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Part 2 of 14

Date: 2026-06-29

Written Submission from Orano Canada Inc.

In the matter of

Orano Canada Inc.

Application to renew the McClean Lake Operating Licence for 2-year term

Hearing in writing based on written submissions

September 2026

Mémoire d’ Orano Canada Inc.

À l’égard d’

Orano Canada Inc.

Demande pour le renouvellement du permis d’exploitation de McClean Lake pour une période de deux ans

Audience par écrit fondée sur des mémoires

Septembre 2026

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3 Facility Design and Operations to Date

An overview design of the tailings management system is presented and discussed in Section 2. The purpose of this section is to present an overview of the operation of the tailings management system, with two main objectives:

1) to summarize performance to date; and

2) to describe operational systems in place that ensure the production of well managed tailings, controlling and minimizing current, near-term, and long-term risks.

General operations include tailings production, placement, and water management. Operational systems are divided based on their objectives of near term and long-term environmental protection:

- Near-term environmental protection is ensured though operational mitigative measures for hydrodynamic containment, spill prevention and response, and sub-aqueous tailings disposal.
- Long-term environmental protection is ensured through the development of operational guidelines for tailings geochemistry and tailings rheology.

3.1 Tailings Production Overview

3.1.1 Past Tailings Production (JEB, Sue A, Sue B, Sue C, Sue E)

Table 3.1-1 presents tailings production numbers for 1999 through 2024.

Table 3.1-1: Tailings Production 1999-2024

Year	Tailings Solids Generated (tonnes)							Annual Generated Tailings Solids (tonnes)
	JEB (tonnes)	Sue C (tonnes)	Sue A (tonnes)	Sue B (tonnes)	Sue E (tonnes)	(MED) SABRE (tonnes)	Cigar Lake (tonnes)	
1999	33,000	--	--	--	--	--	--	33,000
2000	75,000	31,000	--	--	--	--	--	106,000
2001	56,000	60,000	--	--	--	--	--	116,000
2002	53,000	79,000	--	--	--	--	--	132,000
2003	21,000	121,000	--	--	--	--	--	142,000

Year	Tailings Solids Generated (tonnes)							Annual Generated Tailings Solids (tonnes)
	JEB (tonnes)	Sue C (tonnes)	Sue A (tonnes)	Sue B (tonnes)	Sue E (tonnes)	(MED) SABRE (tonnes)	Cigar Lake (tonnes)	
2004	--	162,000	--	--	--	--	--	162,000
2005	--	162,000	26,000	--	--	--	--	188,000
2006	--	96,000	39,000	--	30,960	40	--	166,000
2007	--	17,900	16,000	--	167,000	100	--	201,000
2008	--	--	20,000	25,000	180,000	--	--	225,000
2009	--	--	44,900	44,900	149,000	200	--	239,000
2010	--	--	39,000	41,000	35,000	--	--	115,000
2011	--	--	--	--	--	--	--	567 *
2012	--	--	--	--	--	--	--	460 *
2013	--	--	--	--	--	--	--	1250 *
2014	--	--	--	3,370	--	810	3,650	7,830
2015	--	--	--	--	--	--	39,170	39,170
2016	--	--	--	--	--	--	67,370	67,370
2017	--	--	--	--	--	--	63,410	63,410
2018	--	--	--	--	--	--	64,740	64,740
2019	--	--	--	--	--	--	73,840	73,840
2020	--	--	--	--	--	--	41,814	41,814
2021	--	--	--	--	--	1,901	53,259	55,160
2022	--	--	--	--	--	--	81,137	81,137
2023	--	--	--	--	--	--	84,451	84,451
2024	--	--	--	--	--	--	98,854	98,854
Totals	238,000	728,900	184,900	114,270	561,960	3,051	671,695	2,502,776

* JEB Water Treatment Plant sludge production for treatment through Tailings Preparation process

3.1.2 Current and Potential Future Projects

Table 3.1-2 presents forecasted tailings production based on the mill production schedule.

Table 3.1-2: Tailings Production Schedule – Future Production Forecast

Year	Tailings Solids Generated (tonnes)					Annual Generated Tailings Solids (tonnes)
	SUE B	McClean (tonnes) (SABRE)	Midwest (tonnes)	Cigar Lake Main (tonnes)	Cigar Lake EXT (tonnes)	
2025		7,013		97,478		104,491
2026		8,628		103,982		112,610
2027		9,078		101,527		110,605
2028		9,487		103,467		112,953
2029		14,394		87,450		101,844
2030		19,268	208,475	65,371	5,684	298,799
2031		3,984	176,422	28,004	49,784	258,194
2032		2,078	194,059		102,947	299,084
2033			161,269		108,163	269,432
2034	8,990		154,122		112,272	275,384
2035	14,880		127,188		66,539	208,607
2036	28,898		78,009		49,482	156,389
Totals	52,768	73,930	1,099,544	587,279	494,872	2,308,394
% Total	2.29%	3.20%	47.63%	25.44%	21.44%	100.00%

3.2 Tailings Process Chemistry: Current Methods Development

During the design process for the McClean Lake Mill, tailings chemistry data from Saskatchewan uranium deposits mined since 1981 were reviewed with emphasis on tailings pore water arsenic chemistry. In particular, data were considered for tailings generated based on the ammonium sulfate stripping process, which is employed in the McClean Lake mill. A summary and discussion of historical test work and data are presented in detail in Appendix C, Section A.

Arsenic was identified as a primary constituent of potential concern (COPC). The historical test work reviewed did not focus on minimizing the arsenic source term in tailings pore water but rather was aimed at establishing neutralization and treatment processes which would yield treated effluent which meet the historical arsenic discharge limit of 0.5 mg/L. Test work was typically done under oxidizing conditions and aging tests were carried out in an oxidizing environment since sub-aerial deposition of tailings was being considered at the time.

Although these data do not represent the current McClean Lake tailings preparation process, they are discussed briefly because they represent the starting point for tailings chemistry investigations conducted since 1997 that led to the development of the ferric sulfate process for control of dissolved arsenic in tailings preparation circuit.

The following observations were made based on the review of historical uranium tailings chemistry data from actual mine operations in Northern Saskatchewan:

- Considerable variation in pore water arsenic concentration is observed between tests and ore bodies.

- In the neutralization process, addition of lime is used to raise the pH. Arsenic concentrations are not directly controlled.
- In the high pH environment, most heavy metals, including arsenic, report to the solid phase through secondary mineral precipitation and formation of adsorption complexes.
  Composition of the starting raffinate can affect the final arsenic pore water concentration leading to variable results.

- It was observed that ores that produce high iron/arsenic molar ratios in the starting raffinate achieve lower arsenic pore water concentrations in the final pore water.

- Over the long-term, the high terminal pH used in this tailings preparation technology will decrease, possibly resulting in changes in pore water arsenic concentration.

- In general, long-term concentrations were not well evaluated or documented, creating some uncertainty concerning the evolution of the arsenic pore water concentration into the future.

3.2.1 Pre-Operational Test Work: Development of a Ferric Iron Process for Arsenic Control

3.2.1.1 Arsenic Control Scoping Test Work

Initial groundwater modelling, completed during 1997, focused the tailings preparation technology requirement on improved arsenic control. To avoid potential long-term impact in nearby Fox Lake, the technology utilized, had to consistently achieve low pore water arsenic concentrations in the tailings (≤ 1 mg/L). The arsenic pore water concentrations had to remain low after tailings placement in the TMF and over the long-term.

Scoping tests were initiated to form the basis for selecting the most promising approach to achieve the requirements. The three processes considered either specifically removed arsenic and/or would result in low pore water arsenic concentrations:

1. arsenic precipitation with ferric sulfate and lime addition as a function of Fe^{3+}/As ratio and pH ;

2. arsenic (V) co-precipitation with phosphate; and,
3. arsenic precipitation by chemical reduction with organic matter.

The scoping tests were conducted on samples of JEB tailings and Cigar Lake tailings. Details of the investigations are provided in Appendix C, Section B.

For the ferric - arsenic precipitation tests (scenario 1), it was found that the lowest arsenic concentrations were produced at a near neutral pH. Addition of Fe^{3+} to raffinate prior to neutralization resulted in a ten-fold decrease in the arsenic pore water concentration to less than 1 mg/L.

Initial organic reduction evaluations were carried out (scenario 3) and partial reduction of arsenic was observed. However, it was found that the reactions involving arsenic reduction by the addition of organic matter occur far too slowly for control purposes to be applicable to conventional processing equipment.

Arsenic co-precipitation with phosphate test work (scenario 2) was initiated but never completed. It was quickly apparent that this technique was not compatible with the scoping test study design. Under plant conditions, the expected solubilities were too high, and the neutralization process required a high terminal pH (>9).

Given the extensive published work on ferric - arsenic co-precipitation as secondary minerals as well as arsenic-adsorbed Fe^{3+} oxy-hydroxide mineral phases, and the results of related scoping tests involving JEB raffinate and tailings, it was decided that this approach was best scenario for controlling source arsenic concentrations within the TMF. This decision was based in part on potential costs and engineering difficulties associated with arsenic removal by reduction or phosphate co-precipitation, and on the fact that neither of these alternatives have demonstrated proven performance in practical application.

3.2.1.2 Laboratory Studies (Large-Scale Tests)

Large-scale testing of the ferric iron process was undertaken in the COGEMA/SEPA pilot plant facilities in Bessines, France (Appendix C, Section C, Part A, Subsection C) The purpose of the test program was to evaluate the impact of Fe^{3+} additions on dissolved arsenic concentrations in tailings raffinates of the McClean, Midwest and Cigar Lake ores, and in pore waters of placed tailings.

<u>Neutralization Tests:</u> (designated as Procedure 1: Appendix C, Section C, Part A, Subsection C) These tests were designed to approximate the reactions that take place in the plant tailings preparation process. These tests included the addition of ferric sulfate to raffinate solution/ tailings preparation feed solution to obtain various iron/arsenic ratios prior to neutralization, followed by lime addition to selected terminal pHs. The intent was to define optimal conditions for removal of dissolved arsenic from the raffinate solutions during processing of the tailings and to provide the necessary design criteria for controlling the process in

the JEB mill. Neutralization tests were run for 3 hours, which approximates the residence time of the tailings in the preparation process.

Accelerated Aging Tests: (Procedure 2: Appendix C, Section C, Part A, Subsection C) These tests were designed to facilitate the prediction of the long-term arsenic source concentrations in tailings pore waters. Tests were conducted over durations ranging from 5 days to 50 days. Similar to the neutralization tests, experiments were conducted at varied neutralization pH values and iron/arsenic ratios. All aging tests were conducted under conditions that replicate conditions for placed tailings within the TMF under a water cover. Samples were mechanically agitated throughout the test to accelerate the aging process. For future reference, this aging protocol is referred to as the “SEPA technique” (Appendix C, Section C, Part A, Subsection C).

Tables 3.2-1 and 3.2-2 present summaries of the large-scale test results. The detailed neutralization studies determined that arsenic and nickel concentrations could be maintained at 1 mg/L or less for all ores expected to be processed by the JEB mill. The iron/arsenic molar ratio must be adjusted to 3 or greater prior to neutralization with lime to pH 8. These values were taken as the design criteria for the tailings preparation process.

Modifications to the McClean Lake JEB Mill Tailings Preparation Process, for incorporation of ferric iron addition, were completed during the winter of 1999. The infrastructure added included reagent unloading facilities, tankage for ferric sulfate, pumps and piping for distribution and a launder system to improve reagent addition for the ferric sulfate feed to the mix tank in tailings preparation.

Observations during the experimental work suggested that arsenic in the tailings pore water is precipitated as a mineral phase rather than sorbed onto ferric oxyhydroxides as often reported in literature. Geochemical modelling and mineralogical investigations also supported the view that arsenic in the tailings pore water is controlled by ferric arsenates that are formed during the neutralization process. The predominant presence of arsenate minerals (scorodite) rather than sorbed arsenic provided a high degree of confidence in the predicted concentrations of arsenic over the long term. Predictions indicate that arsenic would remain at around 1 mg/L in the tailings pore water beyond 10,000 years at a temperature of 4°C expected in the TMF. A full discussion of the current updates to the arsenic geochemical model can be found in Section 5.5.1.

3.2.1.3 Mill Process Chemistry Verification

Pre-operational laboratory testing indicated that levels of soluble arsenic in tailings pore water could be maintained below 1 mg/L by addition of iron to the tailings preparation process to ensure a molar iron/arsenic ratio above 3:1. Laboratory testing also showed that the final pH of tailings solutions should be near 8 to minimize the solubility of trace metals such as nickel.

The objective of the mill chemistry verification program was to confirm that the results obtained in the laboratory, specifically the arsenic and nickel control by ferric addition and pH adjustment respectively, are applicable to full-scale tailings production.

The verification program was conducted by operating the JEB mill tailings preparation process (Figure 3.21) at various iron/arsenic ratios and neutralization pH values and observing the resultant arsenic and nickel concentrations in tailings pore water. Each operating setting was maintained for seven to ten days. The details of the test procedures and results are presented in COGEMA (2000). Based on the test results, it was concluded that ferric iron addition to maintain the iron/arsenic ratio above 3:1 with a terminal neutralization pH of approximately 8, control arsenic and nickel concentrations in tailings pore water at or below 1 mg/L. The sensitivities obtained for arsenic and nickel concentrations to iron/arsenic molar ratio and terminal pH are shown in Figures 3.2-2 and 3.2-3, respectively. These findings confirmed the pre-operational test work results.

Table 3.2-1: Experimental Runs Conducted at Selected Fe/As Molar Ratios in the Tailings Raffinate Solutions

	Fe/As Molar	**Temperature**
Ore	**Ratio[1]**	**(°C)**
JEB	2.6, 3.0, 5.0	50
McClean	4.6, 5.0	50
Sue A + B	0.6, 3.0, 5.0	50
Sue C[2]	7.7	50
Cigar[2]	7.5	50
Blend 0 (75% Midwest, 25% Sue A + B)	0.4, 3.0, 5.0	50
Blend 1 (75% Sue C, 25% Cigar)[2]	7.6	50
Blend 2 (55% Midwest, 15% Sue A+B, 30% Cigar)	0.3, 3.0, 5.0	50
JEB	2.6, 3.0, 5.0	25
McClean	4.6, 5.0	25
Sue A + B	0.6, 3.0, 5.0	25
Sue C[2]	7.7	25
Blend 0 (75% Midwest, 25% Sue A + B)	0.4, 3.0, 5.0	25
Blend 1 (75% Sue C, 25% Cigar)[2]	7.6	25
Blend 2 (55% Midwest, 15% Sue A+B, 30% Cigar)	0.3, 3.0, 5.0	25
Cigar[2]	7.5	25
JEB	3.0, 5.0	4
Sue C[2]	7.7	4
Blend 2 (55% Midwest, 15% Sue A+B, 30% Cigar)	3	4

[1] Each Fe/As ratio was tested at nominal neutralization pH values of 7, 8 and 9.
[2] Ores with Fe/As values of greater than 7 reflect the natural high iron content. Ferric iron was not added.

Table 3.2-2: Summary of Source-Term Concentrations Corrected to 4°C

Ore[1]	Fe/As	Arsenic (mg/L) [a]			Nickel (mg/L)[5]		
		Nominal Neutralization pH[2]			Nominal Neutralization pH[2]		
		8	**8.5**	**9**	**8**	**8.5**	**9**
JEB	5	0.68±0.13	0.68±0.13	0.47±0.01[3]	0.64±0.08	0.15±0.03	0.033±0.01
Sue C	7.7	0.10±0.05	0.17±0.04	0.24±0.02	0.55±0.31	0.09±0.06	0.015±0.01
McClean Lake	5	0.43±0.11	1.07±0.38	1.71±0.64	0.19±0.03	0.11±0.03	0.065±0.02
Sue A+B	3	0.51±0.09	1.04±0.30	1.56±0.51	1.35±0.7	0.76±0.7	0.43±0.6
Cigar Lake	7.5	0.17±0.04	0.31±0.05	0.45±0.06	0.59±0.35	0.16±0.10	0.045±0.03
Blend 1	7.6	0.13±0.03	0.20±0.03	0.26±0.03	0.27±0.06	0.10±0.05	0.04±0.03
Blend 2	3	0.54±0.3	0.86±0.32	1.18±0.33	1.53±0.63	0.34±0.12	0.075±0.02
JEB[4]	7	0.35±0.07	0.35±0.07	0.24±0.01	0.64±0.08	0.15±0.03	0.033±0.01
McClean Lake[4]	7	0.22±0.06	0.82±0.31	1.42±0.56	0.19±0.03	0.11±0.03	0.065±0.02

[1] Blend 1: 75% Sue C + 25% Cigar Lake; Blend 2: 55% Midwest + 15% Sue A+B + 30% Cigar Lake.
[2] Concentrations at pH 8.5 were estimated from values at pH = 8 and 9.
[3] Based on only three data points before sample lost - was not used in calculations.
[4] Estimated concentrations for Fe/As = 7 for comparison. Note that only arsenic concentrations are affected. Weighted average concentrations for arsenic in the entire tailings mass is not significantly affected.

[5] Nickel values were calculated as the average values from 4°C and 25° data from Appendix C, Section C, Part A.
[a] mg/L = milligrams per litre

Figure 3.2-1: Schematic of the Original JEB Mill Tailings Preparation Circuit

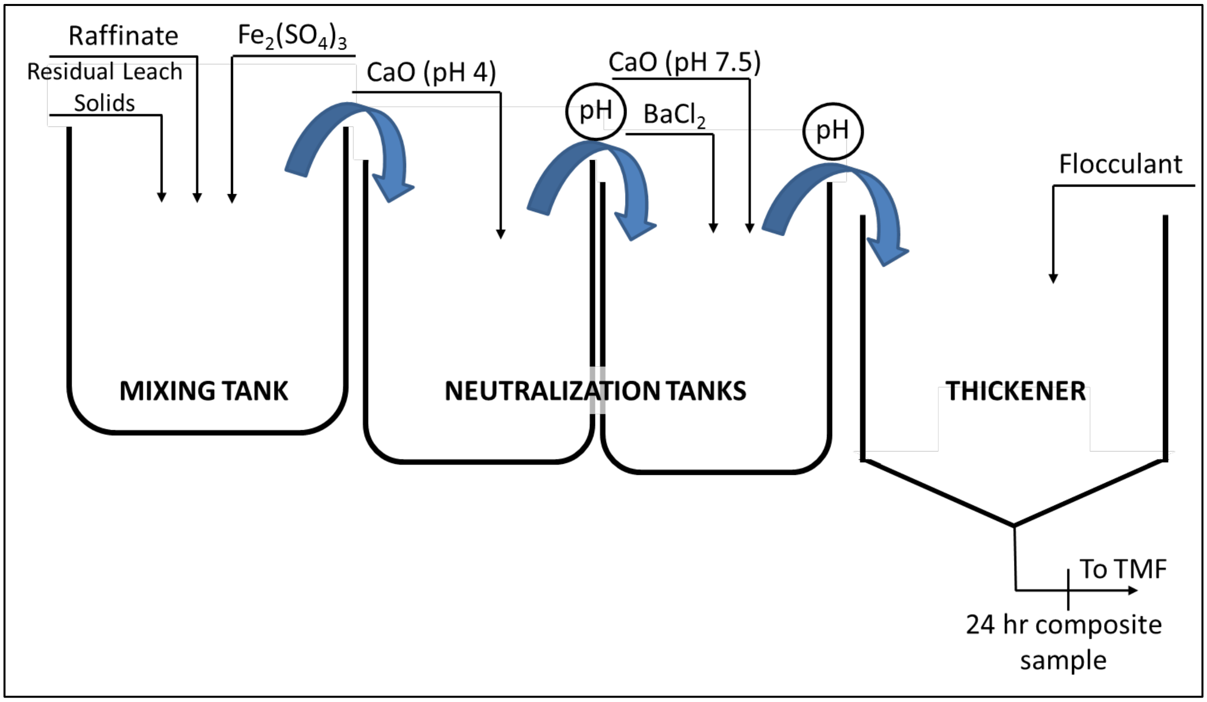


Figure 3.2-2: Effect of Fe/As Ratio on Tailings Pore Water Concentration

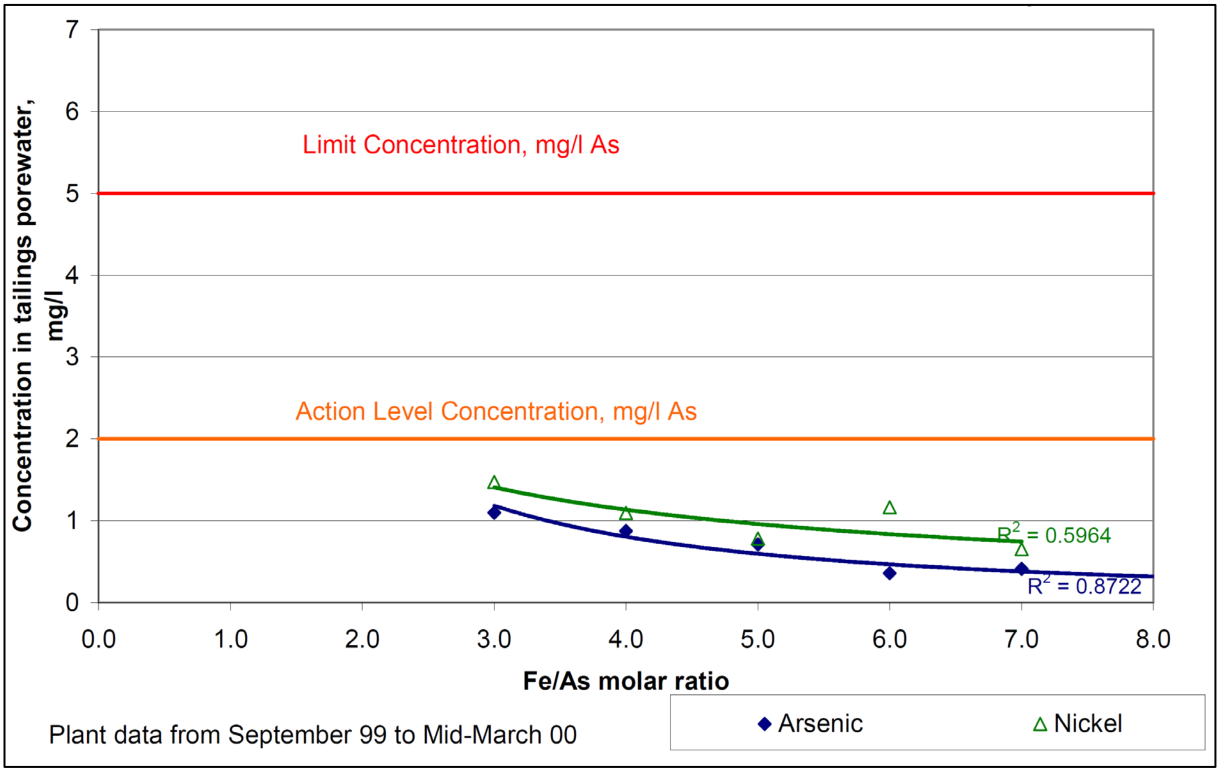
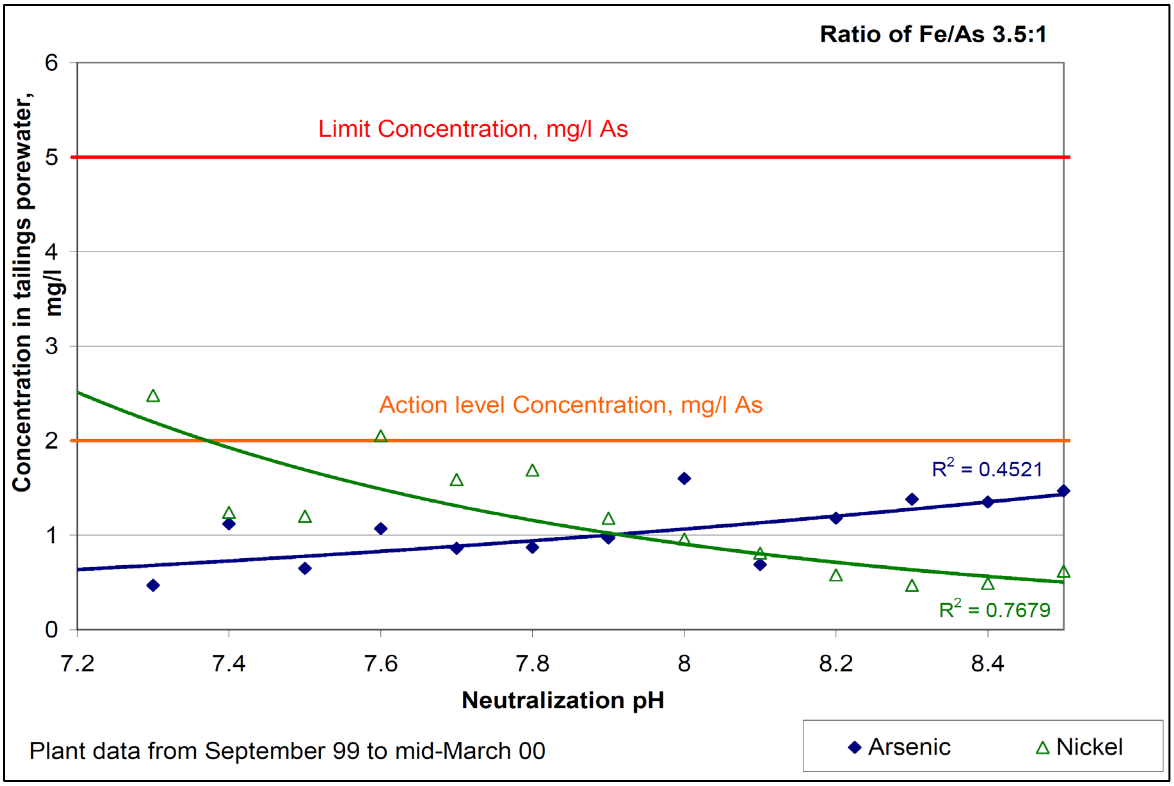


Figure 3.2-3: Effect of Neutralization of pH on Tailings Pore Water Concentration



3.2.2 Operational Test Work: Tailings Production Process Optimization

To build upon the results of the extensive pre-operational laboratory investigations (described above), minimize uncertainties related to the pre-operational test work, and to optimize the tailings preparation process, from 2000 to the present, additional test work has been conducted using operationally produced tailings. From a broad perspective, the studies have focused on several topics:

- investigations of fundamental variables in the tailings process:
  - retention time,
  - pH,
  - iron/arsenic molar ratio,
  - seeding, and
  - oxidation state

- optimization of the control parameters for the existing tailings preparation circuit to produce arsenic bearing secondary minerals with the lowest solubility;

- identification and quantification of the arsenic secondary minerals produced in the tailings preparation circuit; and
- investigation of the long-term stability of arsenic bearing secondary minerals.

The current arsenic treatment process using two-stage neutralization at pH 4 and 8 is meeting the expectations with respect to overall tailings as indicated by the analysis of produced tailings as well as the TMF in situ monitoring results to date (Section 5.7).

3.2.2.1 Precipitation of Long-term Arsenic Mineral Phases:

Adsorption/Desorption Test Work: Assessing Adsorption/desorption of arsenic to ferrihydrite was completed in 2001 and a comprehensive report is included in COGEMA (2002). The study concluded that less than 0.2% of the total arsenic in the tailings was reversibly sorbed to solids. These results supported the conclusions of the pre-operational test work which found that predominant amount of arsenic in the tailings will be precipitated as stable long-term oxidized mineral (scorodite).

Arsenic Mineralogical Studies: Under the TOVP, mineralogical studies have been conducted to identify and quantify the arsenic bearing secondary minerals present in both solids produced in the tailings preparation circuit as well as the placed tailings since the beginning of operations (COGEMA, 2000; COGEMA, 2001a; COGEMA, 2002; COGEMA, 2003; COGEMA, 2004a; AREVA, 2005b; AREVA, 2011a, AREVA, 2015a, Orano 2020 and this document Sections 5.3 and 5.5.1). Techniques utilized for identification include chemical analysis and mass balance, visual microscopy, X-ray diffraction, scanning electron microscopy, electron microprobe analysis, and most recently, synchrotron-based X-ray absorption spectroscopy.

3.2.2.2 Aging of Long-term Arsenic Mineral Phases in Tailings:

Start-Up Aging Tests: Laboratory based aging of mill tailings (TOVP aging tests) has been carried out to assess the long-term stability of the arsenic bearing minerals produced in the tailings preparation circuit. TOVP aging tests were developed and carried out in 2000 and reported in COGEMA (2001a) and COGEMA (2002). These aging tests were conducted for a 10-month duration without agitation and were designed to better approximate the tailings aging process in the TMF. The TOVP aging tests exhibited a transient rise and fall in pore water arsenic concentrations, which was not observed with the SEPA procedure.

Cigar Lake Aging Tests: Additional aging tests have been conducted in conjunction with the milling of Cigar Lake ore. To expand on lessons learned from the results of previous tailings aging tests, samples of tailings from the mill were used and were selected based on variations in actual mill conditions with respect to the iron/arsenic molar ratio. The samples were split, and half were run as “accelerated” aging test, which were rolled at approximately 20°C to advance aging process more quickly, while the second half of the tests were “long-term” and were maintained under static conditions. Aging test results for the Cigar Lake tailings generally demonstrated low and controlled arsenic pore water values throughout the duration of both types of tests. The long-term static testing was introduced to incorporate the lessons learned from the initial McClean Lake aging tests in an attempt to capture the rise and fall of arsenic concentrations in the pore water as detailed in the arsenic geochemical model (Section 5.5.1). No distinctive rise in arsenic concentrations was noted in the long-term aging test. Full aging test results are reported in Section 5.3.

Pore water analytical results from the ongoing TMF in-situ sampling campaigns will continue to be used to confirm that the laboratory aging test work predictions have provided a reliable basis for long term performance of in-situ tailings.

3.2.3 In-Situ Monitoring: Tailings Optimization and Validation Program

In 2001, the first full scale annual assessment of the characteristics of the placed tailings within the TMF was undertaken following deposition of significant quantities of tailings within the TMF. Additional full-scale assessments were conducted in 2002, 2003, 2004, 2008, 2013, 2018 and 2023. As part of these investigations, tailings samples are collected from the mass of placed tailings using a barge-mounted drill rig. Samples are separated into pore water and solid sub-samples for various analyses. The sampling results of the 2023 investigations are presented in Appendix D and full results descriptions of all campaigns are found in Appendix F (COGEMA, 2002; COGEMA 2003a; COGEMA, 2004a; AREVA, 2005a and b; AREVA, 2011a, AREVA 2015a, Orano 2020) and this document in Section 5.0. Through the TOVP, the evolution of pore water arsenic concentrations has been tracked and studied. This has led to important optimizations of the mill process for long-term arsenic control in tailings pore water as described below.

3.2.4 Optimizations to Control Arsenic in Tailings Pore Water

Operational test work and TOVP campaign results have reaffirmed the design of the McClean Lake tailings preparation process with respect to the management of arsenic source terms and have not identified the need for large-scale changes. Testing confirmed that the final pore water arsenic concentration primarily depends on the iron/arsenic molar ratio prior to neutralization in the tailings preparation process and so, over time, the calculation of the molar ratio has been refined to incorporate observations from TOVP sampling campaigns of in-situ tailings:

- Initial Condition: **$\mathrm{Fe}_{(total)}$/ $\mathrm{As}_{(total\ solution):}$**. Under initial mill conditions, the total iron available in the ore was assumed to come into solution in the mill and be available to precipitate arsenic from solution. The amount of ferric sulfate needed to achieve the Fe/As ratio was calculated based on iron analysis of the incoming ore.

- 2004: **$\mathrm{Fe}^{3+}_{(solution)}$: $\mathrm{As}_{(total\ solution)}$**: In certain early ores (Sue C) milled at MLO, the total iron measured in the ore was not completely available to control pore water arsenic concentration. Because total iron in the ore was included in the accounting of iron in the system, insufficient ferric sulfate was added during tailing's preparation to meet the required 3:1 ratio. To account for this, the ratio was adjusted in 2004 to include only Fe^{3+} in solution as measured in the tailings feed tank.

- 2006:

  - The Fe/As ratio remained the same; however, ferric sulfate began being added to the leach circuit as an oxidizing agent. This initiated the precipitation of ferric arsenate minerals (scorodite) earlier in the mill process. The overall Fe/As ratio is then assessed, as previously, in the tailings feed tank and additional ferric sulfate is added as needed.

  - Hydrogen Peroxide (H_2O_2) was added to the tailings preparation process as an additional source of oxidant. This served to further oxidize any reduced mineral phases which were not fully oxidized in the leaching stage of the milling process. This change assisted in oxidizing any residual unleached reduced arsenic.

- 2008: **Fe^{3+}/ As_{tot}+$Mo_{tot\ (solution)}$:** Molybdenum was included in the Fe/As ratio to account for the competing effect of molybdenum using Fe^{3+} to precipitate ferrimolybdite and molybdate adsorbed on ferrihydrite in the tailings process.

- 2018: **Fe^{3+}/ $As_{tot\ (sediment)}$ and Fe^{3+}/ As_{tot}+$Mo_{tot\ (solution)}$** The processing of Cigar Lake ore, which is known to be high in arsenic, introduced a higher proportion of reduced arsenic minerals into the mill process. Not all of this reduced arsenic is fully oxidized in the mill and a residual portion reports to the tailings. It is understood, through examination of previously placed tailings samples, that the oxidation of primary arsenic in the JEB TMF would produce an arsenic source term in the pore water due to aging effects (Section 5.5.1). To eliminate the possibility of developing an elevated arsenic source term in the tailings from the increased loading of unleached arsenic, the Fe^{3+}/As ratio was updated to account for reduced arsenic measured in the Counter Current Decantation (CCD#6) underflow discharge leach residue. This secondary Fe^{3+}/As ratio was 14:1 so as to account for the total leaching, oxidation, and re-precipitation of arsenic in placed tailings as per the reaction below:

$$\underset{\text{(gersdorffite)}}{\overset{[As^{1-}]}{NiAsS\downarrow}} + \mathbf{14Fe^{3+}} + 10H_2O \rightarrow \underset{\text{(scorodite)}}{\overset{[As^{5+}]}{FeAsO_4\cdot 2H_2O\downarrow}} + 13Fe^{2+} + SO_4^{2-} + Ni^{2+} + 16H^+$$

  For the purposes of estimation, the reduced arsenic mineralogy of the Cigar Lake deposit is conservatively assumed to be 100% gersdorffite (NiAsS). Previous ores fed to the McClean Lake Mill contained both Niccoline (NiAs) and Rammelsbergite ($NiAs_2$) which would, assuming they were the only reduced arsenic mineral present, require much less ferric iron at, Fe^{3+}/As ratio of 9:1 and 13:1 respectively. Testing of the Cigar Lake ore (Kacowka, 2017) and mineralogical testing of the Cigar Lake tailings (Section 5.3.2) have confirmed that gersdorffite is the dominant reduced arsenic mineral phase. Niccoline and rammelsbergite are minor accessory phases and therefore no discount to the ferric addition is applied to account for them. The previous Fe^{3+}/ As_{tot}+$Mo_{tot\ (solution)}$ ratio of 3:1 remains unchanged as is applied to the liquid phase only. To manage the addition of ferric iron in the TPC a ferric calculator was developed to account for key process inputs and automatically adjust the amount of ferric sulfate needed on a daily basis further discussed in section 3.3.2.

Validation of these changes are ongoing and will continue to be presented in updates to the TOVP reporting including:

- Evaluation of primary arsenic mineralogy in the Cigar Lake tailings (Orano 2020,Section 5.3.2 and Section 5.3.2 of this document)

- Evaluation of aging tests conducted on Cigar Lake tailings produced using the new 14:1 Fe^{3+}: As molar ratio (Orano 2020, Section 5.3.3)
- Geochemical Modelling investigations of arsenic speciation in the tailings (Section 5.5.1 of this document)
- General overview of geochemical sampling results (Section 5.7 of this document)

In the introduction of the 14:1 Fe^{3+}: As ratio, several assumptions are incorporated which add conservatism to the ferric calculator:

- The 14:1 ratio is applied to arsenic in the solid leach residue, which reports to the tailings preparation process from the CCD#6 underflow after leaching. This solid arsenic is not regularly tested for speciation but is conservatively assumed to be composed of 100% reduced arsenic (As^{-1}) in the form gersdorffite. It is likely, that since ferric sulfate is added to the leach process, some portion of the oxidized/leached arsenic (As^{5+}) will re-precipitate as ferric arsenate and report in the leach residue (CCD#6 underflow) to the tailings preparation circuit. Therefore, a significant portion of the leach residue arsenic may already be in the As^{5+} oxidation state.
- Iron mineral phase(s) in the leach residue may have the potential to act as a long-term source of Fe^{3+} in the placed tailings. Investigations of the evolution of iron mineral phases through the milling and tailings preparation processes are currently in progress in partnership with the University of Saskatchewan
- All of the primary arsenic mineralization, which reports to the McClean Lake mill in the ore, is conservatively assumed to oxidize during milling process and in the placed tailings over time. It is likely that some percentage of the primary arsenic minerals will be prevented from fully oxidizing due to factors such as:
    - Encapsulation by recalcitrant primary mineral such as clays
    - Encapsulation by the precipitation of secondary minerals such as gypsum
    - The development of oxidized rinds around the mineral grain which prevents the core from fully oxidizing.

      The liberation of primary arsenic mineral grains in the tailings is further examined in Orano 2020 (Section 5.3.2) and Section 5.3.2.4 of this document.

- 2020-2023: Refinement of Fe3+/ Astot (sediment) and Fe3+/ Astot+Motot (solution): Test work has been conducted during the current reporting period to refine some of the conservatism in the 14:1 Fe3+/As ratio based on assumptions described above. CCD#6 underflow leach residue samples were collected periodically to characterize arsenic and iron phases using synchrotron based XANES (Figure 3.2-4) and PXRD as well as QEMSCAN analytical techniques (Figure 3.2-5).

The characterization of the CCD#6 underflow leach residue over the reporting period indicates on the average:

- 24% of arsenic in the leach residue, which reports to the tailings preparation circuit, is oxidized (As^{5+});
- 31% of iron in the leach residue occur as secondary mineral phases such as ferrihydrite and goethite; and
- 5% of the arsenic in the leach residue is fully encapsulated by recalcitrant primary mineral such as clays and quartz.

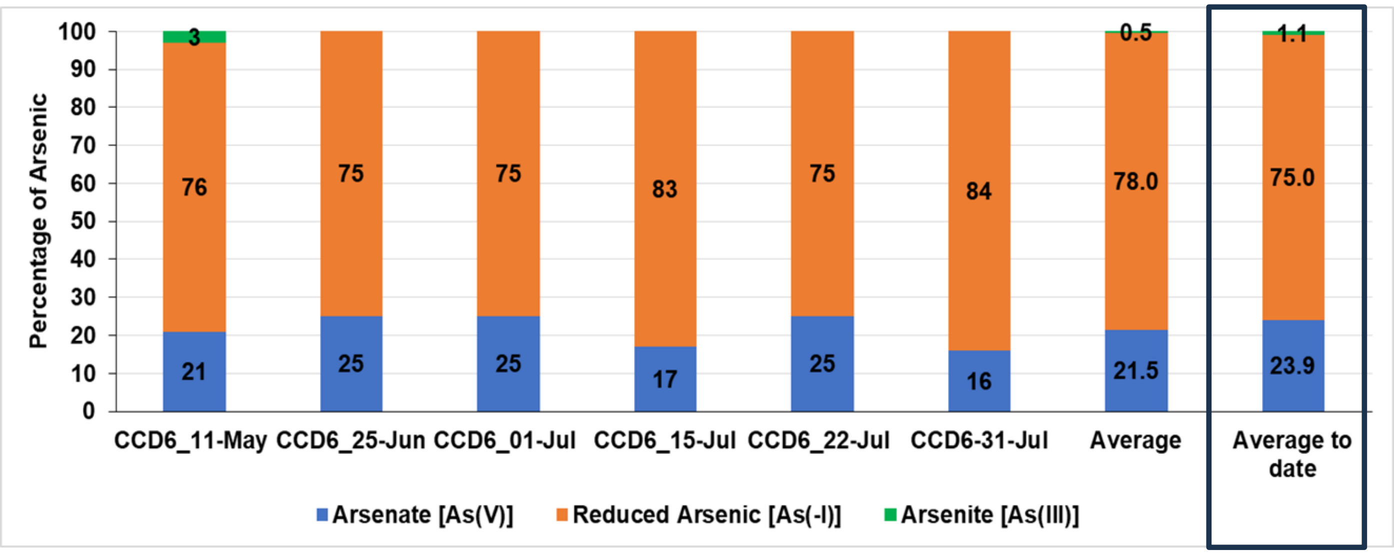
Based on the evaluation of the assumptions in the 14:1 $Fe^{3+/}As_{tot}$ ratio the ferric calculator has been conservatively revised to include the following conservative assumptions:

- 12 % arsenic is in the leach residue, which reports to the tailings preparation circuit, is assumed to be oxidized (As^{5+}); and
- 5% of the solid iron in the leach residue exists as secondary mineral phases, which are assumed to be available as ferric iron in tailings preparation and placed tailings.
- No changes were made based on the observations of encapsulated arsenic phases

These assumptions were selected to remain below the observed test results to maintain a significant amount of conservatism in the ferric calculator. Evaluation of these changes are ongoing with tailings aging tests and collaborative research with Researchers at U of S.

Figure 3.2-4: **Synchrotron based XANES Analysis Results of CCD#6 underflow leach residue samples showing Arsenic (a) and Iron (b) speciation.**

(a)



(b)

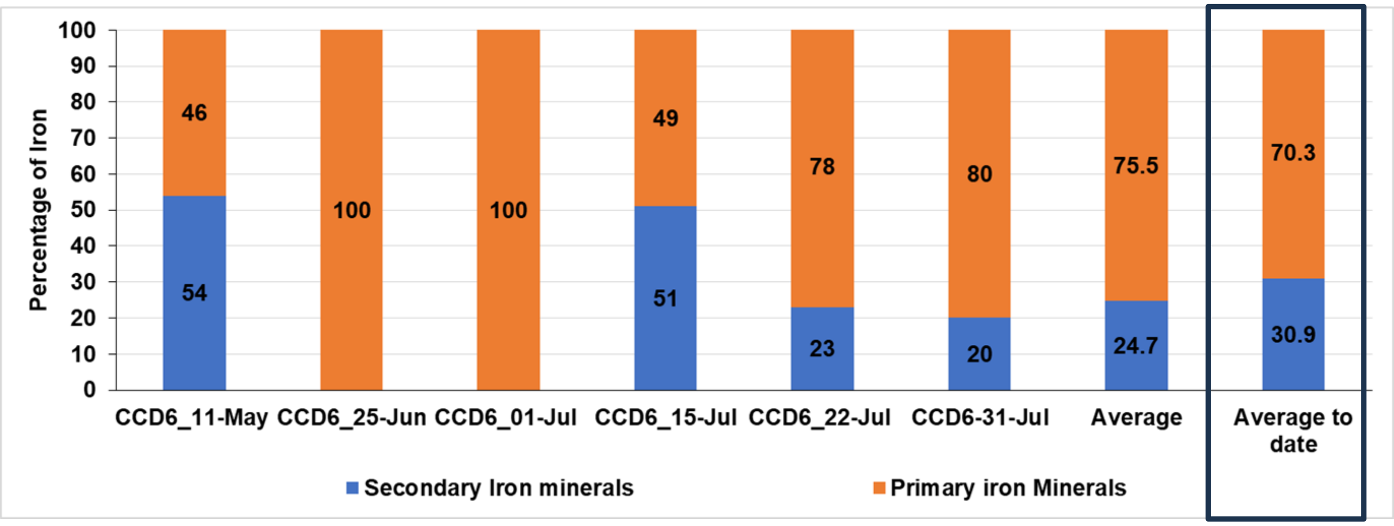
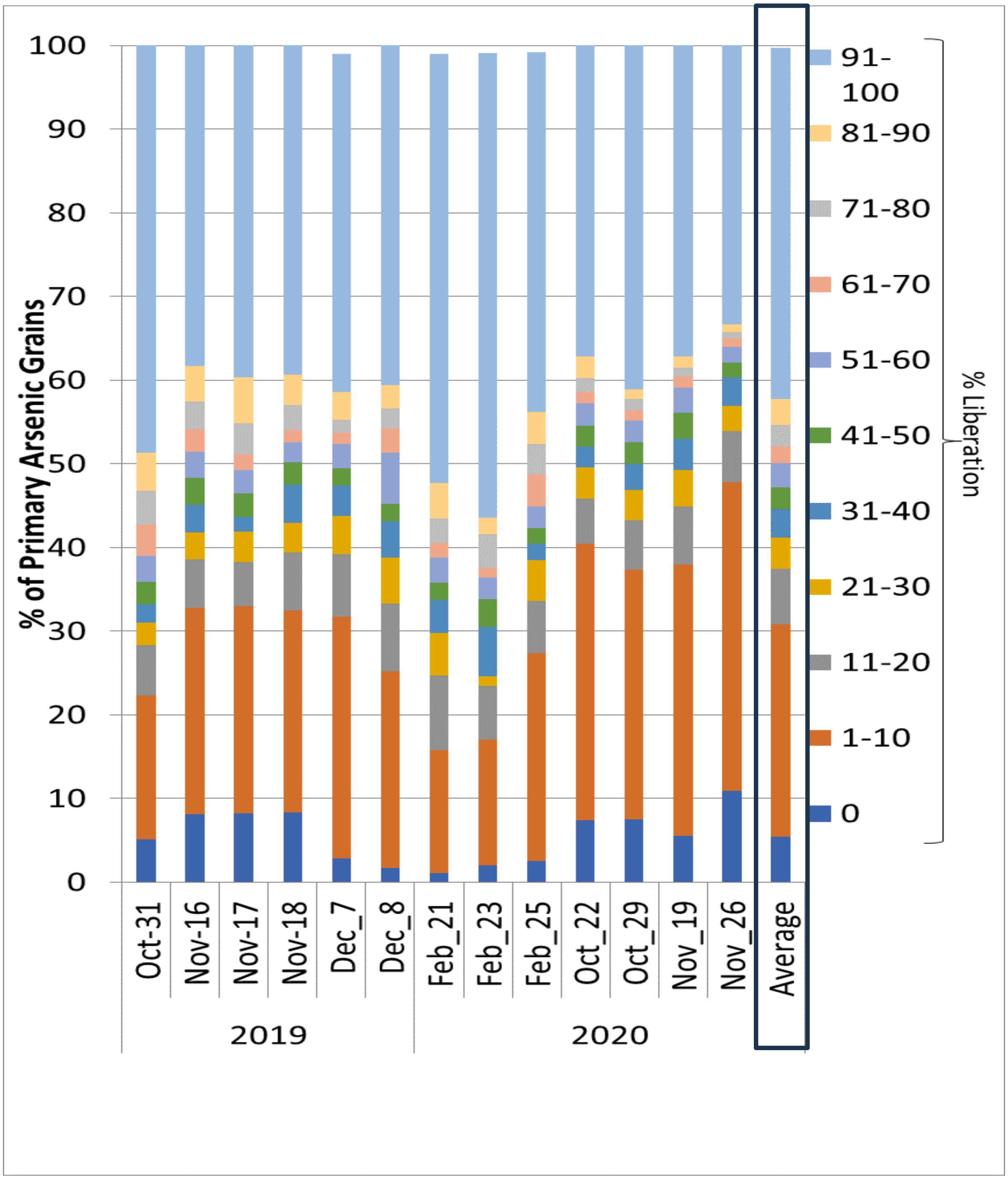


Figure 3.2-5: **QEMSCAN Liberation Analysis of Results of CCD#6 underflow leach residue samples showing ranges for fully encapsulated primary arsenic grains (0) to fully liberated primary arsenic grains (91-100)**



3.3 Mill Operations Tailings Preparations Guidelines

3.3.1 Overview of Key Operational Parameters

The Tailings Preparation circuit guidelines, based on the original design of the process, with subsequent input from optimization efforts, troubleshooting investigations, and findings from the ongoing TOVP program have resulted in the following key operating parameters of the tailings preparation process. Operational and Regulatory guidelines for the monitoring of the Tailings Preparation Process (TPP) are presented in Section 2.2.1.

- Both slurry and liquid wastes are combined and homogenized within the Tailings Preparation circuit feed tank.

- Maintaining the Tailings Preparation circuit feed tank solution pH at less than 1.5. This ensures the dissolution of particulates found in the spent regenerate solution and JEB WTP sludge. Maintaining the feed tank solution pH at less than 1.5 also help drives off CO_2 from any (bi)carbonates so as to the reduce potential for bicarbonate dissolution of uranium in the JEB TMF (Section 5.5.3).

- Dilute hydrogen peroxide (22%) is added to the Tailings feed tank to ensure redox conditions remain oxic, to ensure that reduced aqueous species are fully oxidized for treatment in the tailings preparation process and also to enhance decomposition of any residual organics.

- The Tailings feed tank maintains a ferric iron to combined dissolved arsenic and molybdenum concentration {Fe^{+3}/(As+Mo)} of 3:1 and Fe^{+3}/As molar ratio of 14:1 for any unleached arsenic considered as gersdorffite (from CCD thickener #6 underflow) with the addition of 45% ferric sulfate solution.

- Tailings Preparation reaction tank #1 maintains a solution pH of 4 through addition of slaked lime.

- Enhanced radium removal is observed when barium chloride solution is added to the Tailings neutralization tank #2. This is due to the lower soluble sulfate concentrations in reaction tank #2, after the majority of gypsum precipitation occurs in Tailings reaction tank #1.

- Tailings Preparation reaction tank #3 maintains a terminal pH of 7.5 to 8.5 through slaked lime addition, as well. Tailings preparation slurry is directed to the Tailings thickener, where the slurry is thickened to a target density of ~25 % solids, by weight.

3.3.2 Detailed Treatment Overview of Key COPCs

3.3.2.1 Arsenic Treatment

Arsenic Removal

Removal of arsenic (As) from mill waste solutions is achieved in the TPP through co-precipitation with ferric iron through the following steps:

- Addition and mixing of ferric sulfate solution with the acidic waste streams in the feed tank.
- A primary neutralization step, which involves directing the tailings feed slurry (combination of solution and solids) from the feed tank to a continuous flow reactor. Within the reactor, slaked lime is added to the tank contents to control the solution pH to 4. At this pH, dissolved arsenic is co-precipitated with ferric iron to form poorly crystalline scorodite. The nominal retention time of the Tailings Preparation circuit reaction tank #1 is 90 minutes.
- The slurry from TPP reaction tank #1 is forwarded to TPP reaction tank #2 for additional residence time at pH 4 (optional).
- The slurry from reaction tank #2 is sent to TPP reaction tank #3. Slaked lime is added to this tank to achieve a terminal pH of 7.5 to 8.2. Within this tank, residual heavy metals are precipitated as hydroxides onto the surface of the seed precipitates from reaction tank #1 and #2. The nominal retention time of this tank is also 90 minutes.

Key Reagent: Ferric Iron

Ferric Source: The source of ferric iron for arsenic treatment in tailings preparation is derived from two sources: Primarily, dissolved iron from the ore measured in the raffinate and additionally, ferric iron is provided by the addition of ferric sulfate.

The circuit can use sourced commercial grade ferric sulfate or locally manufactured ferric sulfate product at the McClean Lake mill. In both cases, the ferric sulfate is transferred to the mill reagents area. Pumps distribute the solution to the ferric sulfate reagent loop, where an auto-valve controls the addition rate of ferric sulfate to the tailings preparation circuit.

Ferric Addition Calculation (the Ferric Calculator): Since the raffinate from solvent extraction and the CCD thickener #6 underflow are the primary sources of arsenic as well as ferric feed to tailings neutralization, a composite from these streams is collected on a daily basis and analyzed to determine the additional ferric requirements for tailings preparation. The ferric sulfate addition rate is subsequently adjusted to maintain the desired Fe^{+3}/(As+Mo) molar ratio in the feed tank for tailings preparation. The current processing of Cigar Lake ore, with its high variability for arsenic and other constituents of concerns, has resulted in an evolution of the ferric iron addition rate, to ensure that sufficient ferric iron concentrations are added to the tailings feed solution (as discussed above). Currently, ferric sulfate is added in the feed tank to maintain a dissolved (aqueous phase) Fe/(As+Mo) molar ratio of 3:1 and Fe^{+3}/As molar ratio of 14:1 (with conservative adjustments as discussed above) for any unleached arsenic (from CCD thickener #6 underflow).

3.3.2.2 Radium Treatment

Radium Removal

Radium is removed from solution through co-precipitation with barium sulfate using a barium chloride solution added in the TPP. It is possible to add barium chloride to the tailings neutralization feed tank or the final neutralization tank. The preferred addition point, based on operational performance, is neutralization tank #2 and neutralization tank #3 if required.

Key Reagent: Barium Chloride

Barium chloride is received in 1200 kg totes and mixed into a barium chloride solution made up to an approximate concentration of 12.5% by weight and transferred by pump to a storage tank. The prepared barium chloride solution is metered to the TPP neutralization tank #2 or #3. Originally the barium chloride solution was added to the tailings feed tank. However, visual observations of barium chloride addition to the feed tank identified the rapid precipitation of barium upon contacting the surface of the sulfate enriched solution. Analysis of the tailings feed solution determined that sulfate concentrations were extremely high, resulting in immediate precipitation of barium upon contacting the tailings feed solution. This did not allow for adequate mixing of the reagent with the feed solution, resulting in poor efficiency for the co-precipitation of barium-radium sulfate. Addition to the feed tank required a significant dose rate for effective removal of radium.

Laboratory experimentation determined that barium chloride addition to later stages of the Tailings Preparation process would reduce barium chloride consumption rates, without affecting the removal efficiency of radium. It was determined that dosing barium chloride solution after reaction tank #1, where gypsum precipitation has reduced soluble sulfate concentrations, resulted in enhanced mixing of the reagent, and subsequent enhanced radium removal performance.

3.3.2.3 Molybdenum Treatment

Molybdenum Removal

The treatment of aqueous molybdenum in the TPP involves the addition of ferric sulfate solution to the tails feed tank. The primary purpose of ferric sulfate addition is for treatment of soluble arsenic concentrations in the mill raffinate stream. The ferric sulfate requirement for successful arsenic treatment also facilitates molybdenum removal in Tailings preparation circuit in tank #1 through the formation of ferrimolybdite and molybdate adsorbed on ferrihydrite.

Key Reagent: Ferric Iron

In the event that elevated molybdenum concentrations are fed to the Tailings preparation circuit, the Fe^{3+}/As ratio to calculate the ferric sulfate requirement has been modified to include aqueous molybdenum in the determination of the ferric iron addition rate. The Fe^{3+}/(As+Mo) ratio, determined from the daily SX raffinate sample assays, results in a conservative ferric sulfate addition rate to ensure both dissolved arsenic and molybdenum are successfully treated.

3.3.2.4 Uranium Treatment

Hydrocarbon Removal

The control of uranium pore water concentrations in the placed tailings is dependent on the full oxidation of any residual hydrocarbon material in the TPP carried over from the Solvent Extraction raffinate stream or the JEB WTP clarifier sludge (as described in the uranium geochemical model in Section 5.5.3). To fully oxidize all entrained hydrocarbons, the Eh of the tailings preparation feed tank is targeted at approximately 550 mV.

Key Reagent: Hydrogen Peroxide

Hydrogen peroxide, diluted to 22% by weight, is added to the Tailings Preparation circuit feed tank. Hydrogen peroxide was initially added to the tailings launder but has been relocated to the feed tank to enhance mixing and minimize the generation of extreme redox conditions at the point of addition.

3.4 Water Management

3.4.1 TMF Water Balance

A water balance modelling approach was applied to assess groundwater flux into the TMF and to complement hydrogeologic monitoring in the area surrounding the TMF.

The objective of the JEB TMF Pond model is to improve operation efficiency and for forecasting purposes. The model incorporates meteorological, hydrogeological, tailings, and JEB TMF Pond water level data as of October 31, 2024. The calibration period for the updated model spans from September 1, 2014, to October 27, 2024. A prediction period from October 21, 2024, to March 31, 2025, was simulated to estimate the total anticipated water balance volumes up to March 31, 2025.

The JEB TMF water balance model is developed in GoldSim2 software (version 14.0 R4) to gain understanding of how the water and tailings inflow, meteorological (temperature, precipitation, and evaporation) and water outflow components affect the water level in the JEB TMF pit. The schematic for the various water balance components for the model is presented in Figure 3.4-1.

Details of the methodology and data used to model the JEB TMF pit water balance is presented in Appendix B Section F of the TID.

A plot of the model and the measured JEB TMF Pond levels is presented in Figure 3.4-2. The model was calibrated to the monitored JEB TMF pit water levels from September 1, 2014, to October 20, 2024, based on available JEB meteorological data. The model was calibrated by varying four main parameters (i.e. calibration parameters); runoff factor for rain (Rain Factor), snow melt runoff (Snow Factor) for snow melt raise well fraction (fraction of raise water from the pond), and dry density of Cigar Lake tailings. An optimization procedure was implemented in GoldSim for the studied periods, with these four parameters as optimization variables during the calibration.

Where:

- TT O/F is the total tailings thickener overflow volume.
- TT U/F Liq is the total tailings thickener underflow liquid volume.
- TT U/F Sol is the total tailings thickener underflow solid volume.
- Total Runoff Rainfall +Snowmelt is the total volume from snow and rainfall (direct precipitation and runoff).
- GW is the groundwater inflow.
- Pit_O is the pit water outflow to the surrounding GW.
- Evap is the direct evaporation from the pit.
- Raise Well is the pumping volume from the raise well.
- Reclaim Barge is the total volume pumped from TMF pond to the JEB water treatment plant.

Figure 3.4-1: General water balance schematic for JEB TMF pit.

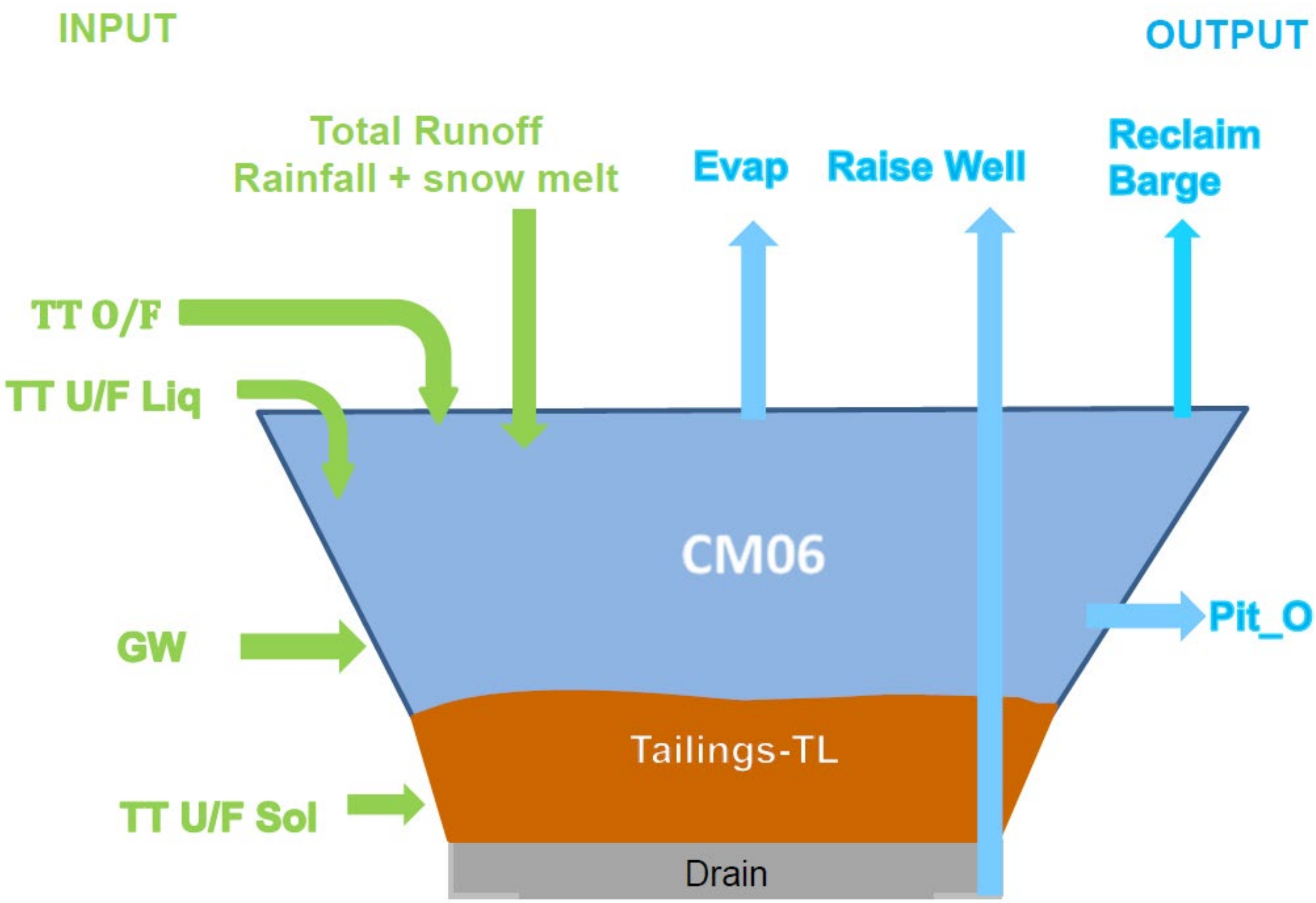
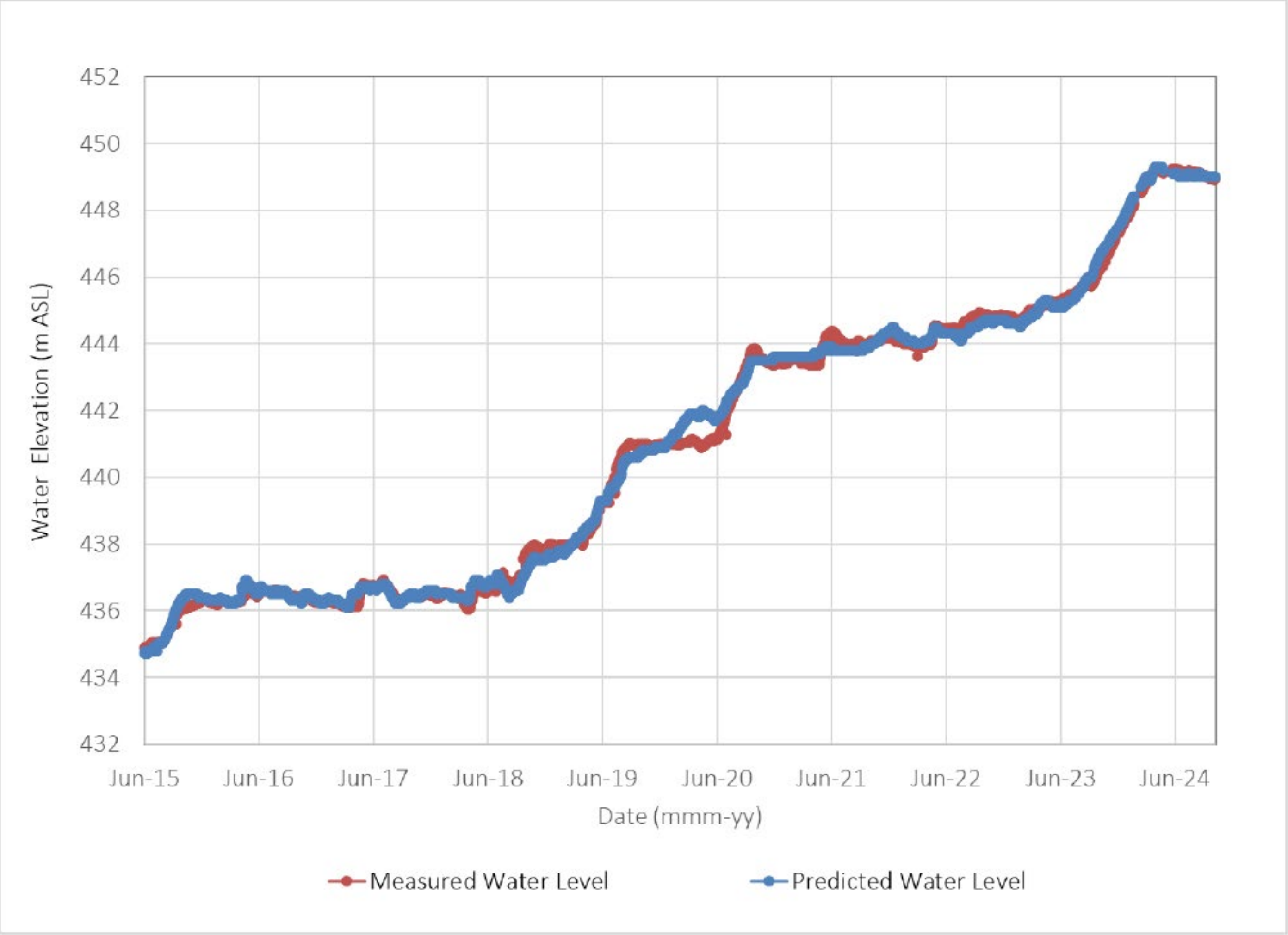


Figure 3.4-2: Calibrated JEB TMF Pond water level



The calibrated model was used to predict water balance component (input and output) to the end of March of 2025.

The annual total predicted volume (inflow and outflow) from September 1, 2014, to March 31, 2025, as shown in Figure 1-1, is presented in Figure 3-3. Also shown on Figure 3-3 is the inflow and outflow volumes excluding solid tailings. Table 3-3 provides the corresponding annual total inflow and outflow volumes. The 2014 and 2025 volumes in Figure 3-3, and Table 3-3 represent totals for the periods September to December 2014 and January to March 2025 respectively.

Key observations from Figure 3.4-3 and Table 3.4-1:

- Inflow volumes generally exceed outflow volumes throughout the given period, except in 2016, 2017 & 2022, when solid tailings were excluded from the inflow volumes. In this case, the outflow marginally exceeded inflow by approximately 67,000 m³, 49,000 m³, and 74,000 m³, respectively. The difference in total inflow volume between the two scenarios (with and without solid tailings) is approximately 900,000 m³ (i.e., 917,000 m3).

- The average annual inflow and outflow volumes (2015–2024) are approximately 1,500,000 m³ and 1,300,000 m³, respectively, for all water balance components. When solid tailings are excluded, the average annual inflow volume is approximately 1,400,000 m³.

- The lowest total inflow and outflow occurred in 2020.

Figure 3.4-3: Total annual inflow and outflow volumes. (The 2014 & 2025 volumes represent totals over the periods September to December & January to March, respectively).

