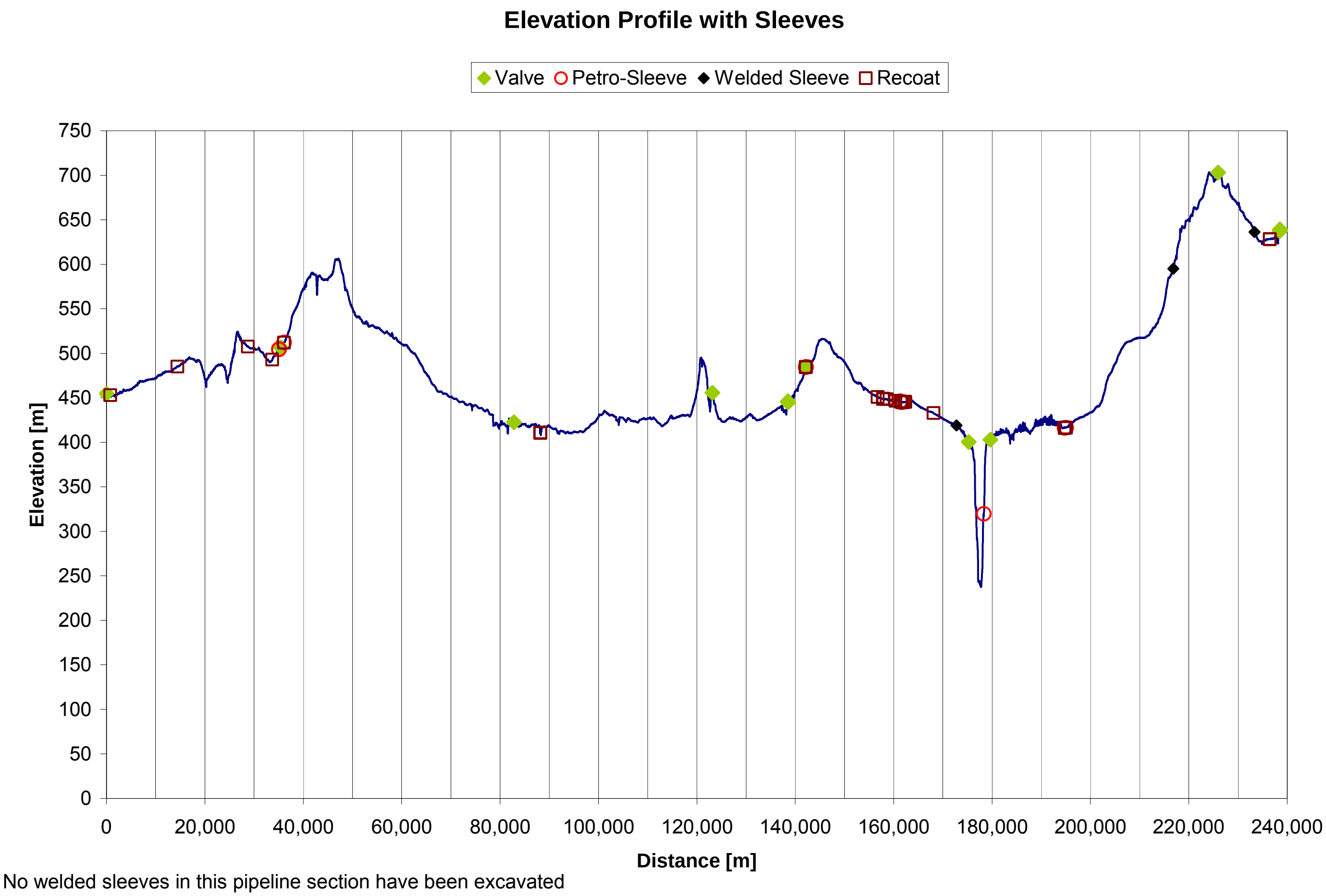


Figure 39 Pipeline Elevation Profile. Rainbow to Cadotte

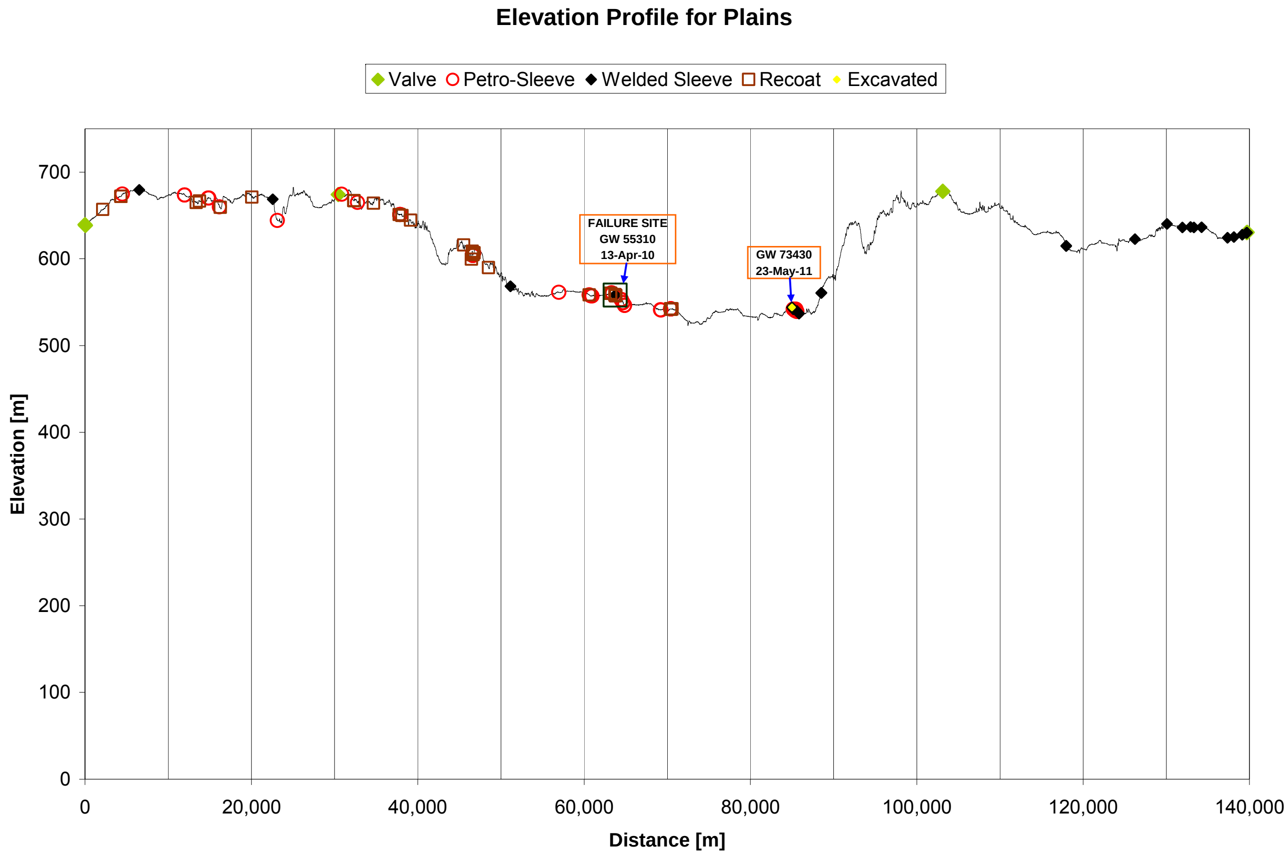


Figure 40 Pipeline Elevation Profile. Cadotte to Utikuma

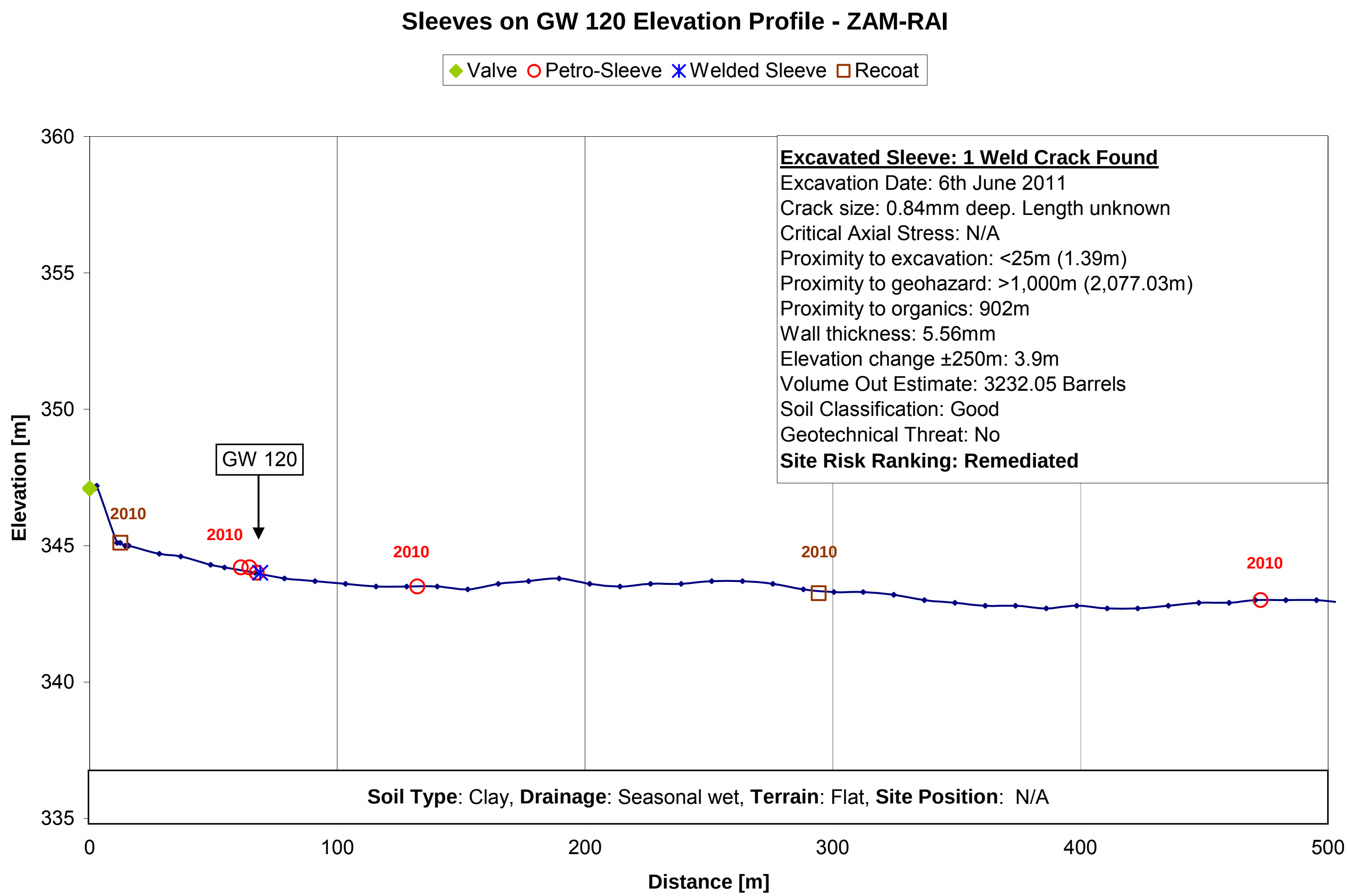


Figure 41 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 120

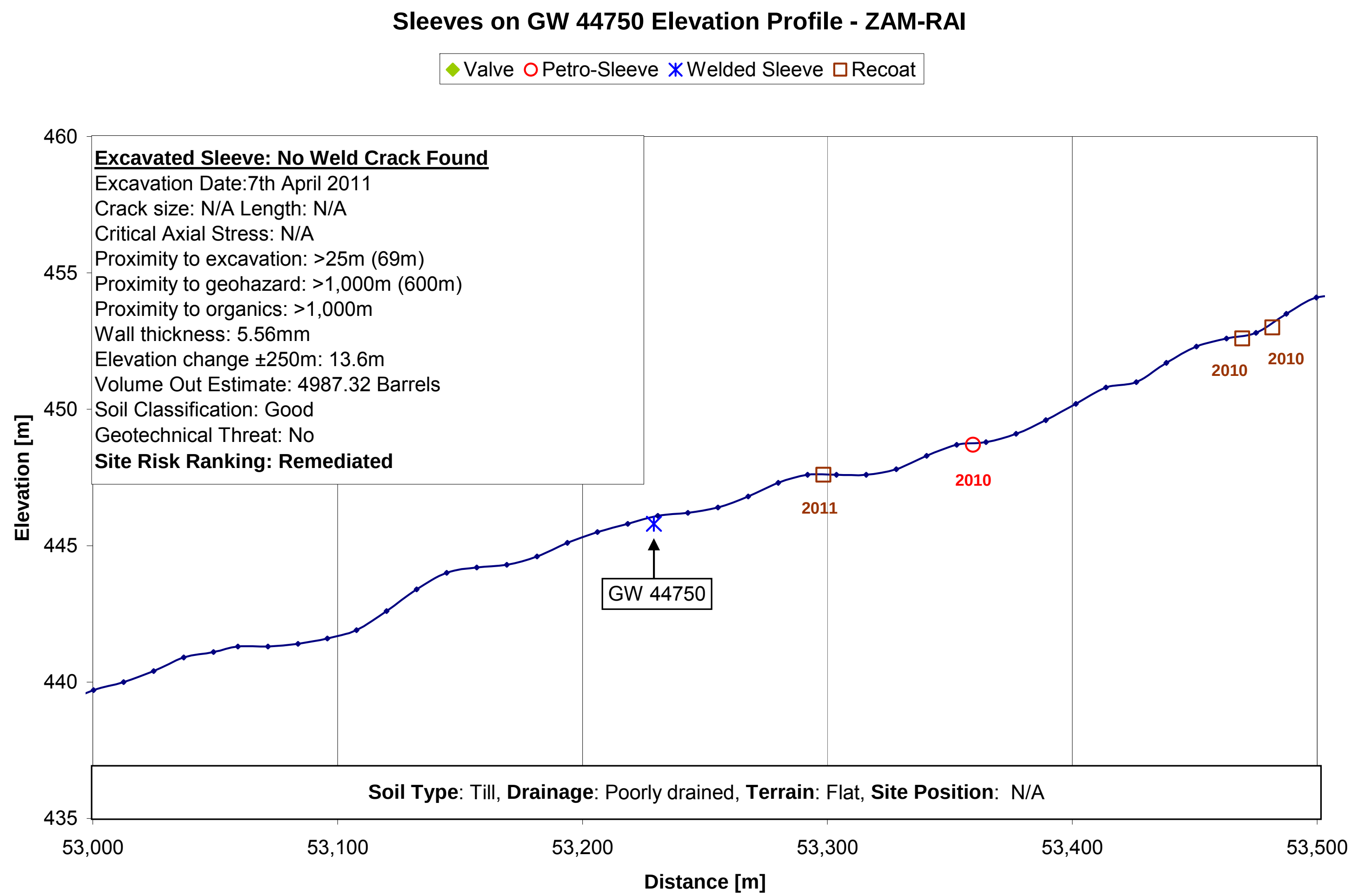


Figure 42 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 44750

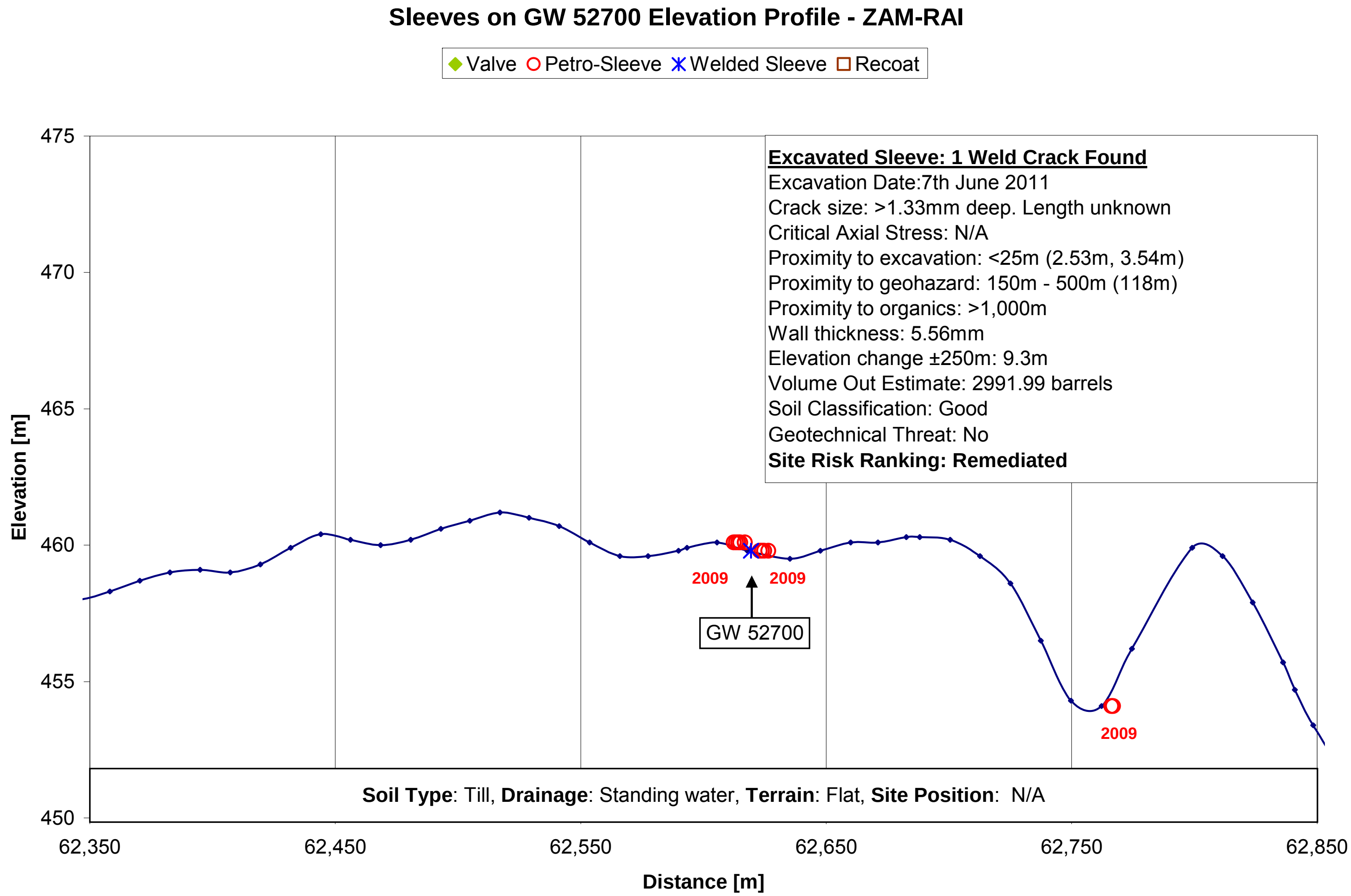


Figure 43 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 52700

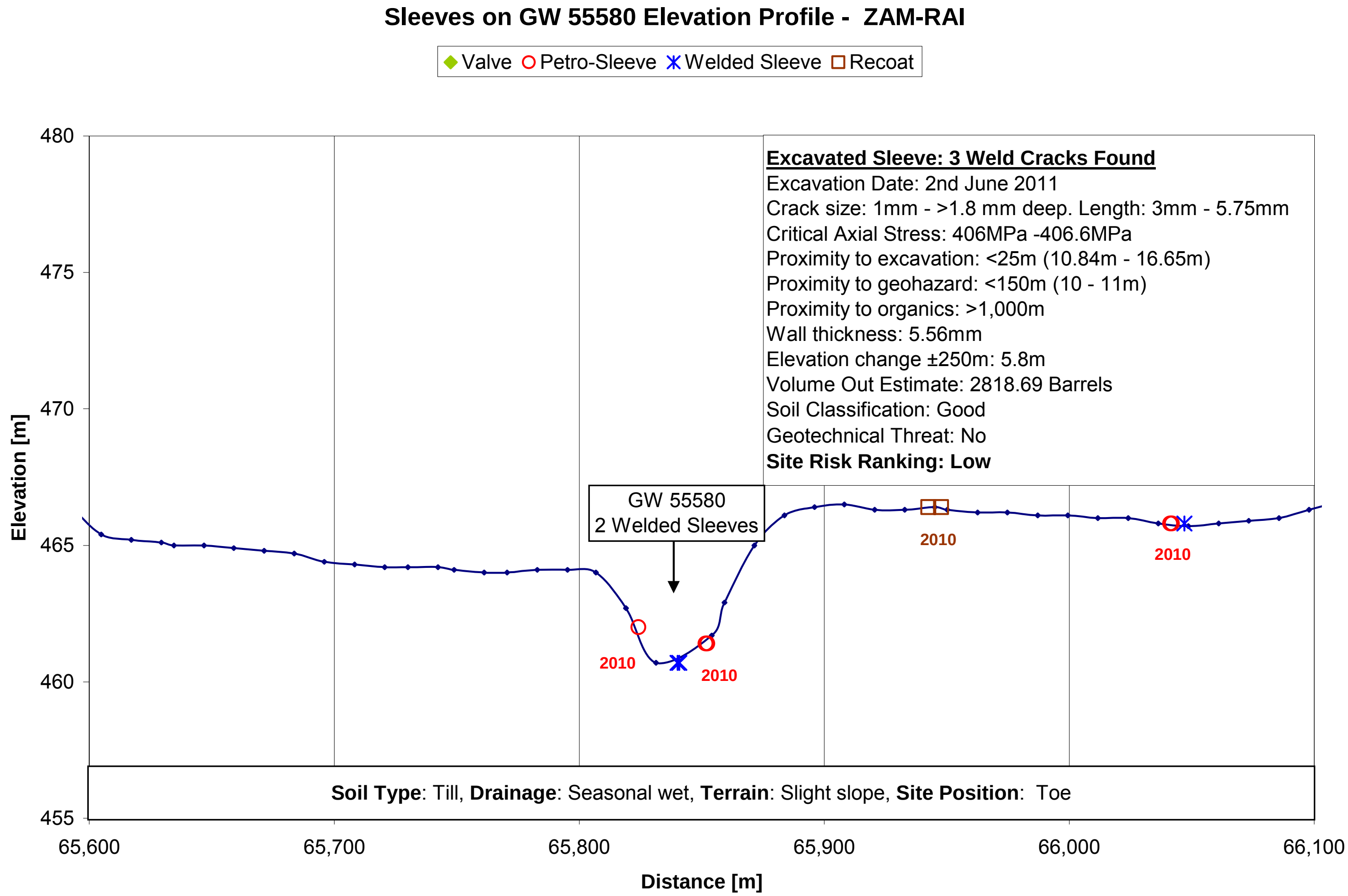


Figure 44 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 55580

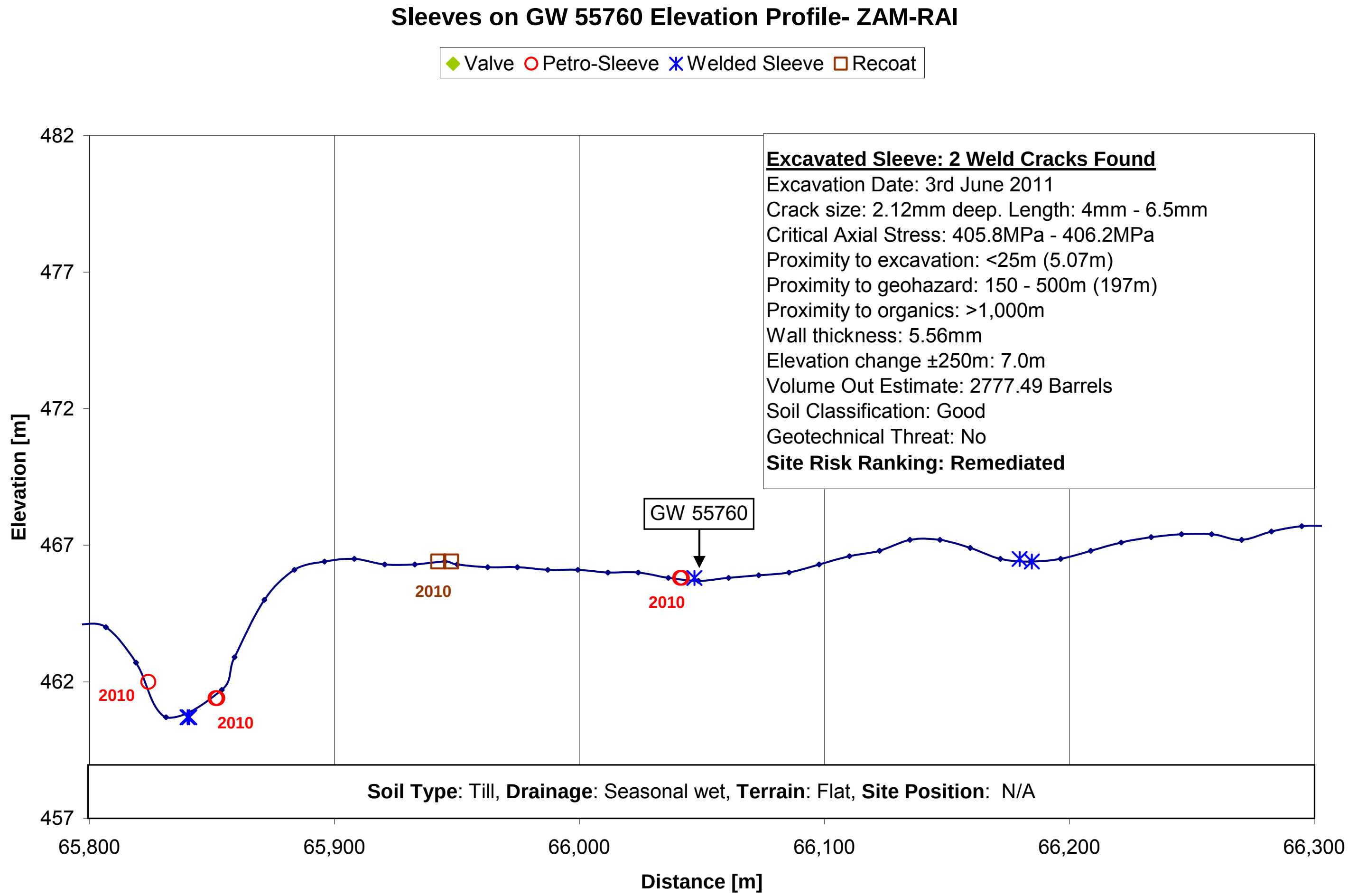


Figure 45 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 55760

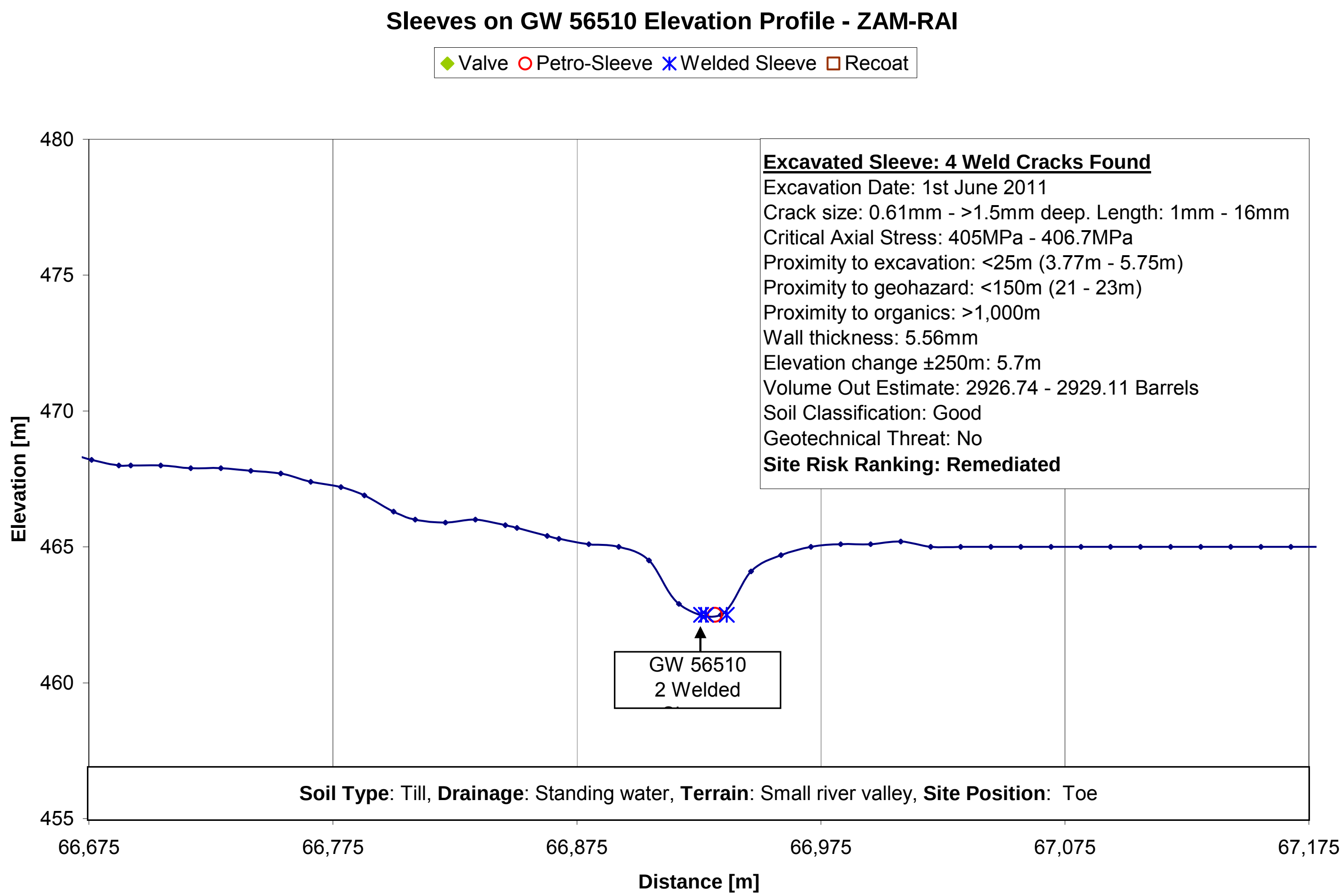


Figure 46 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 56510

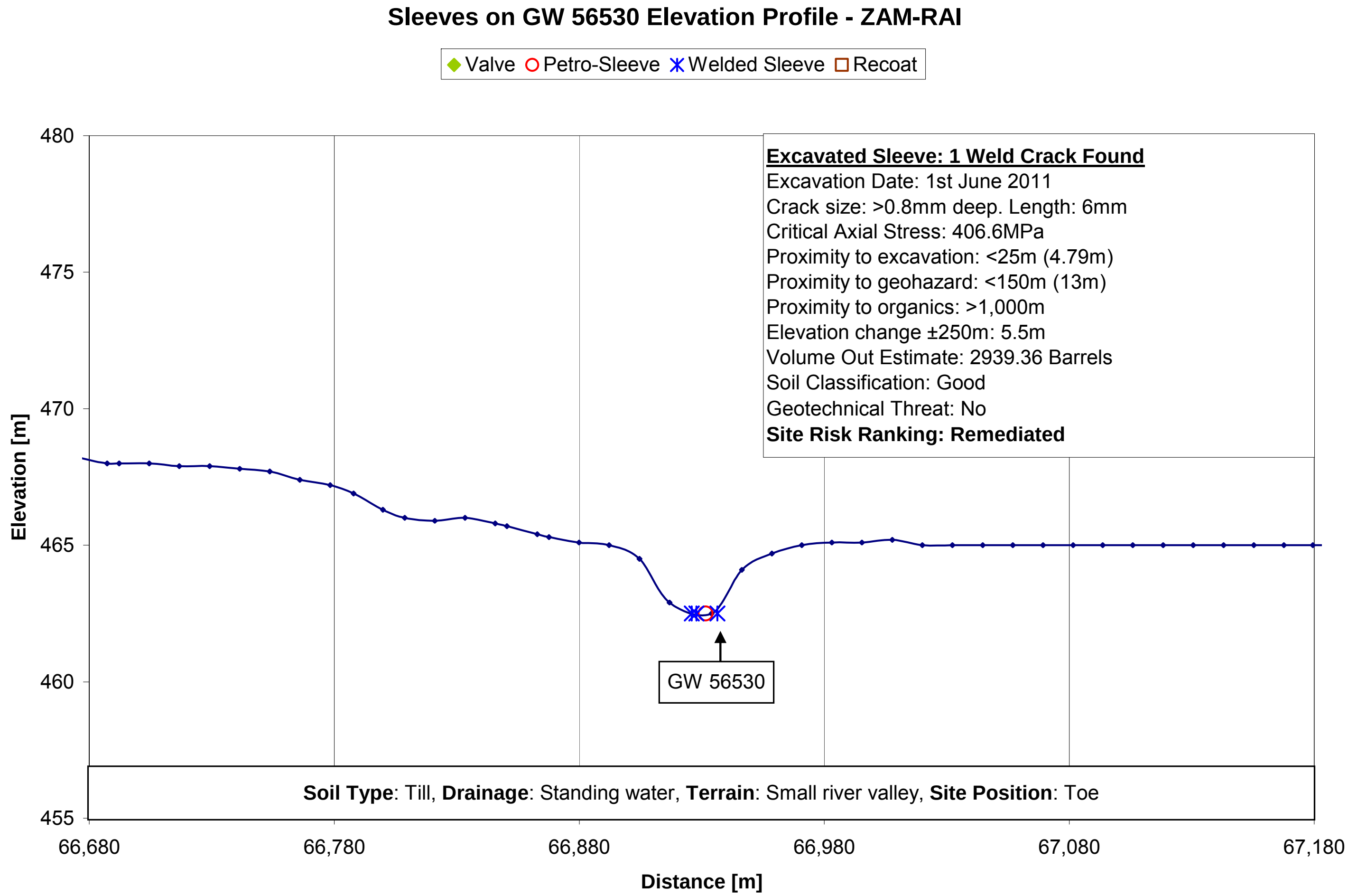


Figure 47 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 56530

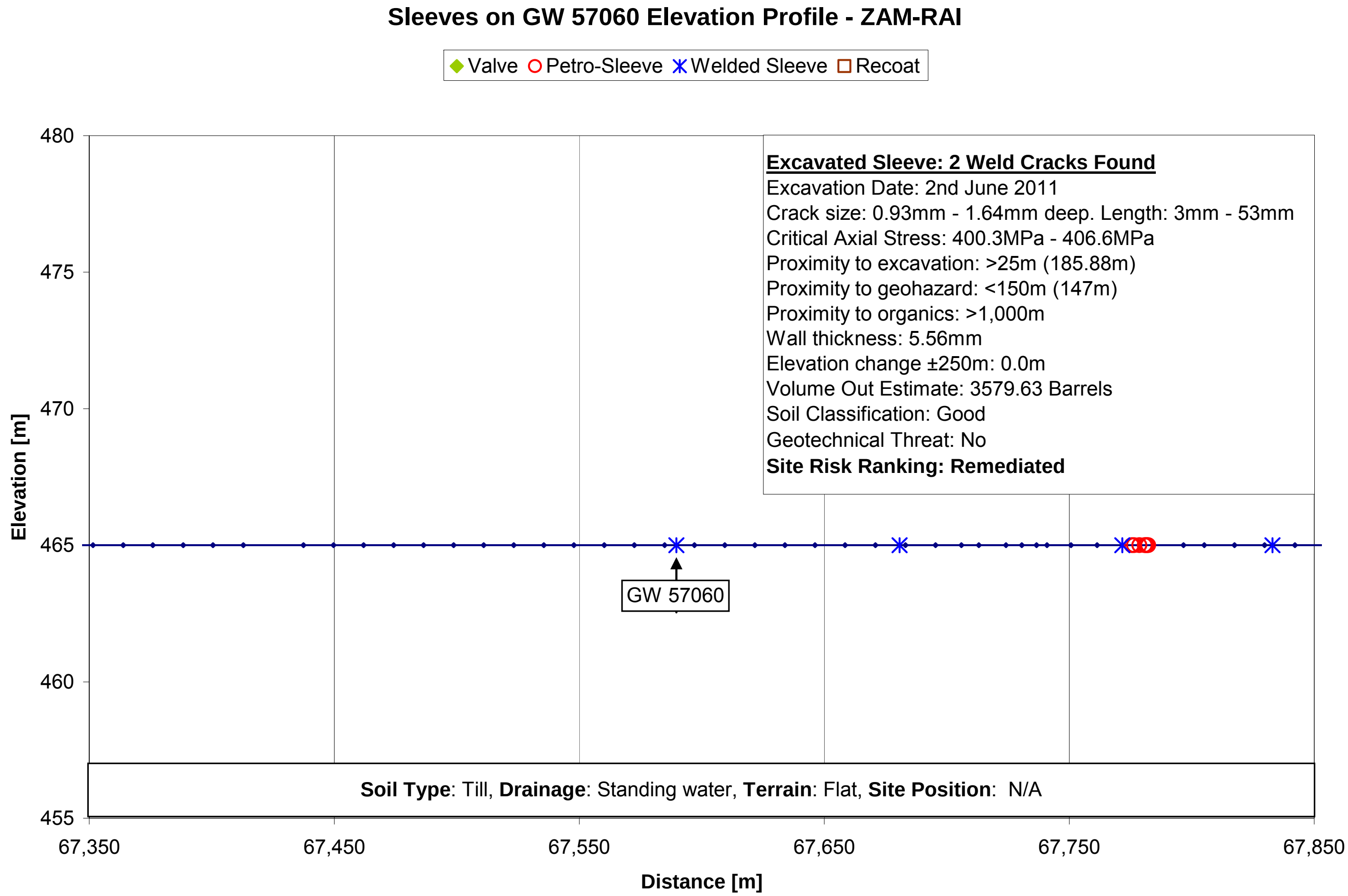


Figure 48 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 57060

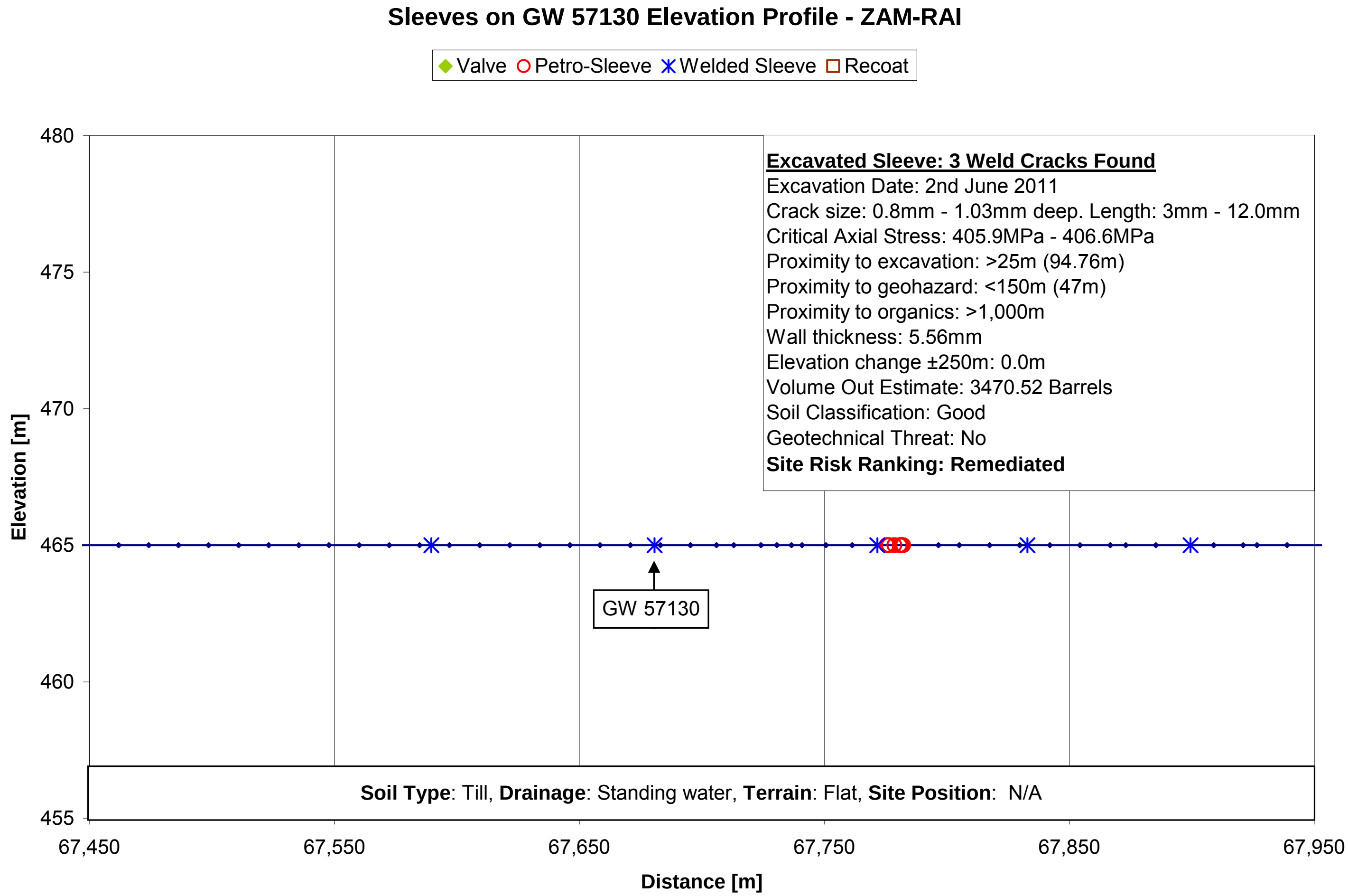


Figure 49 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 57130

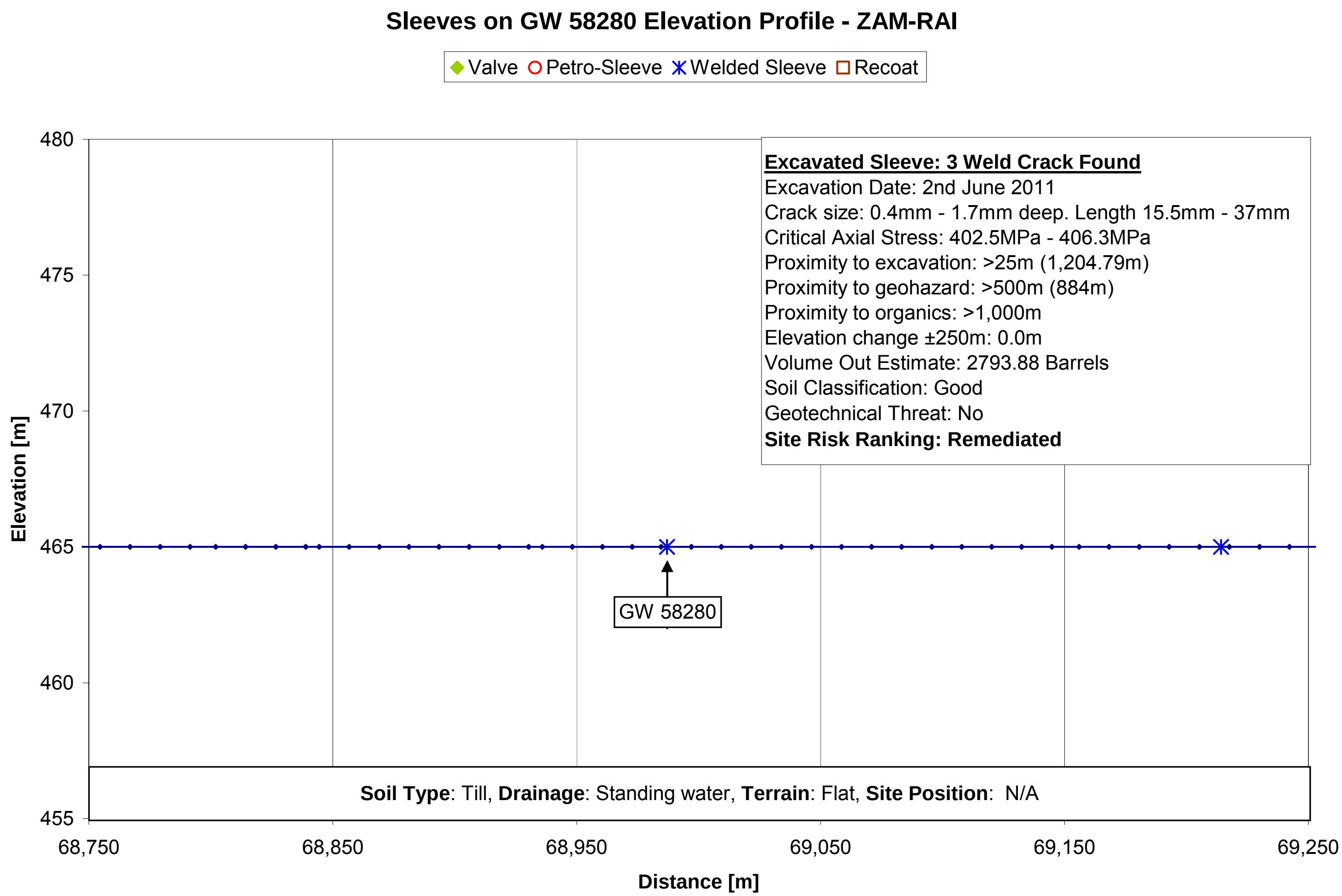


Figure 50 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 58280

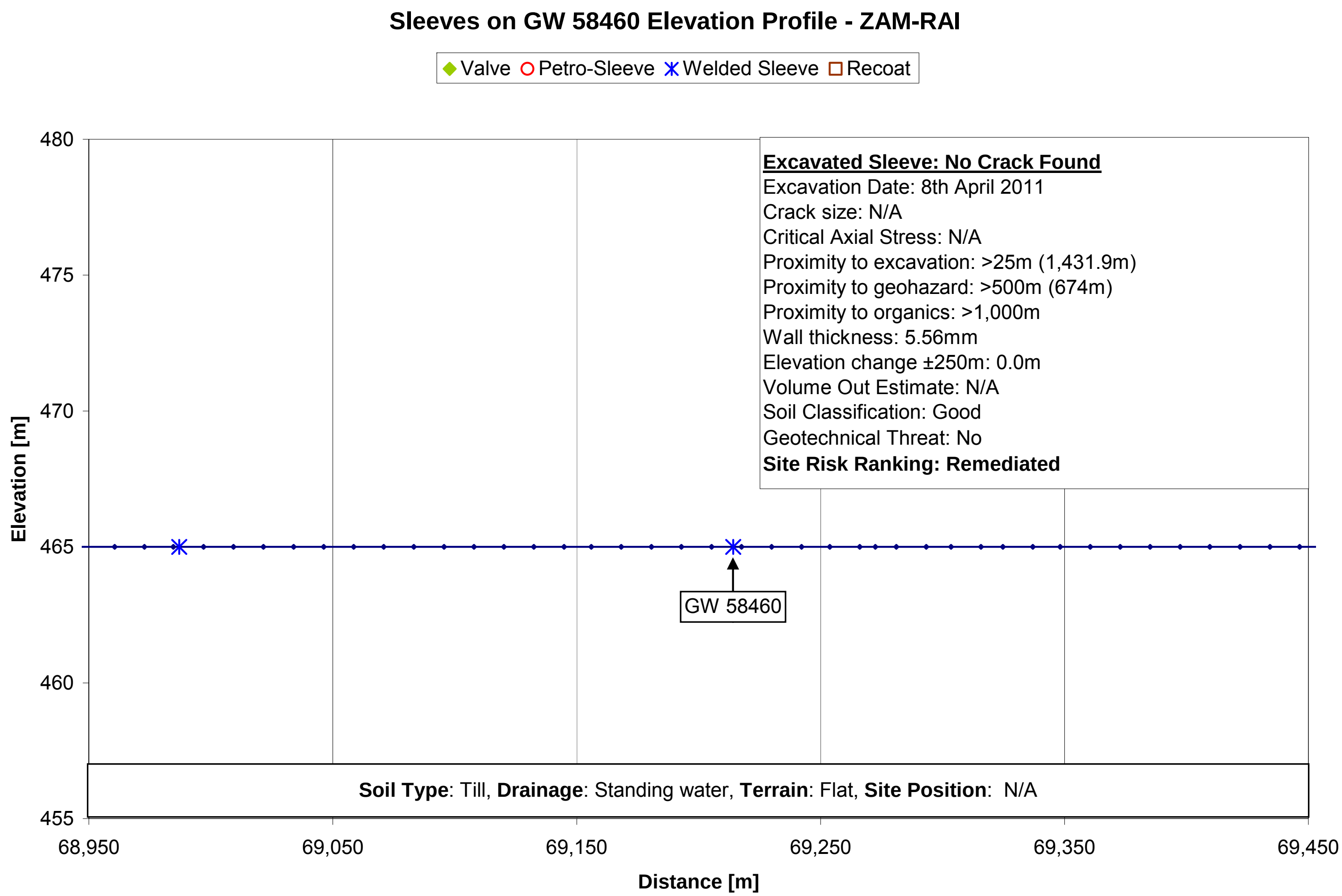


Figure 51 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 58460

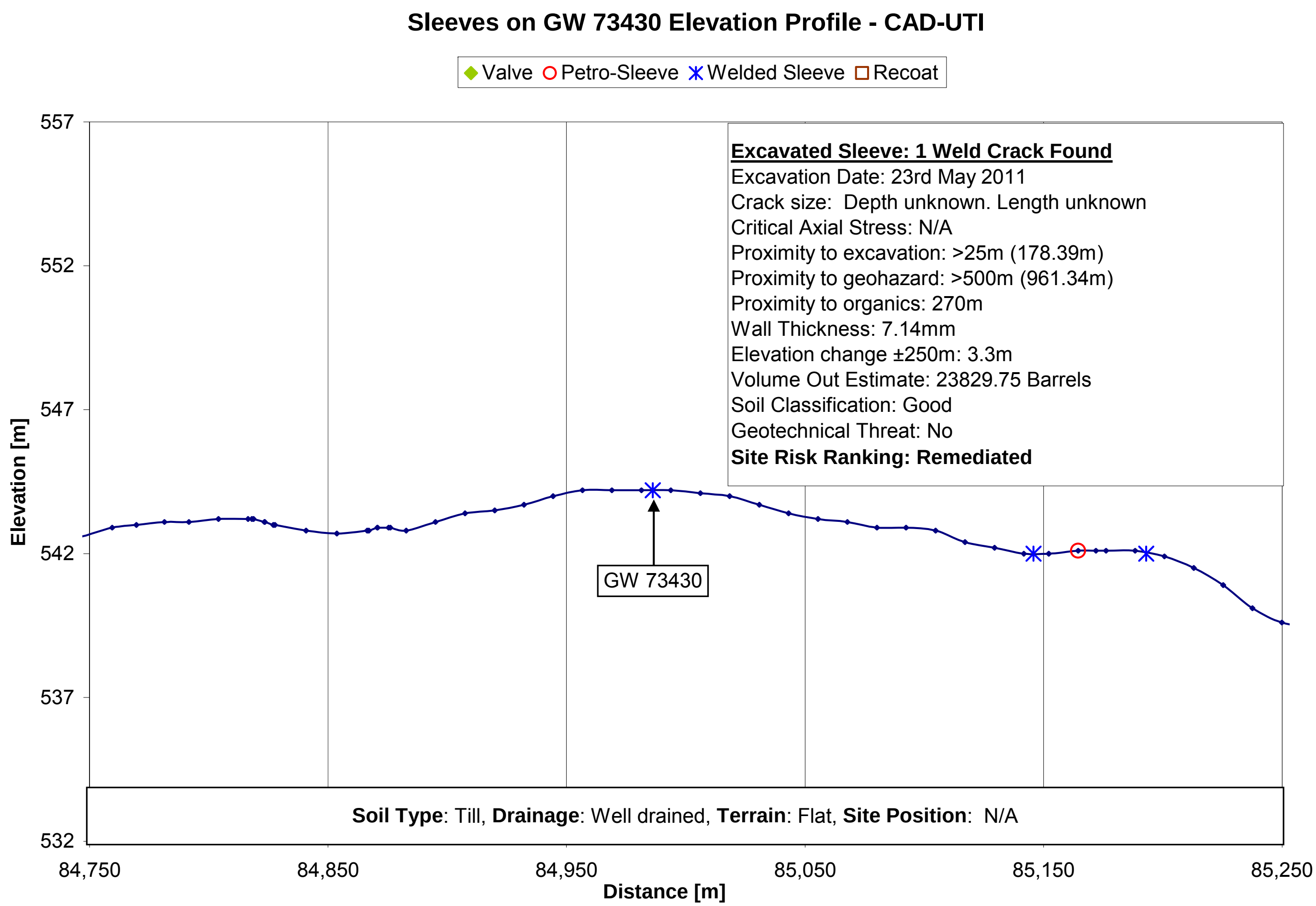


Figure 52 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 73430

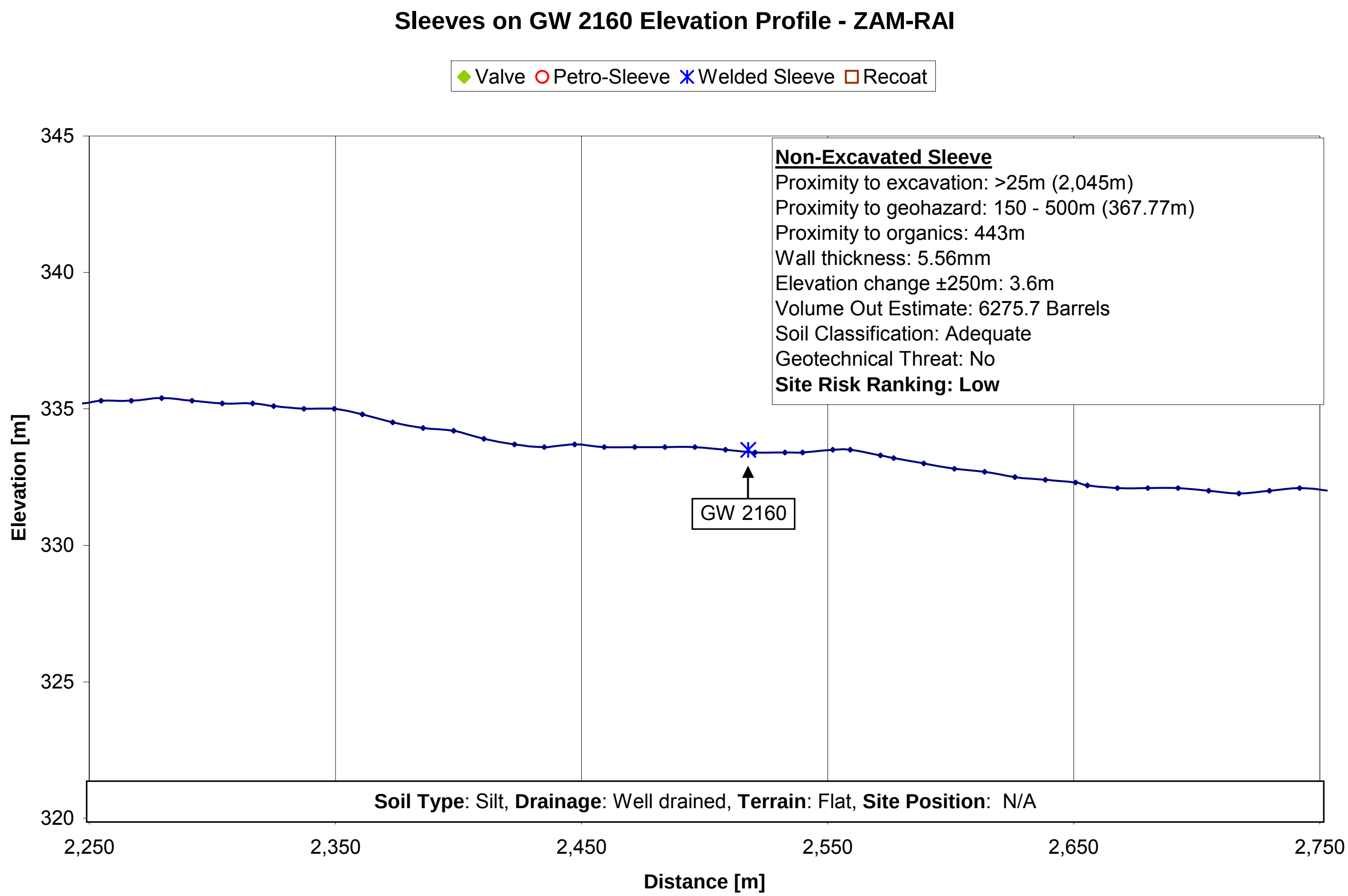


Figure 53 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 2160