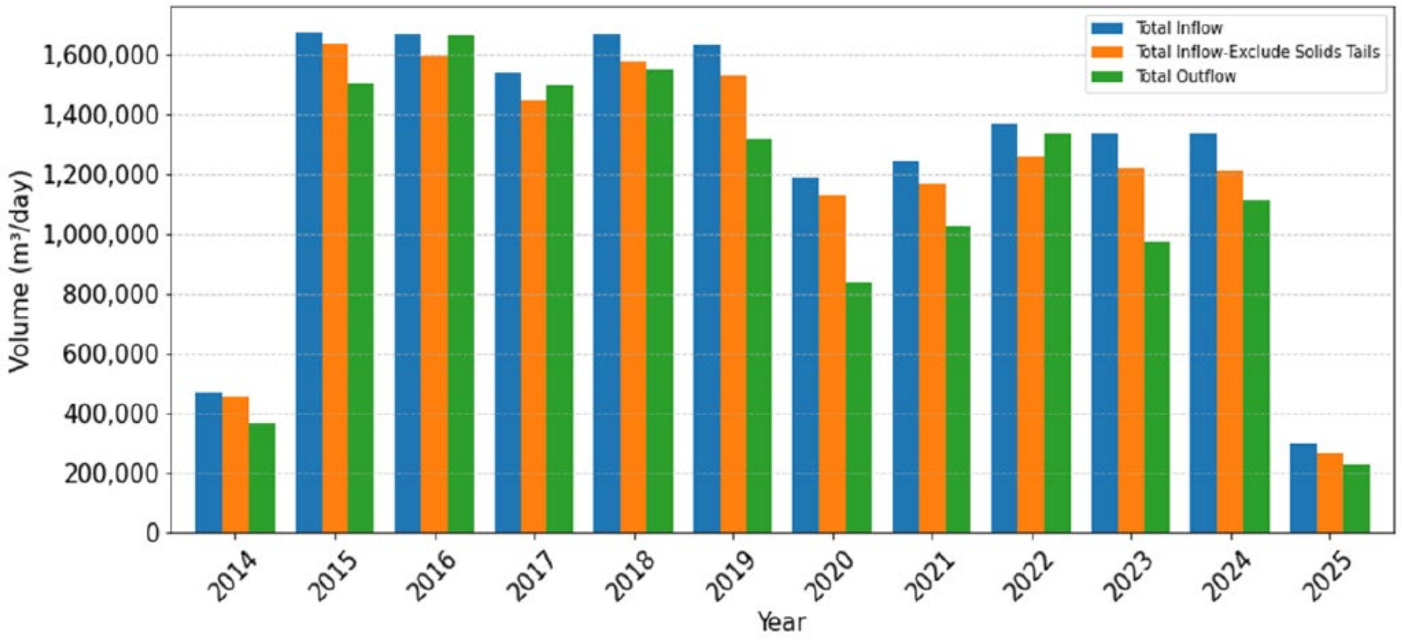
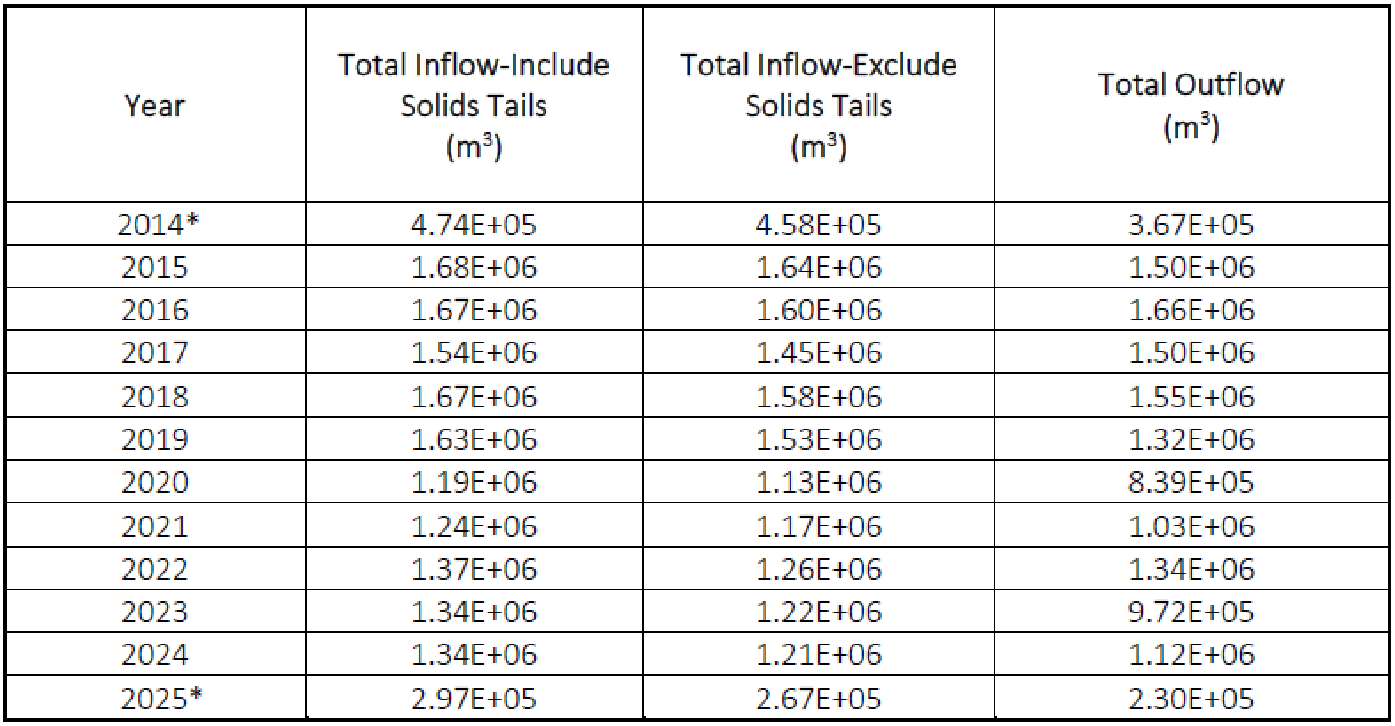


Table 3.4-1: Annual total inflow and outflow volumes.



Year	Total Inflow-Include Solids Tails (m^3)	Total Inflow-Exclude Solids Tails (m^3)	Total Outflow (m^3)
2014*	4.74E+05	4.58E+05	3.67E+05
2015	1.68E+06	1.64E+06	1.50E+06
2016	1.67E+06	1.60E+06	1.66E+06
2017	1.54E+06	1.45E+06	1.50E+06
2018	1.67E+06	1.58E+06	1.55E+06
2019	1.63E+06	1.53E+06	1.32E+06
2020	1.19E+06	1.13E+06	8.39E+05
2021	1.24E+06	1.17E+06	1.03E+06
2022	1.37E+06	1.26E+06	1.34E+06
2023	1.34E+06	1.22E+06	9.72E+05
2024	1.34E+06	1.21E+06	1.12E+06
2025*	2.97E+05	2.67E+05	2.30E+05

The predicted cumulative volumes of all water balance components are shown in Figure 3.4-4. Figure 3.4-5 illustrates the predicted total tailings solid volume available in the JEB TMF from September 1, 2014 (~1,877,000 m³) to March 31, 2025 (~2,800,000 m³). During this period, approximately one million cubic metres (917, 000 m³) of tailings solids were deposited.

Figure 3.4-4: **Predicted cumulative volume of water balance components into and out of JEB TMF pit from September 1, 2014, to March 31, 2025. Also shown is the predicted JEB TMF pit water level.**

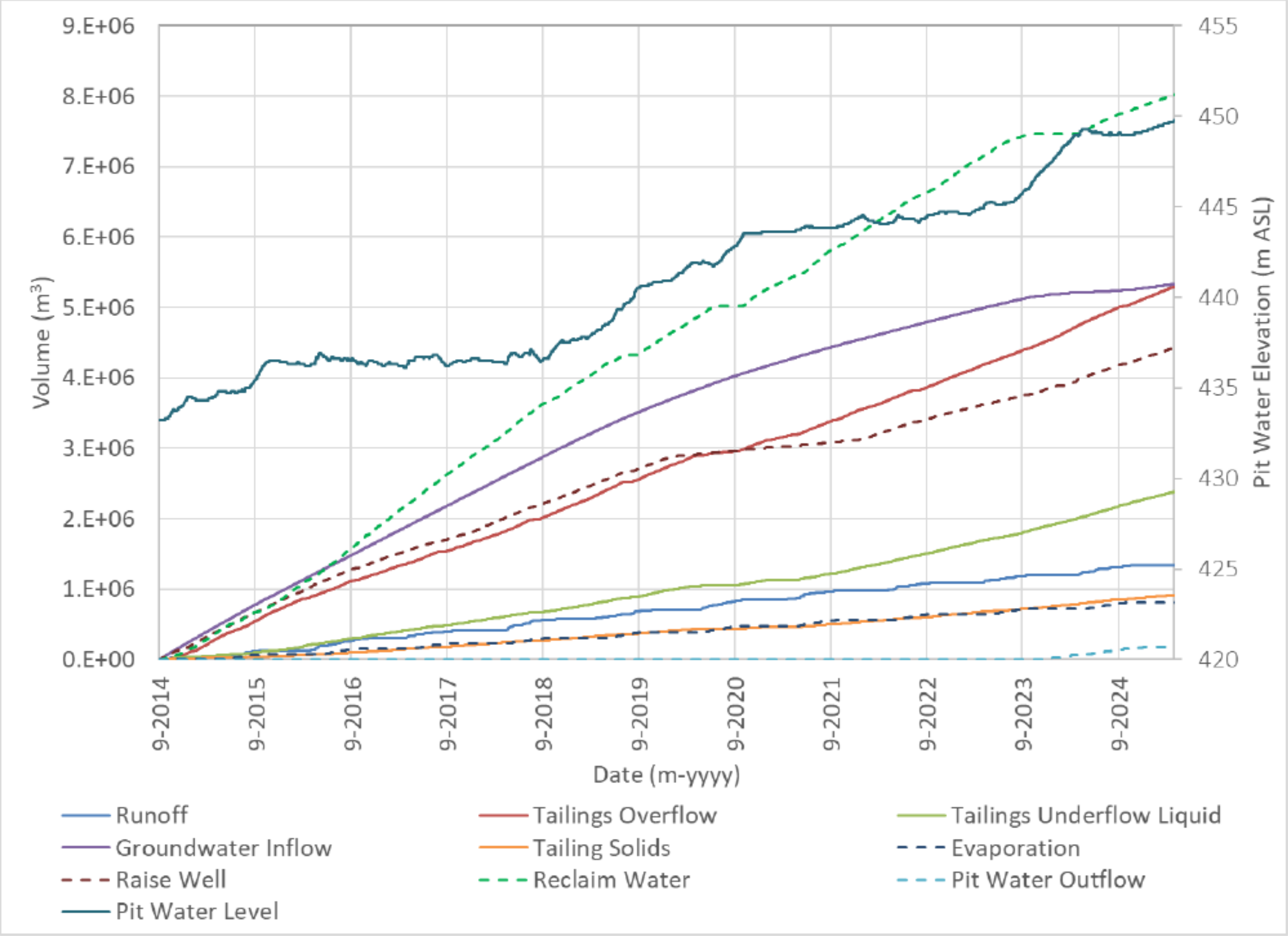
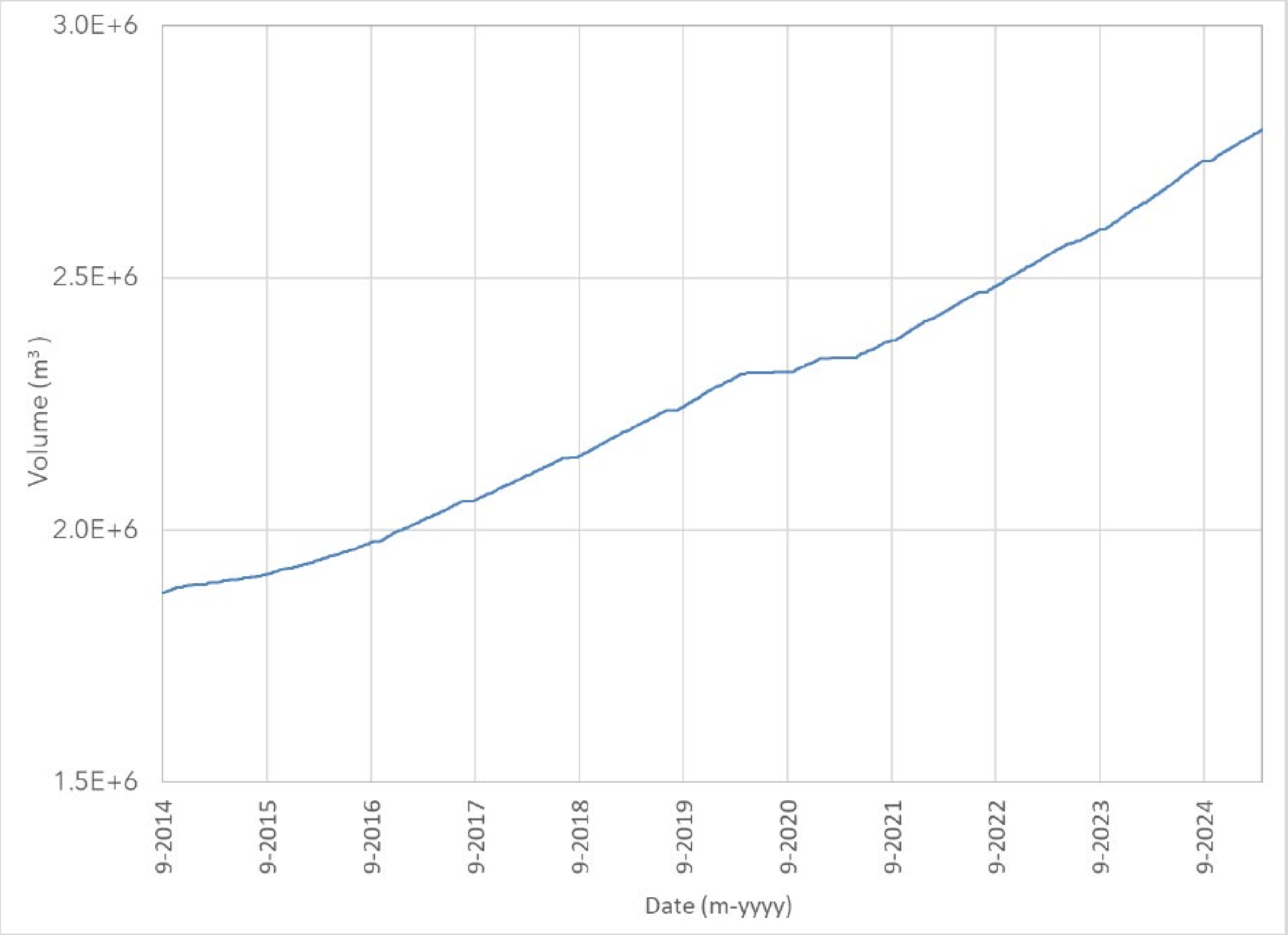


Figure 3.4-5: Predicted cumulative available tailings solids volume in JEB TMF pit from September 1, 2014, to March 31, 2025.



The JEB TMF water balance model predicted that the volume of water stored in the JEB TMF will be approximately 1.6 million cubic metres by the end of 2024. This volume was expected to increase by about 300,000 cubic metres by the end of March 2025, with most of the natural inflow coming from groundwater. The combined volume of water and solid tailings in the JEB TMF pit increased from approximately 2.6 million cubic metres on September 1, 2014, to approximately 4.4 million cubic metres at the end of March 2025.

3.5 Tailings Deposition

As described in Section 2.3.5 Orano has changed the tailings deposition system from tremi to subaqueous in 2018, and has continued to develop the subaqueous deposition system, with the most recent changes occurring in 2024.

Until September 2018, tailings were deposited using a placement barge at the end of the walkway and a shallow injection tremie method when the tailings placement method was changed to incorporate multiple subaqueous deposition points along the walkway, while preserving the flexibility to use the previous tremie method if needed. The alternate subaqueous deposition method was implemented to make more efficient use of the remaining space in the TMF, and avoid barge moves in the winter.

The tailings deposition system was modified again in October 2021 to two single-line horizontal subaqueous tailings deposition pipes extended and supported by a buoy and anchor technique. The new method is flexible and increases the ability to reach previously unutilized portions of the TMF, making more efficient use of licensed space. The tremie and subaqueous deposition systems were discontinued in 2023 and consequently, the tremie barge as well as the flexible walkway associated with subaqueous deposition were removed from the TMF. The portion of the walkway on the TMF, connecting the header barge to the former tremie barge was also decommissioned and removed in 2023.

In 2024 the two-line subaqueous system was modified to have the two tailings thickener underflow lines floating on the pond rather than anchored to the tailings surface to allow for more efficient movement of the deposition points.

3.5.1 Tremie Deposition System

Beginning in 1999, tailings generated from processing JEB and Sue ores were initially deposited from a barge with a vertical discharge pipe releasing tailings below the pond surface but above the surface of the previously placed tailings. This method of sub-aqueous deposition, combined with the physical characteristics of the JEB/Sue tailings, resulted in particle size segregation of the tailings, with coarse particles remaining in close proximity to the deposition pipe, and finer particles travelling farther away from the point of deposition. Groundwater and contaminant transport modelling assumes that the hydraulic conductivity of the decommissioned tailings will be low enough to sufficiently contrast with the surrounding fractured sandstone, thereby enabling preferential flow around the tailings mass. Homogeneous placement of particles with a broad particle-size distribution is preferred to promote consolidation, achieve the target hydraulic conductivity, and conserve tailings space.

In 2001, the tremie deposition method was implemented as a means to reduce the observed segregation. Tremie deposition places tailings through a deposition pipe injected below the surface of previously placed tailings, limiting migration of tailings through the water column. Tremie placement takes its name from the method employed for placing Portland cement concrete under water and is in effect a shallow injection technique. An initial testing program was developed for the tremie, followed by an optimization program to reduce segregation.

3.5.1.1 Summary of Testing and Optimization Programs

An initial test program was conducted over a seven-week period during August and September 2001. The results of the initial test program were favourable and the application of the tremie method was continued throughout the following year (COGEMA 2002). Following a year of operation with the tremie method, field investigations indicated that segregation was significantly reduced but still present. As a result, an optimization program was implemented in 2002 to define suitable ranges of operational parameters (i.e. injection velocities, depths, rates, and injection pipe size), for successful performance of the tremie method (COGEMA 2003). Upon completion of optimization, some residual segregation continued to be observed when using the tremie method. Coarse material was observed to be placed in the vicinity of the deposition location, with finer material travelling radially outwards from the deposition point.

3.5.1.2 Operational Procedures and Validation

Recognizing that some segregation continued to be present using the tremie method, operational procedures were developed to mitigate segregation and ensure that finegrained tailings are placed at the edges of the TMF. The placement of finer material at the edges ensured that the appropriate hydraulic conductivity contrast was maintained, limiting flow through the tailings mass.

The characteristics of placed JEB/Sue tailings vary with position in relation to the deposition point. Dredge sampling results have shown that the zone of coarse tailings typically extends 40 m from the deposition point in all directions before grading towards fine-grained material. To ensure that the material reaching the extents of the JEB TMF is limited to fine material, the positioning of the barge is constrained to greater than 50 m from the pit walls. This operational control has been proven effective through ongoing TOVP sampling, and the placement of fine-grained tailings at the edges of the TMF has been validated (Section 5.7.2; AREVA 2015).

3.5.2 Subaqueous Deposition System

In 2014, the McClean Lake Operation began processing Cigar Lake ore and the resultant tailings. The Cigar Lake tailings were identified as being finer than the JEB/Sue tailings, with a narrower particle size distribution and potentially fewer concerns with segregation during deposition. With an additional need to make the best use of remaining TMF capacity, Orano initiated an investigation to determine alternate deposition methods that either maintained or improved the desired behavior of placed tailings, while providing increased operational flexibility of the deposition system. The selected system was a subaqueous deposition system with multiple deposition points, which was implemented in the fall of 2018 as described in Section 2.3.5.1

To support the selection of the subaqueous system, Orano conducted a short duration field test (25 days) of the system in 2017 to investigate the viability of the method and the tailings behaviour. The results from the subaqueous test are described in detail in the Subaqueous Tailings Method Notification/Application (Orano 2018) and summarized below.

3.5.2.1 Summary of Field Sub-Aqueous Test

Success criteria were defined for the test, focused on the most efficient use of tailings space, operational flexibility, segregation, and TMF water quality. With respect to long-term tailings performance, the key consideration is the resulting geotechnical performance of the tailings, particularly segregation.

The test identified that there was slightly more pronounced particle size segregation immediately adjacent to the deposition point, but more limited in area. Segregation was observed to be predominantly within 5 m, to a maximum extent of 15 m from the deposition point.

3.5.2.2 Operational Procedures and Validation

An evaluation of segregation with respect to the subaqueous system implemented in 2018 was included in the 2020 Tailings TID (Orano 2020, Section 5.6.2). The analysis found that Cigar Lake tailings were predominantly fine-grained; however, tailings meeting the definition of coarse tailings were observed to be deposited up to 40 m from the deposition points. The observed segregation was based on limited data and was highly variable. Tailings had not been deposited closer than 40 m from the pit wall and based on the preliminary observations, an operational control limit distance of a minimum 40 m from pit walls was maintained pending further dredge sampling results supportive of decreasing the distance.

3.5.3 Two Single-line Horizontal Subaqueous Deposition

In 2021, the subaqueous deposition system with multiple deposition points was replaced with two single line extended subaqueous deposition systems. Detailed description of the two single line extended subaqueous deposition systems is presented in Section 2.3.5.1. Although the infrastructure of the deposition system was altered, the essential method of tailings deposition remained the same and so no critical changes to tailings depositional characteristics were anticipated. Tailings dredge sampling has continued to validate the deposition system and results from the current reporting period are detailed in section 5.6.3.4 of this document. Over this period it was observed that the tailings materials had high fines content (>95%) when at least 50m from the deposition point.

In 2024 the deposition system was again slightly altered to have to tailings lines float on the surface of the TMF. This change was made for improved operational utility in relocating the tailings lines, the method of deposition of the tailings remains unaffected and no changes are anticipated to the tailings properties as a result.

3.5.3.1 Operational Procedures and Validation

To optimize space filling in the lower elevation areas of the TMF, the two single-line horizontal subaqueous deposition lines are relocated annually. This also ensures that the capacity at a particular deposition location is not compromised. Monitoring of the depth/elevation to tailing's surface is required to inform the need to change deposition locations. For the former deposition methods (i.e. Tremie and Subaqueous Deposition System) the depth to tailings surface was measured multiple times daily on active deposition points and weekly on inactive deposition points. However, the current deposition method cannot be measured daily since there is no walkway or permanent platform above the active deposition location. Tailings surface surveys are conducted semi-annually to annually, generally coinciding with spring thaw and fall shutdown. The surveys are an important input to tailings deposition modelling and provide validation of tailings deposition predictions and placed densities.

Dredge sampling is also conducted semi-annually to annually, generally coinciding with tailings line moves. The samples inform assessments of segregation, which are discussed further in Section 5.6.3.4.

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4 Potential Environmental Effects

Beginning in 1996 with the dewatering of the JEB pit during initial mining activities, the potential environmental effects of the tailings process at the McClean Lake Mill have been carefully identified, assessed, and tracked. Detailed assessments of material TMF-environment interactions are found in the Environmental Performance Technical Information Document (Orano, 2025). A comprehensive review of environmental impacts from the JEB TMF considering future projects was conducted and is presented in the Application to Construct the JEB Tailings Management Facility Expansion (Orano, 2019b).

This section presents an overview of interactions, screening, and summary of potential effects that are assessed further in the EP TID Volume 2 (Orano, 2025). Discussion of the operational effects related to tailings production and disposal under normal operating conditions are followed by a discussion of potential effects under upset conditions or accident and malfunction scenarios.

4.1 Potential Project-Environment Interactions

Potential project-environment interactions from the JEB TMF are considered in all environmental assessments (EA) which include:

1) The generation of tailings to be deposited in the JEB TMF or involve changes to the JEB TMF facility:

   - The McClean Lake EIS (Minatco, 1991),
   - The Midwest EIS (COGEMA, 1995),
   - The Sue E Project EIS (COGEMA 2004c),
   - The Caribou Project EIS (AREVA, 2009), and
   - The Midwest Project EIS (AREVA, 2011e).

2) Changes to the JEB TMF facility:

   - JEB TMF Capacity Optimization Application (AREVA, 2010b), and
   - Application to Construct the JEB Tailings Facility Expansion (468 mASL) (Orano, 2019b).

These assessments demonstrate that the past, current, and planned future activities at the McClean Lake Operation continue to be within the environmental effects envelope originally reviewed by the Joint Panel in 1993 (Joint Panel 1993). Similarly, potential environmental effects from activities proposed for the optimization and expansion of the JEB TMF are anticipated to be within the bounds of the McClean Lake and Sue E assessments.

The EA conclusions are validated via the regular ERA updates presented in the EP TID Volume 2. The most recent ERA update completed in 2025 has confirmed that environmental risks associated with the JEB TMF operation remain well-controlled and consistent with the findings presented in the previous environmental assessments (Orano 2025c).

4.1.1 Interactions Screened Out

Certain project-environment interactions have been consistently screened out including:

- Groundwater contaminant transport during operations - hydraulic containment consistently maintained during operations as described in Section 2.2.2; therefore, groundwater contaminant transport is screened out from further consideration during the operational period.
- Groundwater contaminant transport post-decommissioning – surface water quality meets SEQG in down gradient lakes (Section 7.0).

4.1.1.1 Monitoring

In addition to the hydraulic containment monitoring detailed in Section 2.2.2, there is also consideration for downgradient surface water bodies in the McClean Lake EMP. Sediment and benthic invertebrates were monitored in Fox Lake as recommended by the Joint Panel (1997). The purpose of monitoring this location was to ensure no COPCs were migrating from the TMF to Fox Lake during operations. By 2005, monitoring demonstrated that contaminants from the TMF were not moving into Fox Lake sediments and monitoring at that location was temporarily suspended and removed from the EMP. Monitoring in Fox Lake resumed in 2018 in preparation for the TMF expansion construction and continued on a three-year sampling cycle. The 2018, 2021, and 2024 data showed that sediment quality and benthos community structure in Fox Lake remained similar to reference and baseline levels (Orano 2025b). All COPC concentrations were well below available sediment quality criteria for the protection of freshwater aquatic life.

4.1.1.2 Consideration of Downstream Effects

Groundwater flow and contaminant transport modelling, as presented in Section 7 and Appendix D Section G, considers meeting SEQG in downgradient lakes as the threshold for screening out the TMF source from further consideration in ecological risk assessment. The determination is based on consideration of predicted mass flux over time in a fully mixed Fox Lake. The current determination of meeting SEQG is conservative due to a series of conservative model assumptions/inputs, such as the use of a non-depleting source term.

The achievement of SEQG in Fox Lake is additionally conservative as it does not consider the surface water-sediment interface. Should the Administrative Level for arsenic pore water be exceeded, further studies and an environmental risk assessment will take place, consistent with CSA N288.6 (CSA, 2022) to ensure that operations and a decommissioned end state will confidently achieve environmental protection and absence of unreasonable risk.

4.1.2 Interactions Carried Forward for Risk Assessment

The Project-environment interactions identified for inclusion in the risk assessment include:

- Dewatering (Section 4.2.1);
- Water treatment (Section 4.2.2); and
- Atmospheric emissions associated with TMF optimization and expansion (Section 4.3).

4.2 Normal Operations

4.2.1 Dewatering Effects

The JEB pit dewatering well system operated from the start of mining operations in March 1996 until 2014. The role of maintaining hydraulic containment is now accomplished through a combination of base drain and reclaim pumping (Section 2.2.2). The liner installed as part of the JEB TMF Optimization Program (described in Section 2.4.1.1) will function to restrict seepage from the operating pond as the pond level is raised over time.

Hydraulic head measurements have been collected monthly over the life of the TMF in the piezometers at the JEB site to monitor the effect of dewatering operations. The locations of piezometers in the vicinity of TMF are presented in Figure 4.2-1. An assessment of the TMF water balance is presented in Section 3.4.1.

Upon initial dewatering of the pit, the measured drawdown in the piezometers completed in basement rock and sandstone reached maximum levels in 1996. Measured hydraulic heads in the piezometers completed in the sandstone and basement rock formations have began recovering towards pre-operational levels in response to the increasing pond water level in the JEB TMF during operations. The recovery of hydraulic heads surrounding the JEB TMF began in 1999, with its initial flooding at the start of operations. Key milestones have been reached in groundwater level recovery over time:

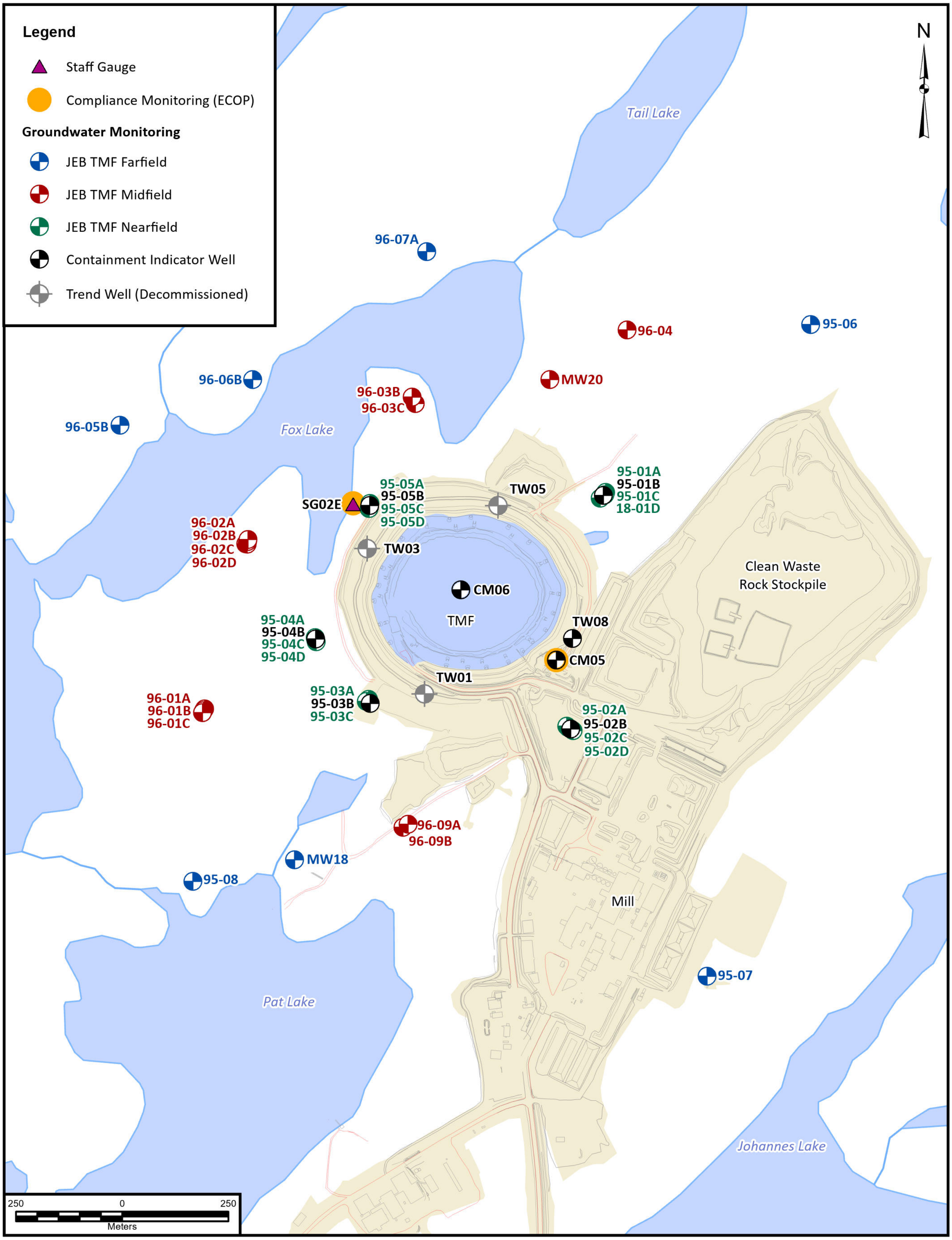
- In 2014 the JEB TMF pond water level moved into the upper stratum of the sandstone and eventually, out of the sandstone into the overburden, after the completion of the JEB TMF Optimization project. The dewatering wells, which were no longer effective in intercepting incoming groundwater, were decommissioned beginning in 2017 and hydraulic containment of the TMF was controlled through pumping of the base drain. This change decreased the radius of dewatering influence around the TMF causing groundwater levels to rise.
- In 2024 the JEB TMF pond water level moved beyond the lowest natural ground level surface around the TMF (449.18 mASL)

For the most recent EP TID Volume 1 (Orano 2025a) it was noted that the groundwater around the JEB TMF is now approaching a fully recovered condition and some of the 95 series well adjacent to the TMF have begun to show artesian conditions which is consistent with their pre mining hydraulic heads, particularly at 95-03, 95-04 and 95-05 (Table 4.2-1)

Table 4.2-1: Historical and Recent Hydraulic Heads at TMF Monitoring Wells in the Sandstone

Monitoring Location	Time Frame	Hydraulic Head Lower Sandstone (m ASL)
95-01	Pre-Mining	453.0
	2025 EP TID	451.2
95-02	Pre-Mining	446.9
	2025 EP TID	446.3
95-03*	Pre-Mining	448.1
	2025 EP TID	446.6
95-04*	Pre-Mining	449.1
	2025 EP TID	446.7
95-05*	Pre-Mining	450.0
	2025 EP TID	448.1
*Indicates a well which was artesian pre-mining		

Measured water levels in piezometers completed within the overburden sediments remained relatively constant, with a perched water table remaining in the drift sediments above the dewatered sandstone. The limited drawdown is consistent with the fine-grained nature of the overburden sediments and corresponding low hydraulic conductivity, compared to the underlying sandstone. The relatively low hydraulic conductivity of the overburden sediments has helped to mitigate any impacts to surface waterbodies surrounding Fox Lake.



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Data Sources: Natural Resources Canada, Geobase®, Nation Topographic Database, ORANO Canada Inc.

McCLEAN LAKE OPERATION

FIGURE 4.2-1

MONITORING FOR HYDRAULIC CONTAINMENT IN THE JEB TMF

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Dewatering effects to the surrounding environment are discussed and assessed in the Environmental Performance TID (Orano, 2025). The 1991 and 1995 environmental assessments predicted that changes in water levels from groundwater dewatering programs associated with mine development and operation at the McClean Lake Operation would have a more pronounced effect on wetland community composition than would natural fluctuations in groundwater hydrology. Therefore, wetland monitoring was initiated to address these concerns. Wetland communities were surveyed in multiple years between 1998 and 2015. Contrary to predictions, observed changes in plant communities were attributed to natural variation rather than mining-related groundwater effects.

As groundwater levels around the TMF have begun to recover to pre mining conditions and based on monitoring and planned future operation, it is unlikely that groundwater dewatering has had or will have anything other than marginal effects on wetland plant communities. The monitoring of wetland vegetation communities was discontinued as part of the McClean Lake Operation's environmental monitoring program.

4.2.2 Water Treatment

Changes approved in July of 2012 (Bourhis to Richards, 2012) allowed site run-off and tailings thickener overflow to be directed to the TMF rather than reporting directly to the WTP. The change provides a significant buffering capacity for flow and concentration variances that would otherwise affect the WTP operation. Surges from these streams have been identified as contributing factors to reduced effluent quality in the past. Additionally, in an effort to utilize all available water recycling opportunities, the raise well water has been segregated from reclaim water and sent directly for use in the mill. The raise water stream represents a significant flow (up to 125 m^3/h).

Reclaim water pumped from the TMF to maintain pond water levels during operations is sent directly to the McClean Lake WTP for treatment prior to discharge to Sink Reservoir. Operational effects of treated effluent discharge are considered in the Environmental Performance TID (Orano, 2025). Predicted effects from discharged effluent, including predicted effluent quality and quantity from the TMF, are within those effects previously predicted and approved in the McClean Lake EAs.

4.3 TMF Construction

TMF Expansion Project activities at the McClean Lake Operation have the potential to generate emissions of airborne dust (and associated uranium metals), radon-222 (radon) and standard pollutants (i.e., NOx and SO_2). The 2025 EP TID Volume 2 ERA included air dispersion modelling to predict potential future effects from these activities in combination with other future potential activities (Orano 2025b). Overall, the air quality assessment showed that the potential effects of the JEB TMF expansion on ambient air quality is minimal and limited to occasional exceedances of 24-hour TSP and PM10 standards in areas to the north of the JEB site. The exceedances are expected to be short-term and stay within 1 km of the lease boundary. For all other COPCs and averaging periods, concentrations were predicted to be less than the applicable standards, criteria or guidelines at all locations beyond the lease boundary. All COPC concentrations are predicted to return to background levels within a few kilometers of the operation. In addition, radon activities were predicted to be at or less than the background level of 15 to 25 Bq/m^3 beyond the lease boundary. This means that at remote locations like Wollaston Lake Community and Hatchet Lake Lodge, air quality effects would not be discernible from ambient baseline concentrations. These findings are consistent with the findings presented in the previous 2016 ERA and the EISs for the McClean Lake Operation (Minatco 1991, COGEMA 1995, AREVA 2009, AREVA 2011, AREVA 2016).

The JEB TMF Expansion uses existing disturbed areas and existing infrastructure for the additional tailings capacity and does not substantially increase the footprint of tailings management activities at the McClean Lake Operation from that previously assessed and approved (Orano 2019b). The TMF Expansion construction includes mitigation to minimize biophysical environment interactions and potential effects on vegetation, wildlife habitat quality, aquatic biota, sediment and water quality and hydrology are expected to remain within those previously assessed and approved.

4.4 Accidents and Malfunctions

Potential accidents and malfunctions are not included in the risk assessment that assumes maintenance of normal operating conditions. They are assessed in terms of likelihood and consequence and past events that may be included in the assessment if screened in (pass a threshold of potential effect that warrants further consideration).

4.4.1 Loss of Containment

4.4.1.1 Conceptual Site Model

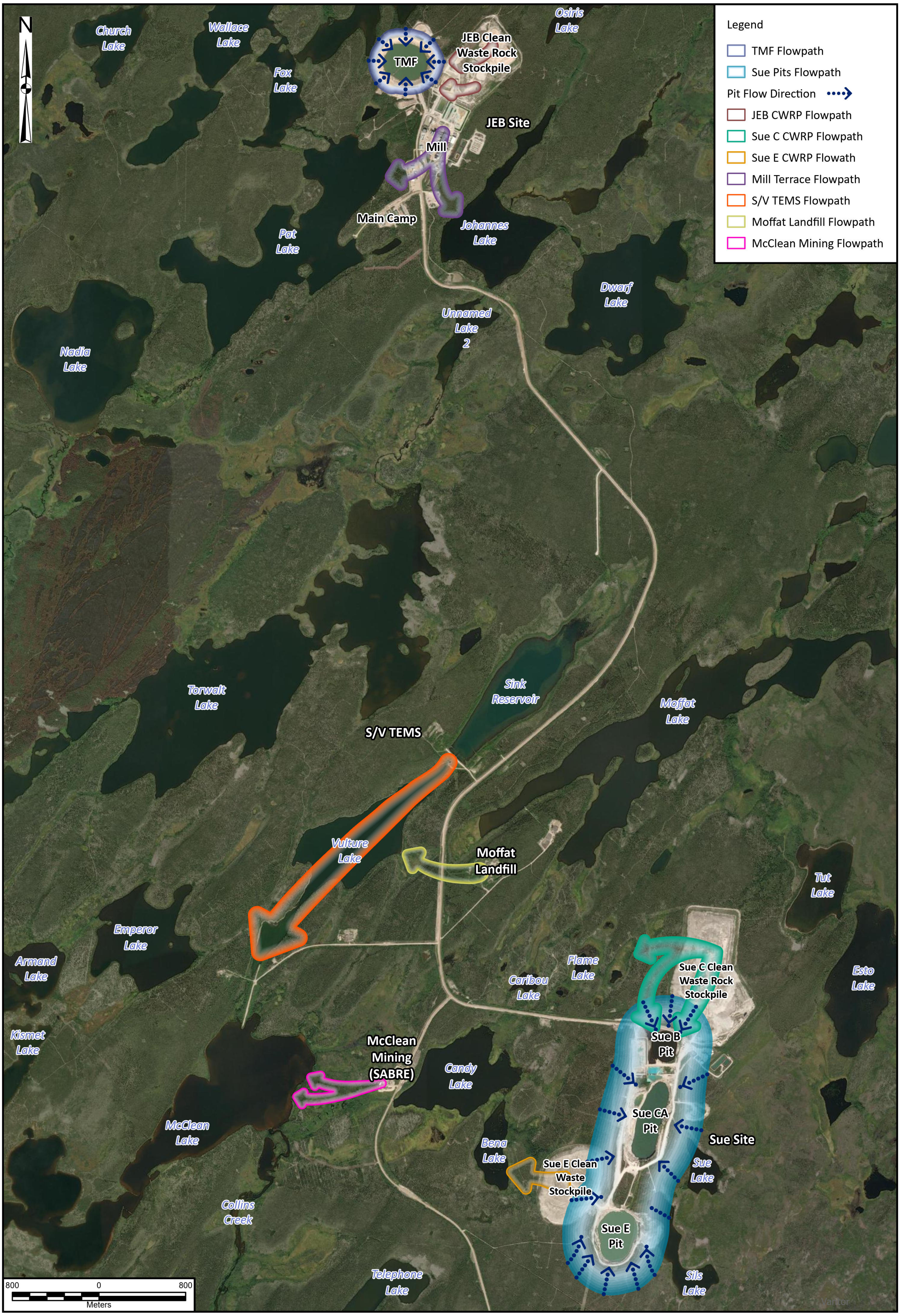
Consistent with N288.6 (CSA, 2022), Figure 4.4-1 and 4.4-2 provides the conceptual model for the McClean Lake Operation during operations and after decommissioning respectively. Operational and decommissioning models for the JEB Site are provided in figures 4.4-3 and 4.4-4. The CMS provides an overview of the current condition of the TMF as well as expected contaminant transport pathways for context in considering loss of containment scenarios.

4.4.1.2 Hydraulic Containment

Until 2012, water levels in the TMF monitoring wells were monitored on a continuous basis using pressure transducers. Recently, the transducers were replaced with vibrating wire piezometers as a result of the TMF Optimization Project (as described in Section 2.4.1.1). The pressure transducers, vibrating wire piezometers, and associated electronic system for constantly monitoring the hydraulic heads in the TMF monitoring wells performed well through operations.

Hydraulic containment has been maintained throughout the operational period, however the key performance indicators of hydraulic containment have evolved over time as the tailings pond level has risen in the TMF with continued tailings deposition. From 1999 to 2014, head differentials were maintained in the range of 0.3 m to 4.3 m between the TMF pond (CM05) and the dewatering ring, as measured at the four outer monitoring wells and TW08 in particular (Figure 4.4-5). This measurement indicated that the pond level was lower than the surrounding groundwater elevation. As the tailings pond level rose above the surrounding groundwater elevation the hydraulic containment of the TMF was measured in the differential between the tailings pond (CM05) and the raise well (CM06) (Figure 4.4-6) which indicates that a drawdown condition exists between the tailings pond and the raise well.

As the TMF pond elevation continues to increase, with TMF expansion activities moving above the natural ground surface, the head differential between Fox Lake and the raise well (CM06) is currently the appropriate indicator that hydraulic containment is being maintained (Figure 4.4-7). Administrative and action levels for TMF hydraulic containment have been derived and presented in the ECOP (Orano, 2023) and are described in detail in Section 2.2.2. The intention of these controls is to ensure proper function of the JEB TMF and ultimately, that hydraulic containment of contaminants is maintained in the JEB TMF.



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McCLEAN LAKE OPERATION

FIGURE 4.4-1

McCLEAN LAKE OPERATION GROUNDWATER FLOWPATHS - OPERATIONAL

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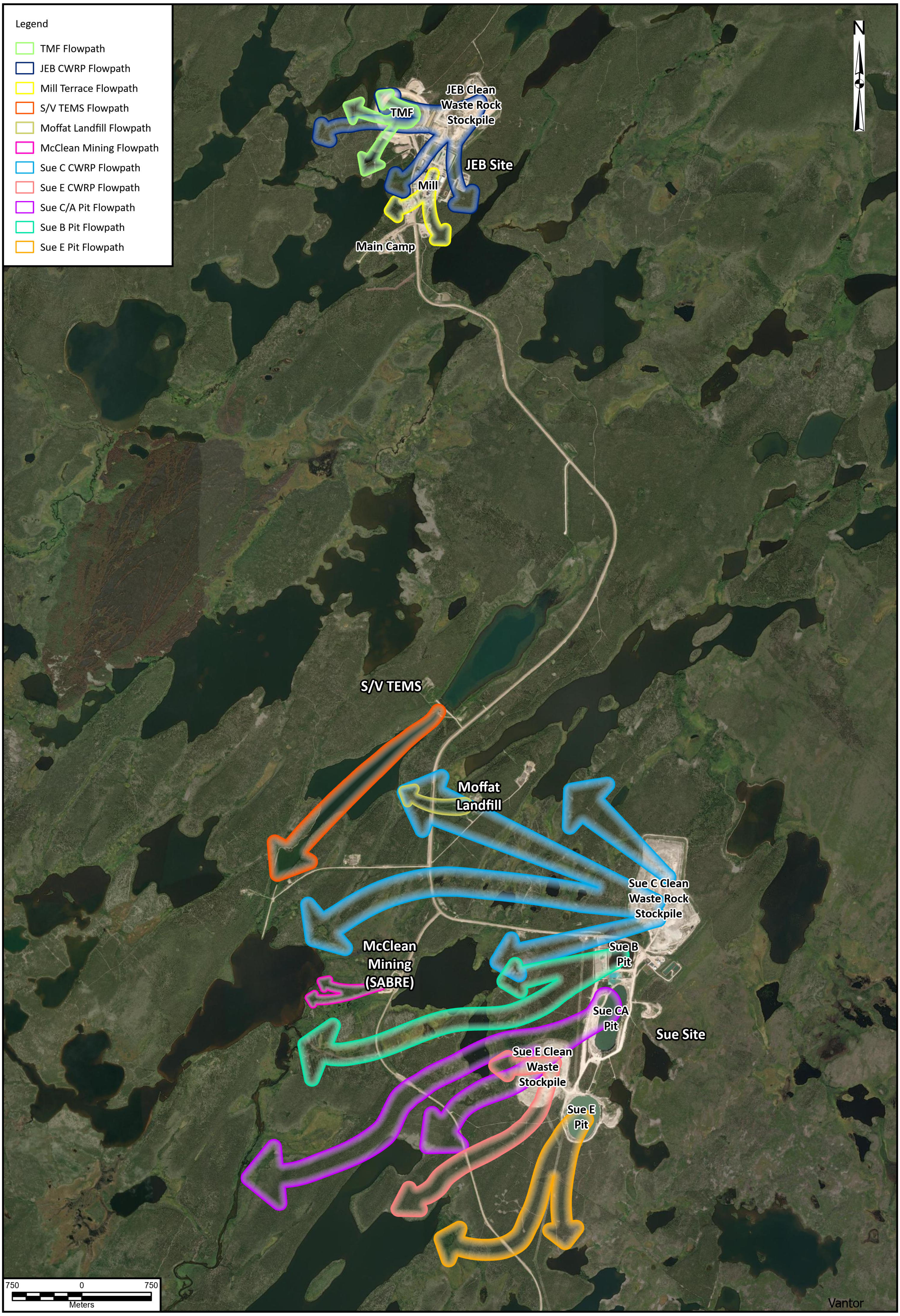

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McCLEAN LAKE OPERATION

FIGURE 4.4-2

McCLEAN LAKE OPERATION GROUNDWATER FLOWPATHS - DECOMMISSIONED

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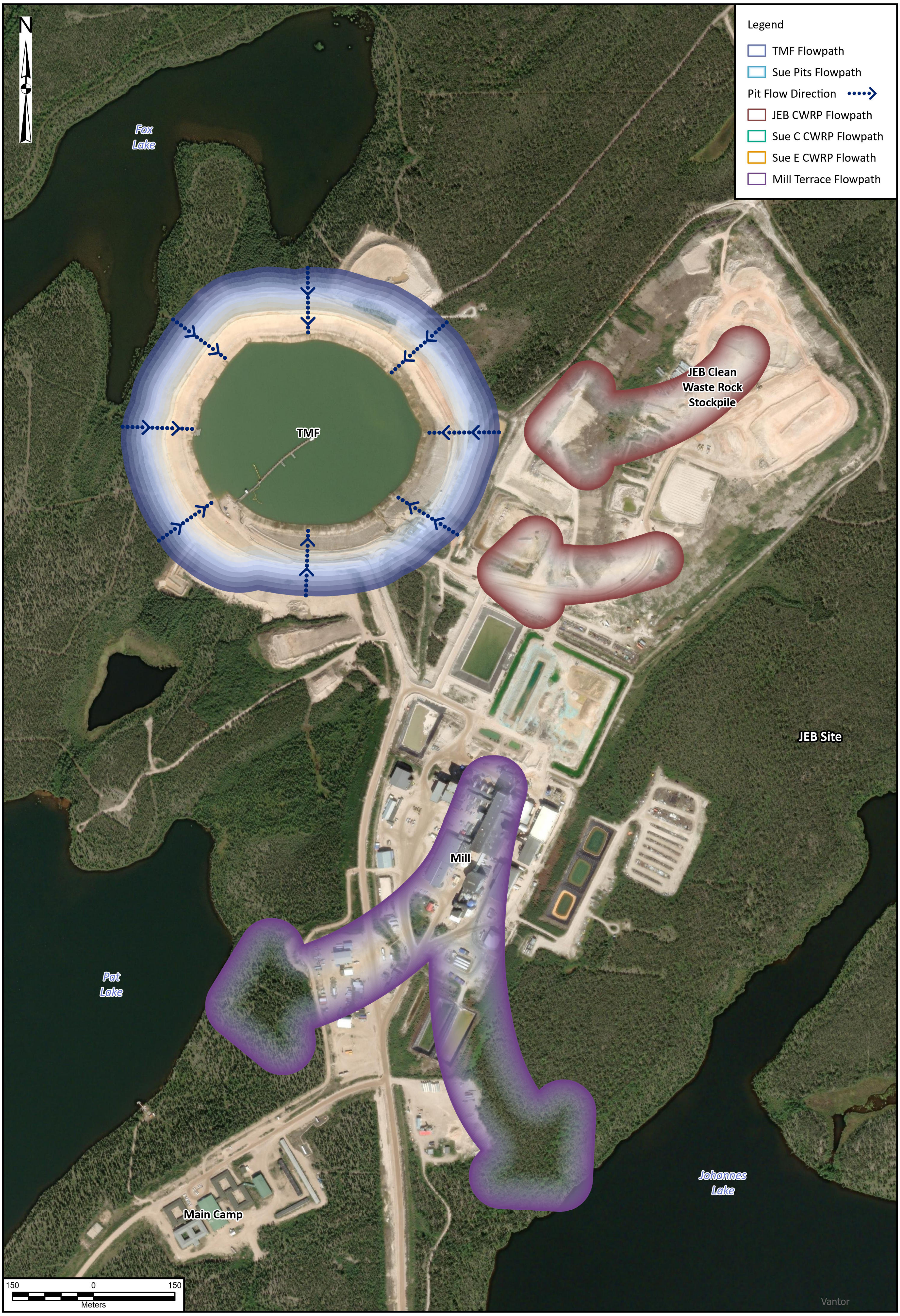

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McCLEAN LAKE OPERATION

FIGURE 4.4-3

JEB SITE GROUNDWATER FLOWPATHS - OPERATIONAL

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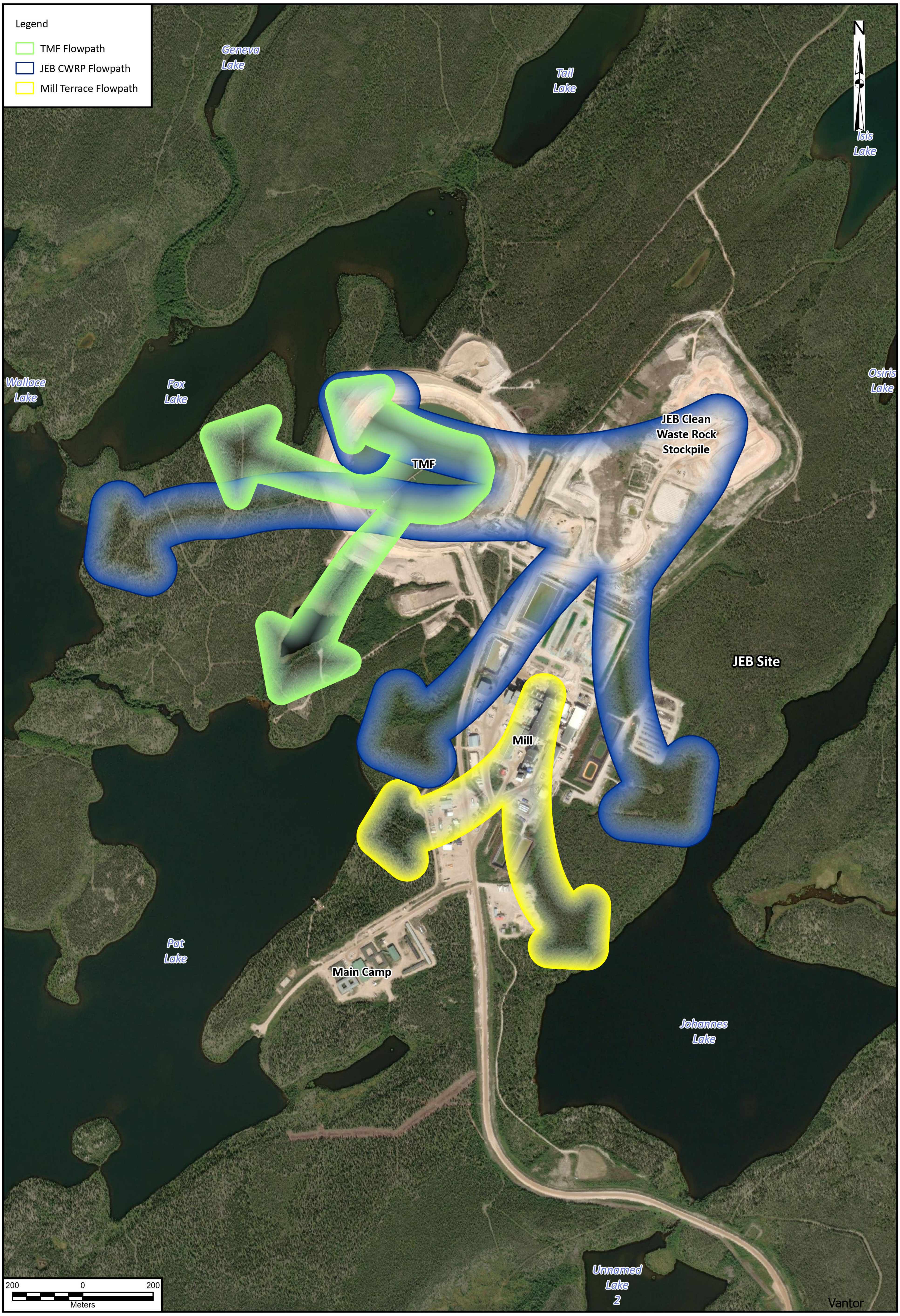

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McCLEAN LAKE OPERATION

FIGURE 4.4-4
JEB SITE GROUNDWATER FLOWPATHS - DECOMMISSIONED

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Figure 4.4-5: **Outer Trend Wells Monthly Average Head Differentials between the Outer Ring of Monitoring Wells and the JEB TMF Pond Level**

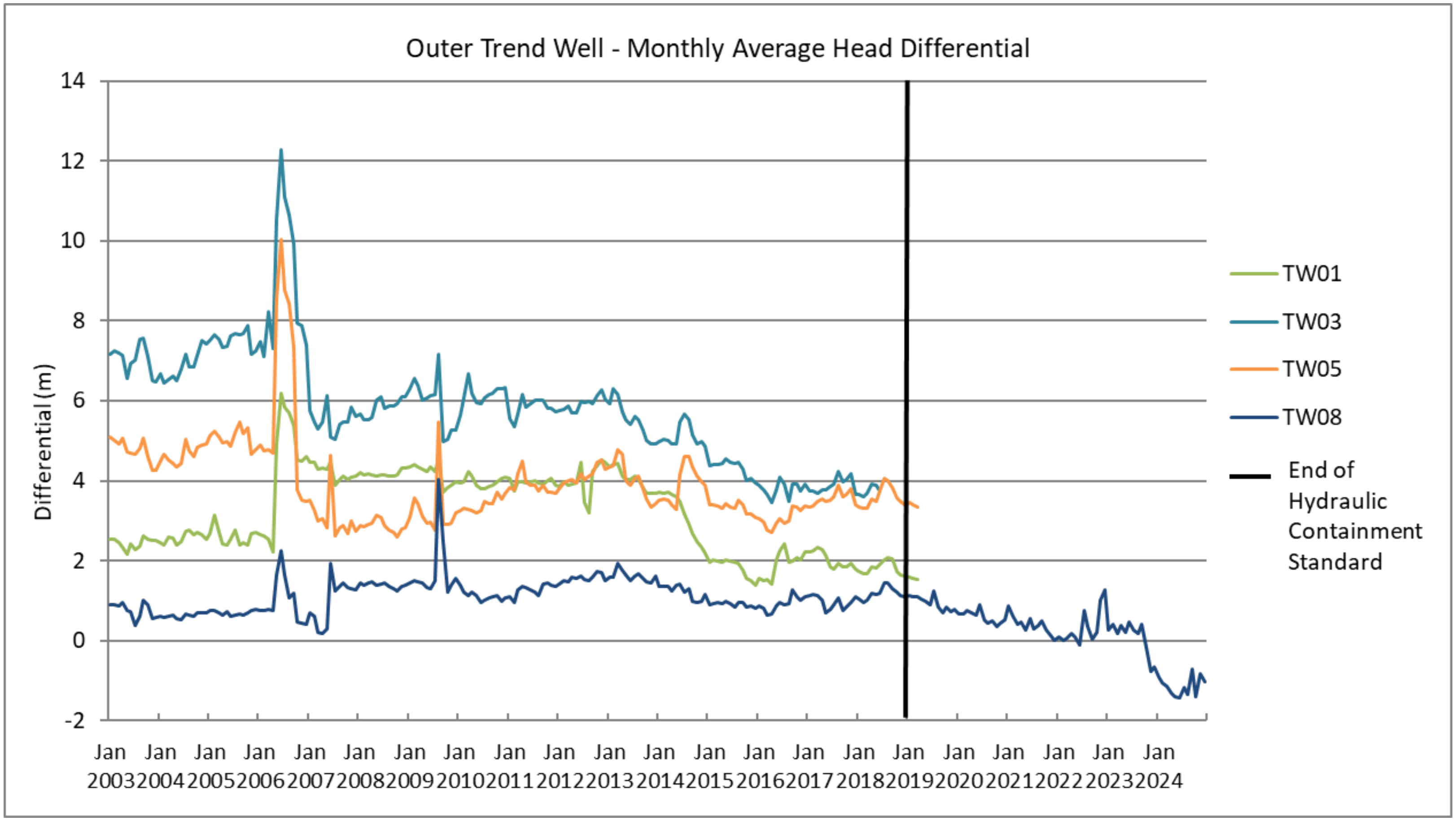


Figure 4.4.-6: TMF Pond Water Level (CM06) Average Head Differential with the TMF Raise Well (CM05)

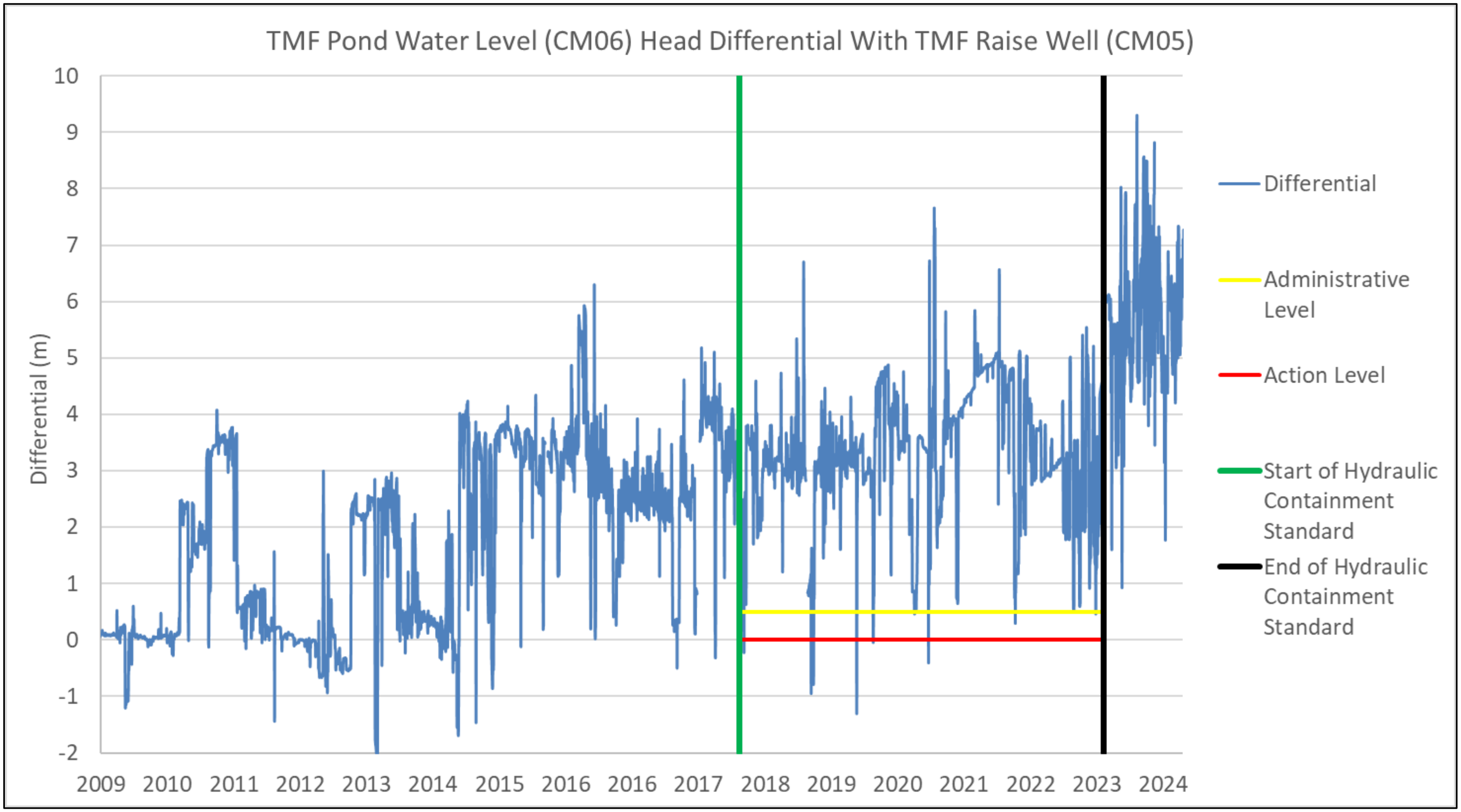
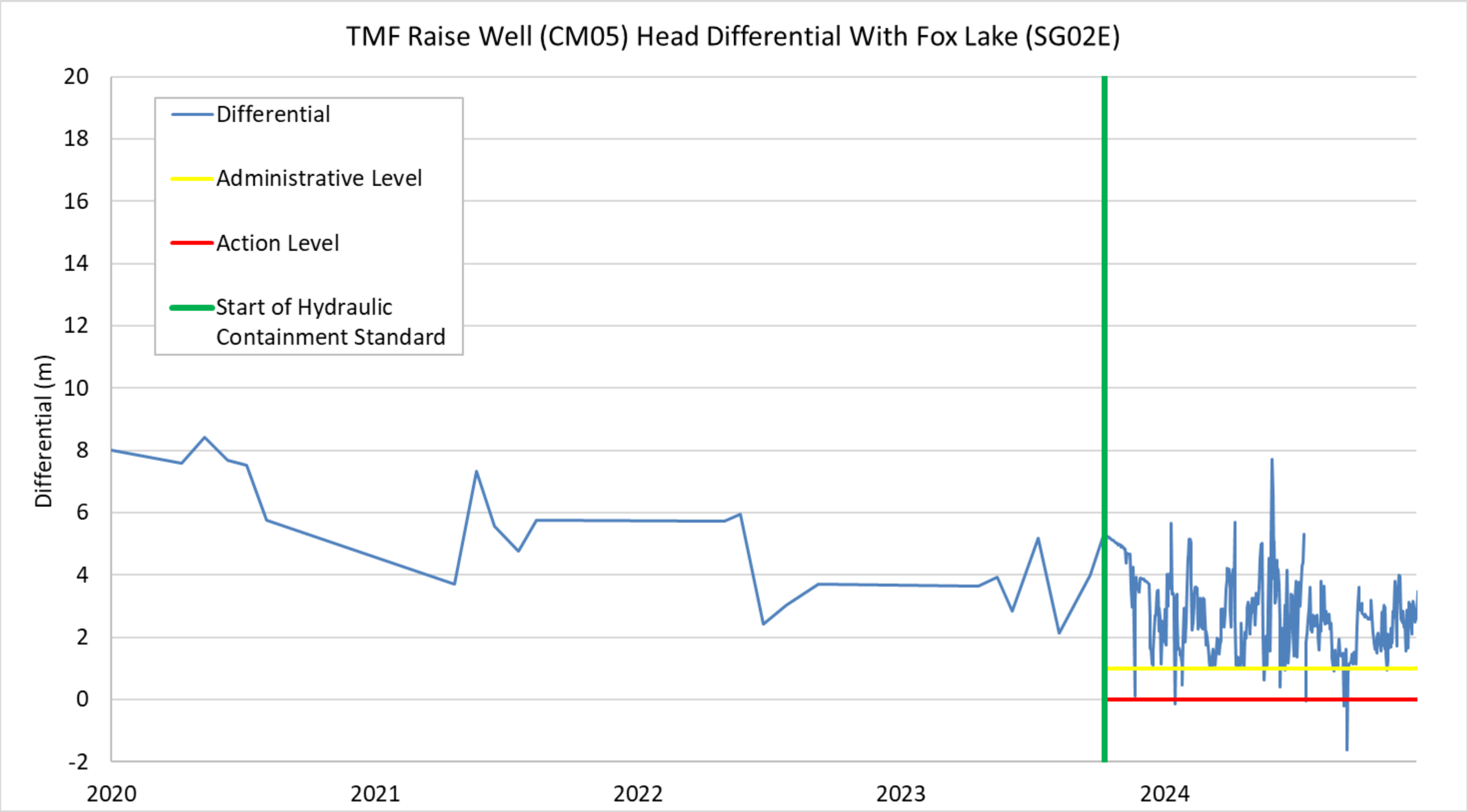


Figure 4.4-7: TMF Raise Well Level (CM05) Average Head Differential compared to the Fox Lake water level.



Before the TMF Optimization and Expansion programs there was the potential for a Possible Maximum Precipitation (PMP) event to result in a temporary loss of containment due to a rapid increase in the TMF pond water elevation. In such a case, pond water would have begun to migrate outward into the surrounding host rock and raise well and reclaim pumping would have continued until pond water levels were restored to their target elevation. After the hydraulic gradient towards the TMF had been re-established, any pore water migrating away from the facility would be drawn back into the pond. This failure mode is no longer a consideration as the installation of the soil bentonite liner fully contains the pond during operations.

4.4.1.3 Ground Water Monitoring

Monitoring results from the 95 series wells indicate that there is no indication of migration of contaminants outwards from the TMF. The results for key COPCs are presented in Figure 4.4-8

In the event of loss of containment chloride and sulfate concentrations would be the first to show increases in the monitoring wells (95 series wells). Chloride and sulfate are conservative tracers in the groundwater and known to migrate through the host rock with only very minor attenuation. Additionally, the concentrations of both chloride and sulfate in the tailings pore water are well above normal groundwater concentrations for the area, and so any loss of containment would be easily identified:

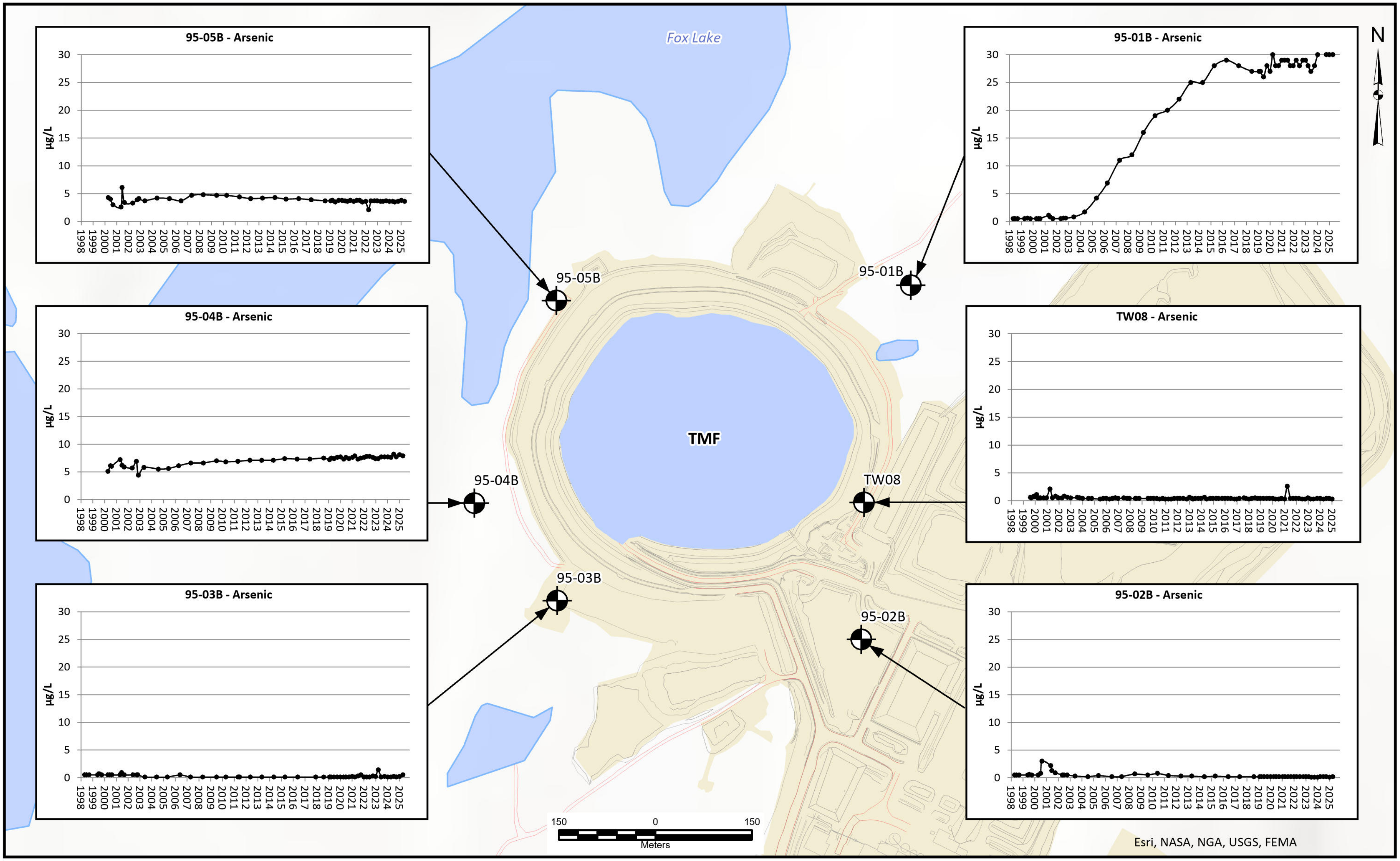
- Weighted average 2023 pore water concentrations in the JEB/Sue tailings pore water for chloride and sulfate were 43.86 mg/L and 2205.84 mg/L, respectively.

- Weighted average 2023 pore water concentrations in the Cigar Lake tailings pore water for chloride and sulfate were 118.12 mg/L and 3292.61 mg/L respectively).

In evaluating groundwater chemistry data adjacent to the TMF a small increase in sulfate and chloride is noted in well TW08; however, values are stabilizing at approximately 8 mg/L and 1.5 mg/L respectively, well below TMF pore water values. TW08 was not decommissioned with the other inner ring TMF monitoring wells to allow for the TMF expansion project, and is now located directly adjacent to the TMF Pond, within the zone of influence hydraulic containment of the TMF. During the reporting period it has been identified that TMF Pond water has been drawn down the outside of the TMF and into the raise well. The pond water is moving from a higher conductivity zone of host sandstone below the liner, that has not yet been covered by tailings placement. This is a short-term operational issue that tailings deposition modelling predicts will end in approximately 2-5 years, depending on when tailings are placed to fully cover the remaining exposed host sandstone of the TMF Pit walls. It should be noted that this does not indicate a loss of hydraulic containment, as all pond water is being captured by the pumping of the raise well system. In the case of TW08, because of its proximity to the TMF, the small increases in chloride and sulfate are confirmative of the drawdown cone surrounding the TMF. TW08 is sampling TMF pond water (diluted by groundwater) as it moves down to the raise well and it is expected that groundwater chemistry values at this location will decrease as tailings are fully placed into the liner.

Some general variability in water chemistry is noted in other monitoring wells in close proximity to the JEB TMF but is minor and is considered to be a natural response to the changes in water level caused by the dewatering for mining of the JEB deposit and then the gradual water level recovery. For most monitoring wells, no significant change in chemistry has been observed.

Well 95-01B, located to the northeast of the JEB TMF, upstream of the natural groundwater flow of, has been noted to display an increasing trend in arsenic. The trend has stabilized well below average pore water concentrations noted in the TMF. No increase in sulfate or chloride is noted at this location and no other keys COPCs from the TMF (such as uranium and molybdenum) are observed. The source of the arsenic increase is likely due to disturbance to the area as the result of overburden stripping operations during the construction of the JEB Waste Rock Pile as described in detail in the 2019 McClean Lake annual report (Orano 2020a, Section 6.7.2.1).



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Data Sources: Natural Resources Canada, Geobase®, Nation Topographic Database, ORANO Canada Inc.

McCLEAN LAKE OPERATION

4.4-8 (1 OF 4)

ARSENIC CONCENTRATION IN WELLS WITHIN THE VICINITY OF THE TMF

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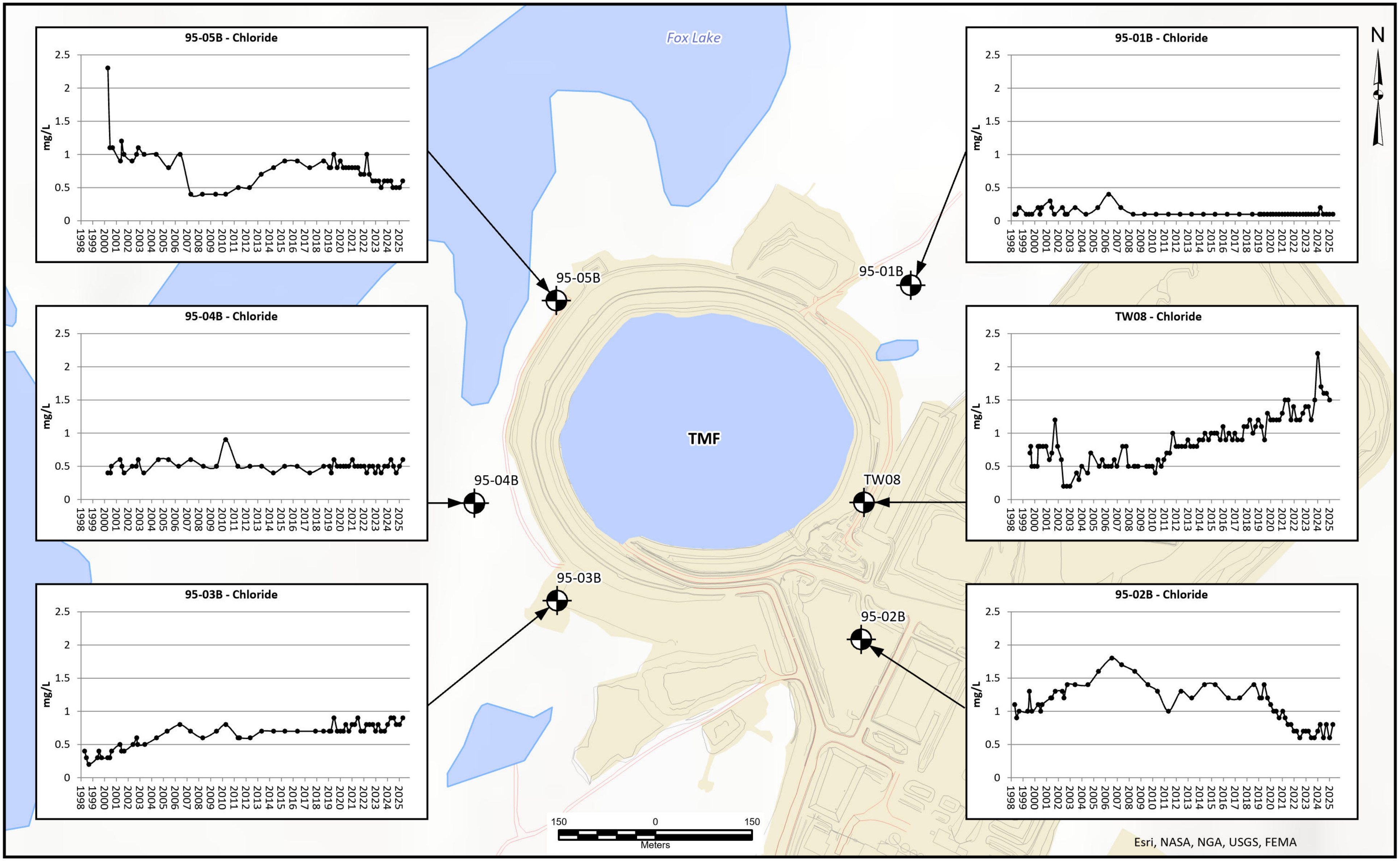

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McCLEAN LAKE OPERATION

4.4-8 (2 OF 4)

CHLORIDE CONCENTRATION IN WELLS WITHIN THE VICINITY OF THE TMF

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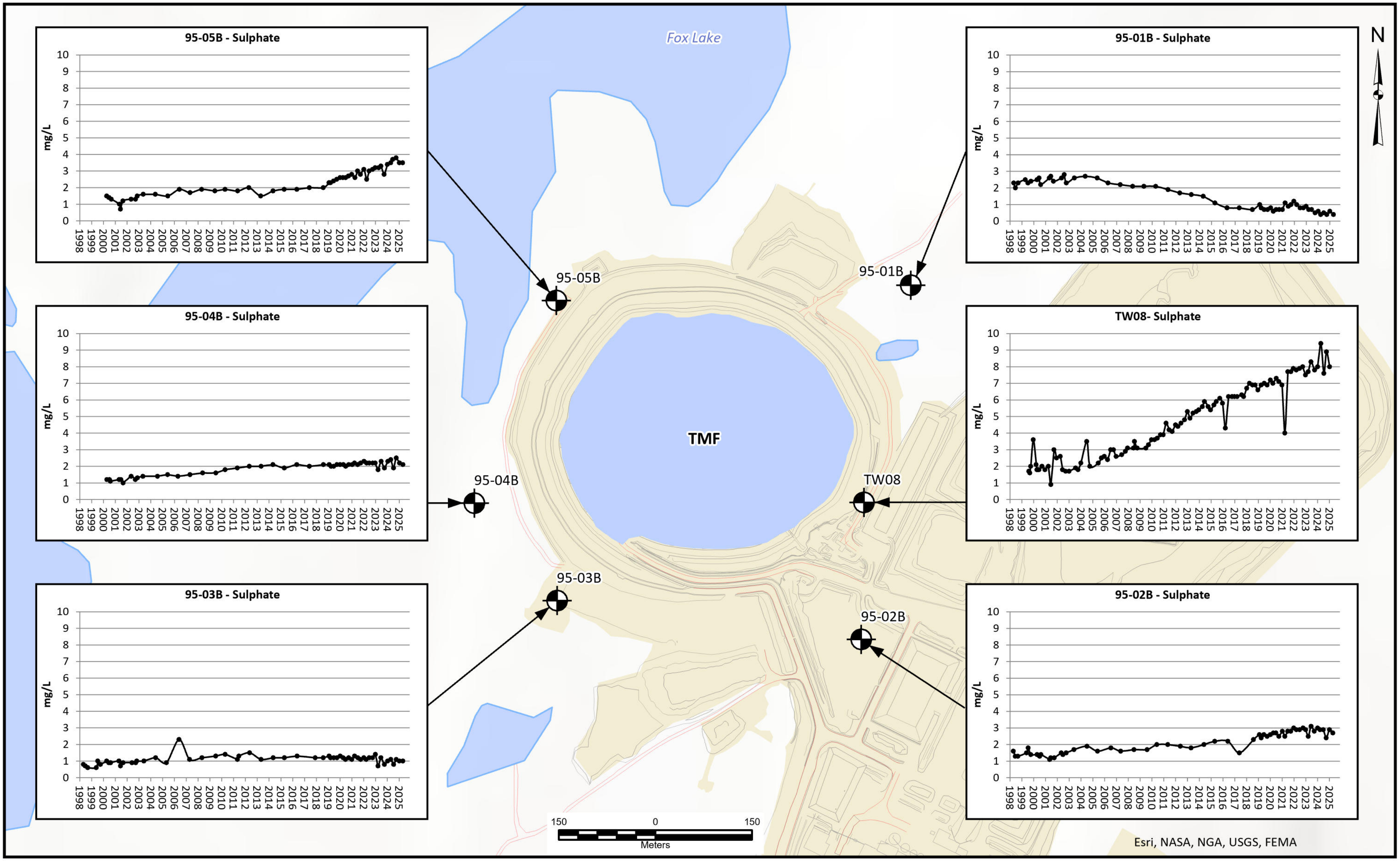

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McCLEAN LAKE OPERATION

4.4-8 (3 OF 4)

SULPHATE CONCENTRATION IN WELLS WITHIN THE VICINITY OF THE TMF

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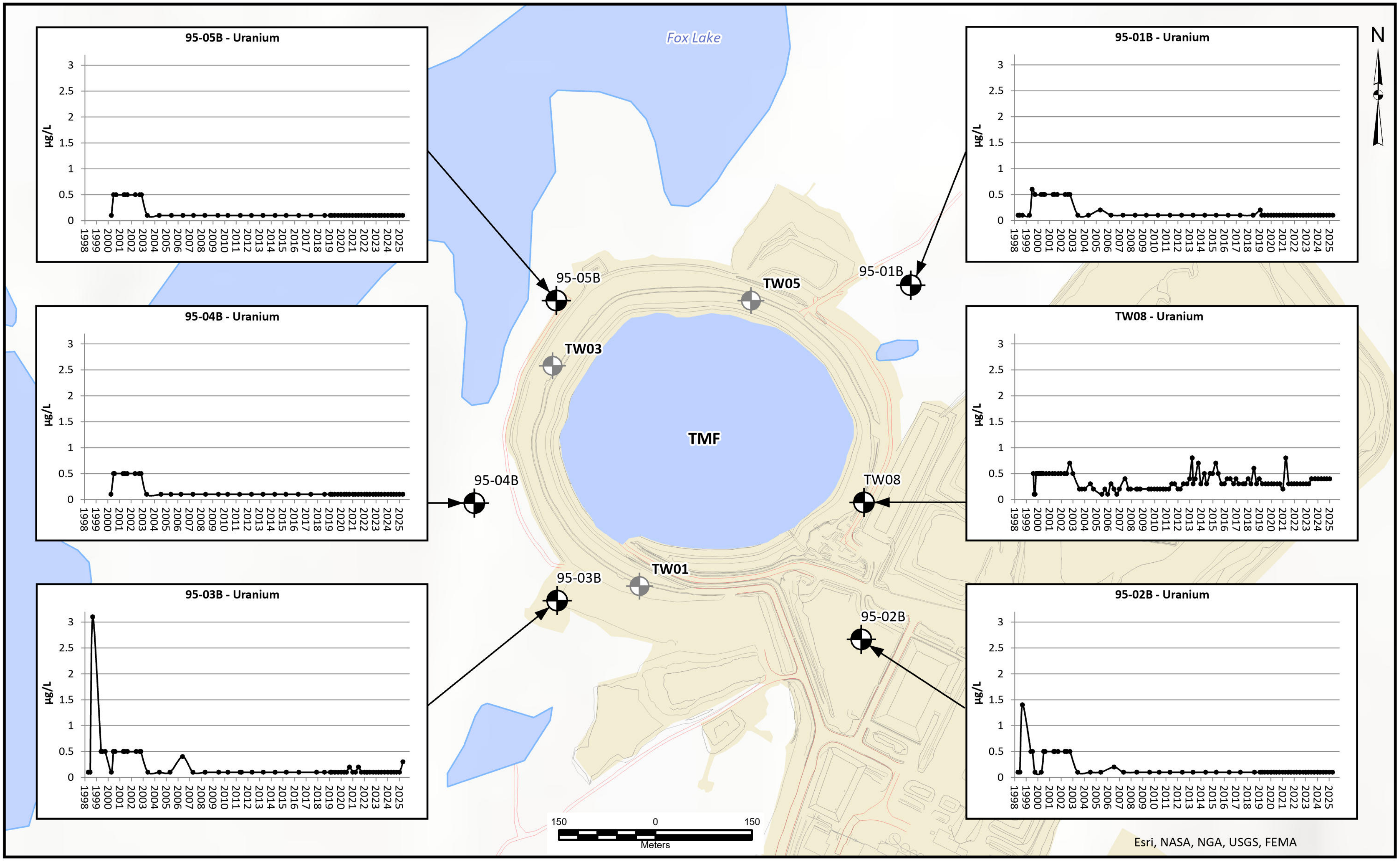

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Data Sources: Natural Resources Canada, Geobase®, Nation Topographic Database, ORANO Canada Inc.

McCLEAN LAKE OPERATION

4.4-8 (4 OF 4)

URANIUM CONCENTRATION IN WELLS WITHIN THE VICINITY OF THE TMF

TAILINGS MANAGEMENT TID

4.4.2 Embankment Failure (Tailings Expansion Project)

A screening level evaluation of the potential environmental consequences to Fox Lake, Pat Lake and downstream water bodies in the Collins Creek watershed resulting from the unlikely failure of the embankment of the expanded TMF was completed (Appendix D, Section F). The assessment is for the operational period subsequent to the expansion under two scenarios:

1) release of pond water to the environment when the pond is at a maximum capacity; and

2) release of pond water and tailings solids to the environment when the JEB TMF is at the maximum capacity.

The hypothetical failure of the JEB TMF embankment was predicted to result in impacted water quality in Fox Lake and limited exceedances of drinking water guidelines were predicted in Pat Lake. No exceedances of the available water quality guidelines and benchmarks are predicted in Nadia Lake and Upper Collins Creek, which indicates that potential negative effects of a JEB TMF embankment failure are limited to Fox Lake and Pat Lake. For up to 7 months following a JEB TMF embankment failure, model predictions indicate that COPC concentrations in Fox Lake are at levels that could potentially affect aquatic species. Various aquatic species may be affected (e.g. fish, aquatic invertebrates, amphibians, and aquatic plants); however, these potential effects are limited to Fox Lake and do not extend further downstream to Pat Lake and Nadia Lake.

Constituent concentrations for tailings solids were not considered directly in the assessment calculations; however, these concentrations are above benchmarks that are set to be protective of aquatic biota. During an unlikely failure of the embankment at the expanded JEB TMF, sediment biota would be expected to be initially and primarily affected by the physical deposition of the solids material (both the tailings and the embankment material that would be carried into the waterbody subsequent to the failure). These materials would mix and cause a physical impact to benthic communities. It is assumed that the tailings solids spill would be remediated and removed from the pond although these remediation efforts would likely not be perfect. The implication of long-term chemical exposure from COPC in tailings solids on benthic invertebrates would depend on the post-remediation sediment concentrations, therefore this analysis was not included in the assessment.

In summary the results of the screening level assessment indicate that the consequences of an embankment failure at the TMF would not have catastrophic effects on the Collins Creek watershed downstream of the facility. While water and sediment quality and the health of aquatic biota in Fox Lake would be expected to be affected and recovery of the lake could take many months or years, it is not anticipated that water bodies downstream of Fox Lake would be negatively impacted over the short or long term.

4.4.3 Spills

Secondary containment is applied to all pipelines used for pumping of reclaim water and tailings associated with the operation of the JEB TMF. Additionally, procedures are in place for response, reporting, and clean-up of spills at the McClean Lake Operation. The combination of designed containment systems and operational procedures serves to mitigate the effects of spills through prevention and response.

4.5 Conclusions

Over the operation of the TMF, the operational effects of this facility have been found to be minimal and within consistent with the findings presented in the environmental assessments as described in the Environmental Performance TID Volume 1 (Orano, 2025a). Efforts of continual improvement are ongoing to evaluate new methods of mitigating environmental impacts, as shown by changes recently made to water management using the TMF to eliminate surges to the water treatment plant. The entire tailings system is carefully monitored and inspected for upset conditions, accidents, and malfunctions and, as such, neither loss of hydraulic containment nor major reportable spills have occurred.

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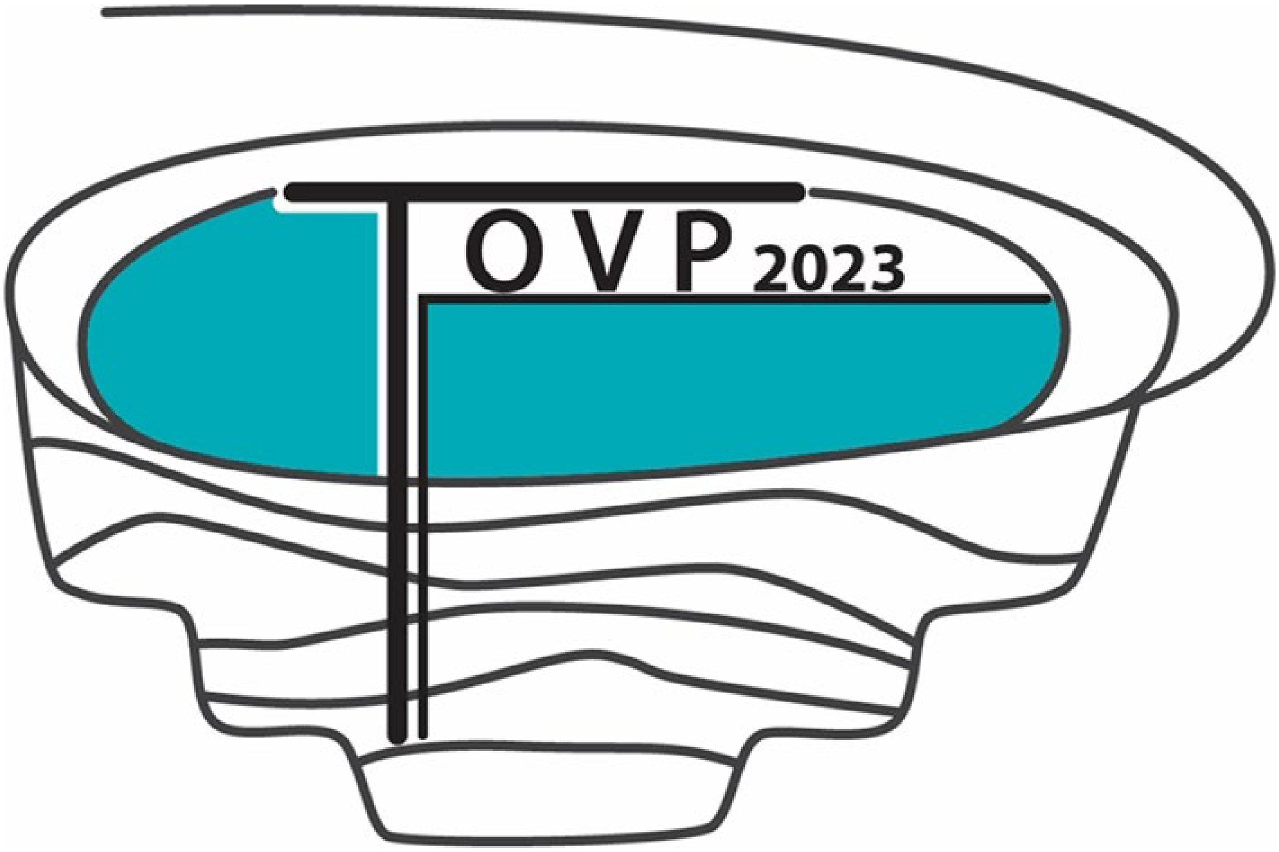
Figures



5 Validation of Long-term Tailings Performance

The Tailings Optimization and Validation Program (TOVP) is the mechanism for validating the long-term performance of tailings. A combination of geochemical controls on pore water concentrations of COPCs and a low final hydraulic tailings conductivity will limit the migration of COPCs from the tailings into the surrounding environment. The TOVP confirms that these controls are present or developing and provides key inputs for groundwater and contaminant transport modelling (Section 7) to validate that the tailings will be suitably protective of the environment in the long-term.

The continued evolution of tailings (i.e. aging) is an important component of long-term tailings performance. While long-term chemical equilibriums are relatively straightforward in theoretical systems, variations in ore and tailings preparation add complexity to the long-term equilibrium conditions in the placed tailings. The TOVP validates the predicted tailings evolution, adjusts predictions based on known and anticipated changes to ore and process, and proposes process optimizations with an understanding of risk. Over time, the tailings system will move towards a chemical equilibrium where pore water concentrations of COPCs are controlled by the solubility of stable mineral phases. Following fundamental chemical principles, the process is predictable and expected, moving the system towards its lowest energy state, and ultimately establishing the passive control of COPCs.

The timing of the evolution to chemical equilibrium varies by COPC. The evolution is controlled by many interrelated factors including: the magnitude of redox change occurring, the availability of accessory ions, and the solubility of predicted mineral phases. In the TOVP, COPCs have been generally considered in two main categories as the program has evolved:

- **Group 1: Insignificant COPCs** (divided into two sub-categories):
  - **Group 1a:** The COPCs in this category are well below the threshold of concern to the downstream environment. The majority of COPCs fall into this category. Significant trends in pore water concentrations are not observed, and therefore average pore water values are calculated and used in groundwater and contaminant transport modelling. The COPCs are predicted to have no environmental impacts and are tracked for completeness and ongoing validation that they remain insignificant. It is likely that the majority of these COPCs undergo simple complexation and redox reactions, which are principally completed in the mill before the tailings are deposited. These COPCs have already reached near equilibrium conditions and will not evolve over time.
  - **Group 1b:** The COPCs in this category are still considered insignificant but have triggered proactive preliminary investigations due to potential developing trends. COPCs may be elevated from Group 1a to Group 1b for a phase of evaluation, to determine if further study is warranted. Current COPCs in this category include copper, lead, and selenium, which were all identified for further evaluation based on results from the 2018 in-situ sampling campaign (Orano 2020, Section 5.7). COPCs in this category may either
    1) move from Group 1b to Group 2 over time as monitoring progresses and persistent trends are confirmed, or
    2) be confirmed as insignificant and returned to Group 1a.
- **Group 2: COPCs of Key Interest:** The COPCs in this category include arsenic, molybdenum, and uranium, which are tracked closely over time. These COPCs are subject to numerous operational controls and have specific programs in place for ongoing validation and refinement (Section 5.5.1-5.5.3.)

In addition to geochemical considerations, the geotechnical evolution of the tailings is also monitored under the TOVP. The overall goal of the geotechnical program is to confirm the development of a hydraulic conductivity contrast between the tailings mass and the surrounding host rock, which will allow groundwater to preferentially flow around the tailings in the long-term (Section 5.6).

Ultimately, the TOVP optimizes tailings performance in a fully decommissioned TMF, provides assurance that predictions of downstream effects are within acceptable risk thresholds, and effectively minimizes decommissioning liabilities.

5.1 Introduction

5.1.1 Regulatory Background

The Tailings Optimization and Validation Program (TOVP) is a component of the documents accepted by the CNSC establishing the licensing basis for the McClean Lake Operation, as described in Section 2.1.

At the time of initial licensing, Orano introduced new technology to the tailings preparation process in the mill at the McClean Lake Operation for the long-term control of soluble constituent concentrations in the tailings pore water. A key geochemical design parameter for tailings discharged from the mill is the arsenic pore water concentration. In the years since production began in 1999, the arsenic content in the ore feeding the mill has ranged over two orders of magnitude and has increased further with the processing of the Cigar Lake ore. Despite the large range of arsenic concentration fed to the mill, the arsenic concentration in the discharged tailings pore water has never exceeded the Action Level identified in the McClean Lake Operation's Environmental Protection Code of Practice and has achieved the predicted operational performance. The effectiveness and robustness of the milling process for the control of soluble arsenic concentration has been clearly verified.

The five-year interval between the publications of the 2020 and 2025 Tailings Management TIDs saw the continued milling of the Cigar Lake ore at the McClean Lake Mill, and continued advancement in scientific and technical studies. Deposition of tailings produced from the Cigar Lake mine is particularly of note for important differences in both the geochemical and geotechnical aspects of the Cigar Lake tailings compared to the earlier JEB/Sue tailings. Significant efforts have been made using the data collected from the 2023 TOVP sampling campaign to advance a clear understanding of how the Cigar Lake tailings compare to the JEB/Sue tailings and to identify new areas of study resulting from any changes.

As the TOVP program matures, greater research effort is assigned to long-term tailings geochemistry in the TMF. Synchrotron based X-ray absorption spectroscopic techniques have been applied to tailings solids and the presence of poorly crystalline arsenic mineral scorodite and the molybdate mineral powellite have been identified. In this report, particular investigative effort has been expended to further validate the aging process for arsenic and to validate the mechanisms which control concentrations of radium-226 in the tailings. The work has led to improved scientific understanding of the fundamental processes that are controlling the pore water concentrations of key constituents of concern for the long-term, regardless of the ore source.

A key geotechnical design parameter for the TMF is the hydraulic conductivity of the placed tailings, particularly those placed against the TMF walls. Geotechnical studies have confirmed that the tailings will consolidate to provide a sufficient hydraulic conductivity contrast with the sandstone host rock which will be suitable to encourage preferential groundwater flow around the decommissioned facility.

During the reporting period efforts have been undertaken to apply a new statistical method (Baysian Networks) to the interpretation of the tailings geotechnical data. This methodology uses geotechnical parameters which are more straightforward to obtain (e.g grain size, density, porosity etc) to predict parameters which are difficult to measure (e.g. hydraulic conductivity). This work allows a broader understanding of the tailings by leveraging the wealth of existing data. This technique is well suited to the JEB TMF tailings data set, as the Baysian network is strengthened through the collection of additional data, and can be improved upon and validated with each subsequent tailings sampling campaign.

The 2018 TOVP field program presented the first opportunity to collect placed Cigar Lake tailings samples and so the number of samples of Cigar Lake tailings were limited. This report on the 2023/2024 sampling campaign incorporates a more detailed picture of the Cigar Lake results into the ongoing validation of tailings geochemical and geotechnical properties.

5.1.2 Response to Regulatory Comments

In 2024 Orano submitted a preliminary report of the tailings sampling campaign performed in 2023 to describe challenges encountered in obtaining deep tailings samples (Braithwaite to Akhter, January 2024). Initial responses to comments on that report were provided with the commitment to provide details in context in the Tailings Management TID (Hughes to Akhter, November 2024). Detailed responses to the comments from that initial reporting are contained in this document and can be found in the following sections as presented in Table 5.1-1:

Table 5.1-1: Regulatory Comments Concordance Table

Expectations to Address Comment	Interim response	Location of Follow-up Information
#1: Challenges to drilling and sampling		
The licensee is recommended to consider whether borehole collapse could be a consequence of liquefaction. Additionally, Orano is recommended to consider to develop countermeasures to address the technical challenges, including: reducing the vibrational disturbance to the in-situ tailings during drilling and sampling (e.g., by reducing the rotational speed of drills, using static press instead of hammering to advance sampler etc.), in order to improve stability of the boreholes. developing new drill head that can prevent tailings from entering the borehole during drilling but can be opened for sampler to advance during sampling	When planning the 2028 TOVP sampling campaign Orano will investigate the potential for liquefaction to affect borehole stability and develop counter measures as needed such as: reducing vibration and potentially using new technology (such as a drill head) to improve sample recovery. Analysis of geotechnical data collected in 2023 and 2024 will be used for this purpose and a preliminary discussion of potential liquefaction will be included in the 2025 Tailings Management TID.	Section 5.6.3.3.5
#2: Impacts of additives		
The licensee is expected to consider the potential impacts of the additives to the	Acknowledged, Orano will address this concern with a discussion accompanying the	Section 5.2.1

Expectations to Address Comment	Interim response	Location of Follow-up Information
geochemical characteristics of tailings when analyzing the experimental results and preparing for the 2025 tailings TID.	geochemical analysis presented in the upcoming 2025 tailings TID.	And Section 5.7.6
#3: Borehole coverage		
The licensee is expected to consider the overall borehole coverage of the TMF for the TOVP when preparing for the 2025 tailings TID.	Acknowledged, Orano will include a discussion and justification of borehole location selection in the 2025 Tailings Management TID.	Section: 5.2.4 (overview) 5.2.4.1 (specific response)
#4: Potential effects of sonic drilling on sample disturbance and its impacts on tailings geotechnical properties		
The licensee is expected to assess the potential impacts of the sample disturbance on the geotechnical properties of the 2024 sampling campaign.	In order to reduce uncertainty from the introduction of a new drilling method, and because the more problematic deep boreholes were not being drilled in 2024 Orano chose not to attempt sonic drilling in 2024. Instead Orano continued successfully with a standard drill and piston sampler as in all past campaigns. Orano will provide a general assessment of sample disturbance to geotechnical sample properties in the upcoming 2025 Tailings Management TID based on 2024 geotechnical sampling results in preparation for the possibility of using a different drilling technique in 2028. Additionally, please note that Orano intends to provide a presentation on the tailings TID to the CNSC in person after its submission so that any questions can be discussed with all the relevant information collected in the TID.	Section 5.6.3.3.6

5.1.3 JEB TMF Facility Background

The JEB TMF is designed to minimize the migration of soluble constituents from the facility to the receiving environment, both during the operating and post-decommissioning periods as described below:

- **Operational Period:** Hydrodynamic containment provides a condition where the consistent inflow of groundwater to the facility prevents migration of soluble radionuclides and heavy metals into the surrounding aquifer (Section 2.2.2)

- **Post-Decommissioning Period:** The key to the long-term performance of JEB TMF is the hydraulic isolation of the tailings materials within the decommissioned facility from the surrounding aquifer. The following passive controls are established to ensure the long-term environmental performance of the TMF:

    - *Geochemical Controls:* The design of the decommissioned facility relies on the control of source concentrations within the tailings pore water; and

    - *Physical Containment/Geotechnical Controls:* A hydraulic conductivity contrast between the tailings mass and the surrounding host rock is established to allow groundwater to preferentially flow around the tailings.

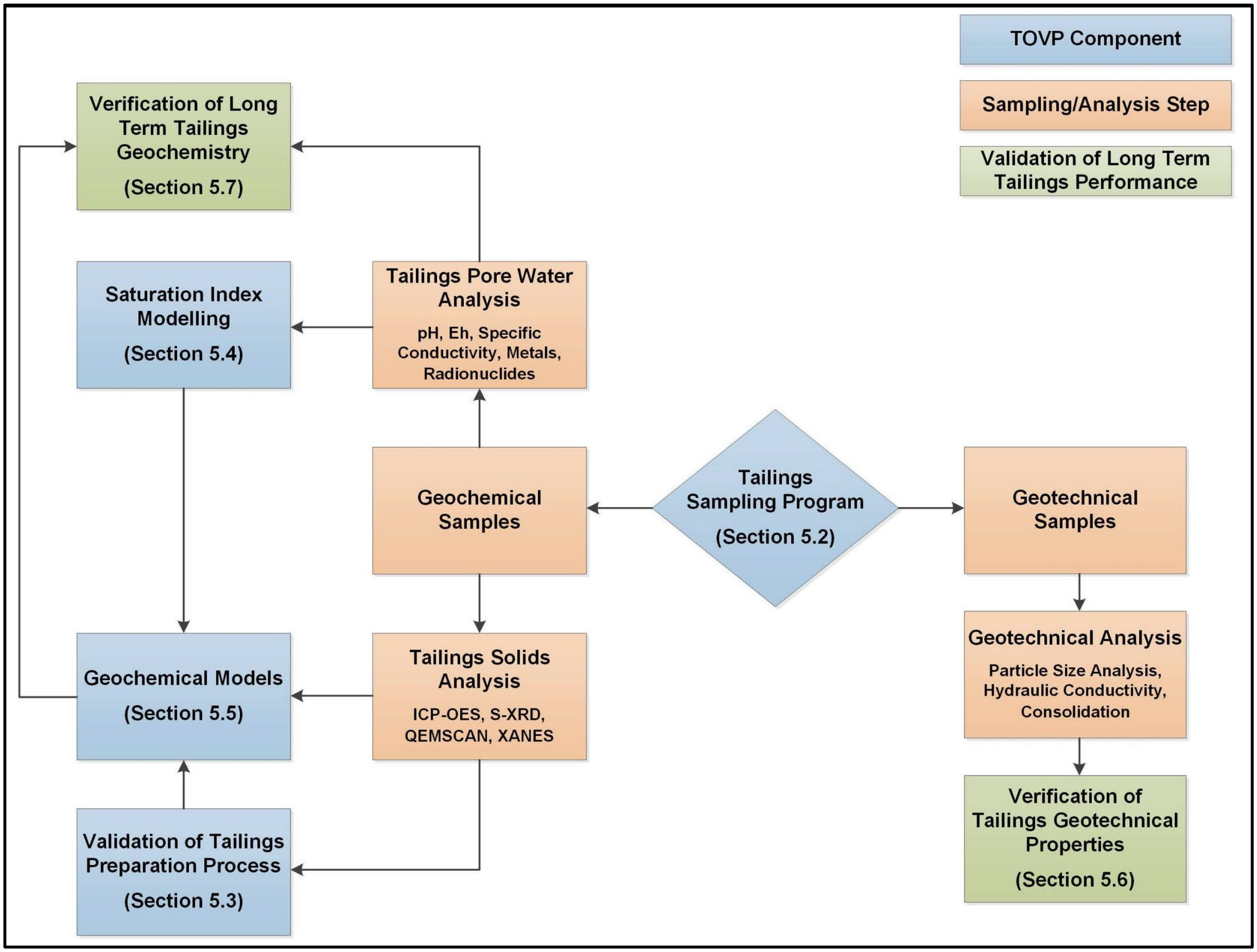
5.1.4 Roadmap

The TOVP consists of several interrelated components. Figure 5.1-1 provides a roadmap to the TOVP, showing the relationships between the various components and where the information can be found within this section. The program ultimately validates the long-term performance of the tailings by

1) confirming the establishment of geochemical and geotechnical passive controls, and

2) determining the predicted source terms and end state hydraulic conductivities which are then carried forward into groundwater and contaminant transport modelling (Section 7).

Figure 5.1-1: TOVP Roadmap



5.2 Tailings Sampling Program

The long-term environmental performance of the JEB TMF is reliant upon both the geochemical and geotechnical properties of the tailings disposed of within the facility. Test work undertaken to characterize tailings for the design of the TMF was performed on laboratory produced tailings synthesized from samples of various ores to be processed in the McClean Lake Mill. In situ monitoring and sampling of tailings materials deposited in the JEB TMF verified that the properties of tailings produced by the mill met the design criteria for the facility as presented in previous TOVP reports. Investigative assessments are conducted at approximately five-year intervals to confirm that this continues to be the case.

To date, geotechnical and geochemical characteristics of placed tailings have been investigated through eight TOVP campaigns between 2000 and 2023/2024. Initially, samples and in situ measurements of tailings deposited within the JEB TMF were collected during annual field monitoring campaigns. The results of each field program were reported in annual TOVP Status Reports (COGEMA, 2001; COGEMA, 2002; COGEMA, 2003; COGEMA, 2004a; AREVA, 2005a; AREVA, 2011a; AREVA, 2015: Orano, 2020) as required under the initial TOVP commitments (COGEMA, 1999). Results from the most recent TOVP in 2023/24 are presented and discussed in this report. Table 5.2-1 presents a summary of activities undertaken as part of these intrusive investigations.

Table 5.2-1: TMF Sampling and Monitoring Campaigns – Number of Samples

Year	Boreholes	Geochemical Samples	Geotechnical Samples	Cone Penetrometer Test Borehole Logs
2000	10*	20	20	
2001	12	44	35	19
2002	9	31	20	12
2003	11	26	32	--
2004	14	38	36	--
2008	14	66	39	20
2013	19	106	89	18
2017	15	0	98	15
2018	19	121	78	15
2021	17	30	48	15
2023/2024	19	156	60	14

*surficial core samples only (0 to 500 mm below tailings surface)

The objective of the 2023/24 intrusive assessment was to further characterize the tailings placed in the JEB TMF from a geotechnical and geochemical perspective and to provide additional characterization of the newly placed Cigar Lake tailings. Previous test work has been duplicated to further examine the aging behaviour of placed tailings and to assess the amenability of the new Cigar Lake tailings. Key parameters, indicative of TMF long-term environmental performance, were assessed with a focus on the hydraulic conductivity of placed tailings and the tailings pore water and solids chemistry. The density and rate of consolidation of placed tailings are also key parameters, to ensure an adequate long-term disposal volume within the TMF and to inform decommissioning plans.

The specific objectives of the 2023/24 intrusive assessment were:

To assess the characteristics of the placed tailings within the TMF, including:

- average in situ density (void ratio);
- tailings surface contours; and
- tailings structure/stratigraphy.

To obtain samples of tailings for geotechnical and geochemical testing and characterization for the purposes of analyses to assess the long-term behaviour of tailings within the JEB TMF. Parameters of interest include:

- consolidation curves;
- hydraulic conductivity versus void ratio/effective stress curves;
- pore water chemistry;
- solids chemistry;
- solid/aqueous phase chemical interaction (aging effects);
- solids mineralogical composition; and
- grain size distribution.

The 2023/24 intrusive assessment comprised field activities in support of the objectives of the investigation as presented below in Table 5.2-2.

Table 5.2-2: Field Activity Summary

Activity	Focus	Objective
Core Sampling	Stratigraphy (visual classification)	Assessment of placement method
		Segregation
	Geotechnical samples	Predict consolidation behaviour
		Long-term permeability
		Grain size distribution
	Geochemical samples	Pore water chemistry
		Solids chemistry & mineralogy

Activity	Focus	Objective
		Grain size distribution
Surface Sounding	Tailings surface profile (conducted in June and September 2023)	Average in situ volume/density

The 2023/24 intrusive assessment targeted shallow tailings placed since the most recent sampling campaign for geotechnical characterization, and comprehensive samples of both previously sampled tailings and new tailings for further characterization of geochemical aging behaviour.

Shallow geotechnical boreholes were advanced at eleven locations (TMF23-09 through TMF23-20) in the JEB TMF. Geotechnical holes were generally drilled along transects moving outwards from deposition locations to intersect the material placed since the last sampling campaign in 2018. Additional geotechnical samples were also collected from six geochemical holes. Borehole locations were chosen such that spatial change in placed tailings and temporal changes in older tailings properties could be identified.

Four deep boreholes (TMF23-01 to TMF23-04) were advanced at locations previously sampled since 2001 for the purpose of geochemical characterization of all deposited tailings. Figure 5.2-1a shows tailings surfaces by year. Samples from the deep boreholes were collected at depths corresponding to strata previously sampled in 2001, 2002, 2003, 2004, 2008, 2013 and 2018. Three additional geochemical holes established in 2013 (TMF23-05, TMF23-06, and TMF23-07), and one additional geochemical hole established in 2021 (TMF23-08), were also sampled. The three newer geochemical boreholes from 2013 were sampled to intersect tailings further from the deposition point near the periphery of the pit. Borehole TMF23-08 was chosen to resample a location where Cigar Lake tailings, with a higher-than-average arsenic grade, were deposited in 2019. Where possible, deep boreholes were advanced to the riprap associated with the TMF filter package. Typical shallow and deep boreholes are pictured in Figure 5.2-1b.

Figure 5.2-2a presents the locations of boreholes in the 2023/24 TMF intrusive assessment. TMF23-01 through TMF23-08 are geochemical sampling locations, while the remainder are geotechnical sampling locations. Geochemical and geotechnical borehole locations for current and historical TMF intrusive assessments are presented in Figure 5.2-2b and 5.2-2c respectively. Drilling was conducted from a barge-mounted drill rig, shown in Figure 5.2-3. SRK Consulting was retained to conduct the sample collection and cone penetrometer testing (CPT) was conducted by Schwartz Soil Tech under the direction of Orano personnel. Paddock Drilling Limited (Paddock) mobilized the drill and crew to perform the tailings sampling. Geochemical characterization was completed by the Saskatchewan Research Council (SRC), ALS Laboratories, McClean Lake Chem Lab and the Canadian Light Source, while further geotechnical characterization was completed WSP consultants in Saskatoon.

Figure 5.2-1a: TMF Cross Sections Showing Tailings Deposited by Year

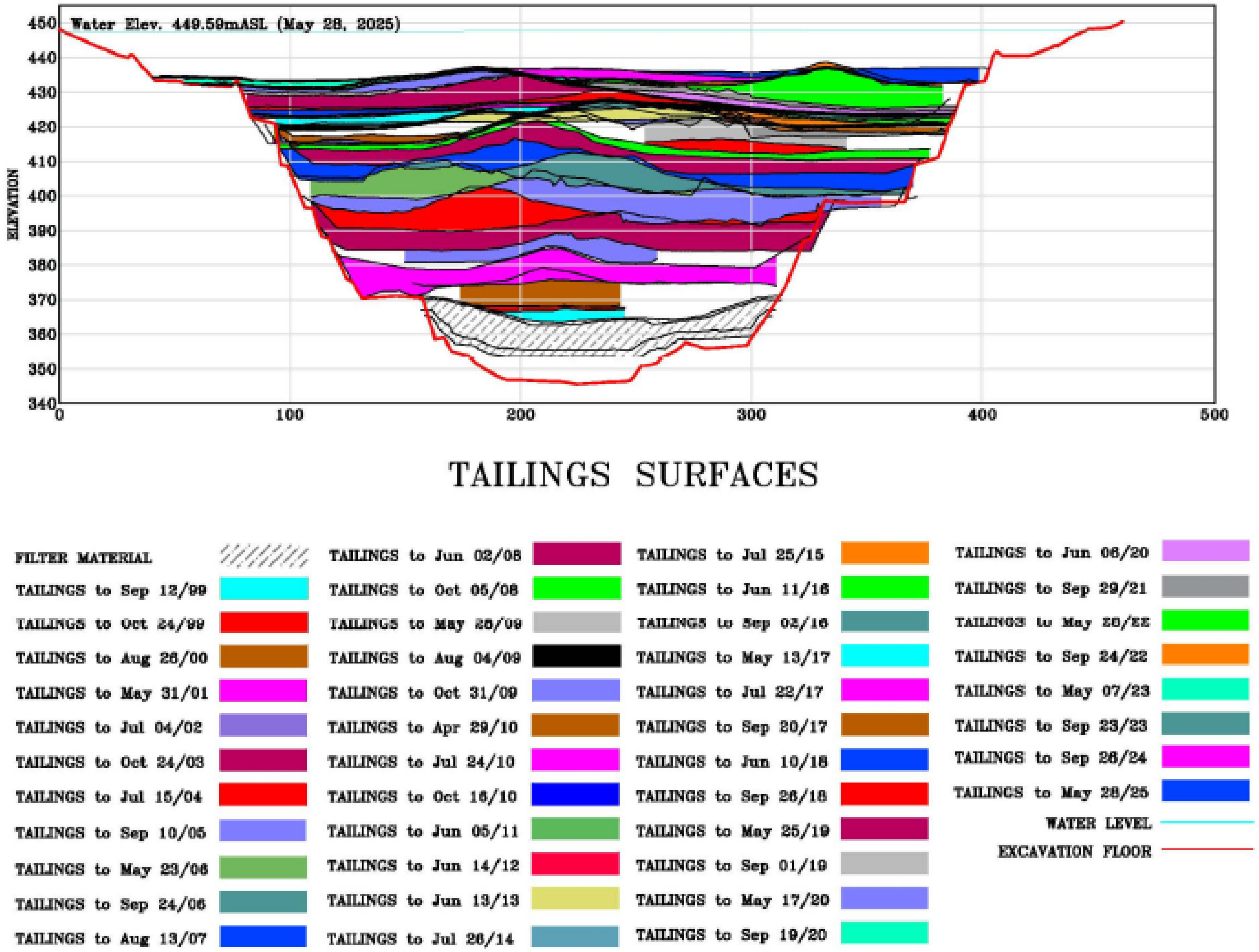


Figure 5.2-1b: TMF Cross Sections Showing Typical Geochemical and Geotechnical Borehole Depths

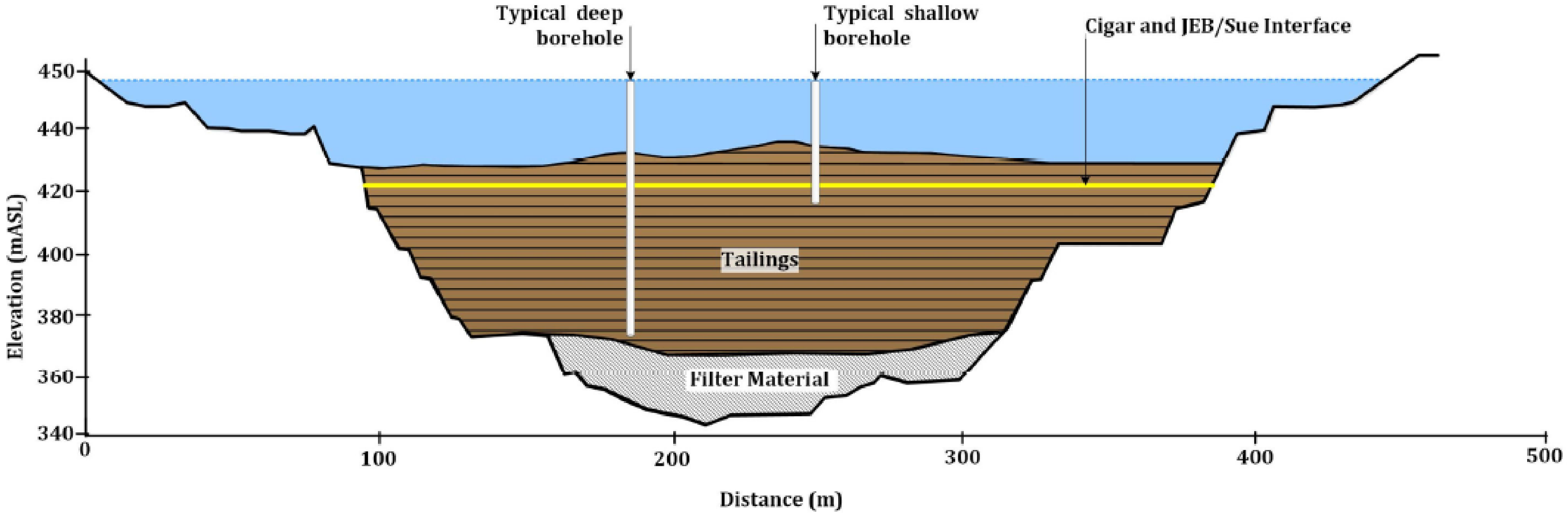


Figure 5.2-2a: Borehole Locations in 2023 TOVP Field Program

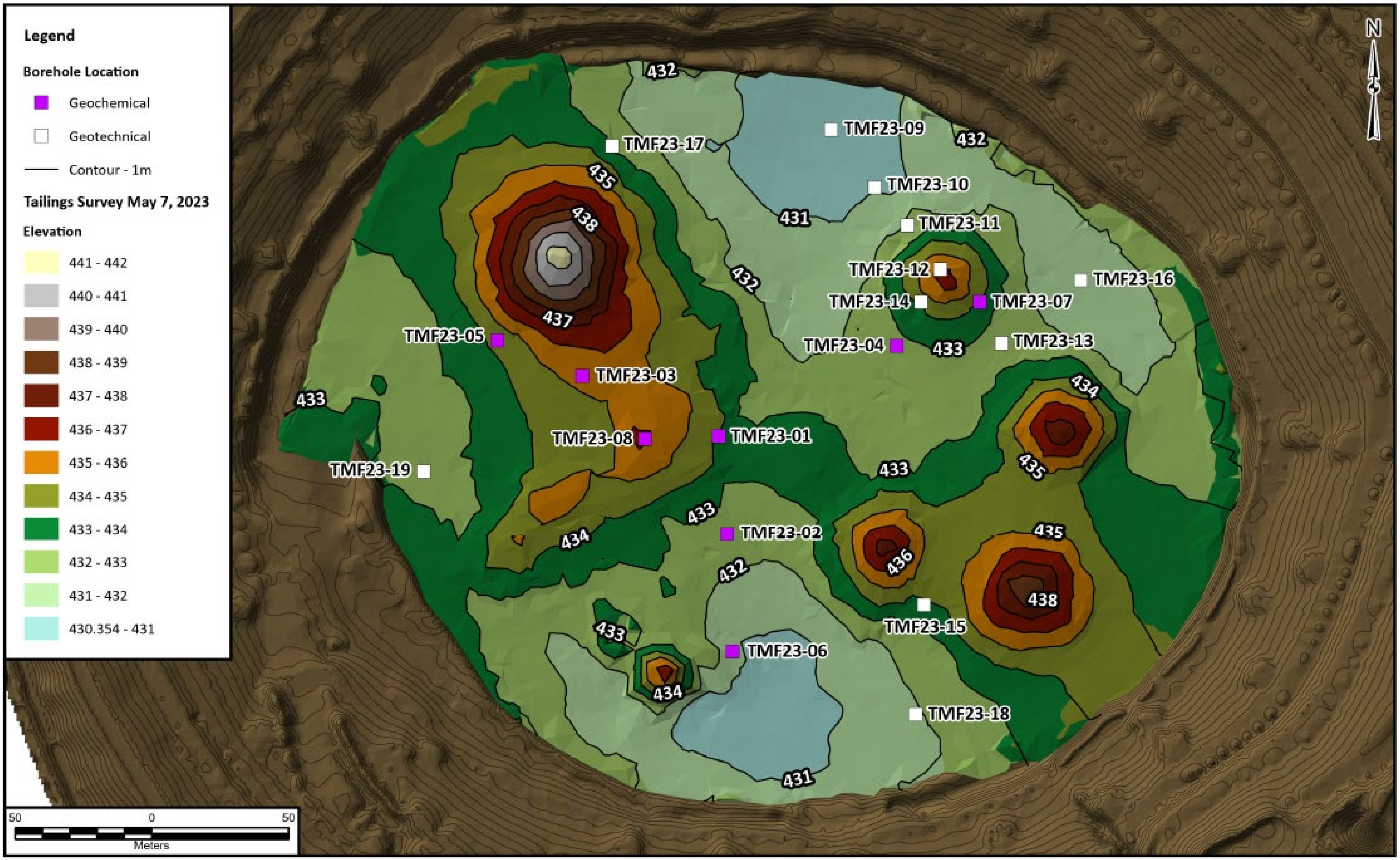


Figure 5.2-2b: Geochemical Borehole Locations in all TOVP Field Programs

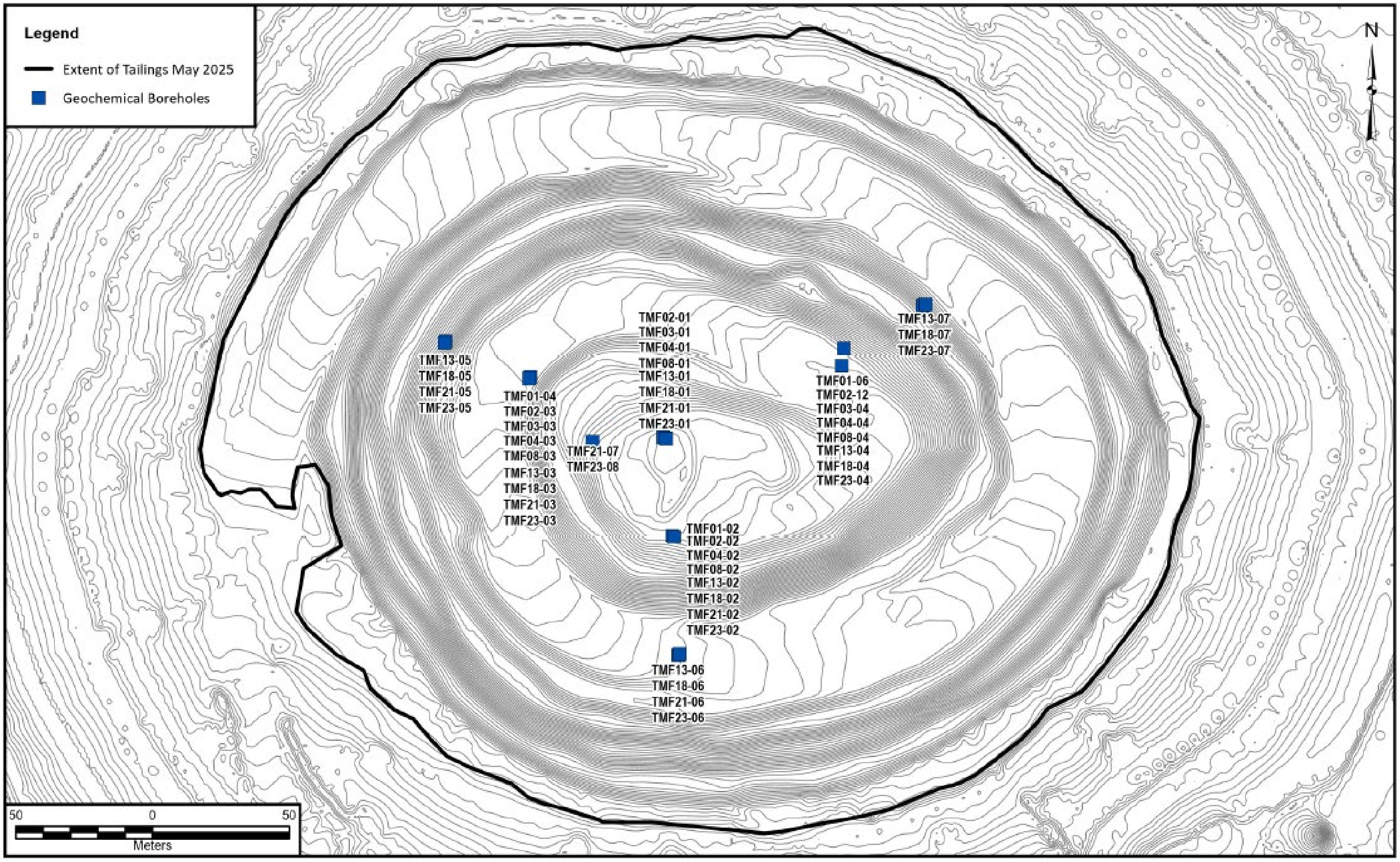


Figure 5.2-2c: Geotechnical Borehole Locations in all TOVP Field Program

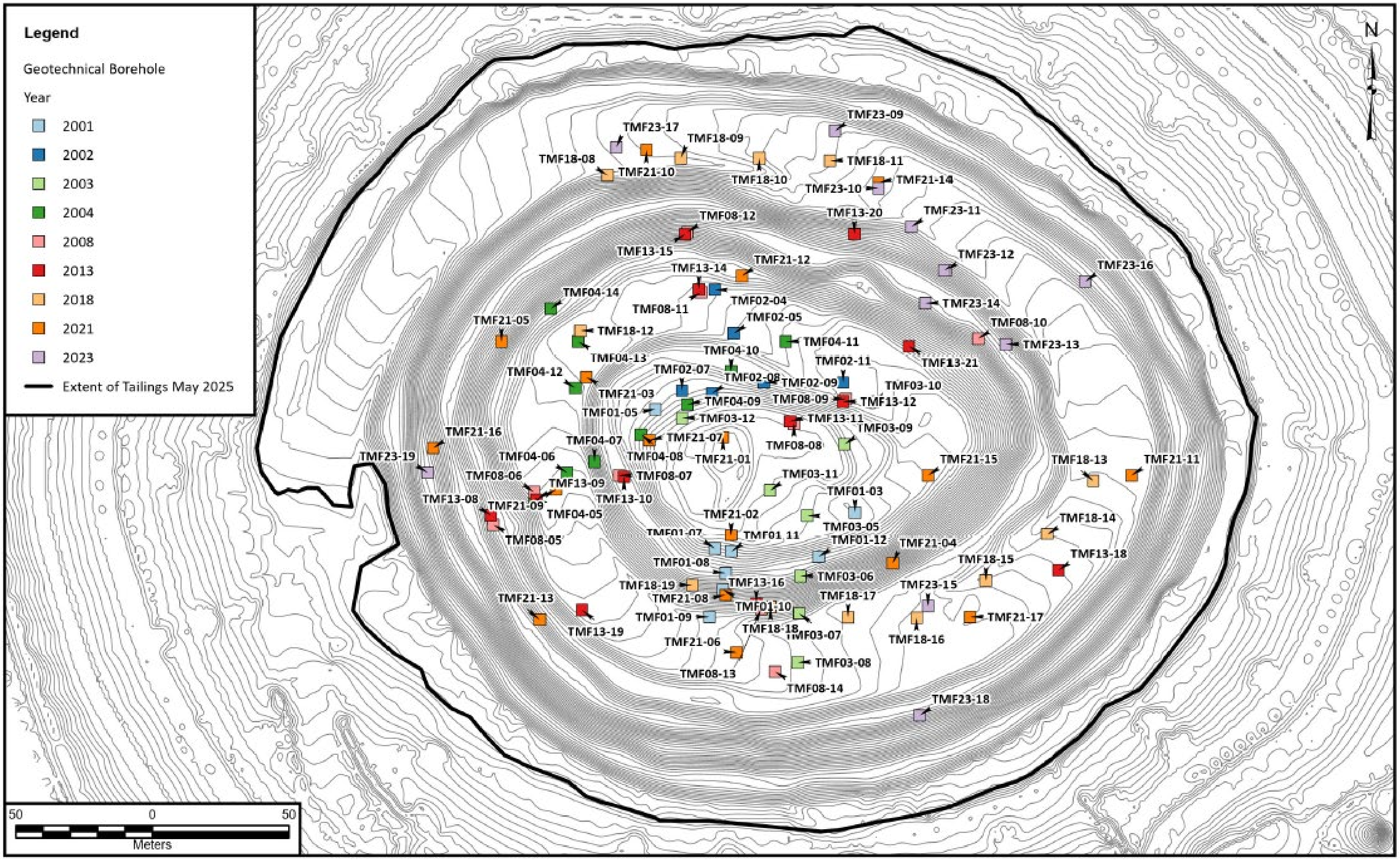


Figure 5.2-3: Barge-Mounted Drill Rig 2004 (upper left), 2018 (upper right) and 2023 (lower)

5.2.1 Drilling Methods and Sample Collection

Tailings sampling drilling was conducted by advancing HW casing (100 mm diameter) to the sampling point by wash boring with extra high yield bentonite drilling mud. A thin-walled sampler was lowered through the casing and pushed into the tailings beneath to collect intact samples. A commercially available Gregory type piston sampler that uses hydraulic pressure, applied through the drill rods, was used to push a 76.2 mm stainless steel Shelby tube into the tailings. In 2023 the shelby tube recovery method met refusal at lower depths of the tailings (as discussed in detail in section 5.6.3.3). When sampling using the piston sampler was no longer possible a split spoon sapling method was used until the either refusal was again encountered or the bottom on the hole was reached. Difficulties in reaching the deepest samples were encountered particularly in boreholes TMF-01, -02, -03 and -04. The only deep borehole which was sampled to the bottom was TMF23-04.

- TMF23-01 was sampled to 383.59 masl (Sample 19) and six additional samples were not collected.
- TMF 23-01 was sampled to 379.70 masl (Sample 19) and three additional samples were not collected.
- TMF23-03 was sampled to 381.17 masl (Sample 21) and three additional samples were not collected.
- TMF23-04 was sampled to the bottom (373.61 masl)

In 2023 while attempting to collect the most difficult samples additional drilling mud additives were used to attempt to stabilize the bore hole. The use of this mud is not anticipated to have any impact on the geochemistry of the collected samples for the following reasons:

- The drilling mud is used in the drill holes prior to sample collection. Drilling stops above the level of the sample to be taken and the sampling device (Gregory piston sampler or split spoon sampler) is pushed or driven down into the undrilled tailings below. Any influence from the drilling mud would be above the level of the sample.