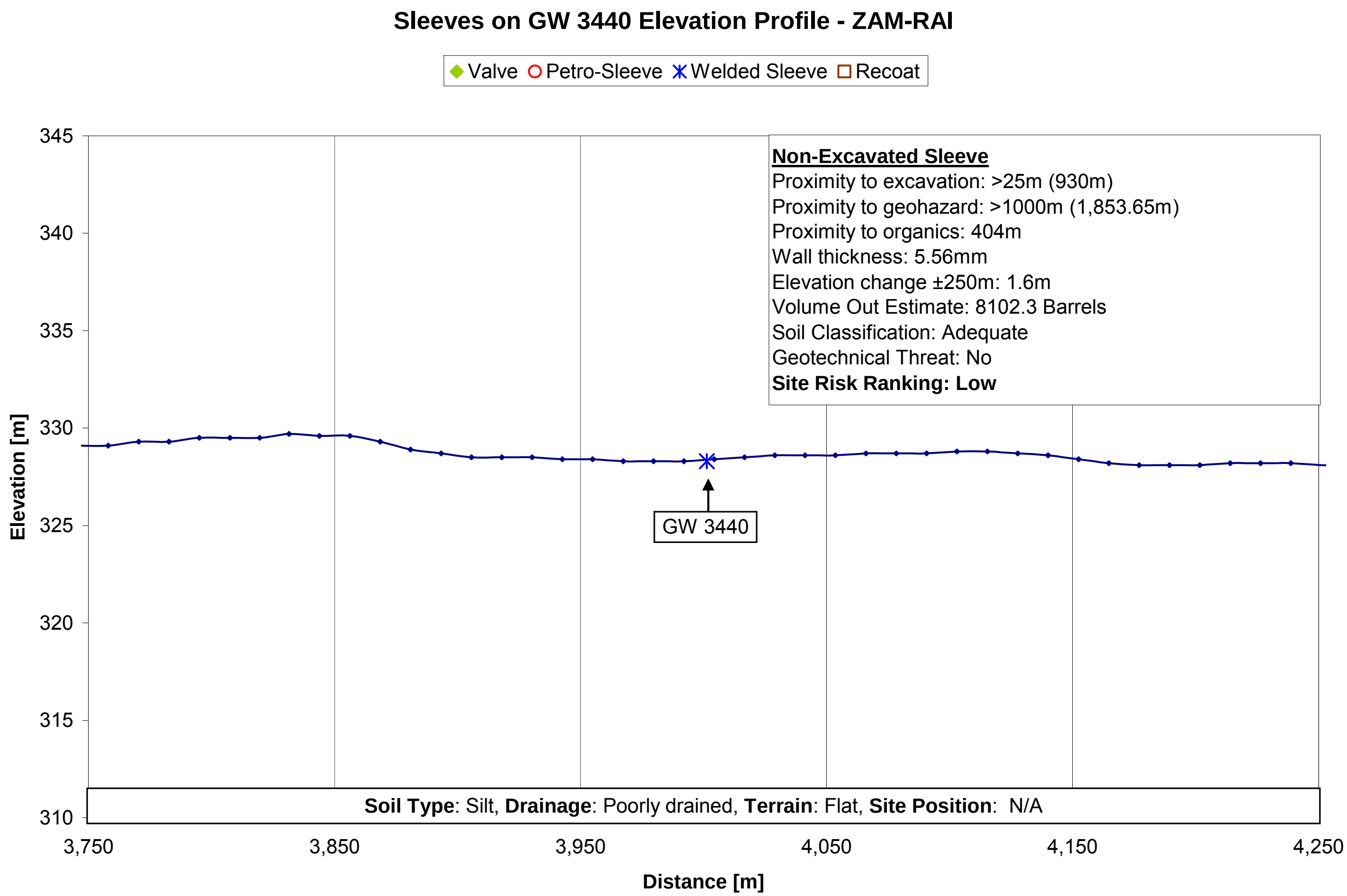


Figure 54 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 3440

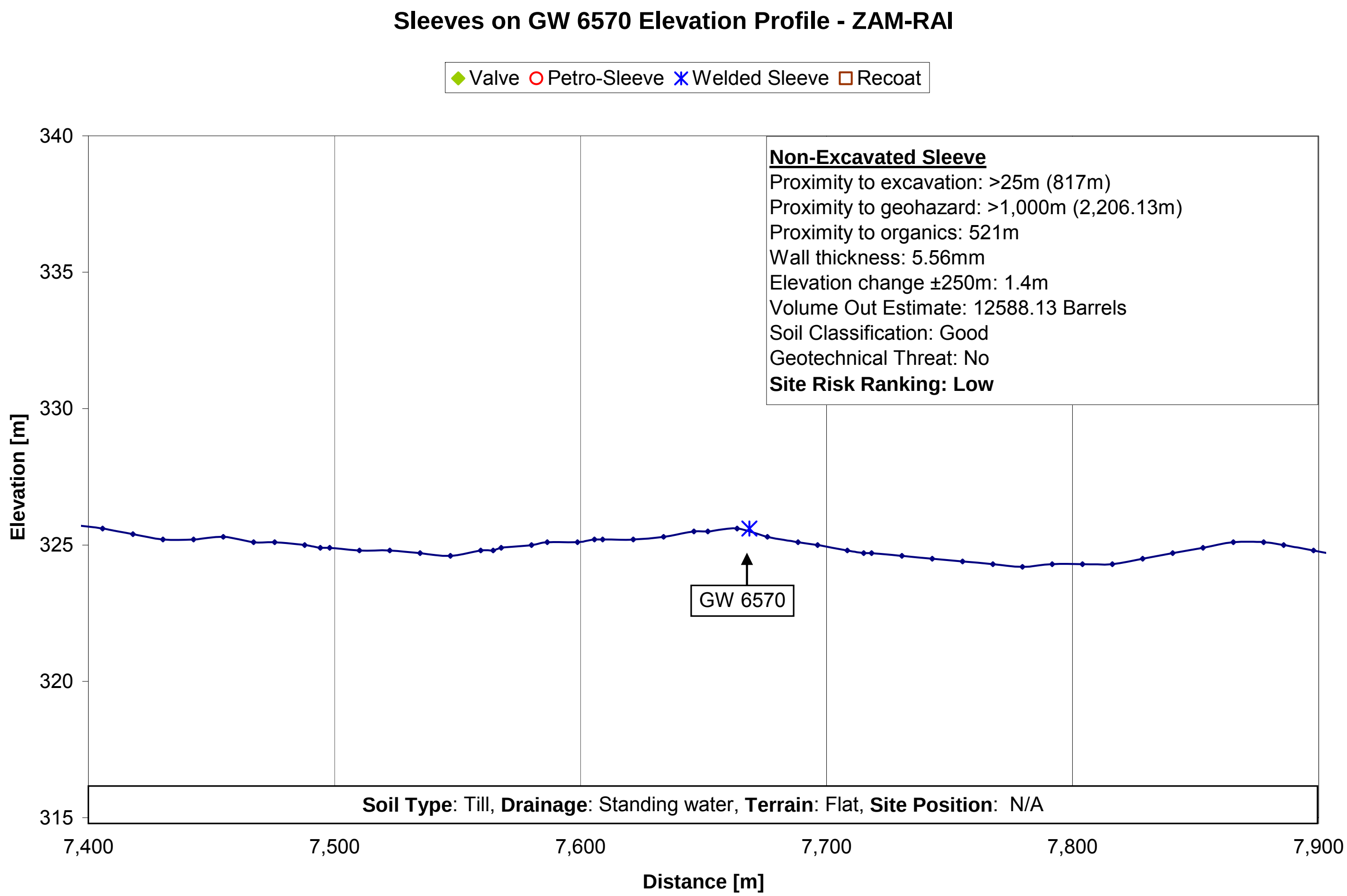


Figure 55 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW6570

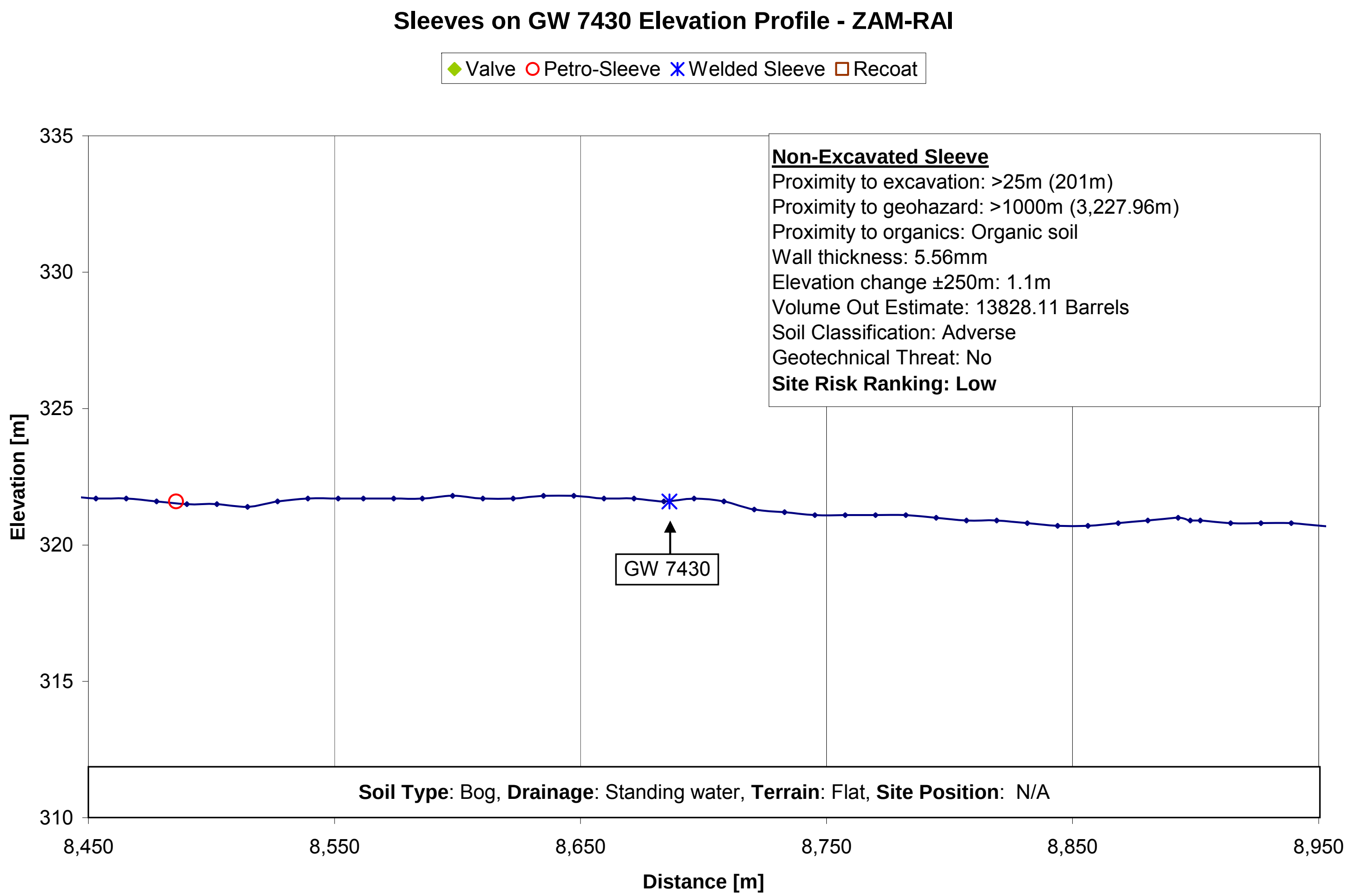


Figure 56 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 7430

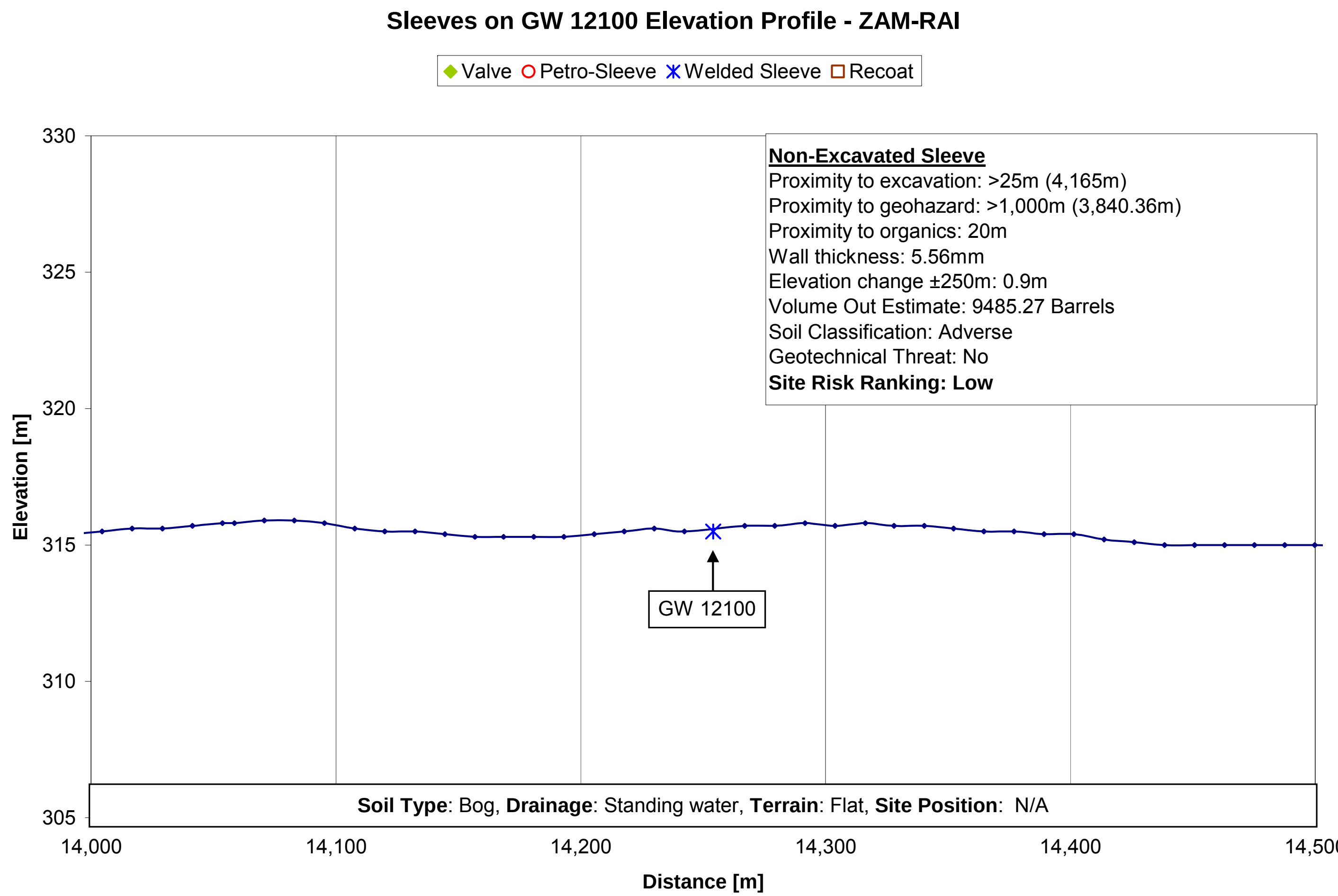


Figure 57 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 12100

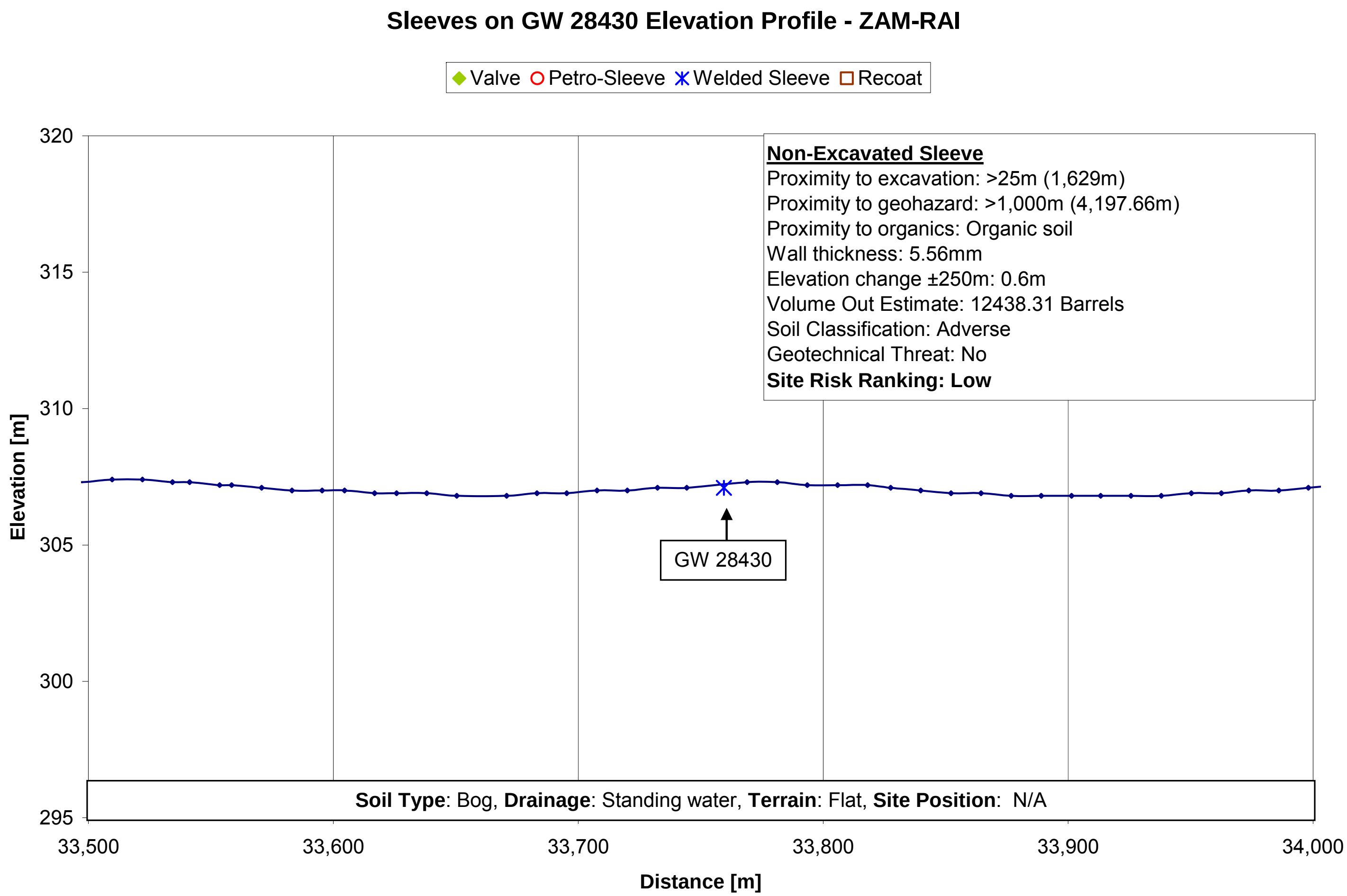


Figure 58 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 28430

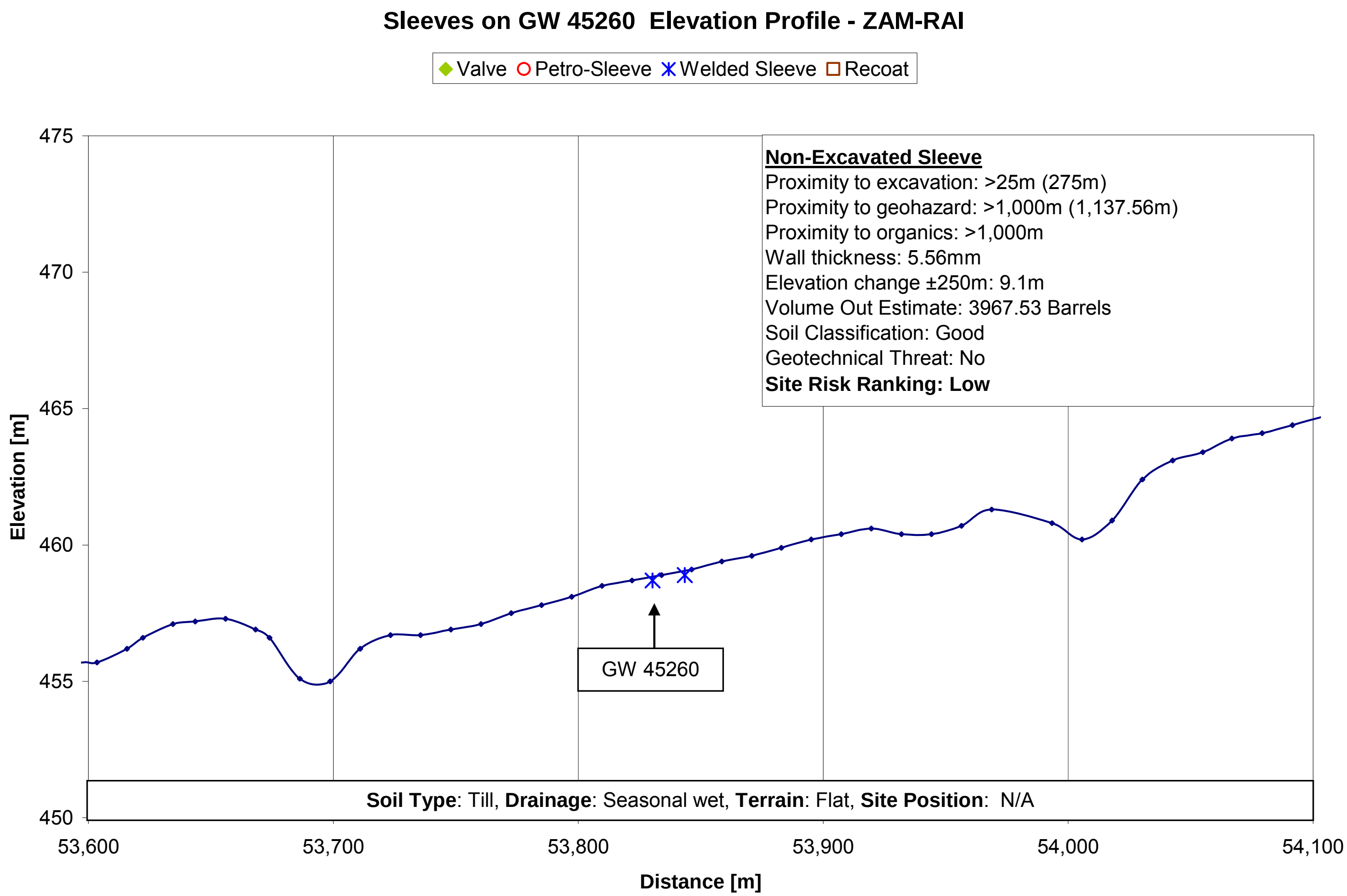


Figure 59 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 45260

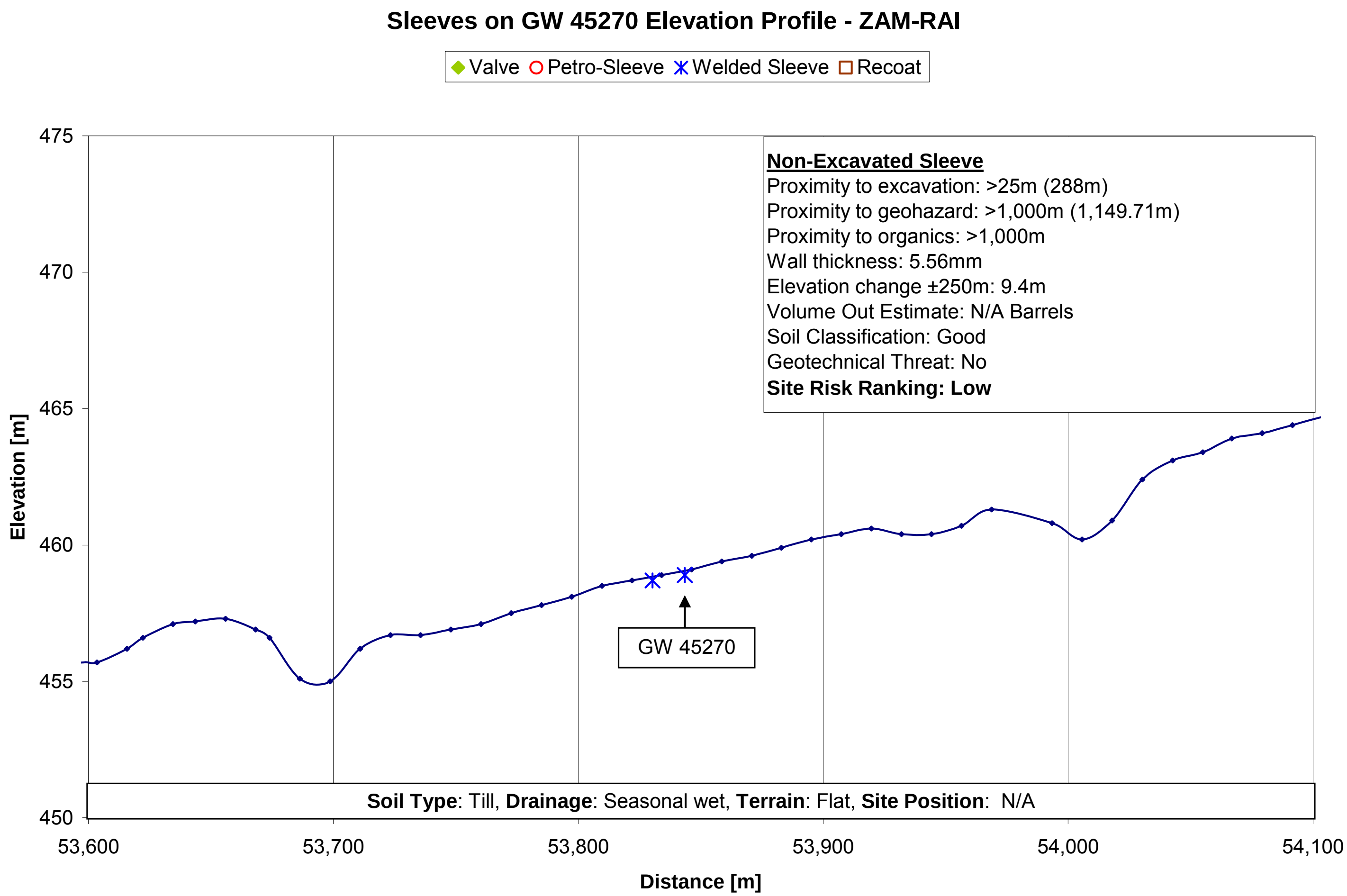


Figure 60 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 45270

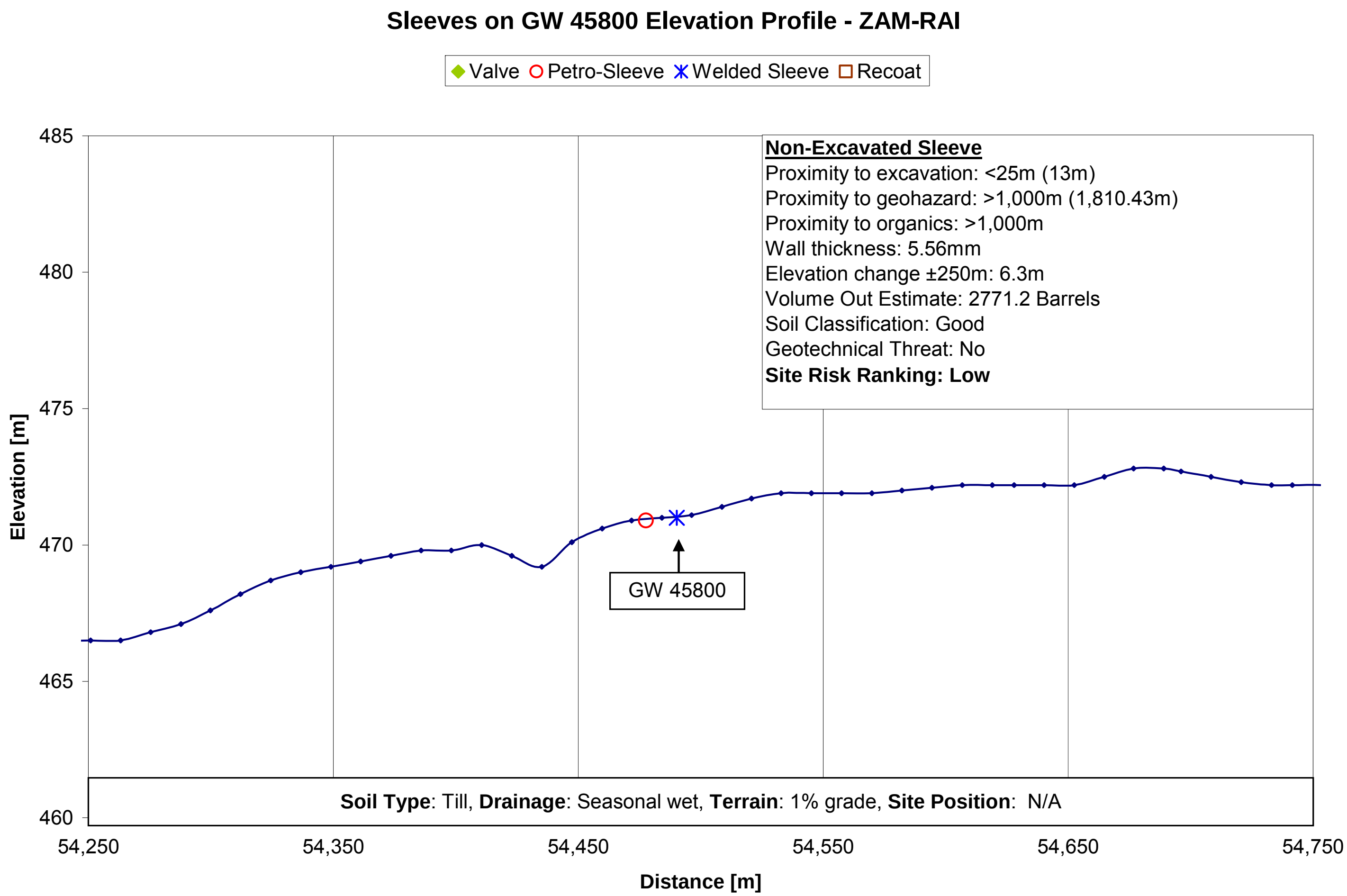


Figure 61 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 45800

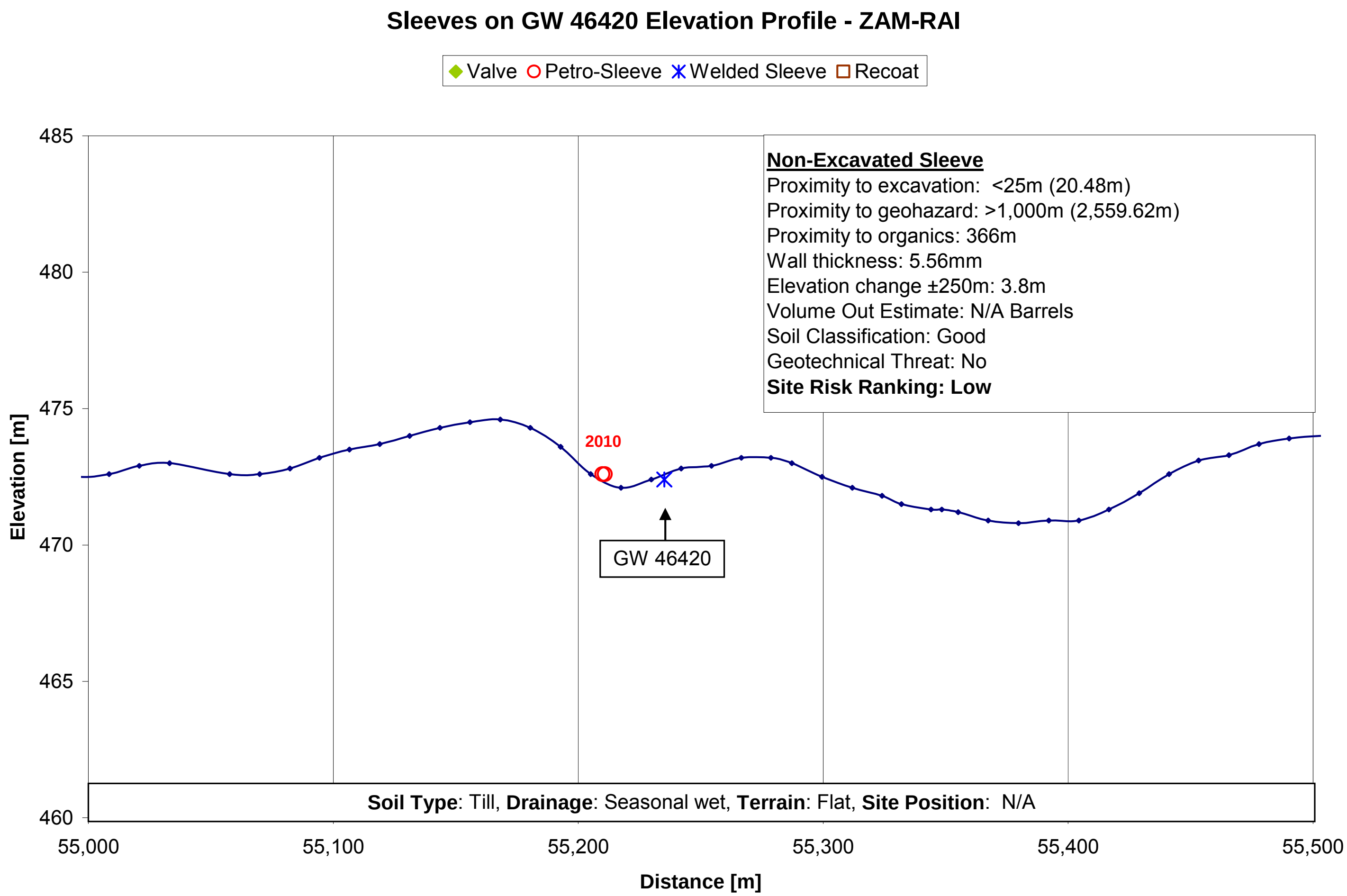


Figure 62 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 46420

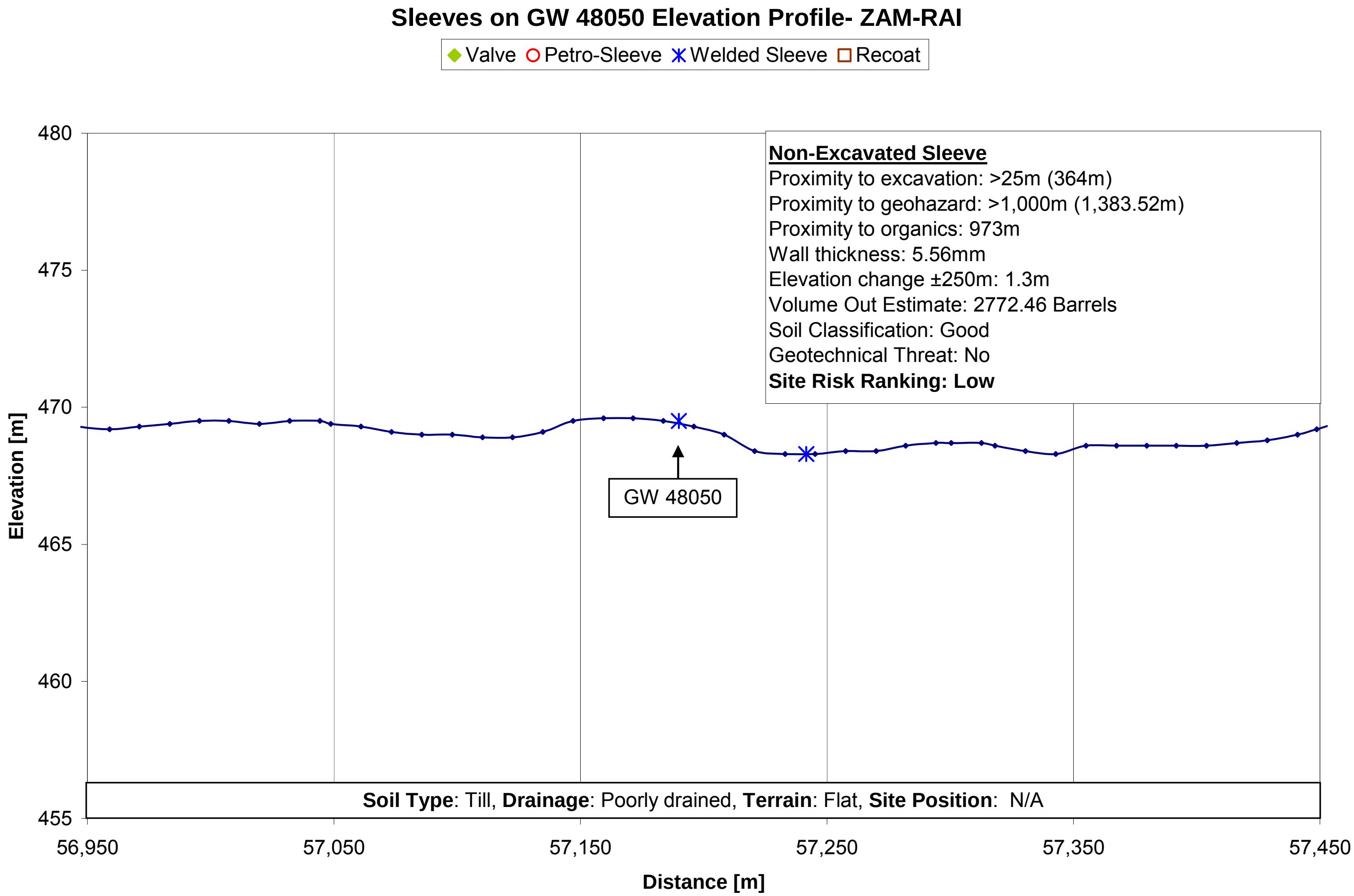


Figure 63 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 48050

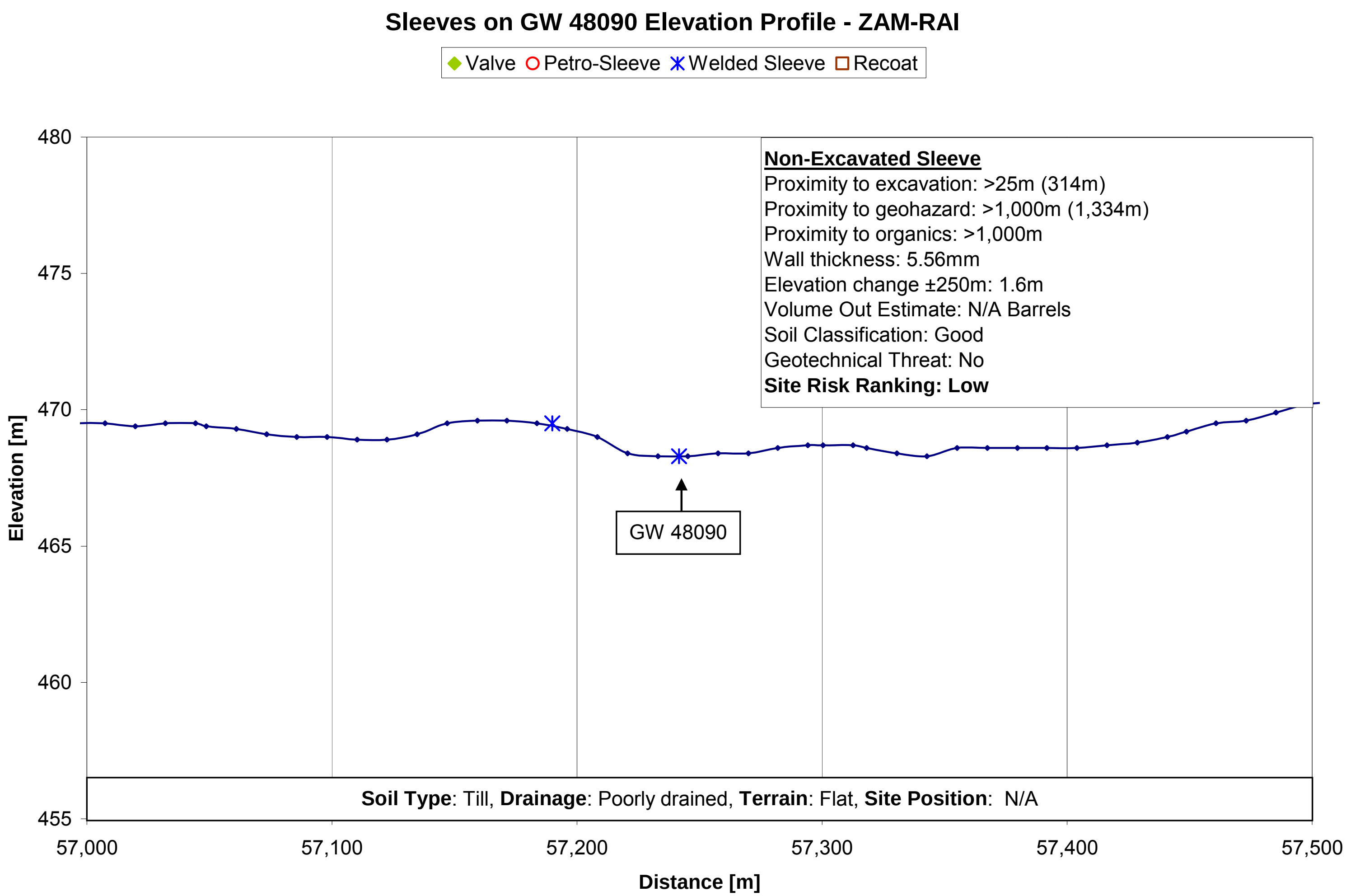


Figure 64 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 48090

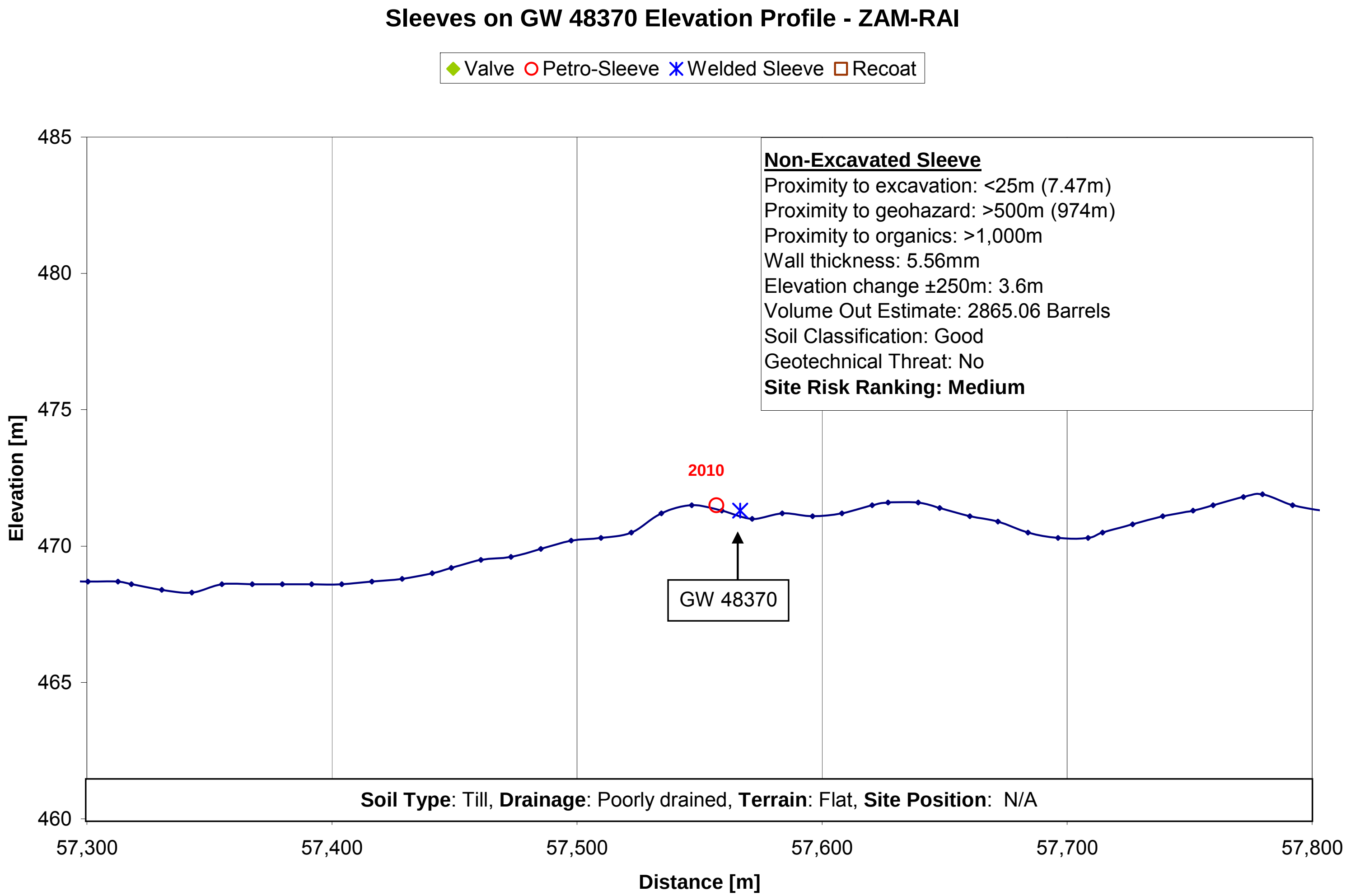


Figure 65 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 48370

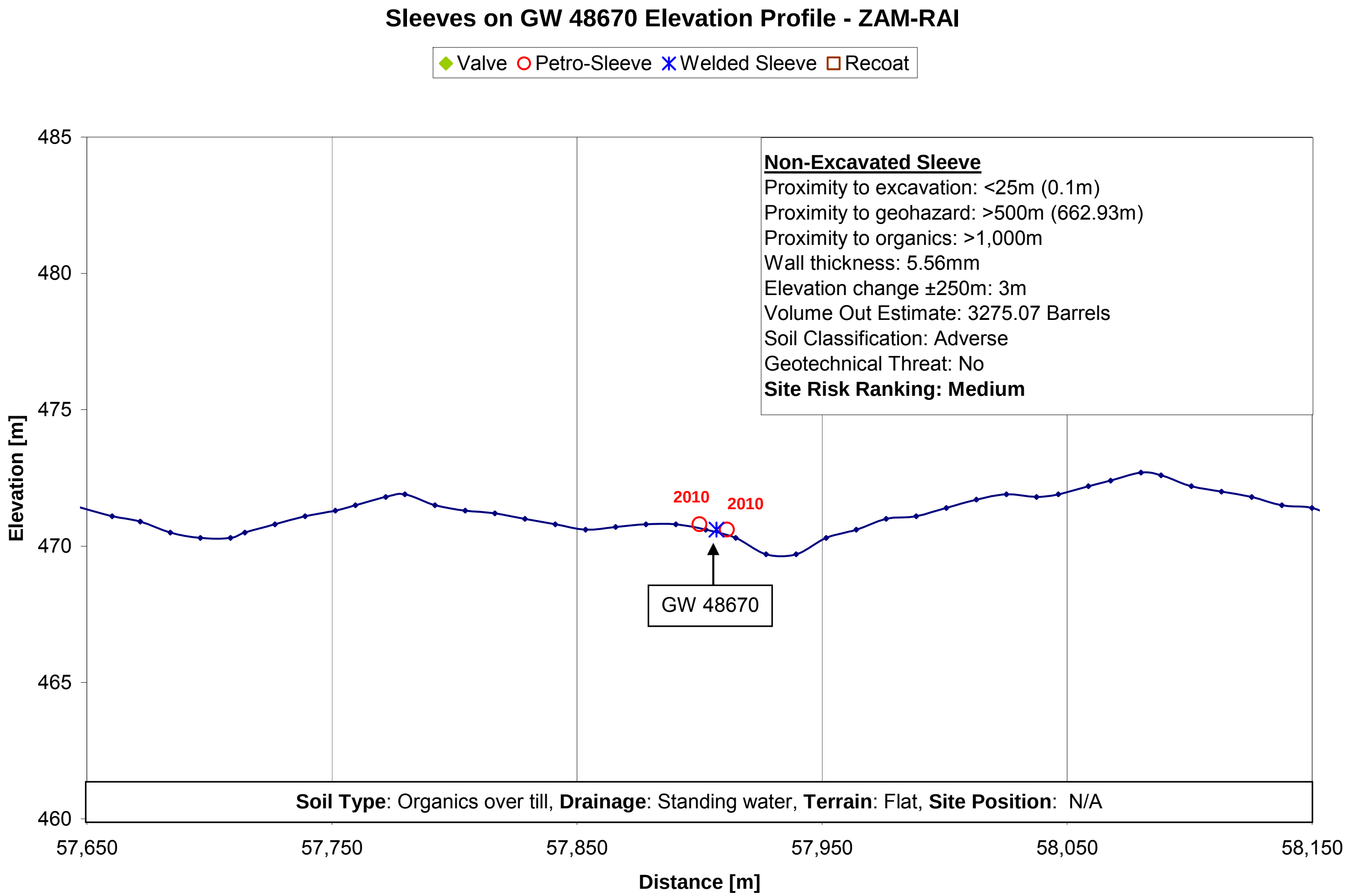


Figure 66 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 48670

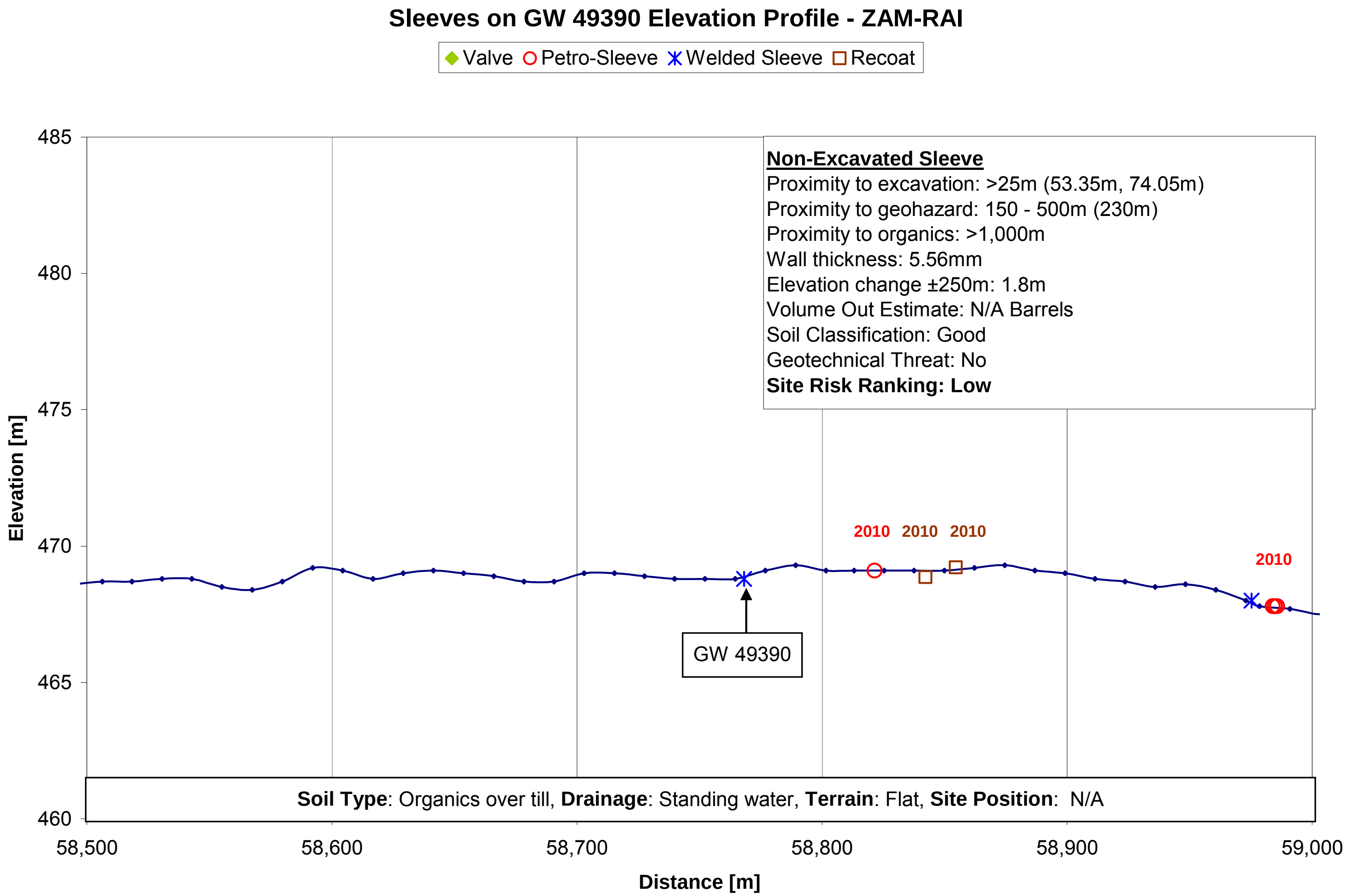


Figure 67 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 49390

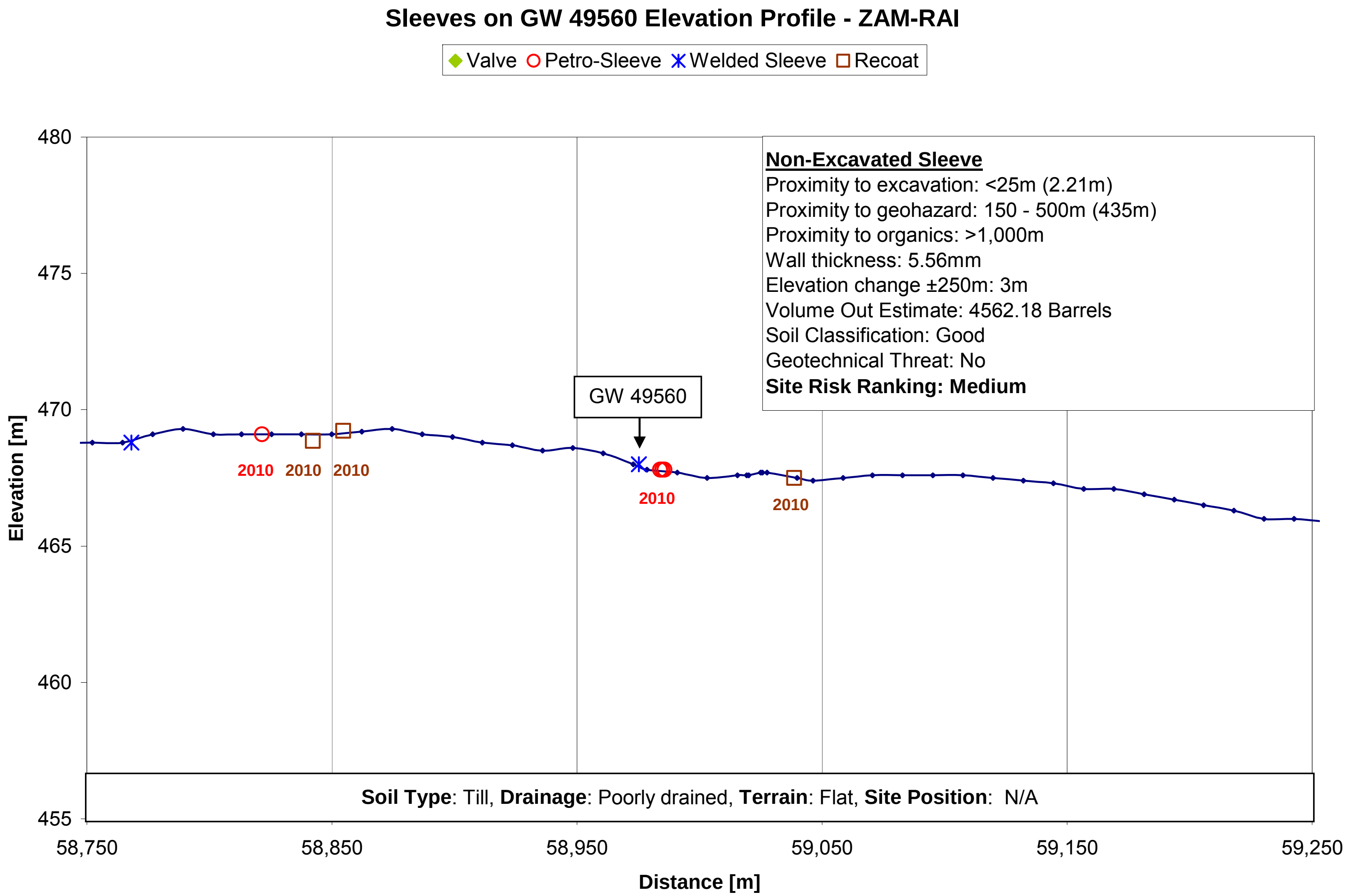