- Additionally the geochemical tailings sampling results themselves (section 5.7) present data of key COPCs that, in many cases, identifies trends which persist over several sampling campaigns. The same trends were again identified in 2023 (e.g. arsenic, molybdenum and uranium). No significant changes in the concentrations of major ions

TMF Drilling locations were surveyed in advance of the project and marked with buoys. For the geochemical samples collected from previously established locations (TMF23-01 to TMF23-08), the drilling barge was positioned carefully in the field using a GPS to ensure that samples were collected as closely as possible to the previous locations.

Upon retrieval of each tailings sample, the Shelby tube ends were sealed with wax, capped and wrapped with duct tape. Each sample designated for chemical analyses was transported to the sample preparation area, stored vertically, and maintained at approximately 10 °C prior to processing. Samples obtained through split spoon sampling were removed from the sampler on the barge and stored in Ziploc bags until sampling. Due to the delays in drilling, the split spoon samples were largely sub-sampled for geochemical analysis the same day, or the morning after their sampling, otherwise they were stored at 5^{o}C until they were processed. Geotechnical samples were stored temporarily in barrels at the sample preparation area, before being packaged and shipped to Saskatoon for further analysis.

The sampling method and sample handling/processing protocols for geochemical samples is described below. Pore water and solids chemical analyses for the samples obtained from the deep geochemical boreholes are located in Appendix D, Section B.

5.2.2 Geochemical Sampling Methods

Samples for chemical analysis were processed as soon as possible after sample collection. Processing of tailings samples designated for chemical analysis proceeded as follows:

1. A small volume of tailings was removed from the bottom of the stainless-steel tube to accommodate the piston head of the extruder. The end of the Shelby tube was lined up with the head with the head of the piston to avoid damage to the equipment.

2. A sample was extruded and sectioned into three approx. 13 cm sections while the very end, which was exposed to air, was removed, and discarded.

3. Each of the 13 cm sections was loaded into one titanium squeezing apparatus. Any excess sample was retained in the Shelby tube to limit its contact with the atmosphere in case it was needed later.

4. Each titanium squeezer was inserted into a hydraulic shop press and pore water was slowly pressed out into a 60 mL syringe as the tailings sample was compressed. The pore water was collected initially for field measurements and secondly for further laboratory testing.

5. The various sets of parameter list for pore water are described in Table 1. Depending upon the analyses selected for pore water from each tube sample, sample preparation was as follows:

- 25 mL for immediate field parameter determinations, pH, Eh, conductivity, and temperature (Class D);

- 20 mL for immediate dissolved oxygen measurement (Class E);

- 1L (500 mL minimum) collected and stored at 4°C for ICP metal analysis, general chemistry and radionuclides (Class F)

- 50 mL (minimum) collected, filtered, and preserved with hydrochloric acid for As^{3+} and As^{5+} speciation analysis (Class G);

- 50 mL (minimum) collected and preserved with sulphuric acid for Nutrient analysis (NH_3, DOC, COD and TOC) (Class H);

- 125 mL (required) collected, filtered, and preserved with EDTA provided from ALS Laboratories for methylated arsenic speciation (for select samples only) (Class I).

6. The solids were extruded from the squeezing apparatus for sub-sampling (5.2-4a and b, 5.2-5a and b). The various sets of parameter list for tailings solids are described in Table 5.2-3. Tailings solids sub-samples were prepared for the selected sets of analyses for each core sample.

7. According to the analyses selected for tailings solids from each core segment, and subject to available sample quantities, sample preparation was as follows:

- 500 g, for archive, nitrogen purge vacuum sealed, and stored for possible future analyses (Class A);

- 200 g for ICP metal analysis (Class B);

- 10 g for grain size determination (Class C) and,

- 100g for hydrocarbon analysis

8. All sample containers were labelled with date, preparation/preservation method, borehole number, location, core segment, sample interval, and analysis to be performed.

Sample identification information, preparation methods and measurements were recorded on the applicable data sheets.

Figure 5.2-4a: Titanium Sample Squeezing Apparatus

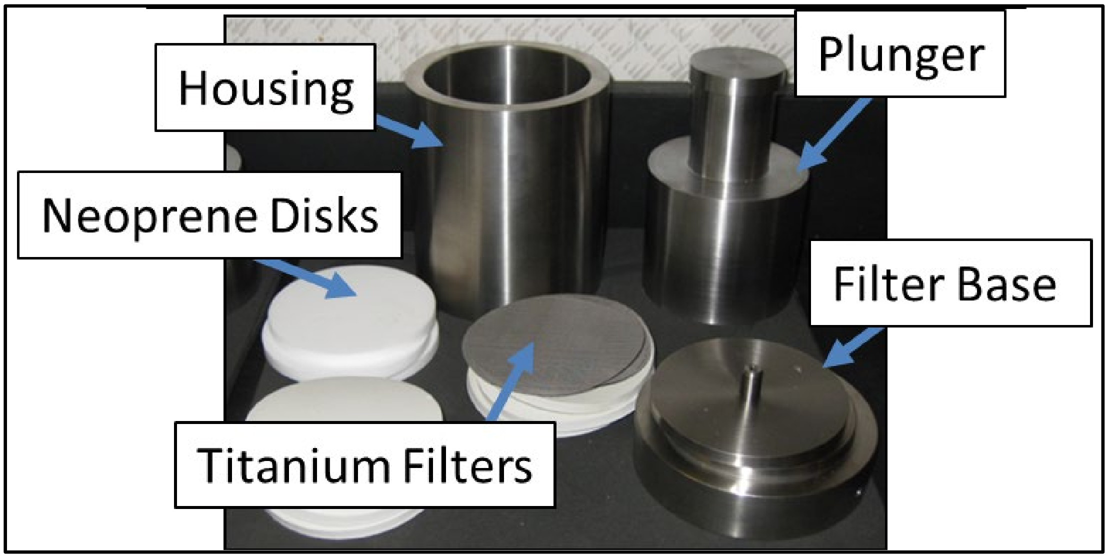


Figure 5.2-4b: Solids Core Squeezing Stand.

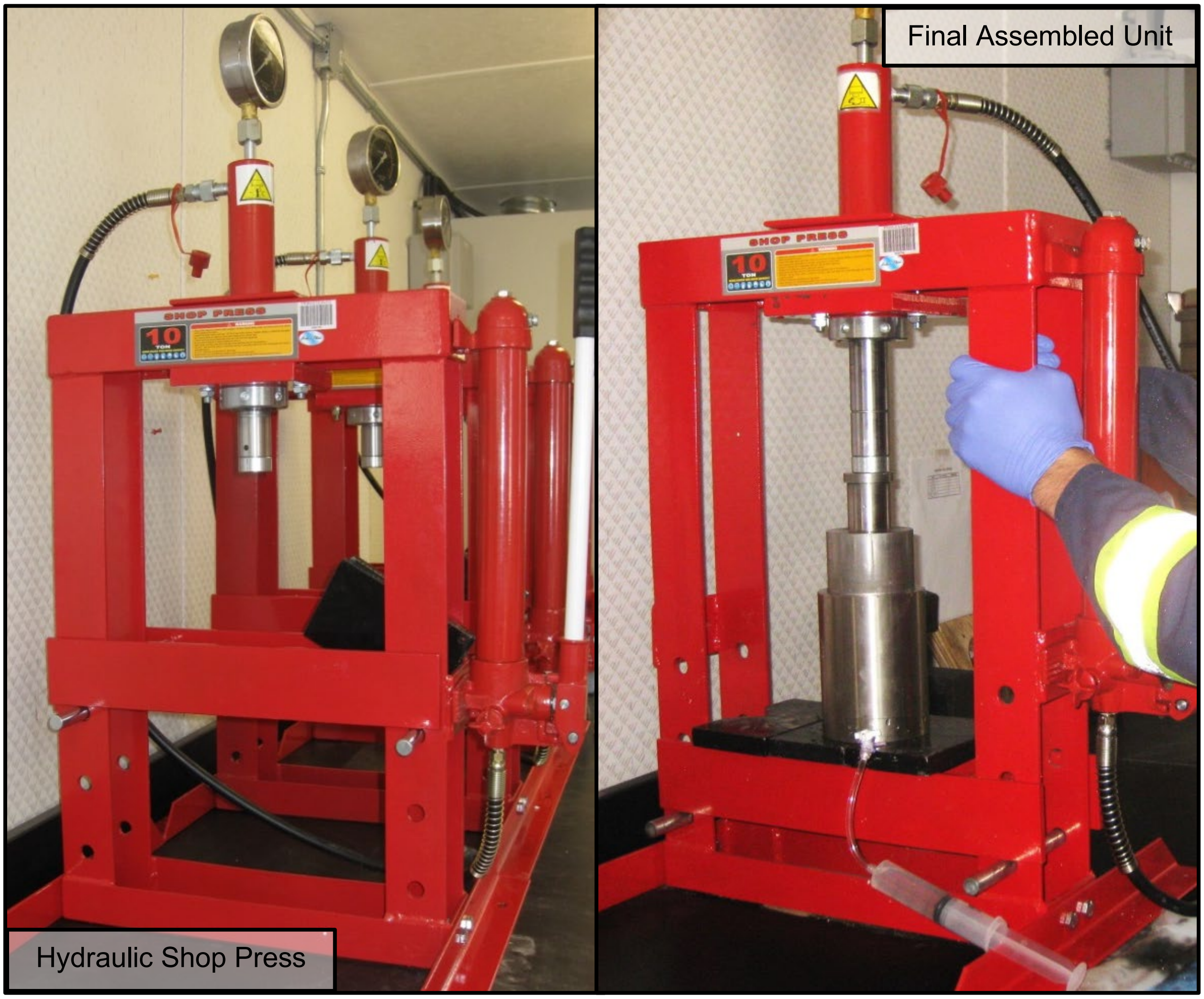


Figure 5.2-5a: A shallow Cigar Lake Tailings Solids Sample from Borehole TMF23-02

Figure 5.2-5b: Deep JEB/Sue Tailings Solids Sample from BoreholeTMF23-02.

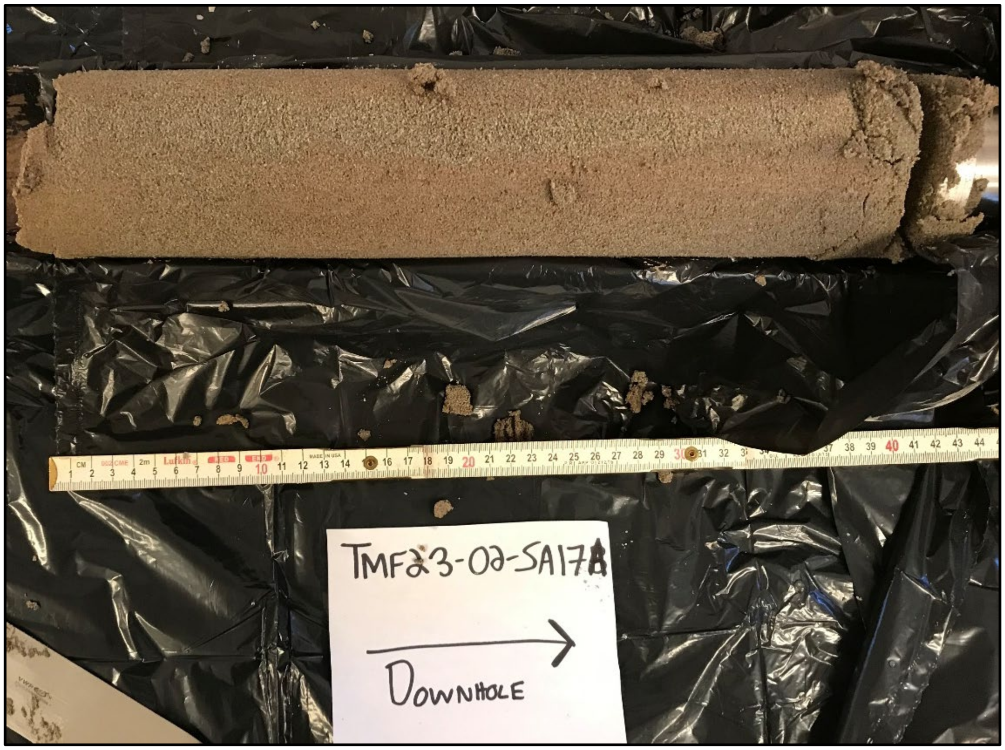


Table 5.2-3: Parameter Class Summary.

Parameter Class	Medium	Sample Quantity	Preservative	Analyses
A	solids	500 g	dried / vacuum Sealed	Archive
B	solids	100 g	vacuum Sealed	ICP metals (Ag, Al, B, Ba, Be, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Se, Si, Sr, Ti, V, Zn, Zr) + As + U
C	solids	500g	none	Grain Size Determination
D	pore water	25 mL	field measurement	pH, Spec. Cond., Temp, Eh,
E	pore water	20 mL	field measurement	DO
F	pore water	1L	no air/ cold	ICP metals (Ag, Al, B, Ba, Be, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Se, Si, Sr, Ti, V, Zn, Zr) + arsenic + U
				PO_4^{3-}, NO_3^-, Cl^-, SO_4^{2-}, OH^-, CO_3^{2-}/HCO_3^-, Total Alkalinity
				^{210}Pb, ^{210}Po, ^{226} Ra, ^{230}Th
G	pore water	50 mL	no air/ cold	As^{3+}/As^{5+}
H	pore water	35 mL	sulphuric acid	$NH_{3,}$, TOC, COD,
I	pore water	125 mL	EDTA	MMA, DMA, As3+/ As5+

5.2.3 Field Measurements

Several measurements were taken in the field and during sample preparation. Table 5.2-4 shows the methods employed and the equipment used.

Table 5.2-4: Summary of Field Measurements

Parameter	Equipment	Description of Method/Calibration
pH	Thermo Scientific Orion VERSA STAR meter with accompanying pH electrode	pH and temperature measured. pH values automatically corrected for temperature. Meter calibrated daily with pH 4, 7, and 10 buffer solutions
Eh	Thermo Scientific Orion VERSA STAR meter with a platinum electrode and a silver/silver-chloride reference electrode	Oxidation-reduction potential (ORP) measured and converted to Eh Meter calibrated daily with excess quinhydrone in pH 4.01
Specific Conductivity	Thermo Scientific Orion VERSA STAR meter with a conductivity module	Meter calibrated daily with a standard solution of 1413 µS/cm at 25 ^{o}C
Dissolved Oxygen	Thermo Scientific Orion VERSA STAR meter with a DO module	Meter calibrated daily to water saturated air

5.2.4 Methods of Chemical Analyses of Samples from In Situ Sampling

Analytical testing of tailings solids and pore water were performed by Saskatchewan Research Council (SRC) Analytical Laboratories in Saskatoon. Testing was done according to SRC's standard methods and quality assurance program. In addition, As^{3+} / As^{5+} speciation analysis was conducted for as many samples as possible (given sufficient sample volume) by ALS Laboratories. As^{3+}/ As^{5+} speciation analysis for selected samples with sufficient additional pore water volume was also conducted at the McClean Lake Chem Lab to confirm results.

5.2.5 Calculation of Volume Averaged Pore Water Concentration

5.2.5.1 Sampling Location Selection

The choice of drilling locations for tailings sampling has remained largely consistent since the initial tailings sampling program in 2001 (locations being TMF-01, TMF-02, TMF-03 and TMF-04) with a notable step change in 2013 where three additional boreholes were added to the program to account for the increase in tailings volume (TMF-05, TMF-06 and TMF-07). The investigation of the same sampling locations throughout the program has enabled an evaluation of tailings of similar composition over time, leading to a stronger understanding of geochemical and geotechnical evolution. As the tailings mass continues to expand Orano will evaluate the tailings sampling locations to determine if additional locations are needed to capture the evolution of the Cigar Lake tailings.

The process of selecting new borehole locations targeting Cigar Lake tailings will involve the following considerations:

Borehole Distribution: In calculating the weighted average pore water values of COPCs in the TMF the most straightforward method involves selecting borehole locations to give the most even possible coverage of the total TMF area. Selecting evenly spaced boreholes also allows for reproducible comparisons between campaigns as the TMF is filled.

Increased Tailings Surface Area: With the changes to deposition method (as discussed in Section 2.3.2.3) and the much greater surface area of the current uppermost tailings mass, deposition locations are now targeted at filling low areas in the tailings. Tailings no longer form layers over the entire surface area of the tailings mass as they are deposited, and so consideration will be given to specific deposition points when selecting new sampling locations. For example, in the current sampling campaign, location TMF23-08 targets an area of Cigar Lake tailings known to be produced from high arsenic ore to track the evolution of specific tailings more closely.

In each TOVP sampling campaign the geochemical borehole locations remain the same while the geotechnical borehole locations are targeted to sample newly placed tailings and answer specific geotechnical questions. In designing the TOVP sampling campaign for 2028 Orano will consider a hybrid approach to selecting geochemical boreholes:

1) Locations will be selected which will be revisited during subsequent campaigns to evenly cover the tailings surface and,

2) Locations will be chosen to test tailings deposited since the previous sampling campaign and identify any areas of specific geochemical interest which will not necessarily be sampled in subsequent campaigns.

5.2.5.2 Calculation of Average Solute Concentration

The average solute concentration of each constituent in tailings pore water is calculated based on the chemical analysis of samples collected during the field investigation. Results for 2023 are presented in Appendix D, Section B. In 2023, a total of 156 samples were collected from eight boreholes advanced as far as possible through the full depth of the tailings mass as well as one borehole (TMF23-08) advanced through the Cigar Lake tailings. The results of TMF23-08 were not included in the average pore water calculation as those samples were taken to observe the evolution of a small zone of Cigar Lake tailings with particularly high arsenic concentrations which are not representative of average tailings.

To calculate the average solute concentration, each sample was weighted by the volume of tailings it represented. The tailings mass was divided spatially into seven zones consisting of a center circular region, three inner segments, and three outer segments as depicted in Figure 5.2-6. In each of the zones, three-meter layers (Figure 5.2-7) were used as the basis for averaging the chemical analysis in each of the seven previously described zones. ArcGIS was used to calculate the volume of each 3 m interval in each of the seven spatial zones, providing the weighting for each zone.

The weighted mean was calculated as follows:

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \tag{1}$$

Where $x_1, x_2, \ldots, x_n$ are the concentrations of constituents in each sample. $w_1, w_2, \ldots, w_n$ are the associated weights.

If a sample was not available to represent each volume; the weights of the available samples were adjusted accordingly to ensure the total volume for each layer was represented.

Figure 5.2-6: Zones Used to Determine the Weighted Average Pore Water Values of Elements of Concern.

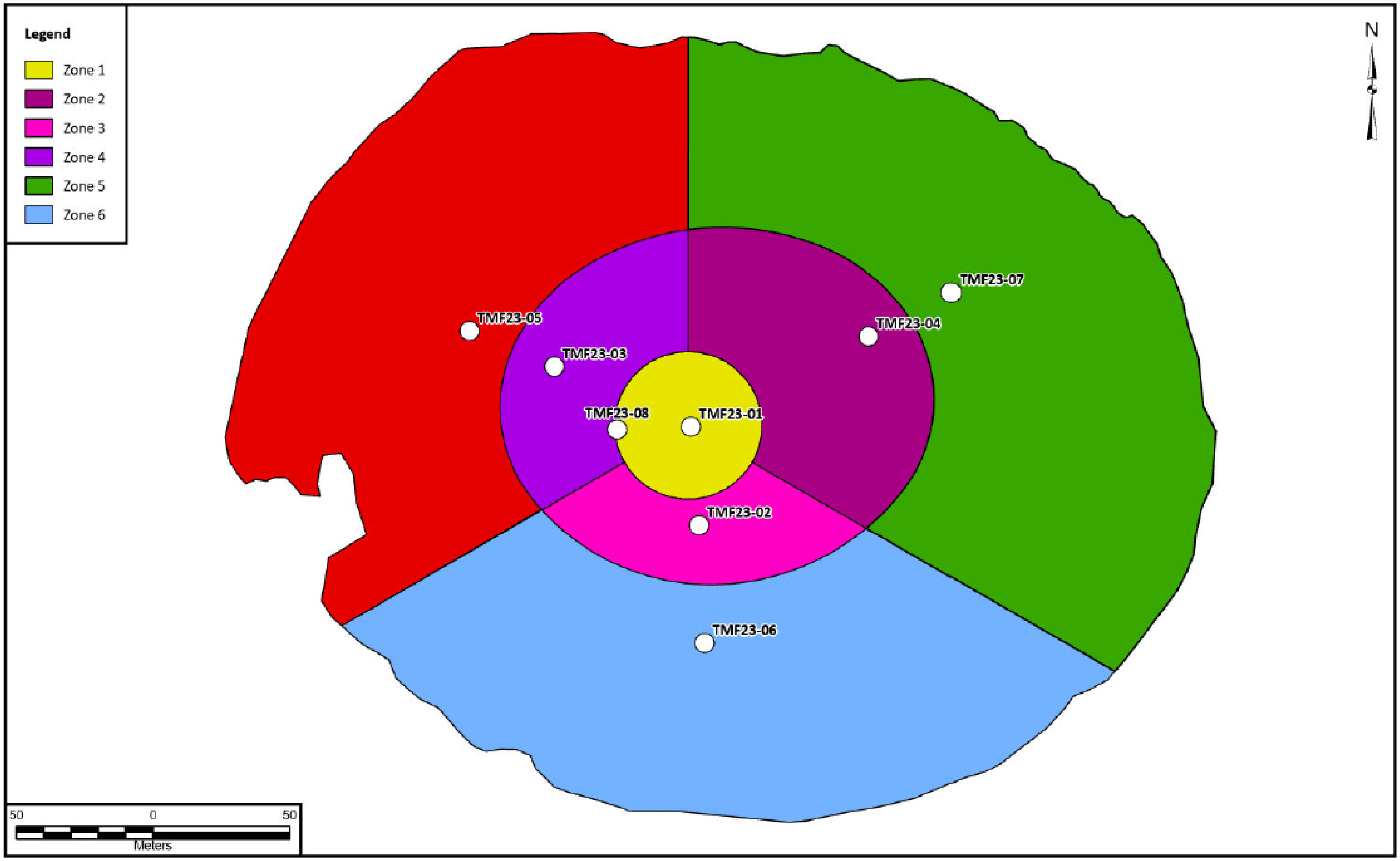
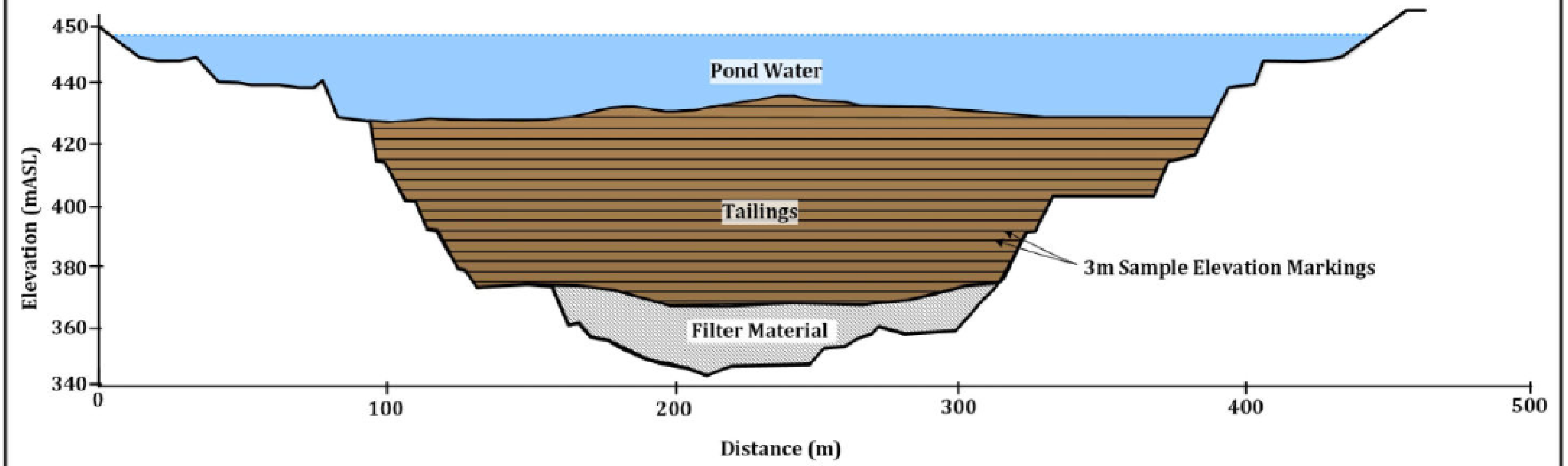


Figure 5.2-7: Average pore water solute concentration weighting layers.



5.2.6 Statistical Analysis

In past TOVP campaigns data for each constituent is statistically analyzed to remove outliers. Outliers greater than three times the interquartile range added to the Q3 value or subtracted from the Q1 value were removed from the data set. The interquartile range is defined as the difference between the 75th and 25th percentiles. Outliers were not considered representative of normal operational conditions. Examples of abnormal mill operation include shut down periods where equipment is cleaned and the resulting crud is deposited directly in the TMF, or equipment failure that results in a narrow geochemical signature.

Upon review of the 2023 geochemical data (Section 5.7) values classed as outliers were identified that likely represented a normal level variation in the tailings data, which is inherently variable. The decision was taken to include the entire data set to remain conservative. It is likely that this data set may contain examples of true outlier data that represents mill upset conditions, but this approach will ensure that the full picture of tailings geochemical variation is represented. This is particularly important now that a larger portion of the data represents the Cigar Lake tailings. While milling the JEB/Sue tailings blending various ore sources was used to maintain more consistent grades through the mill. In milling the Cigar Lake ore, blending is not used and so larger variations in feed ore and tailings composition are noted.

5.3 Verification of the Tailings Preparation Process

5.3.1 Overview

Over time, a number of significant studies have been completed with respect to the validation of the tailings preparation process. Table 5.3-1 shows a general timeline of these studies. The focus of this document is from 2020 to present, i.e. the period since the submission of the 2020 Tailings Management TID (Orano, 2020b). Geochemical models and the validation of long-term tailings properties are discussed in Sections 5.4, 5.5, 5.6, and 5.7.

Table 5.3-1: Tailings Preparation Process Validation Timeline and Key Milestones

Period	Reference	Key Topics
2005	AREVA, 2005	• Numerous laboratory investigations in support of the JEB mill tailings preparation process; process improvements • Process considered optimized for arsenic removal
2009	AREVA, 2011a	• Key papers published relating to 1) the discovery and investigation of highly crystalline scorodite scale in certain JEB mill process tanks; 2) optimization of tailings preparation process for selenium removal
2010 to 2014	AREVA, 2015	• Care and maintenance. • Mill upgrades. • Geochemical studies of the tailings preparation process not conducted at this time

Period	Reference	Key Topics
2014 to 2020	Orano, 2020b	- Commenced processing Cigar Lake ore. - Test work initiated in 2017 to further understanding of the Cigar Lake mineralogy. - Mineralogical studies of as-discharged tailings samples - Aging tests of as-produced tailings - Commissioning of expanded tailings neutralization circuit in 2016
2020 to Present	Current Tailings Management TID	- Continued the milling of the Cigar Lake ore with increasing arsenic grades. - 2021 supplementary tailings sampling campaign focused on the Cigar Lake tailings geotechnical properties, and evaluation of arsenic source terms. - Continued evaluation of mineralogy of the Cigar Lake tailings (Section 5.3.2) - Development of a Bayesian network for geotechnical data analysis (Section 5.6.3.2) - Research into Ra^{226} behaviour in solid solution with barite in the tailings (Section 5.7.5)

5.3.1.1 Oxidation State - Terminology

Throughout the discussion of tailings geochemistry, key terms are used in describing the oxidation state of COPCs in the tailings. In general, the tailings are an oxidizing environment. Newly placed tailings may still contain residual amounts of primary reduced mineralization from the ore that survived the mill process. The mill process used in the extraction of uranium is highly oxidizing, and the bulk of COPCs are oxidized in the mill process. Therefore, the TMF is designed to remain in an oxidizing state as the final long-term condition. The number of oxidation states varies by COPC, and the majority have two oxidation states that are important in the tailings system. For example, iron has soluble reduced (Fe^{2+}) and less soluble oxidized (Fe^{3+}) states. Arsenic has three important oxidation states as described below in Table 5.3-2 for clarity throughout the following discussion.

Table 5.3-2: Terminology Used in Describing the Geochemistry of Arsenic in the Tailings

Oxidation State	Condition	Examples
As^{-1} Primary ore minerals	Reduced minerals, found in tailings sediment; not found as a soluble species in tailings pore water. Depending on context in this document this oxidation state may be referred to as: - unleached arsenic, - primary arsenic, - or reduced arsenic	Gersdorffite (NiAsS Niccoline (NiAs), Rammelsbergite ($NiAs_2$)

Oxidation State	Condition	Examples
As^{3+} Intermediate Step (First Oxidation Step)	Adsorbed onto ferrihydrite in tailings sediment; very soluble in tailings pore water	$H_3AsO_3^0$ (arsenous acid) (aq).
As^{5+} Final Step (Fully Oxidized)	Mainly amorphous mineral phases that become more crystalline over time and minor adsorption onto ferrihydrite; relatively less soluble than As^{3+} in tailings pore water. May be referred to as oxidized arsenic or secondary arsenic in this document	Amorphous ferric arsenate (Am. $FeAsO_4$) Crystalline scorodite ($FeAsO_4 \cdot 2H_2O$)

5.3.2 General Mineralogical Analysis of the Cigar Lake Tailings

Using the samples collected during the 2023 TOVP, various analytical techniques have been used to develop an overview of the mineralogy of the Cigar Lake tailings since their placement began in 2014. The goal of the mineralogical analysis is to identify key differences between the JEB/Sue tailings and the Cigar Lake tailings and understand variation within the placed Cigar Lake tailings.

5.3.2.1 Ore Properties and Handling

The properties and handling of Cigar Lake ore differs from that of JEB and Sue ores. The following is a summary of key differences:

Ore Form: Cigar Lake ore is received at the McClean Lake Mill as slurry and is not stockpiled as was done with JEB and Sue run-of-mine ores. The slurry is received at the mill via truck and is stored in pachucas until processing.

Blending Capacity: The McClean Lake Mill has limited blending capability for Cigar Lake ore. Cigar Lake ore is currently the only ore being processed by the mill. The Cigar Lake ore fed to the mill may be blended between pachucas; however, the storage capacity is limited, which lessens the potential for blending.

Variability: The elimination of ore stockpiling results in more variation in the ore feed to the mill, and consequently more variation in the tailings produced. The variation in the tailings is most easily noted in the major ore forming minerals (e.g. silicates, phyllosilicates, and clays) which reflect different areas of the Cigar Lake deposit as they are mined. Variation is also observed in more minor phases such as sulphide minerals, which are the main sources of COPCs (e.g. arsenic, nickel, copper, and lead) in the placed tailings.

Abundance of COPCS: The abundance of key COPCs in the Cigar Lake ore is higher than in the previously milled JEB/Sue ores as will be noted in the presentation of results below. Sulphide minerals are noted to be the main hosts of COPCs such as arsenic, molybdenum, nickel, cobalt, selenium, zinc, and uranium, in studies of the Cigar Lake deposit (Kaczowka et al, 2021). This is of note particularly for arsenic which has been encountered in grades up to ~4% in the incoming ore. Changes in the mill process to account for the higher concentrations of COPCs in the Cigar Lake ore are discussed in section 3.2.3

5.3.2.2 Analytical Techniques

To date, four principal techniques have been used to investigate the tailings mineralogy:

1) Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)

- **General Description:** The ICP-OES is a general elemental analysis technique that uses the emission spectra of an acid digested tailings sample to identify and quantify the elements present.
- **Use and Benefits:** ICP-OES provides a general understanding of the total elemental composition present in each tailings solid sample.
- **Limitations:** ICP-OES does not provide information on the mineral species present in the sample.
- **Presentation of Results:** ICP-OES results are not described independently in this document but are important to support the interpretation of the following more specialized techniques.

2) Synchrotron-Based X-ray Diffraction (S-XRD) with Rietveld Refinement

- **General Description:** The S-XRD was used in place of traditional laboratory-based XRD analysis because the spectra resolution achieved at the Canadian Light Source (CLS) is accurate enough to collect information on the minor mineral phases present in the tailings. In XRD analysis the diffraction of X-rays from the atoms of the sample is used to quantify crystalline phases present. Rietveld refinement, a mathematical refinement of the data using a least squares approach, was conducted on the tailings samples to identify the portion of each sample composed of secondary (amorphous) mineral phases.
- **Use and Benefits:** S-XRD analysis provides good information on crystalline mineral phases. This technique is useful in the semi-quantification of residual primary arsenic in the tailings and will be useful to identify and quantify secondary arsenic minerals in the tailings as they gradually evolve to become crystalline over time. Rietveld refinement provides important additional information to understand the relative abundance of crystalline phases. Although the nature of secondary minerals cannot be determined the information helps to understand the overall composition of the tailings.
- **Limitations:** S-XRD analysis will not identify secondary arsenic minerals unless they are sufficiently crystalline.
- **Presentation of Results:** S-XRD results are presented and discussed in Section 5.3.2.3.

3) Quantitative Evaluation of Materials by Scanning Electron Microscopy (QEMSCAN)

- **General Description:** QEMSCAN is a micro-analytical technique where back-scattered electron (BSE) images and energy-dispersive X-ray spectroscopy (EDS) spectra are collected from individual points (grains) in the sample. The point analysis is collected over an entire sample surface, in order to provide a semi-quantitative analysis of various parameters such as grain size distribution, mineral associations, and liberation. Mineral modal abundances are also determined based on a comparison of the collected spectra to an existing mineral reference database. Modal mineralogy in a sample is calculated from the combined analysis of the BSE images and the mineral identification from the EDS data. The volumetric abundance of the minerals is converted to mass percent from density data for typical mineral compositions.

- **Use and Benefits:** QEMSCAN is useful for identifying and quantifying crystalline mineral phases, such as residual primary arsenic mineral grains in the tailings samples.
- **Limitations:** QEMSCAN can identify and quantify secondary arsenic mineral phases, as these phases tend to occur as amorphous or poorly crystalline thin layers on other mineral surfaces. The X-rays of the EDS penetrate too deeply into the sample surface to accurately detect thin secondary mineral layers.
- **Presentation of Results:** QEMSCAN results are presented and discussed in Section 5.3.2.4.

4) X-ray Absorption Near-Edge Structure (XANES) Spectroscopy: X-ray Absorption Near-Edge Structure (XANES) Spectroscopy

- **General Description:** Since 2008, XANES analysis at the CLS has been used exclusively to evaluate the mineralogy and redox speciation of arsenic in the tailings. XANES is an element-specific, bulk-spectroscopic analytical technique that provides chemical information, such as oxidation state, as well as molecular speciation of the element of interest (e.g. arsenic) in the tailings solids.
- **Use and Benefits:** XANES requires minimal sample preparation and therefore preserves the in-situ chemical speciation of arsenic in the complex tailings matrix. XANES is not limited by the crystallinity of mineral phases and can be used to identify and quantify both primary and secondary arsenic mineralogy as well as the redox speciation of arsenic in the tailing solids. Spectra are collected from each sample with a practical detection limit of 10 ppm and are characterized with previously collected spectra of reference standard arsenic minerals. The relative amounts of arsenic mineral phases in each tailings sample are determined by linear combination fitting (LCF) analysis of the sample spectra to the reference standards.
- **Limitations:** The LCF analysis of XANES data can raise the detection limit due to the inherent limitations of the technique. The LCF analysis of XANES data has a detection limit of approximately 10% (Blanchard et.al. 2017), and therefore minor arsenic mineral phase(s) that occur as ≤10% of the total arsenic in the sample may be reported as 0%. To identify and quantify arsenic minerals known to occur in low concentrations in the tailings, a secondary micro-analytical technique such as QEMSCAN can be used to compliment the results from the XANES analysis.
- **Presentation of Results:** XANES results for arsenic are presented and discussed in Section 5.5.1.3

5.3.2.3 S-XRD with Rietveld Refinement

Based on synchrotron-based X-ray Diffraction (S-XRD) with Rietveld refinement, the major minerals in all the tailings samples analyzed are gypsum, quartz, and clays (muscovite/illite kaolinite and clinochlore) with a large component of amorphous secondary minerals (assumed to be primarily ferric iron precipitates and additional gypsum). Other minerals present in small quantities (<2 rel. wt.%) in the tailings are iron oxide and sulfide minerals including, hematite (Fe_2O_3) magnetite (Fe_3O_4), pyrite (FeS_2), and chalcopyrite ($CuFeS_2$.). Anatase and rutile (both TiO_2) are also observed in low concentrations in many of the tailings samples analyzed.

Traces of arsenic-bearing minerals such as gersdorffite (NiAsS) were identified in some of the higher arsenic concentration samples, particularly in the Cigar Lake tailings. Nickeline/Niccolite and rammelsbergite were not identified, with exception of minor amounts found using QEMSCAN (Section 5.3.2.4). Nickeline and rammelsbergite were known to be present in the JEB/Sue ores and so the absence of both minerals suggests that they oxidize more quickly than gersdorffite and are likely more efficiently oxidized in the mill process. Work on the Cigar Lake tailings has identified that gersdorffite is the primary arsenic mineral phase and so the presence of other primary arsenic minerals is not expected.

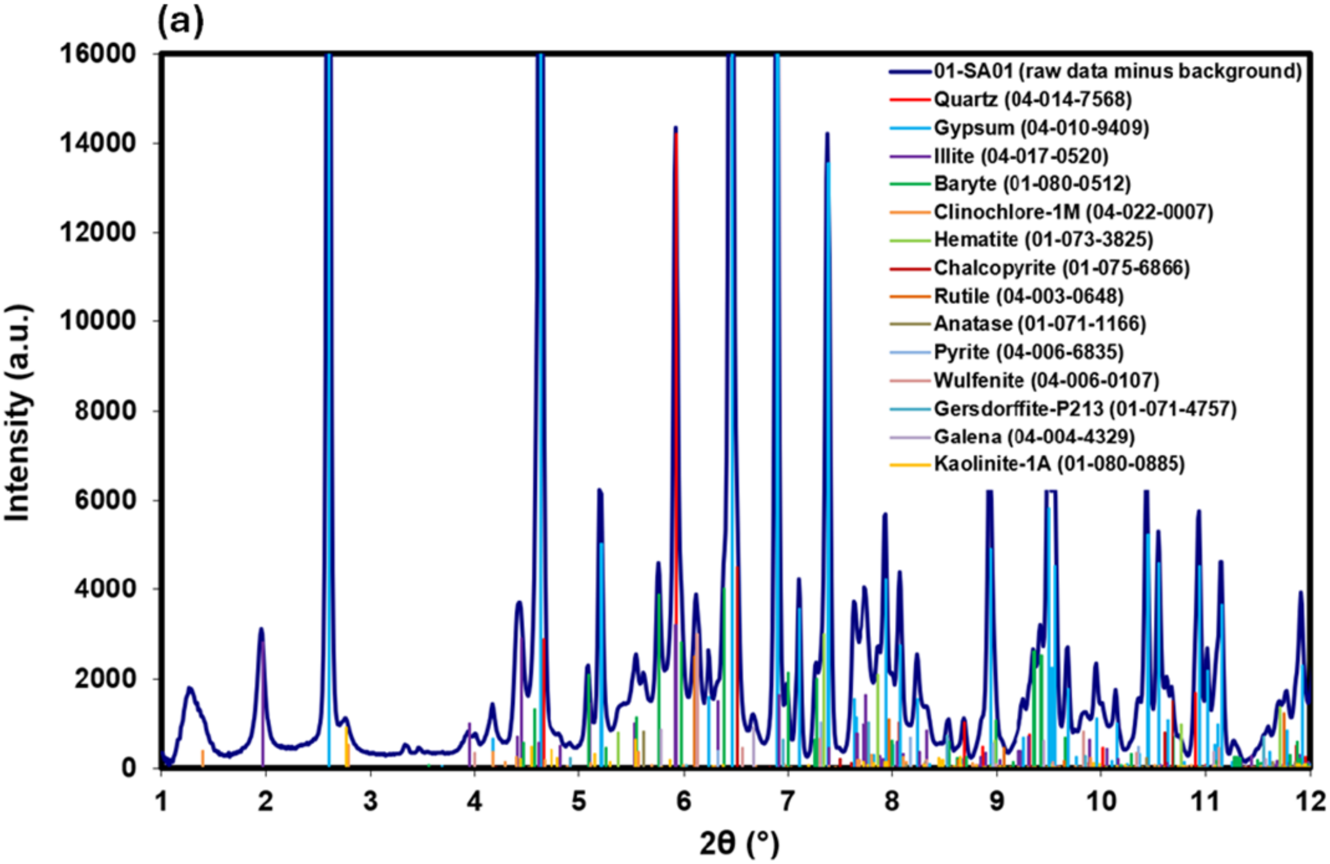
Comparison of Cigar Lake and JEB/Sue Tailings

Figure 5.3-1 shows:

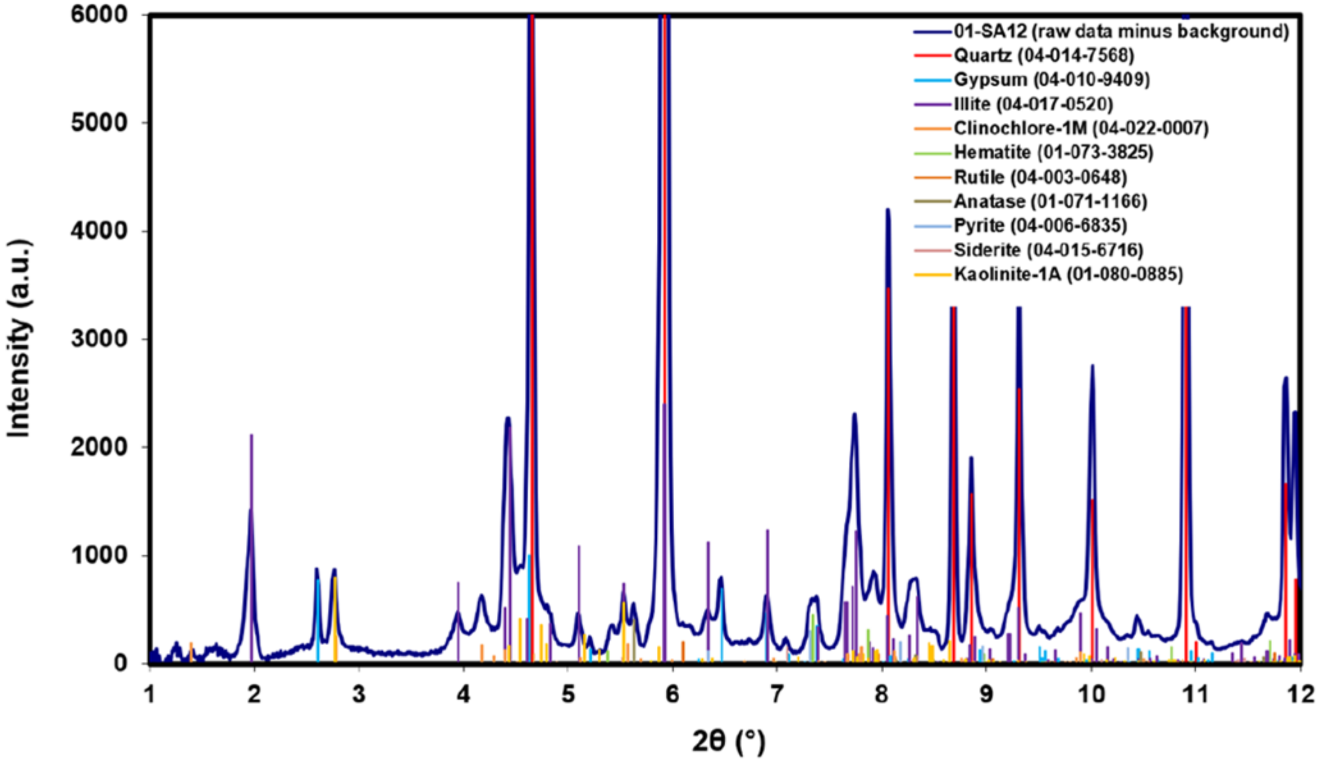
- (a) The S-XRD spectrum for TMF23-01-SA01, which is representative of the recently deposited Cigar Lake tailings;
- (b) The S-XRD spectrum for TMF23-01-SA12, which is representative of the previously deposited JEB/Sue tailings; and
- (c) The elevation profile of TMF23-01 with respect to the bulk mineralogical make-up of the tailings.

The results show that JEB/Sue tailings (~≤ 421 mASL) are predominantly quartz and clay, while Cigar Lake tailings (~≥ 421 mASL) are predominantly gypsum and clay. In the JEB/Sue tailings (n=44) analyzed, an average of 37 rel. wt.% tailings occur as quartz, while for Cigar Lake tailings (n=23), an average of 41 rel. wt.% tailings occur as gypsum. These number are a significant reduction from values identified in 2018 due to the inclusion of the Rietveld Refinement technique which increases the accuracy of the analysis by specifically identifying the portion of the sample composed of unidentified amorphous species. Table 5.3-3 presents a general comparison of key mineral phases between the JEB/Sue and Cigar Lake tailings samples analysed using S-XRD with Rietveld refinement.

Figure 5.3-1: Bulk S-XRD analyses of tailings samples. Typical bulk S-XRD spectrum for solid sample SA01 (a) and SA12 (b) collected from bore hole TMF23-01 and bar chart (c) Rietveld Refined Analyses of S-XRD showing bulk mineralogy vs. Elev. (maSL) for all samples collected from TMF23-01.

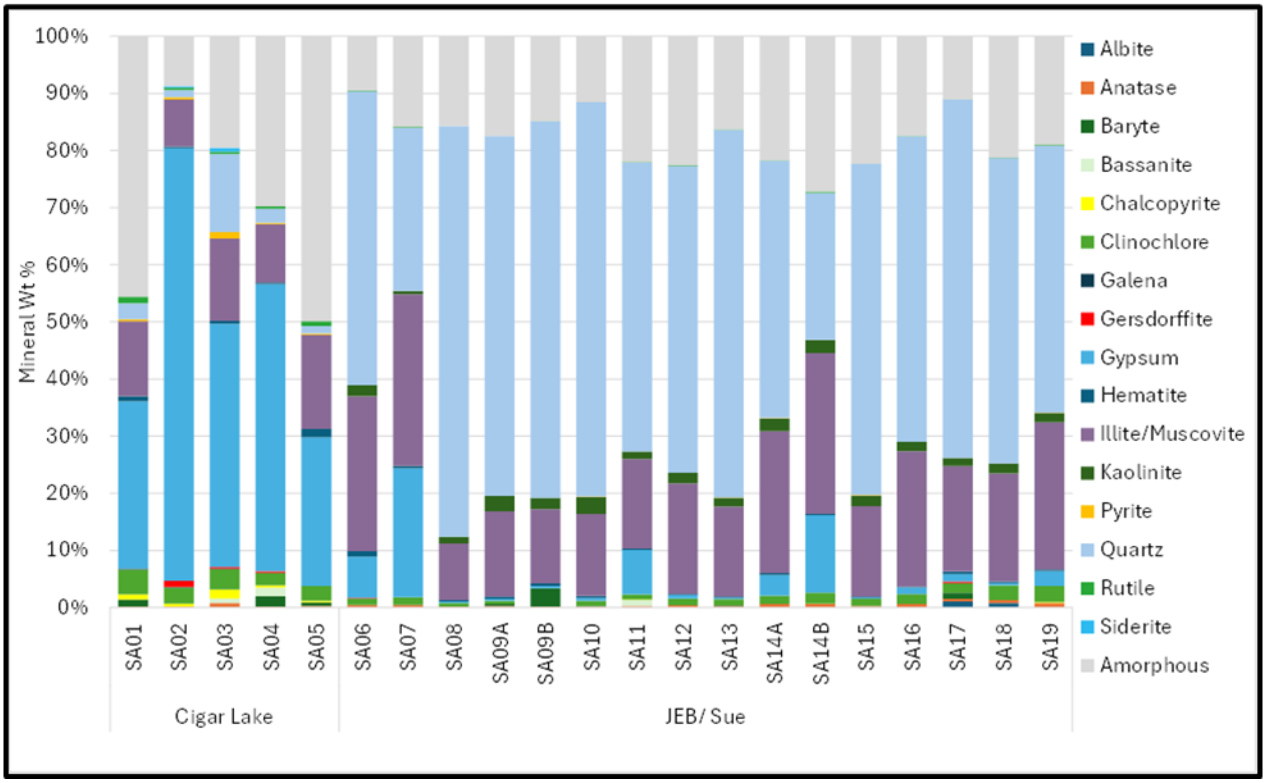


(b)



Intensity (a.u.)
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
10
11
12
2θ (°)
01-SA12 (raw data minus background)
Quartz (04-014-7568)
Gypsum (04-010-9409)
Illite (04-017-0520)
Clinochlore-1M (04-022-0007)
Hematite (01-073-3825)
Rutile (04-003-0648)
Anatase (01-071-1166)
Pyrite (04-006-6835)
Siderite (04-015-6716)
Kaolinite-1A (01-080-0885)

(c)



Mineral Wt %
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
SA01
SA02
SA03
SA04
SA05
SA06
SA07
SA08
SA09A
SA09B
SA10
SA11
SA12
SA13
SA14A
SA14B
SA15
SA16
SA17
SA18
SA19
Cigar Lake
JEB/ Sue
Albite
Anatase
Baryte
Bassanite
Chalcopyrite
Clinochlore
Galena
Gersdorffite
Gypsum
Hematite
Illite/Muscovite
Kaolinite
Pyrite
Quartz
Rutile
Siderite
Amorphous

Table 5.3-3: Weight % Mineralogy as determined by S-XRD with Rietveld Refinement comparing major phases of the Cigar Lake and JEB/Sue tailings, based on samples from the 2023 in-situ TOVP sampling campaign

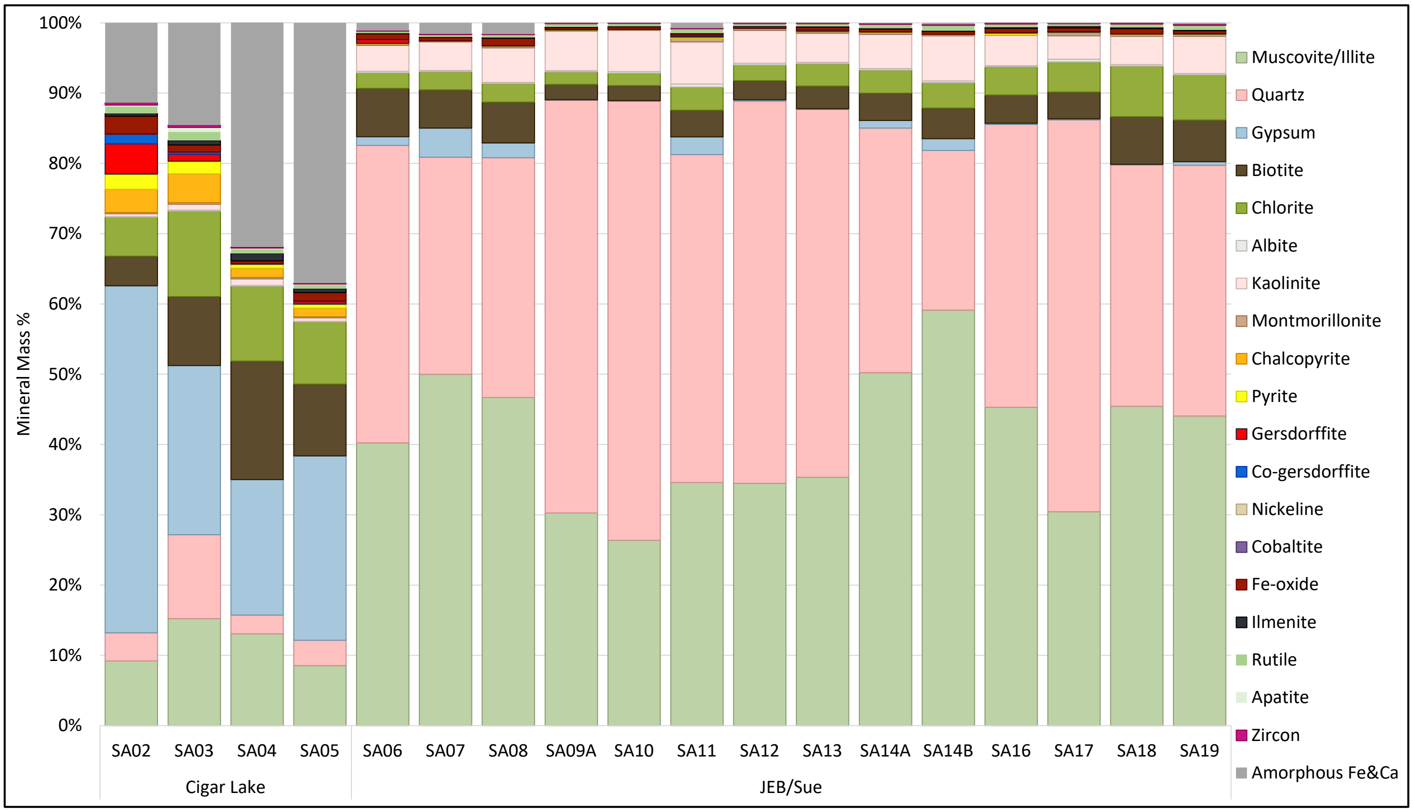
Mineral	Cigar Lake Tailings(n=23)			JEB/Sue Tailings (n=44)		
	Average	Max	Min	Average	Max	Min
Barite	0.47	1.8	0.1	0.71	3.2	0.1
Sulphides	1.58	3.6	0.3	0.36	0.5	0.3
Clays and Phylosillicates	17.88	36.7	9.9	27.46	47.4	9.6
Gersdorffite	0.67	2.4	0.1	0.15	0.3	0.1
Gypsum	41.46	75.8	6.7	9.65	27.3	0.2
Hematite	0.97	3.2	0.3	0.54	2.2	0.2
Quartz	8.58	58.7	0.5	36.92	71.9	7.5
Scorodite				1.19	2.1	0.9
Amorphous	28.51	49.9	8.7	24.28	43.9	9.5

5.3.2.4 QEMSCAN

Evaluation of the Cigar Lake Tailings Variability

A comparison of the JEB/Sue tailings and Cigar Lake tailings was presented in the previous tailings managment TID (Orano, 2020, Section 5.3.2.4). In this iteration of the TID QEMSCAN analysis was used primarily to look at samples of Cigar Lake tailings only, to better define their inherent variability although the variability noted in 2018 between the JEB/Sue and Cigar Lake tailings is still evident in data collected from the 2023 tailings as noted above in results from the S-XRD (Figure 5.3-1c). Samples from the same borehole (TMF23-01) were also analysed using the QEMSCAN, to provide additional context to the data, particularly identifying amorphous iron bearing phases (Figure 5.3-2). In Figure 5.3-1, several amorphous phases have been consolidated as “Amorphous Fe&Ca”, which were identified by the main elements in order of abundance: Ca-Fe-Al-Si-S, Ca-K-Al-Fe-Si-S, Fe-Al-Si-S, Ca-Mg-Al-Si-Fe, Ca-Mg-Fe-Si, Ca-Fe-Al-Si, Ca-Fe-Si, Fe-Ti-Ca-Si.

Figure 5.3-2: QEMSCAN analyses of Tailings samples collected from TMF23-01



Modal mineralogy for the Cigar Lake samples collected in 2023, as in 2018, showed a higher level of variability compared to the JEB/Sue tailings. Potential causes of the variation are as follows:

- Variation in the Cigar Lake ore body (no blending with other low-grade ores as discussed in Section 5.3.2.1);
- Start-up conditions from the commissioning of the upgraded McClean Lake Mill (2014 and 2015);
- Commissioning of the upgraded tailings preparation circuit (2017);
- Mill upset conditions or variation encountered during routine shutdowns and maintenance;
- Continual improvement initiatives ongoing in the mill (e.g. optimizing the addition of ferric sulfate to the Tailings Preparation Circuit and investigating various types of flocculants used throughout the mill); and
- Segregation of the tailings upon deposition, where boreholes close to the deposition point will capture a slightly coarser component of the tailings, which is likely to contain fewer fines such as fine clays and secondary precipitates. Although this phenomenon is likely still present in the Cigar Lake tailings, it was more notable in the coarser JEB/Sue tailings (as discussed in Section 5.6).

Testing in the current review period focused on growing the number of Cigar Lake samples analyzed for a more fulsome picture of the range of tailings produced.

In 2021 more in-situ samples of Cigar Lake tailings were obtained and QEMSCAN analysis of those samples is presented here (Figure 5.3-3). Boreholes TMF21-01 and TMF21-02 represent the standard TMF-01 and TMF-02 borehole sampling locations as sampled in previous TOVP campaign, while TMF21-08 represents a new location selected to sample tailings known to have been milled from high arsenic ore (~2%). At locations TMF21-01 and TMF21-02 the main variability is noted in major mineralogical components such as gypsum, clays and quartz. In TMF21-08 it is noted that far greater amounts of ferric oxide minerals are identified which represent the increased dosing of ferric sulfate in the tailings preparation process to respond to the higher arsenic load in the ore. These samples also contain greater concentrations of gersdorffite (the primary reduced arsenic mineral found in the Cigar Lake ore) as well as key sulphides (chalcopyrite and pyrite). Although in certain samples gersdorffite and other sulphides make up a larger percentage of the total, when considering this data, it is important to identify that these are relative percentages, and that not all amorphous minerals are accounted for using the QEMSCAN technique. It is likely that highly crystalline minerals are overrepresented in with respect to the actual composition of the tailings. Figure 5.3-4 to Figure 5.3-7 show typical grain images from the QEMSCAN for TMF samples. Two sets of grains are shown Figures 5.3-5 and 5.3-6 show total grains analysed while Figures 5.3-5 and 5.3-6 show only sulphide, arsenide and uraninite bearing grains.

Figure 5.3-3: Comparison of modal % mineralogy in samples of Cigar Lake tailings (TMF 21-01, TMF21-02 and TMF21-07)

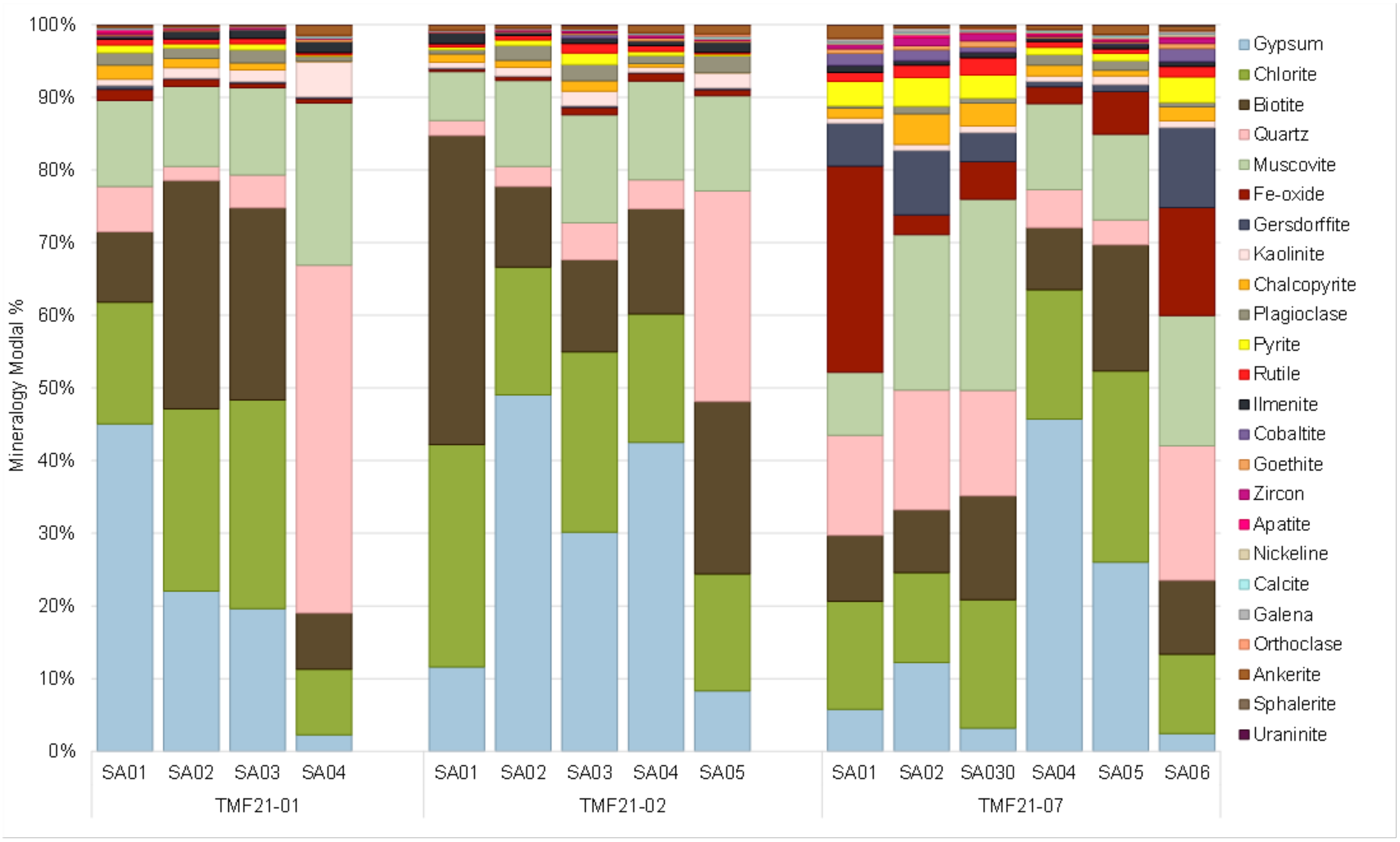


Figure 5.3-4: Colourized backscatter image of QEMSCAN analysis data for TMF23-01 SA02 sorted by grain size

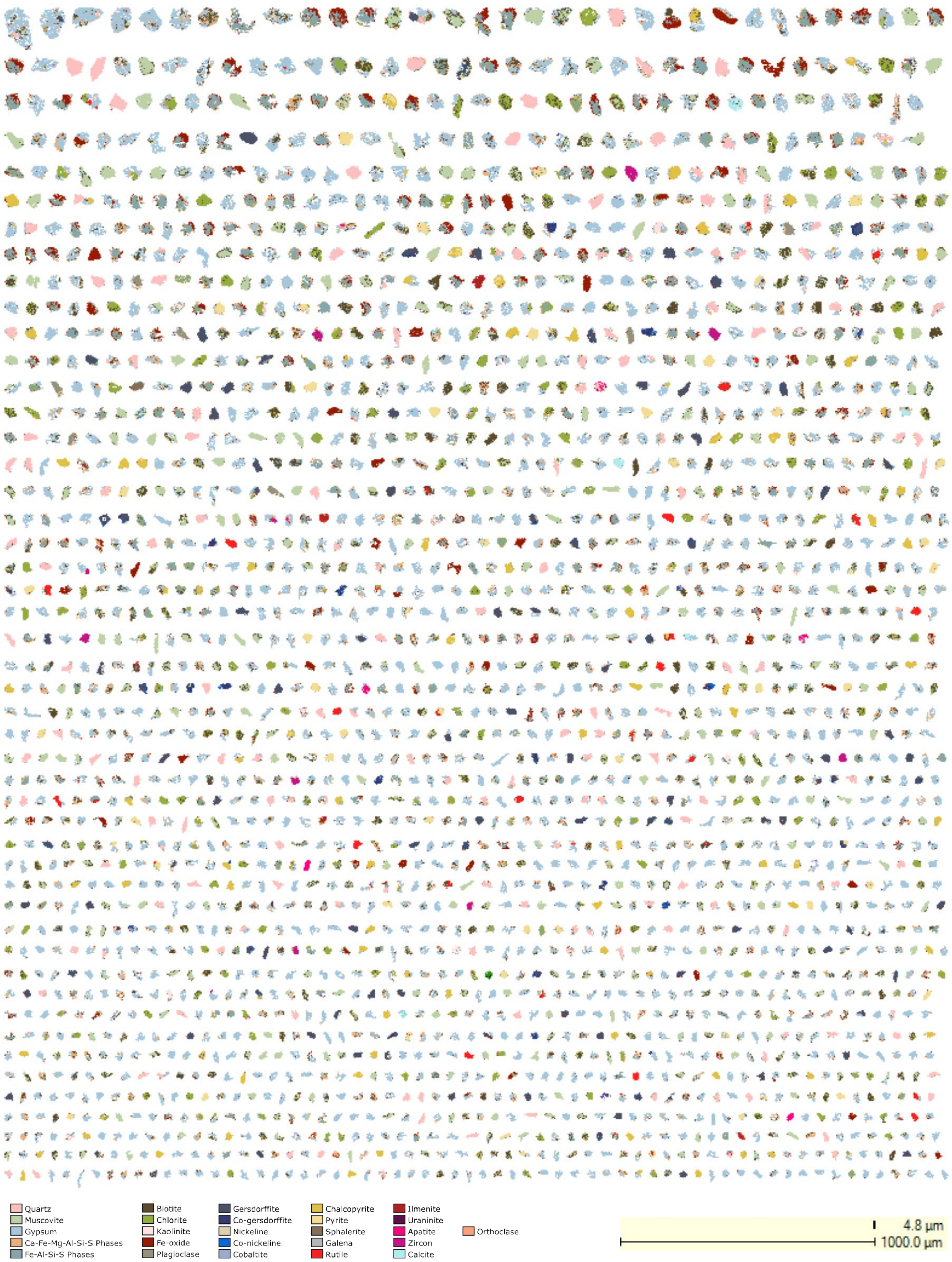


Figure 5.3-5: Colourized backscatter image of QEMSCAN analysis data for TMF23-01 SA02 (just primary sulfide, arsenic and uranium minerals) by grain size

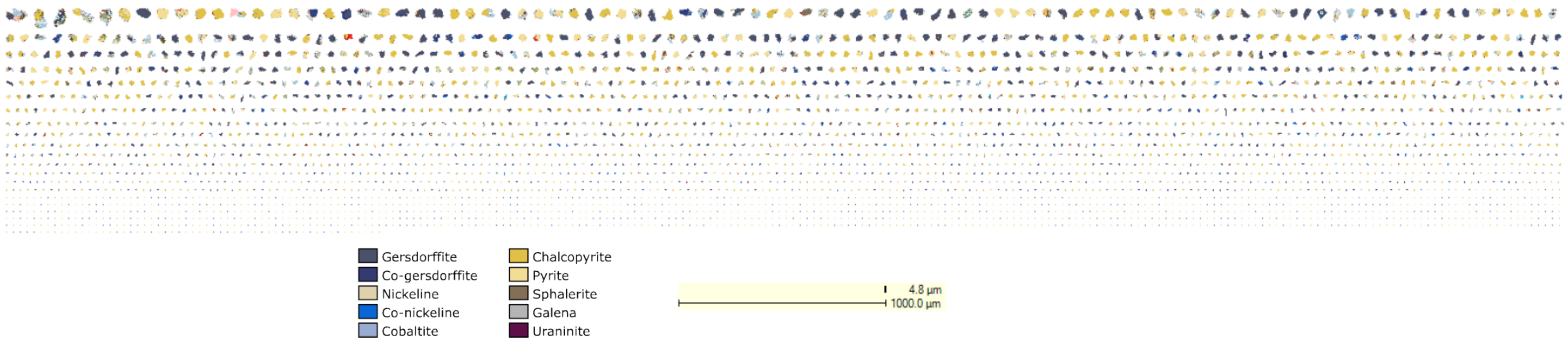


Figure 5.3-6: Colourized backscatter image of QEMSCAN analysis data for TMF23-01 SA12 sorted by grain size

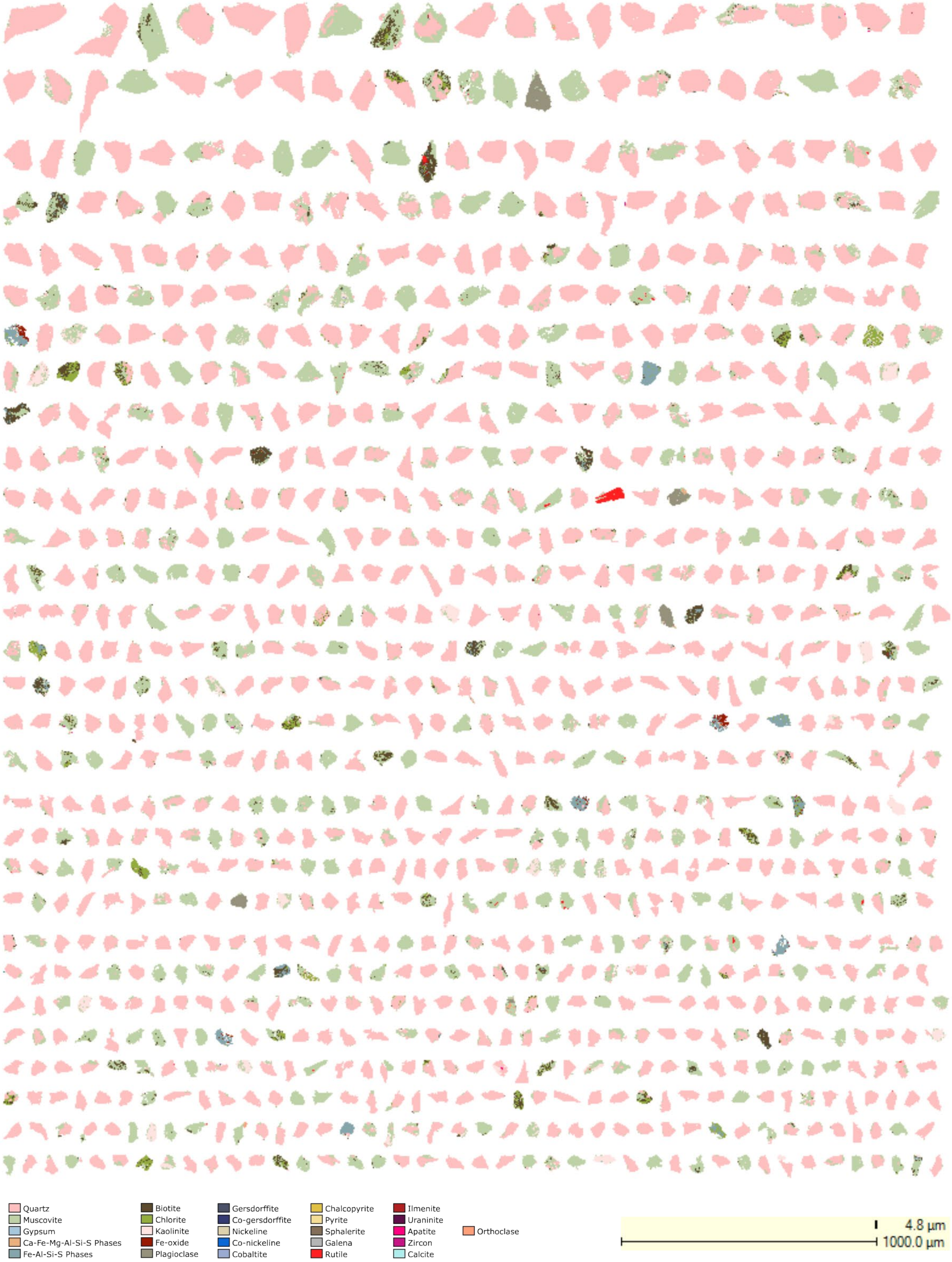
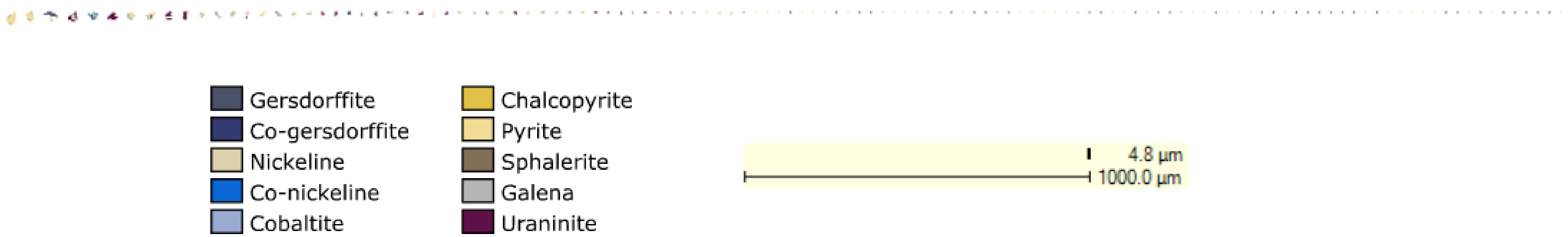


Figure 5.3-7: Colourized backscatter image of QEMSCAN analysis data for TMF23-01 SA12 (just primary sulfate, arsenic and uranium minerals) sorted by grain size



As described in Section 5.3.2.2, QEMSCAN is limited by the penetration of the X-rays into the surface of the material. Secondary minerals, which precipitate on the surfaces of existing mineral grains, are often too thin to be identified and instead the underlying mineral grain is reported.

In the tailings samples analyzed, secondary minerals such as gypsum are observed as well as other poorly defined secondary semi-crystalline or amorphous mineralization. Identification of these secondary minerals using QEMSCAN indicates that they are precipitating in abundance through the Tailings Preparation Circuit and precipitation continues after deposition in the tailings. Although there is a large increase in gypsum and other secondary mineral phases in the Cigar Lake tailings, the overall modal % of secondary mineral phases is likely still underestimated. Thin layers of mineralization will not be distinguished, and secondary mineralization is widely distributed throughout the tailings.

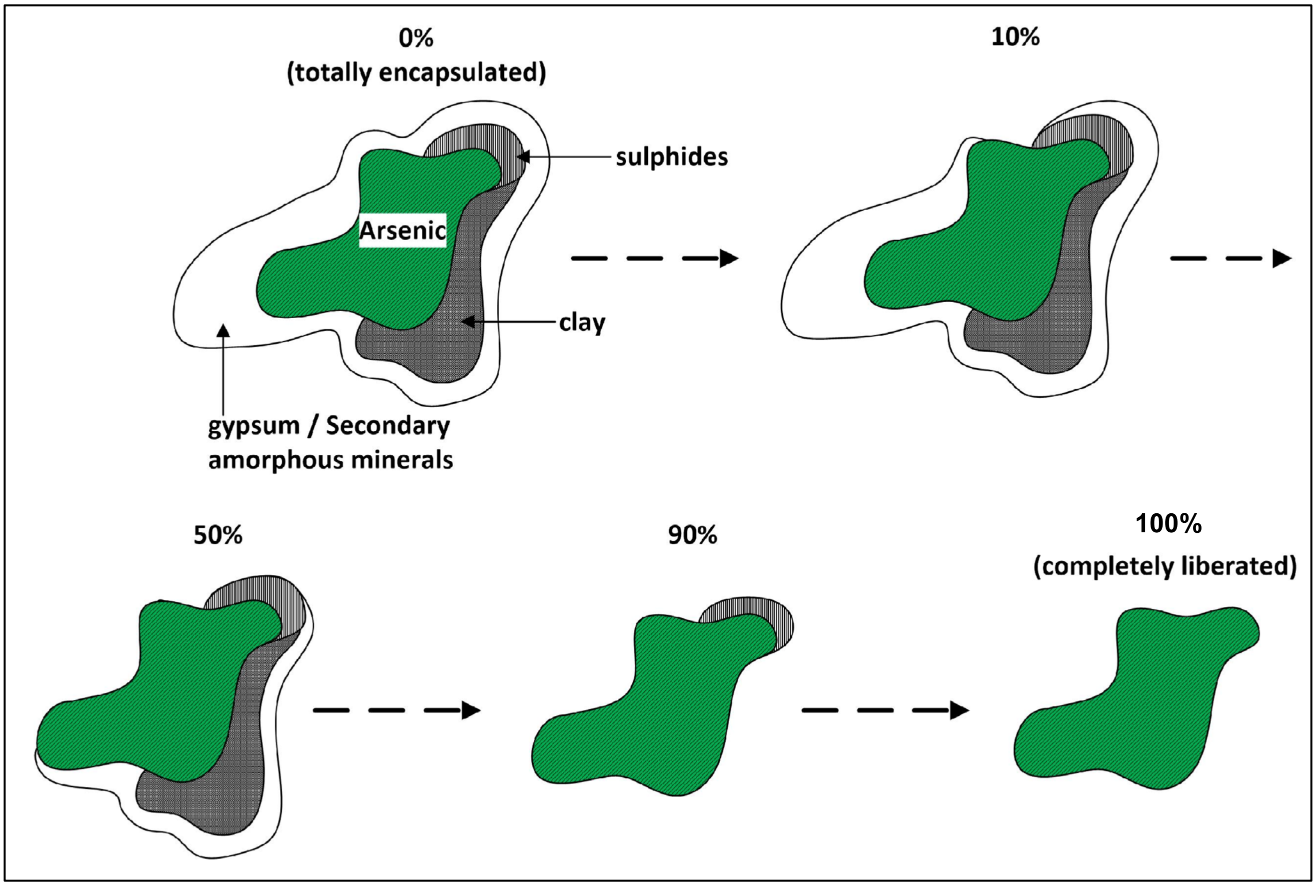
In Figure 5.3-4, significant percentages of TMF23-01 SA02 is composed of two poorly defined phases: Ca-Fe-Mg-Al-Si-S and Fe-Al-Si-S. Both of these phases were not assigned to known minerals and are instead agglomerations of amorphous precipitates from solution. The precipitates reflect the larger usage of reagents in the mill process for Cigar Lake ore than JEB/Sue ore. In particular, the addition of ferric sulfate has increased in response to the higher concentration of COPCs (principally arsenic). The increase in COPC bearing minerals is best reflected in the increase in average modal percent of sulphides and uraninite noted in the Cigar Lake samples. An increase in the proportion of arsenic bearing primary minerals has also been observed, and in response, Orano has pursued liberation analysis using QEMSCAN as a new technique in tailings mineralogical analysis.

Liberation Analysis of Key Minerals in the Tailings

Liberation analysis was conducted on the TOVP tailings samples for the first time in 2018 and has been followed up with additional analysis of 2023 tailings data and tailings dredge samples from annual campaigns. The purpose of liberation analysis is to gain insight into the availability of redox sensitive species to interactions with the tailings pore water. The greater the % liberation, the more the mineral surface is available to be oxidized (Figure 5.3-8). This analysis is a useful initial stage to launch future investigations into the process and timeframe for how primary COPC bearing ore minerals such as gersdorffite (NiAsS) and chalcopyrite ($CuFeS_2$) are oxidized in the tailings. It is well understood that reduced primary minerals oxidize in the tailings and release COPCs into the pore water (Section 5.5.1). Orano has conservatively assumed that 100% of the reduced primary minerals which are deposited with the tailings will gradually be fully oxidized over time. However, some of the primary mineralization may be completely encapsulated by other less souble minerals, and not available for interaction with tailings pore water. As the Cigar Lake tailings are known to contain a higher percentage of these primary COPC bearing minerals, liberation analysis is being pursued to further understand and quantify the amount of reduced primary minerals that interacts with tailings pore water.

Liberation analysis can be focused on any particular mineral of interest identified using QEMSCAN analysis. In this study, gersdorffite (NiAsS) is the focus as arsenic is the primary COPC of interest and gersdorffite is the primary reduced arsenic mineral identified the 2018 and 2023 tailings samples.

Figure 5.3- 8: Liberation Analysis



Percentage Liberation indicates how much of the surface of each reduced arsenic mineral grain analyzed is “liberated” (not encapsulated by another mineral phase). The total grains found to fall into each % liberation step (i.e. 0% liberation, 1-10% liberation) are presented as a % of the total reduced arsenic in each sample and averaged in the table. Note that in 2023 the buckets used to define liberations steps were slightly altered to reflect that no sample tested has grains which were 0% liberated, while larger percentages of samples were 100% liberated than in 2018. Meaning, no grains were observed to be completely encapsulated but many were completely liberated.

Table 5.3-4 provides an overview of the liberation analysis conducted on 2018 and 2023 TOVP tailings samples. Key observations in the table are summarized below:

- In table 5.3-4 it can be noted that there are significant changes in the % liberation between 2018 and 2023 in that there were more 90-100% liberated arsenic grains in the JEB/Sue samples in 2023. In this report, the focus will be on the 2023 results and, as more data is accumulated through subsequent tailings campaigns, Orano will also look at trends over time; however, this change in the data may be attributed to the following:
    - The 2023 QEMSCAN data found that, as expected, the Cigar Lake samples contained, on average, more reduced arsenic mineralisation than the JEB/Sue samples (Cigar Lake average:

    1.5%; JEB/Sue average: 0.01%). The Cigar Lake samples also contain a significantly larger proportion of amorphous phases (Cigar Lake average: 20.25%; JEB/Sue average 2.12%) which may partially obscure more crystalline phases and/or decrease the likelihood that any particular arsenic grain will be liberated.

  - As there is proportionally very little reduced arsenic found in the JEB/Sue tailings, each individual grain identified has a much larger effect on the overall % liberation. For example, in sample TMF23-06 SA14, 50% of the reduced arsenic is 1% liberated and 50% is 9% liberated which suggests that there are two distinct grains of reduced arsenic in the entire sample. Figures 5.3-5 and 5.3-7 show the contrast between a Cigar Lake sample and a Jeb/Sue sample in terms of the number of residual mineral grains present.

  - In 2023, more samples were tested (particularly a larger number of JEB/Sue samples) providing a more robust average understanding of the JEB/Sue tailings above ~380masl, and the evolution of the Cigar Lake tailings as they are deposited.

  - The JEB/Sue tailings sampled in 2023 are missing the oldest (deepest) tailings which were included in 2018. For the 2023 results, it is likely that fewer tailings samples with fully leached primary arsenic are captured and the data reflects this by showing a higher percentage of 90-100% liberated arsenic grains.

  - The QEMSCAN analytical technique is being uniquely applied in data analysis primarily to investigate ore samples to see the liberation of target resource elements and is not generally used to track the evolution of mineral liberation over time. As this technique continues to be employed in the analysis of the McClean Lake tailings, it will be validated for the tracking of evolution of mineral liberation over time in geoenvironmental systems such as tailings.

- Significant percentages of the reduced arsenic present on average in both the Cigar Lake and JEB/Sue tailings is found in grains which are between 0 and 10% liberated in 2023 (Cigar Lake 13.4%, JEB/Sue 13.27%). This portion of these samples are likely to never fully oxidize, and it may be possible to use this data over time to reduce the conservatism of future contaminant transport modelling.

- The most notable difference between the Cigar Lake and JEB/Sue tailings is the percentage of grains which are 90-100% liberated.

  - In older JEB/Sue tailings, a significant percentage of the primary arsenic minerals are between 90-100% liberated (average 50.26%) which indicates that, although the percentage of reduced arsenic minerals at these locations is minor, they have not yet fully oxidized. It possible that these grains represent “remnant” reduced arsenic grains which may have developed oxidized rims (not distinguishable using QEMSCAN) which will limit their continued oxidation.

  - Cigar Lake tailings, on average, retain a large portion of liberated reduced arsenic (average 31.15% of total reduced arsenic, which is very similar to the value noted in 2018). The distribution of reduced arsenic grains is more uniform between the different percentages of liberation in the Cigar Lake tailings. This is expected in recently placed tailings samples uniformly treated and agitated in the mill process. As the Cigar Lake samples are followed through their evolution it will be important to note if this distribution of liberated grains remains the same (possibly as oxidation may be limited by the presence of amorphous secondary precipitates still forming), or the distribution begins to shift as liberated minerals are preferentially oxidized.

- This technique provides a snapshot of the tailings at a moment in their evolution; however, it does not provide an understanding of how much arsenic was originally present upon the initial deposition of the sample. It will be useful to continue to perform liberation analysis on the Cigar Lake tailings, where early samples have been analyzed, to track the evolution in the amount of fully liberated reduced arsenic over time to allow for an understanding of the rate of oxidation as it occurs.

Figure 5.3-9 presents the liberation of arsenic bearing minerals Cigar Lake and JEB/Sue tailings samples identified in Figure 5.3-2. Variation between individual samples is observed; however, it is evident that a higher percentage of primary arsenic minerals are more encapsulated in the Cigar Lake samples than in the Jeb/Sue samples.

Mineral liberation data can be refined further to identify associated minerals which are potentially limiting the liberation of the target mineral (gersdorffite). Figure 5.3-10 presents an example of the breakdown of the principal minerals associated with gersdorffite in select tailings samples from Figure 5.3-9. Associated minerals are reported as unique mineral phases unless there is a combination of minerals present when the phase is given as “complex”. A key observation for the Cigar Lake samples in Figure 5.3-10 (SA02 to SA05) is that more gypsum (light blue) and amorphous secondary phases (grey) are observed to be in contact with the arsenic mineral grains. In the JEB/Sue samples, a larger portion of the grains are in contact with clays. The larger amount of gypsum and amorphous phases in contact with arsenic grains in the Cigar Lake samples likely accounts for the higher % of more encapsulated samples.

Table 5.3-4: Average, Maximum, and Minimum Values of % Liberation for JEB/Sue and Cigar Lake Tailings

2018		**JEB/Sue (n=17)**			**Cigar Lake (n=13)**		
		Average	**Max**	**Min**	**Average**	**Max**	**Min**
		% of Total Reduced Arsenic					
% Liberation	**0**	15.58	35.71	0	9.87	29.11	0
	1-10	42.36	62.5	17.65	29.24	40.79	8.41
	11-20	9.11	18.18	0	6.03	10.34	1.32
	21-30	8.5	25	0	1.52	4.07	0
	31-40	9.3	29.41	0	2.96	6.25	0
	41-50	4.57	20	0	3.54	6.54	0
	51-60	4.37	20	0	4.01	6.54	0
	61-70	2.91	20	0	2.16	5.61	0
	71-80	0.95	5.88	0	3.96	12.5	0
	81-90	1.43	12.5	0	4.65	16	0
	91-100	0.93	6.06	0	32.06	50	12.66
2023		**JEB/Sue (n=38)**			**Cigar Lake (n=19)**		
		Average	**Max**	**Min**	**Average**	**Max**	**Min**
		% of Total Reduced Arsenic					
% Liberation	**0**	0	0	0	0	0	0
	0-9	12.89	100	0	12.70	45.68	0
	10-19	6.78	100	0	3.76	9.79	0
	21-30	2.15	14.21	0	3.77	11.72	0
	31-40	2.25	24.78	0	2.13	4.56	0
	41-50	1.88	18.43	0	2.51	7.94	0
	51-60	3.57	33.14	0	5.32	12.32	0.97
	61-70	3.08	36.84	0	9.00	32.90	3.11
	71-80	5.10	36.36	0	9.60	21.84	0
	81-90	11.42	83.67	0	17.94	31.20	0
	91-100	26.25	90.80	0	17.96	48.43	0
	100	24.62	93.01	0	15.31	39.63	3.23

Figure 5.3-9: Comparison of % liberation of reduced arsenic grains (gersdorffite) in samples of Cigar Lake and JEB/Sue ores from borehole TMF23-01

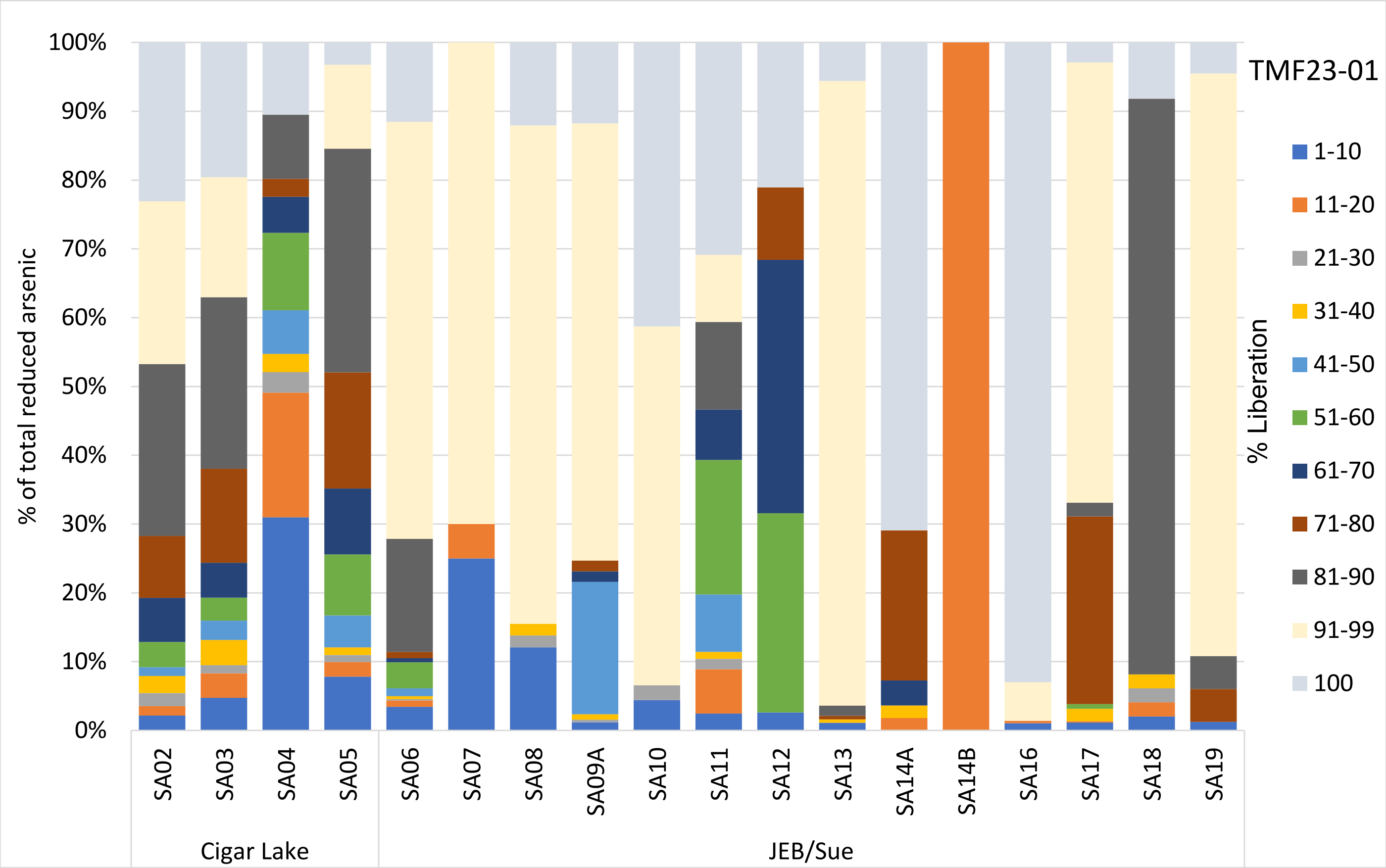
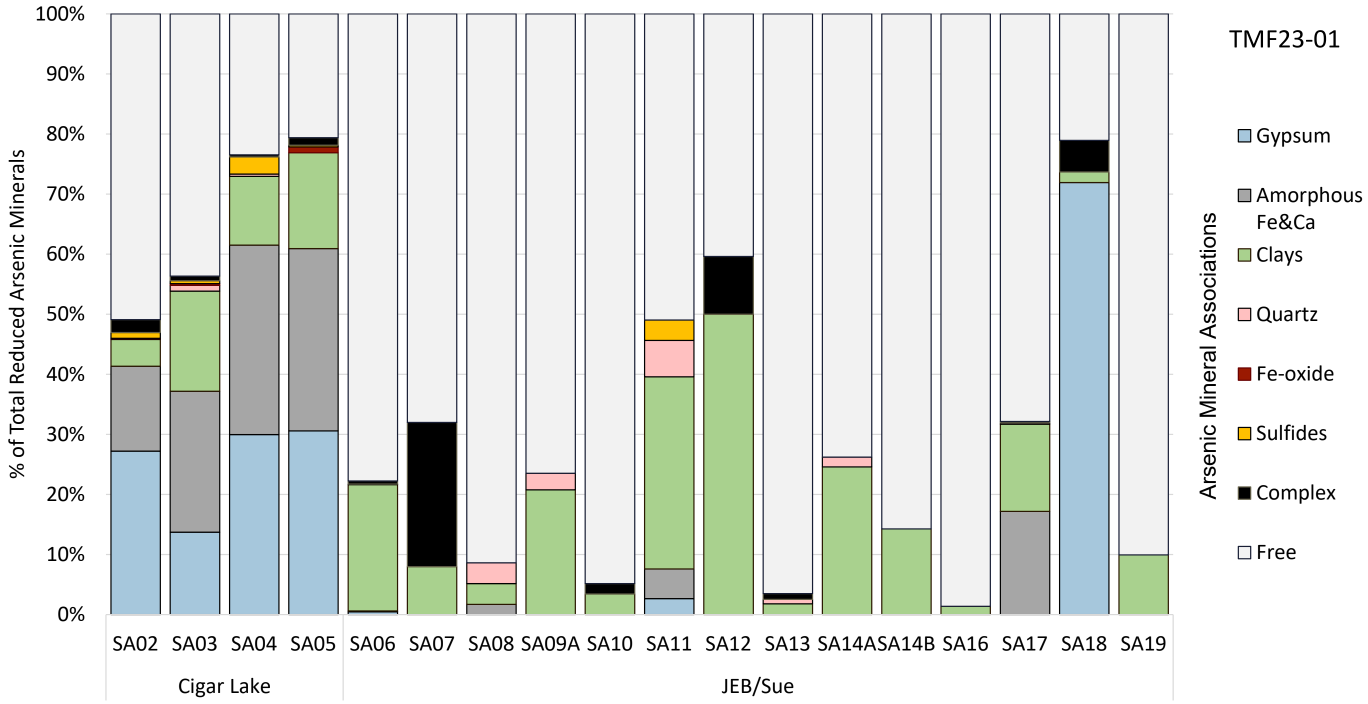


Figure 5.3-10: Percentage reduced arsenic mineral grains in contact with different mineral types (TMF23-01)



Conclusions of Preliminary Liberation Analysis:

- The liberation analysis of the tailings has provided further useful insight into the potential evolution of the tailings mineralogy over time. Thermodynamic constraints on the evolution of minerals in the tailings, particularly arsenic minerals, are well understood; however, the kinetics of the reactions are not well defined despite being an important factor in controlling the length of time that the tailings require to approach equilibrium conditions.

- Liberation analysis suggests that some percentage of primary arsenic minerals may persist in their reduced forms, as they are unable to interact with tailings pore water due to the influence of other less soluble minerals. As a result, the percentage of primary arsenic minerals that are not accessible may not oxidize over time. In particular, reduced arsenic mineral grains which are encapsulated by gypsum, amorphous sulfate minerals, or clays may not be exposed the pore water to undergo oxidation in the tailings. Based on the refinement of the percentage of primary arsenic which is encapsulated, a certain amount may be excluded from consideration for long-term oxidation as it will likely remain encapsulated and stable in the tailings solids over time as discussed in relation to the tailings preparation process in section 3.2.4.

- In the JEB/Sue tailings, the percentage of reduced primary arsenic minerals is relatively small, and observations of pore water arsenic values have already clearly indicated that, in the oldest tailings, where insufficient ferric iron was added, primary arsenic minerals have oxidized creating a pore water source term (discussed in Section 5.5.1). The percentage of reduced arsenic in the tailings which is not liberated (i.e. not in contact with the pore water) is expected to be insignificant to the overall understanding of the arsenic system.

- In contrast to JEB/Sue tailings, the Cigar Lake tailings contain more reduced arsenic mineralization. The tailings preparation process has been modified accordingly, and additional ferric iron is being added as discussed in Section 3.2.4. The liberation of primary reduced arsenic will be an important consideration for the Cigar Lake tailings and will continue to be monitored under the TOVP.

5.4 Saturation Index Modelling

The investigation of long-term tailings geochemistry is accomplished through a series of scientific studies, in support of established geochemical models. The models follow the evolution of each constituent of potential concern (COPC) as the COPC approaches equilibrium within the tailings. The purpose of the models is to provide a framework for scientific investigation with the goal of identifying solid mineral phases that will control the pore water concentrations of COPCs after the JEB TMF is decommissioned. The evolution of COPCs is traced from their behaviour in the mill process, in freshly placed tailings, and finally as their respective tailings pore water concentrations reach equilibrium with stable mineral phases.

In 2023, similar to 2013 and 2018, the main COPCs are arsenic, molybdenum, and uranium (controlled by hydrocarbon oxidation). Through work presented in past TOVP reports, the mill process has been thoroughly investigated and is considered optimized (AREVA, 2005b; AREVA, 2011a). The analysis presented in this section was conducted with pore water results from the 2023 TOVP sampling campaign and evaluates the potential evolution of the tailings after their deposition in the TMF. For clarity, where applicable, representative examples have been chosen from the large set of TOVP 2023 sampling data.

The measured pore water concentrations of dissolved species, Eh, and pH data for each geochemical sample from the 2023 campaign were input into the geochemical modelling code PHREEQC (Parkhurst and Appelo, 1999) to calculate saturation indices (SI) of pertinent secondary minerals. Of note for the 2023 data was the observation that the iron pore water concentrations were on average lower than in past campaigns. Orano is investigating these results with the analytical lab which conducted the analysis (The Saskatchewan Research Council) and currently an analytical error in the iron data is suspected, but not identified. A full discussion of the potential error in the iron data set is provided in the introduction to section The SI is a useful quantity to determine whether the tailings pore water is saturated (at equilibrium), undersaturated (dissolving), or supersaturated (precipitating) with respect to a mineral or potential mineral that act as a solubility control on a COPC in the tailings.

The SI is generally represented by the equation:

$$SI = \log \frac{IAP}{K_{sp}}$$

Where: $IAP = Ion\ Activity\ Product$

$$K_{sp} = Solubility\ Product$$

If; IAP = K_{sp}, then SI is zero and pore water is in equilibrium with mineral.
IAP < K_{sp}, then SI is negative, and pore water is undersaturated with respect to mineral.
IAP > K_{sp}, then SI is positive, and pore water is supersaturated with respect to mineral.

Models were run at 4°C to approximate the in-situ temperature of the deposited tailings using an updated version of the MINTEQ.v4.dat thermodynamic database, except where noted (*), to calculate the saturation indices.

The purpose of this modelling is to evaluate possible long-term mineral phases that control the pore water concentrations of COPCs (e.g. As is controlled by scorodite) and determine if they are stable under TMF conditions. When SI values are observed to be consistently close to zero, it is likely that the minerals thermodynamic solubility will play a role in controlling the concentrations of related dissolved constituents. This data is combined with the geochemical models (Section 5.5) to support the findings of other ongoing scientific studies.

The secondary mineral phases considered in the modelling primarily contained arsenic, nickel, iron, molybdenum, calcium, carbonate, and sulfate. The SI modelling results with respect to the key COPCs (arsenic, molybdenum, and uranium) are described in detail below.

5.4.1 Arsenic

5.4.1.1 Overview and Theory

SI modelling was first completed on TOVP aging test data in the 2002 TOVP Report (COGEMA, 2002). The 2002 aging test work predicted equilibrium saturation of scorodite with pore water. The SI modelling has been revisited with each subsequent TOVP. This document focuses on 2023 results, with some comparisons to results from previous studies. A full discussion of the arsenic geochemical model follows in section 5.5.1.

5.4.1.2 Results

Figure 5.4-1 shows the correlation of SI with sample elevation for various minerals for the 2023 field data. TMF23-01 and TMF23-03 are presented as representative results. A summary of observations is as follows:

- Gypsum is at saturation (i.e. in equilibrium) with the pore water at all elevations, as expected due to its known abundance of approximately 10% of the total JEB/Sue tailings and approximately 43% in the Cigar Lake tailings.

- The SI is plotted for both crystalline and amorphous scorodite. The results parallel each other; however, amorphous scorodite is predicted to be undersaturated while crystalline scorodite is near saturation.

The above observations are fully consistent with the results of the initial SI modelling completed in 2002.

Ferric oxyhydroxides (ferrihydrite ($Fe_2O_3 \cdot H_20$) and goethite ($FeO(OH)$)) are included in the modelling because of the role they are believed to play in the adsorption of As^{5+} and As^{3+} species (discussed further in Section 5.5.1). Ferrihydrite is found to closely parallel crystalline scorodite, although it is usually slightly more saturated. Goethite is found to be supersaturated at all locations indicating that both minerals are likely to precipitate under TMF conditions.

Figure 5.4-1: Sample Elevation vs. Saturation Indices for Relevant Iron and Arsenic Minerals for a) TMF23-01 and b) TMF23-03

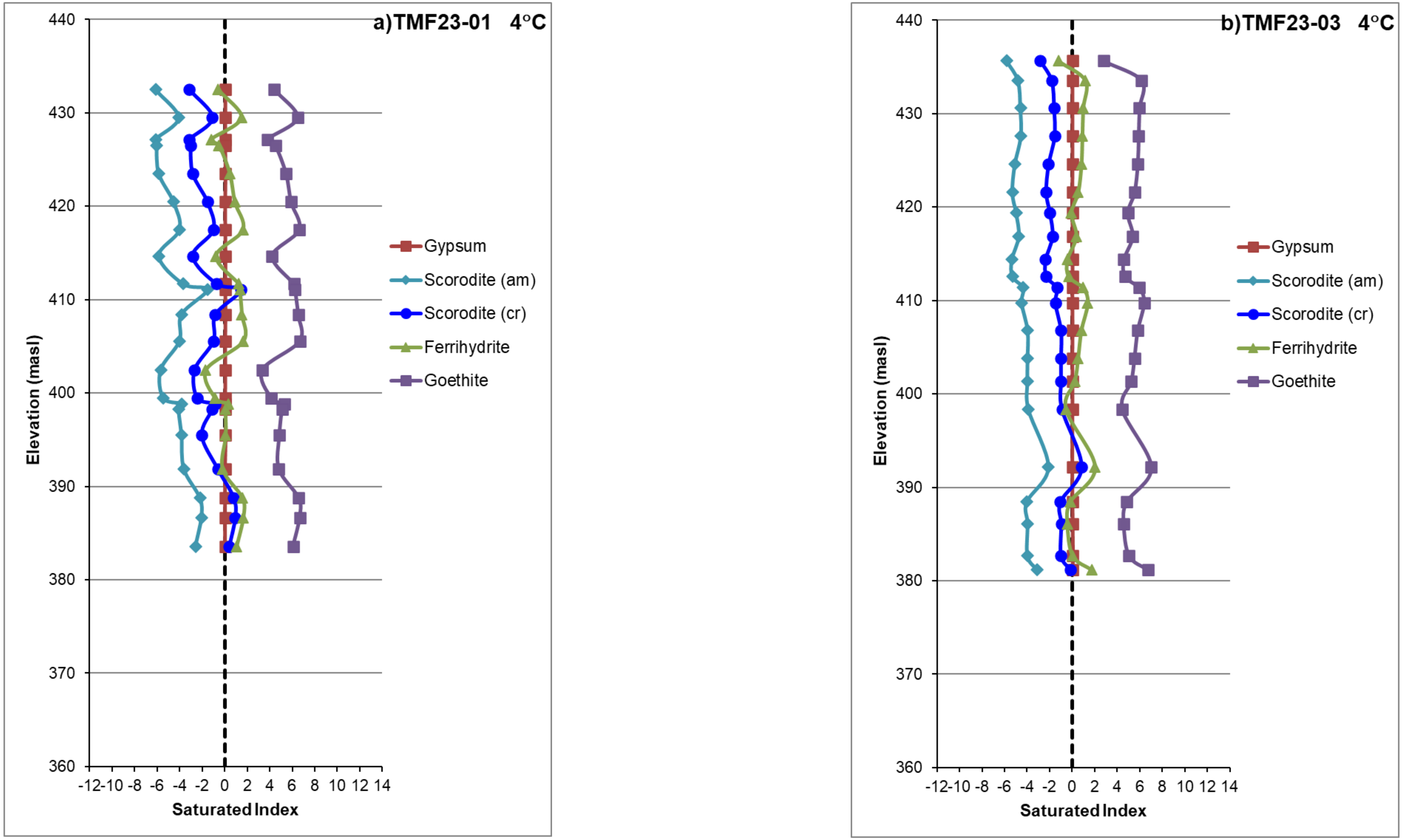


Figure 5.4-2 shows a comparison of scorodite saturation values between 2013, 2018 and 2023 from borehole TMF-01 and TMF-03 (see Section 5.2 for a discussion of the 2023 sampling campaign design). The values are similar although the 2023 values are generally slightly lower than previous years as discussed below. The 2023 results from other, more distant borehole locations (TMF-02, TMF-03 and TMF-04) show a similar saturation index of scorodite but no decrease in overall variability when compared to 2018 results. This is likely due to particle size segregation in the tailings. The outer boreholes have finer average grain sizes, resulting in a lower hydraulic conductivity which decreases geochemical reaction kinetics (i.e. slows down geochemical reactions). Borehole TMF-01, due to its coarser average grain size, is the most geochemically evolved location and therefore may provide the best evidence for the long-term stability of scorodite saturation values in the TMF.

Table 5.4-1 provides a comparison of the average saturation indices for selected minerals calculated from analytical data obtained from pore water sampled in the 2001 -2023 TMF monitoring campaigns. The actual SI for scorodite as discharged from the tailings preparation circuit is thought to be somewhere between the amorphous and crystalline SI plots. It is reasonable to assume that scorodite will gradually become more crystalline with time after placement in the TMF. In general, the SI modelling of the data from each TOVP sampling campaign has confirmed that crystalline scorodite is, on average, slightly above saturation under observed TMF conditions, indicating its long-term stability as a terminal mineral phase of arsenic. However, the 2023 average SI for both amorphous and crystalline scorodite showed a small degree of under saturation in the pore water. This can be attributed the lower pore water iron values in 2023. Although the SI for ferric oxyhydroxides, ferrihydrite and goethite (Figure 5.4-1), are also lower than previous years, all are saturated under TMF conditions, and are likely present in abundance as adsorption sites for intermediate aqueous arsenate species.

This data presents a hypothetical system looking for the precipitation of scorodite out of a pore water solution; However, in the tailings, the system is complicated through the interactions of intermediate amorphous and crystalline solid phases in contact, and potentially out of equilibrium with, the pore water. Although lower iron pore water values in 2023 indicate scorodite would not preferentially precipitate, interactions in the micro-environments at mineral surfaces are likely to promote scorodite formation and cannot be represented through the current model. Particularly, the presence of ferric oxyhydroxides will facilitate the formation of amorphous scorodite and its eventual crystallization to crystalline scorodite. As the tailings age these amorphous mineral interactions will become more critical to the crystallization of solid arsenic mineral phases. Additional geochemical modelling is planned to evaluate the liquid/solid interactions in the tailings with respect to key mineral phases.

Table 5.4-1: Average Saturation Indices in Pore Waters Sampled from the JEB TMF in 2001, 2002, 2003, 2004, 2008, 2013, 2018 and 2023.

Mineral	Solubility Product (Ksp)	Saturation Index							
		2001	2002	2003	2004	2008	2013	2018	2023
scorodite (c) $FeAsO_4 \cdot 2H_2O$	-25.87	0.86 ±0.56	0.66 ±0.73	0.73 ±1.28	0.39 ±0.74	0.20 ±1.11	0.73 ±1.18	0.75 ±1.18	-1.55 ±0.96
scorodite (am) $FeAsO_4 \cdot 2H_2O$	-22.89	-2.12 ±0.56	-2.32 ±0.73	-2.25 ±1.28	-2.58 ±0.79	-2.78 ±1.11	-2.25 ±1.18	-2.23 ±1.18	-4.53 ±0.96
ferrihydrite $Fe(OH)_3$	-31.0	1.87 ±0.27	2.30 ±0.55	2.02 ±1.07	2.20 ±0.51	1.65 ±0.93	1.15 ±1.28	2.94 ±1.02	0.59 ±0.98
gypsum $CaSO_4 \cdot 2H_2O$	-4.59	-0.01 ±0.01	0.04 ±0.02	-0.01 ±0.06	0.02 ±0.02	-0.03 ±0.08	0.05 ±0.03	0.07 ±0.19	0.05 ±0.01
am = amorphous, c = crystalline									

5.4.1 Molybdenum

5.4.1.1 Overview and Theory

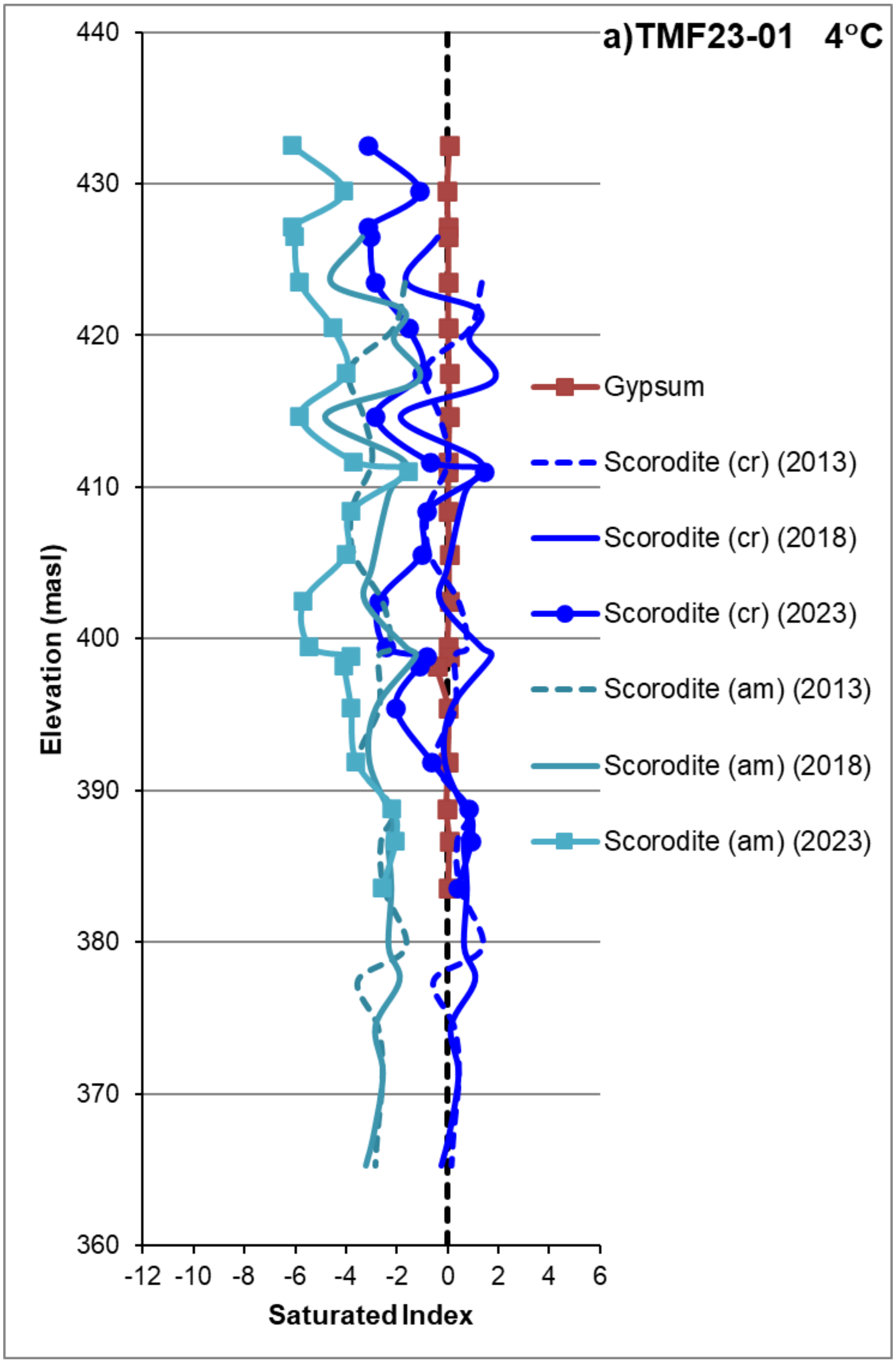
Geochemical studies on molybdenum were initiated in the 2008 TOVP (AREVA, 2011a). In the 2015 Tailings Management TID (AREVA, 2015), a review of the geochemical controls on molybdenum (Mo) concentration in the JEB TMF was completed. The study concluded that, of the molybdate bearing phases identified as possible solubility controls on Mo concentrations in the tailings pore water, $CaMoO_4$ (powellite) appears to be a likely candidate for the long-term control of Mo in the tailings pore water.

The SI modelling has been revisited with the 2023 sampling campaign pore water results. This document focuses on 2023 results, with some comparisons to results from previous studies.

5.4.1.2 2023 Results

Figure 5.4-3 correlates the sample elevation with the saturation index for selected molybdate minerals calculated from the data collected in 2023 from boreholes TMF23-01 and TMF23-03. Based on the results of the saturation index modelling, powellite appears to be gradually approaching saturation in pore waters in contact with older tailings solids (in lower elevations of TMF). The great abundance of gypsum in the newer tailings ensures that pore water calcium concentrations will remain steady at relatively high levels over the long-term. This has the advantage of stabilizing pore water molybdenum concentrations at relatively low levels, through the formation of powellite as observed in the lower elevations of the TMF (find the discussion of the molybdenum geochemical model in section 5.5.2).

Figure 5.4-2: **Sample Elevation vs. Scorodite (Amorphous and Crystalline) Saturation Indices for a) TMF-01: 2013, 2018, 2023 and b) TMF-03 2013, 2018, 2023**



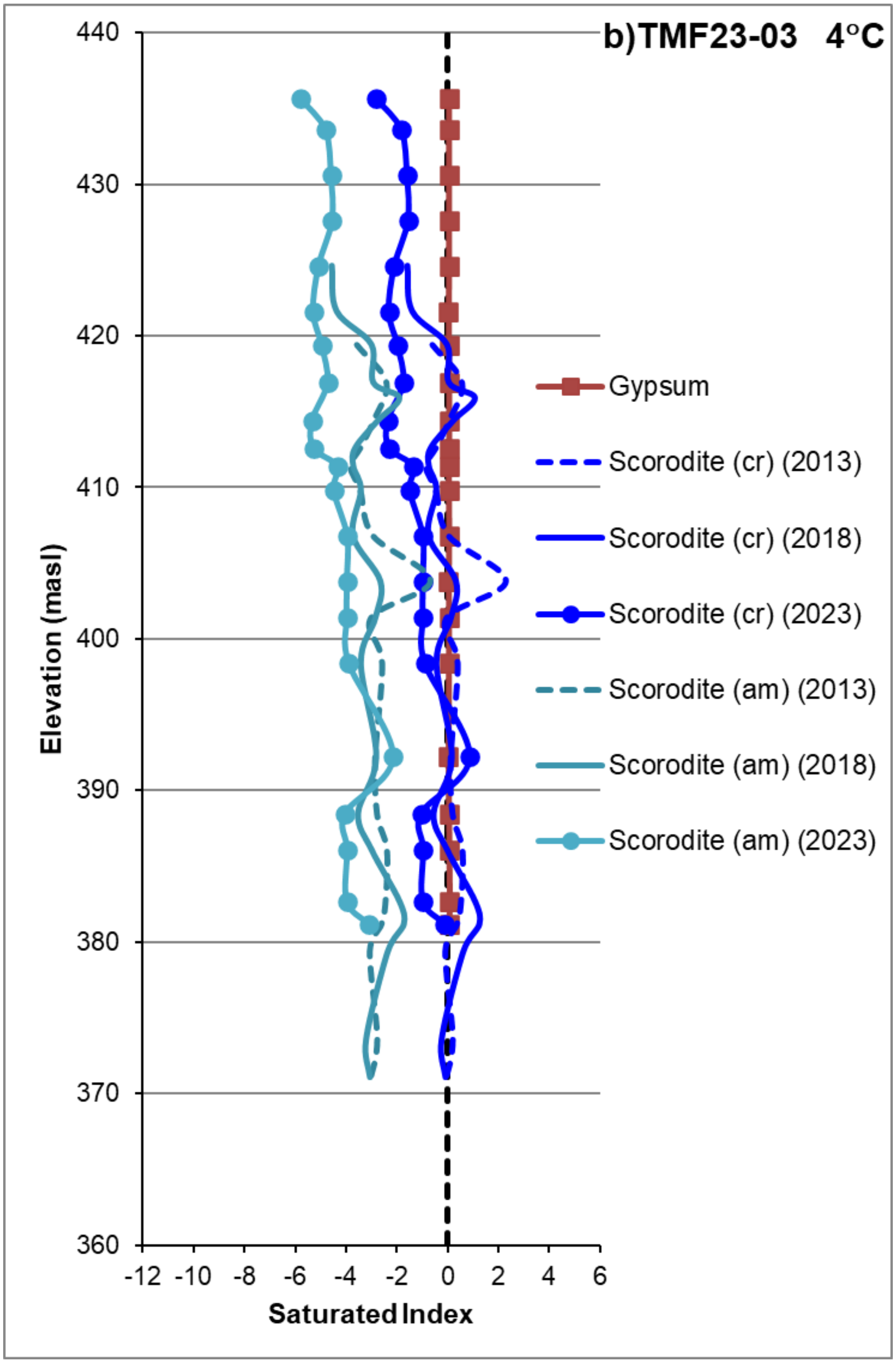

b)TMF23-03 4°C
440
430
420
410
400
390
380
370
360
Elevation (masl)
-12
-10
-8
-6
-4
-2
0
2
4
6
Saturated Index
Gypsum
Scorodite (cr) (2013)
Scorodite (cr) (2018)
Scorodite (cr) (2023)
Scorodite (am) (2013)
Scorodite (am) (2018)
Scorodite (am) (2023)

Figure 5.4-3: Sample Elevation vs Saturation Index for Molybdate Minerals for Borehole a) TMF23-01 and b) TMF23-03

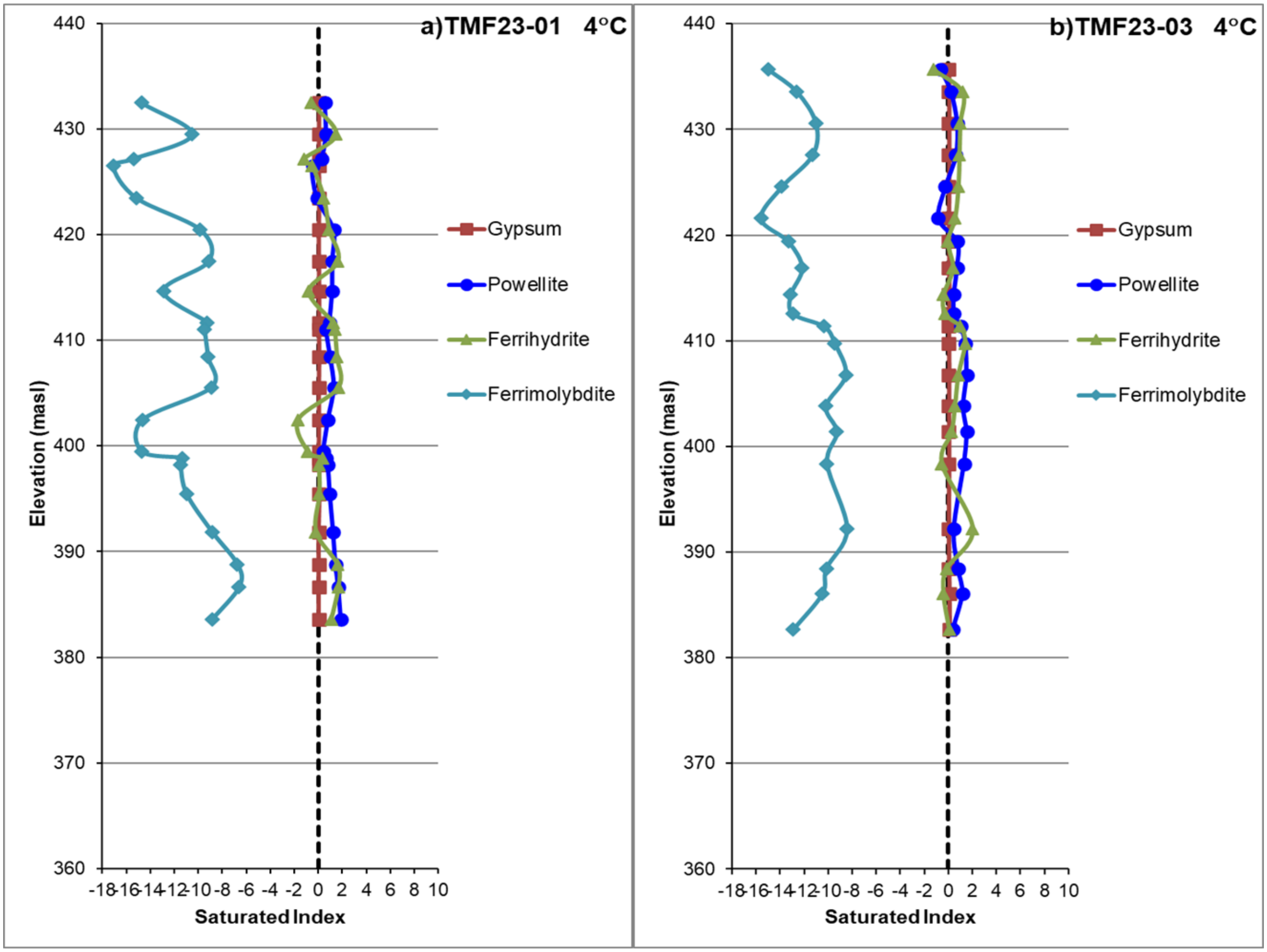


Figure 5.4-4 correlates the 2023 powellite solubility data from borehole TMF-01 and TMF-03 with the corresponding 2013 and 2018 data. The 2023 data shows that in general the molybdenum system has remained stable, which is demonstrated consistently in all boreholes compared with 2013 and 2018 data. The stability of the powellite solubility agrees well with both the proposed molybdenum geochemical model and published studies from University of Saskatchewan (Section 5.5.2 and Appendix E).

Table 5.4-2 provides average saturation indices, calculated for these molybdate phases, from all the pore water samples from the 2008, 2013, 2018 and 2023 sampling campaigns. The oxic conditions that help stabilize arsenic in the tailings inhibit the formation of ferrous molybdate ($FeMoO_4$). Recent data on the stability of Nickel Molybdate ($NiMoO_4$) suggest that it also is too soluble to control molybdenum concentrations (Morishita and Navotsky, 2003). Because the minimum solubility of ferrimolybdite occurs around pH 3.25, this species forms together with molybdate adsorbed on ferrihydrite in the initial stage of the tailings preparation circuit but is far too soluble to act as a long-term control on Mo concentrations in tailings pore water under conditions (i.e. average pH of 7.5) found in the TMF.

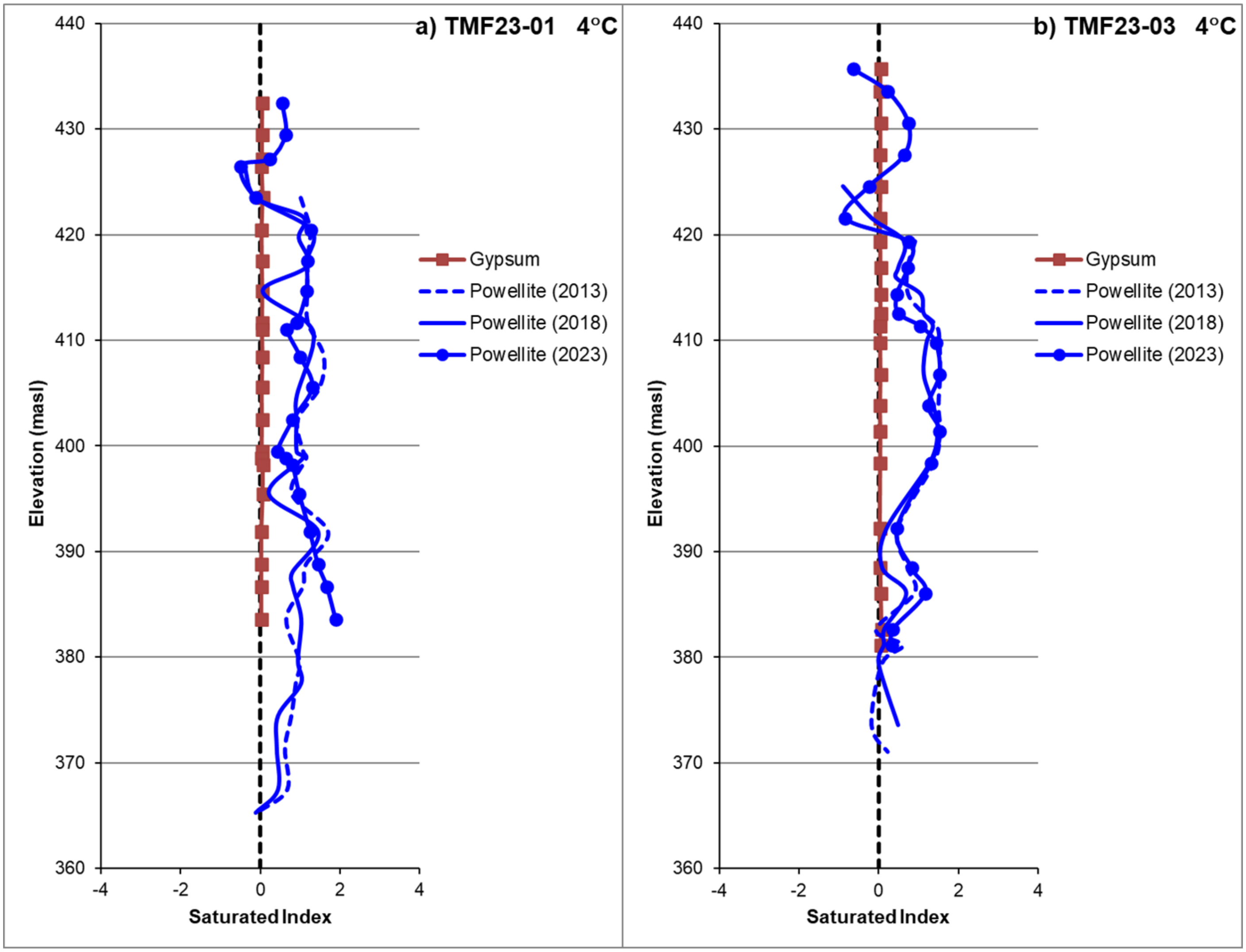
In agreement with the 2013 and 2018 modelling results, the SI modelling calculations in 2023 indicate that powellite appears to be a likely candidate for the long-term solubility control of molybdenum in tailings pore waters. Studies conducted on the tailings at the Canadian Light Source in partnership with the University of Saskatchewan, which were presented in of the 2015 Tailings Management TID (AREVA, 2015, Section 5.4.2.2), confirmed this endpoint. Due to initial crystallization, the powellite phase within the TMF may be slightly more soluble than the phase reported to have a log Ksp of -7.94 in the PHREEQC database.

Table 5.4-2: Summary of Saturation Index Modelling Calculations for Various Molybdate Phases

Mineral	Formula	Solubility Product (Ksp)	Saturation Index			
			2008	2013	2018	2023
Gypsum	$CaSO_4 \cdot 2H_2O$	-4.59	-0.04±0.084	0.05±0.03	0.07 ±0.19	0.05 ±0.01
Powellite	$CaMoO_4$	-7.94	0.72±0.44	0.88±0.44	0.61 ± 0.62	0.60 ±0.57
--	$NiMoO_4$	-6.50*	-3.89±0.63	-3.92±0.98	-4.54±1.16	-4.48±1.03
--	$FeMoO_4$	-10.02	-3.53±1.65	-0.54±0.91	-1.15±0.97	-2.80±1.37
Ferrimolybdite	$Fe_2(MoO_4)_3$	-35.29	-12.24±2.51	-5.86±2.65	-6.93 ± 3.23	-11.75 ± 2.44
Ferrihydrite	$Fe(OH)_3$	-31.0	1.65±0.93	1.15±1.28	2.94±1.02	0.59±0.98

* Morishita, M and Navrotsky, A. 2003

Figure 5.4-4: Sample Elevation vs Saturation Index for Powellite for Boreholes a) TMF-01 and b) TMF-03 in 2013, 2018 and 2023



5.4.2 Calcite (Uranium)

5.4.2.1 Overview and Theory

Studies of controls on uranium were initiated in the 2008 TOVP (AREVA, 2011a). A geochemical model for the control of uranium concentrations in the tailings pore water is detailed in Section 5.5.3. Generally, where hydrocarbons in deposited tailings oxidize over time to bicarbonate (HCO_3^-) in the tailings pore water. The HCO_3^- forms complexes with uranyl ions increasing the solubility of uranium. Controlling the solubility of uranium in the tailings pore water is therefore closely tied with controlling the solubility of HCO_3^-. As carbonate minerals are proposed as important long-term solubility controls on bicarbonate concentrations in the tailings pore water, saturation indices for these minerals have been calculated. The tailings pore water is saturated with calcium, which is in equilibrium with gypsum, a significant component of the tailings. The availability of calcium in the tailings pore water makes calcite, in theory, the most likely carbonate mineral to form in the presence of excess HCO_3^-.

The SI modelling has been revisited with the 2023 sampling campaign pore water results. This document focuses on 2023 results, with some comparisons to results from previous studies.

5.4.2.2 2023 Results

Figure 5.4-5 correlates the sample elevation with the saturation index for selected carbonate minerals calculated from the data collected in 2023 from boreholes TMF23-01 and TMF23-02.

Results from 2023 saturation index modelling find that calcite is, generally, at or slightly above saturation while other carbonate minerals such as dolomite and siderite are generally undersaturated and are not likely to form in the TMF (Table 5.4-3). The calcite solubility data generally falls into two zones divided at 400 mASL where hydrogen peroxide (H_2O_2) addition to the tailings preparation circuit was initiated. The routine addition of H_2O_2 during tailings preparation caused most of the hydrocarbons in the tailings to be oxidized prior to tailings deposition so that much less HCO_3^- was produced in situ. As a result of the reduction of available HCO_3^- in the tailings pore water, calcite tends to be undersaturated at elevations above 400 mASL (Figure 5.4-5). Generally, the saturation indices for calcite have remained consistent since 2013 (Figure 5.4-6) especially below 400 mASL. This can be attributed to relatively higher tailings pore water HCO_3^- concentration below 400 mASL. These findings are consistent with the proposed uranium/calcite geochemical model (Section 5.5.3), which is currently being investigated with collaborators at the University of Saskatchewan.