Figure 68 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 49560

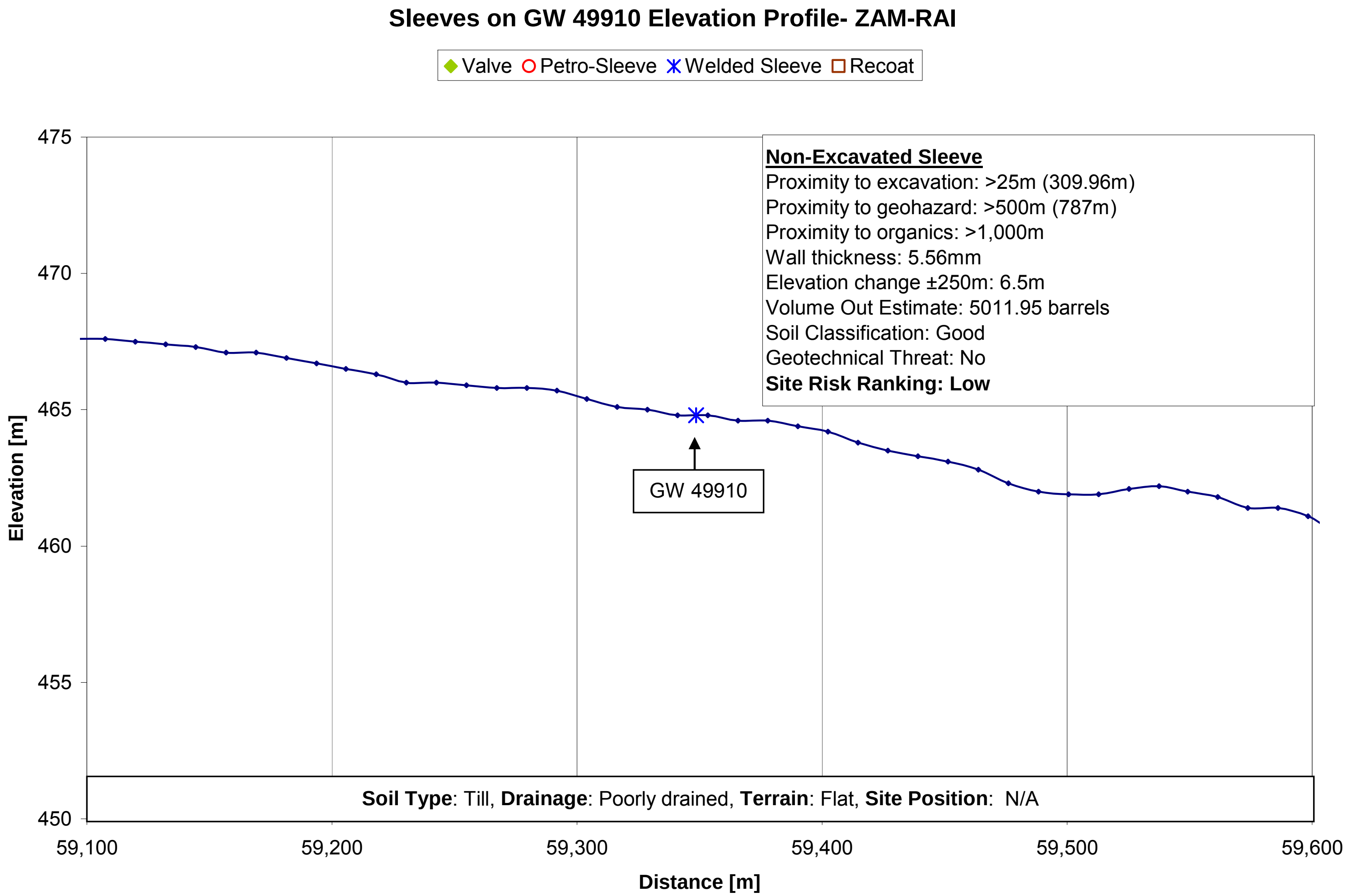


Figure 69 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 49910

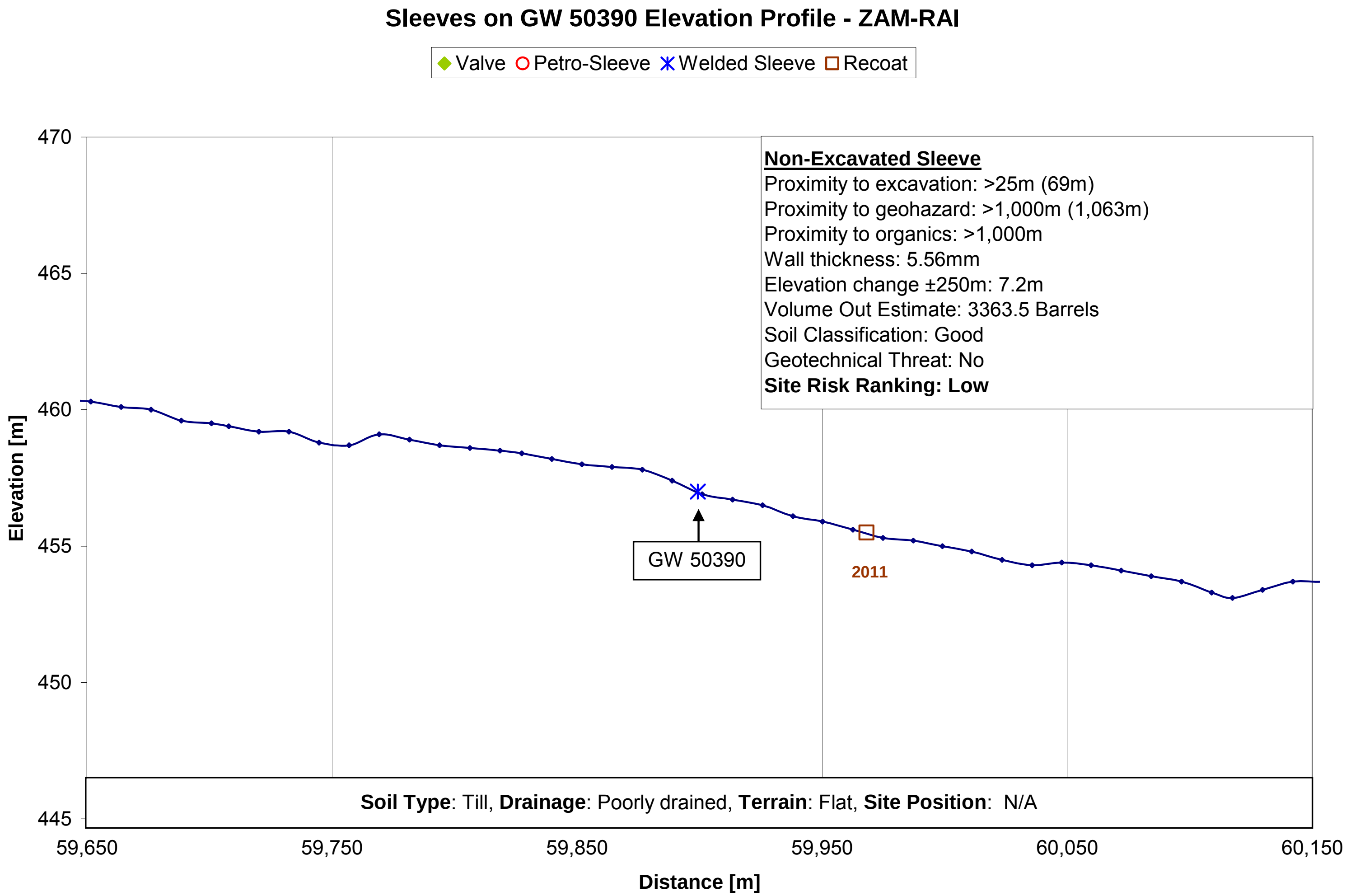


Figure 70 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 50390

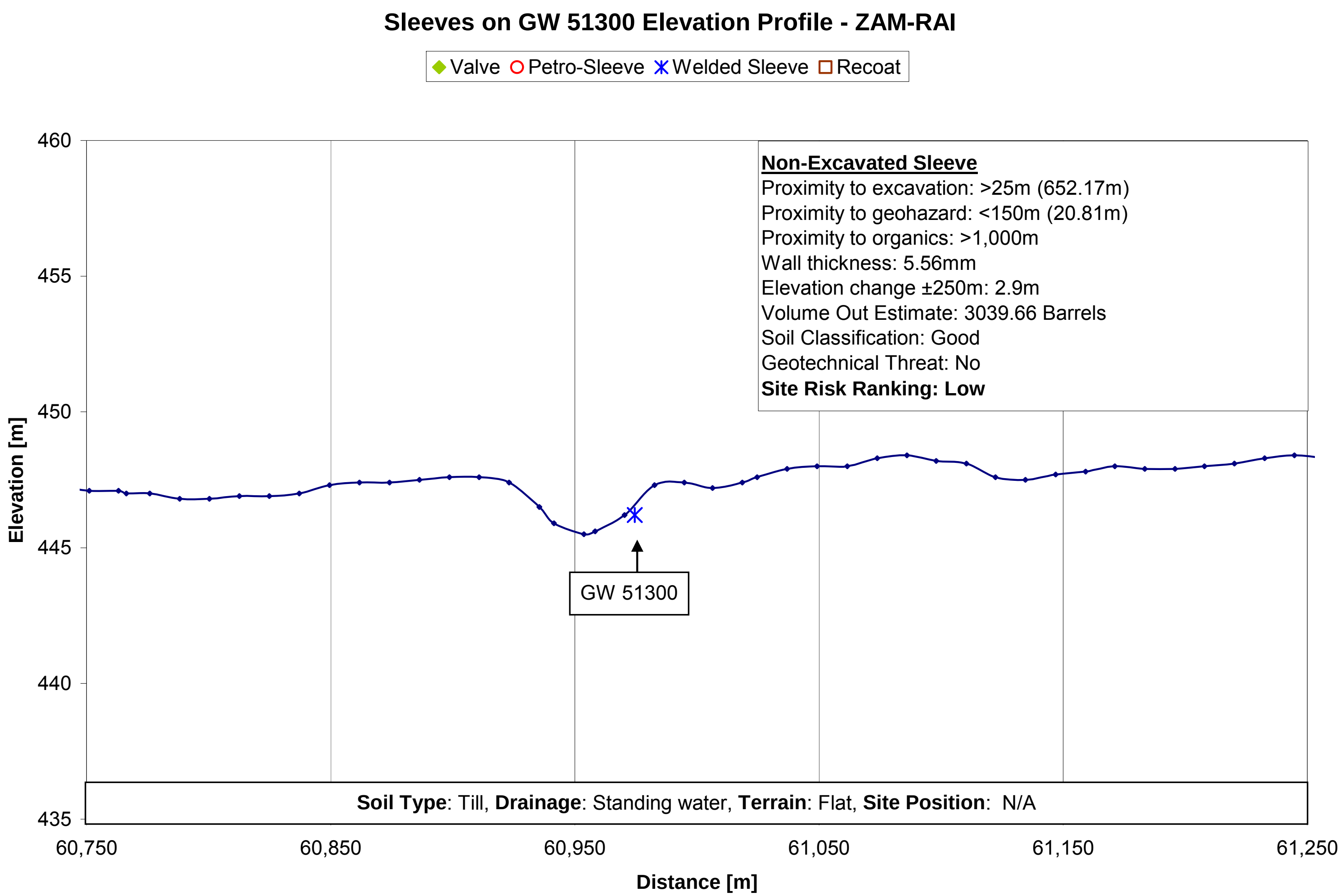


Figure 71 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 51300

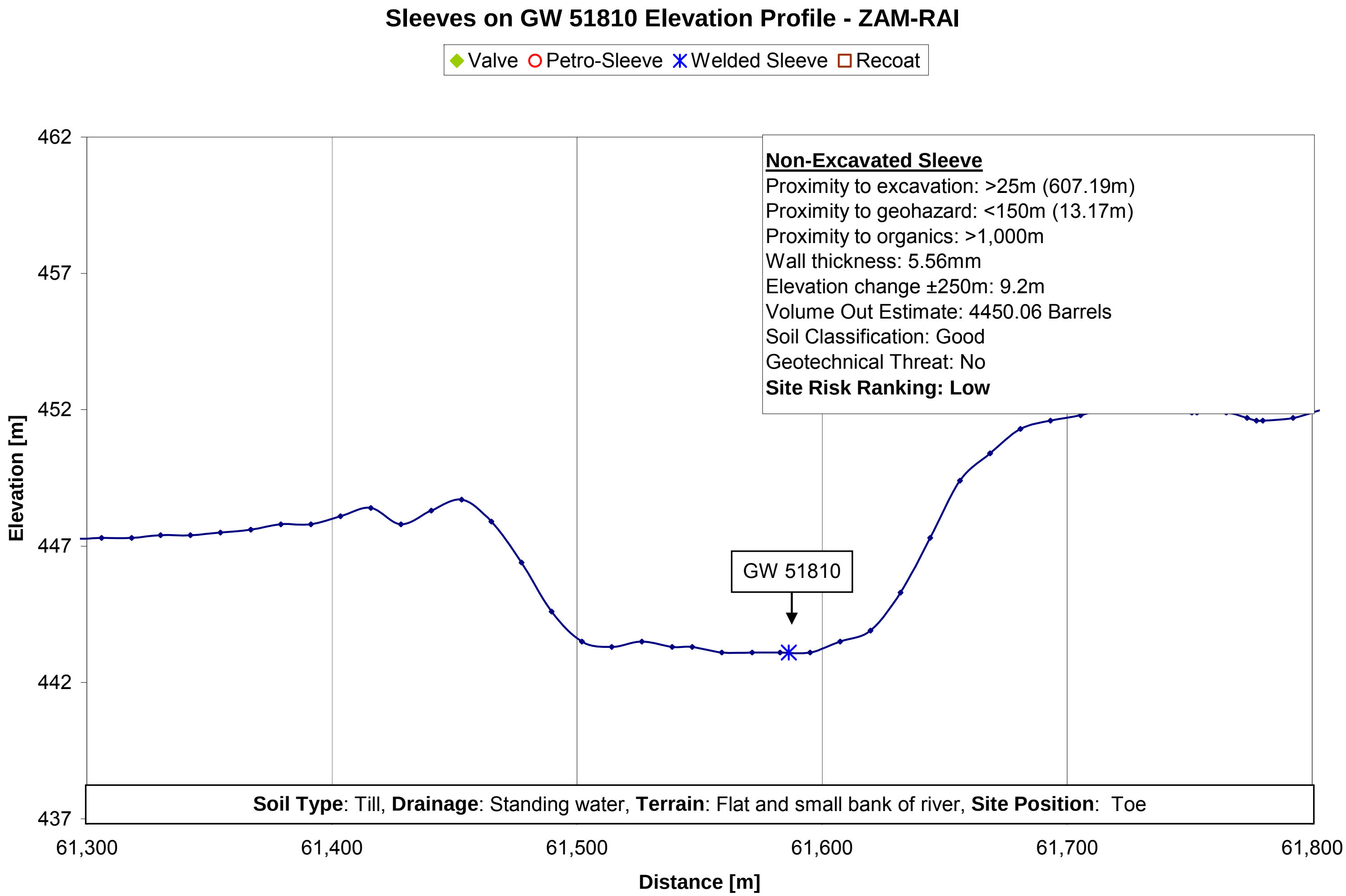


Figure 72 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 51810

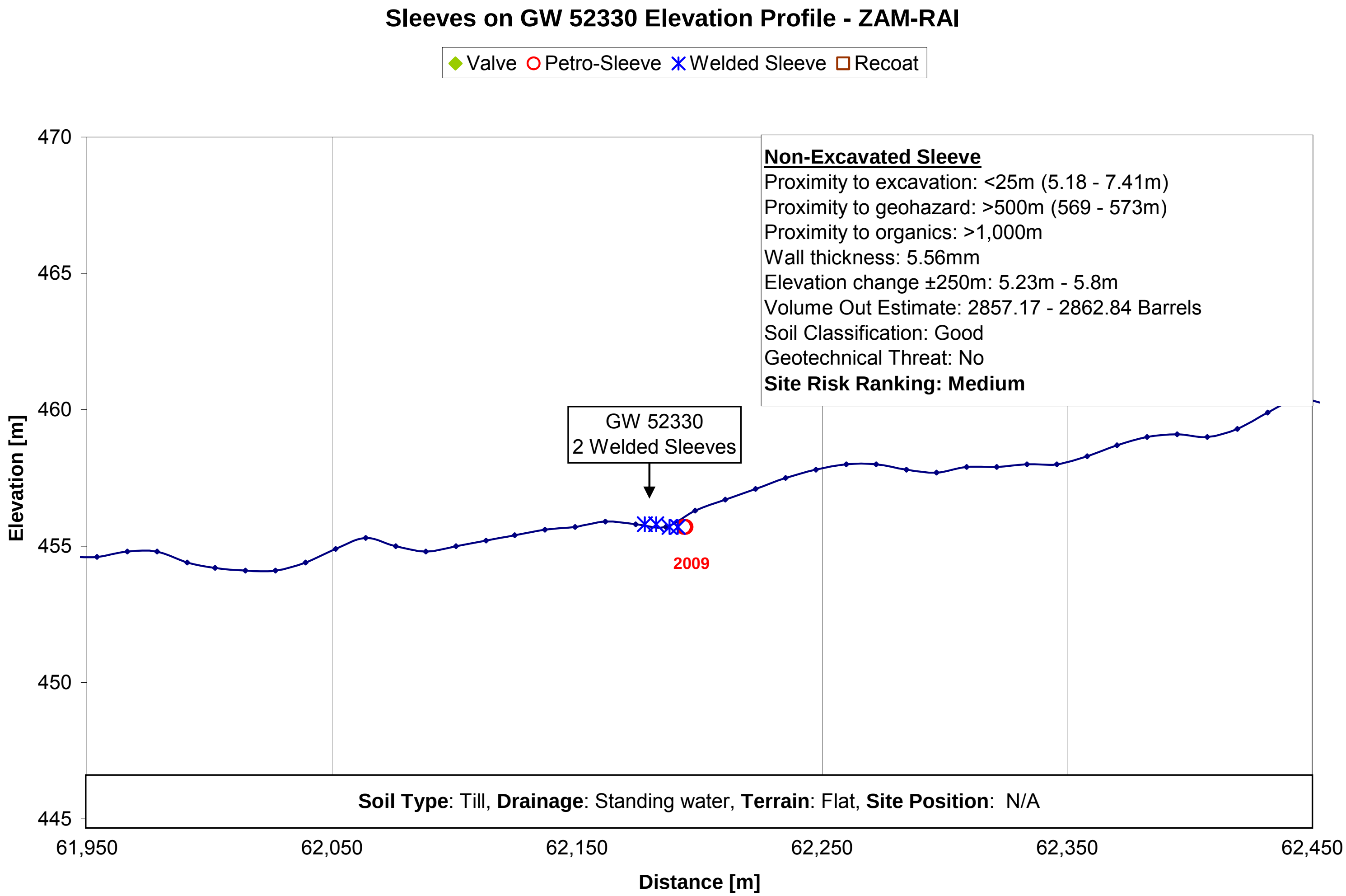


Figure 73 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 52330

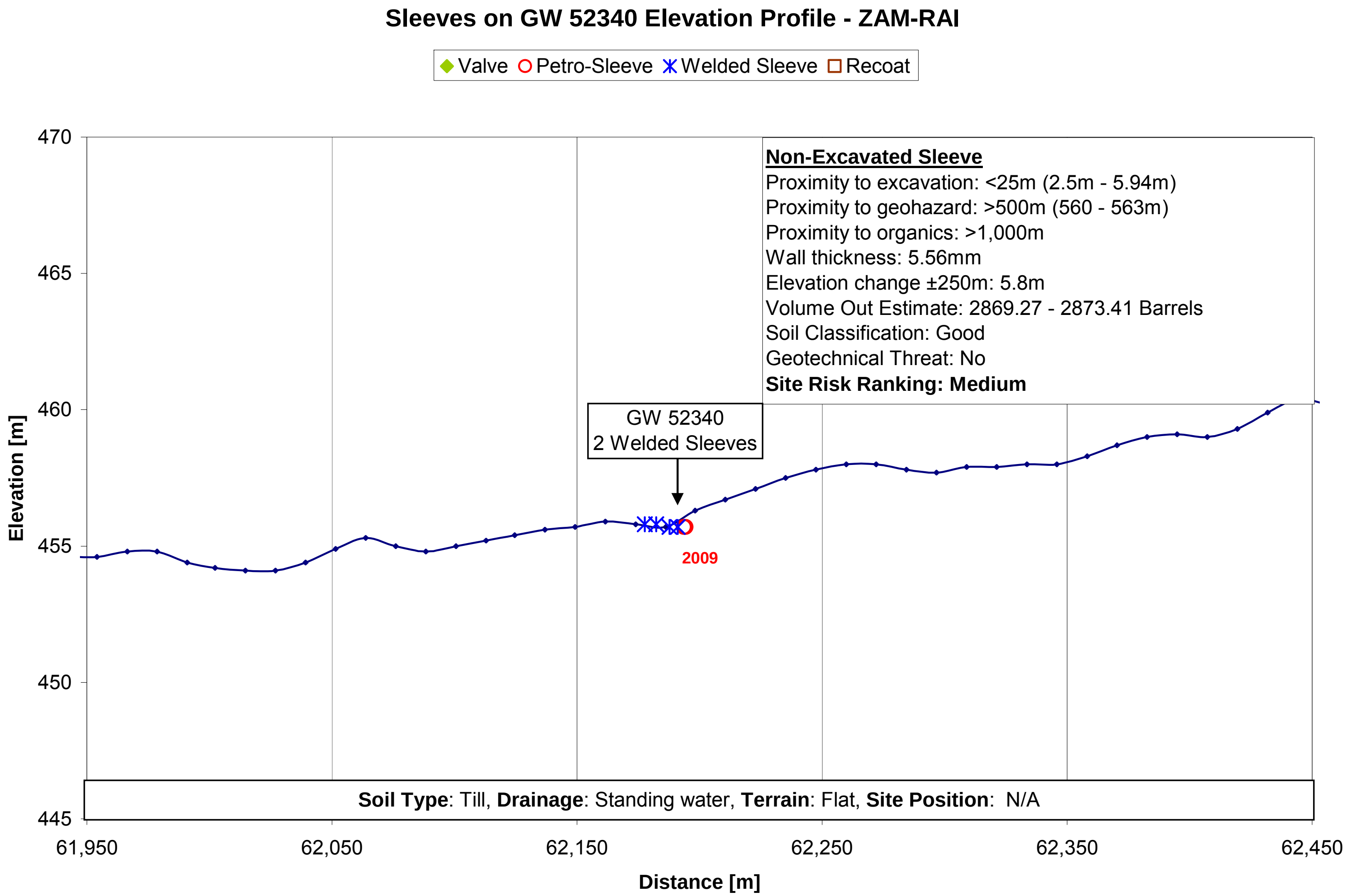


Figure 74 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 52340

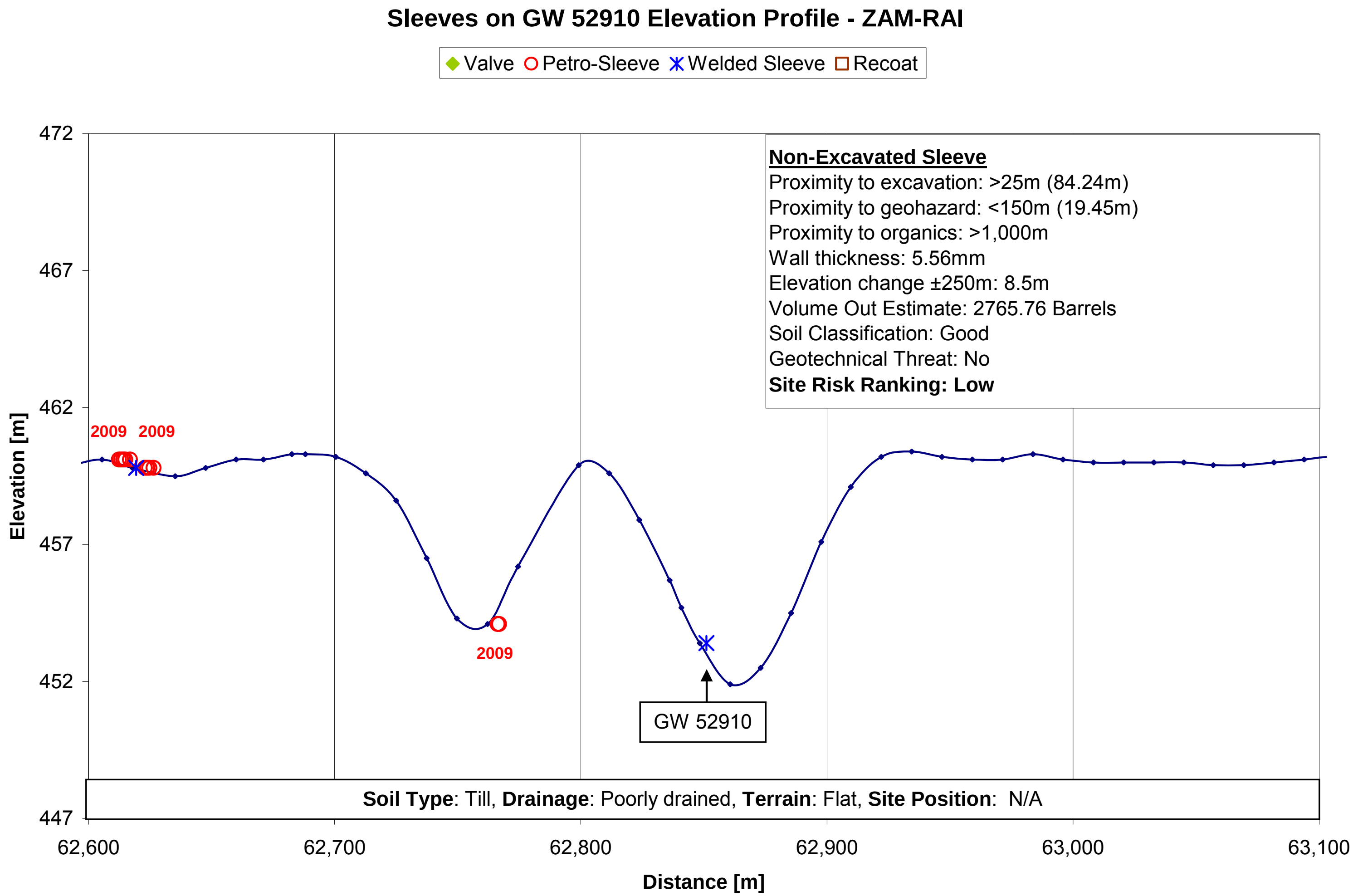


Figure 75 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 52910

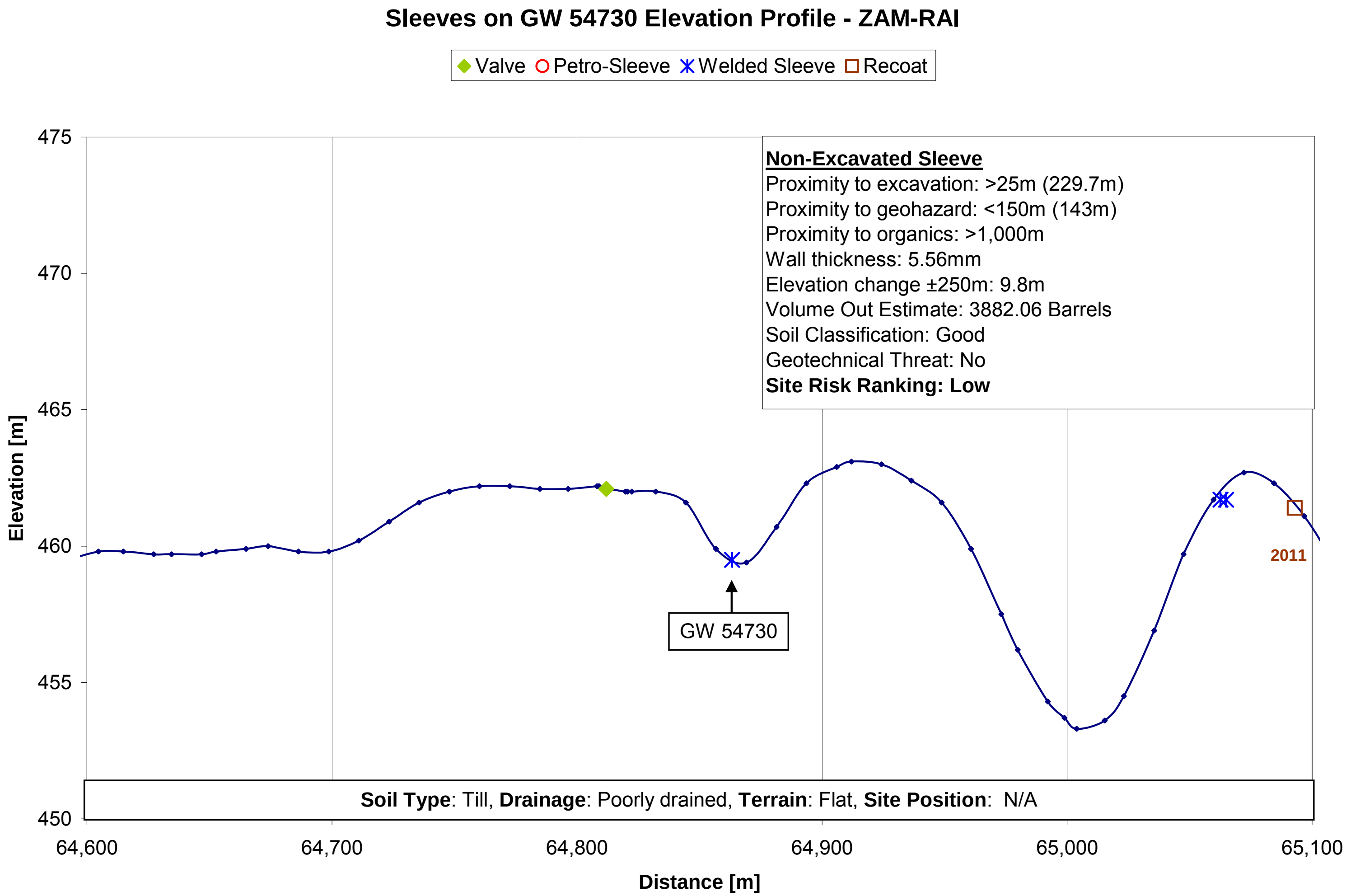


Figure 76 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 54730

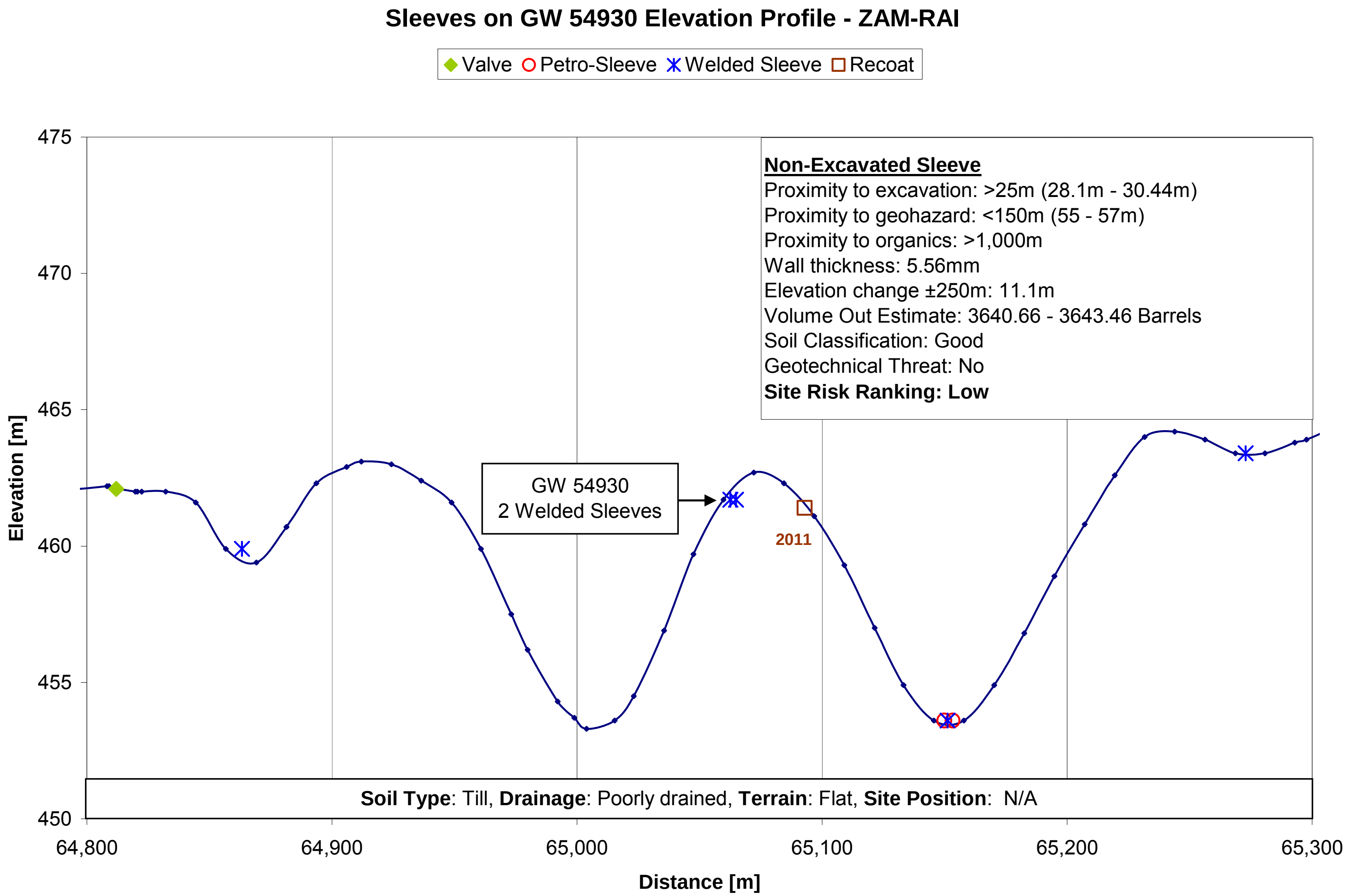


Figure 77 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 54930

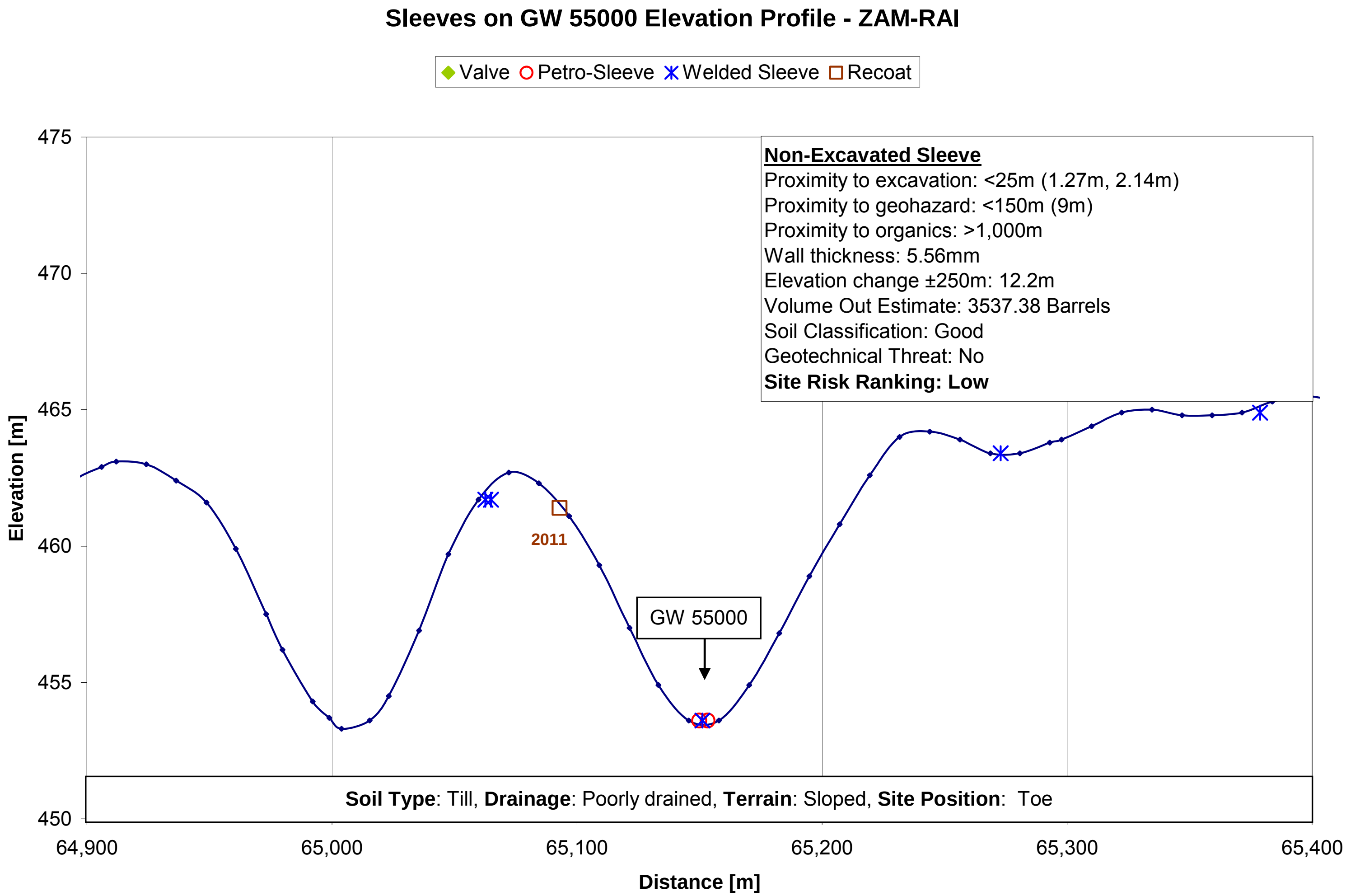


Figure 78 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 55000

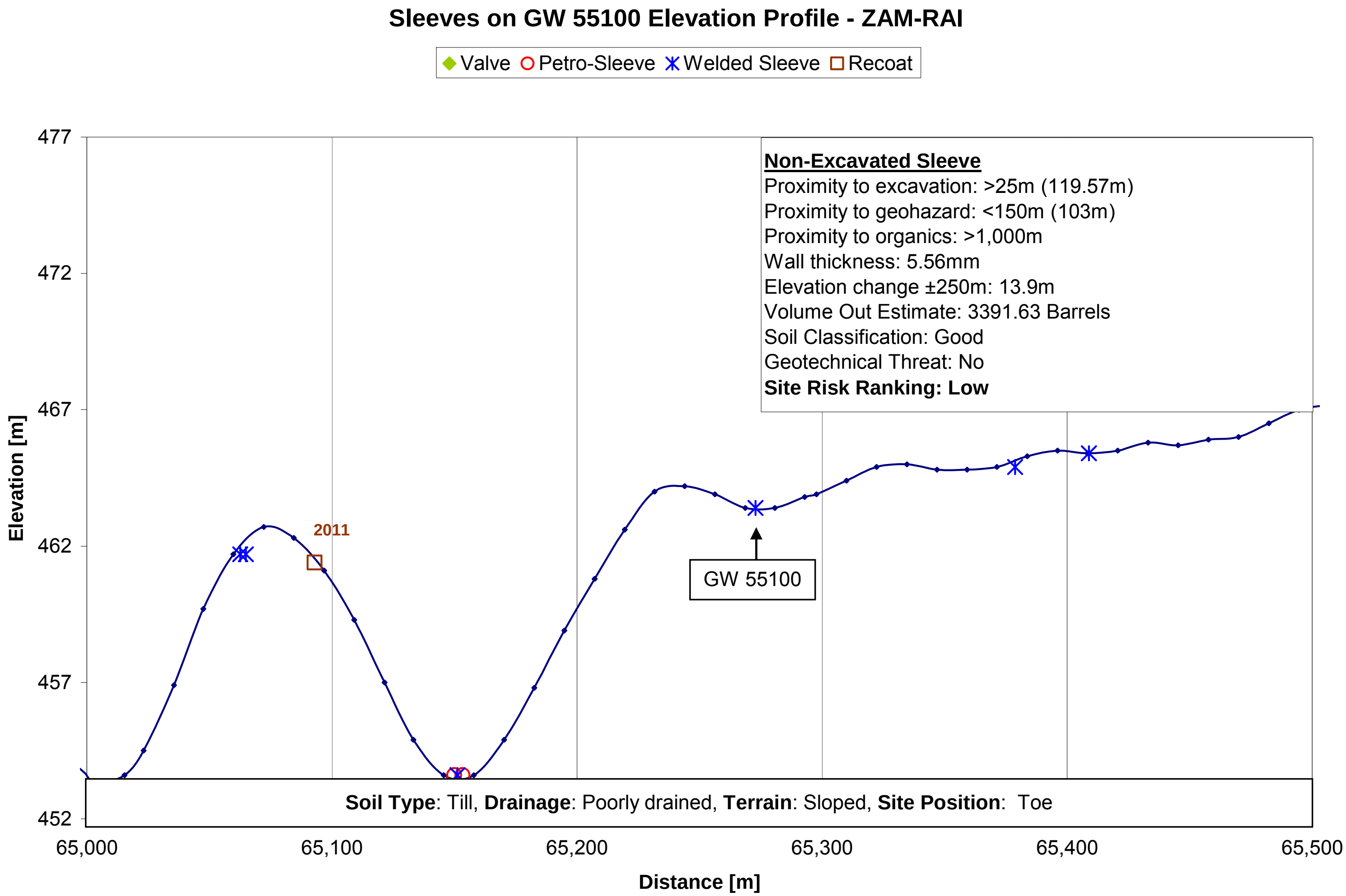


Figure 79 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 55100

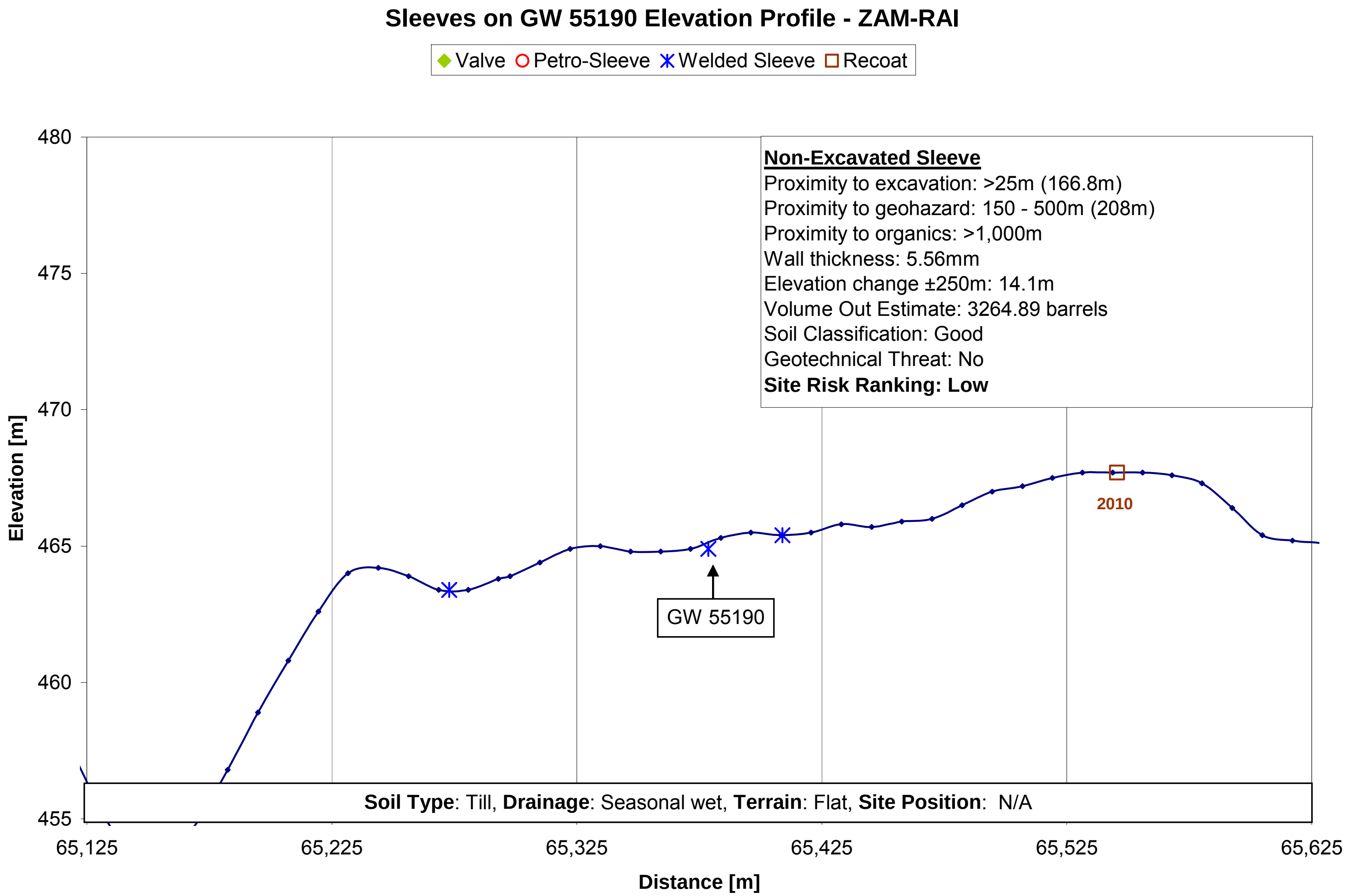


Figure 80 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 55190

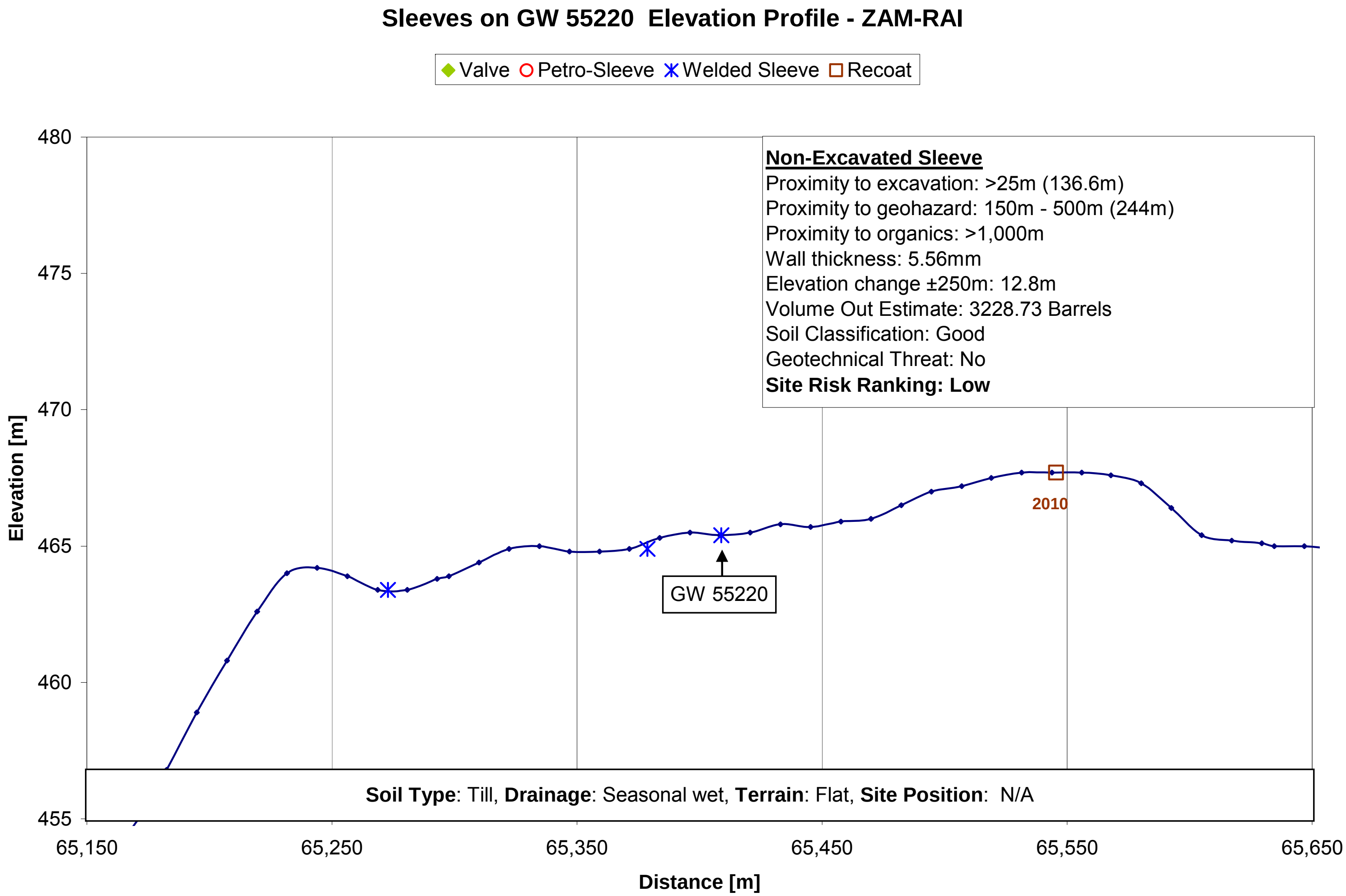


Figure 81 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 55220

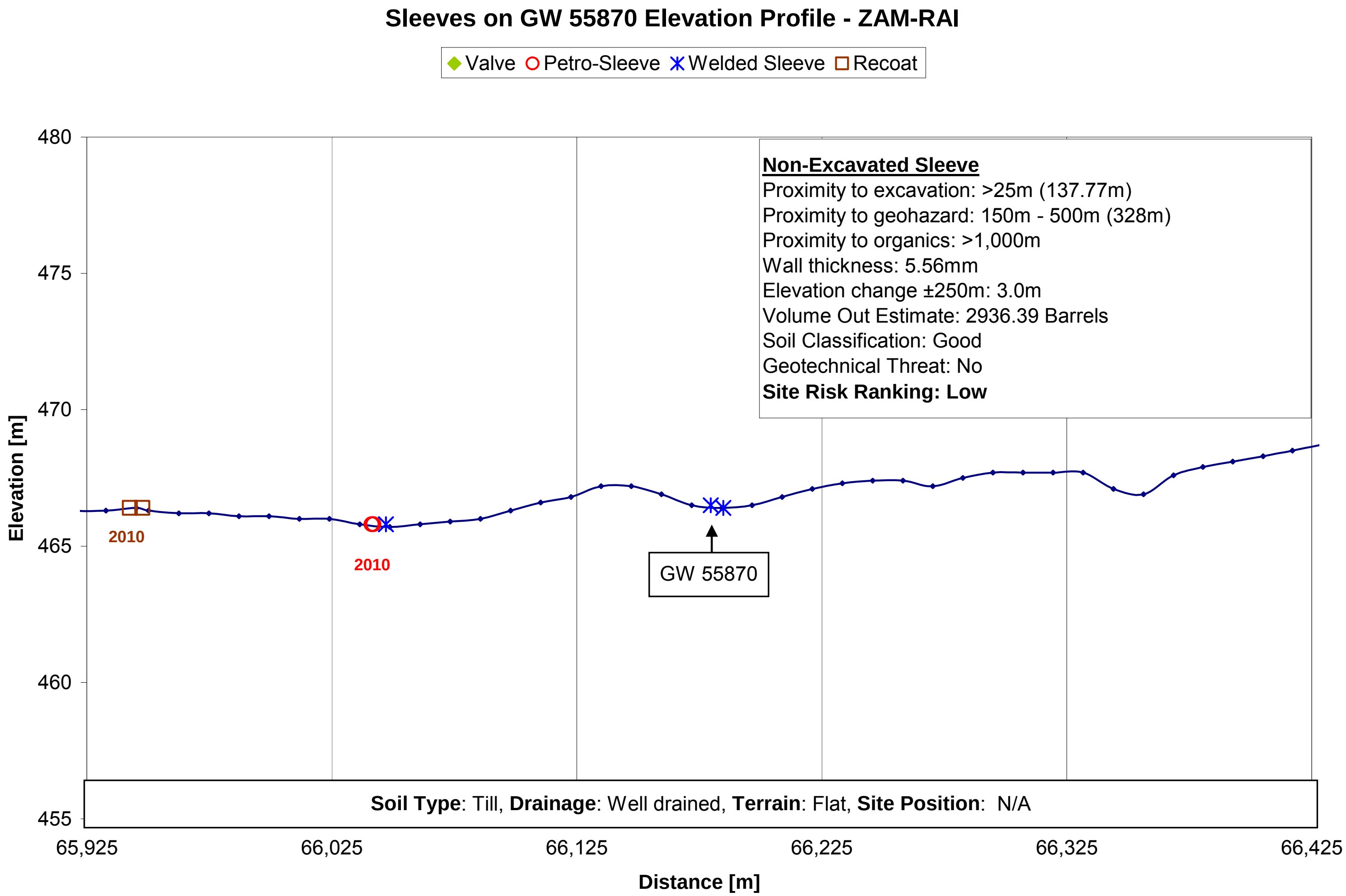


Figure 82 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 55870