Table 5.4-3: Summary of Average Saturation Index Values for the HCO_3^- /carbonate system

Mineral	Formula	Solubility Product (Ksp)	Saturation Index			
			2008	2013	2018	2023
Gypsum	$CaSO_4 \cdot 2H_2O$	-4.59	-0.04±0.084	0.05±0.03	0.07±0.19	0.05 ±0.01
Calcite	$CaCO_3$	-8.48	0.22±0.62	-0.28±0.62	0.02±0.53	0.10 ±0.29
Calcite (<400mASL)			0.32±0.44	0.13±0.47	0.23±1.10	0.18 ±0.27
Dolomite	$CaMg(CO_3)_2$	-17.09	-0.23±1.31	-1.28±1.33	-0.45±1.10	-0.22 ±0.60
Siderite	$FeCO_3$	-10.89	n/a	-1.36±1.10	-1.50±1.59	-2.50 ±0.83

Figure 5.4-5: Sample Elevation vs Saturation Index for Relevant Carbonate Minerals for Borehole a) TMF23-01 and b) TMF23-02

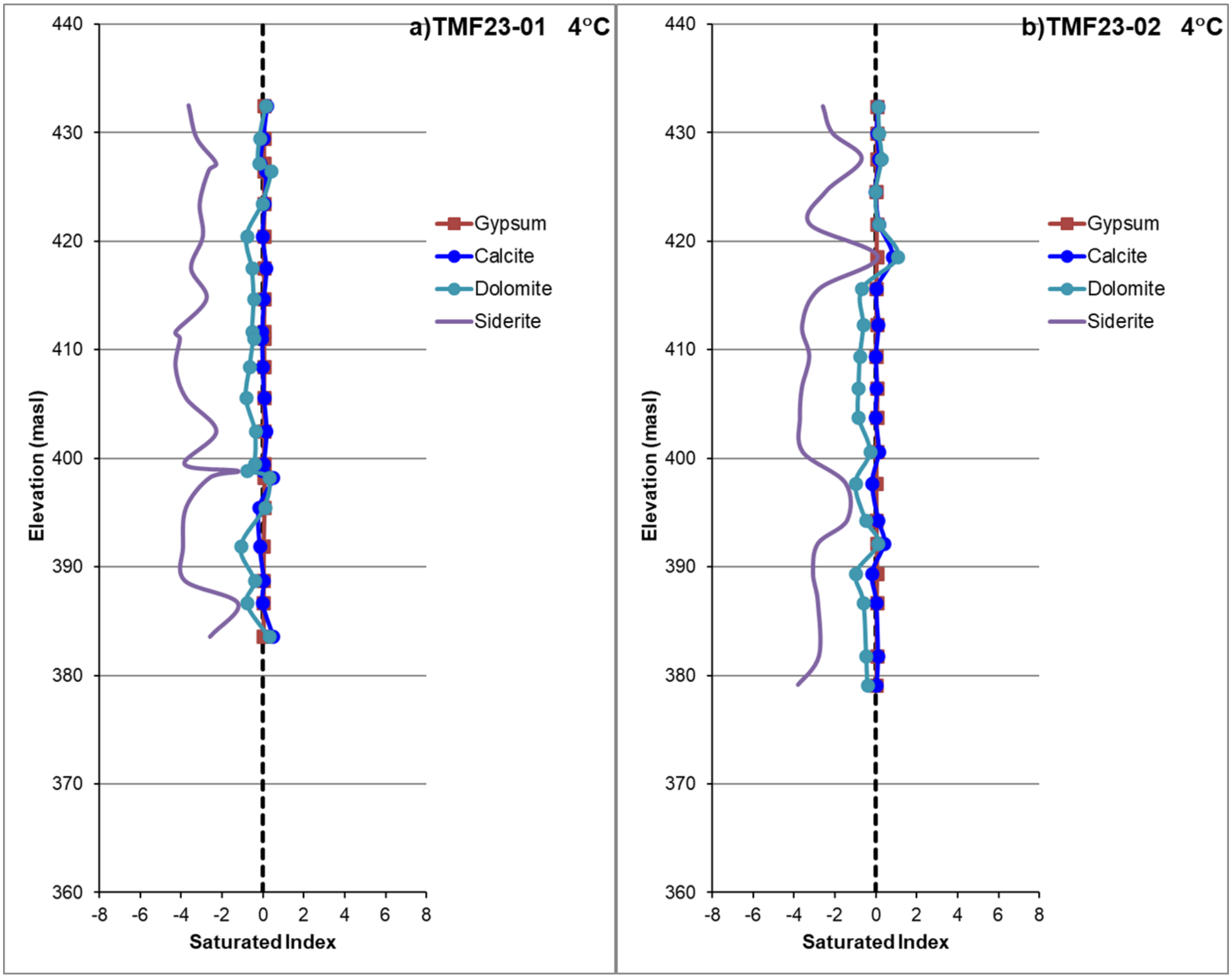
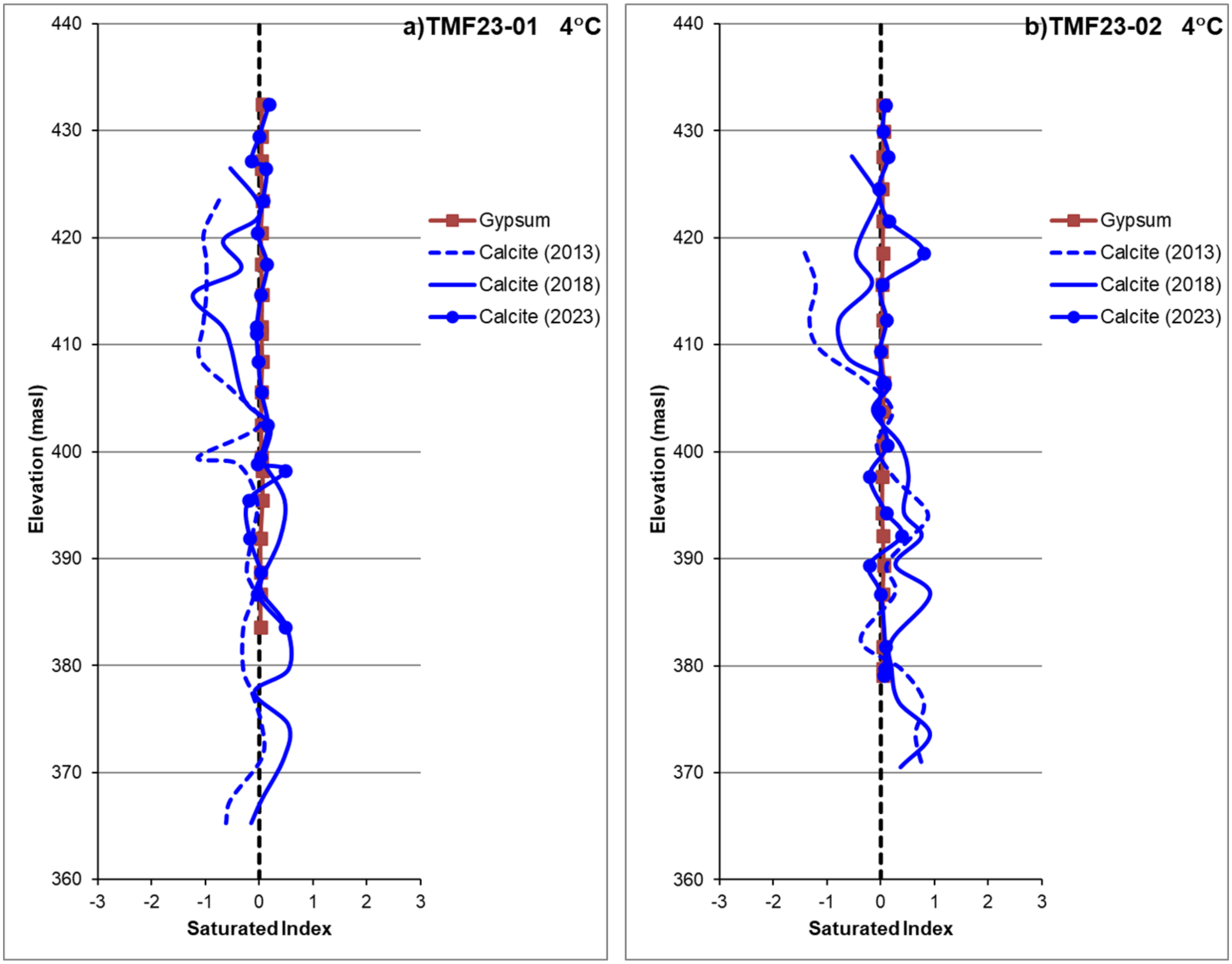


Figure 5.4-6: Sample Elevation vs Saturation Index for Calcite for Boreholes a) TMF-01and b) TMF-02 in 2013 2018 and 2023



5.4.3 Saturation Index Modelling – Conclusions

The findings of saturation index modelling for 2023 are supportive of the proposed geochemical models (Section 5.5) for arsenic, molybdenum, and bicarbonate/uranium. For each of the three systems, one mineral (scorodite, powellite, and calcite respectively) has been identified through the modelling to act as a stable long-term solubility control on the tailings pore water concentrations of the COPCs with which they have been associated. Each of these minerals is identified to be at saturation with respect to the sampled tailings pore water geochemistry. Further, each mineral has been demonstrated to be at saturation in the tailings over at least three successive sampling campaigns, representing ten years of residence time.

5.5 Geochemical Models

For the long-term, the concentrations of constituents of potential concern (COPCs) in the tailings pore water will be controlled through equilibrium reactions with geochemically stable minerals present in the tailings solids.

Following each TMF in-situ sampling campaign, a table of pore water concentrations for 18 constituents is prepared as detailed in Appendix D, Section C. The constituents and their concentrations in this table are used to predict potential long-term environmental effects in Pat and Fox Lakes, through groundwater contaminant transport modelling, as described in Section 7.

Most COPCs: Most COPCs are observed to be stable under TMF conditions and source term concentrations used in contaminant transport modelling are calculated using a weighted average of pore water concentrations throughout the tailings.

Arsenic, Molybdenum, Uranium: A few of the COPC concentrations are observed to change over time through an aging process, indicating that the respective mineral phases acting as solubility controls are evolving to more stable forms in the TMF solids. The dominant driver for change in the mineralogy of the solids as they age is chemical potential energy. The principal species participating in oxidation reactions are reduced minerals and hydrocarbons in the leach residue component of the tailings solids. The reduced minerals were not fully oxidized during the leaching process, and residual amounts of petroleum hydrocarbons (HC) are adsorbed onto the tailings solids from the mill process. The COPCs that are observed to undergo significant aging processes are arsenic, uranium and molybdenum. For each of these constituents, a geochemical model describing the mineral evolution has been developed. A long-term pore water concentration, based on the model endpoint, is also calculated for use in the prediction of long-term effects. This sub-section describes each of the three geochemical models.

5.5.1 Arsenic

5.5.1.1 Overview and Roadmap

Orano's understanding of arsenic behaviour in the TMF is the result of over 25 years of studies and investigations regarding arsenic evolution and its expected endpoint in the TMF. A general roadmap of arsenic studies relating to the TMF is presented below, with details provided in following sections.

- **1999 Initial Theory - Redox Control as a Stable Oxidized Mineral Phase:** The JEB TMF and tailings preparation process were initially designed to control the release of arsenic to the environment (Section 3.2.1). Arsenic transport and resulting potential downstream environmental effects were identified as a primary concern to regulators. Regular sampling of the tailings was mandated to validate arsenic control and the TPP performance in general. Redox control of arsenic as a stable oxidized mineral phase was proposed at this time and is outlined in the initial TOVP document in 1999 (COGEMA, 1999) and supported by laboratory testing.

- **2000-2002 Field versus Laboratory Comparison:** Deviations from original laboratory in tailings pore water arsenic values were identified during initial TOVP sampling campaigns. As a part of initial test work validating the TPP, a collaborative research program was initiated with McGill University and mill samples were analyzed using synchrotron based XANES analysis (COGEMA, 2001) The expected arsenic pore water concentration endpoint (i.e. long-term equilibrium value) was first predicted in 2001, based on observations of early in-situ tailings data and general principles of redox chemistry.

- **2005 Conceptual Geochemical Model** (Section 5.5.1.2): From 2003 to 2005, the initial theory of arsenic evolution in the tailings was refined into a conceptual geochemical model. The conceptual model was presented in the 2005 tailings report (AREVA, 2005b). Aging tests and collected TOVP field data supported the development of the conceptual model. The model was focused on the end state of arsenic in the TMF. Consistent with the initial theory, the model concluded with the eventual formation of a stable mineral phase (scorodite).

- **2005 – 2012 Geochemical Model Validation** (Section 5.5.1.3): The identification of scorodite has been supported by field data, PHREEQC geochemical modelling, research studies conducted at McGill University, and synchrotron-based analyses. The evolution of arsenic into scorodite in the TMF occurs through several oxidation steps as the tailings age. The validation of the geochemical model with in-situ data is ongoing with each TOVP reporting period and is a key focus of the TOVP program.

- **2013 Geochemical Model Refinement** (Section 5.5.1.3): Beginning in 2013, the geochemical model for arsenic has been refined through an iterative process based on continued monitoring of the tailings placed in the TMF. As arsenic evolves through several oxidation steps and intermediate phases, Orano has conducted studies clearly define these intermediate phases over time. TOVP field data, PHREEQC geochemical modelling, and synchrotron-based analytical methods have all been used to refine the geochemical model over time and validate that intermediate phases will ultimately lead to the expected arsenic end state.

- **Overall Model Validation** (Section 5.5.1.4)**:** To conclude this section, the various components of the arsenic program are integrated. Specific examples from the TMF are provided to validate Orano's understanding of the arsenic geochemical model.

As demonstrated by the studies presented in this section, arsenic behaviour in the TMF is well understood. The in-situ field data validates the geochemical model, demonstrates progression towards the expected arsenic end state of scorodite, expands understanding of the intermediate phases, and confirms the long-term control of arsenic in the tailings pore water.

5.5.1.2 Conceptual Geochemical Model

General Theory

From the inception of the TOVP to 2010, McGill University conducted a research program related to arsenic removal from solution through co-precipitation with Fe^{3+}. Orano was a corporate sponsor of this work, which was supported through a series of NSERC grants. Orano provided input into the study designs, and the resulting NSERC program content was complimentary to TOVP requirements and provided insight into the geochemical behaviour of the tailings. The research primarily focused on the optimization of the co-precipitation process of AsO_4^{3-} with Fe^{3+} (i.e. a process geochemically analogous to the tailings preparation process used at the McClean Lake Operation). Appendix E contains the papers published during this partnership.

The work supports Orano's understanding of tailings geochemical behaviour as described in this section and provides an introduction to the general theory of expected arsenic behaviour in the tailings. A summary is provided below.

The long-term stability of the Fe^{3+} and AsO_4^{3-} phases was extensively studied by the McGill researchers. In 2006, a paper was published, describing the conversion of adsorbed AsO_4^{3-} onto ferrihydrite to an amorphous $FeAsO_4$ chemical phase, in approximately two weeks of aging at room temperature, pH 3, and initial Fe/As molar ratio of 2 (Jia et.al., 2006). The amorphous $FeAsO_4$ chemical phase is a precursor of poorly crystalline scorodite, in that the crystal structure is likely present but too small to be detectable. At a temperature of 75°C, the amorphous $FeAsO_4$ phase transformed into crystalline scorodite in approximately two months (Jia et.al., 2007). Figure 5.3-1 provides a comparison of XRD spectra illustrating this mineral evolution. The rate of transformation of amorphous $FeAsO_4$ into crystalline scorodite was found to be strongly pH dependent and sensitive to the Fe/As molar ratio; the higher the value of these two parameters the more slowly the crystallization proceeds (Jia et.al., 2007; LeBerre et.al., 2008). Within the relatively short observation period, crystalline scorodite was not observed at a near neutral pH. Crystalline yukonite was produced when this aging experiment was repeated at pH 8, Figure 5.3-2 (Jia and Demopoulos, 2008).

Increase in temperature to accelerate the formation of crystalline terminal minerals containing arsenic introduces the question as to whether the same minerals would develop over a much longer term at ambient temperatures. Investigations into arsenic mineralogy associated with historic mine sites appears to provide pertinent insight. Crystalline scorodite is a relatively common secondary mineral formed from the oxidation of arsenopyrite and other arsenide minerals. It is often associated with old mine waste stockpiles, commonly from gold or base metal mines, where acid rock drainage conditions have been established for several decades (Haffert and Craw, 2008). Under this oxic and Fe^{3+} rich acidic environment, arsenic is sequestered as scorodite. Similarly, yukonite is found as a natural weathered product under oxic, alkaline, Ca^{2+} and Fe^{3+} rich conditions.

Figure 5.5-1: Comparison of XRD patterns of Fe/As = 2 arsenate ferrihydrite sorption solids at pH 3 illustrating mineral evolution to amorphous $FeAsO_4$ and finally to crystalline scorodite (Jia et.al., 2007).

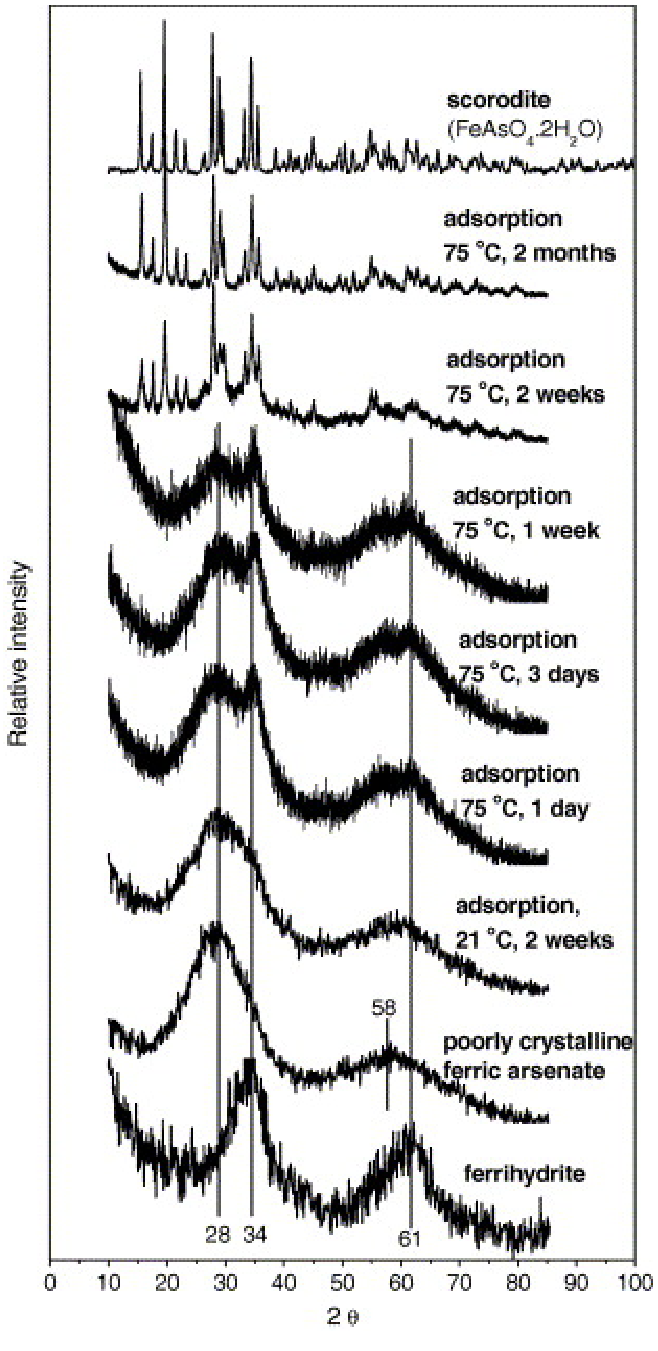
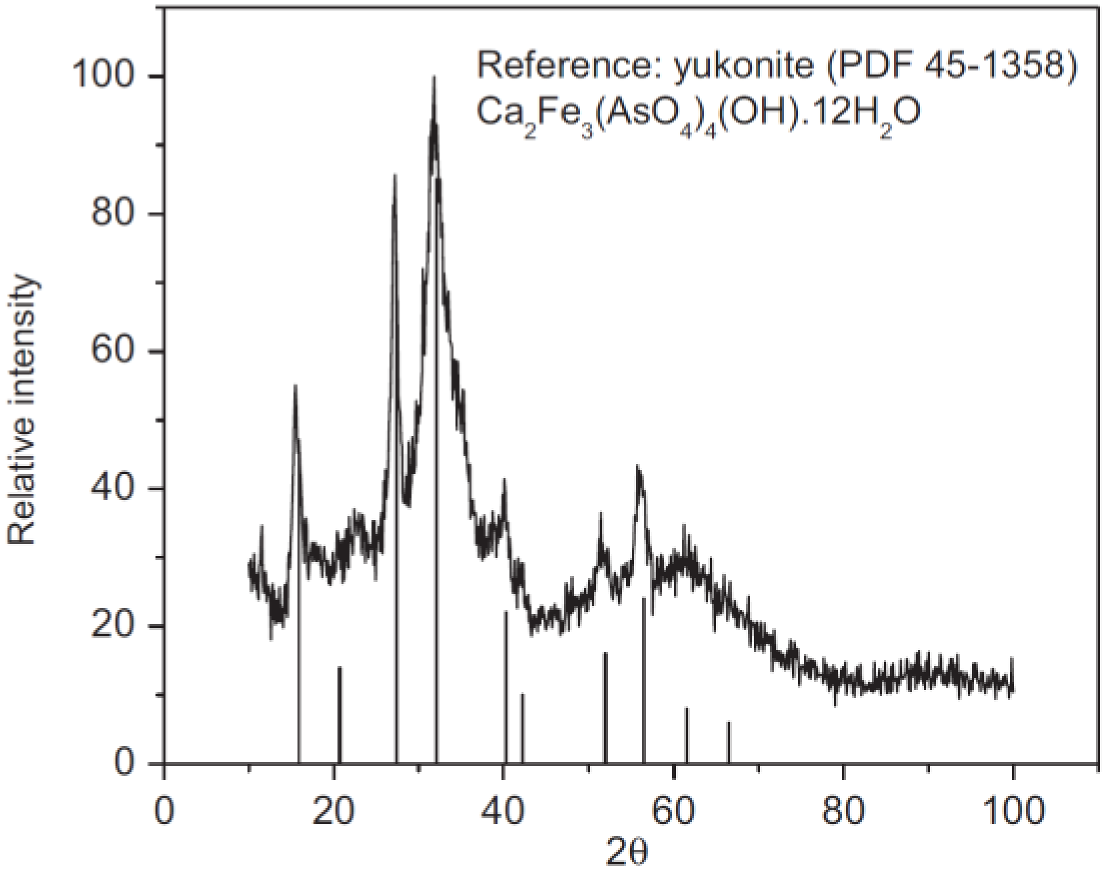


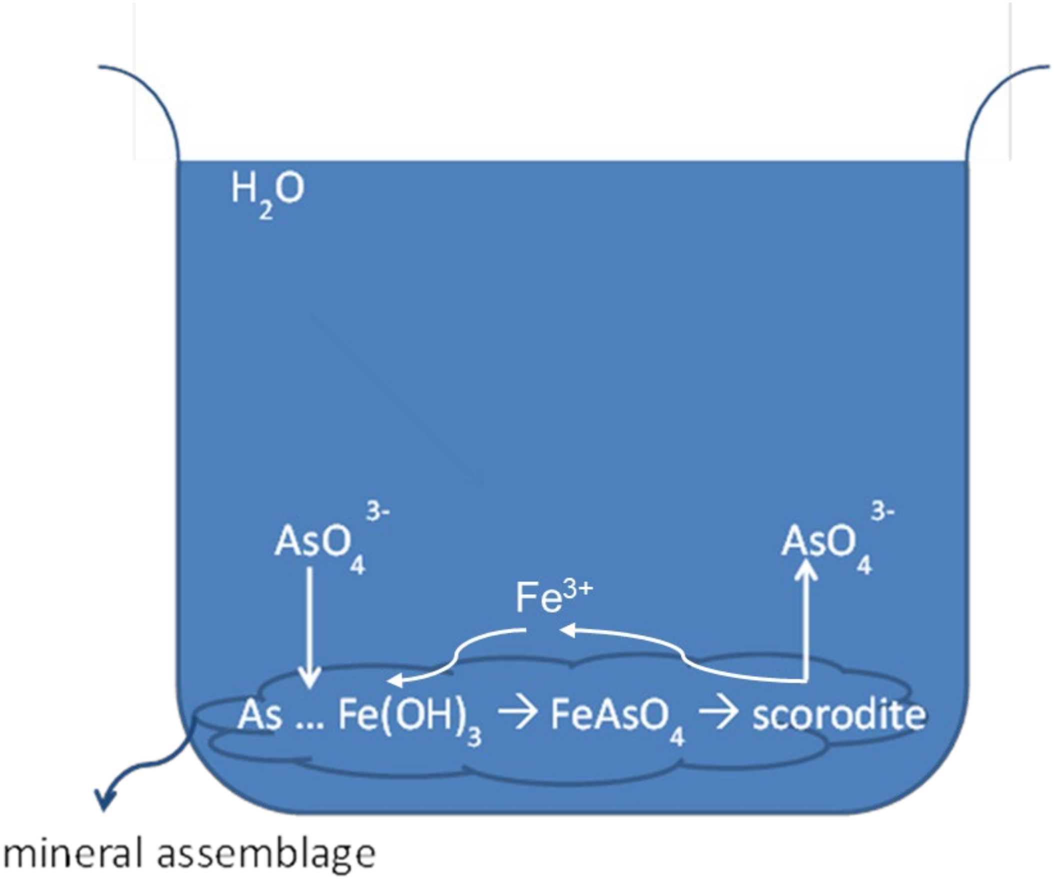
Figure 5.5-2: XRD pattern of solids following 7-week accelerated aging at 70 °C with Fe/As = 2 co-precipitate at pH 8 (Jia and Demopoulos, 2008).



Most gold mines use oxygen and lime in their extraction process, and suitable conditions can exist leading to the formation of crystalline yukonite in old mine wastes (Tyrrell et.al., 1913). Similar mineralogical endpoints for arsenic have also been reported by researchers from Queen's University and Natural Resources Canada (NRCan). These researchers have studied a number of historic Fe - As rich tailings deposition sites in Nova Scotia, some of which date back more than a century (Walker et.al, 2009). At locations where tailings are oxidized with a near neutral pH, arsenic is reported as a mixture of crystalline scorodite and yukonite. The mineralogical evolution found in laboratory aging experiments completed at McGill University appears to be confirmed through observations at historic mine sites.

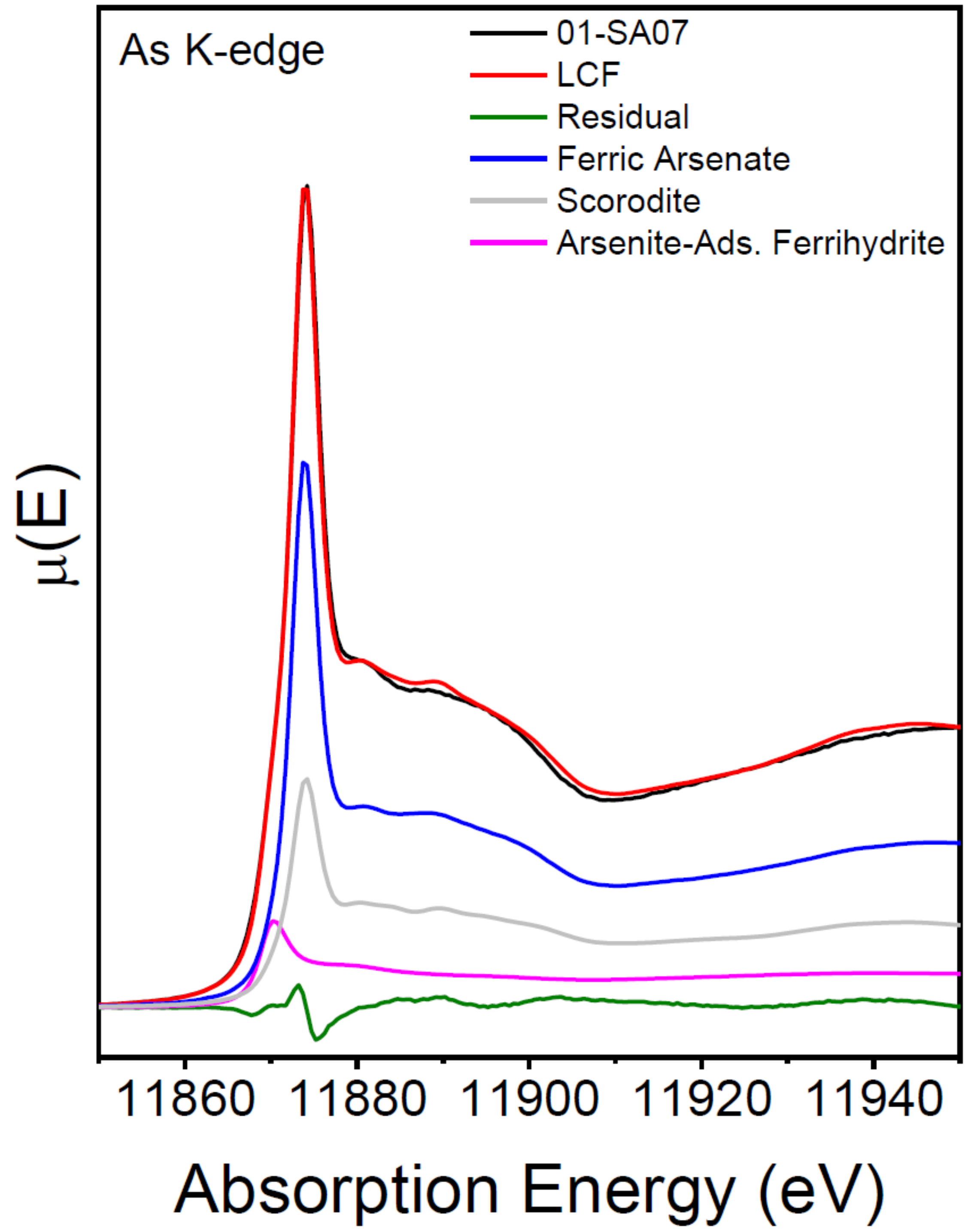
Scorodite, when placed in water at a near neutral pH, will begin to dissolve incongruently i.e. the Fe/As molar ratio in the solution is different than in the solid. The Fe^{3+} released to solution will precipitate as ferrihydrite and initially the AsO_4^{3-} will remain in solution. However, as the arsenic concentrations increase in the solution, AsO_4^{3-} will be adsorbed onto the ferrihydrite initiating the mineral evolution process described in the previous paragraphs. It is apparent that the dissolution is reversible via a mechanism involving an assemblage of these three Fe^{3+} - AsO_4^{3-} phases. Eventually, equilibrium will be established with scorodite dissolving at the same rate as it is being formed. A distinct amount of AsO_4^{3-} would be distributed among the three phases, Figure 5.3-3.

Figure 5.5-3: Simplistic drawing illustrating control of As^{5+} solution concentration by equilibrium with synergistic Fe^{3+} - AsO_4^{3-} mineral assemblage.



In the 2023 TOVP sampling campaign, arsenic mineralogy was assessed using X-ray absorption near-edge structure (XANES) spectroscopy at the As K-edge. Principal Component Analysis (PCA) and Linear Combination Fitting (LCF) analyses were employed to identify the arsenic-bearing minerals present in the samples by fitting the As K-edge XANES spectra of the samples to a spectra database of arsenic-bearing standards. An illustration of a typical fitted As K-edge XANES spectrum is presented in Figure 5.5-4 for tailings sample TMF23-01-SA07. The XANES technique is unable to distinguish between AsO_4^{3-} adsorbed on ferrihydrite or amorphous $FeAsO_4$, and therefore the spectrum identified as amorphous $FeAsO_4$ in the fit (Figure 5.5-4) represents the total of these two arsenic phases. The TMF23-01-SA07 As K-edge spectrum shows that arsenic occurs predominantly as As^{5+-} (partitioned as amorphous $FeAsO_4$ and scorodite) with minor amounts of As^{3+} present as arsenite adsorbed on ferrihydrite. 68 samples were submitted for XANES analysis from the 2023 TOVP sampling campaign. The samples were collected from eight boreholes, with samples from four entire boreholes being submitted for analysis. The XANES results confirm that, throughout the entire TMF, the arsenic occurs predominantly as As^{5+} with minor amounts of As^{3+} (Appendix D Section D Subsection A)(see As geochemical model Section 5.5.1, Figure 5.5-10).

Figure 5.5-4: The As K-edge XANES spectrum of TMF23-01-SA07



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Presentation of Model

Typically, tailings solids contain small residual amounts (<1%) of primary arsenic bearing mineralization that was not fully oxidized during the ore leaching process. The amount and type of primary arsenic mineralization is controlled by the metallogeny of the original ore body. These reduced arsenide minerals primarily consist of niccoline ($NiAs$), rammelsbergite ($NiAs_2$), and gersdorffite ($NiAsS$). Notably, the JEB/Sue ore deposits were observed to contain all three types of arsenide mineral, while the Cigar Lake deposit hosts dominantly gersdorffite with minor components of other arsenides (Kaczowka, 2017).

Under the pH and Eh conditions present in the TMF, primary arsenic minerals are not stable and will undergo oxidation to secondary mineral phases. The oxidation of arsenides to stable arsenates occurs through a two-step process. An example of this process is provided in equation 5.5-1, considering the primary arsenic mineral gersdorffite. The first step involves oxidation of gersdorffite, which dissolves to produce As^{3+} in the tailings porewater.

$$\underset{\text{(gersdorffite)}}{\overset{[As^{1-}]}{NiAsS\downarrow}} + 11Fe^{3+} + 7H_2O \rightarrow \overset{[As^{3+}]}{H_3AsO_3^0} + SO_4^{2-} + 11Fe^{2+} + Ni^{2+} + 11H^+ \qquad \text{equation 5.5-1}$$

At pH 7, the most abundant As^{3+} aqueous species is the zero charged solution complex $H_3AsO_3^0$ (arsenous acid). As concentrations of As^{3+} accumulate in the tailings pore water, the arsenous acid partitions to the tailings solid phase through adsorption onto ferrihydrite.

The second step involves oxidation of the As^{3+} solution complex to As^{5+} (equation 5.5-2). $HAsO_4^{2-}$ is the most stable As^{5+} solution complex under the pH and redox conditions in the TMF.

$$\overset{[As^{3+}]}{H_3AsO_3^0} + 2Fe^{3+} + H_2O \rightarrow \overset{[As^{5+}]}{HAsO_4^{2-}} + 2Fe^{2+} + 4H^+ \qquad \text{equation 5.5-2}$$

The $HAsO_4^{2-}$ solution complex has a relatively low solubility in the presence of ferric iron and results in the precipitation of ferric arsenate which, given sufficient time, will crystallize into the mineral scorodite, equation 5.5-3.

$$HAsO_4^{2-} + Fe^{3+} + 2H_2O \rightarrow \underset{\text{(scorodite)}}{FeAsO_4 \cdot 2H_2O\downarrow} + H^+ \qquad \text{equation 5.5-3}$$

Overall, the oxidation of reduced arsenic mineralization to stable oxidized forms in the tailings solids is obtained by summing equations 5.5-1, 5.5-2 and 5.5-3. Notable in equation 5.5-4, is the overall requirement for a total of 14 moles of Fe^{3+} per one mole of As. This is the basis of the Fe:As molar ratio used in the tailings preparation circuit for unleached arsenic.

$$\underset{\text{(gersdorffite)}}{\overset{[As^{1-}]}{NiAsS\downarrow}} + 14Fe^{3+} + 10H_2O \rightarrow \underset{\text{(scorodite)}}{\overset{[As^{5+}]}{FeAsO_4 \cdot 2H_2O\downarrow}} + 13Fe^{2+} + SO_4^{2-} + Ni^{2+} + 16H^+ \qquad \text{equation 5.5-4}$$

Of the two oxidation steps, the second step described by equation 5.5-3 is rate limiting and controls the overall reaction rate once the primary mineralization has begun to oxidize. Under TMF conditions, these reactions occur very slowly due to lack of physical mixing, low liquid/solid ratio, and low temperature. The very slow process of molecular diffusion provides the principal means of mixing. Each in-situ sampling campaign therefore provides a snapshot in time of the ongoing reaction progress.

5.5.1.3 Model Validation and Refinement

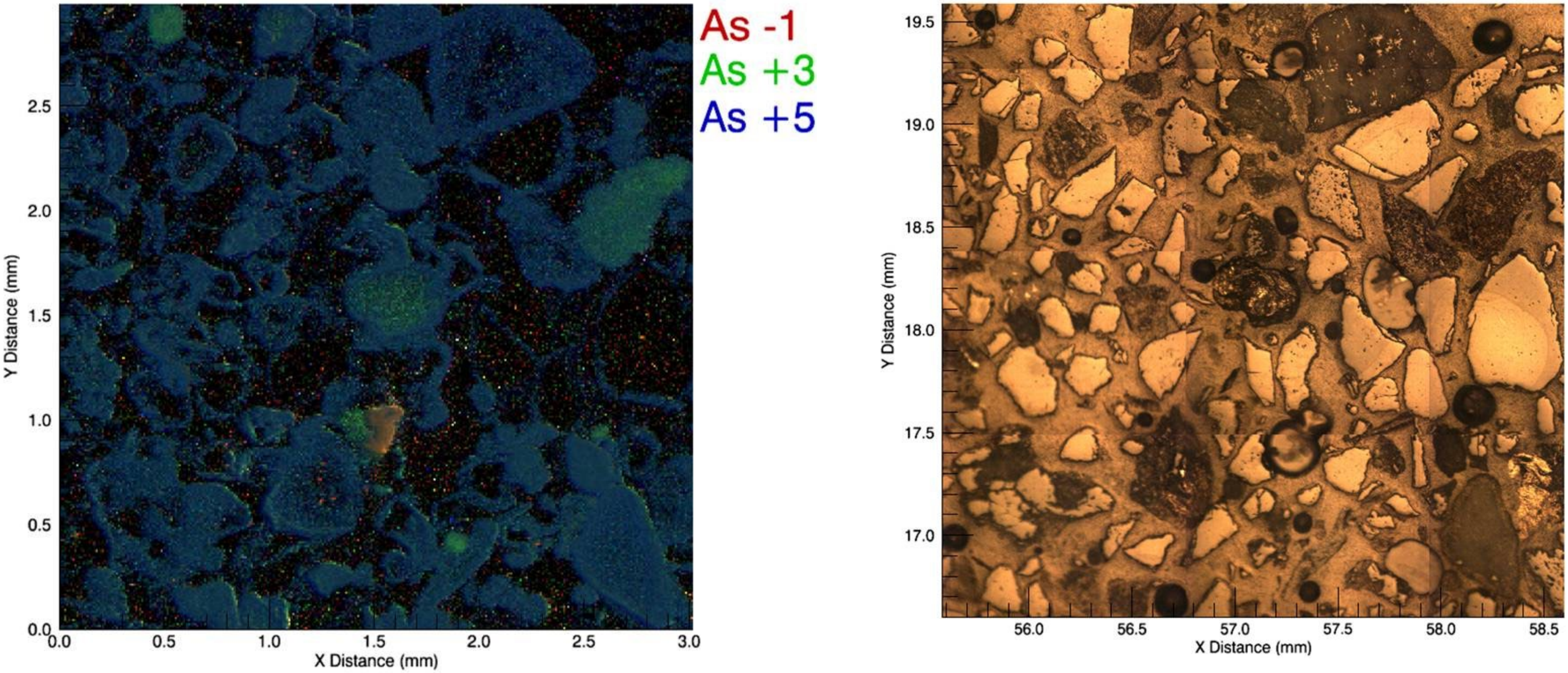
Historical Validation

To verify the evolution of reduced arsenic in the tailings solids, tailings samples from the 2008 sampling campaign were sent to the National Synchrotron Light Source at Brookhaven National Laboratory to be examined using the X26A X-Ray Microprobe Beamline. A Micro-X-ray Florescence (µ-XRF) image of the tailings from the experiment, presented in Figure 5.5-5, show a microscale arsenic speciation in the tailings solids. In the image, a primary arsenic mineralization (As^{1-}) is clearly identified. The grain of As^{1-} is partially oxidized to As^{3+}. All other occurrences of As^{3+} in the sample are at the cores of grains that are otherwise coated in As^{5+}. Tailings pore water As^{3+} concentrations are initially observed to rise until the source of the As^{3+}, the residual As^{1-}, has been depleted. The As^{3+} concentrations then decrease to a low stable value during the final oxidation step.

The geochemical reaction series involving oxidation of primary arsenic to secondary mineral phases in the tailings is kinetically controlled. The reaction will require several years to reach equilibrium, and the exact duration depends on many geochemical and physical factors. Currently, the evolution of this reaction series is ongoing in the TMF and is being carefully tracked over time.

The most recent results from 2023 are presented below.

Figure 5.5-5: a) μ-XRF Imaging of Arsenic Speciation in TMF08-01 SA05 b) The Same Area in Plane Polarized Light



PHREEQC Geochemical Modelling

Stability fields of aqueous arsenic species in an As-O_2-H_2O system are shown on an Eh-pH diagram generated with Geochemist's Workbench®, using 2023 sampling geochemical data (Figure 5.5-6). The 2023 data shows that the conditions in the tailings are oxidizing and as expected, arsenate (As^{5+}) species are predominant over arsenite (As^{3+}). An example of arsenic mineral species stability was further modeled using PHREEQC (Parkhurst and Appelo, 1999) for various dissolved and solid phases in a Ni-Fe-As-Ca-S-O_2-H_2O system which is a closer approximation to the conditions found in the TMF (Figure 5.5_7). Iron-containing arsenates are predominately stable under acidic (pH <7), oxic conditions. In contrast, calcium-containing arsenates are most stable under basic (pH >7.5), oxic conditions. Primary arsenic mineralization is mostly stable under anoxic conditions. The blue box represents Eh-pH values of samples of tailings pore water.

Figure 5.5-6: Eh-pH diagram of the As- O_2-H_2O system

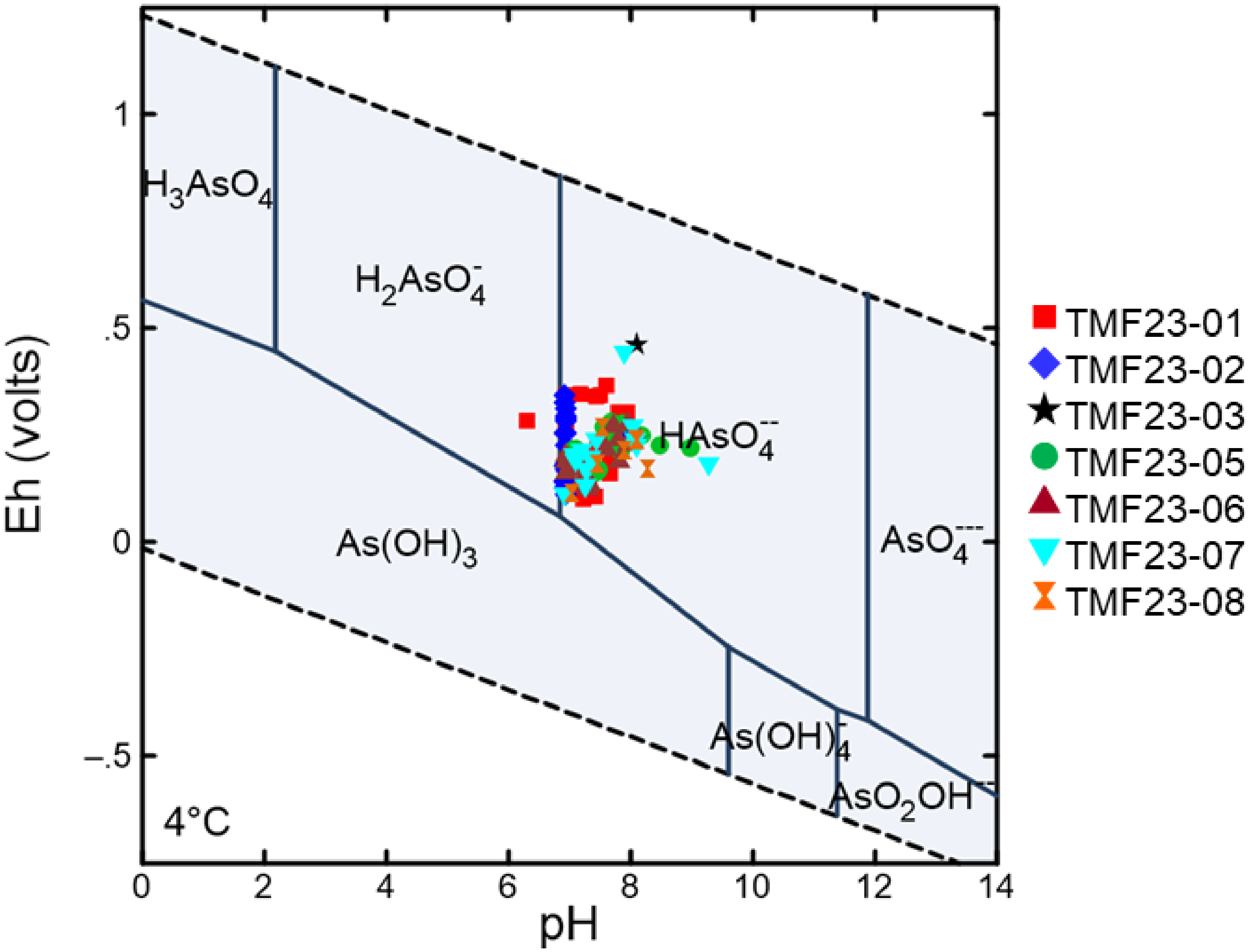
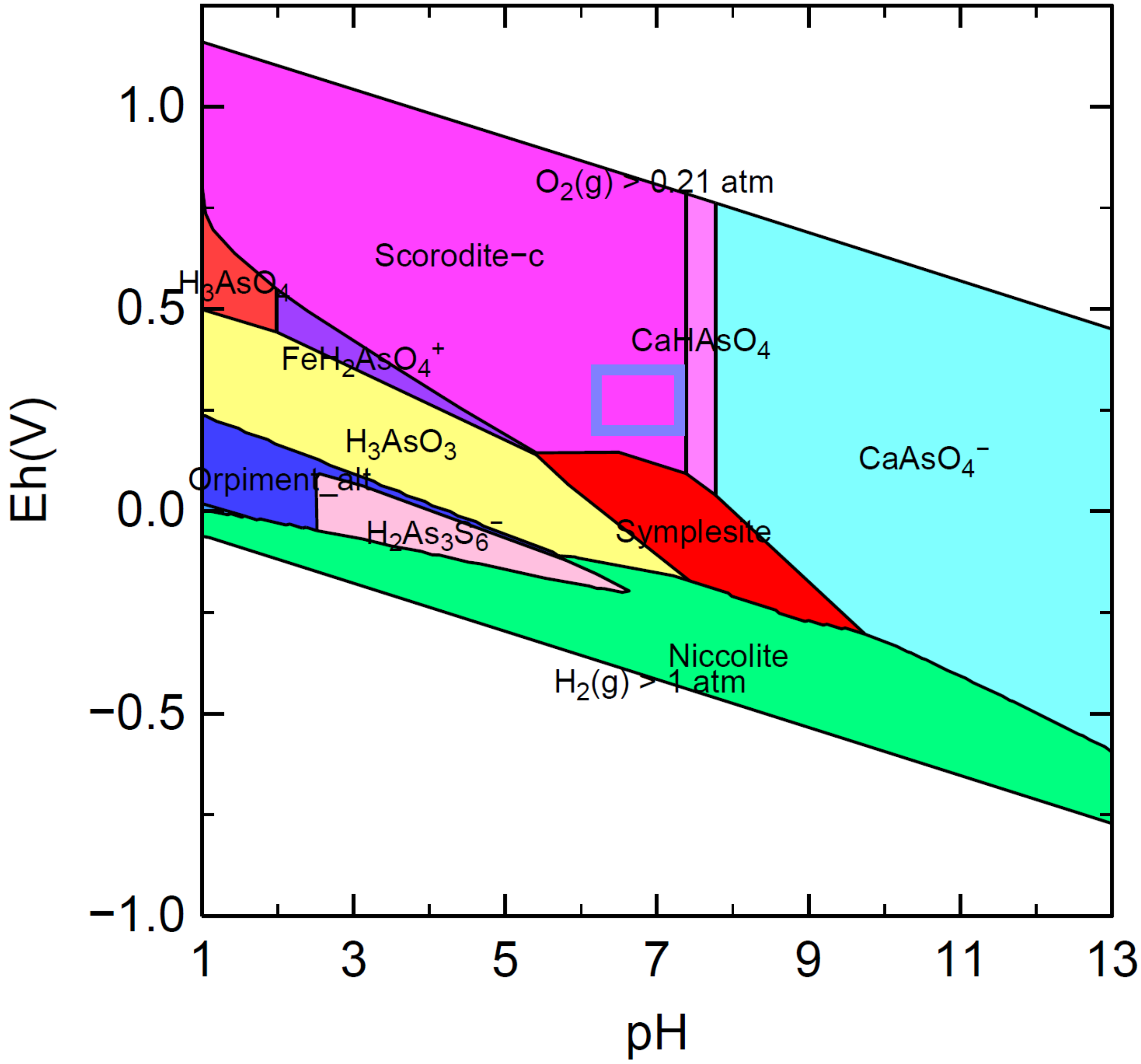


Figure 5.5-7: Eh pH diagram of the system Ni-Fe-As-Ca-S-O_2-H_2O[1]



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[1] System modeled at 25ºC showing dominant dissolved or solid phases of As Ferrihydrite present as log K = 6.4, Scorodite log Ksp =-25.87, Ni 10.0mg/L, As 5.0mg/L, Ca 400mg/L, Fe 500 mg/L, SO4-2 2000 mg/L, Mg 100 mg/L.

Solids Mineralogy of Tailings

Background – Sue C Experience

The investigations of the solids mineralogy of the tailings presented here are the continuation of years of study triggered by geochemical observations of the evolution of arsenic in the Sue C tailings. Comprehensive introductory work on this topic may be found in the 2005 TOVP Validation Report (Appendix F).

The Sue C tailings were produced and deposited before the complete development of the arsenic geochemical model as it currently exists. The iron to arsenic ratio was applied with the assumption that all the arsenic in the system had been leached, and that sufficient total iron was present in the ore to oxidize soluble As^{3+} to As^{5+} before the tailings were deposited. Therefore, limited ferric iron was added during tails preparation. Although the Sue C ore contained less primary arsenic than the other McClean Lake deposits, less was leached during the uranium extraction process resulting in the presence residual primary arsenic in the Sue C tailings. This is because Sue C deposit was a partially basement hosted, and the associated primary arsenic mineralogy was relatively more difficult to leach than the primary arsenic mineralogy associated with sandstone hosted deposits (i.e. Sue E). The presence of residual primary arsenic minerals coupled with limited ferric iron added during preparation of Sue C tailings have resulted in tailings pore water arsenic source term has been observed in the Sue C tailings and Orano has since applied lessons learned from this experience and its associated investigations.

To eliminate further excursions in pore water arsenic concentrations, the ferric iron addition during tailings preparation was adjusted in 2004 (Section 3.2.4) to account for partially oxidized and reduced arsenic in as-discharged tailings. Subsequent increases in arsenic source terms have not been observed, indicating that the improvements to the TPP have been successful in controlling tailings pore water arsenic (Figure 5.5 8). Figure 5.5-9 illustrates the results of tailings pore water sampling campaigns over time in the central borehole, TMF-01, which intersects all tailings types placed in the TMF and captures the oldest tailings. Data is presented by sampling year (TMF23-01 represents samples collected in 2023 from TMF-01, TMF18-01 represents samples collected in 2018 from TMF-01, etc.) The pore water results show that arsenic concentrations are low and controlled above ~400 mASL, reflecting the time period after Sue C and the application of lessons learned.

The Sue C experience has led to the extensive study of the evolution of arsenic in the tailings geochemical system. Results of these studies during the most recent reporting period (i.e. 2023 samples) are presented below.

Figure 5.5-8: General Representation of Tailings by Ore Source and Elevation.

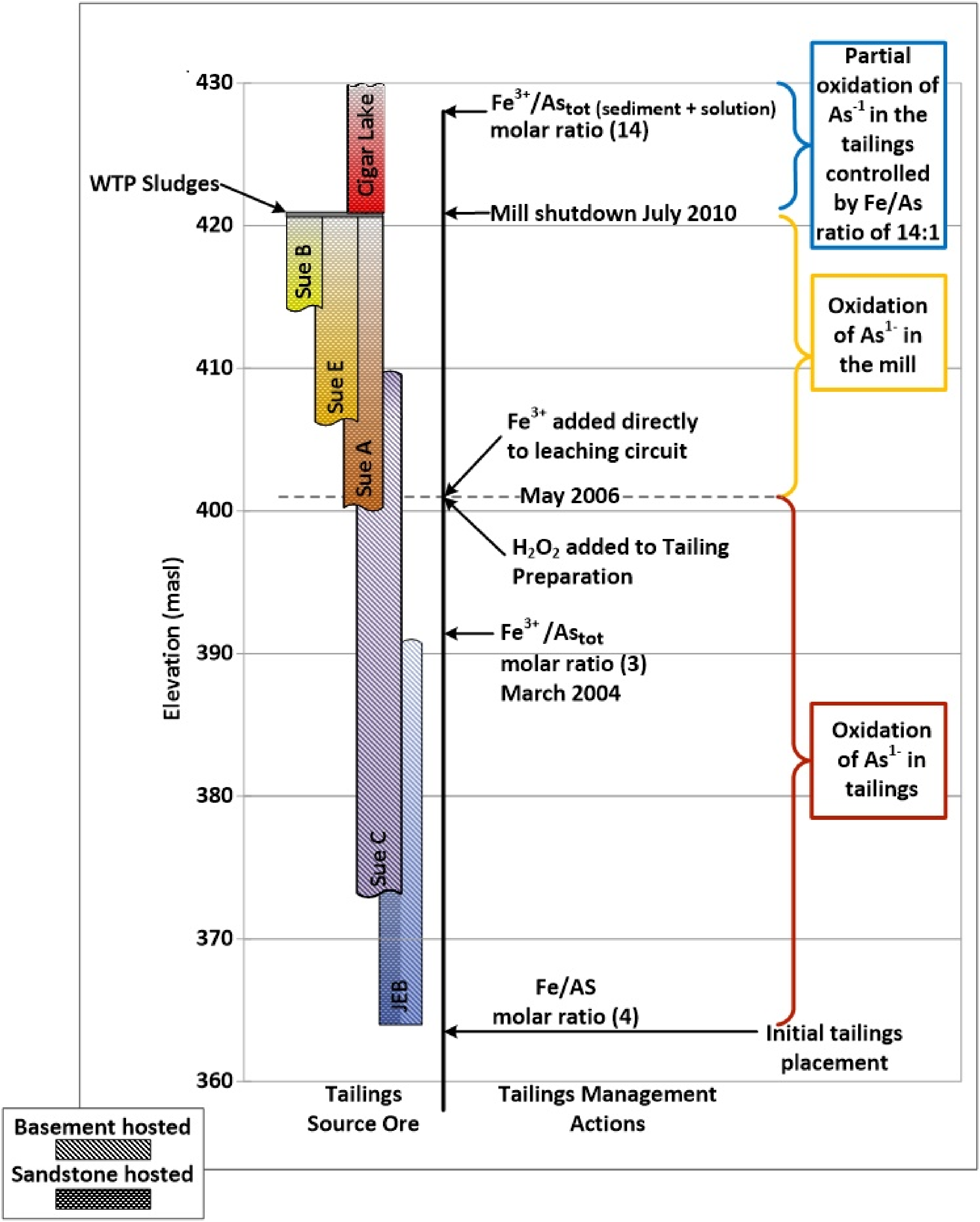
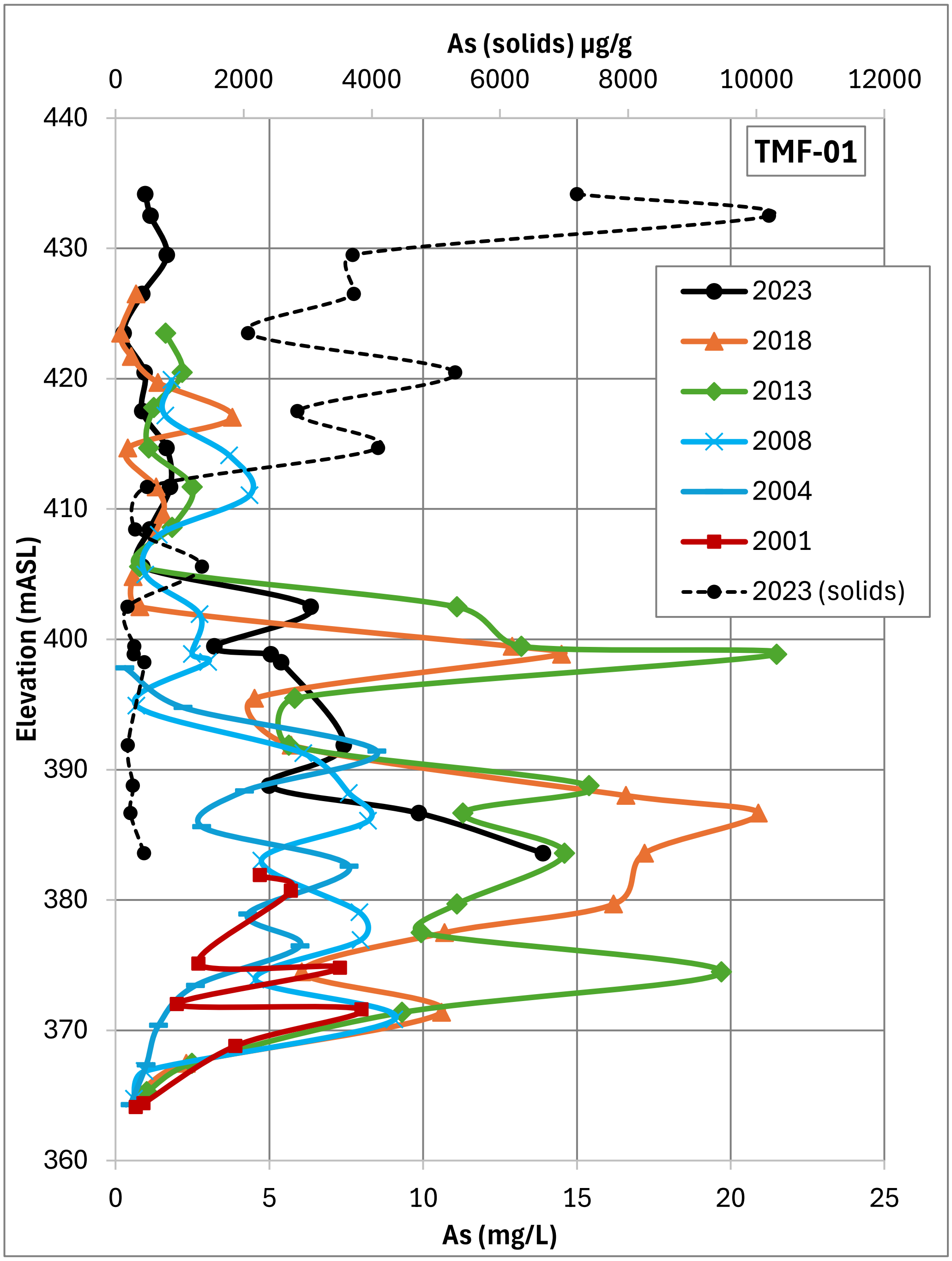


Figure 5.5-9: Evolution of Arsenic in the pore water of borehole TMF-01 over the life of the TMF



Overview of Analytical Techniques

The evolution of the Sue C tailings have been carefully followed over time as discussed in more detail in the arsenic geochemical modelling sections of the 2011 TOVP (Section 3.2.3.4, AREVA, 2011a) and 2015 Tailings Management TID (Section 5.3.1, AREVA 2015). The solids chemistry of the tailings has been tracked and a uniquely large catalogue of sample analysis data has been assembled. In 2018, Orano initiated studies to further understanding of the mineralogy of the new Cigar Lake tailings and identify differences from the previous JEB/Sue tailings which have been continued in this report. Four principal analytical techniques were used for the studies as detailed in Section 5.3.2.

This section presents the results of the studies relating to arsenic on the 2023 TOVP samples. Table 5.5-1 outlines the details of each technique used for the analysis of arsenic.

Table 5.5-1: Summary of detection limits and data presentation by analytical technique

Technique	Detection Limit	Data Presentation	Key Considerations
ICP-OES	10-20 ppm	Data is presented in ug/g	Bulk analysis of total solid As in the sample.
QEMSCAN	0.001-0.002 % (10-20 ppm)	Data is presented as a weight % of the mineral in the total sample. To obtain ug/g of arsenic the atomic weight of arsenic in the mineral observed is considered (e.g. the formula of gersdorffite (NiAsS) contains 44% arsenic by atomic weight. Therefore, of the wt % attributed to gersdorffite, 44% is used to calculate ug/g arsenic.	Microanalysis of individual "spots" (grains) in the sample combined for an overview of the sample;(i) identifies the presence and spatial distribution of primary As minerals at the micron scale as well as their association with other minerals (ii) provide a semi-quantitative analysis of the primary As minerals present.
XANES	Bulk Arsenic Detection: 10 ppm Resolution of arsenic species (observational) :100 ppm	Data is presented as a relative percentage of the total arsenic in the sample which can be combined with ICP-OES analysis of total arsenic to obtain ug/g of each species	Bulk analysis of arsenic speciation (redox and mineral phases) in tailings solids. Arsenic speciation is determined using linear combination fitting of sample spectra to spectra of reference standards.

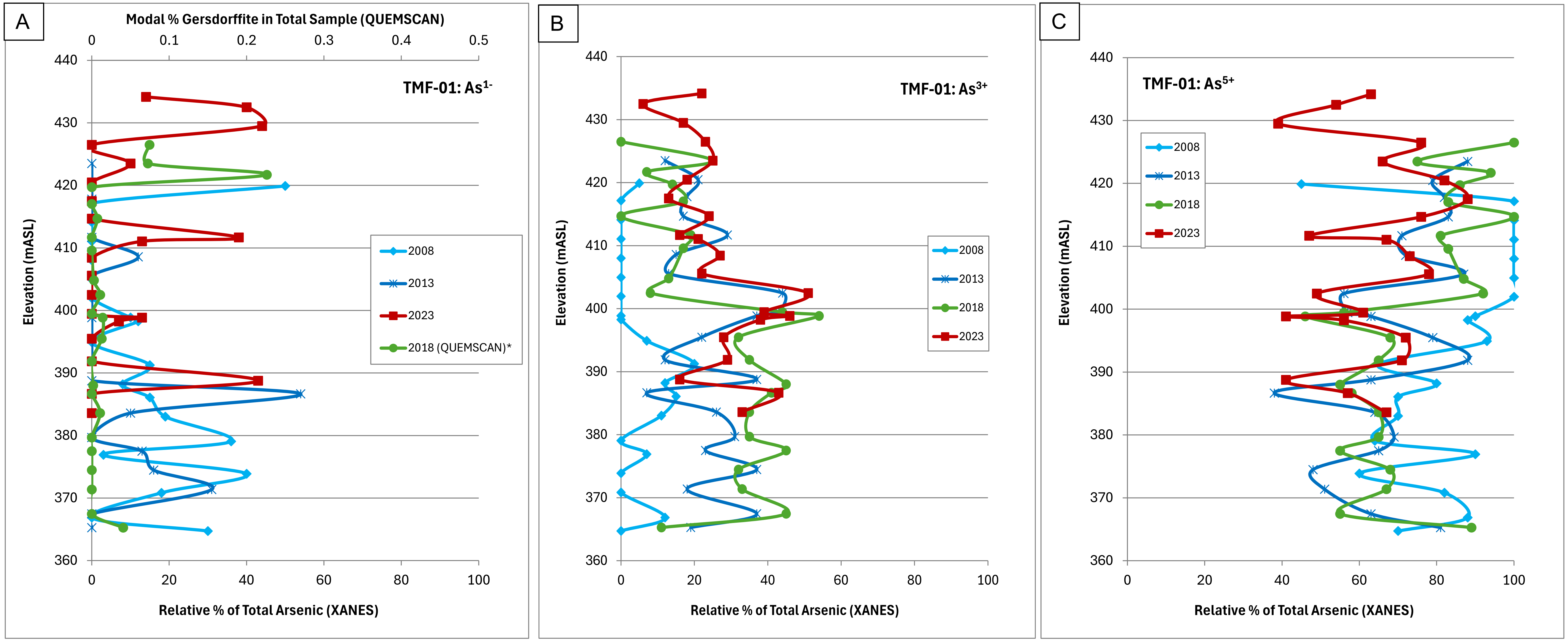
Overview of Results

XANES spectroscopy has been performed on selected tailings samples over four sampling campaigns (2008, 2013, 2018 and 2023). In 2008, a full suite of samples from TMF08-01 was analyzed for arsenic redox speciation without identifying specific mineralogy. In 2013, the program was expanded adding full depth samples from TMF13-02 and TMF13-06, and linear combination fitting with a comprehensive set of arsenic standards to identify arsenic mineral species. In 2018 and 2023 the samples of 2013 were replicated with the addition of samples from the Cigar Lake tailings (Full 2023 results in Appendix D, Section D, Subsection A).

The change in proportion of arsenic species over time can be observed in TMF-01 beginning in 2008 (Figure 5.5-10abc), providing a clearer picture of arsenic oxidative behaviour. The collection of a full range of XANES samples in 2013, 2018 and 2023 provides the opportunity to compare a full suite of XANES analyses between successive sampling campaigns. There is some limitation in the comparison of the data between sampling campaigns due to the inherent heterogeneous nature of the tailings. For this reason, general trends will be evaluated more than the evolution of any one particular data point in the interpretation.

Specific observations relating to the evolution of arsenic over time are provided below.

Figure 5.5-10: Evolution of the Redox Speciation of Solid Arsenic in the Borehole TMF-01 over 2008, 2013, 2018, and 2023. A) As^{-1} , B) As^{+3}, C) As^{5+}



*QEMSCAN values are calculated as a % of the mineralogy of the total sample compared to XANES data which is presented as relative % of the total As in the sample. Average total (reduced and oxidized) arsenic in all tailing samples in 2018 was 0.37%

-

As^{-1}: XANES Results

In past campaigns, primary reduced arsenic (As^{-1}) was identified in most boreholes, particularly at depth in the area of the Sue C tailings (~365-400 mASL, Figure 5.5-8) and in the Cigar Lake tailings (~>420masl) Figure 5.5-10a. In 2018 and 2023 more As^{-1} species have been found in the newer Cigar Lake tailings, as expected (Section 5.3.2.1) and the bulk of the primary arsenic mineral present in all samples has been identified as gersdorffite (Sections 5.3.2.3 and 5.3.2.4).

XANES spectroscopic analysis results show the abundance of primary arsenic in tailings in selected samples of 2023 tailings compared with results from 2008, 2013 and 2018 (Figure 5.5-10). Primary arsenic minerals have been identified in all three boreholes selected for XANES analysis (TMF23-01, TMF23-03, and TMF23-06). In 2023, less As^{1-} was observed on average in the older JEB/Sue tailings than in the newer Cigar Lake tailings. The results validate two assumptions:

1) The Cigar Lake tailings contain a higher percentage of arsenic overall than the JEB/Sue tailings

2) as As^{1-} mineralization oxidizes over time, arsenic solubilizes into tailings pore water and precipitates initially as As^{3+} adsorbed onto ferrihydrite, therefore less primary arsenic will be found in older tailings samples.

In Figures 5.5-10a and 5.5-11c note that As^{1-} minerals were not identified using XANES analysis in most 2018 samples. In 2018, residual gersdorffite (As^{-1} mineral) was quantified using QEMSCAN analysis and used to compare results from XANES analysis. Comparison of XANES vs QEMSCAN results for identification of reduced arsenic is shown in Table 5.5-2. Residual As^{-1} was identified in 2023 samples which demonstrates two key factors in interpreting this data set: 1) the inherent variability of the tailings and 2) the expected larger amount of reduced arsenic present in the Cigar Lake tailings. Figure 5.5-11 compares primary arsenic mineralization identified in 2013, 2018 and 2023 in borehole TMF-01 with the corresponding arsenic pore water concentrations. (Note that because the deeper tailings samples could not be obtained from borehole TMF23-01, data from TMF23-03 borehole is also shown to provide a corollary of the behaviour of deeper samples.) Below ~400masl, although arsenic pore water concentrations of As^{3+} remain elevated, As^{-1} in the solids has been substantially depleted, indicating that arsenic pore water concentrations in the JEB/Sue tailings have likely peaked. Above ~420masl in the Cigar Lake tailings, As^{3+} and As^{5+} pore water concentrations remain low although significant reduced arsenic is noted in the solid phase. The controlled As pore water concentrations in the Cigar Lake tailings indicate the amount of ferric sulfate added to these tailings in the mill TPP has been sufficient to control the arsenic pore water source term. As As^{-1} is oxidized from the reduced phases in the solids to the soluble As^{3+} phase, it is quickly absorbed into secondary minerals composed of ferric iron already present in the tailings. The abundance of ferric iron secondary minerals in the Cigar Lake tailings act as an effective solubility control on arsenic pore water concentrations compared to the older JEB/Sue tailings (below ~400masl) which has limited amount of ferric iron secondary minerals. The unleached reduced arsenic minerals are accounted for in the tailings preparation process through the addition of ferric iron using a ferric calculator (Section 3.2.4). The geochemical model (Equation 5.5-4) demonstrates that this preparation method provides sufficient oxidative potential to fully oxidize gersdorffite to a geochemically stable mineral endpoint (i.e. scorodite).

Figure 5.5-11a, b, c and d: As Pore Water Speciation and Associated Primary Arsenic Mineralization in A)TMF23-01 B)TMF23-03 C)TMF18-01 and D)TMF13-01

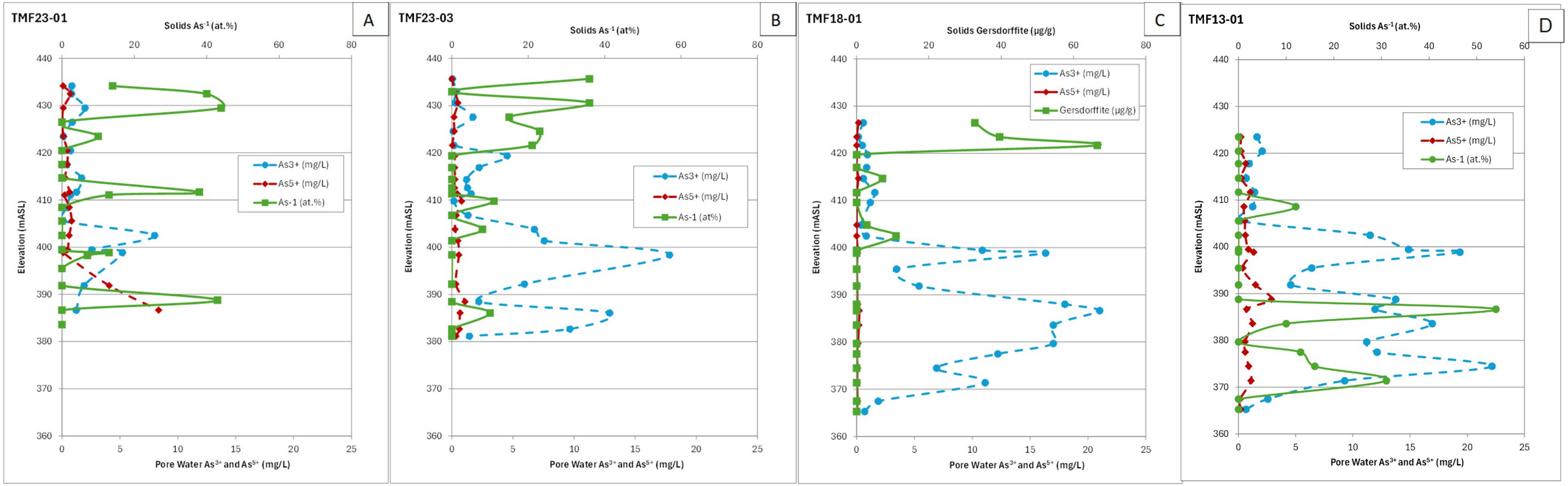


Table 5.5-2: Comparison of the identification of reduced arsenic in the tailings solids using various analytical techniques.

Borehole	TMF18-01 (11 samples, Cigar Lake and JEB/Sue)	TMF18-06 (5 Samples, all Cigar Lake)	TMF23-01	TMF23-06
ICP-OES Average (total As) µg/g	2329.7	2230	21 Samples 5 Cigar Lake: **5378** 16 JEB/Sue: **1092.6**	17 Samples 6 Cigar Lake: **2675.3** 11 JEB/Sue: **7377.5**
µXRD Gersdorffite Average Rel. Wt. % of total sample	0	0.06	21 Samples 5 Cigar Lake: **0.9** 16 JEB/Sue: **0.031**	17 Samples 6 Cigar Lake: **0.9** 11 JEB/Sue: **0.1**
QEMSCAN Gersdorffite Average Rel. Wt.% of total sample	0.022	0.27	21 Samples 5 Cigar Lake: **1.43** 16 JEB/Sue: **0.09**	14 Samples 5 Cigar Lake: **0.39** 9 JEB/Sue: **0.1**
XANES Rel. % of total Arsenic Average (As^{-1} ug/g)	0	13	21 Samples 5 Cigar Lake: **21.6** 16 JEB/Sue: **7.13**	17 Samples 6 Cigar Lake: **24.5** 11 JEB/Sue: **0**

As^{3+}: XANES Results

The deeper tailings of the TMF-01 borehole (i.e below 400 mASL), principally composed of the JEB and Sue C tailings, provide the best opportunity to observe the arsenic aging process as it occurs when there is not sufficient ferric iron present to immediately remove As^{3+} from tailings pore water. As^{3+} can be observed to gradually increase over time in both the tailings pore water (Figure 5.5-9) and solids (Figure 5.5-10b) in this borehole. The largest increase in relative percentage of As^{3+} in the tailings solids appears to have occurred from 2008 to 2013, with a smaller increase occurring from 2013 to 2018. In 2023, although the six deepest samples were not obtained, no increase in As^{3+} was observed in the solid samples taken at elevations below 400 mASL. 2023 is the second sampling campaign that has shown a slowing trend in As^{3+} increases which suggests that the oxidation of arsenic from As^{1-} to an adsorbed intermediate As^{3+} phase is still occurring, but at a slower rate as the tailings move towards an equilibrium condition. The lack of increase in As^{3+} in the solids is consistent with the smaller percentage of reduced arsenic (As^{-1}) below 400masl. The bulk of primary As^{-1}, initially present when the tailings were placed in the TMF, appears to have been oxidized. In the future, the relative percent of As^{3+} is expected to decline as As^{3+} continues to oxidize to As^{5+} (equation 5.5-2) with little to no replenishment. It is also noted in Figure 5.5-11 that in 2023 there is a decrease in the As^{3+} in the pore water samples analyzed compared 2018. Decreasing pore water arsenic concentrations are a supportive indication that the oxidation of As^{-1} to As^{3+} is decreasing and the secondary oxidation of As^{3+} to As^{5+} has begun to be the dominant reaction in the system, sequestering As^{3+} out of the pore water and into the solid phase. It is expected that these reactions will occur more quickly in borehole TMF-01 as it is located at the centre of the TMF and during early operations tailings were deposited at that location from the tremi barge. TMF-01 therefore represents the approximate centre of the cone of deposition and contains the most coarse-grained tailings with more pore space for contact with pore water to allow reactions to occur. The observations in the TMF-01 borehole are all consistent with the geochemical model.

At higher elevations (above 400 mASL), where lessons learned were applied after processing Sue C tailings, only a small increase in the relative percentage of As^{3+} in the tailings solids was noted between 2008 and 2013 (Figure 5.5-10b). In 2008, As^{3+} was not reported in the higher elevation (above 400 mASL) but was later observed in 2013 and 2018 which is expected as the minor amounts of As^{-1} in those tailings oxidize over time. In 2023, As^{3+} concentrations above 400 mASL have slightly increased. The observed increase of As^{3+} above 400 mASL is not generally mirrored by high As^{3+} concentrations in the pore water, which indicates that As^{3+} is being removed from solution as it is oxidized from As^{-1} because of the presence of sufficient ferric iron.

In the Cigar Lake tailings above ~420mASL all three solid forms of arsenic are found (Figure 5.5-10), but pore water arsenic values are low (Figure 5.5-11a and b). The introduction of the ferric calculator in the TPP to account for unleached arsenic and consequently control the pore water arsenic source term for the Cigar Lake tailings is successful and reactions are principally occurring as an efficient process of oxidative transition between solid phases without releasing significant arsenic into the liquid phase.

***As^{5+}*: XANES Results**

XANES data shows that the relative percentage of As^{5+} in the tailings solids has been stable at lower elevations in the tailings over time. (Figure 5.5-10c). Below 400 mASL the stability of the relative percentage of As^{5+} indicates that the majority of arsenic reactivity has been captured through the oxidation of As^{-1} to As^{3+}. As As^{-1} has been largely depleted, the reaction step from As^{3+} to As^{5+} (equation 5.5-2) is now expected to become more dominant in the system. The oxidation step from As^{3+} to As^{5+} is known to occur slowly and will likely be observed gradually over many years. It is expected that the oxidation to As^{5+} will be best observed in the JEB tailings due to their age. In 2023, only two samples, from the bottom of borehole TMF23-04, which are likely to represent the JEB tailings were obtained (Table 5.5-3). As discussed in section 5.6.3.3 new methods are being investigated to obtain more deeper samples in 2028. The oldest tailings samples from the JEB tailings in 2023 were found to have no As^{-1} and be composed of greater than 70% As^{+5} suggesting that they have fully completed the first step of oxidation.

Table 5.5-3: XANES results from JEB tailings in 2023

Year:	TMF23-04			
Sample	**Elevation**	**As^{-1} (at.%)**	**As^{3+} (at.%)**	**As^{5+} (at.%)**
SA20	377.8	0	28	72
SA21	373.61	0	26	74

In the newer tailings (above 400 mASL), the relative percentage of As^{5+} declines slightly in the solids from 2018 to 2023 As discussed for As^{3+}, there are likely two mechanisms at work:

1) As^{-1} continues oxidizing to As^{3+}, increasing the relative percentage of As^{3+} in the system and consequently causing the relative percentage of As^{5+} to decrease. In this scenario, the change in the actual concentration of As^{5+} may be minimal.

2) As a result of the disequilibrium conditions of the newer placed tailings (particularly the Cigar Lake tailings), some portion of As^{5+} in the solids may be opportunistically used as a mild oxidizing agent for reduced minerals such as pyrite (which have persisted through the mill process and been deposited in the tailings). While geochemical modelling has identified this possibility, this is the first potential evidence that this process is occurring.

Transitory disequilibrium conditions can be more clearly observed as the TMF data set grows over time. The collection of additional data in 2023 has allowed for a better opportunity to examine these conditions, which are important for validating the geochemical model.

Summary of Solids Mineralogy

Monitoring of older tailings demonstrates that primary reduced arsenic (As^{-1}) is decreasing with time, validating geochemical model predictions that this form of arsenic will evolve into As^{3+} adsorbed on ferrihydrite over time. Analytical methods have proven to be capable of capturing As^{-1} in tailings, which is primarily residual gersdorffite. Cigar Lake tailings contain generally higher concentrations of As^{-1}, which is expected given the mineralogy and recent deposition.

The observations of As^{3+} in the TMF further validate the arsenic geochemical model. Increases in the relative percentage of As^{3+} are observed in the lower JEB/Sue tailings (Figure 5.5-10b), as expected, due to their age and the oxidation of reduced arsenic (As^{-1}) minerals over time. The oldest tailings will show a gradual reduction in As^{3+} as time passes, supporting the theory that As^{3+} will continue to oxidize to As^{5+} (i.e. scorodite).

In tailings below 400 mASL, most of the arsenic evolution to date has been dominated by the initial oxidation step from As^{1-} to As^{3+}. Although the second oxidation step of (i.e. As^{3+} to As^{5+}) has likely been occurring concurrently to a minor extent, there are signs that the tailings are moving into a second phase where the second oxidation step will become more dominant. The second oxidation step is predicted to occur slowly and therefore is most likely to be observed in the oldest tailings (i.e. JEB tailings). In the Sue tailings above 400 mASL, the arsenic appears mainly as the As^{5+} species. Due to improvements in mill processes the oxidation of As^{1-} to As^{5+} occurred largely in the mill, reducing the “rise and fall” pattern (i.e. the reaction step from As^{1-} to As^{3+}) for arsenic that was observed in older tailings. Above ~420 mASL, in the Cigar Lake tailings, as expected there is a relatively lower abundance of As^{5+} as more As^{-1} is deposited in the tailings. This area of the tailings is understood to be most active in geochemical disequilibrium, and so the low pore water arsenic values are supportive that managing the relatively higher abundance of solid As^{-1} through the addition of sufficient ferric iron is an effective arsenic management strategy.

5.5.1.4 Overall Model Validation

Case Study: TMF23-01

Borehole TMF-01 generally intersects the oldest tailings in the TMF and has been sampled and evaluated at consistent elevations over several campaigns. This borehole provides the best opportunity to evaluate arsenic evolution over the life of the TMF to date. In 2023, as previously discussed, not all samples from the deepest location in borehole TME23-01 were obtained and for completeness, data from TMF23-03 and TMF23-04 are used for additional context.

In Figure 5.5-12a, the pore water concentrations for As^{3+} and As^{5+} are plotted with the sample elevation in TMF23-01. The relative amounts of reduced arsenic (As^{1-} and As^{3+}) in the tailings solids are also plotted with the sample elevation on the secondary axis.

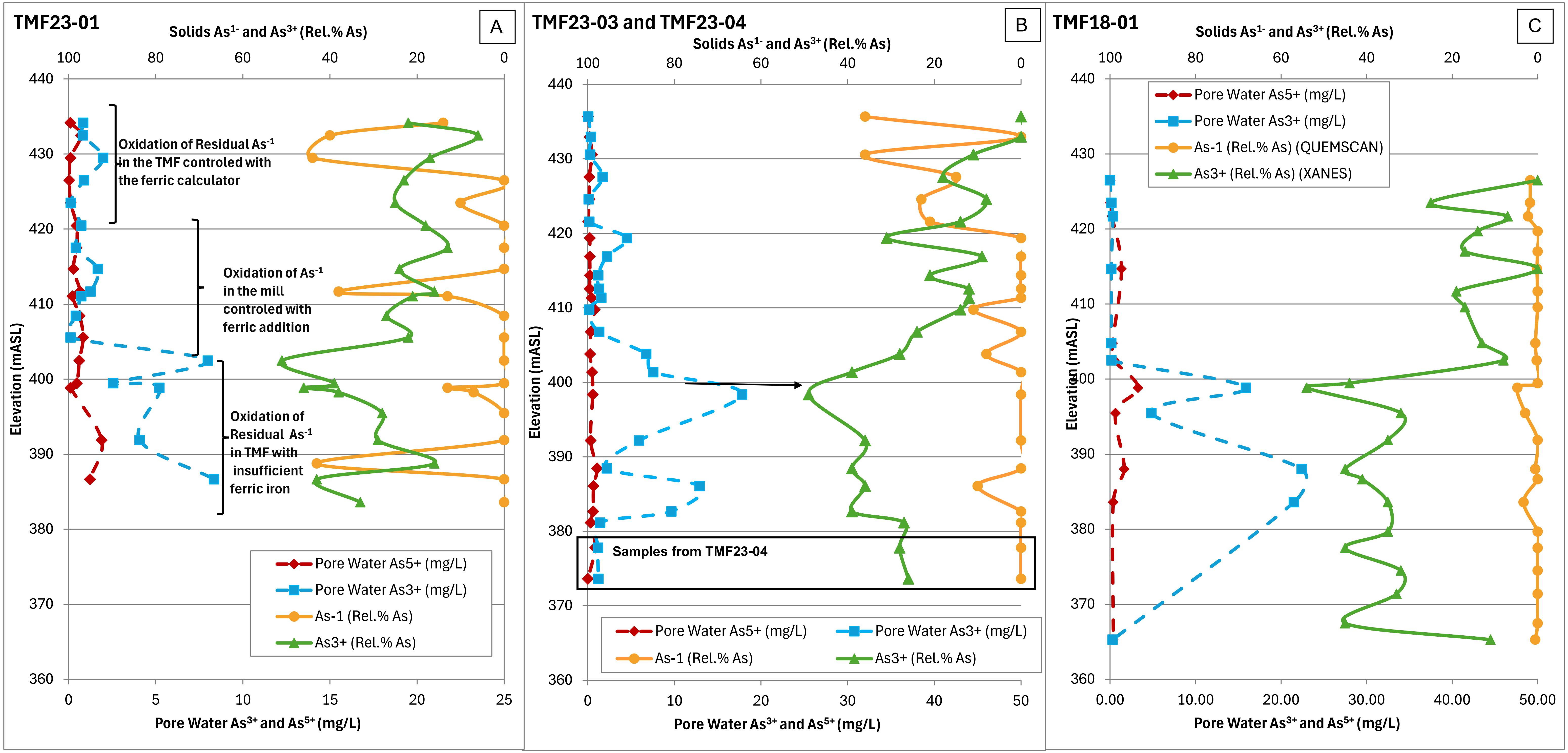
In addition to the observations of arsenic evolution in the sections above, two key observations in Figure 5.5-12a support the long-term geochemical model for arsenic control:

1) The pore water As^{5+} concentration remains steady in most samples at <1.5 mg/L. Therefore, the rise and fall in pore water arsenic concentration is entirely due to the presence of As^{3+}.

2) The increase of As^{3+} in the tailings pore water only occurs at locations where the relative amount of As^{1-} and/or As^{3+} in the solids is elevated (below approximately 400 mASL). Above 400 mASL, lessons learned from previous placed tailings performance were applied to the mill process. The following changes were made: 1) ferric iron was added directly to the leaching circuit; and 2) peroxide was added to the tailings preparation circuit. The changes have resulted in the majority of the As^{1-} being oxidized before tailings are discharged from the mill to the TMF, and the remaining arsenic appears mainly as As^{5+} species in the tailings solids in the upper elevations with notably less As^{3+}.

It is clear that pore water As^{3+} is only elevated where reduced As (As^{3+} and/or As^{1-}) makes up a higher percentage of the arsenic in the solids. This correlation shows that elevated pore water As^{3+} concentrations are due to the oxidation of residual amounts of primary reduced arsenic (As^{1-}) mineralization in the solids as they are converted to stable As^{5+} mineral forms. The 2023 findings are consistent with data collected from the same locations in 2018, indicating that major pore water arsenic trends have been captured and are not transitory phenomena (Figure 5.5-12).

Figure 5.5-12: As Speciation Data As^{3+} in the Pore Water vs in the Solids A) TMF23-01, B) TMF23-03 and TMF23-04 C) TMF18-01



Aging Test Predictions vs. In-Situ TMF Aging

Figure 5.5-13 provides a comparison of pore water arsenic concentrations over time for the following:

- SEPA (now known as CIME) aging tests conducted in 1997 (Langmuir et.al. 1999);
- TOVP aging tests conducted from 2006 -2009 (Appendix D, Section D, Subsection E); and
- actual TMF aging at approximately 370 mASL in TMF-01 tracked over time.

The specifics of each aging test, and how predictions compare to measured results are discussed further below.

SEPA (CIME) Aging Tests: The SEPA tests were pre-operational tests conducted on laboratory produced tailings. The samples were mechanically agitated continuously in reactor vessels and showed no rise and fall in pore water As concentration. The SEPA line in Figure 5.5-13 is not drawn from the data obtained from a single aging test but rather is a generalized line representing the results of many tests.

TOVP Aging Tests: The TOVP aging tests were static tests (i.e. no mixing) conducted on real tailings generated by the McClean Lake Operation (COGEMA 2001, p. 3-31). The TOVP aging test shown in this Figure coincided with the initial processing of Sue A ore and took place over three years (from 2006-2009). A pronounced rise and then fall to less than 2 mg/L occurred as the aging test progressed.

Actual TMF Aging in Borehole TMF-01: Typical aging of tailings solids in the TMF is represented by tracking TMF-01 over time at 370 mASL. A rise and fall in pore water As^{3+}concentration is observed. As indicated in Figure 5.5-13 with XANES data, As^{3+} concentrations in the pore water begin to decline once the As^{1-} content in the solids has been depleted. Figure 5.5-13 includes data up to 2013 for TMF-01. Data is not presented after 2013 due to a number of factors that have reduced the ability to track pore water evolution at one specific location: 1) continued consolidation of the tailings, 2) normal variability between samples over each sampling campaign, and 3) continued pumping of water from the base drain. Currently, for lower depths in particular, general trends are followed using pore water averages. The Sue C tailings presents the best opportunity to evaluate arsenic evolution, due to its residual As^{-1} content upon placement. The 3 m intervals that intersect Sue C tailings are included in Figure 5.5-14. An overall rising trend is noted, but in some locations a decreasing trend is observed to develop. On average, pore water arsenic concentrations in the Sue C tailings have increased and generally plateaued.

It is probable that equations 5.5-1 to 5.5-4 are all occurring in each of the three aging investigations depicted in Figure 5.5-13 and in the placed tailings as presented in Figure 5.5-14; However, pore water arsenic concentration observations are different between the lab studies and placed tailings due to the degrees of mixing and temperature effects:

- **SEPA Aging Tests:** The continuous agitation of the SEPA tests caused the arsenic oxidation reactions to occur much more quickly. Accumulation of As^{3+} in the pore water, if it occurs, is likely much smaller in magnitude and has not been captured by the sampling schedule.

- **TOVP Aging Tests / Actual Aging:** The static TOVP aging tests and in-situ samples are reaction rate limited by a lack of mixing. Therefore, reactions have occurred at a slower rate controlled by molecular diffusion. The initial oxidation step is evident through the temporary rise and fall of pore water As^{3+} concentrations, and complete oxidation appears to require about 400 days under laboratory conditions. Due to greater consolidation and lower temperatures in the TMF, the effective molecular diffusion rate is lower for actual placed tailings and reactions occur even more slowly. Within the oldest Sue C tailings, the completion of oxidation reactions that create a temporal rise and fall in pore water As^{3+} concentration appear to require at least 7000 days (Figure 5.5-14).

The observations of pore water arsenic concentration in TOVP studies to date support the geochemical model of arsenic mineral evolution in the tailings solids.

Figure 5.5-13: Comparison of As Concentrations Observed in SEPA Aging, TOVP Aging, and Actual Aging in TMF to 2013

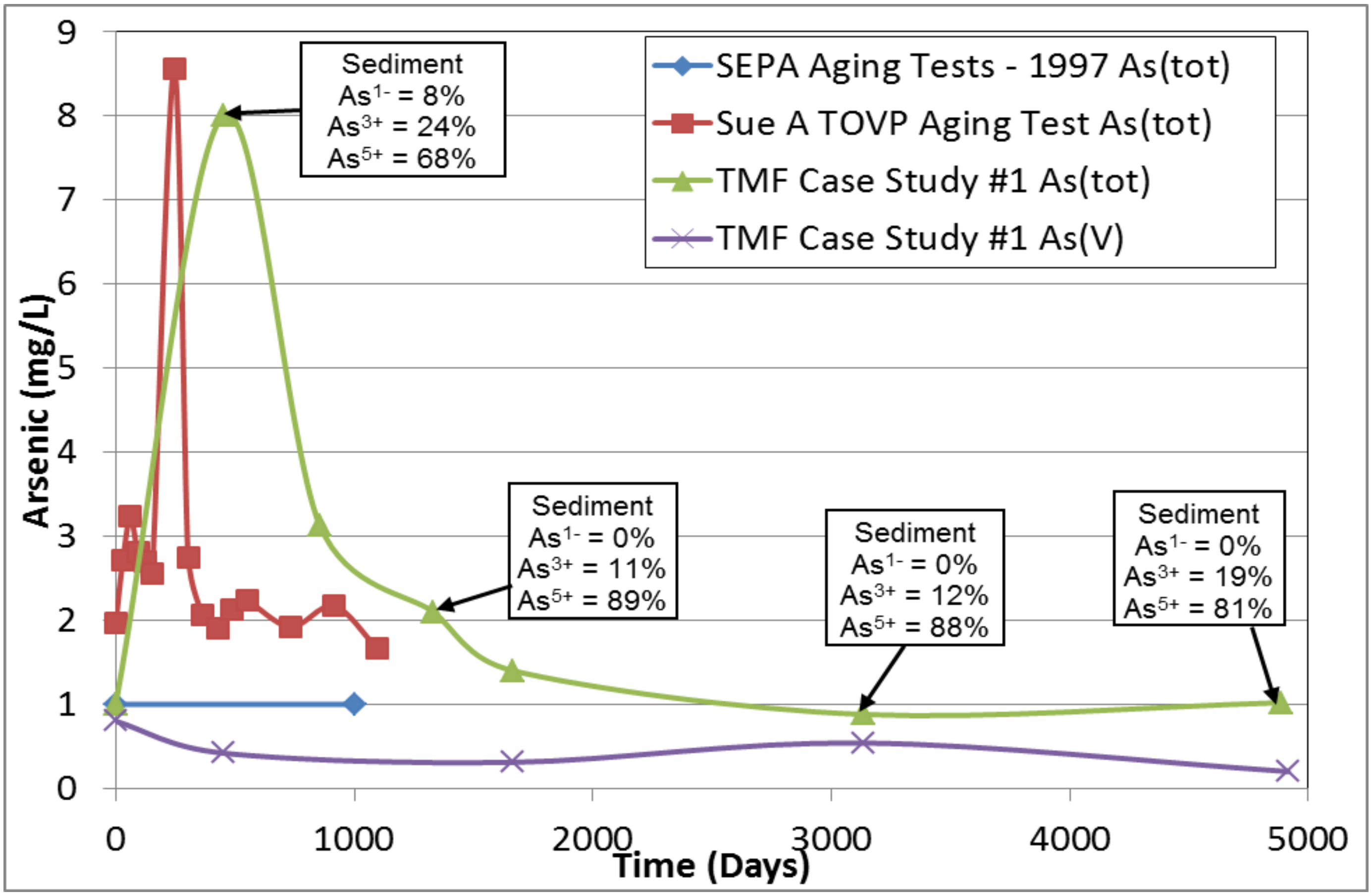
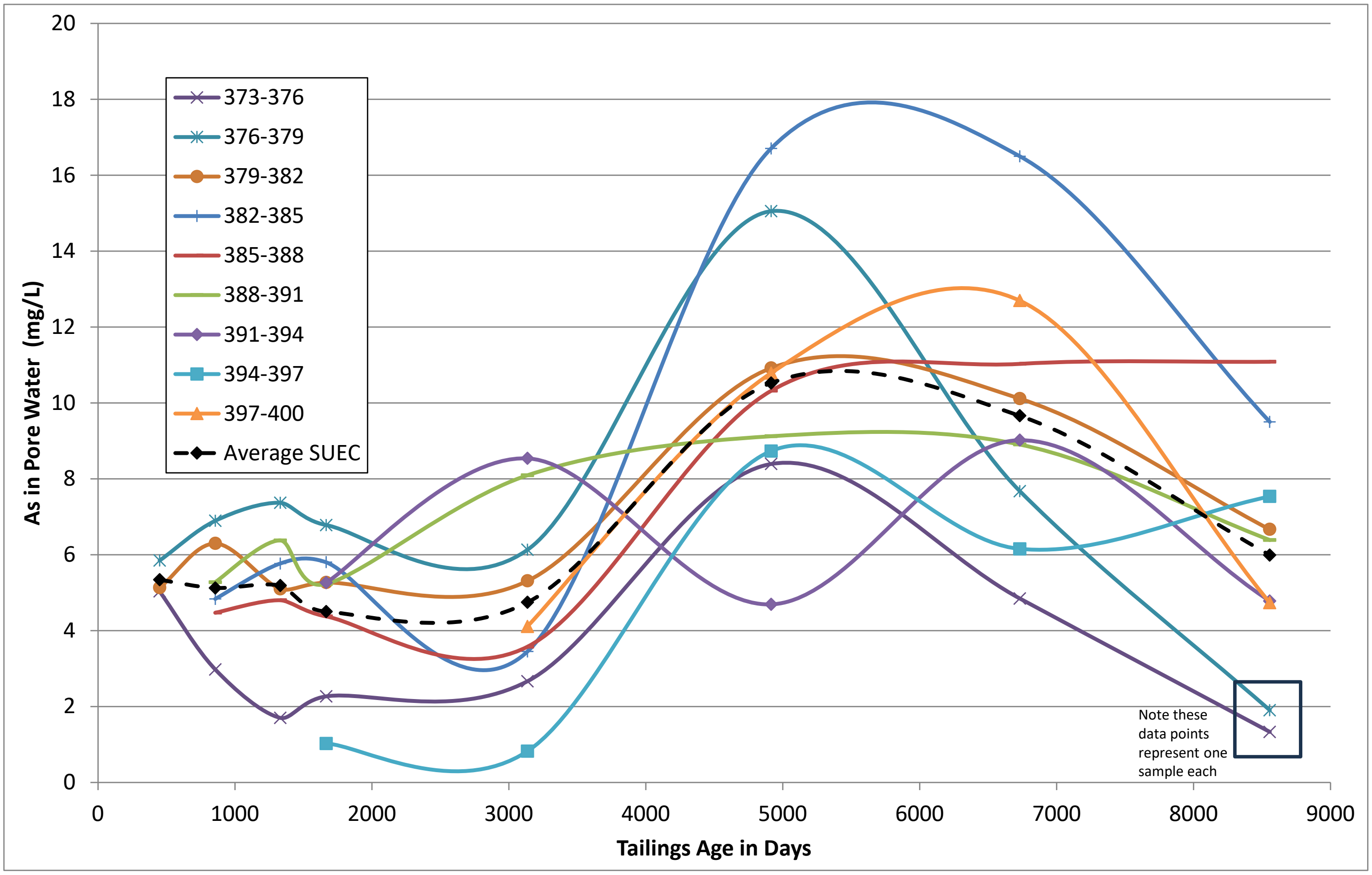


Figure 5.5-14: Observation of the rise and fall in arsenic pore water concentrations by 3m interval of Sue C placed tailings.



Identification of Scorodite

XANES analyses (described in Section 5.3.2.2) were conducted at the CLS in 2023 on samples from boreholes TMF23-01, TMF23-03, TMF23-06 and TMF23-08, similar to work done in 2013 and 2018. XANES provides clearer evidence of the evolution of arsenic in the tailings through the identification of mineral species, and an analysis from past TOVP sampling has been published in a peer-reviewed article (Blanchard et.al. 2017). Relative amounts of arsenic mineralogy in the tailings solids were estimated using XANES spectroscopy and compared with the corresponding pore water concentrations of arsenic.

Figure 5.5-15a and b demonstrates how scorodite is related to arsenic concentrations in the pore water. In 2013, 2018 and 2023 data, borehole TMF-06 clearly shows that arsenic is the highest in the pore water when there is little or no scorodite present – an observation that is made in all three boreholes. In 2023, at lower elevations where scorodite has increased slightly, it is noted that pore water arsenic concentrations have declined. It has been well demonstrated over successive sampling campaigns that the bulk of the arsenic in the pore water is composed of the As^{3+} species (Table 5.5-3), as explained in the model. Pore water samples for arsenic speciation were collected from each borehole during several TOVP campaigns. In 2018, arsenic speciation samples were lost due to a technological failure at the primary testing facility. In response, secondary samples were collected from selected TMF locations. In 2023, learning from the 2018 experience, as many samples as possible were duplicated and sent do to different labs (the McClean Lake Chemistry Lab and ALS Analytical). When considering the resulting 2023 arsenic speciation results, in each case where a duplicate sample was taken the higher result is used to remain conservative. The results are presented in Table 5.5-4 and clearly demonstrate that As^{3+} is the dominant dissolved species when total pore water arsenic concentration is high.

Figure 5.5-15: **Scorodite with total As in solids and As^{3+} and As^{5+} in the pore water A) TMF23-06 B) TMF18-06 C) TMF13-06**

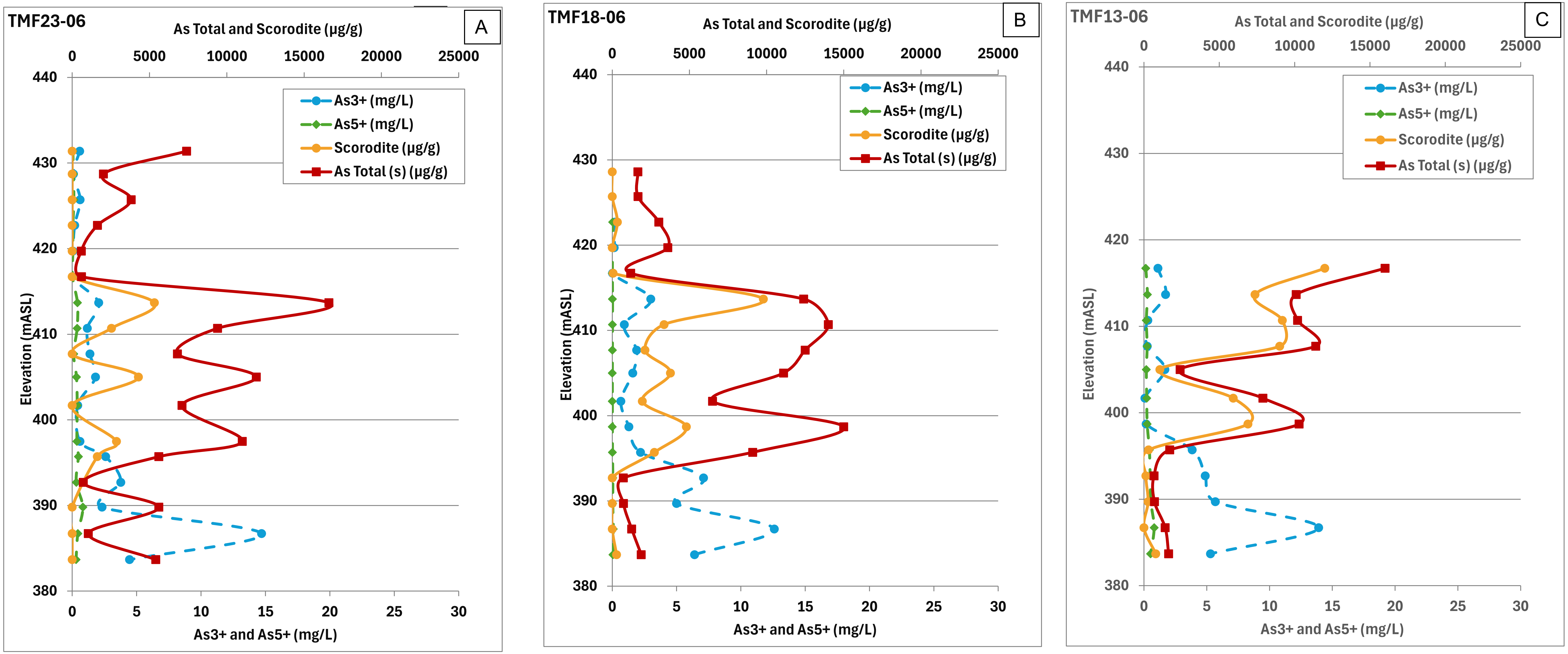


Table 5.5-4: Comparison of pore water arsenic speciation results by TOVP sampling campaign

Sampling Campaign	Total Samples	Average As $^{3+}$ (mg/L)	Average As $^{5+}$ (mg/L)
2002	10	3.15	0.94
2003	6	2.40	0.80
2004	38	3.23	0.86
2008	65	2.48	1.21
2013	105	5.10	0.56
2018	24	5.02	0.59
2023	140	2.42	0.43

In addition to crystalline phases such as scorodite, The XANES technique is able to identify amorphous secondary mineral phases; Therefore, XANES allows for a better characterization of mineral evolution of arsenic occurring in the tailings.

The results of XANES linear combination fitting analysis identify the presence of amorphous ferric arsenate (Am. $FeAsO_4$), as an intermediate As^{5+} mineral phase, before crystallization to a final mineral phase (scorodite)

In 2023 Am. $FeAsO_4$ comprised a significant proportion of the arsenic in the tailings (58%) similar to 2018 (64%) which was a greater proportion than in 2013 (16.5%). Although the amount of Am. $FeAsO_4$ has changed year by year the overall proportion of As^{5+} mineral phases is stable (2013: 64%; 2018: 65%; 2023: 66%).

It is generally challenging to distinguish between ferric-based arsenate species due to the similarities in the XANES spectral line shapes. Am. $FeAsO_4$ will gradually crystallize over time to scorodite ($FeAsO_4 \cdot 2H_2O$) in a solid solution; therefore, its identification is a precursor to scorodite formation. Identifying the exact point where molecules of Am. $FeAsO_4$ may be categorized as scorodite is subjective, as their spectral line shapes are very similar (Figure 5.5-17).

Between 2014 and 2018, the beamline at the Canadian Light Source underwent substantial improvements and optimizations. The improvements led to increased resolution in XANES spectral line shapes and therefore a better distinction between Am. $FeAsO_4$ and scorodite. As described in Section 5.5.1.1, under TMF pH conditions, scorodite will always be associated with some amount of AsO_4^{3-} adsorbed on ferrihydrite and Am. $FeAsO_4$. It is the synergistic assemblage of these three minerals, in which scorodite is the principal component at equilibrium, that is controlling the As^{5+} pore water concentrations to <1.5 mg/L.

Figure 5.5-16: Example Data of As K-edge XANES showing the similar line shapes of Am. $FeAsO_4$ (Ferric Arsenate) and Scorodite

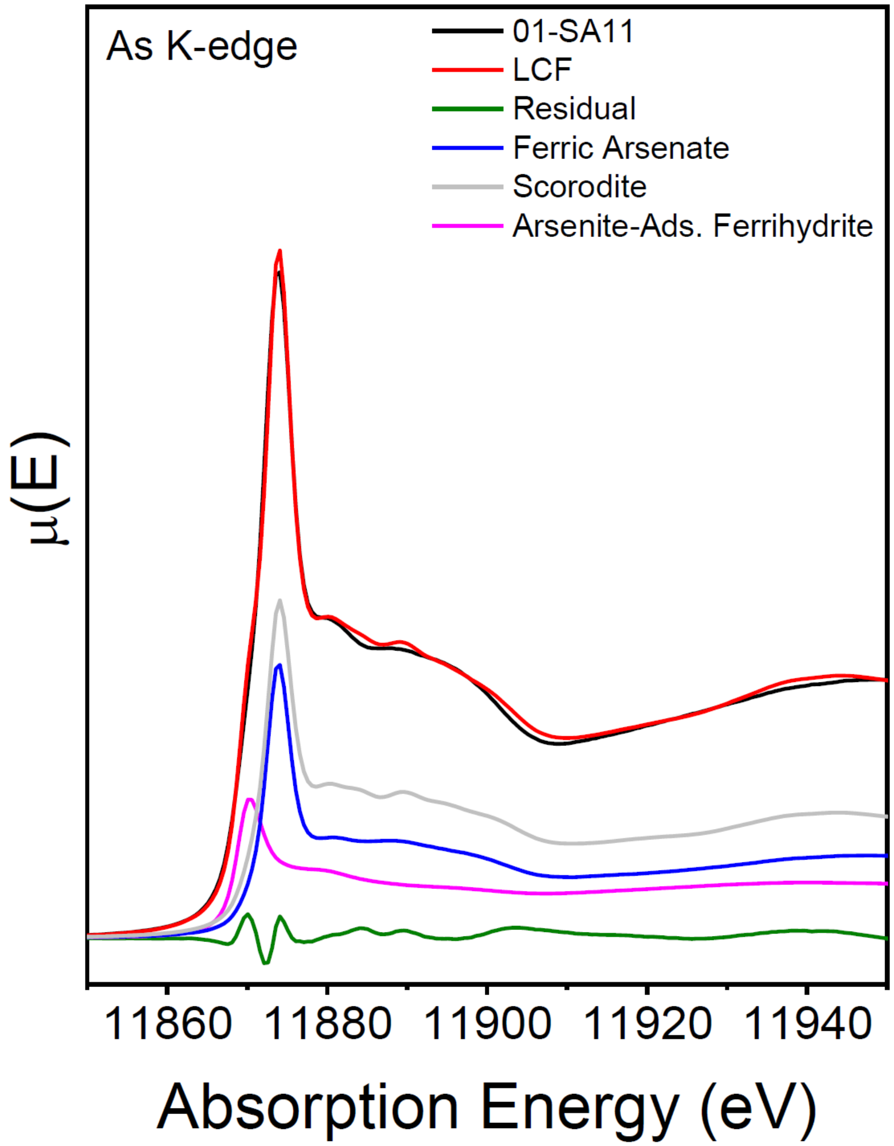


Figure 5.5-17 presents a combination of As^{5+} minerals (Am. $FeAsO_4$ and scorodite) in the tailings solids and As^{5+} concentration in the tailings pore water, plotted against the overall solids arsenic content in each sample. Overall, As^{5+} concentrations in the pore water remain stable and independent of the arsenic concentrations in the tailings solids (plotted on the x-axis). It is clear that, in areas where there are increases of As^{5+} concentrations in the pore water, a relatively lower % of As^{5+} mineral phases have formed in the tailings solids. As^{5+} in these areas is in flux – it has recently oxidized from As^{3+} but has yet to be adsorbed out of solution onto ferrihydrite to begin the process of crystallizing into scorodite. At locations with greater overall arsenic concentrations in the tailings solids, there is correspondingly greater As^{5+} in the tailings solids and the pore

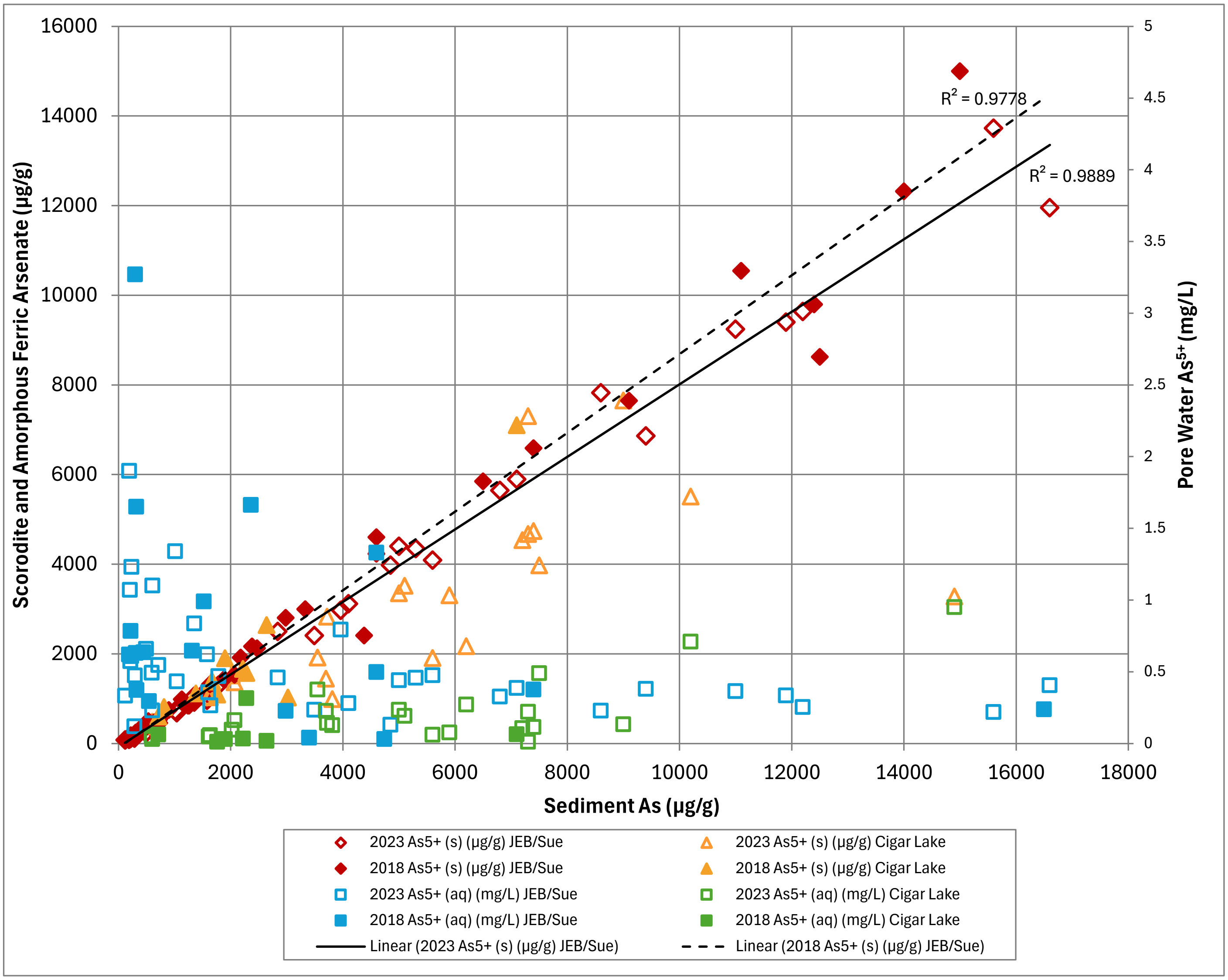
water As^{5+} concentration is controlled to below 0.5 mg/L. The line of best fit through the 2018 As^{5+} tailings solids data for the JEB/Sue tailings in Figure 5.5-18 shows a strong correlation (R^2=98%) to total arsenic in tailings solids. In 2023, total As^{5+} in JEB/Sue tailings solids also correlates strongly (R^2=99%) to total arsenic in the tailings solids. The correlations exclude the Cigar Lake tailings data as they are newly placed and are in a state of disequilibrium. Overtime it is expected that Cigar Lake locations will evolve towards the same linear correlation as they become more fully oxidized.

Overall, the well-defined correlation between total arsenic and As^{5+} in the solids, contrasted with the stable controlled As^{5+} pore water values, allows for the following conclusions:

- The amount of arsenic in the tailings system has no effect on the essential outcome of As^{5+} as the final mineralized endpoint for all arsenic.
- The process of tailings preparation is successful in controlling tailings pore water arsenic, regardless of the overall amount of arsenic present.
- The amount of arsenic in the tailings system does not influence the pore water As^{5+} concentrations, which will govern arsenic pore water concentrations at equilibrium over the long-term (consistent with the conceptual geochemical model).

The data was also reviewed in the context of ore source. The correlations presented in Figure 5.5-17 correspond well with what is observed in the tailings from the depth intervals that represent the ore sources processed to date (Figure 5.5-8). Data for the Cigar Lake samples are highlighted on the Figures (Figure 5.5-15, -16 and -18) and overall, the data trends well with that of JEB/Sue tailings above 400 mASL with controlled arsenic pore water values. The similarity indicates that the Cigar Lake tailings will continue, as expected, to evolve consistently with other JEB/Sue tailings placed after 400 mASL. The observations further support that the lessons learned applied after the milling of Sue C are successfully controlling arsenic in the placed tailings.

Figure 5.5-17: Solid As^{5+} (Scorodite and Amorphous Ferric Arsenate) (ug/g) and dissolved As^{5+} (mg/L) by total As in solids (ug/g) for 2023 and 2018



Identification of Intermediate As^{3+} Solid Phases

An intermediate (transitional) stage amorphous mineral phase formed with As^{3+} has also been identified using XANES and has been used to refine the geochemical model over time. Overall, the average relative % of total sold arsenic composed of As^{3+} in the samples analyzed increased slightly from 18% in 2013 to 22% in 2018 and then to 24% in 2023. The solid phase of As^{3+} is difficult to identify, as it composes a smaller percentage of the total arsenic in the tailings solids and is a transitory phase persisting only until As^{3+} is oxidized to As^{5+}.

The linear combination fitting (LCF) first performed on the 2013 XANES data found that arsenite (As^{3+}) adsorbed on ferrihydrite (As ads. HFO) provided a good fit for the As^{3+} data; however, this analysis was not definitive. To better understand the environment of adsorbed As^{3+} in the tailings solids, a series of geochemical models were prepared and presented in the 2015 Tailings Management TID to demonstrate the extent of arsenite surface complexation on ferrihydrite (AREVA 2015, Section 5.4,). The models of adsorbed As^{3+} phases in the tailings solids support the arsenic geochemical model. The models demonstrate that solid As^{3+} phases identified in the XANES analysis are adsorbed phases, which are unstable under TMF conditions. The adsorbed As^{3+} phases will eventually oxidize to As^{5+} under the oxidizing geochemical environment in the TMF.

Figure 5.5-18 shows a scenario similar to that for As^{5+} solids in Figure 5.5-16 but considers arsenite adsorbed on ferrihydrite and As^{3+} in the pore water plotted against total arsenic in the solid phase. The correlation between arsenite adsorbed on ferrihydrite and overall arsenic solids concentration is not as strong (2018: r^2=41%; 2023: r^2=59%) as was found for As^{5+} in the tailings solids (Figure 5.5-16). The lower correlation is expected for an intermediate stage where the constituents are known to be in flux. The same general system trend is present in pore water concentrations of As^{3+} and As^{5+}. When there is a higher arsenic in the solid phase, aqueous As^{3+} is well controlled below approximately 2 mg/L. Higher values of aqueous As^{3+} are only observed in areas with low amounts of solid arsenic. These observations suggest that:

- For JEB/Sue ores with a higher arsenic content, the majority of the oxidation of arsenic (As^{-1} to As^{5+}) occurred in the mill and so less intermediate As^{3+} is produced once the tailings are placed.

- For ores with lower, but more recalcitrant, amounts of As^{-1} (i.e. Sue C), arsenic oxidation was less effective in the mill. Oxidation is ongoing in the placed tailings, resulting in increases of As^{3+} in the pore water. As^{3+} in the pore water can adsorb onto ferrihydrite in the tailings solids or further oxidize to As^{5+}.

- For Cigar Lake ores with higher arsenic content sufficient ferric iron has been added to the tailings to rapidly remove As^{3+} aqueous phases from solution, through the adsorption of As^{3+} to HFO.

The above observations are further supported by Figure 5.4-19, which illustrates the relationship between As^{3+} in solution with the primary arsenic mineralization (gersdorffite) identified using XANES. The more elevated aqueous As^{3+} values are associated with tailings containing relatively low total arsenic in the solids, where the oxidation of small amounts of primary arsenic mineralization created relatively higher source terms due to a lack of sufficient secondary ferric iron mineral phases.

Figure 5.5-18: Arsenite ads. on HFO (ug/g), As^{3+} (mg/L) vs Solids As (ug/g) 2018 and 2024

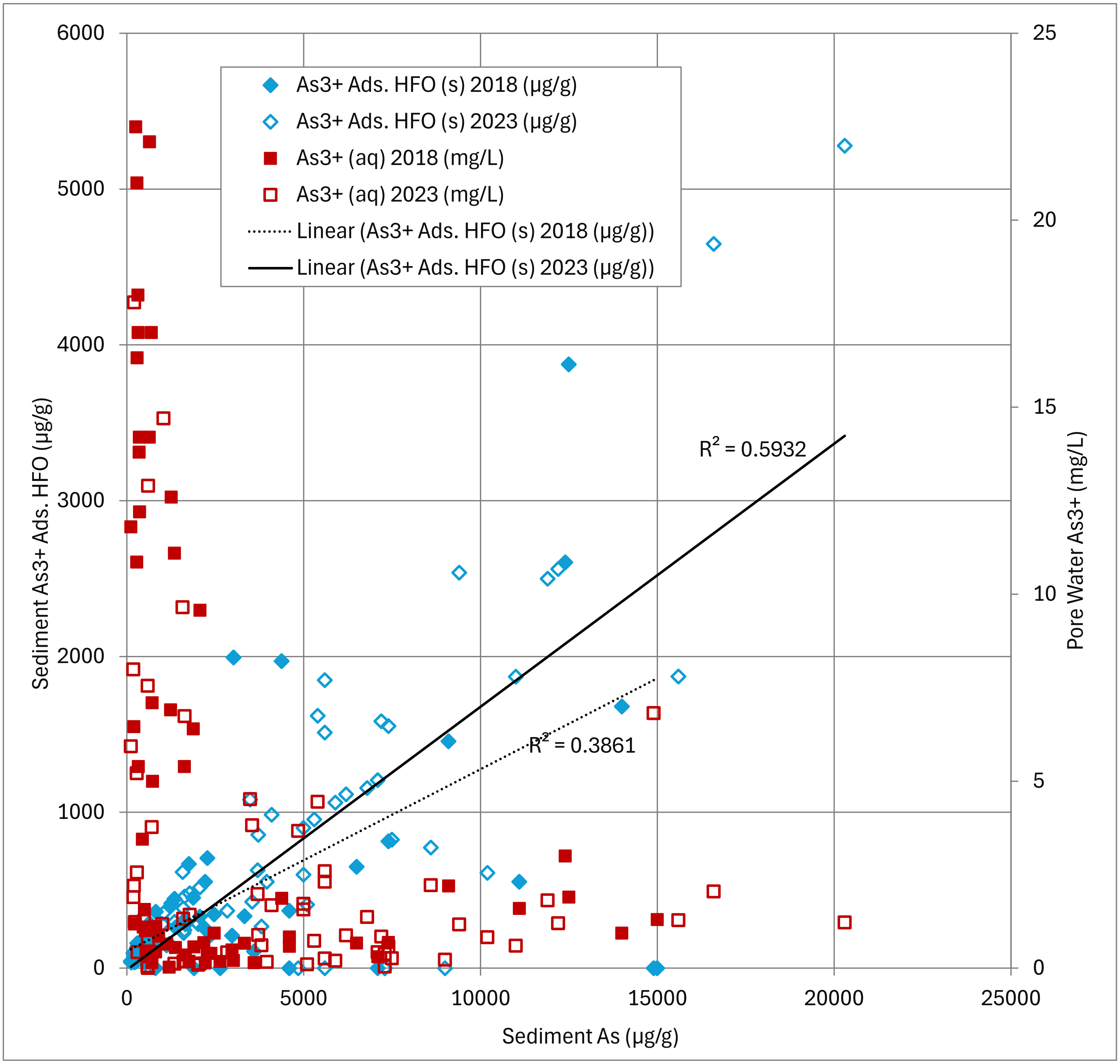


Figure 5.5-19: Gersdorffite (ug/g), Pore water As^{3+} (mg/L) vs Solids As (ug/g) in 2023

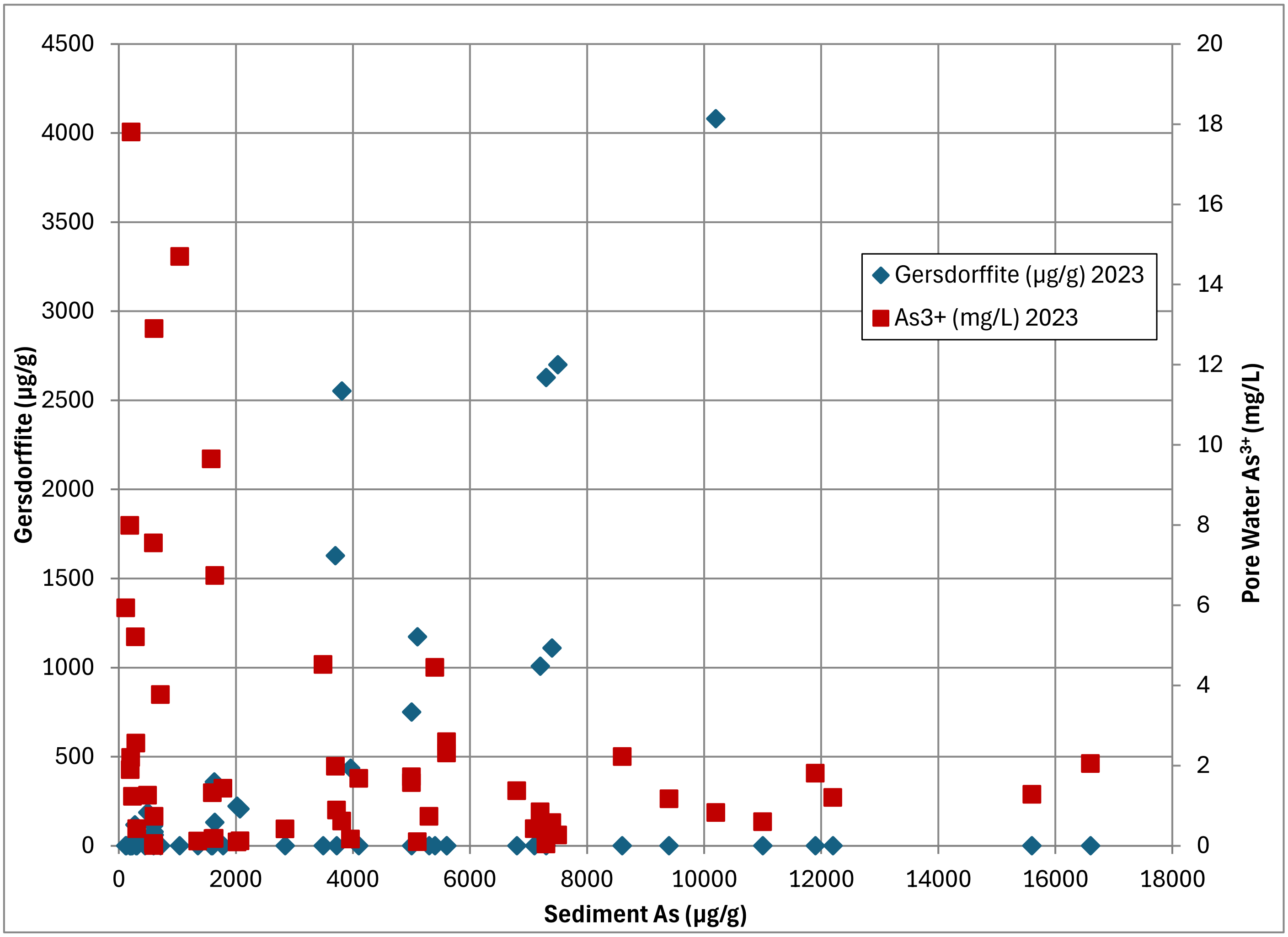
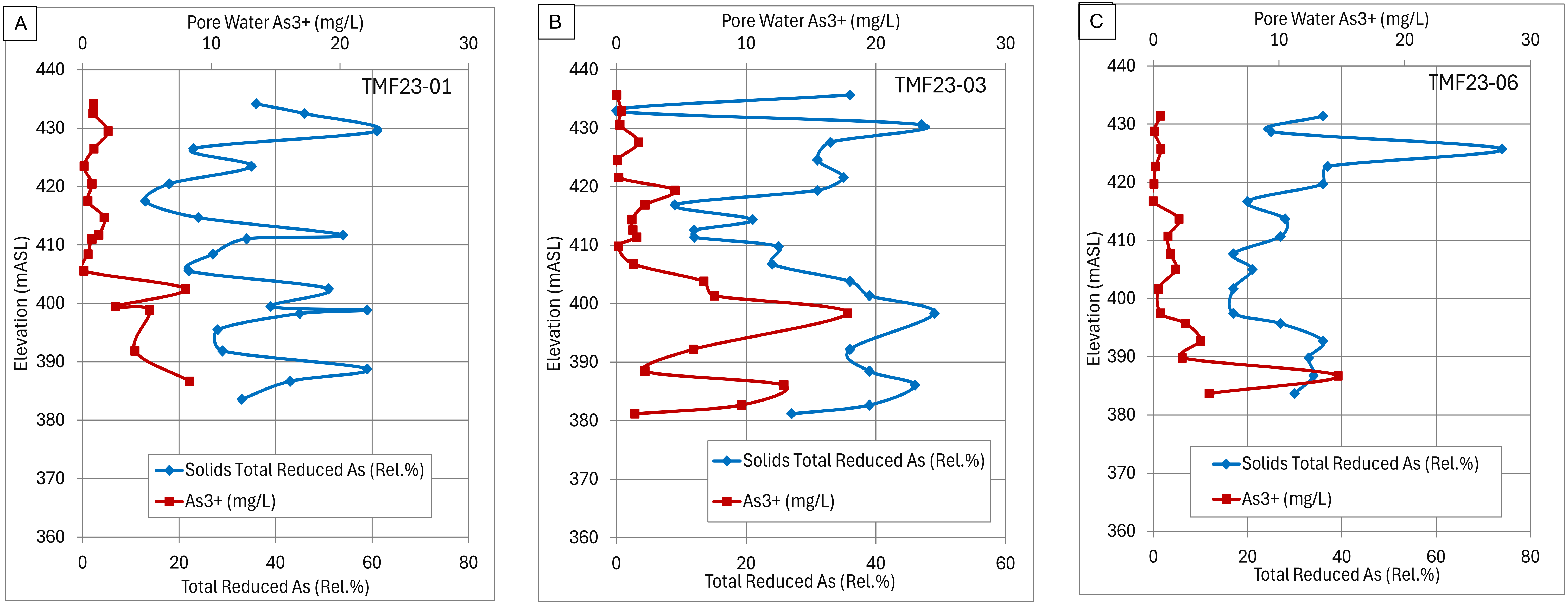


Figure 5.5-20abc shows the close relationship between the sum of the two more reduced arsenic phases (As^{-1} and As^{3+}) in the tailings solids, and As^{3+} in the associated pore water. In each case below ~400mASL, where there is a greater percentage of reduced arsenic minerals in the solids, there is an accompanying increase of As^{3+} in the pore water.

The strong correlation between arsenic in the pore water and reduced arsenic in the tailings solids demonstrates that elevated As^{3+} values are controlled by the progressive oxidation occurring in the tailings solids. Therefore, as the oxidation reactions in the solids approach equilibrium, the As^{-1} is consumed and the amount of associated As^{3+} in the pore water will see an accompanying decline. In the long-term, the final arsenic in the tailings pore water will be As^{5+} with concentrations controlled by the solubility of scorodite.

Figure 5.5-20: Boreholes A) TMF23-01, B) TMF23-03 and C) TMF23-06, Elevation vs As^{3+} (mg/L) and Total Reduced As



Conclusions – Arsenic Geochemical Model

The following is a summary of the conclusions from the overall arsenic model validation:

- While As^{3+} values in tailings pore water can at times be elevated, it is clear that As^{5+} is the dominant species in the solids (Figure 5.5-21).
- The relative mineral abundance by borehole shows that amorphous ferric arsenate (Am. $FeAsO_4$) is the dominant As^{5+} mineral both by borehole and by tailings ore source (Figure 5.5-22).
- Overall, As^{3+} in the tailings solids (arsenite adsorbed onto ferrihydrite) does not exceed 27 wt % of arsenic in any of the boreholes. The observations are consistent with the theory that As^{3+} is not accumulating but rather being oxidized to As^{5+} minerals over time.
- Scorodite, or precursors of scorodite, are identified in samples collected from boreholes in the TMF. There is some minor variation in the percentage of scorodite between central boreholes (i.e. TMF23-01 and TMF23-03) and peripheral boreholes (i.e. TMF23-06). The variation is thought to be the result of coarser grain size distribution in the more central boreholes in the JEB/Sue tailings (Section 5.6), and the larger quantity of reduced arsenic mineralization associated with coarse particles. Cigar Lake tailings geotechnical properties differ from those of the JEB/Sue tailings, due to 1) a change in deposition method in 2018, and 2) the overall clay rich nature of Cigar Lake tailings. As more Cigar Lake tailings are deposited it is expected that the ore source, rather than the deposition location will have a greater influence over differences in solid arsenic speciation.
- Figure 5.5-22b presents the overall XANES data by approximate ore source. The results show that less scorodite is present in the Cigar Lake and Sue C ores, as expected. In these tailings, the oxidation of residual reduced arsenic is not as advanced but for different reasons:
  - In Sue C recalcitrant reduced arsenic was not fully oxidized in the mill and was unaccounted for in the addition of sufficient ferric iron in the tailings process. The arsenic system in these tailings has evolved more slowly than in other locations.
  - The oldest Cigar Lake tailings sampled in 2023 had been placed for 9 years, however the majority are much newer. Amorphous As^{5+} minerals formed in the mill, or in the tailings, have not had enough time to fully crystalize as scorodite, and additionally reduced arsenic which survived the mill process has only just begun to oxidize in the tailings.
- The most reduced arsenic mineralization is present in the Cigar Lake ore, as anticipated, due to its comparatively higher arsenic content. Although most of the reduced arsenic was oxidized in the mill, because the concentration of arsenic present in the Cigar Lake ore is much greater than for other ore sources, the small percentage of reduced arsenic which reaches the tailings is a greater actual amount of arsenic than from other ores.

- In the tailings from each deposit, the largest percentage of arsenic in the solids is ferric arsenate. Despite ore source and process differences, the overall trend towards oxidizing equilibrium conditions persists throughout the entire tailings mass.

The arsenic mineralization as identified by the XANES analysis and additional technical work is fully supportive of the arsenic geochemical model.