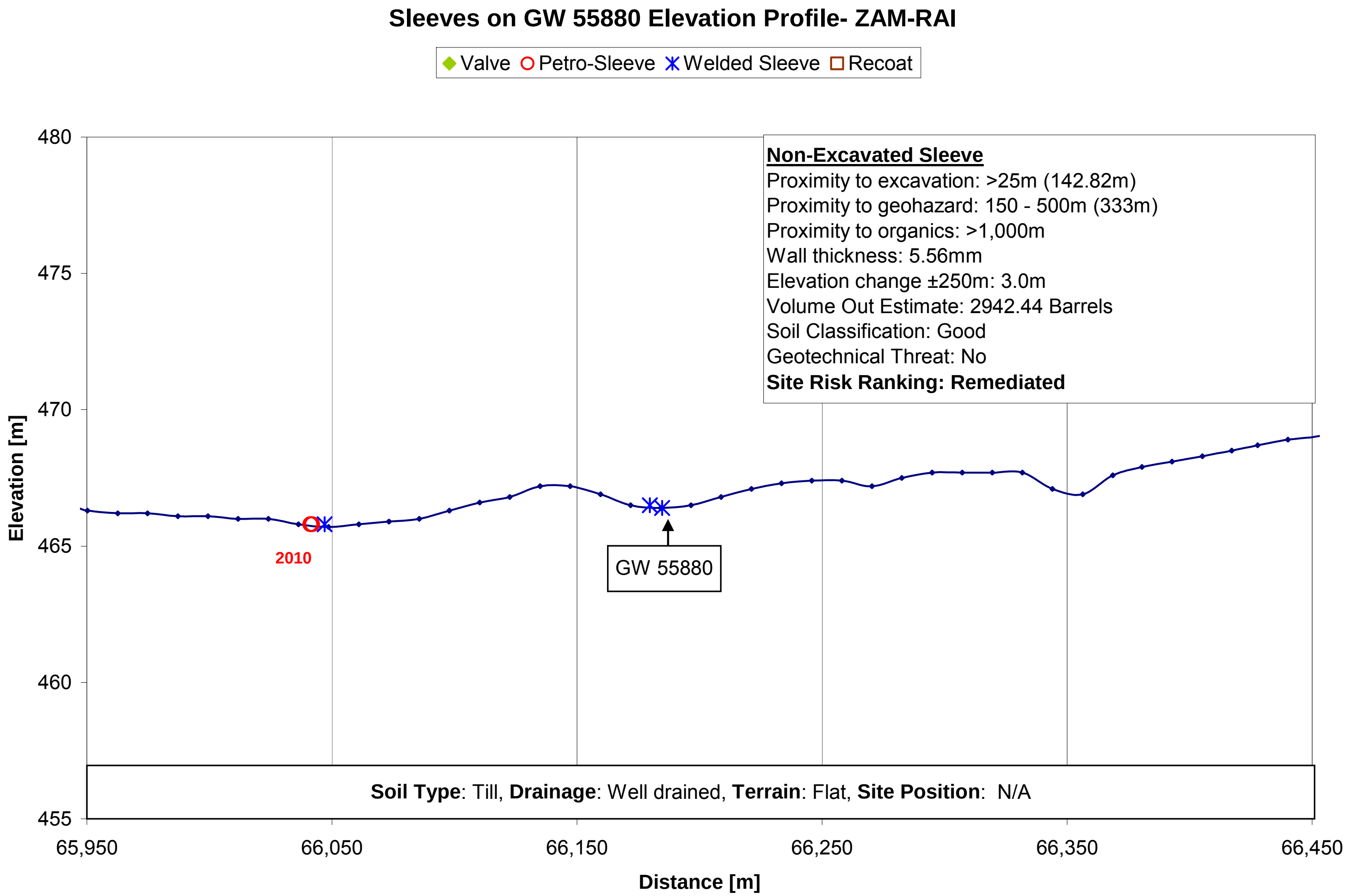


Figure 83 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 55880

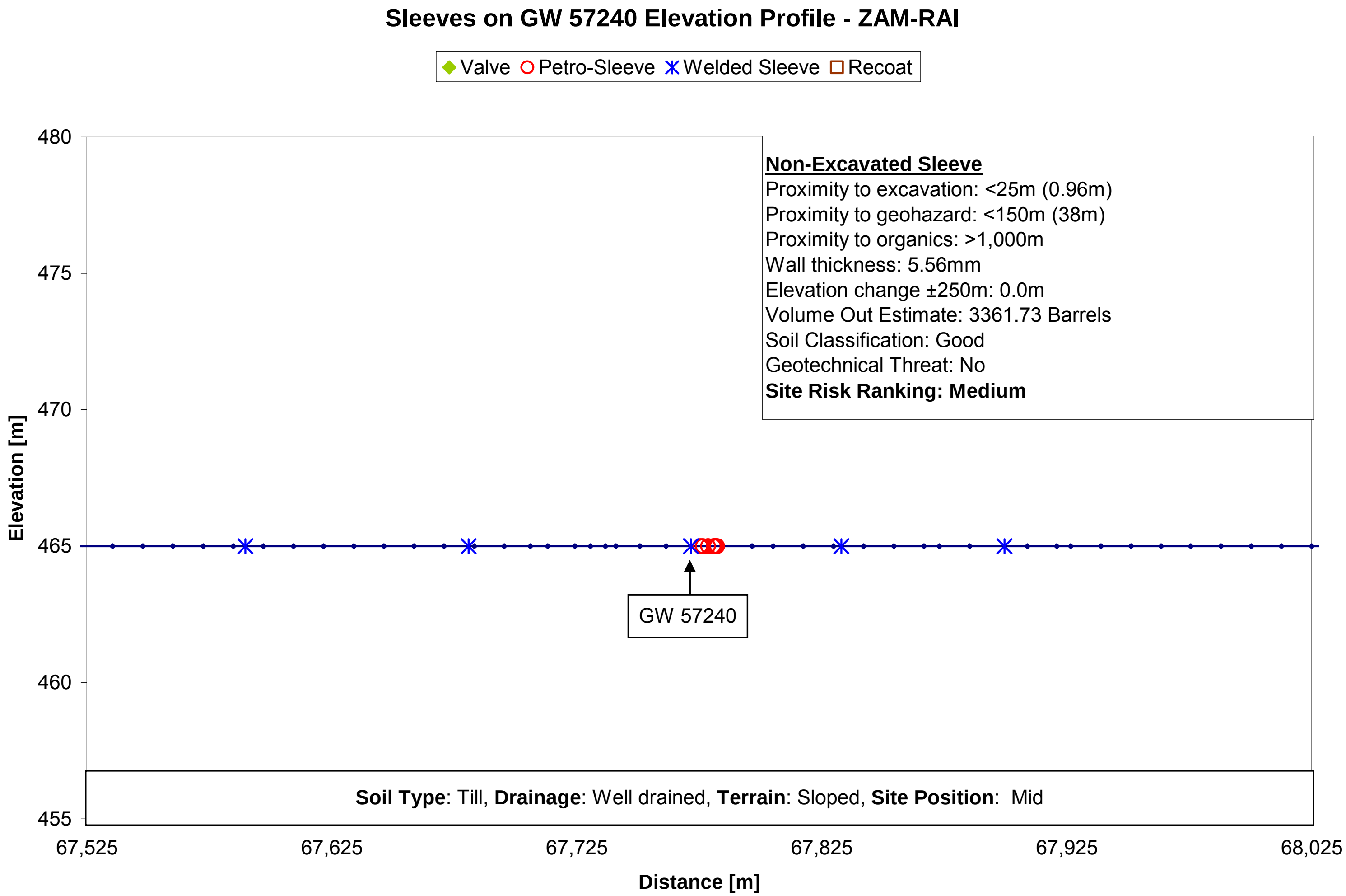


Figure 84 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 57240

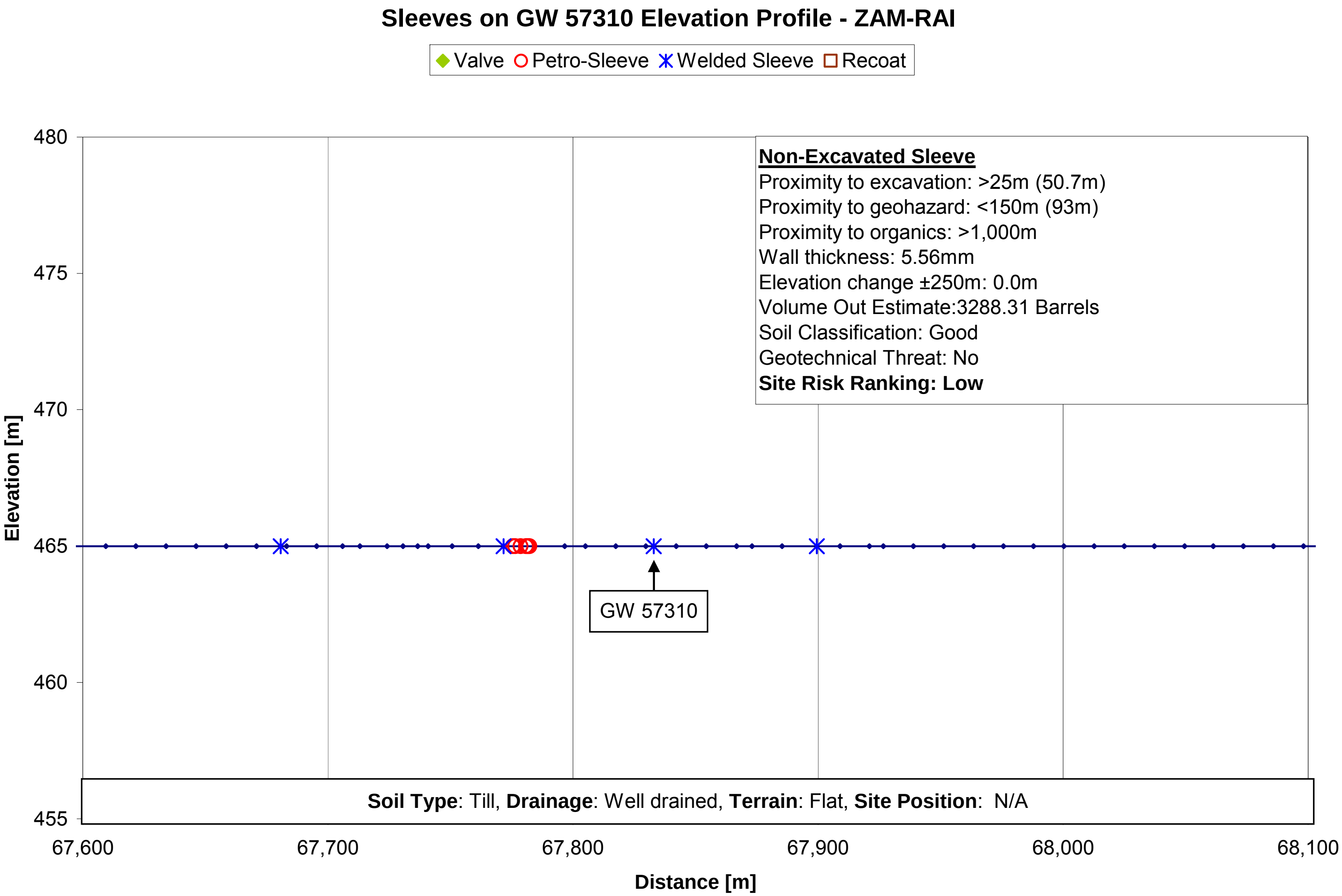


Figure 85 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 57310

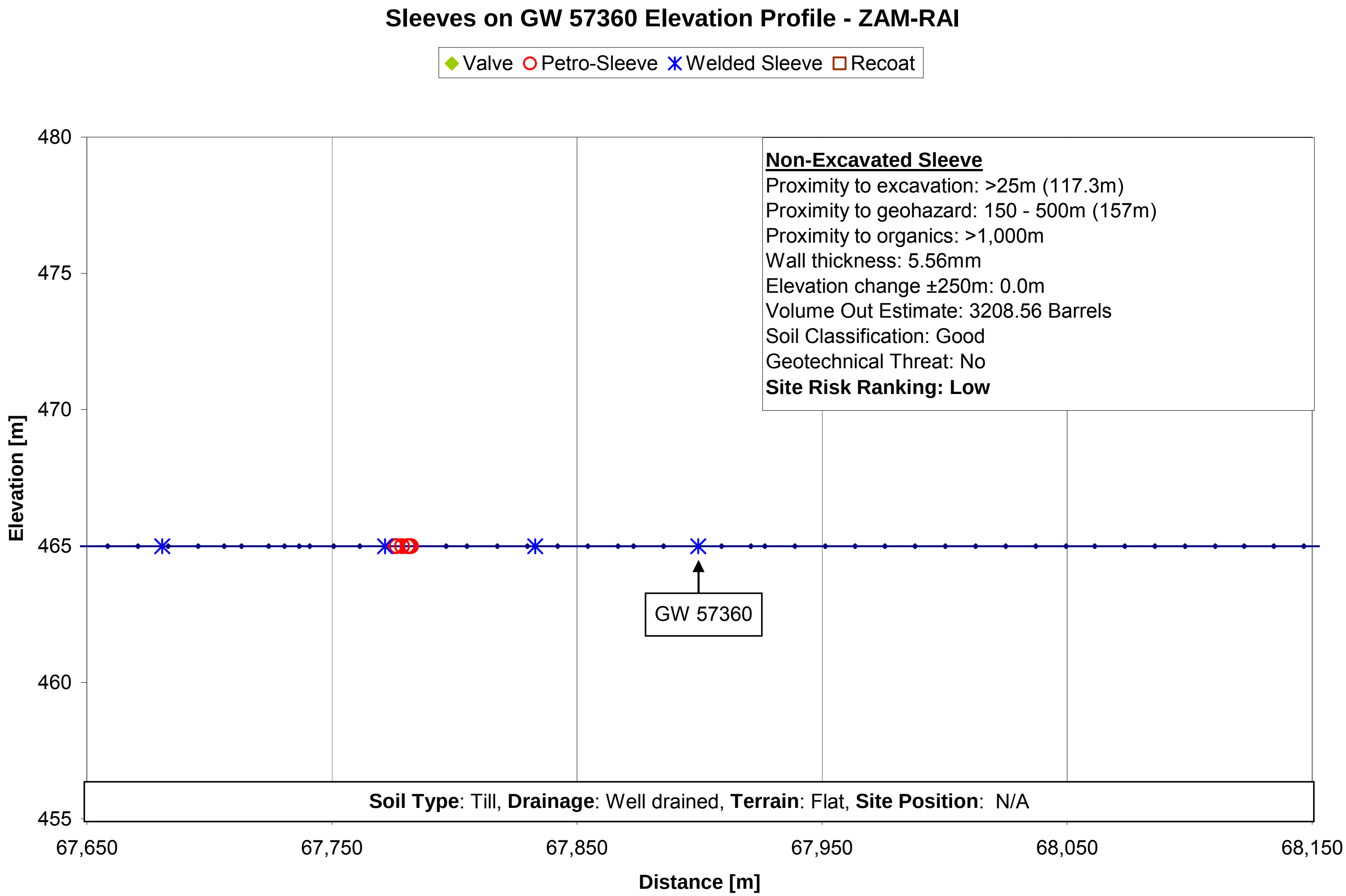


Figure 86 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 57360

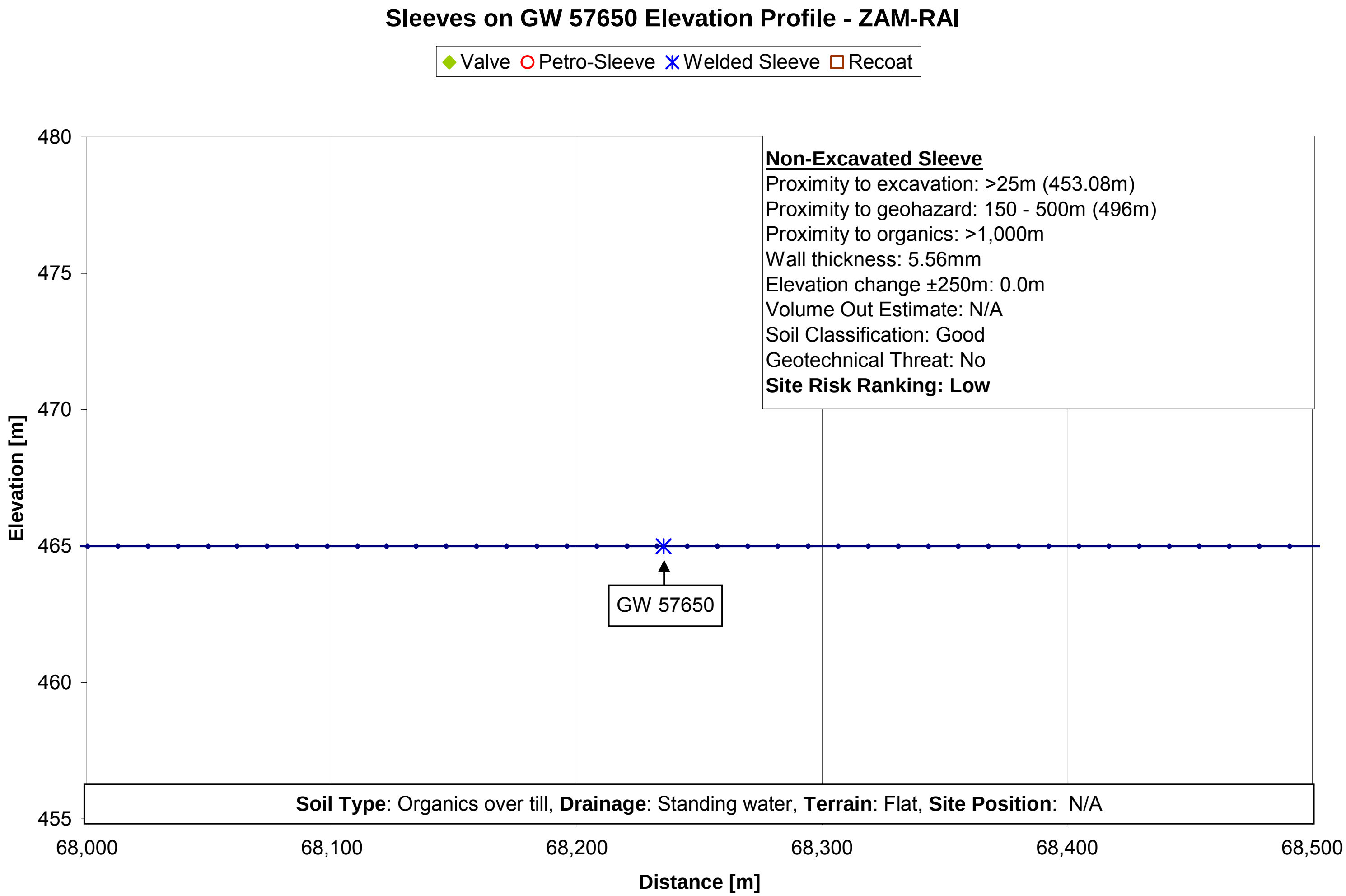


Figure 87 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 57650

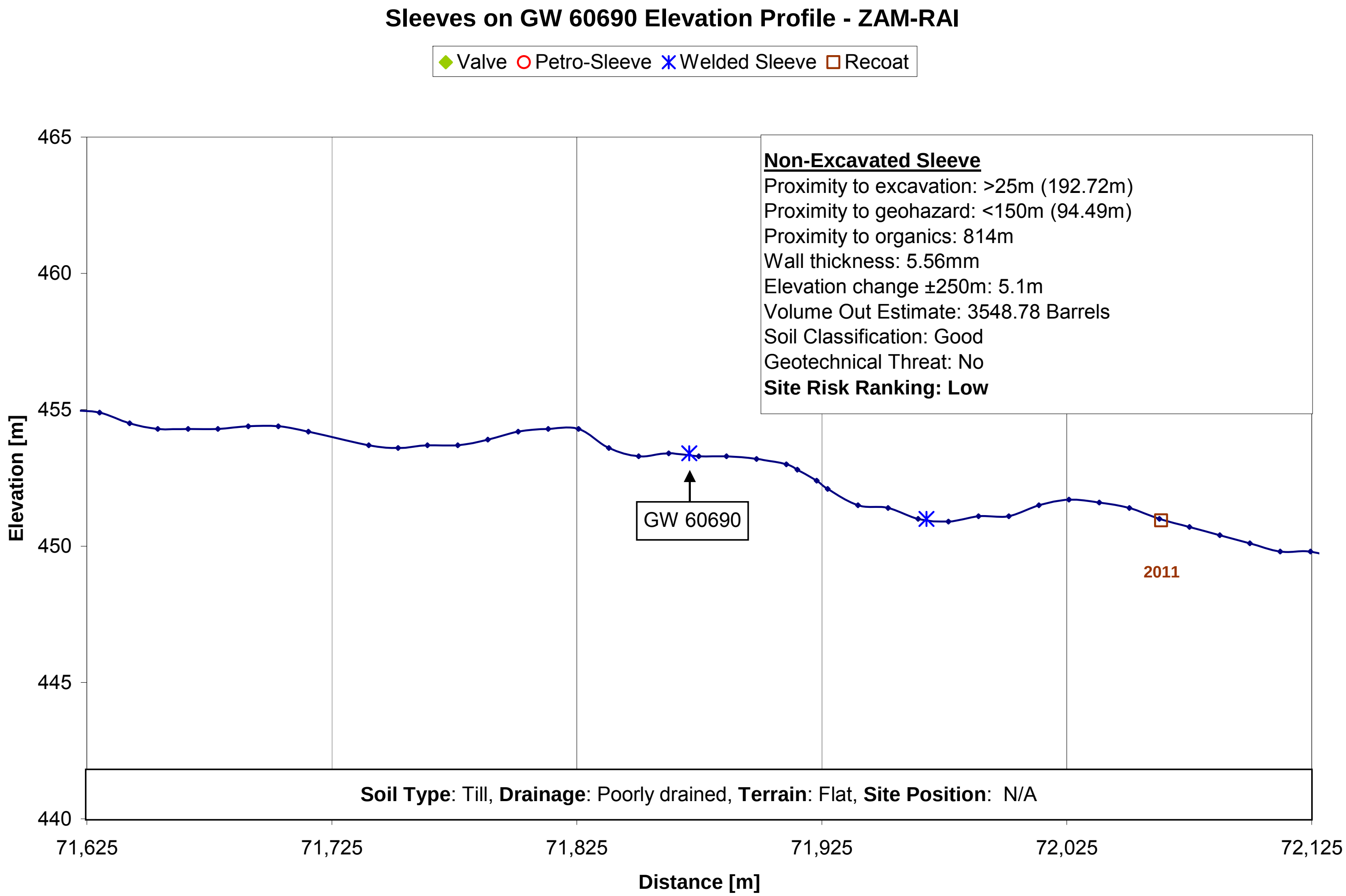


Figure 88 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 60690

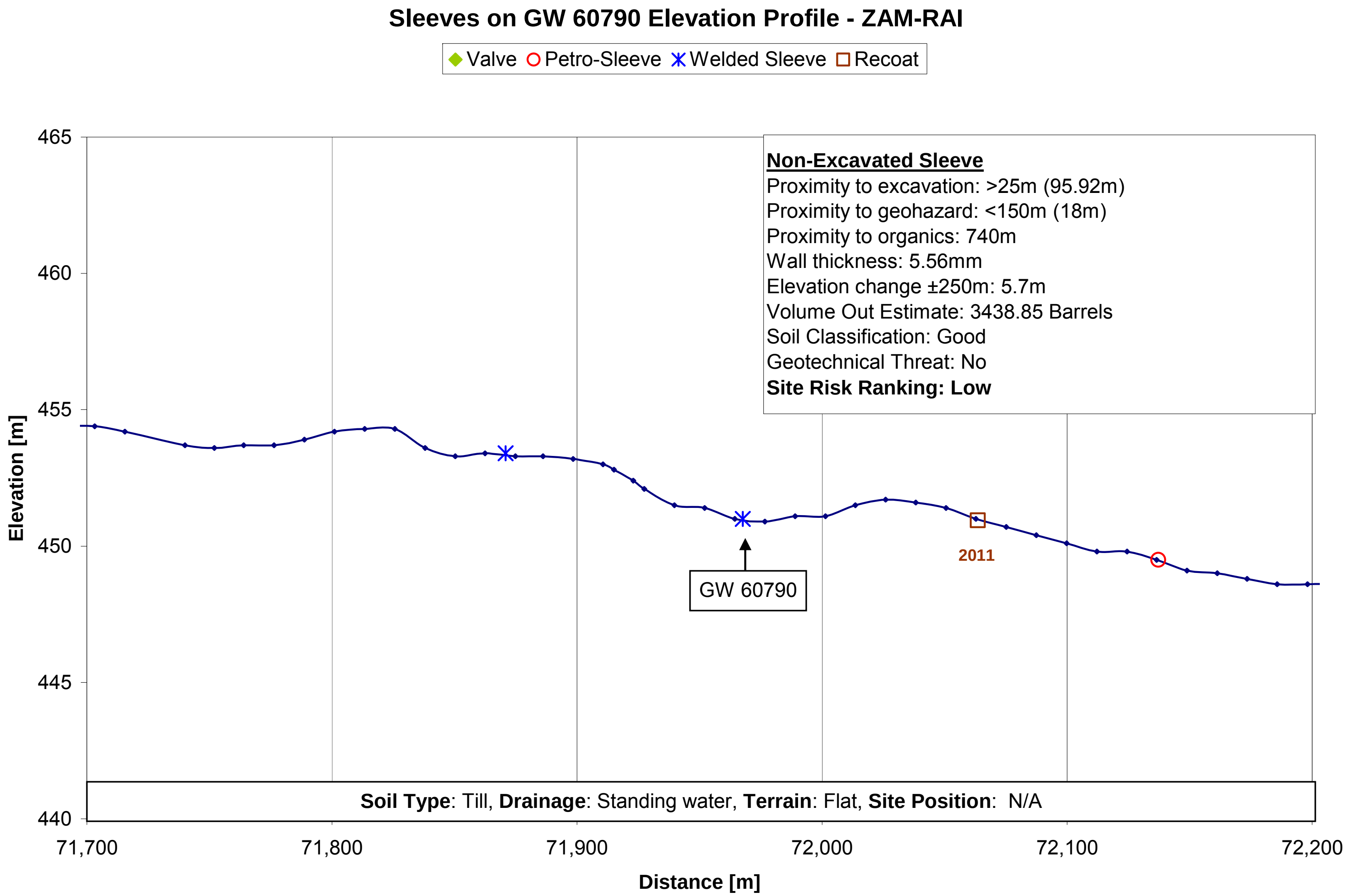


Figure 89 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 60790

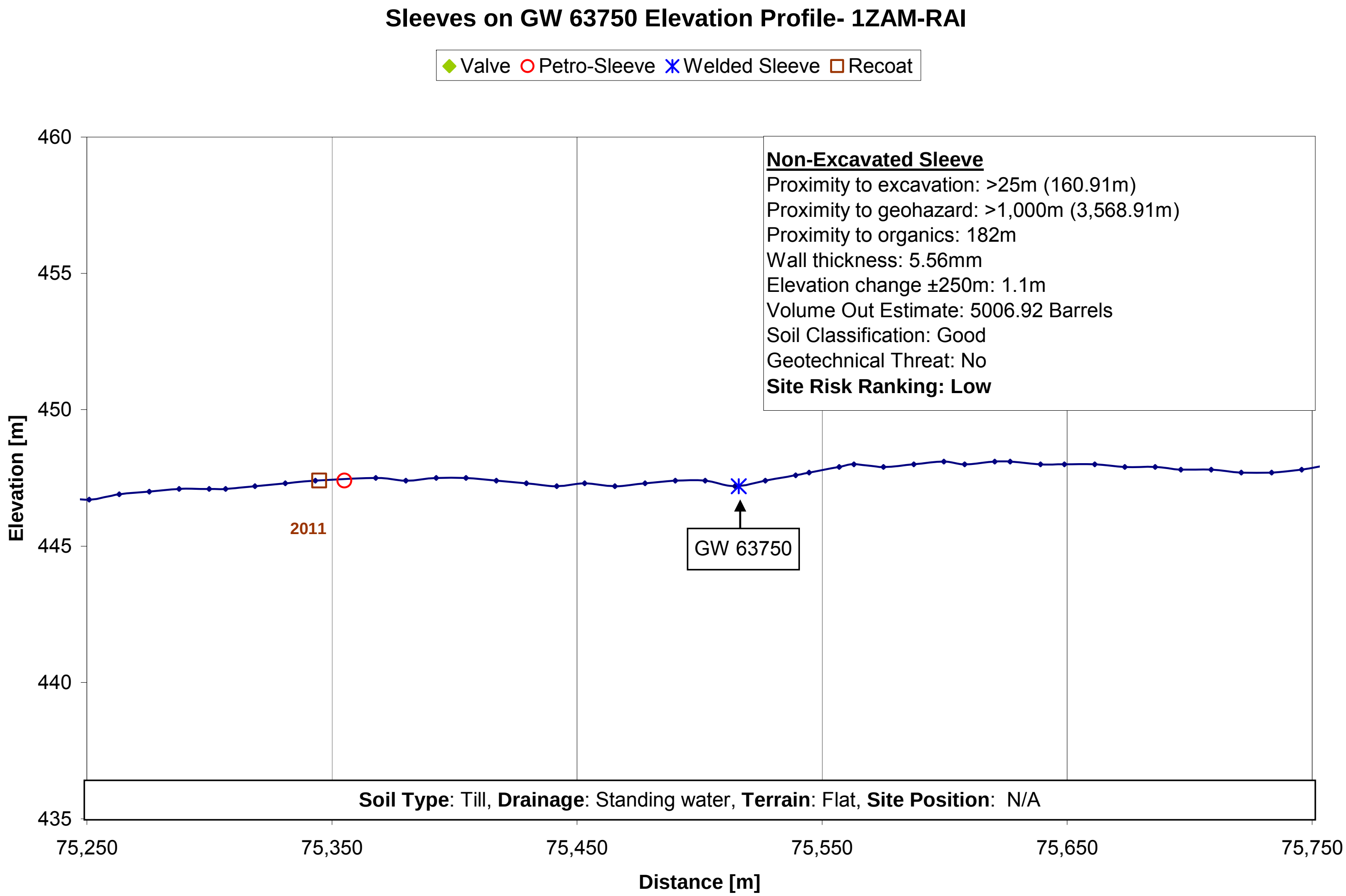


Figure 90 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 63750

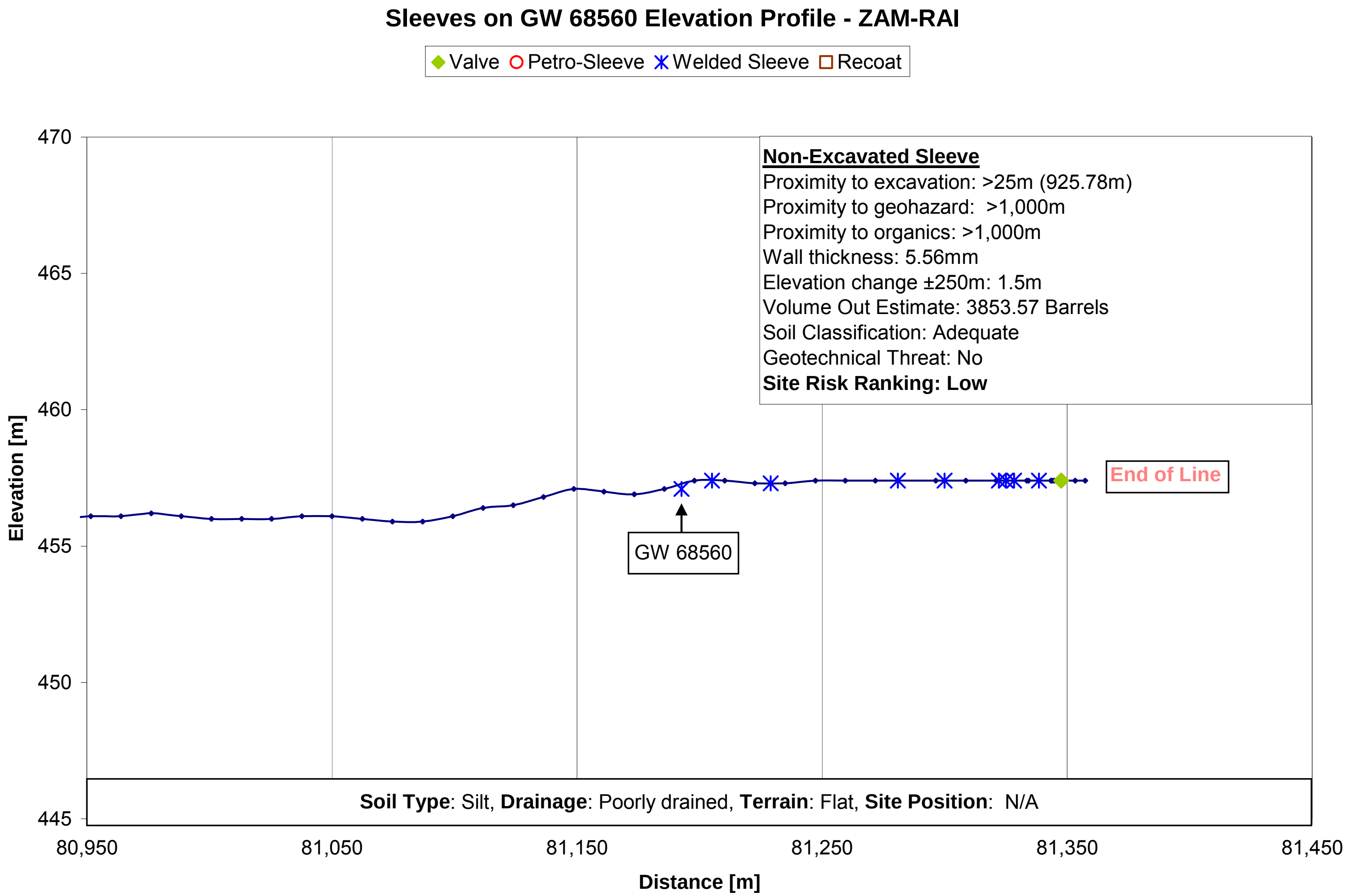


Figure 91 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 68560

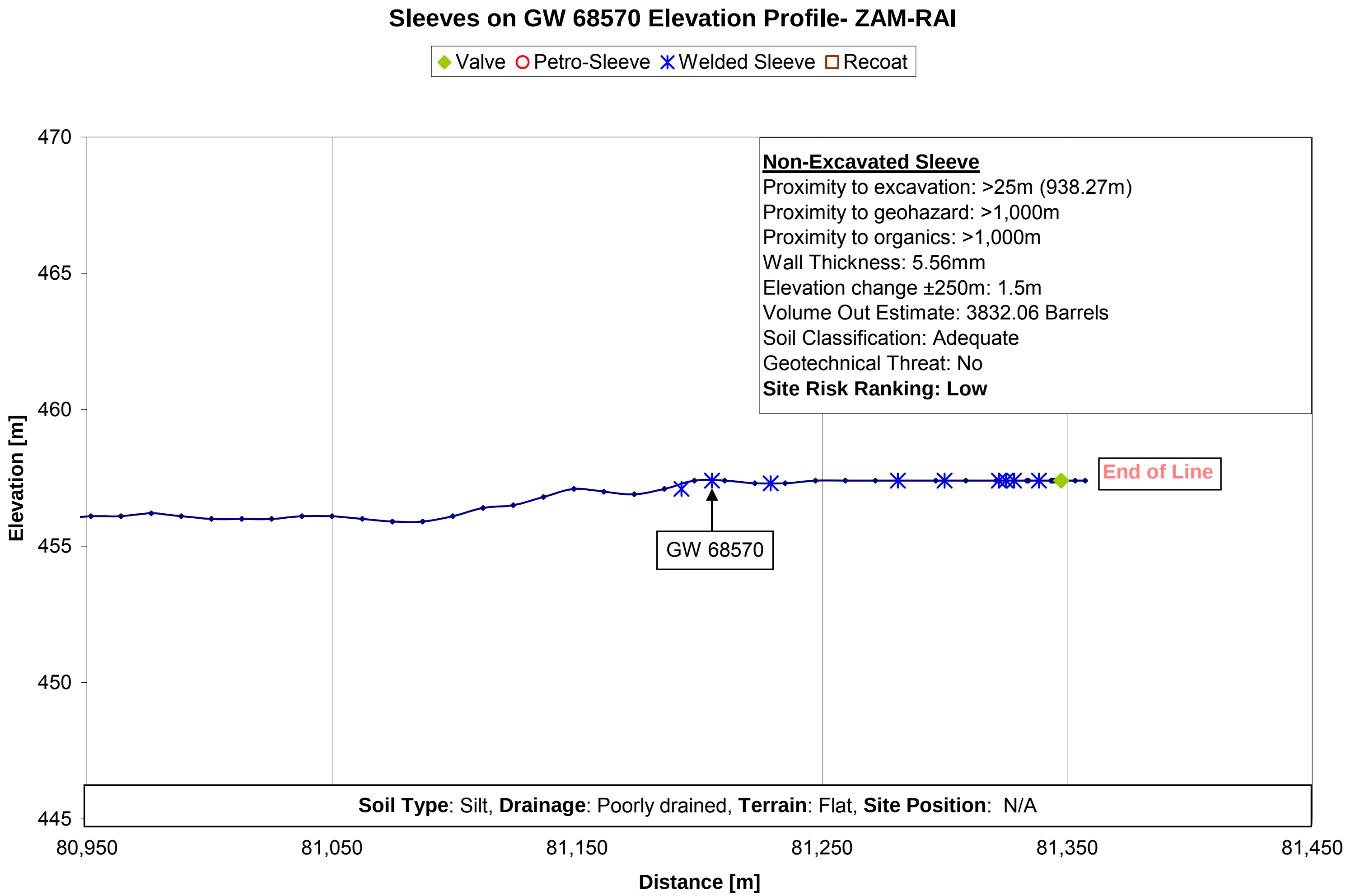


Figure 92 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 68570

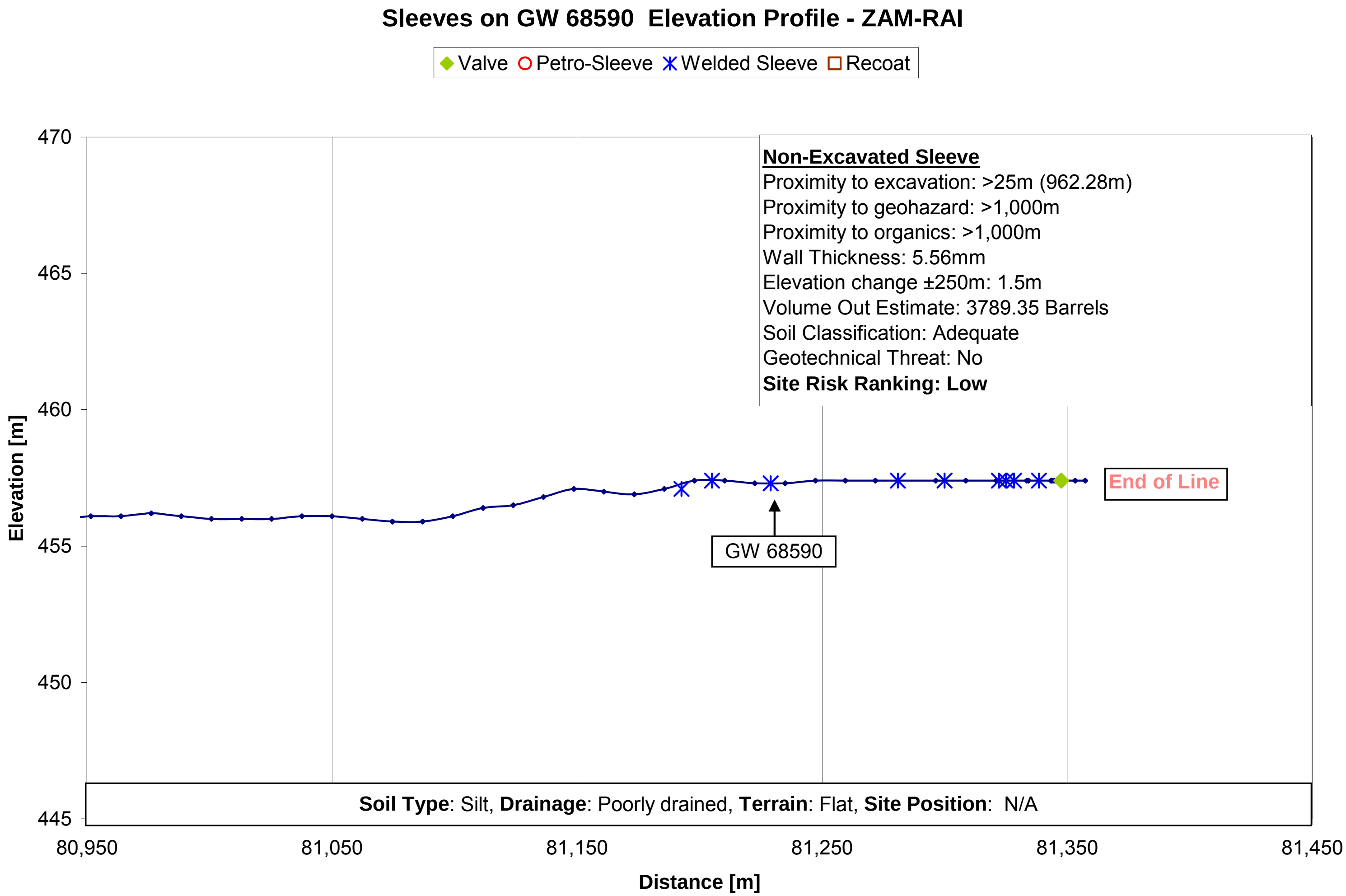


Figure 93 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 68590

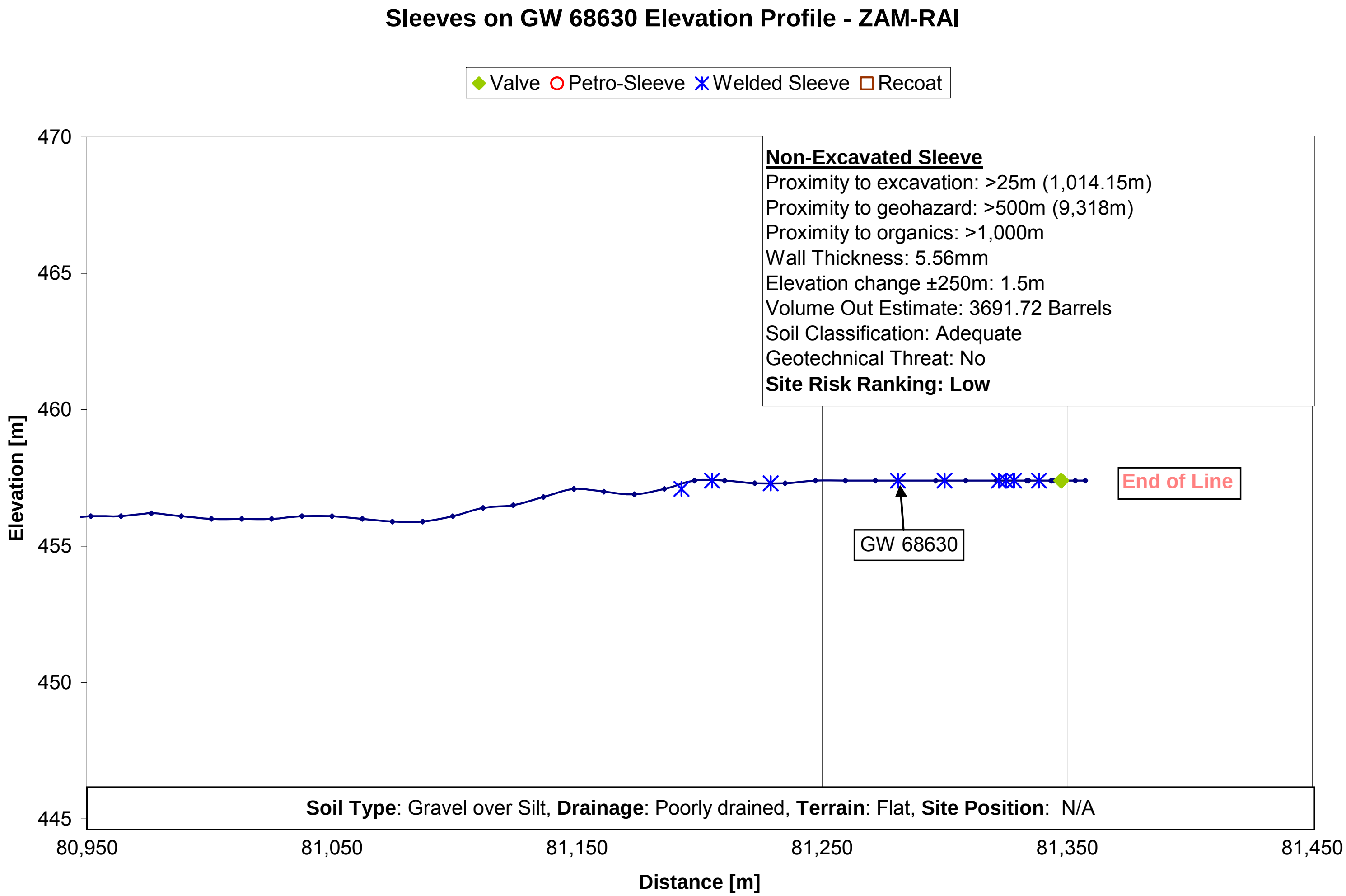


Figure 94 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 68630

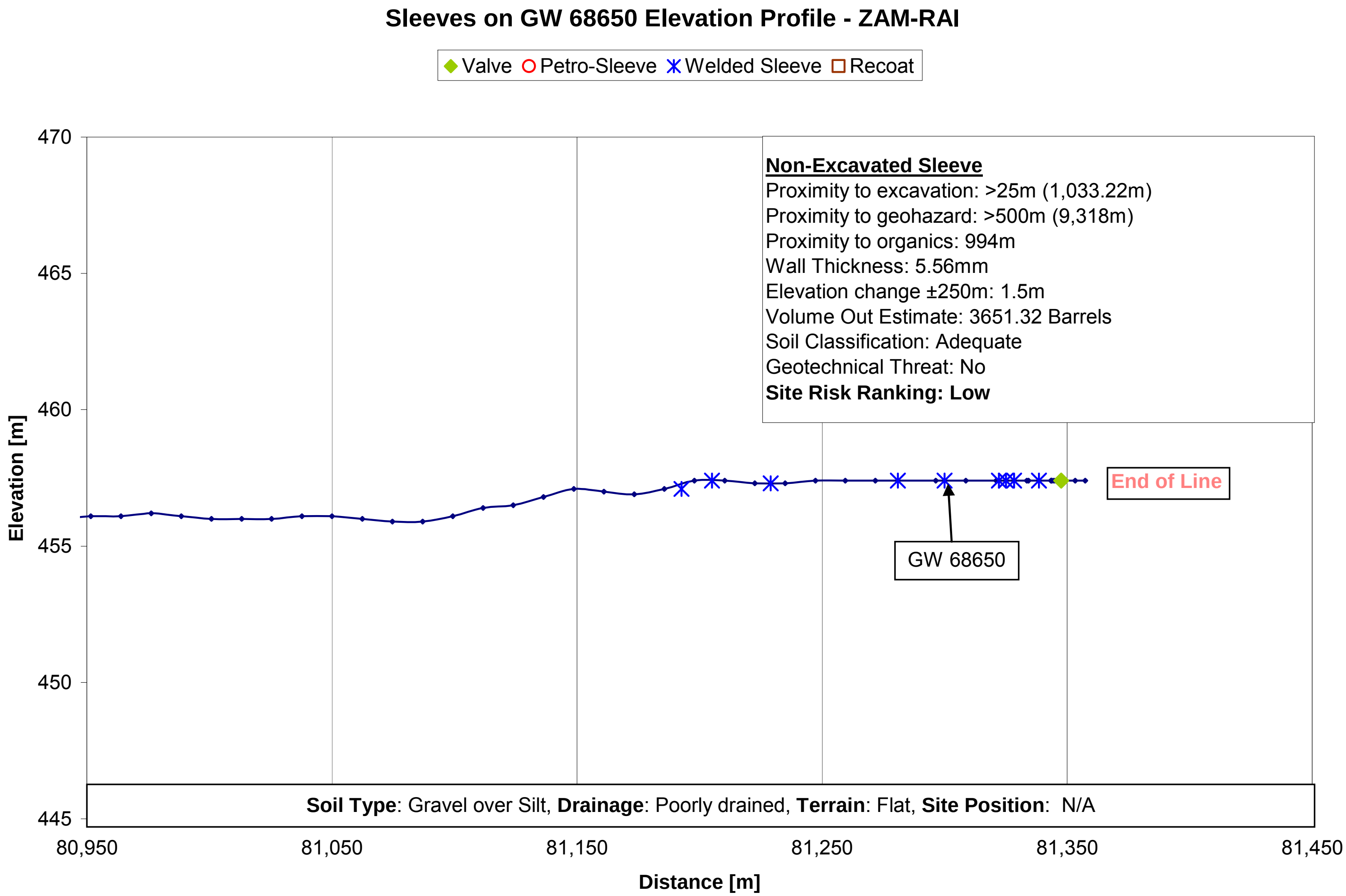


Figure 95 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 68650

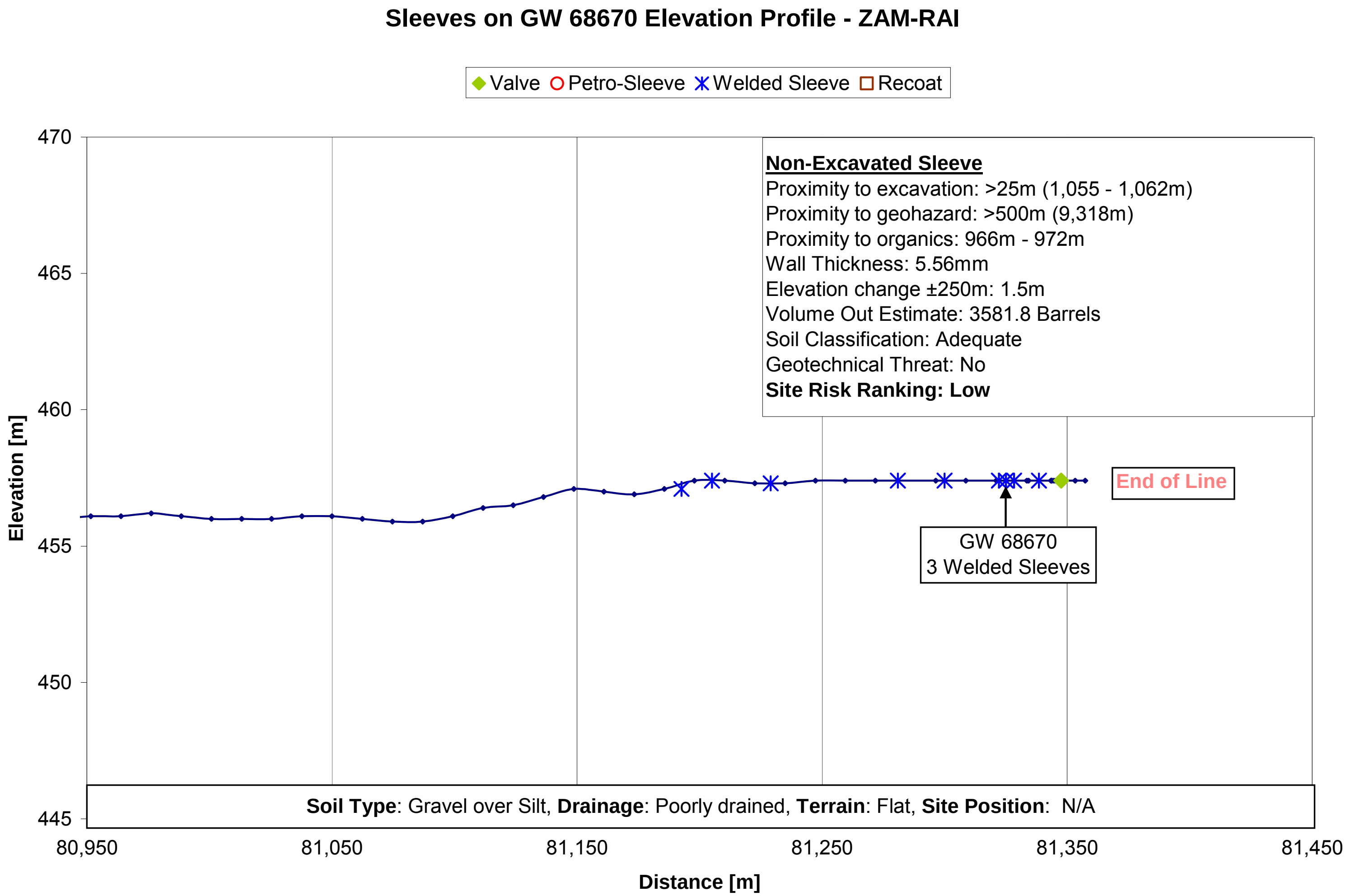


Figure 96 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 68670

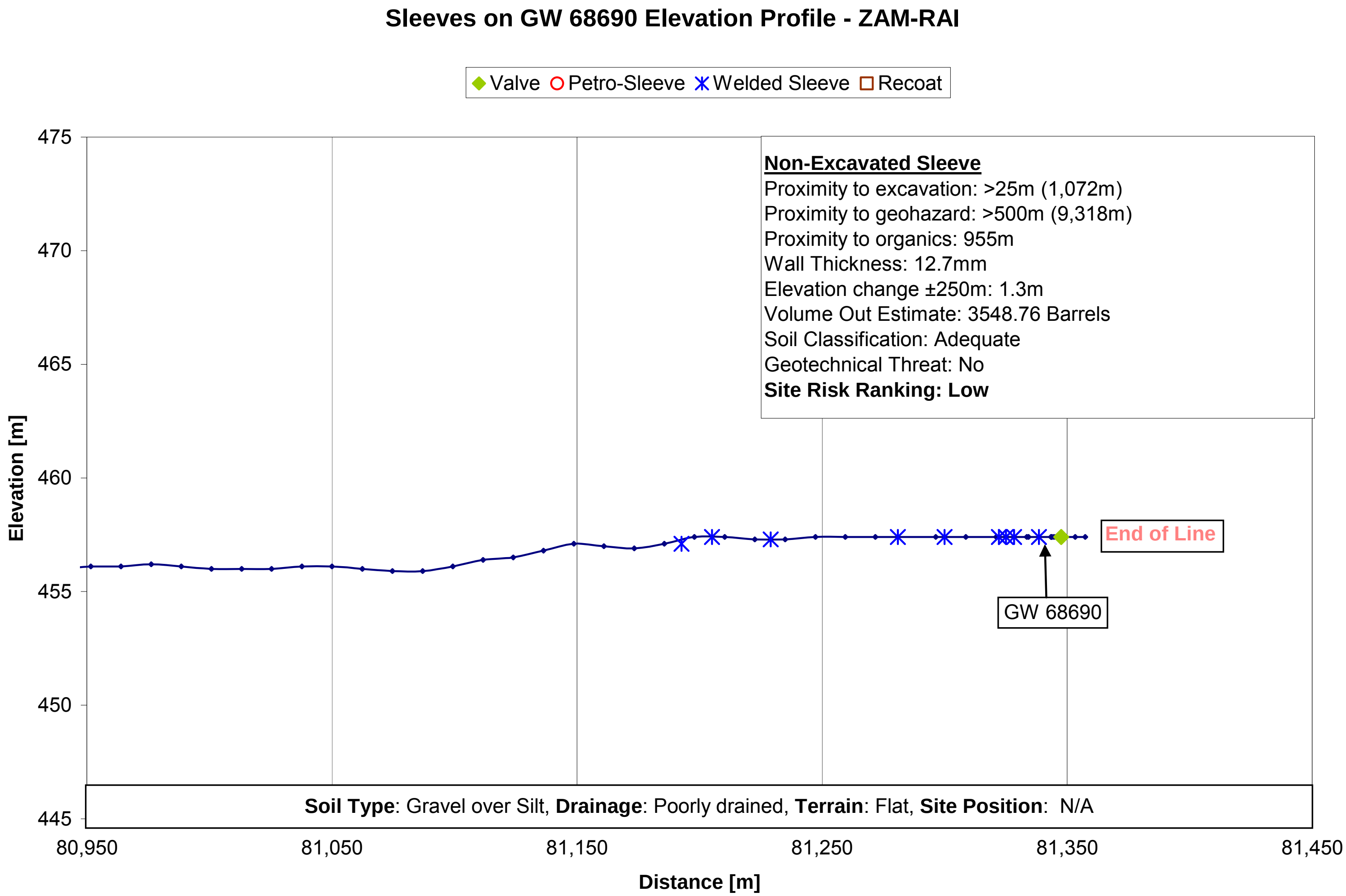


Figure 97 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 68690

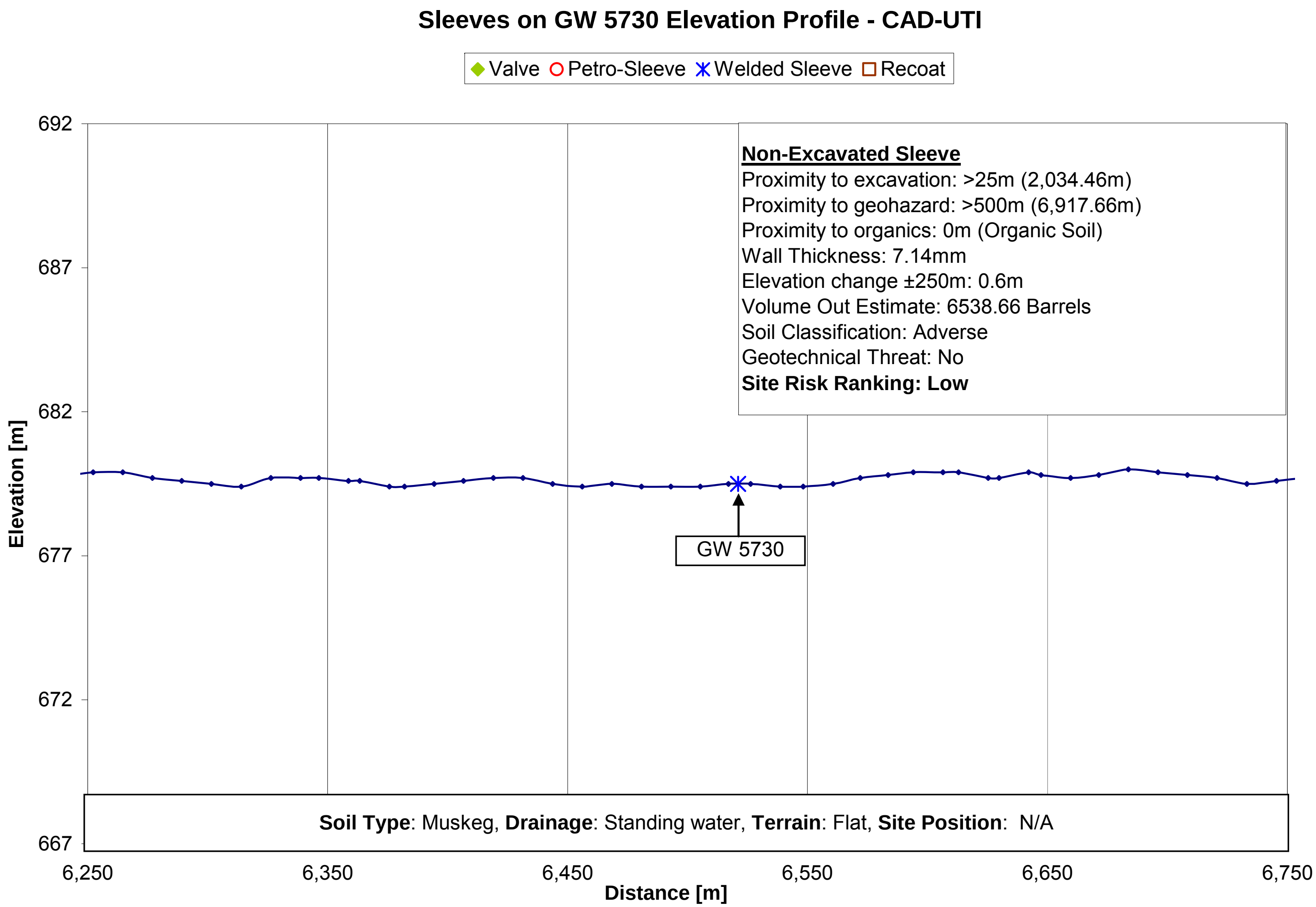


Figure 98 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 5730

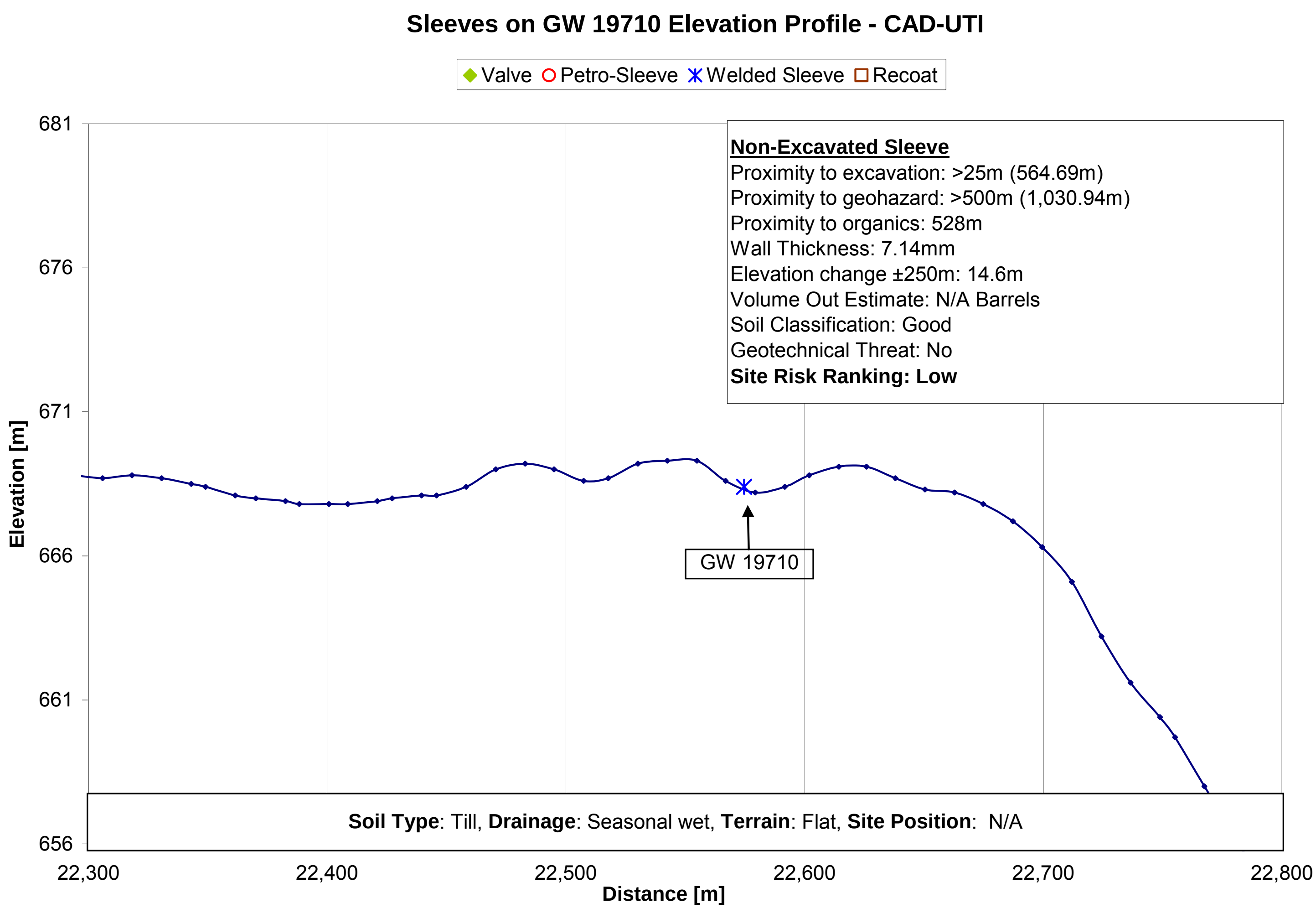


Figure 99 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 19710

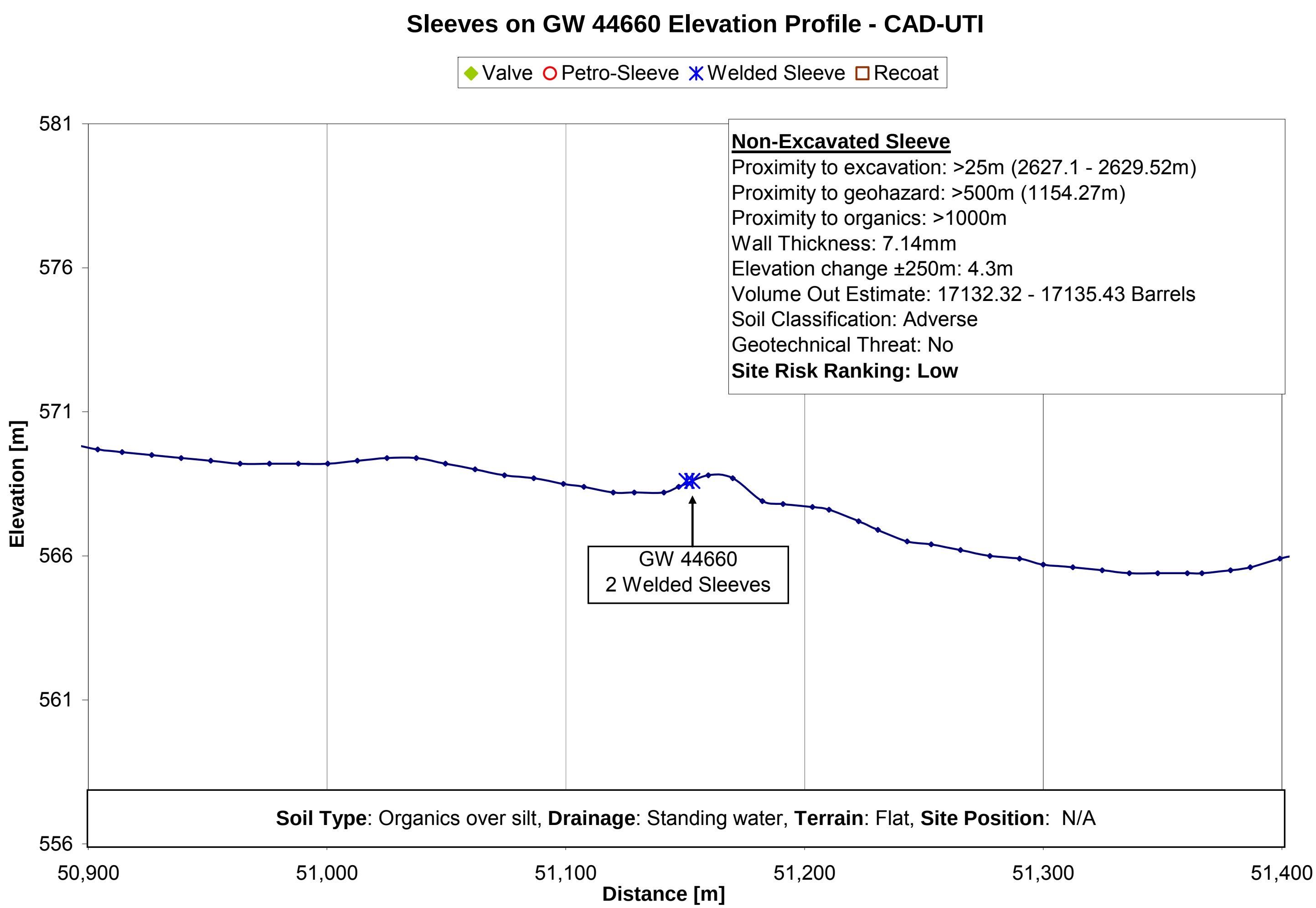


Figure 100 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 44660

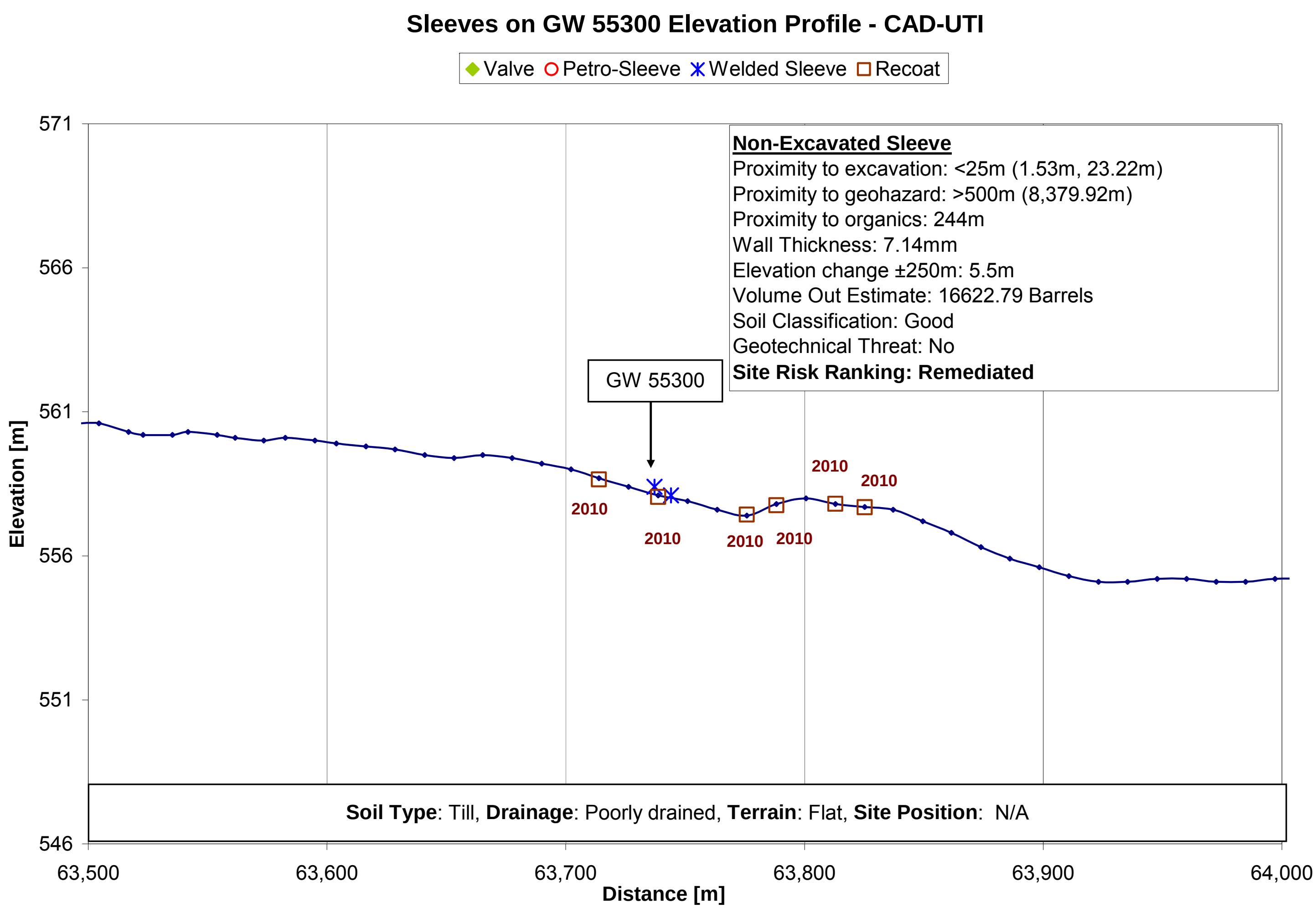


Figure 101 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 55300

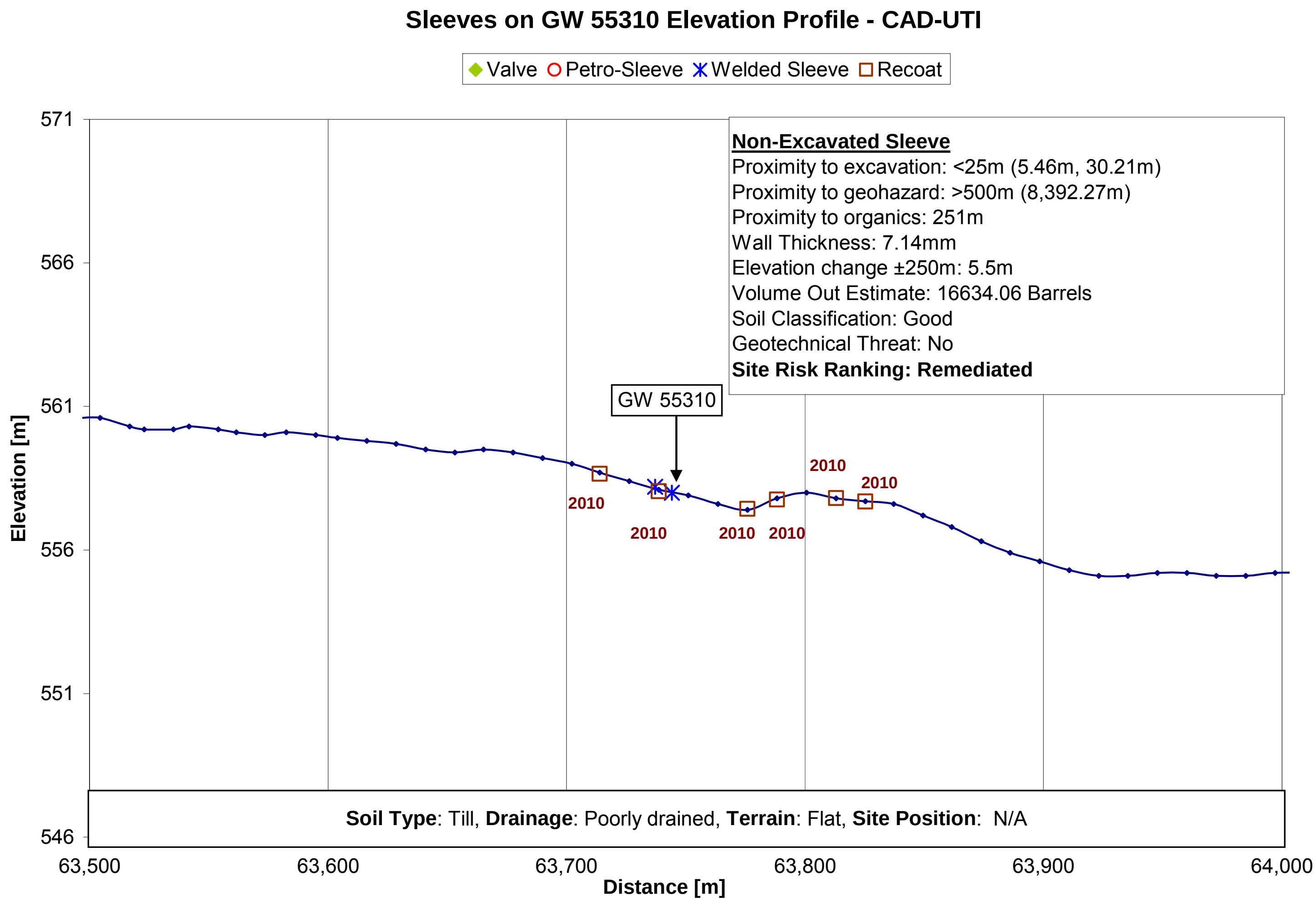


Figure 102 Pipeline Elevation Profile at Welded Sleeve. ZAM-RAI. GW 55310

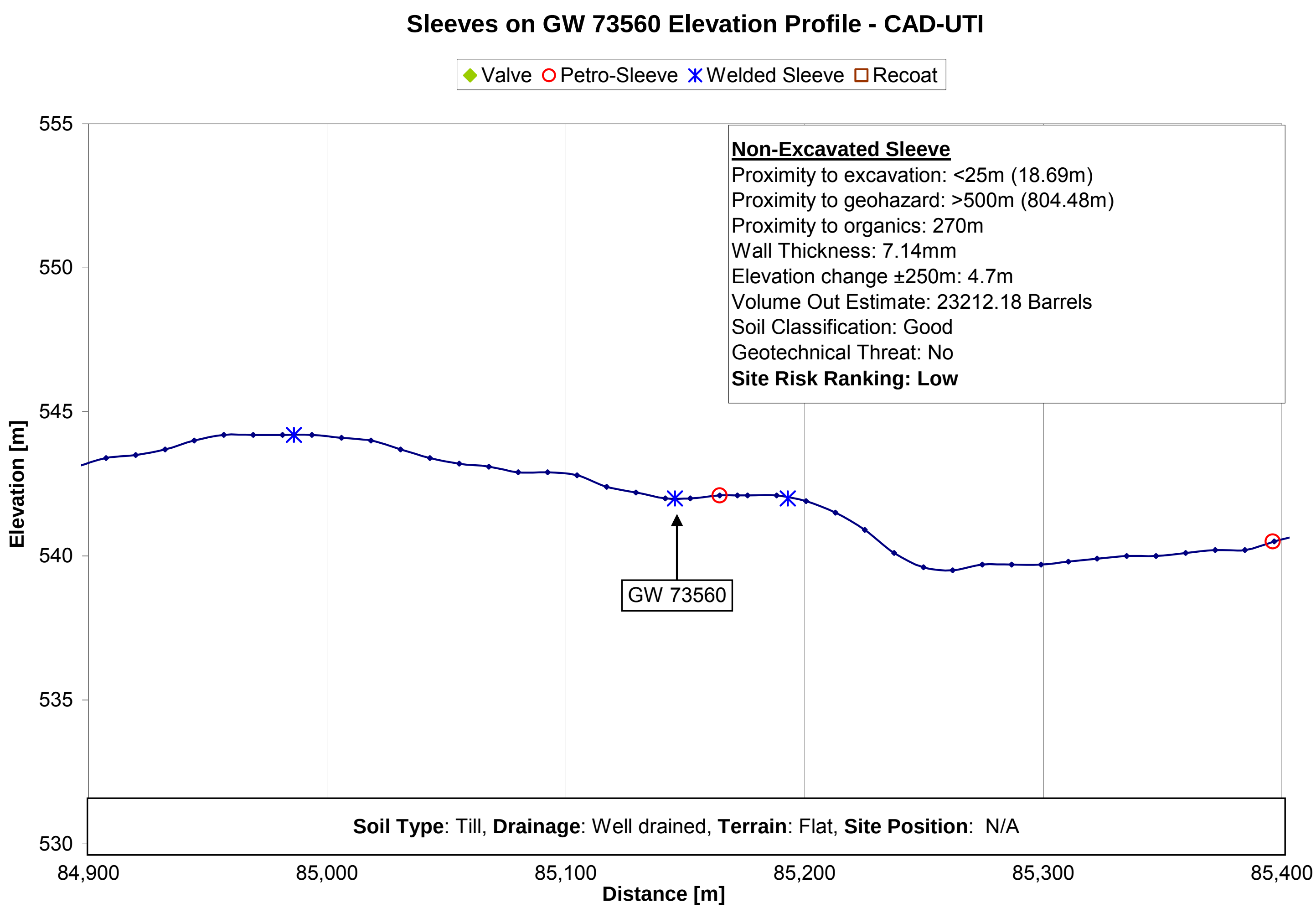


Figure 103 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 73560

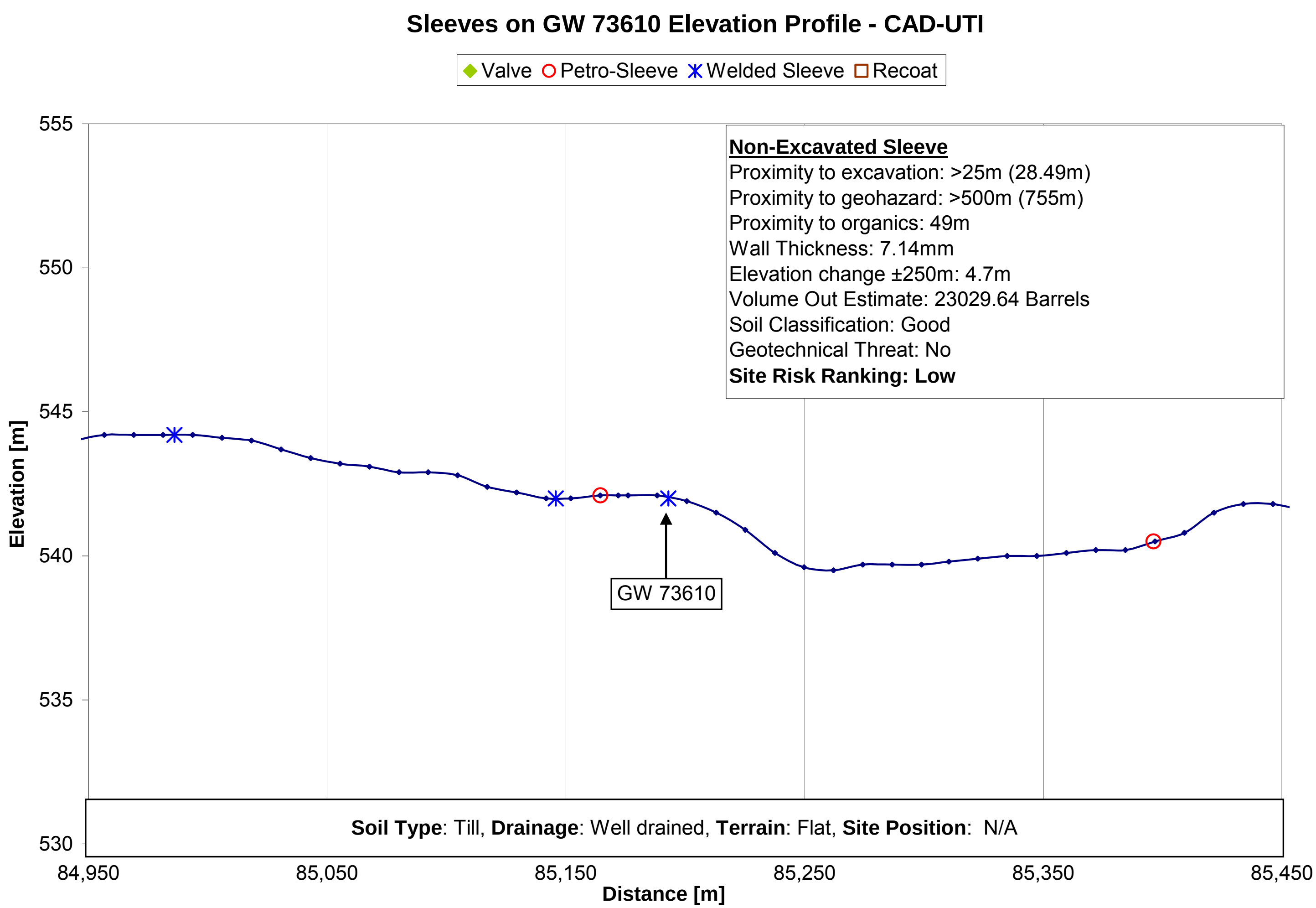


Figure 104 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 73610

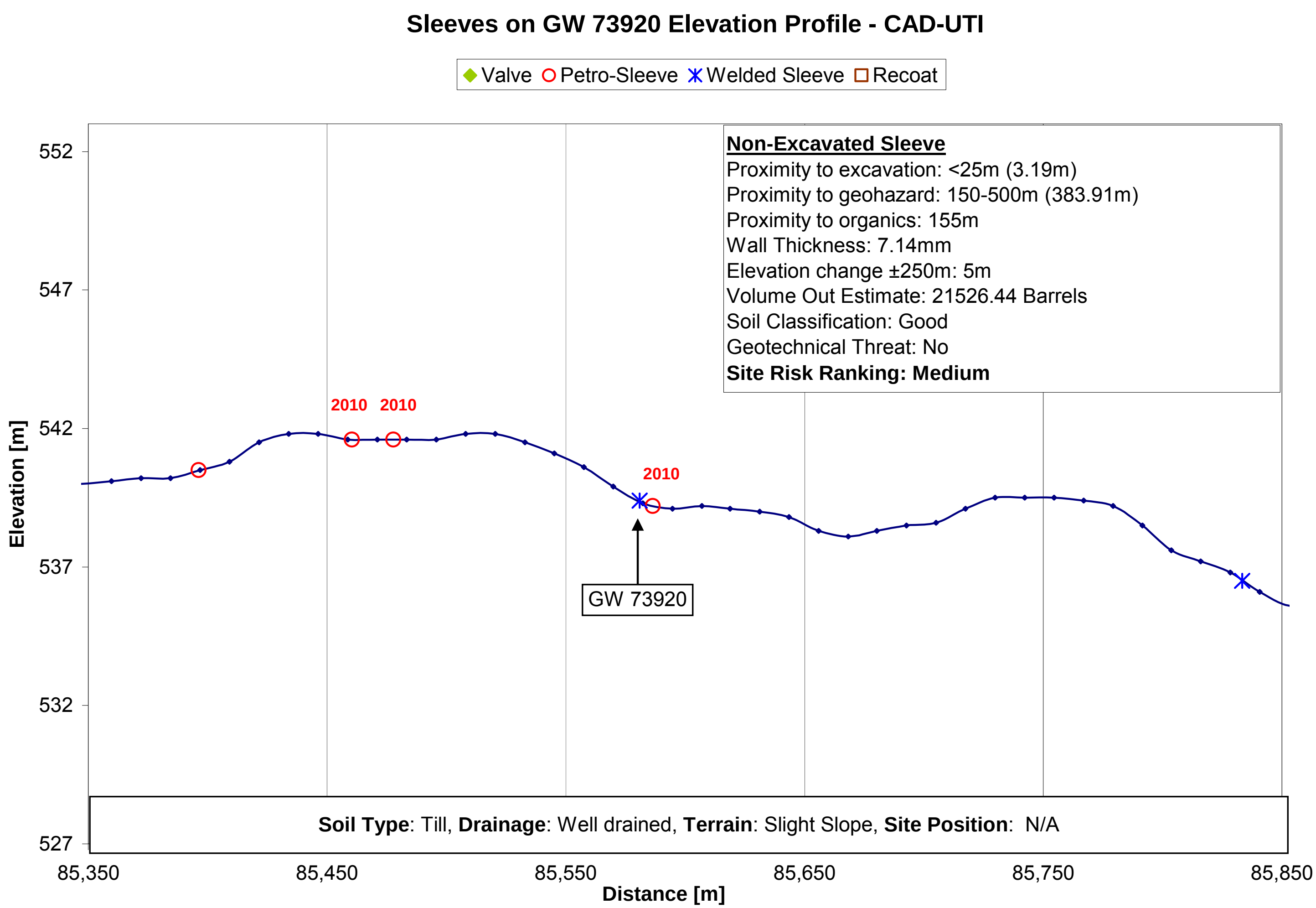


Figure 105 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 73920

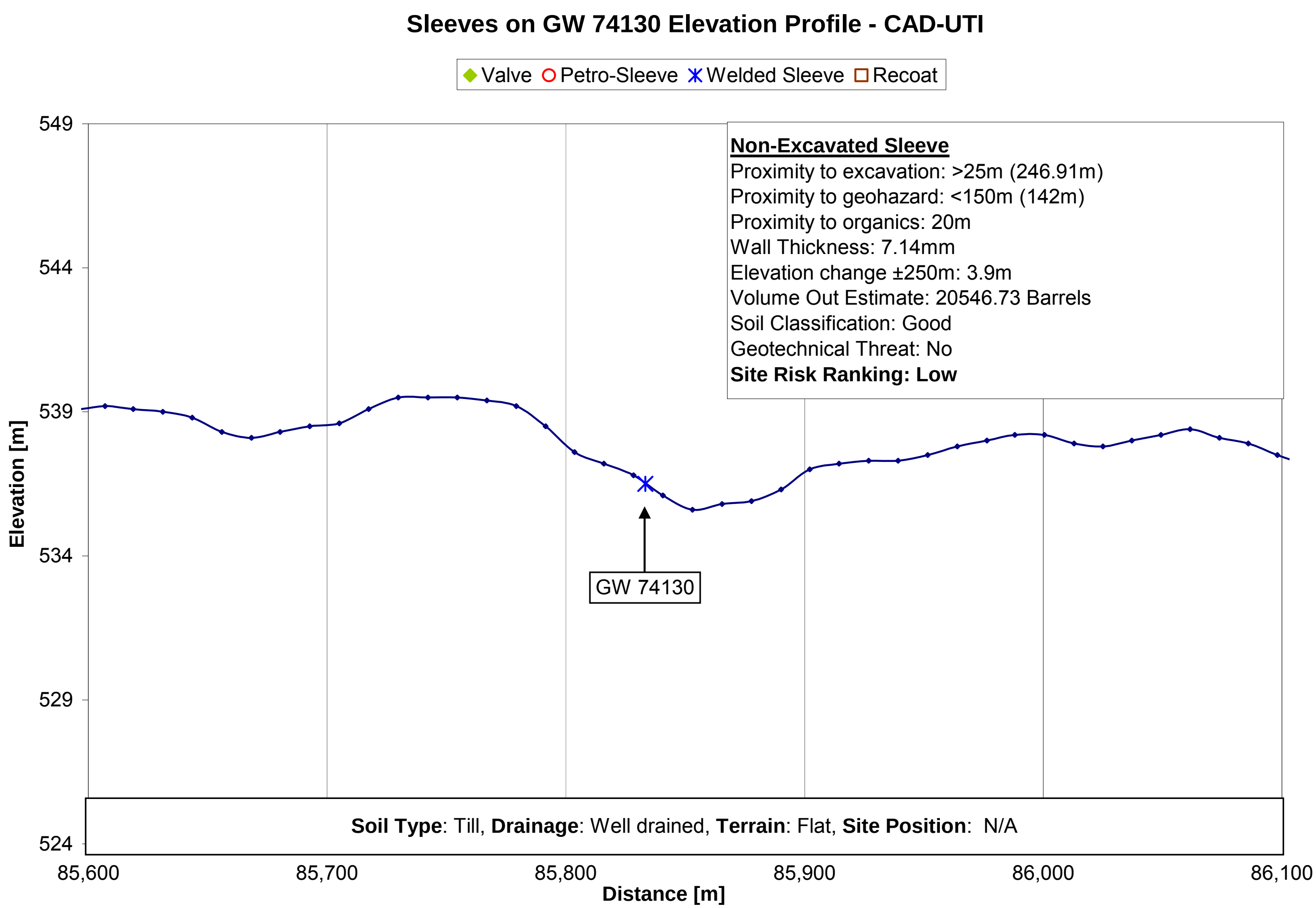


Figure 106 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 74130

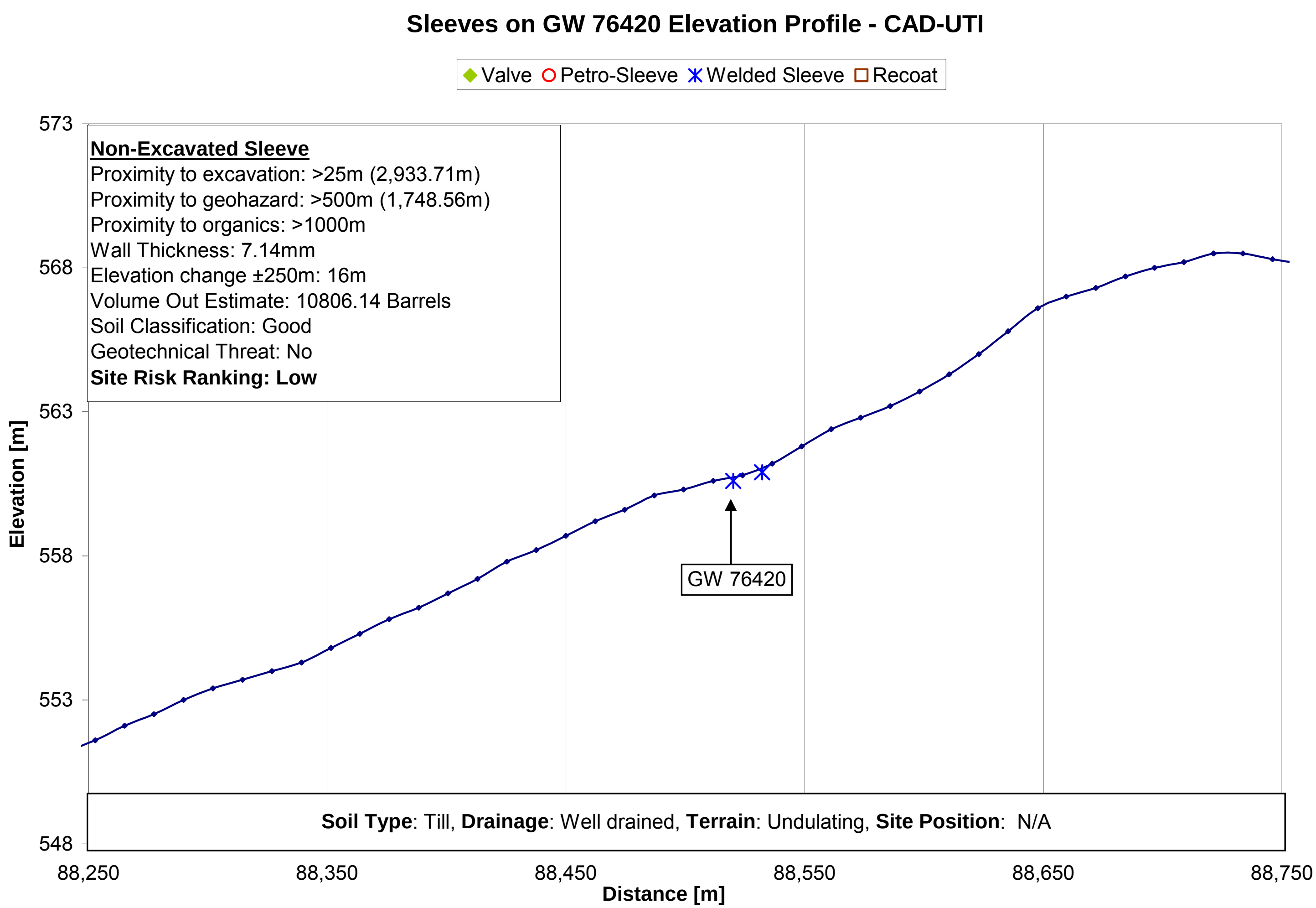


Figure 107 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 76420

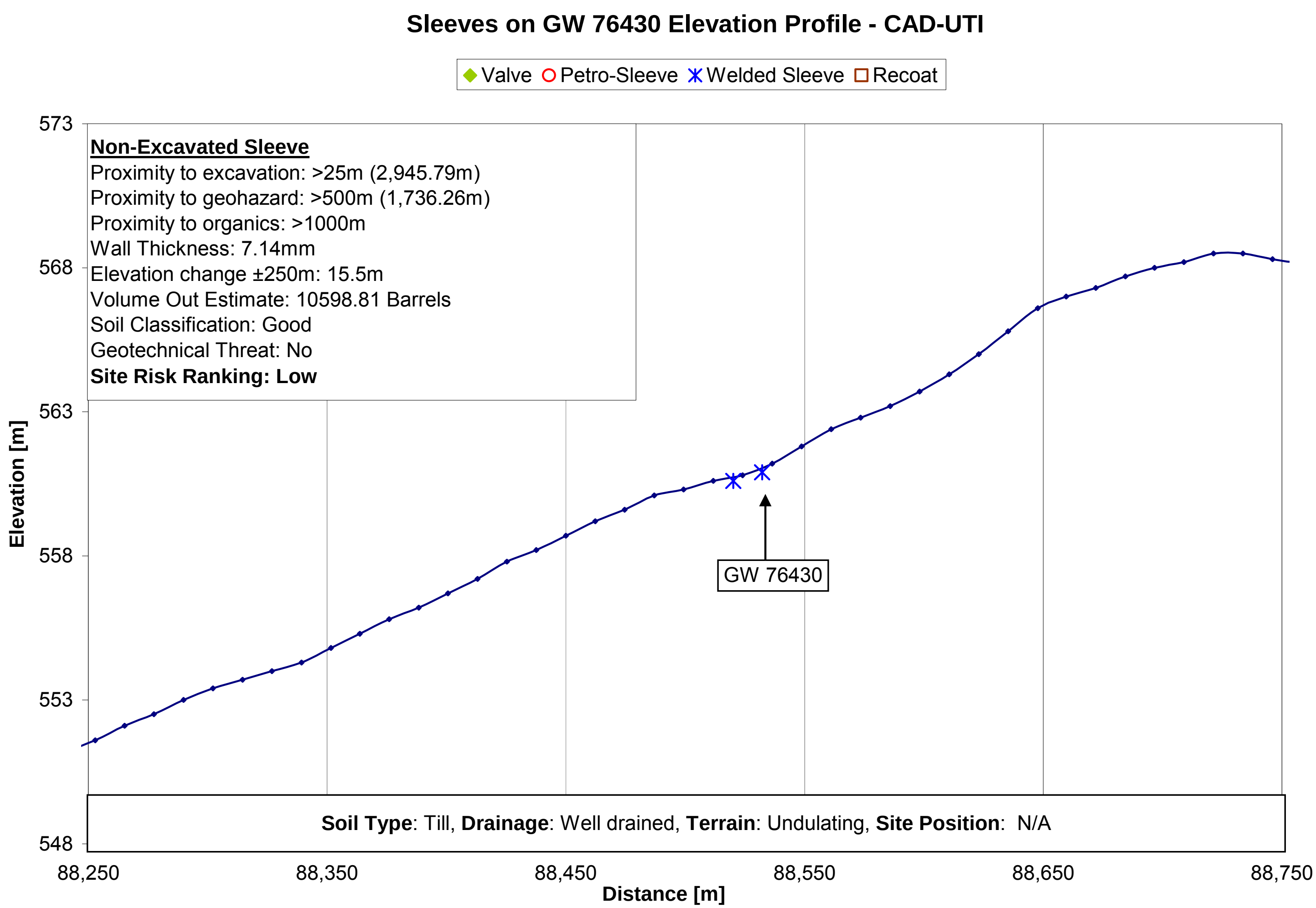


Figure 108 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 76430

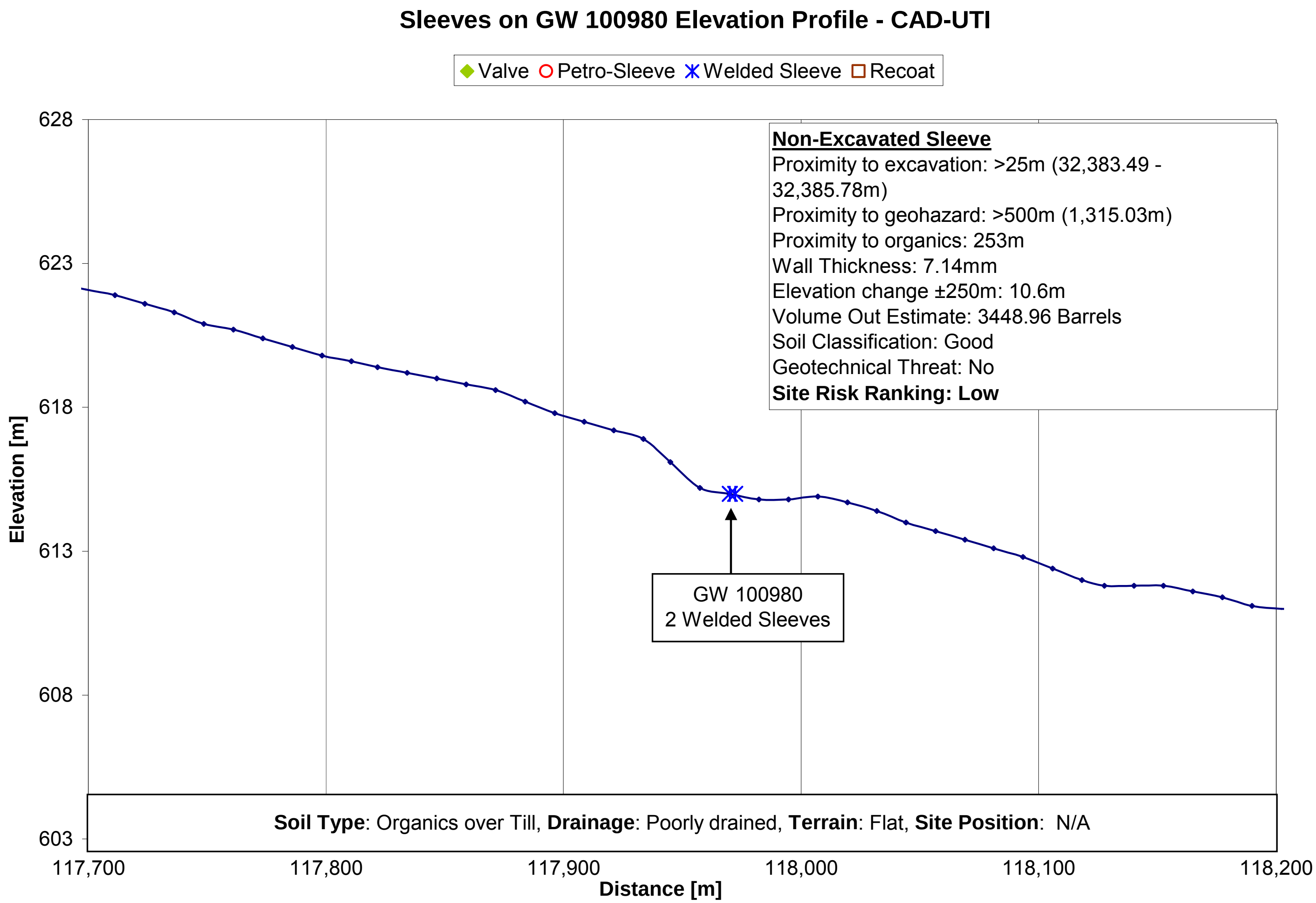


Figure 109 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 100980

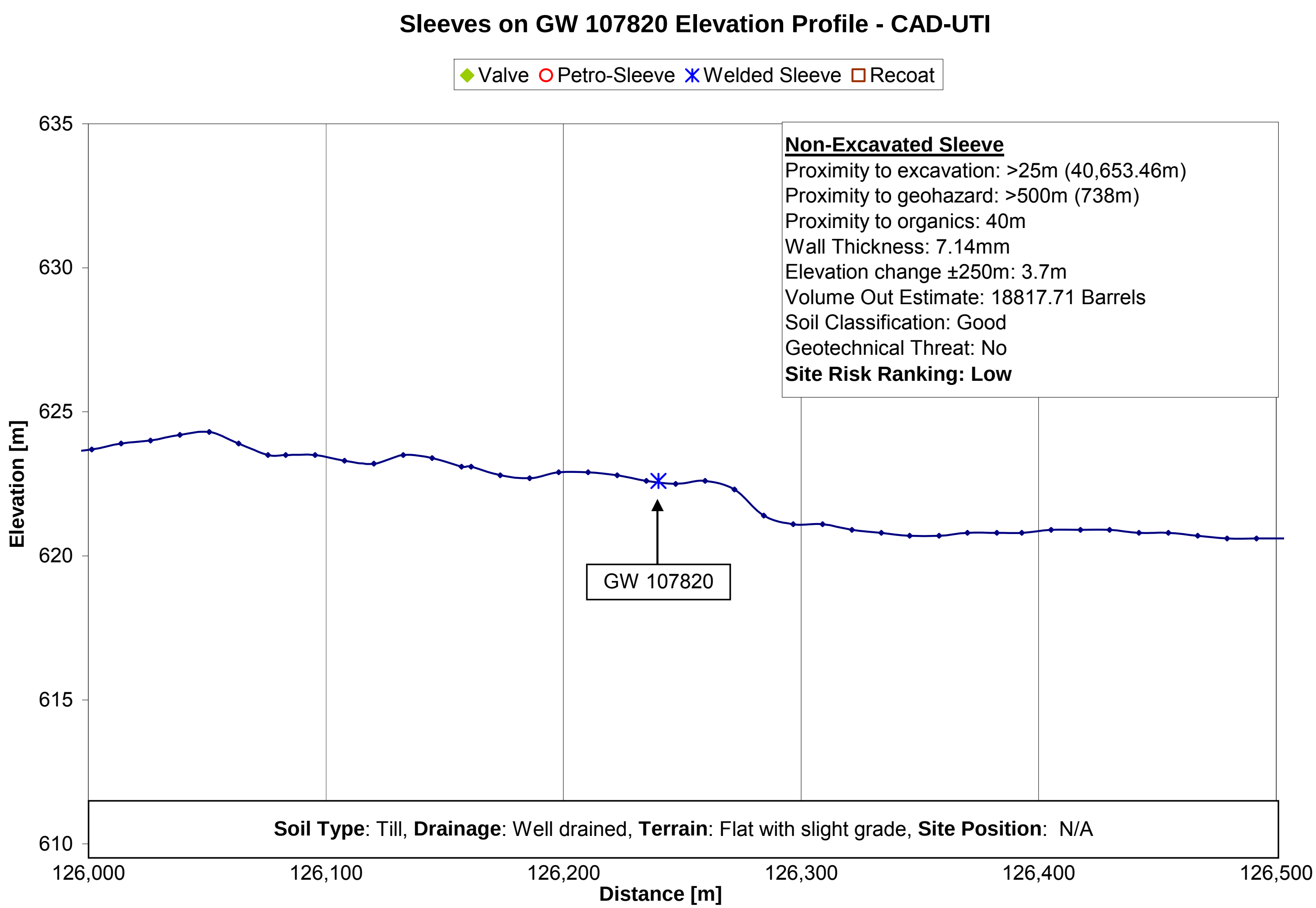


Figure 110 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 107820

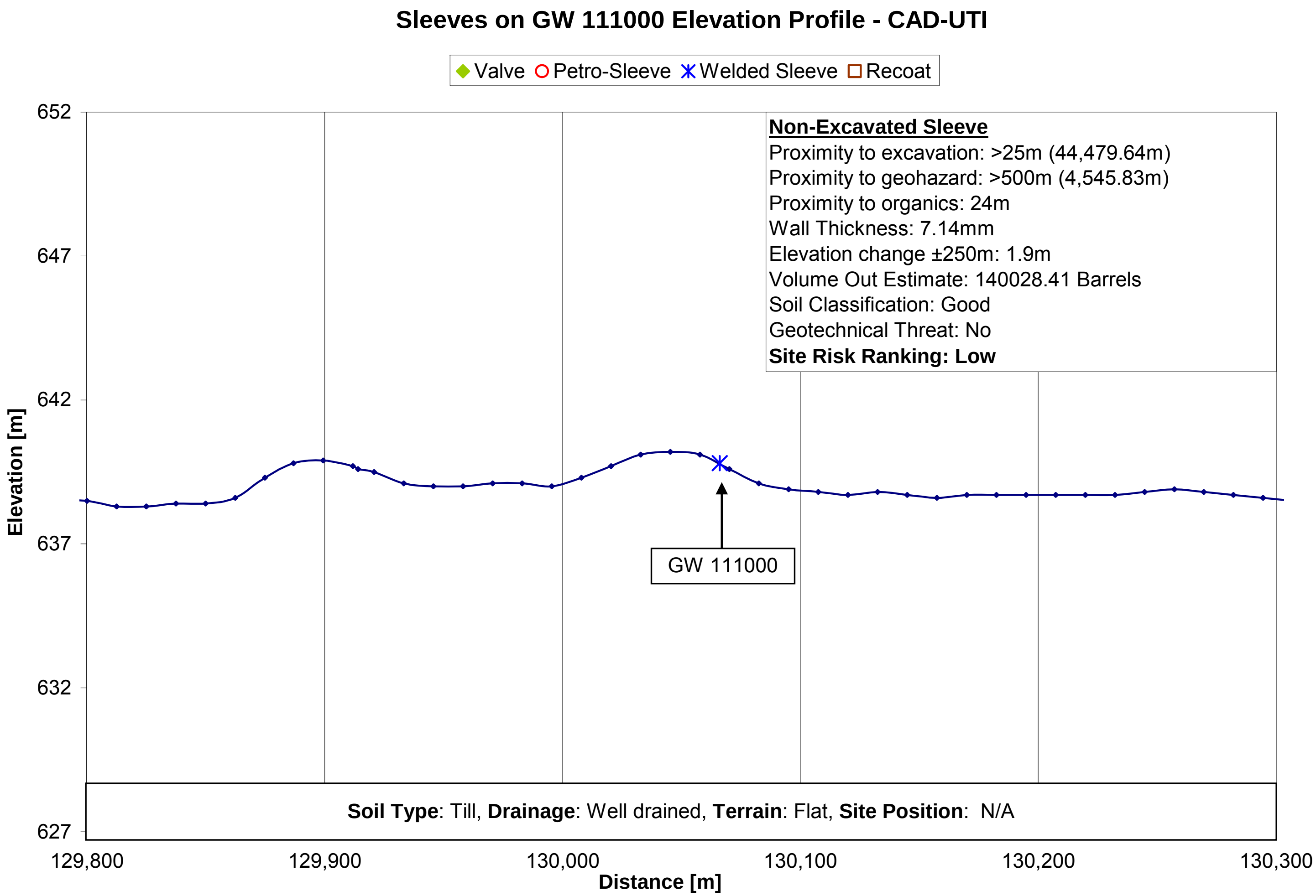


Figure 111 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 111000

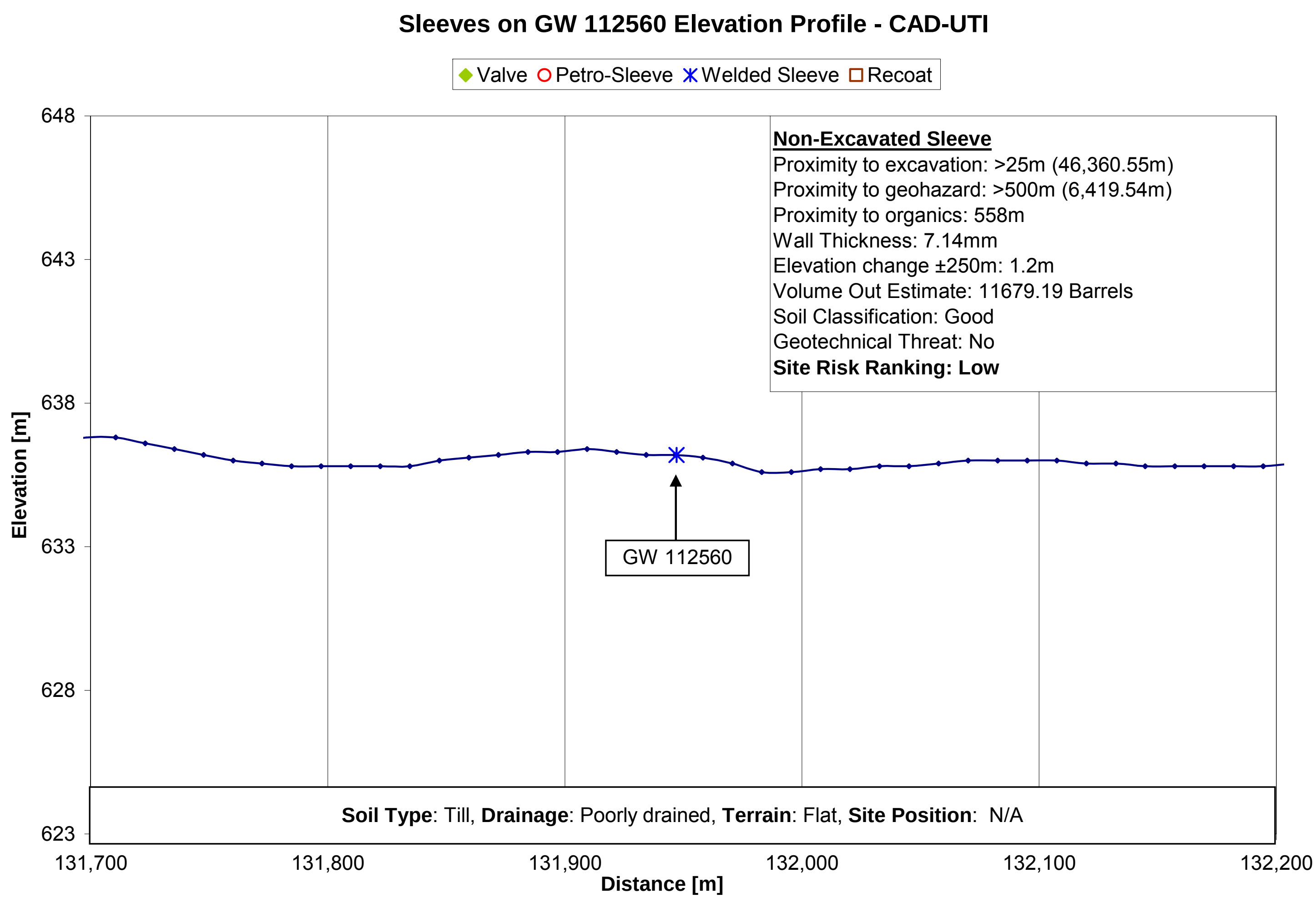


Figure 112 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 112560

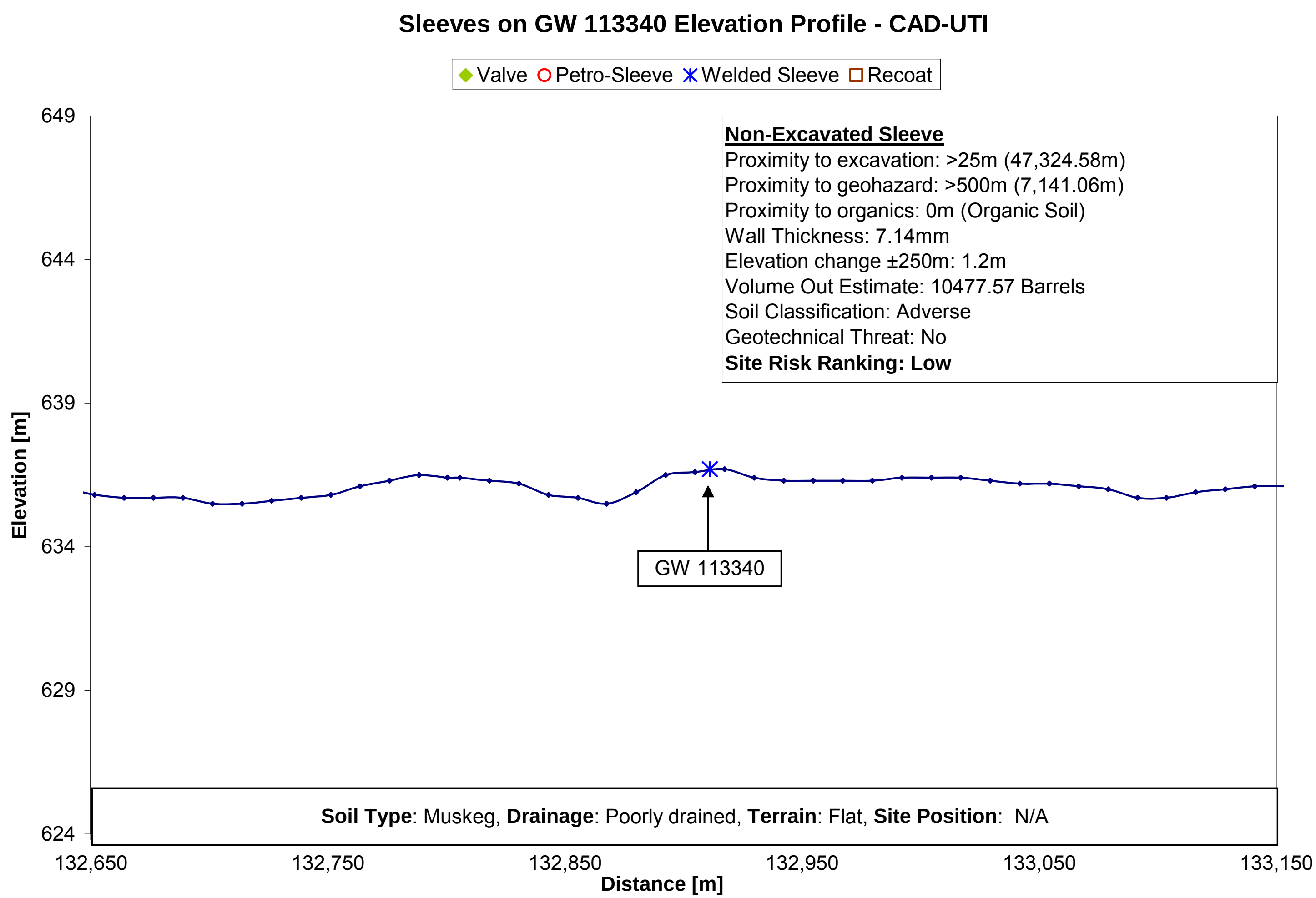


Figure 113 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 113340

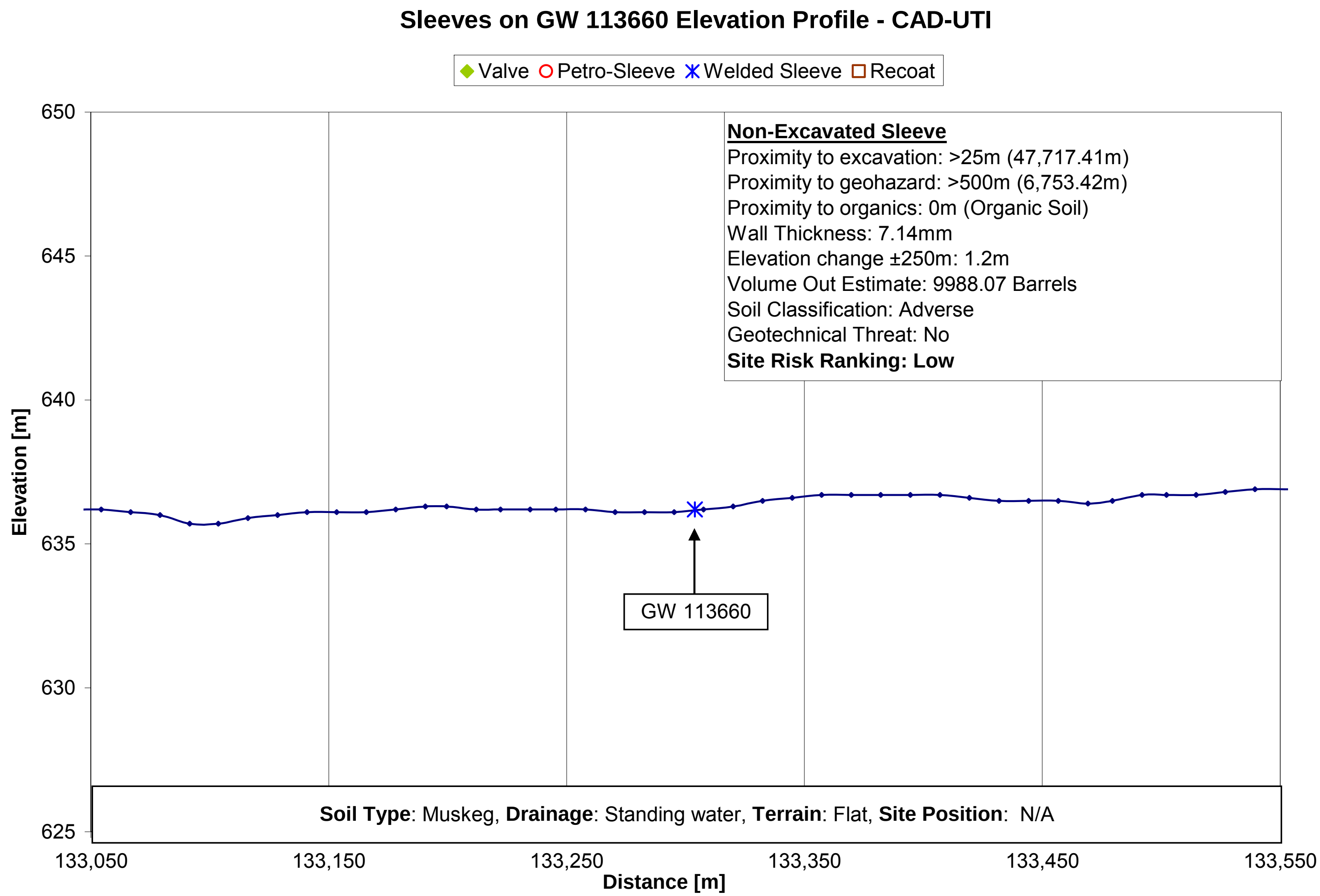


Figure 114 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 113660

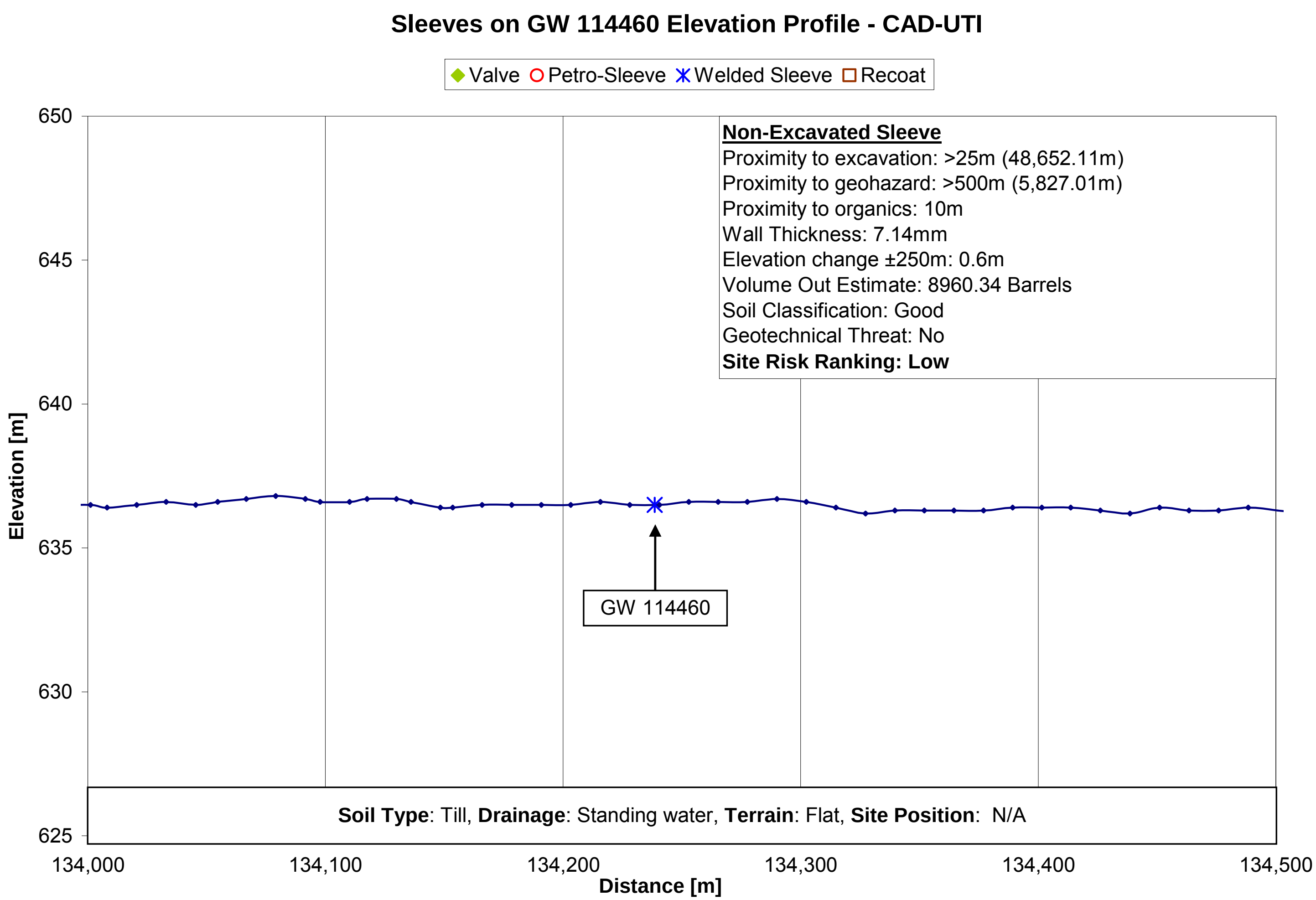


Figure 115 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 114460

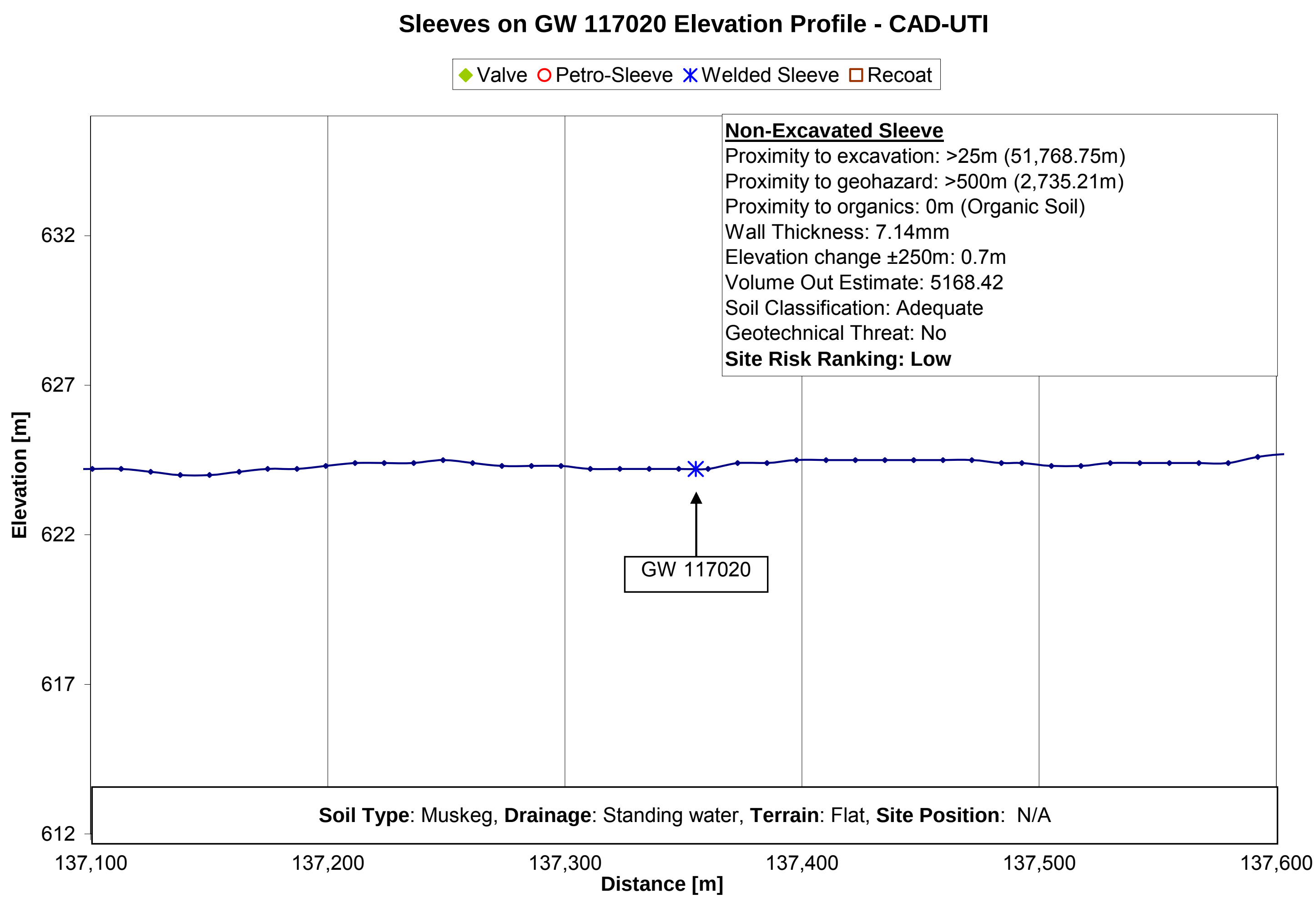


Figure 116 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 117020

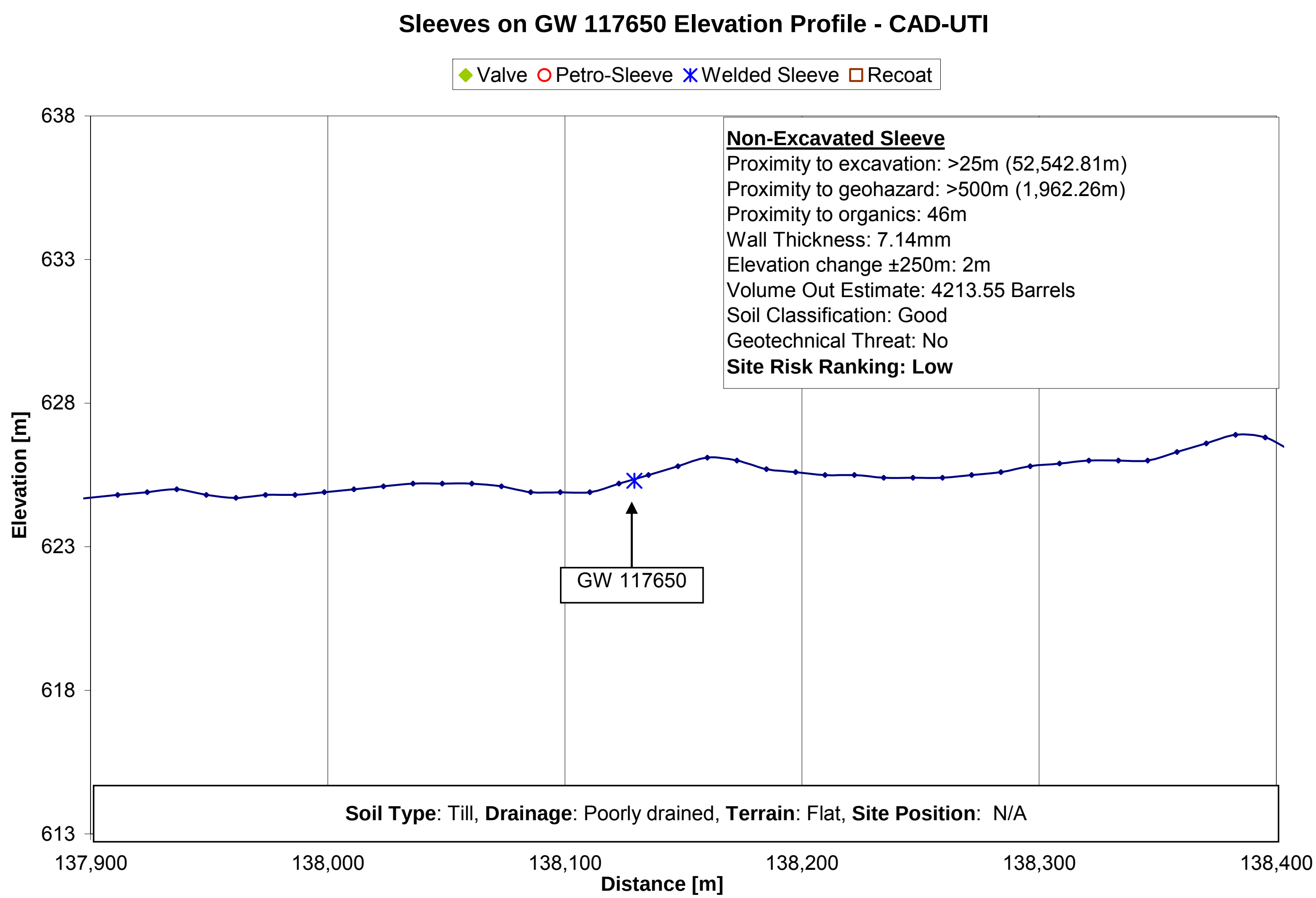


Figure 117 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 117650

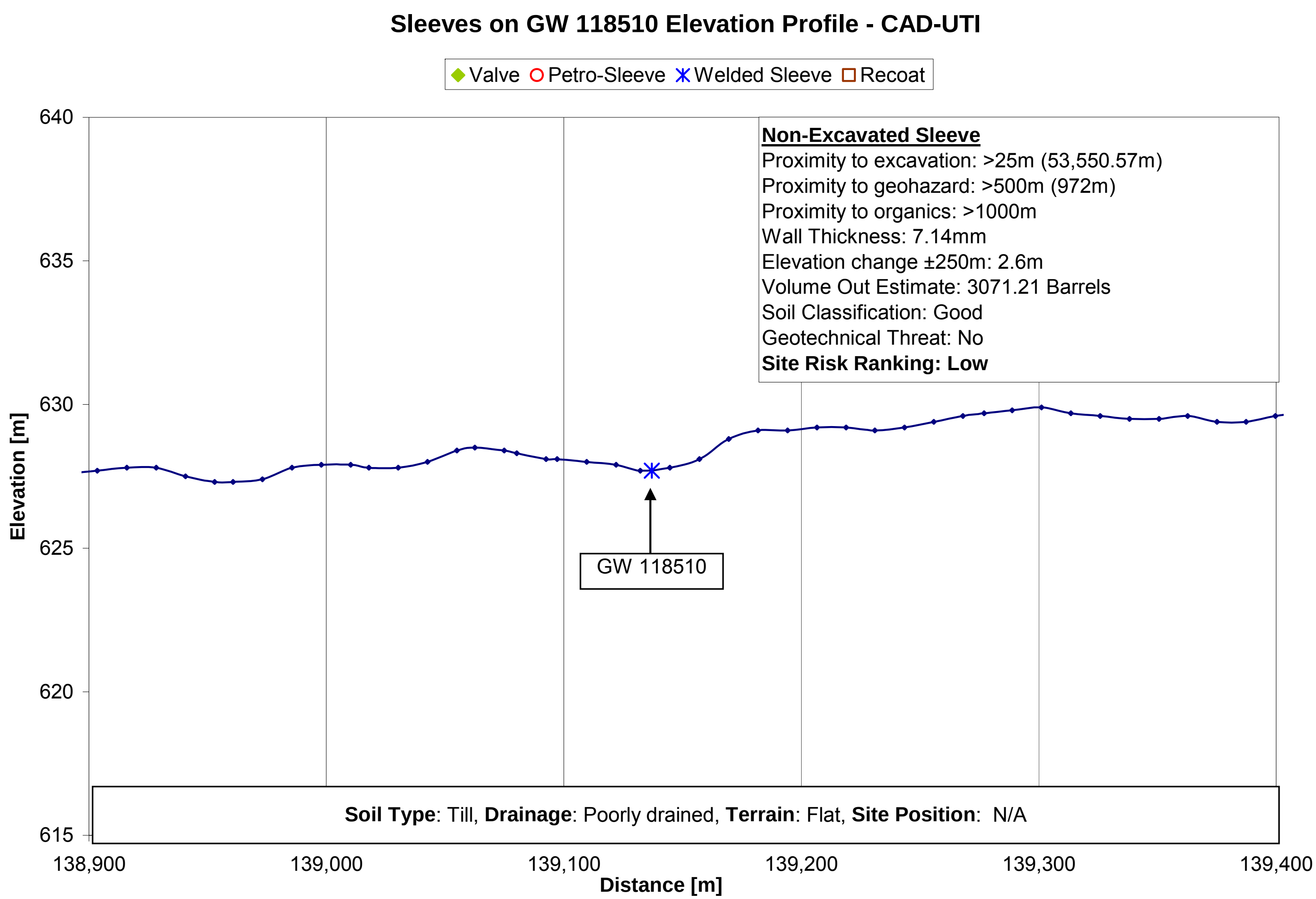


Figure 118 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 118510

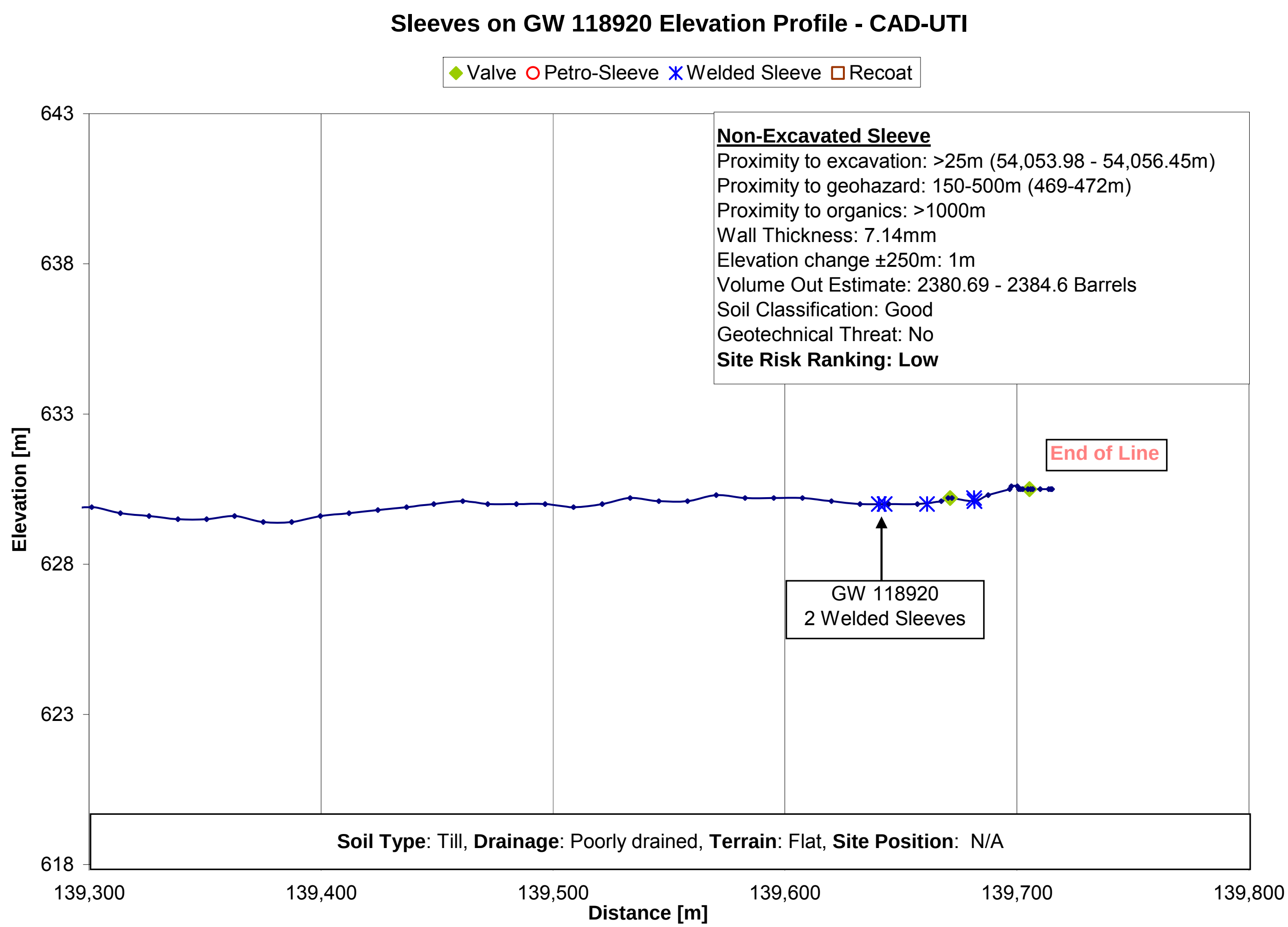


Figure 119 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 118920

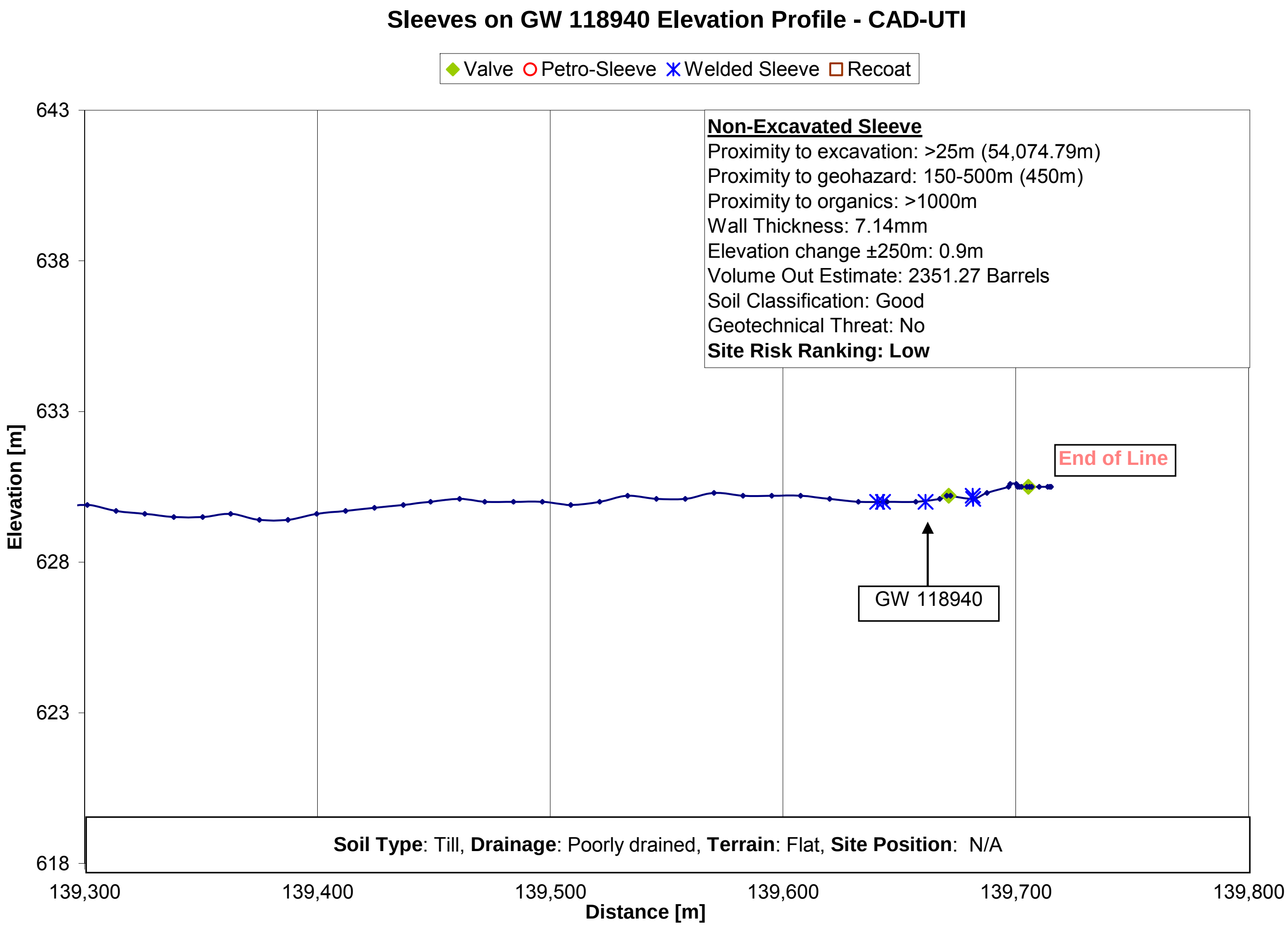


Figure 120 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 118940

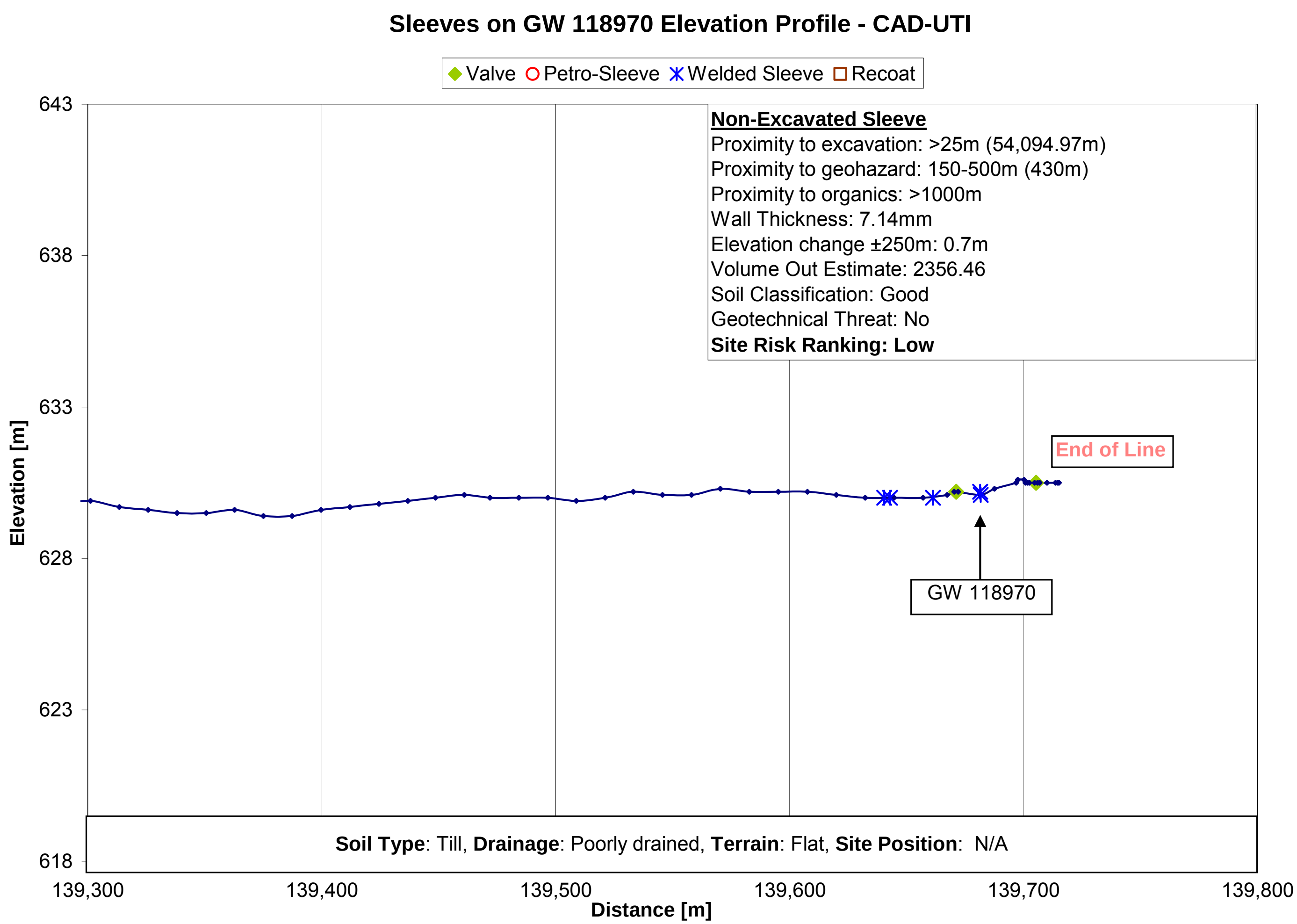


Figure 121 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 118970

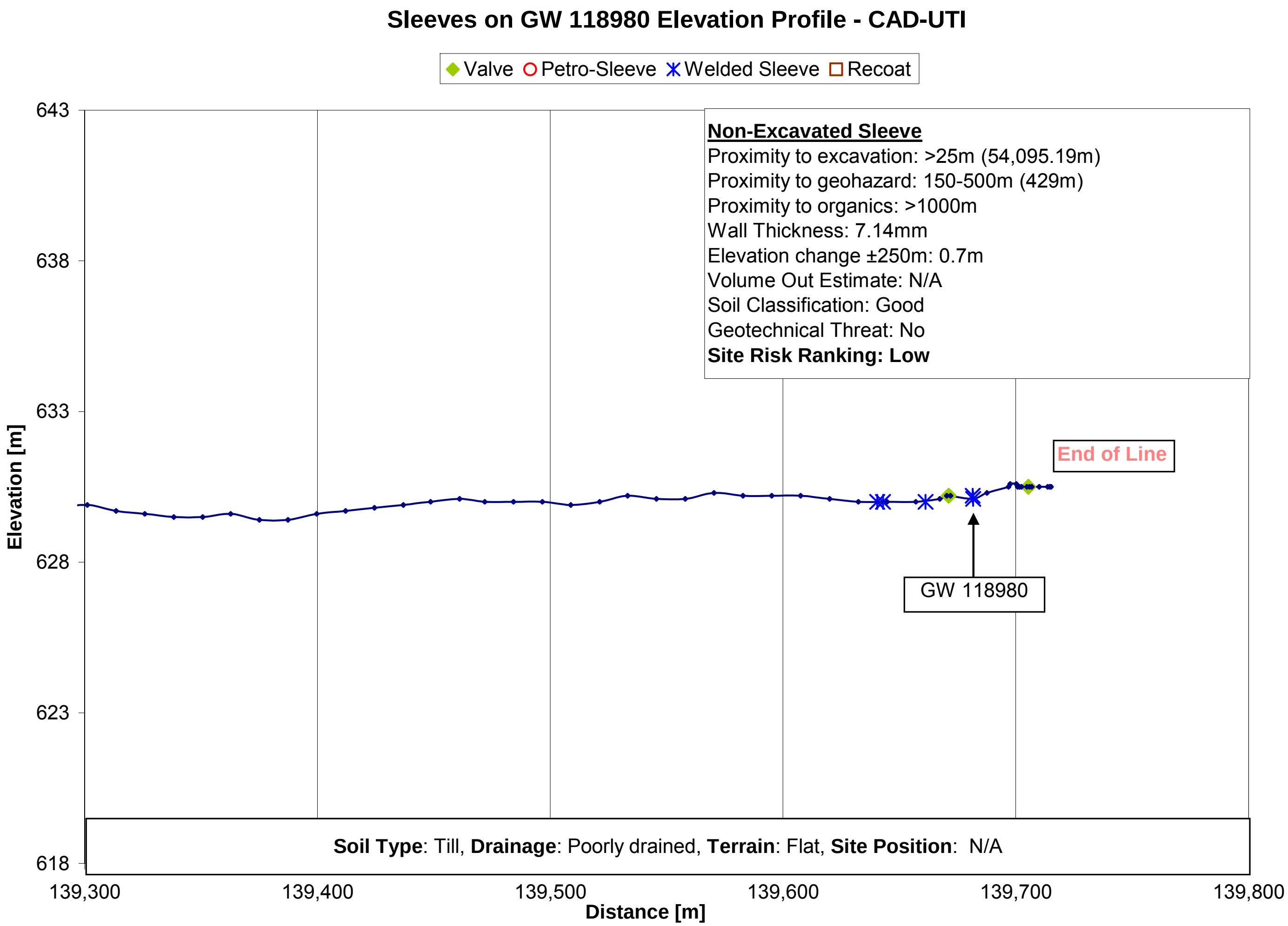


Figure 122 Pipeline Elevation Profile at Welded Sleeve. CAD-UTI. GW 118980

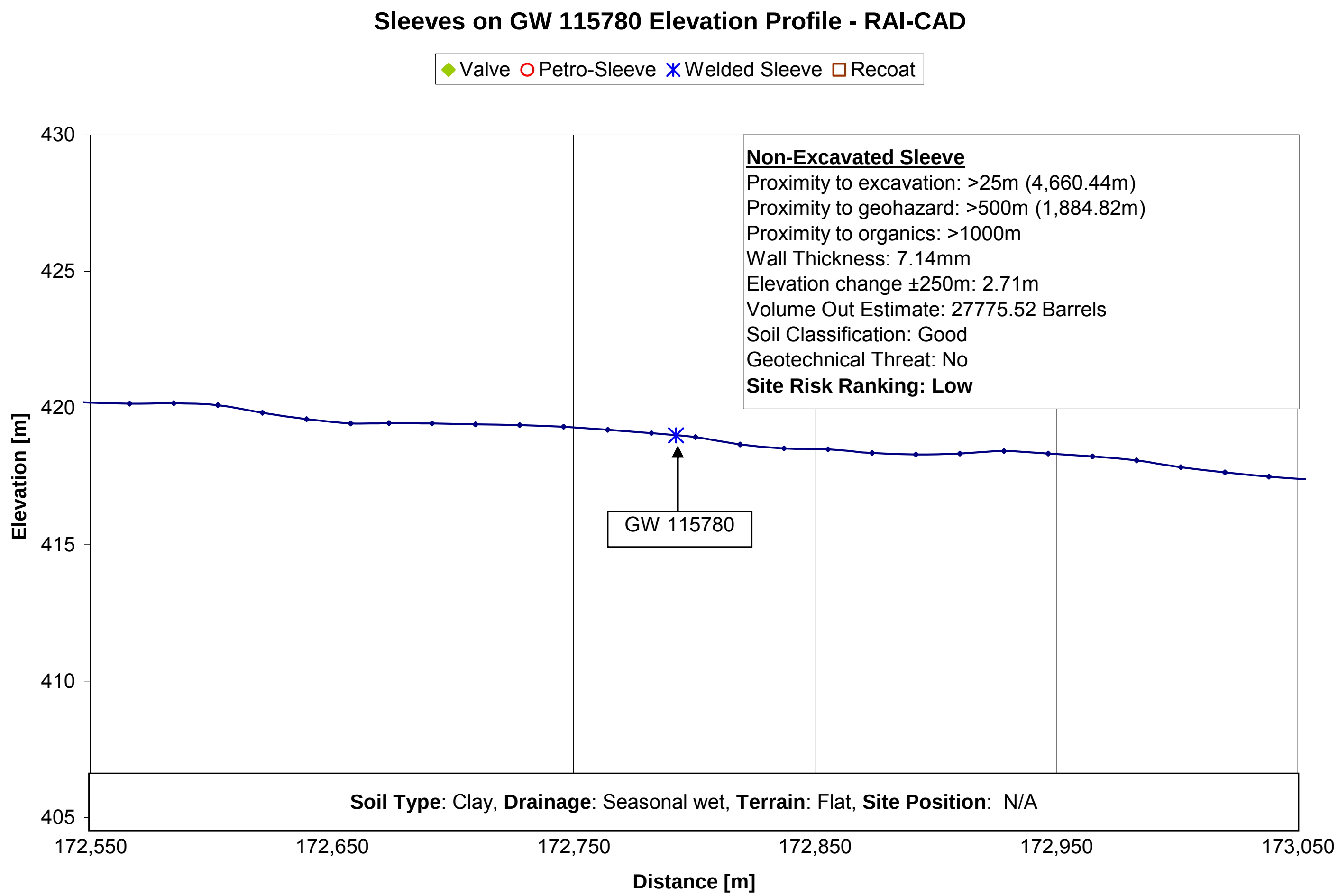


Figure 123 Pipeline Elevation Profile at Welded Sleeve. RAI-CAD. GW 115780

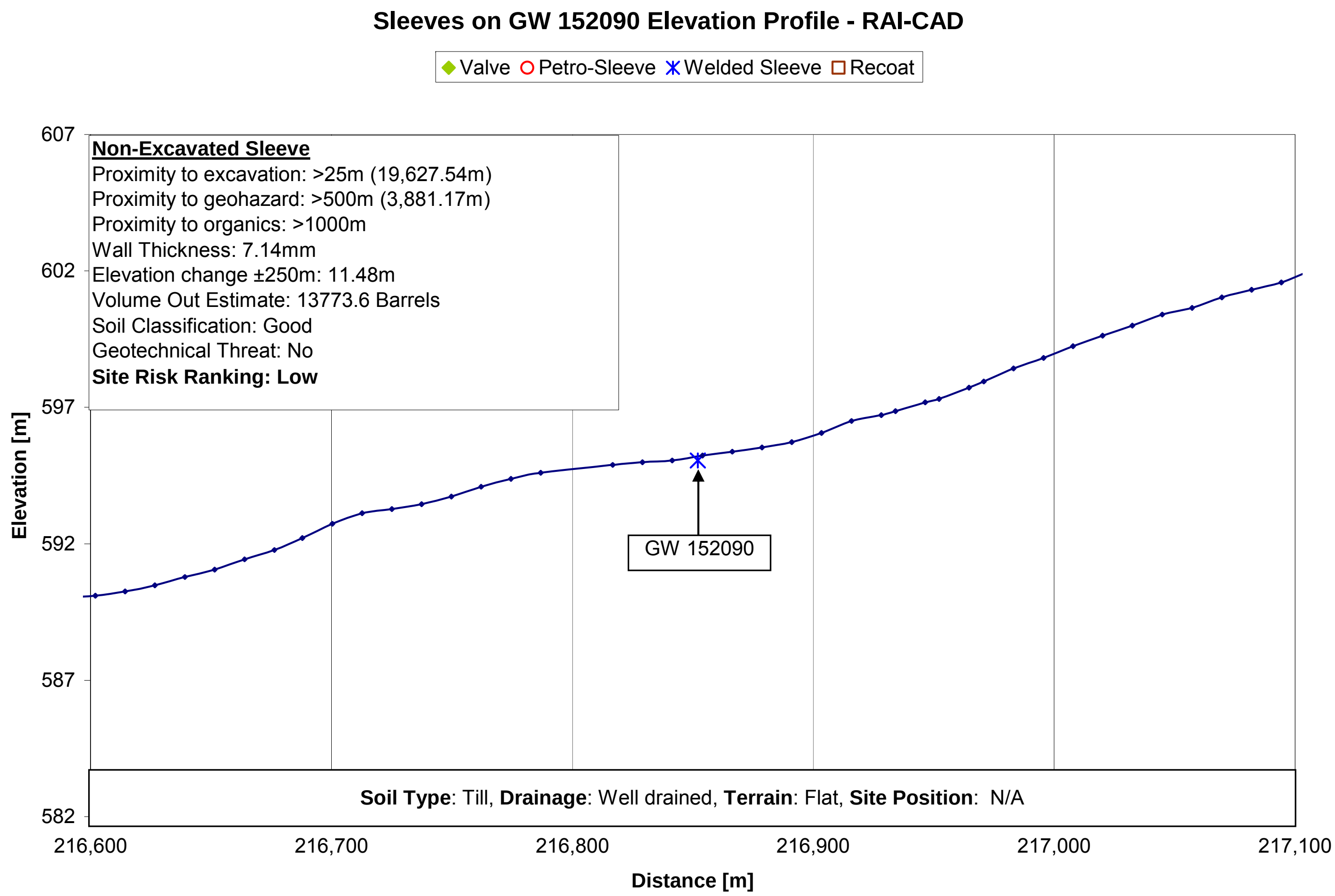


Figure 124 Pipeline Elevation Profile at Welded Sleeve. RAI-CAD. GW 152090

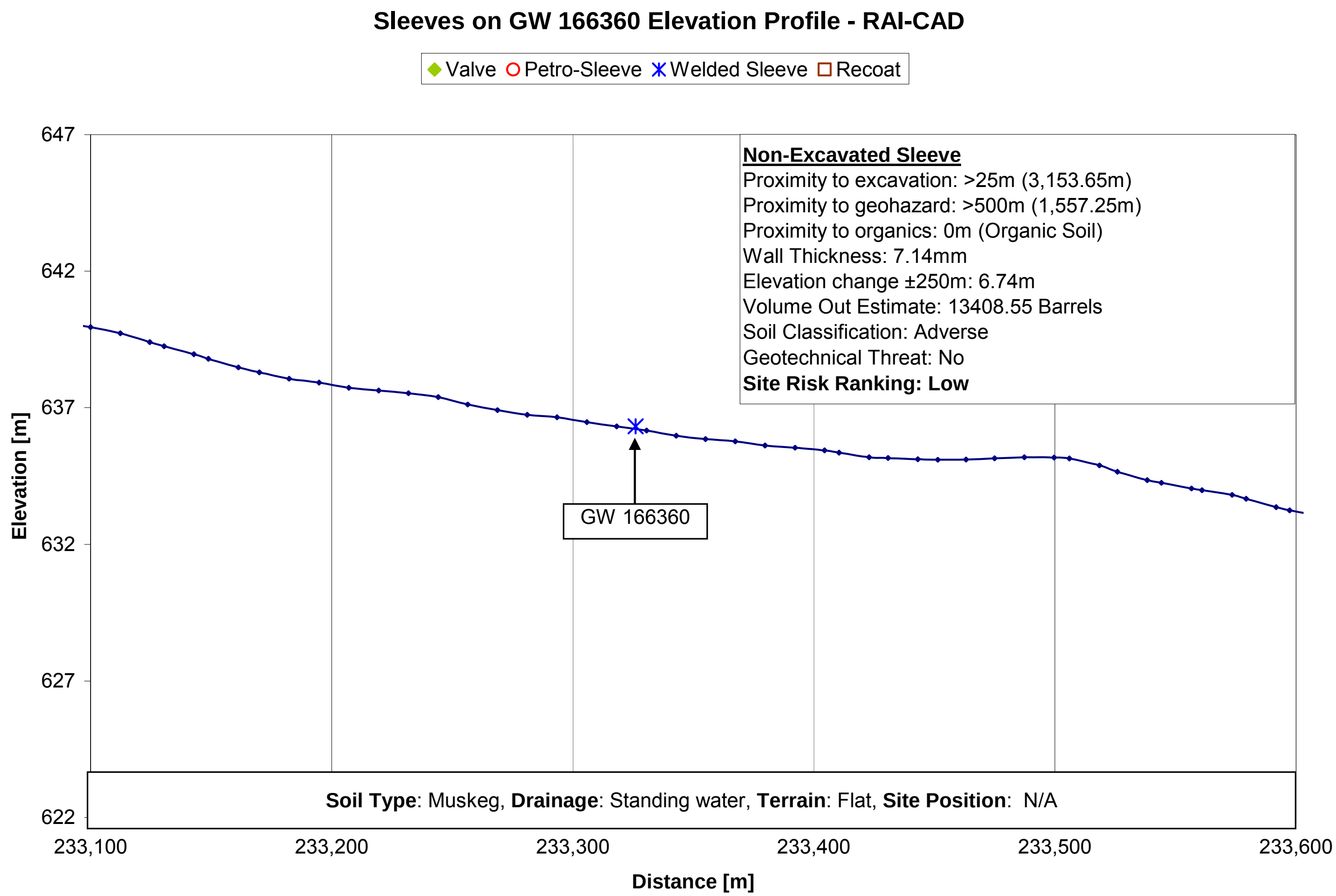


Figure 125 Pipeline Elevation Profile at Welded Sleeve. RAI-CAD. GW 166360

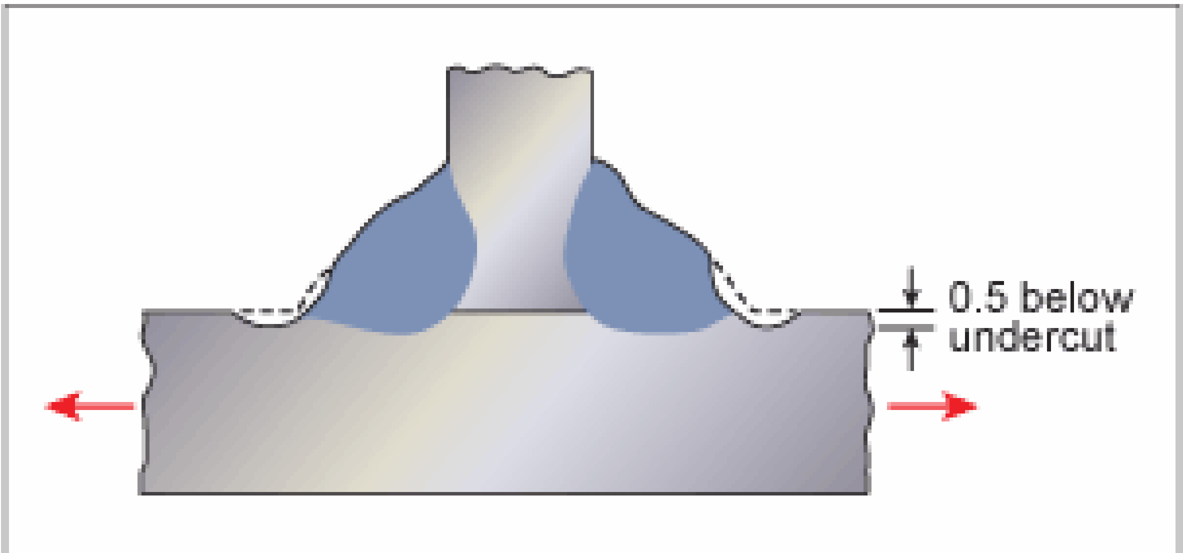


Figure 126 Illustration of weld toe dressing

Figure 127 Rotary files used for weld toe dressing

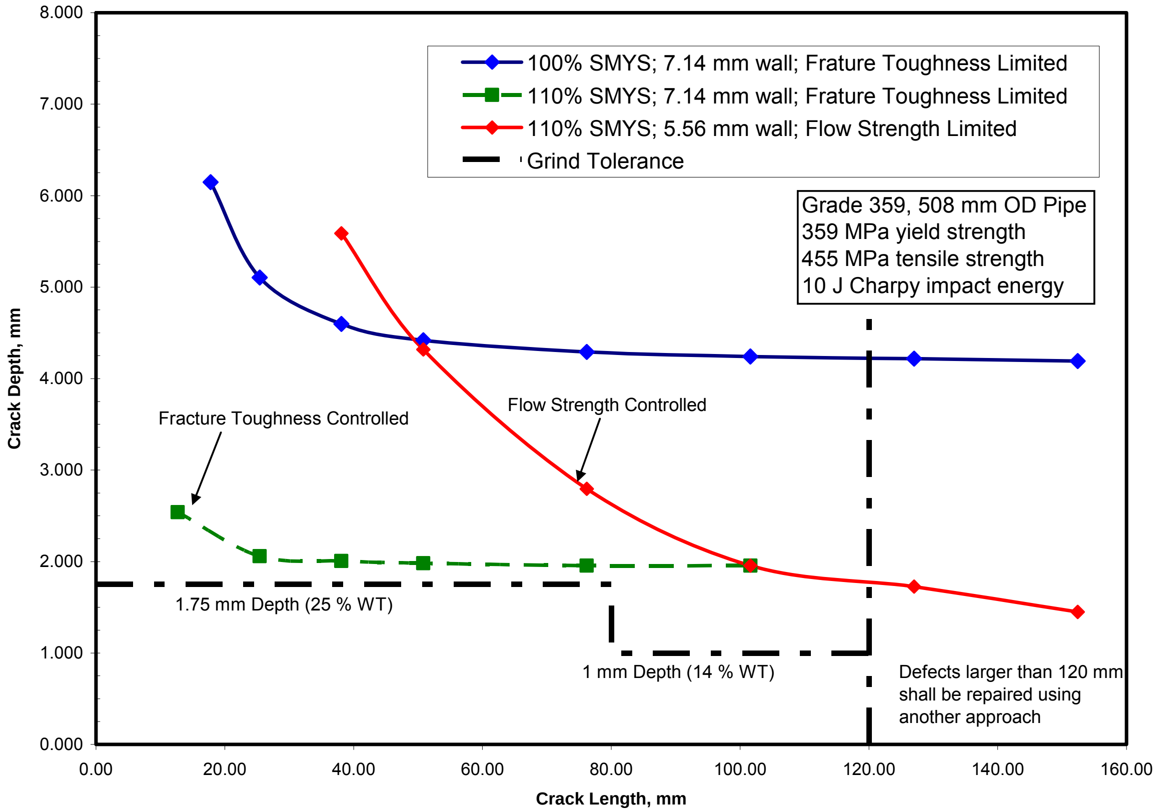


Figure 128 Grind Tolerance for 7.14 mm Wall Thickness

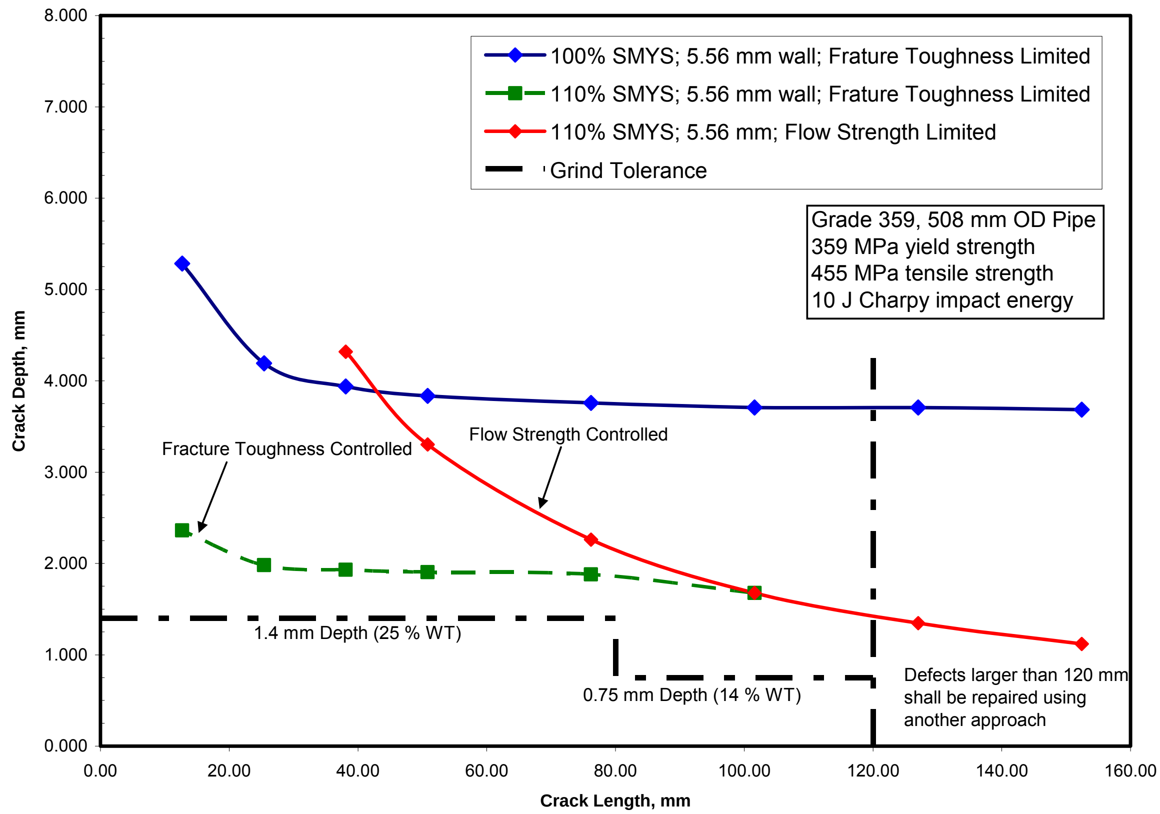


Figure 129 Grind Tolerance for 5.56 mm Wall Thickness

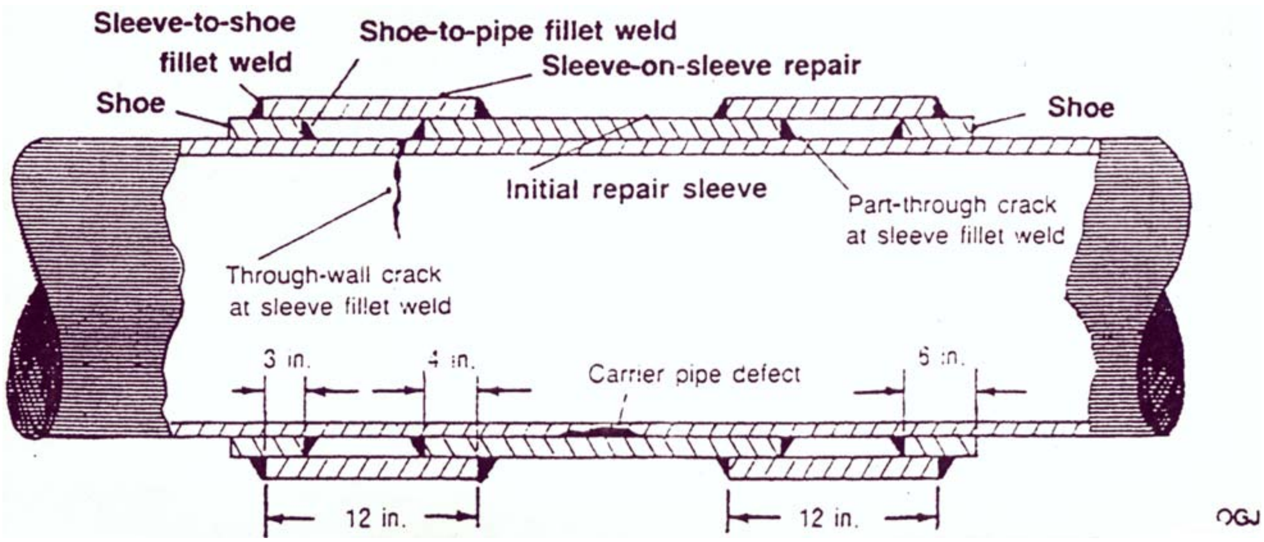


Figure 130 Illustration of sleeve-on-sleeve repair

Chapter 8

Remedial Measures for Cracked Fillet Welds

Recommendation 5.9 as it appeared in the Inquiry report required that all welds containing cracks be removed by cutting out and replacing the cylindrical piece of pipe containing the defect.

The Committee argued that it should be permissible to repair or "remove from service" fillet welds found to contain unacceptable cracks.

Amoco and TNPL submitted that not all welds that contain cracks should necessarily be cut out. TMPL suggested that cut-outs or double sleeving be applied only for weld toe cracks of such depth (greater than 0.5 mm) that they could not be repaired by grinding and re-welding.

PTC argued that toe cracks should be removed from service while root cracks may or may not require removal depending on whether they were judged to be injurious.

IPL submitted in its letter of 2 November 1989 that whenever possible, fillet welds found to contain cracks should be treated by cut-out and pipe replacement. However, IPL stated that "removing the cracked section from service by containing it within a sleeve-on-sleeve repair or grinding to remove the crack while leaving a pipe wall thickness of not less than 92%, have been proven to be successful." Finally, IPL considered that procedures involving grinding and rewelding and ECA "can be finalized in the near future" as a result of "ongoing activity around the world".

Views of the Board

The Board agrees that certain repair techniques in addition to cutting out and replacing a cylindrical piece of pipe containing the defect are acceptable as remedial measures for cracked fillet welds. The techniques that could be used to treat fillet weld cracks were addressed in the Board's decision dated 22 July 1988 on Recommendation 5.11, as amended on 16 February 1989. The effect of this decision was to allow the repair of fillet weld cracks by the following additional methods:

(i) repair of the crack by grinding out the affected area, followed by rewelding if necessary; and

(ii) enclosure of the cracked weld within a pressure-tight sleeve-on-sleeve assembly.

The decision on Recommendation 5.11, as amended, details the various constraints applicable to the use of these techniques.

The Board finds that, where remedial measures for cracked fillet welds are required by this decision, the acceptable methods shall be those permitted under Recommendation 5.11, as amended.

Figure 131 Chapter 8 from National Energy Board report "Reason for Decision – Interhome Energy Inc., which carries on its pipeline operations as Interprovincial Pipeline Company, a division of Interhome Energy Inc.", NEB Report No. OHW-1-89, September 1990.

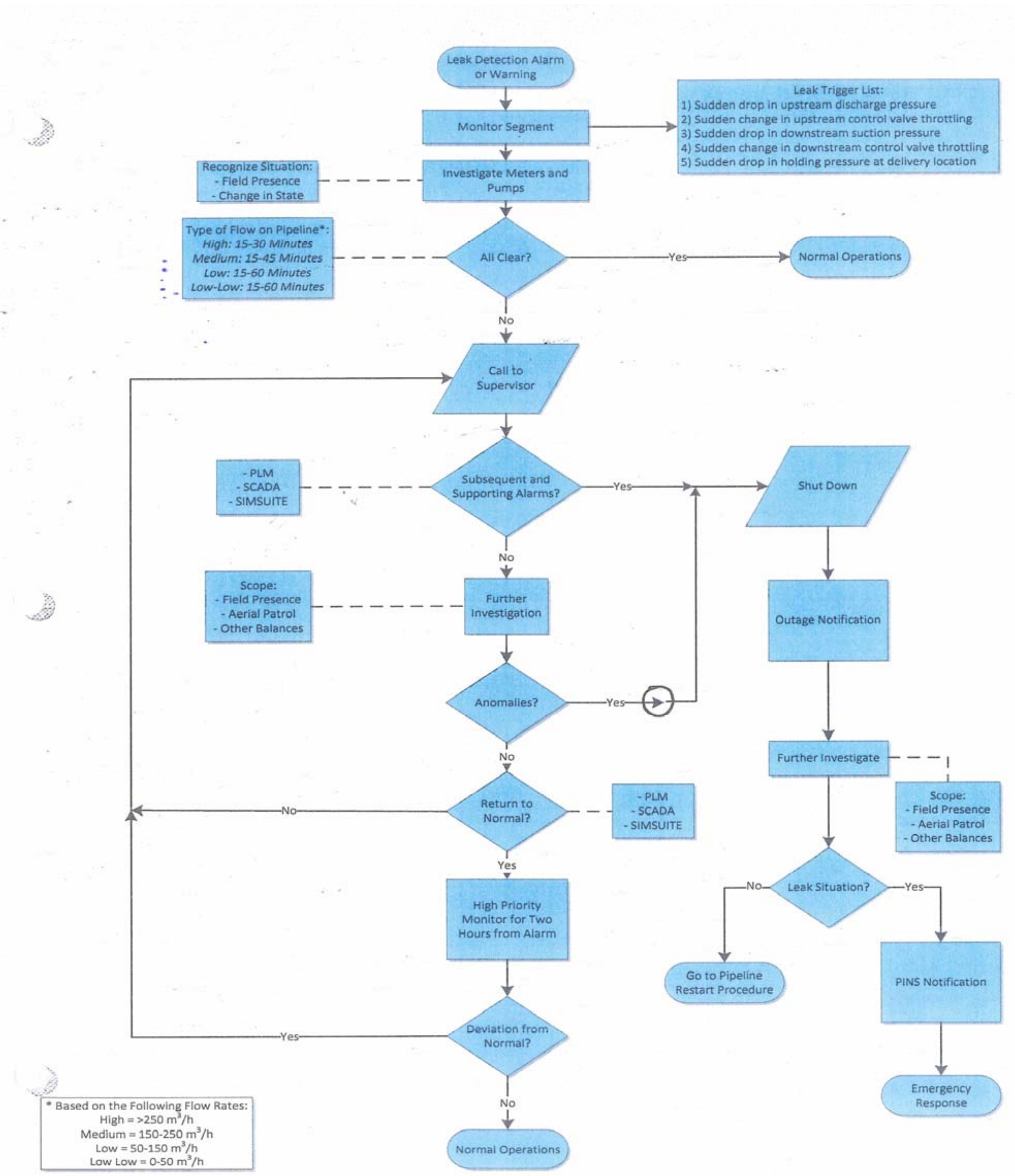


Figure 132 Plains Leak Alarm Response

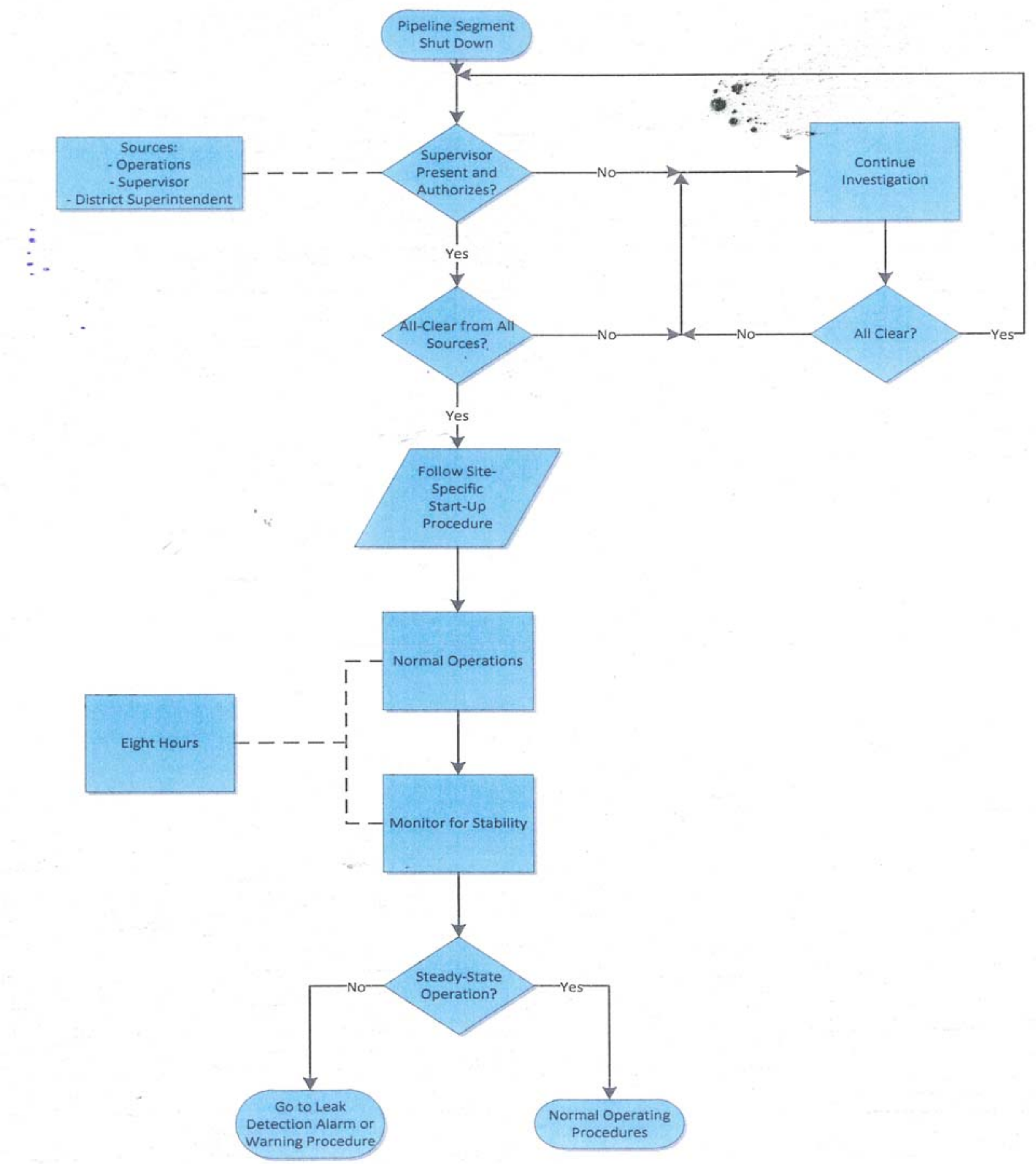


Figure 133 Plains Pipeline Restart Procedure

DNV Energy

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