Figure 5.5-21: Relative Arsenic Speciation (weight %) by borehole

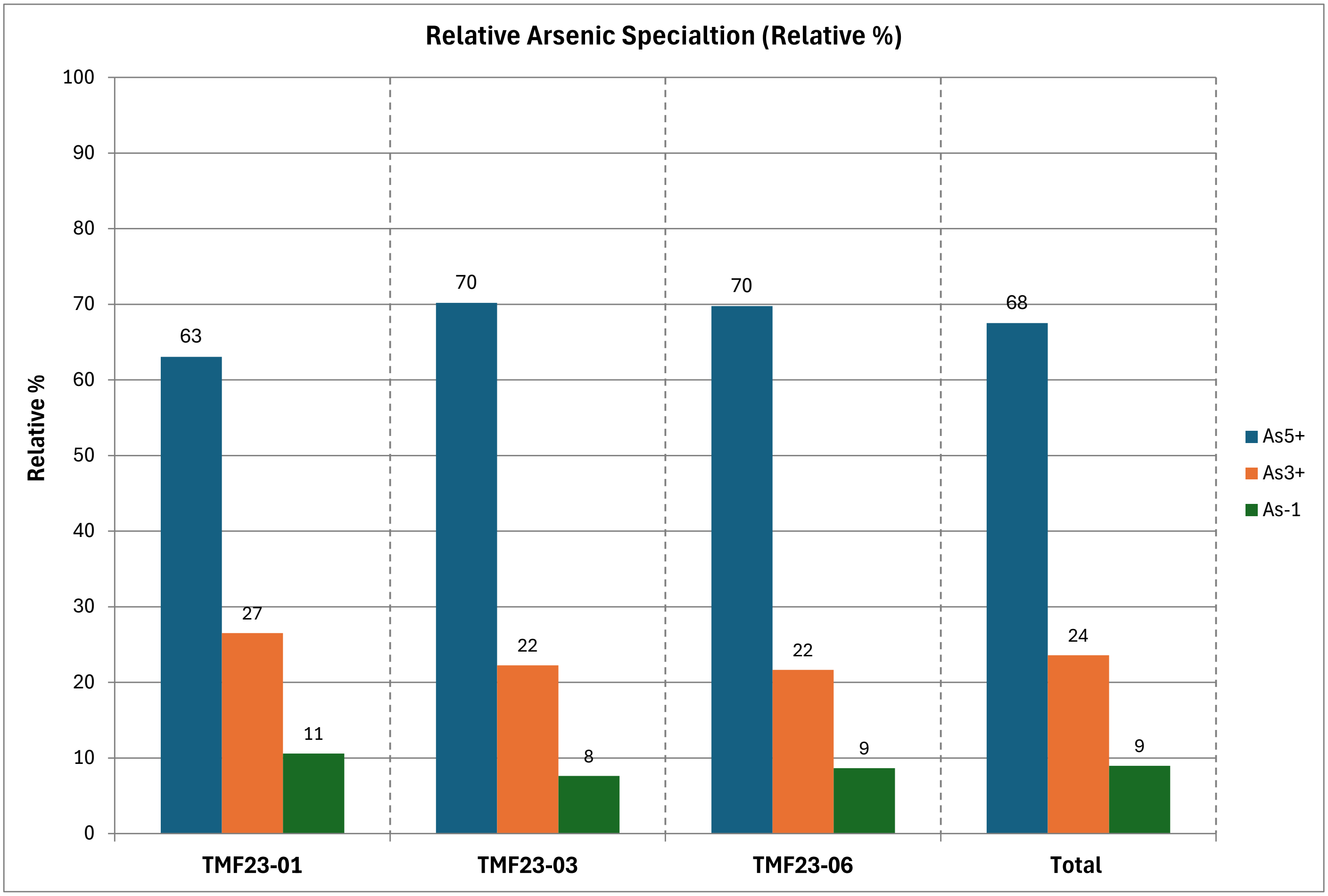
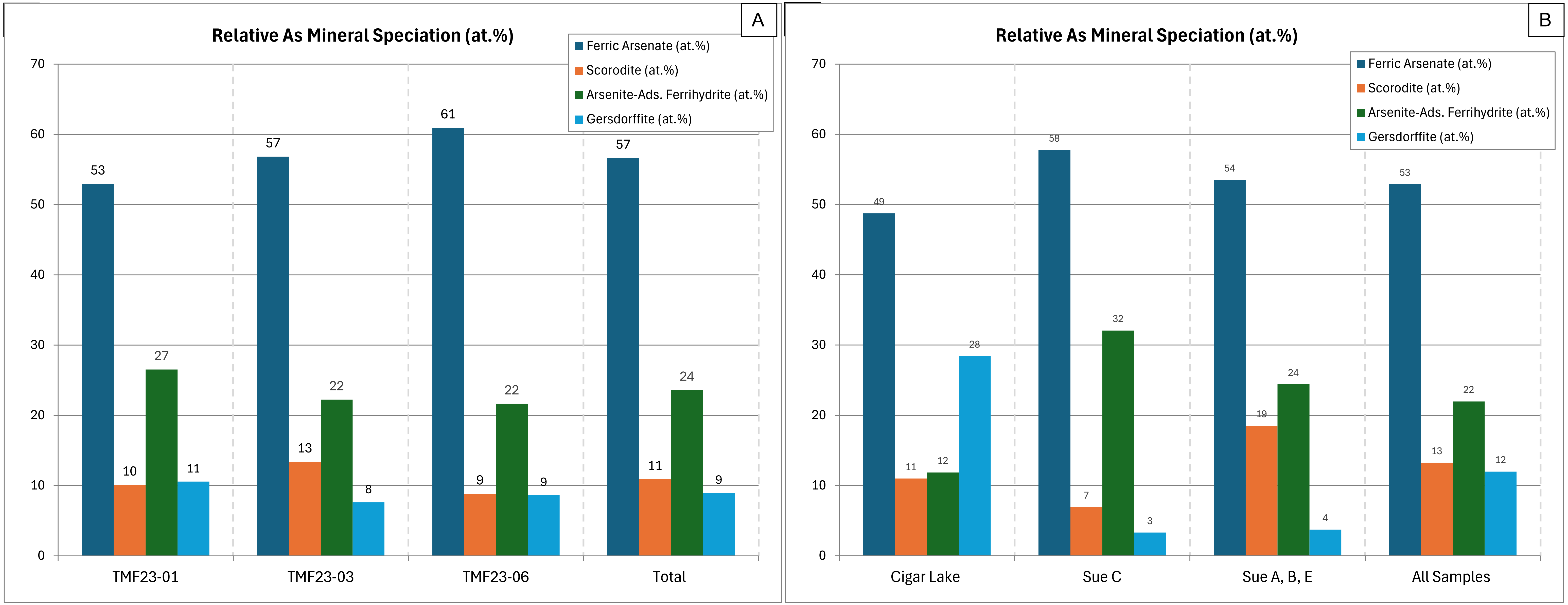


Figure 5.5-22: Relative Arsenic Mineral Speciation (weight %) by A) borehole and B) ore source



5.5.2 Molybdenum

5.5.2.1 Overview and Roadmap

Based on TOVP results which showed elevated molybdenum concentrations in the tailings pore water in 2001, Orano proactively initiated studies to develop a geochemical model for molybdenum. The goal of the model was to develop a comprehensive understanding of molybdenum evolution and endpoint in the tailings. A general roadmap of molybdenum studies relating to the TMF is presented below, with details provided in following section:

- **Initial Observations:** In 2001, molybdenum concentrations were observed to increase in the pore water of newly placed tailings and then gradually decrease as the tailings age. In response, Orano initiated technical studies specific to molybdenum in the tailings.

- **Conceptual Geochemical Model (Section 5.5.2.2):** A geochemical model was developed for molybdenum and was first presented in the 2010 TOVP report (AREVA 2011a, Section 3.2.3.4). The geochemical model proposed that the precipitation of powellite will provide a long-term solubility control on molybdenum in the tailings

- **Investigative Model Validation:** A research partnership was initiated with the University of Saskatchewan (U of S) Chemistry Department to validate the molybdenum geochemical model from 2012 to 2015. The full results of the research project completed with the U of S were presented in the 2015 Tailings Management TID (Appendix F), which provides a comprehensive understanding of the molybdenum evolution in the tailings.

- **Model Validation through Tailings Sampling (Section 5.5.2.3):** The results from the 2018 and 2023 TOVP are compared with the expected model results as an ongoing validation.

5.5.2.2 Conceptual Geochemical Model

The control of molybdenum concentrations in the tailings pore water shares some similarities with the geochemical evolution of arsenic. Dissolved molybdenum in mill waste solutions precipitates as a ferric-molybdate phase at low pH in the tailings preparation circuit, in a manner resembling ferric arsenate/scorodite for arsenic. The molybdate (MoO_4^{2-}) mineral analogue to scorodite is the mineral ferrimolybdite ($Fe_2(MoO_4)_3 \cdot 8H_2O$), which precipitates during tailings preparation.

The minimum solubility of ferrimolybdite occurs at approximately pH 3.25. Therefore, at a placed tailings pH of 7 in the TMF, the mineral is too soluble to control pore water molybdenum concentrations and dissolves. Table 5.5-5 demonstrates that the molybdenum removal performance of the tailings preparation process is very efficient. At the pH 4 neutralization step, nearly all of the molybdenum has been precipitated from solution as ferrimolybdite and molybdate adsorbed onto ferrihydrite. Following this step, approximately 25% of the molybdenum re-dissolves at the pH 7.5 (terminal) step of the tailings circuit process. Eventually, the redissolved molybdenum is recovered by the JEB Water Treatment Plant and returned to the tailings preparation process for permanent disposal in the TMF.

Table 5.5-5: Example of Overall Wastewater Management Mo Mass Balance for McClean Lake During Normal Operations Over a Ten-Month Period.

Process Location		Mo Concentration (mg/L)	Mo Mass (kg/day)	Mo Removal Efficiency (%)
Tailings preparation:	feed	89.0	238.8	--
	discharge pH 4.0	0.6	1.7	99.3
	discharge pH 7.5	26.0	60.1	74.8
Water Treatment Plant:	feed	12.2	62.5	--
	discharge	0.197	1.0	98.4
Overall:	feed	89.0	238.8	--
	discharge	0.197	1.0	99.6

*measured at tailings thickener under flow

If not complete prior to placement in the TMF, the incongruent dissolution of ferrimolybdite (equation 5.5-5) in the tailings solids continues to completion.

$$\underset{\text{(ferrimolybdite)}}{Fe_2(MoO_4)_3{\cdot}8H_2O\downarrow} + 6OH^- \rightarrow 3MoO_4^{2-} + \underset{\text{(ferrihydrite)}}{2Fe(OH)_3\downarrow} + 8H_2O \qquad \text{equation 5.5-5}$$

There is a potential secondary source of molybdate in the tailings, originating from the oxidation of primary molybdenum mineralization (MoS_2). MoS_2 is only a minor component of molybdenum in the tailings but may act to slightly extend the time period where elevated molybdenum concentrations are observed in the TMF. Over time, MoS_2 slowly oxidizes to soluble MoO_4^{2-}.

As the concentration of MoO_4^{2-} increases in the tailings pore over time, it complexes with the relatively high Ca^{2+} concentrations present in the tailings pore water from gypsum saturation (550 mg/L), as shown in equation 5.5-6.

$$\underset{\text{(gypsum)}}{CaSO_4{\cdot}2H_2O\downarrow} \leftrightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \qquad \text{equation 5.5-6}$$

The Ca-MoO_4 complexes formed in the tailings pore water eventually precipitate as powellite ($CaMoO_4$), as shown in equation 5.5-7. The precipitation of powellite results in an eventual decrease in pore water molybdenum concentration with time.

Under TMF conditions, saturation index modelling (Section 5.4.2) indicates that powellite ($CaMoO_4$) is slightly supersaturated in most places in the TMF and that the supersaturation trend increases as the tailings age (equation 5.5-7).

$$Ca^{2+} + MoO_4^{2-} \rightarrow \underset{\text{(powellite)}}{CaMoO_4\downarrow} \qquad \text{equation 5.5-7}$$

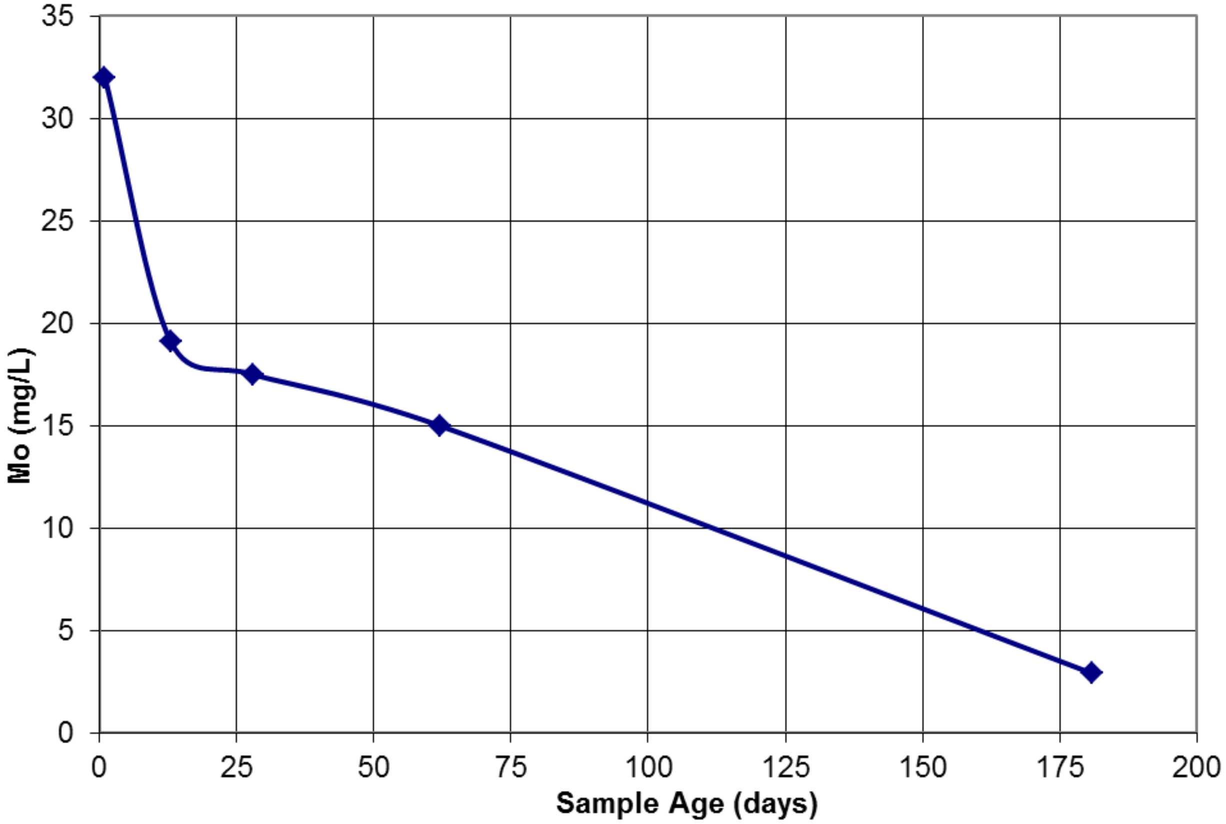
The overall reaction resulting in the precipitation of powellite from gypsum saturated tailings pore water is presented in equation 5.5-8. The equation is obtained by the addition of equations 5.5-6 and 5.5-7.

$$\underset{\text{(gypsum)}}{CaSO_4{\cdot}2H_2O\downarrow} + MoO_4^{2-} \rightarrow \underset{\text{(powellite)}}{CaMoO_4\downarrow} + SO_4^{2-} + 2H_2O \qquad \text{equation 5.5-8}$$

To support the development of the conceptual model, a TOVP aging test on Mo evolution in the tailings was conducted in 2004 (Appendix D, Section D, Subsection E). In general, the aging test results identified final pore water molybdenum values of less than 5 mg/L (Figure 5.5-23).

The aging test supported geochemical model predictions and has since aligned with sampling results.

Figure 5.5-23: Mo (mg/L) Over Time in a Laboratory TOVP Aging Test (2004)



5.5.2.3 Model Validation

Field Observations

Since 2008, molybdenum pore water concentrations in the tailings below 395 mASL have been low and controlled at between ~5.0 to 6.0 mg/L (Table 5.5-6). Note that in 2023 several of the lowest samples in the tailings were not obtained which, in past sampling campaigns, have shown the lowest molybdenum concentrations; therefore, the weighted average Mo in 2023 is slightly higher than in past campaigns. In these oldest tailings, molybdenum aging is reaching equilibrium values and powellite crystallization is the dominant solubility control of Mo in the pore water. Continued tracking of molybdenum values in the lower tailings continues to validate the geochemical model and suggest low and controlled long-term molybdenum concentrations.

The geochemical processes described in the molybdenum geochemical model are apparent in Figure 5.5-24. In the upper tailings (430 to 409 mASL), Mo concentrations in the pore water are increasing or elevated which is indicative of ferrimolybdite dissolution. A decrease in Mo concentration begins in the middle tailings (approximately 409 to 389 mASL), suggesting the initiation of $CaMoO_4$ precipitation. Below 389 mASL, Mo concentrations decline only slightly and in the oldest tailings they appear to approach equilibrium with crystalline powellite (see Figure 5.4-4).

Table 5.5-6: Tracking the Long-term stability of Pore Water Molybdenum Concentrations in Mature Tailings

***In-Situ* Sampling Campaign**	**Number of Depth Intervals**	**Weighted Average Molybdenum Concentration Below 395 mASL**
2023	7	6.3
2018	9	5.4
2013	10	5.0
2008	10	5.3

PHREEQC Geochemical Modelling

The presence of powellite as the final step of the Mo geochemical process is supported by geochemical modelling using TOVP field data. An Eh-pH diagram (Figure 5.5-25) of the expected long-term Mo geochemistry shows that powellite precipitated in the tailings will be thermodynamically stable under the Eh-pH conditions in the TMF.

Figure 5.5-24: Sample Elevation vs Average 2008 and 2013 Mo Pore Water Concentration

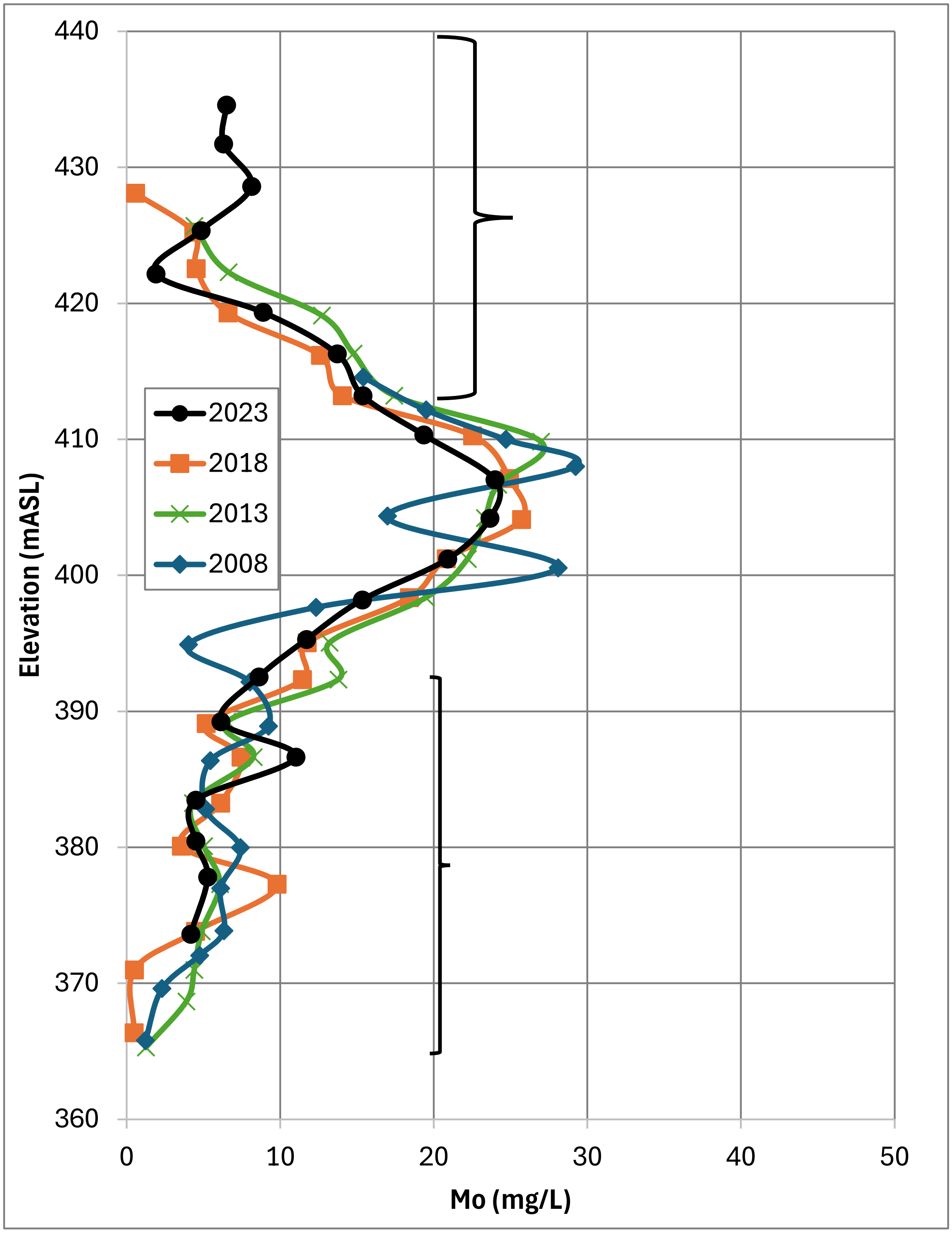
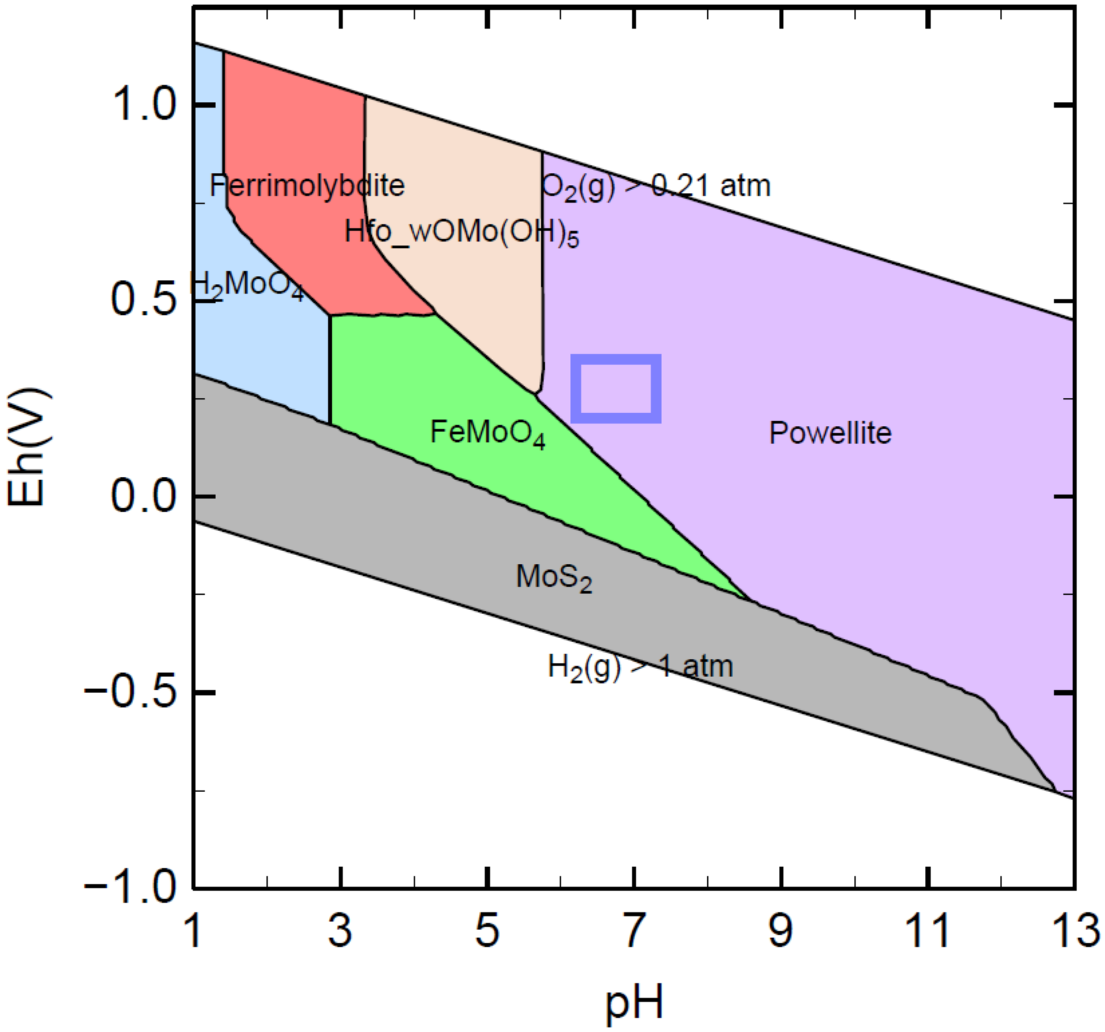


Figure 5.5-25: Eh-pH diagram for the system Fe-Mo-Ca-S-O_2-H_2O at 25ºC dominant dissolved, or adsorbed species and solid phases. Mo 14mg/L, Ca 600mg/L, $Fe(OH)_{3(a)}$ 5 x10^{-3}mol, SO_4^{-2} 2000mg/L. The blue box indicates TMF Eh pH conditions.

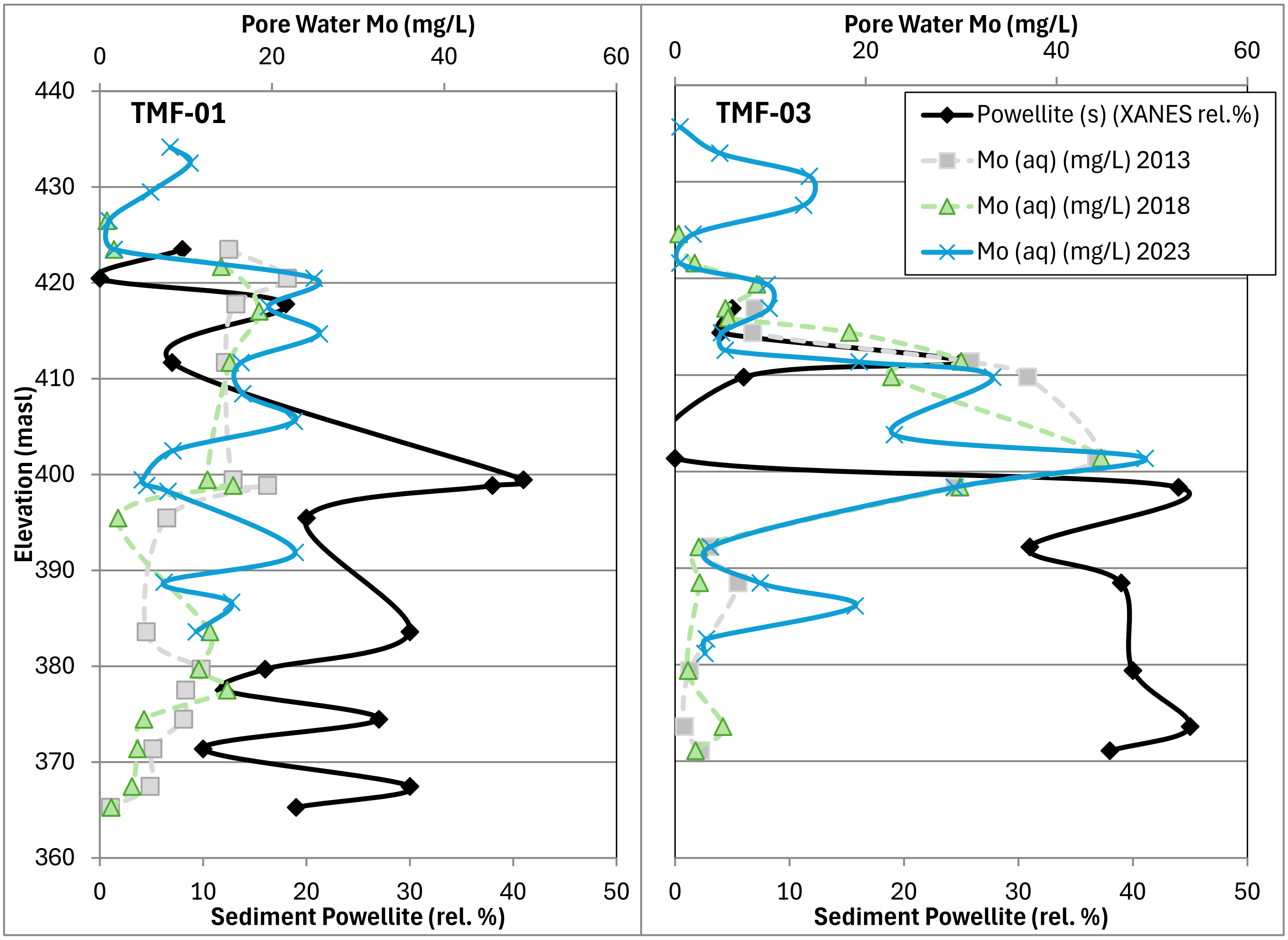


University of Saskatchewan Molybdenum Studies

In 2012, a project to identify Mo bearing minerals in the tailings was initiated with the University of Saskatchewan and the Canadian Light Source (using X-ray Absorption Near-Edge Spectroscopy, XANES). Two papers have been produced from this project (Appendix E: Hayes, et.al. 2014; Blanchard et.al. 2015), using tailings samples collected in the 2013 TMF in-situ sampling campaign from boreholes TMF13-01 and TMF13-02. Overall, the findings are supportive of the Mo model presented above. As proposed, powellite ($CaMoO_4$), ferrimolybdite ($Fe_2(MoO_4)_3.8H_2O$), molybdate adsorbed on ferrihydrite ($Fe(OH)_3$-MoO_4), and molybdenite (MoS_2) have been identified as the main Mo bearing minerals in the TMF.

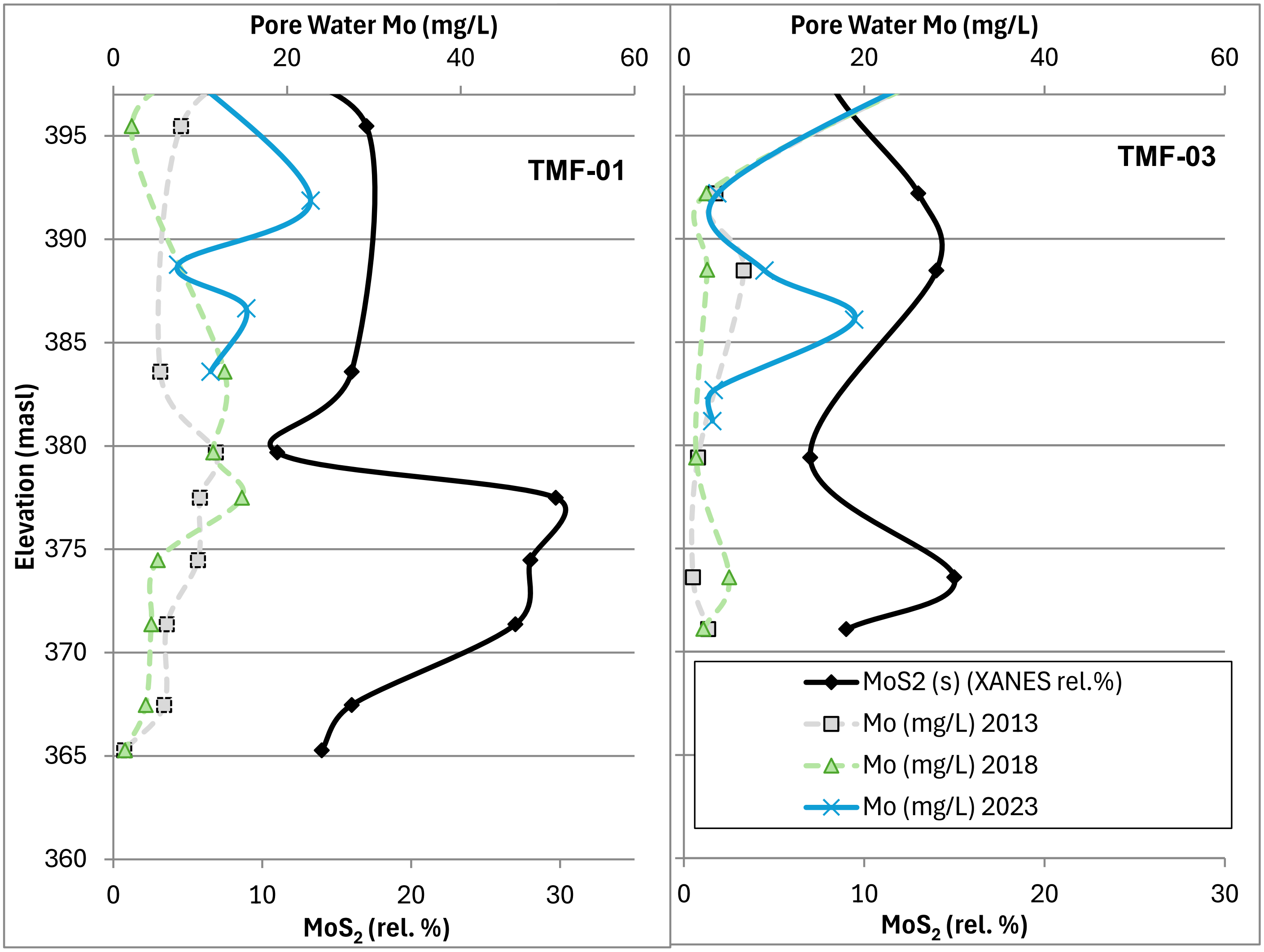
Powellite was observed to be the most abundant Mo mineral phase in the middle and lower tailings (below 400 mASL), which supports the Mo geochemical model and indicates that powellite is the long-term stable Mo mineral phase which forms as the tailings age (Figures 5.5-26). Powellite also correlates well with Mo concentrations in the pore water of the two sampled boreholes. In general, where there is more powellite mineralization, the concentration of Mo in the pore water is relatively less (Figure 5.5-23).

Figure 5.5-26: Powellite Mineralization Control on Pore Water Mo Concentration by Depth in TMF-01 and TMF-03 (2013, 2018 and 2023)



The U of S XANES study also identified minor amounts of MoS_2 in the tailings (approx. 10% on average of the total Mo identified). The presence of MoS_2 confirms that some residual primary molybdenum mineralization is present in the tailings, which may extend the time required for the system to reach equilibrium. In general, the MoS_2 identified does not seem to have a significant effect on the tailings pore water Mo concentrations based on the TOVP sampling data. One exception is observed in the lower elevations of borehole TMF-01, where the pore water Mo concentration does not respond as quickly to the precipitation of powellite (Figure 5.5-26). When the pore water Mo concentrations are observed in the context of the amount of primary Mo mineralization, it is clear that there is a correlation between an increase of MoS_2 in the solids and Mo in the associated pore water (Figure 5.5-27). The effect is observed in TMF-01 and not TMF-03. TMF-01 is the central borehole, and therefore at this depth in the JEB/Sue tailings has a coarser particle size (representing the JEB/Sue tailings). A correspondingly larger hydraulic conductivity in TMF-01 causes reactions (such as the oxidation of MoS_2) to occur relatively faster. Note that in Figure 5.5-27, for simplicity pore water concentrations are shown only at depths were corresponding MoS_2 analysis was conducted in 2013 when presenting the 2013 and 2018 data. In 2023, because the tailings have consolidated since 2013, and several samples of the lower tailings were not obtained, all available data is presented.

Figure 5.5-27: Molybdenum Sulphide (MoS_2) Mineralization compared to Pore Water Mo Concentration by Depth in TMF-01 and TMF-03 (2013, 2018 and 2023)



5.5.2.4 Conclusions – Molybdenum Geochemical Model

The 2023 in-situ tailings sampling results correlate well with the overall molybdenum geochemical model, and no significant deviations from the model are observed. Results from the Cigar Lake samples correlate well with expected molybdenum behaviour based on the Mo geochemical model. The behaviour of molybdenum in Cigar Lake tailings will continue to be validated in future TOVP programs.

5.5.3 Uranium

5.5.3.1 Overview and Roadmap

Uranium has also been identified as a key COPC in the tailings, and Orano proactively initiated studies to develop a geochemical model for uranium in 2008. The goal of the model was to develop a comprehensive understanding of uranium evolution and endpoint in the tailings. A general roadmap of uranium work relating to the TMF is presented below, with details provided in following section:

- **Conceptual Geochemical Model (Section 5.5.3.2):** The evaluation of the evolution and long-term controls on uranium has been a component of the TOVP since 2005 (AREVA, 2005a). Uranium differs from other key COPCs (i.e. arsenic, molybdenum) as it is *indirectly* controlled – its behaviour in tailings pore water is primarily driven by bicarbonate (HCO_3^-), and HCO_3^- is controlled by the formation of carbonate minerals. The geochemical model describes: 1) how HCO_3^-, originating from the use of hydrocarbons in the mill, influences the concentration of uranium in pore water; and 2) how the presence of gypsum in the tailings results in the formation of carbonate minerals, which ultimately provide an upper bound to HCO_3 and therefore uranium.

- **Model Validation (Section 5.5.3.3):** Historical pore water observations from the TOVP support the geochemical model predictions, and 2023 data continues to validate the model. In addition, a research partnership with the University of Saskatchewan (U of S) Chemistry Department identified potential a carbonate mineral that may be controlling HCO_3 in the tailings as described below. This work is continuing in 2025/2026 after a hiatus due to limitations from the Covid-19 pandemic and extended downtime at the Canadian Light Source (the principal analytical technique used for this work).

5.5.3.2 Conceptual Geochemical Model

General Theory

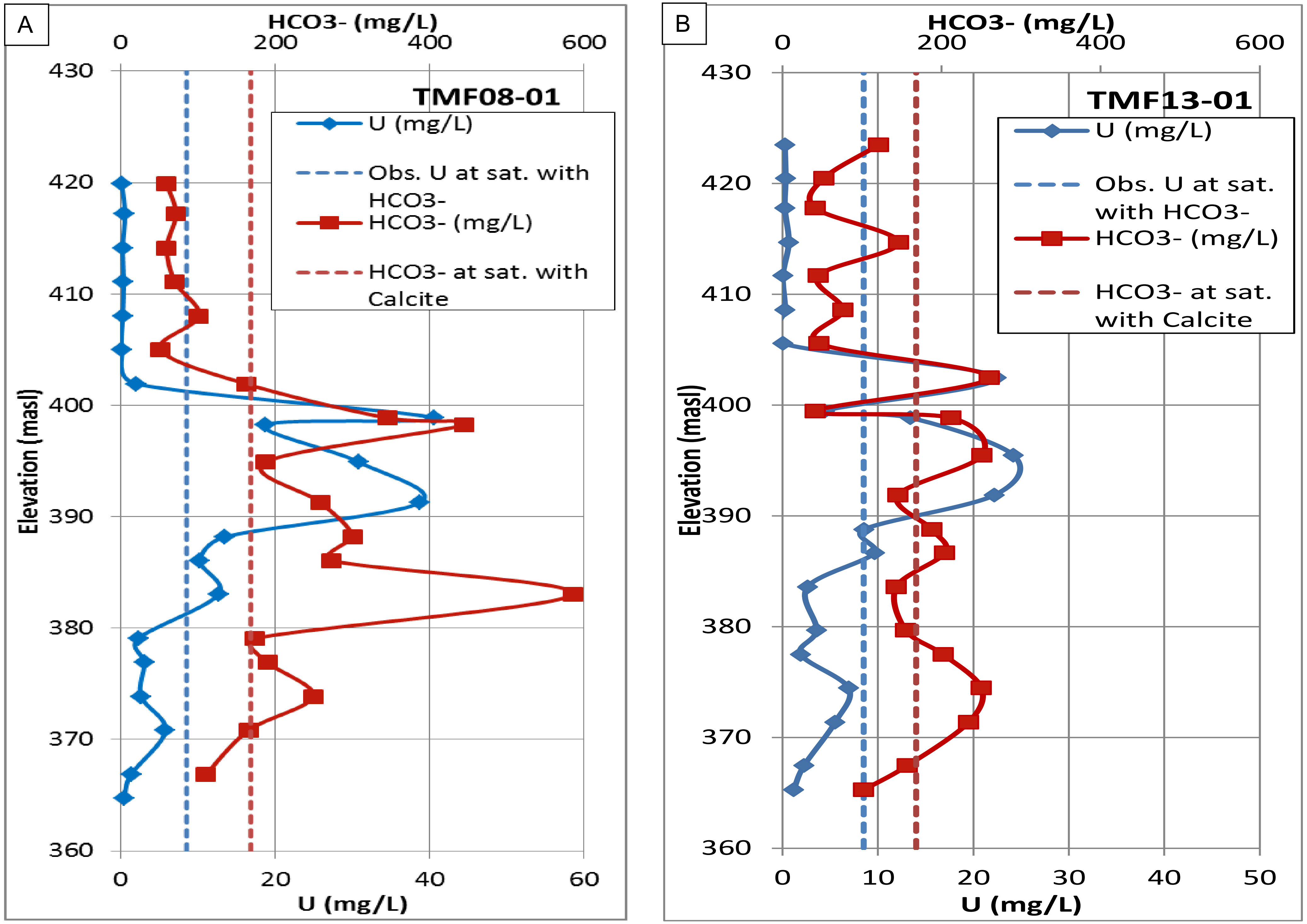
Under the oxidizing conditions of the TMF, any residual uranium will ultimately reach a fully oxidized state (U^{6+}) as the uranyl ion (UO_2^{2+}). In this state, the pore water concentration of uranium is principally controlled through sorption and desorption onto hydrated ferric oxide (HFO) in the tailings solids. The uranyl ion also forms strong solution complexes with carbonate species, which are poorly sorbed by HFO (Langmuir 1997). An increase in pore water bicarbonate concentration will tend to form more uranyl carbonate complexes, leading to the desorption of uranium from HFO and an increase in the uranium concentration in the tailings pore water. This geochemical process has been observed consistently in sampling data from the TOVP

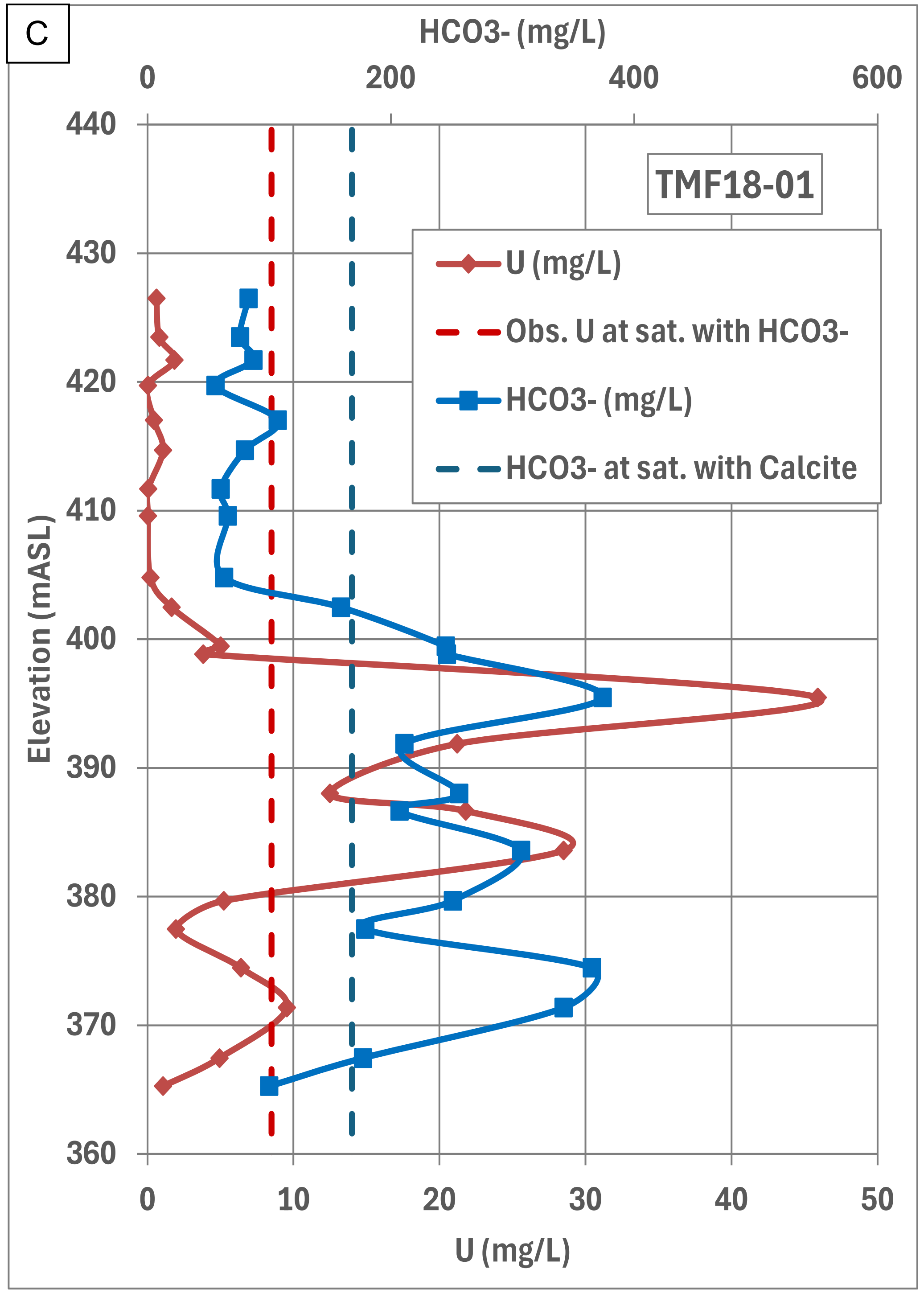
(Figure 5.5-28). As observed in groundwater, U^{6+} generally forms a pH-dependent suite of uranyl-carbonate complexes:

$UO_2^{2+} + CO_3^{2-} = UO_2CO_3$ (pH 4.8 to 6.2)
$UO_2^{2+} + 2CO_3^{2-} = UO_2(CO_3)_2^{2-}$ (pH 6.2 to 8.4)* **TMF conditions.**
$UO_2^{2+} + 3CO_3^{2-} = UO_2(CO_3)_3^{4-}$ (pH 8.4 to 14)

Above ~400 mASL in the tailings, the relationship between uranium and bicarbonate is not a dominant control on uranium evolution in the pore water. The change corresponds to the implementation of peroxide (H_2O_2) addition to tails feed, which was a tailings treatment process optimization driven by TOVP findings. The addition of H_2O_2 is intended to oxidize any residual entrained organic carbon and eliminate most of the source of HCO_3 (organic carbon) in the placed tailings pore water. The elimination of HCO_3 effectively controls the uranium source term (Figure 5.5-29)

Figure 5.5-28: U and HCO_3^- correlated over time in Borehole TMF-01 A)2008, B)2013, C)2018 and D)2023




C
HCO3- (mg/L)
0
200
400
600
TMF18-01
U (mg/L)
Obs. U at sat. with HCO3-
HCO3- (mg/L)
HCO3- at sat. with Calcite
Elevation (mASL)
440
430
420
410
400
390
380
370
360
0
10
20
30
40
50
U (mg/L)

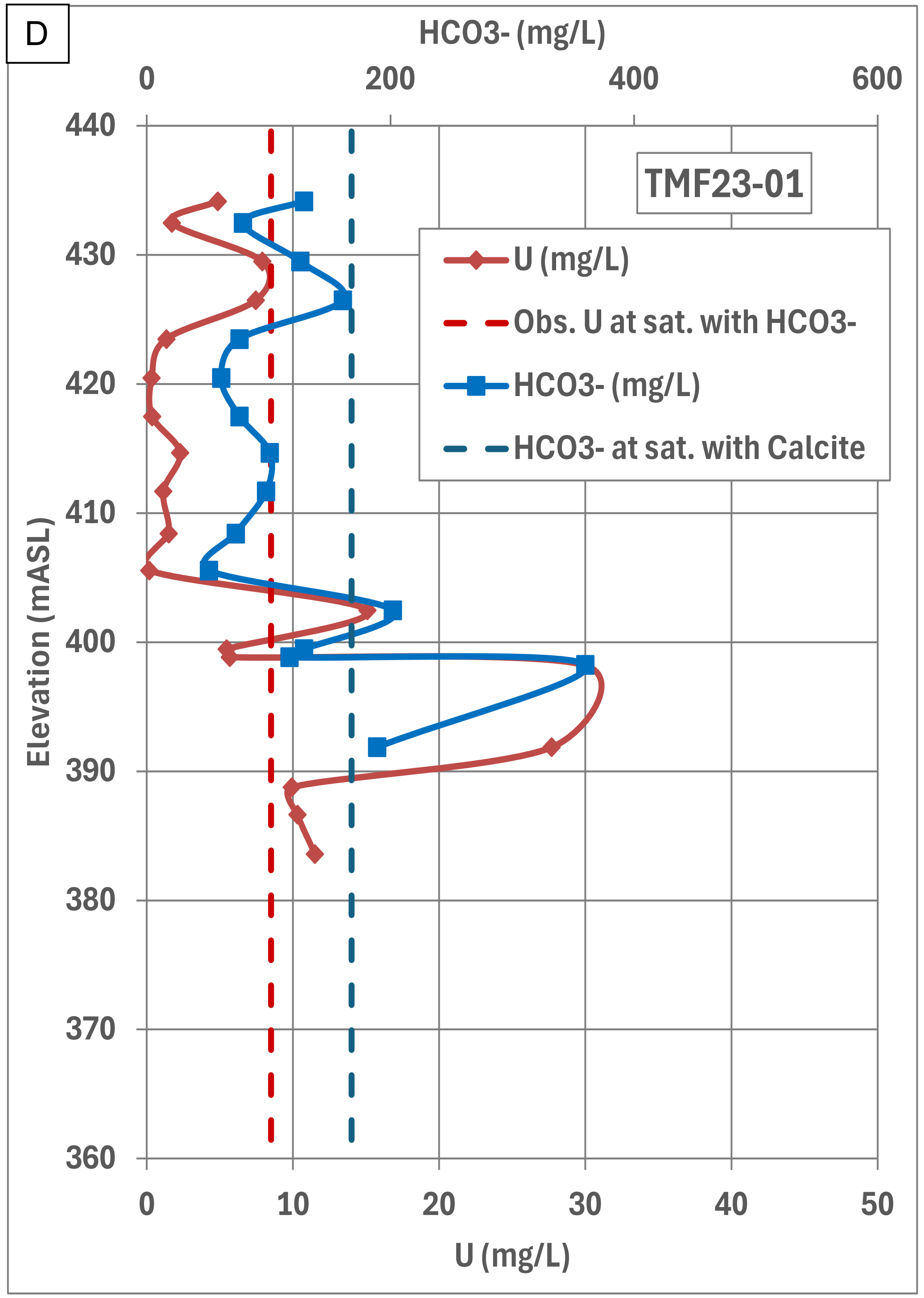
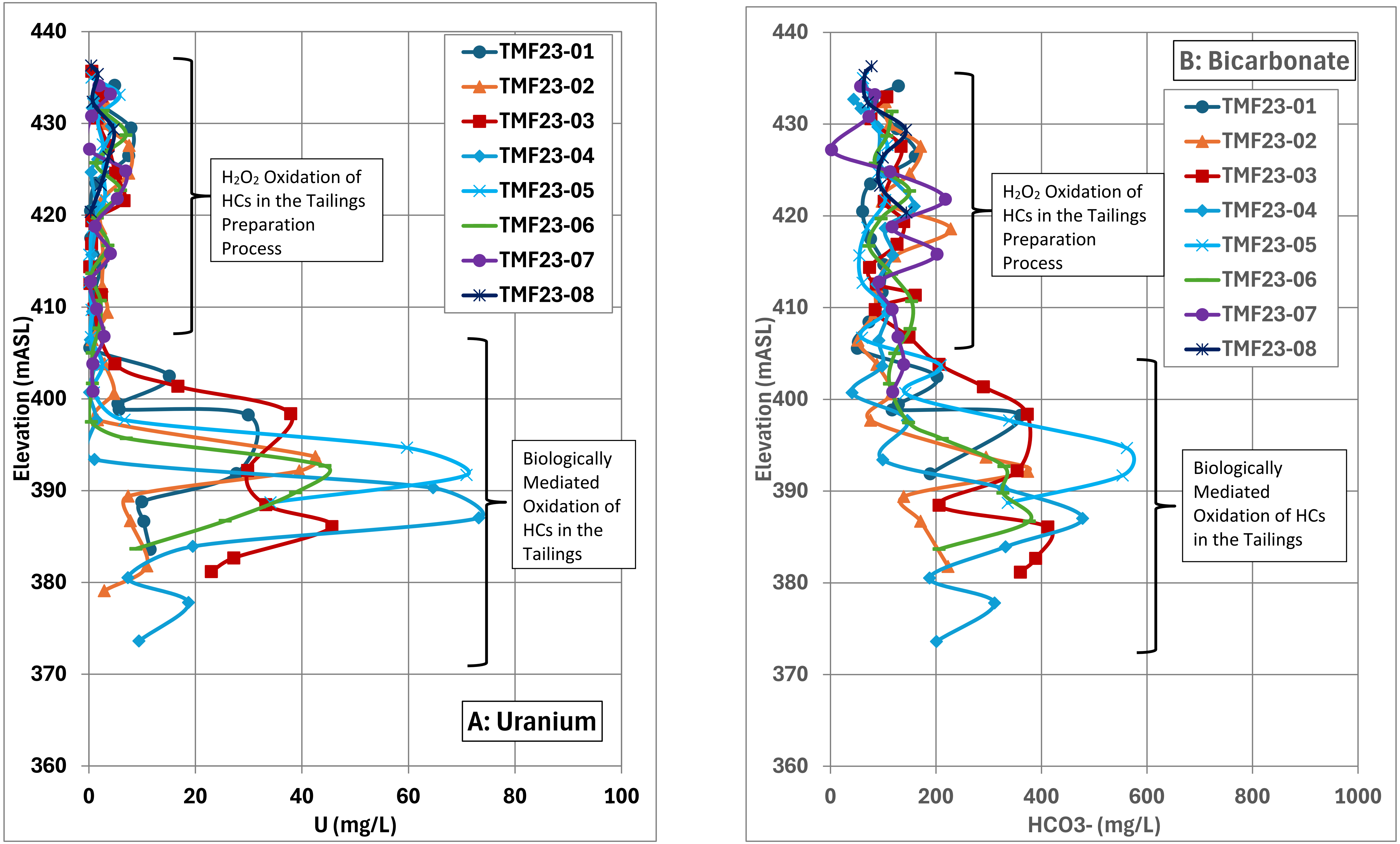

D
HCO3- (mg/L)
0
200
400
600
TMF23-01
U (mg/L)
Obs. U at sat. with HCO3-
HCO3- (mg/L)
HCO3- at sat. with Calcite
Elevation (mASL)
440
430
420
410
400
390
380
370
360
0
10
20
30
40
50
U (mg/L)

Figure 5.5-29: Uranium (A) and Bicarbonate (B) pore water values for each borehole location in 2023 showing the effects of H_2O_2 addition to the tailings preparation circuit at approximately 400mASL



Hydrocarbons – Role and Influence on Uranium

The mill process is continually consuming small amounts of hydrocarbon reagents. The largest sources of hydrocarbons are organic flocculant (generally used as a settling aid throughout the process), followed by smaller amounts of tri-capryl amine, isodecanol, and kerosene reagents used in the solvent extraction process. Of the hydrocarbon reagents used in the mill, the source of the largest amount of hydrocarbons identified in the tailings is the kerosene diluent used in the solvent extraction process. Residual amounts of kerosene are entrained in the raffinate solution that reports to the Tailings Preparation Circuit. Prior to the introduction of H_2O_2 to tailings preparation process (i.e. for placed tailings above ~400 mASL in the TMF), the hydrocarbon material adsorbed onto the surface of the tailings solids and was subsequently deposited in the TMF.

Figure 5.5-30 illustrates the relationship between HCO_3^- and hydrocarbons using borehole TMF-02 as an example and demonstrates the influence of H_2O_2 addition above 400 mASL. All hydrocarbon data may be found in Appendix D, Section B. The following observations can be made in Figure 5.5-30:

- Hydrocarbon analysis supports that the majority of samples contain mainly kerosene (i.e. carbon numbers of 10 to 16, including kerosene and isodecanol).

- Above 400 mASL, the relative change in HCO_3 concentrations from below 400 mASL can be observed. The decrease in HCO_3^- is a result of the addition of peroxide during this period as a tailings process optimization.

- In early years (2001-2004), the hydrocarbon content measured in most of the samples (now areas below 400 mASL) had values that were representative of expected organic solvent loss for normal mill operation (500 and 1,100 µg/g, COGEMA, 2005a). In the 2018 sampling, hydrocarbon content of the tailings is clearly decreased from the 2001-2004 initial values, at an average of 37.1 µg/g (see Table 5.5-7). The consistently low concentrations of hydrocarbons over several sampling years provides evidence that most of the hydrocarbons have been consumed.

- When comparing 2018 and 2023 data, there is a noted stabilization of HCO_3^- values. This observation, in conjunction with the consumption of hydrocarbons noted above, is expected to result in an ongoing decline of HCO_3^- and consequently uranium values over time.

- Occasionally, samples have elevated hydrocarbon content, and these are identified at elevations known to be related to organic crud disposal operations. The elevated point in 2018 at approximately 385 mASL likely corresponds to one of these areas. The isolated areas of higher-than-average hydrocarbon content will likely persist in the tailings over longer periods of time, as they are the remnants of small mill cleaning events or isolated upset conditions. The higher concentrations of hydrocarbons will take longer to fully oxidize. These discrete areas are expected to have only minor local effects on the pore water uranium source term, given the small scale of each upset event combined with the continued consolidation of the tailings (which limits pore water migration).

Figure 5.5-30: **Sample Elevation vs Solids HC10-16 (ug/g) and Pore Water HCO3- (mg/L) for Borehole TMF18-02 and TMF23-02**

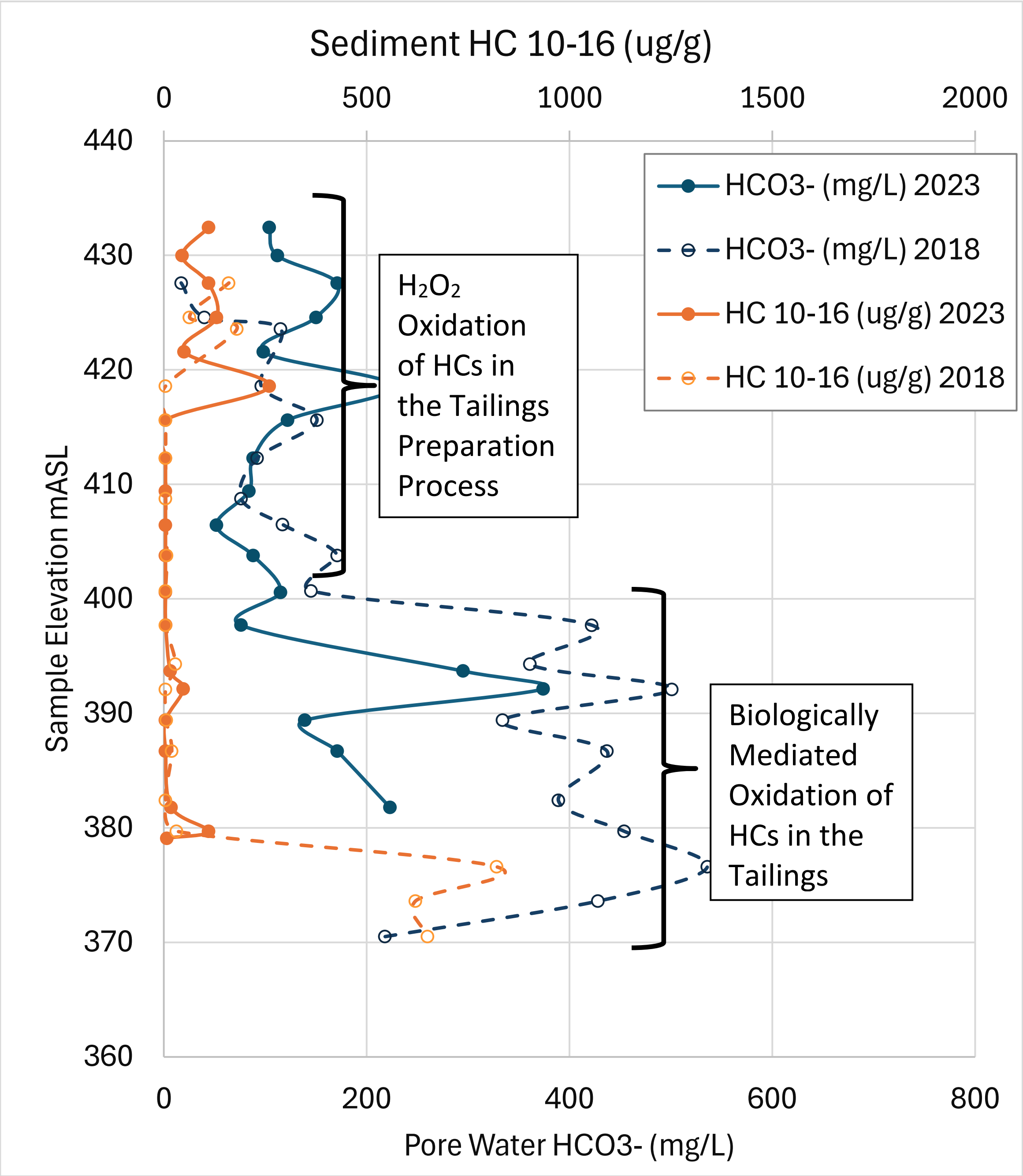


Table 5.5-7: Hydrocarbon concentrations compared over sampling year in Borehole TMF-01

Year	Average Hydrocarbon (10-16) ug/g	
	<400 mASL	>400 mASL
2023	9.4[2]	311.9[3]
2018	37.1[1]	53.89
2013	48.14	48.07
2008	19.26	24.7

1: one outlier value removed (1600mg/L) which represents a likely area of crud disposal from mill maintenance activities.

2: Several samples below 400 mASL were not retrieved in 2023 and so this average is likely to be an underestimate

3: One outlier value removed (2200mg/kg) which represents a likely area of crud disposal from mill maintenance activities.

Presentation of Model

Hydrocarbon species are not thermodynamically stable under the oxidizing conditions in the TMF. Entrained hydrocarbons in the tailings solids are gradually converted to soluble HCO_3^- in the tailings pore water. The increase in HCO_3^- concentration is facilitated by the presence of communities of microorganisms in the deposited tailings, which use the organic carbon as an electron source causing the oxidation to HCO_3^-. The oxidation of organic carbon by bacterial activity is generalized by equation 5.5-9.

$$CH_2O + O_2 \xrightarrow[\text{(microorganisms)}]{} HCO_3^- + H^+ \tag*{equation 5.5-9}$$

The tailings in the TMF contain relatively large amounts of gypsum. Consequently, the tailings pore water Ca^{2+} concentration is approximately 550 mg/L everywhere in the TMF, in equilibrium with the gypsum in the tailings solids (equation 5.5-10).

$$\underset{\text{(gypsum)}}{CaSO_4{\cdot}2H_2O\downarrow} \leftrightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \tag*{equation 5.5-10}$$

Under TMF conditions, gypsum is more soluble than the carbonate mineral calcite ($CaCO_3$); therefore, the pore water HCO_3^- concentration cannot continually increase without reaching saturation with calcite (equation 5.5-11). While calcite is used to represent carbonate mineral precipitation in the tailings in the model, new evidence suggests that other carbonate minerals also contribute to these reactions. The identification of carbonate minerals was the focus of research conducted by the University of Saskatchewan and is discussed further in Section 5.5.3.3.

$$Ca^{2+} + HCO_3^- + OH^- \rightarrow \underset{\text{(calcite)}}{CaCO_3\downarrow} + H_2O \tag*{equation 5.5-11}$$

The overall reaction showing a common ion driven conversion of gypsum to calcite is obtained by summing equations 5.5-10 and 5.5-11.

$$\underset{\text{(gypsum)}}{CaSO_4{\cdot}2H_2O\downarrow} + HCO_3^- + OH^- \rightarrow \underset{\text{(calcite)}}{CaCO_3\downarrow} + SO_4^{2-} + 3H_2O \qquad \text{equation 5.5-12}$$

Due to lack of mixing, a low liquid to solid ratio, and low temperatures, the reaction described by equation 5.5-12 proceeds very slowly in the TMF. The slow reaction generally allows the HCO_3^- concentration in the pore water to reach saturation and precipitate as carbonate minerals. An upper bound to pore water concentration for HCO_3^- (168 mg/L), is estimated based on a predicted system at equilibrium with the solubility of calcite. Based on that estimate, it is possible to estimate an equilibrium concentration of uranium (8.5 mg/L) from in-situ pore water data. Figure 5.5-30 shows the pore water uranium concentration in borehole TMF-01 over time. It is clear that the system below 400 mASL is still principally out of equilibrium with respect to both HCO_3^- and uranium, and that the concentrations of both remain elevated. Notably, the increase in the concentrations of both HCO_3^- and U has slowed. Increases from 2008 to 2013 are much larger than noted from 2013 to 2018 and 2018 to 2023.

5.5.3.3 Model Validation

Pore Water Studies

Pore water data collected through TOVP campaigns shows evidence of the occurrence of the above reaction series primarily in the deeper tailings (below 400 mASL). In this area, hydrocarbons were deposited within the tailings as no H_2O_2 was added to the TPP. The potential precipitation of carbonate minerals in this area has been observed to be episodic, in that, areas of likely carbonate precipitation identified in one sampling campaign will dissipate when examined in the next. An example of this episodic behaviour can be seen in samples collected from 2008-2023 in borehole TMF-03:

- **2008 – TMF08-03 (372 mASL to 382 mASL):** Probable carbonate mineral precipitation was observed (HCO_3^- and Ca^{2+} were drawn down, SO_4^{2-} and Na^+ increased) (Figure 5.5-32).

- **2013 – TMF13-03 (372 mASL to 382 mASL):** Key indicators of carbonate precipitation were not observed (HCO_3^- has increased slightly, Ca^{2+}, SO_4^{2-} and Na^+ returned to normal concentrations) (Figure 5.5-32).

- **2018 – TMF18-03 (388 mASL):** A new area of potential carbonate precipitation was observed (HCO_3^- and Ca^{2+} drawn down, SO_4^{2-} and Na^+ increased) (Figure 5.5-33).

- **2023 – TMF23-03 (388 mASL):** Concentrations of HCO_3^- and Ca^{2+} increased while, SO_4^{2-} and Na^+ decreased showing that after a period of potential carbonate precipitation the pore water in the area is rebounding towards equilibrium conditions with gypsum.

The presence of a competing stable mineral, gypsum, is the reason for the episodic nature of these observations in the system. Unlike arsenic and molybdenum, the carbonate mineral reaction series controls pore water uranium concentrations indirectly. The carbonate mineral reaction series are subject to control by the solubility of several secondary ions which are, in turn, controlled by separate mineral phases. Major reactants, Ca^{2+} and HCO_3^-, decrease in concentration as carbonates are precipitated; however, long-term control of aqueous Ca^{2+} concentrations is maintained by the pore water saturation with gypsum at approximately 550 mg/L. Past sampling campaigns have shown examples of a temporary decrease below saturation (or a decrease from supersaturated conditions) of Ca^{2+} concentrations while carbonate precipitation is in progress (Figure 5.5-31,32 and 33). In pore water, SO_4^{2-} concentrations rise as a direct result of the drawdown of HCO_3^- and Ca^{2+} concentrations as carbonate minerals precipitate (due to local dissolution of gypsum). The rising SO_4^{2-} concentrations in the pore water must be charge balanced by an appropriate cation, which is observed to be Na^+.

The 2008 pore water concentration trends for Ca^{2+}, HCO_3^-, SO_4^{2-}, and Na^+ below 382 mASL for borehole TMF08-03 clearly demonstrate the interrelated nature of these major ions. At the same location in 2013, disequilibrium values of the key major ions were not observed. In this area, it is likely that gypsum dissolution had reached a point of disequilibrium where no additional gypsum could be dissolved. As no further Ca^{2+} was available to precipitate carbonate minerals, concentrations of HCO_3^- rebounded (Figure 5.5-31).

In 2018, pore water HCO_3^- has slightly increased in concentration from 372 to 382 mASL. In this area, if enough hydrocarbons remain unoxidized in the tailings solids, HCO_3^- is expected to increase until precipitated as carbonate minerals. The “rise and fall” pattern for HCO_3^- will occur until all hydrocarbons are depleted. As shown in Figure 5.5-30, it is likely that hydrocarbons at depth in the tailings are now principally depleted. Fluctuations in HCO_3^- values are expected to be minor or localized going forward (Figure 5.5-32).

At 388 mASL in borehole TMF18-03, another area of potential carbonate precipitation has developed. In 2013, this zone showed only a small decrease in Ca^{2+} accompanying a large depression in HCO_3^- concentrations, with no noted accompanying increases in SO_4^{2-} and Na^+. Obvious increases in SO_4^{2-} and Na^+ were seen in 2018 data, and this allowed for a broad understanding of the speed of the reactions as they occur in the tailings. Revisiting the same tailings depth in 2023 found that concentration of HCO_3^- , Ca^{2+}, SO_4^{2-} , and Na^+ had rebounded towards equilibrium conditions again. Following the path of the reaction it appears to take over 10 years from initiation to completion of one cycle of carbonate precipitation (Figure 5.5-33).

Figure 5.5-31: **Major Ion Pore Water Concentrations in TMF-03 Indicating Calcite Precipitation below 384 mASL in 2008 and a return to equilibrium in 2013. The red line notes an area of probably carbonate precipitation that begins developing in 2013 and is not present in 2008**

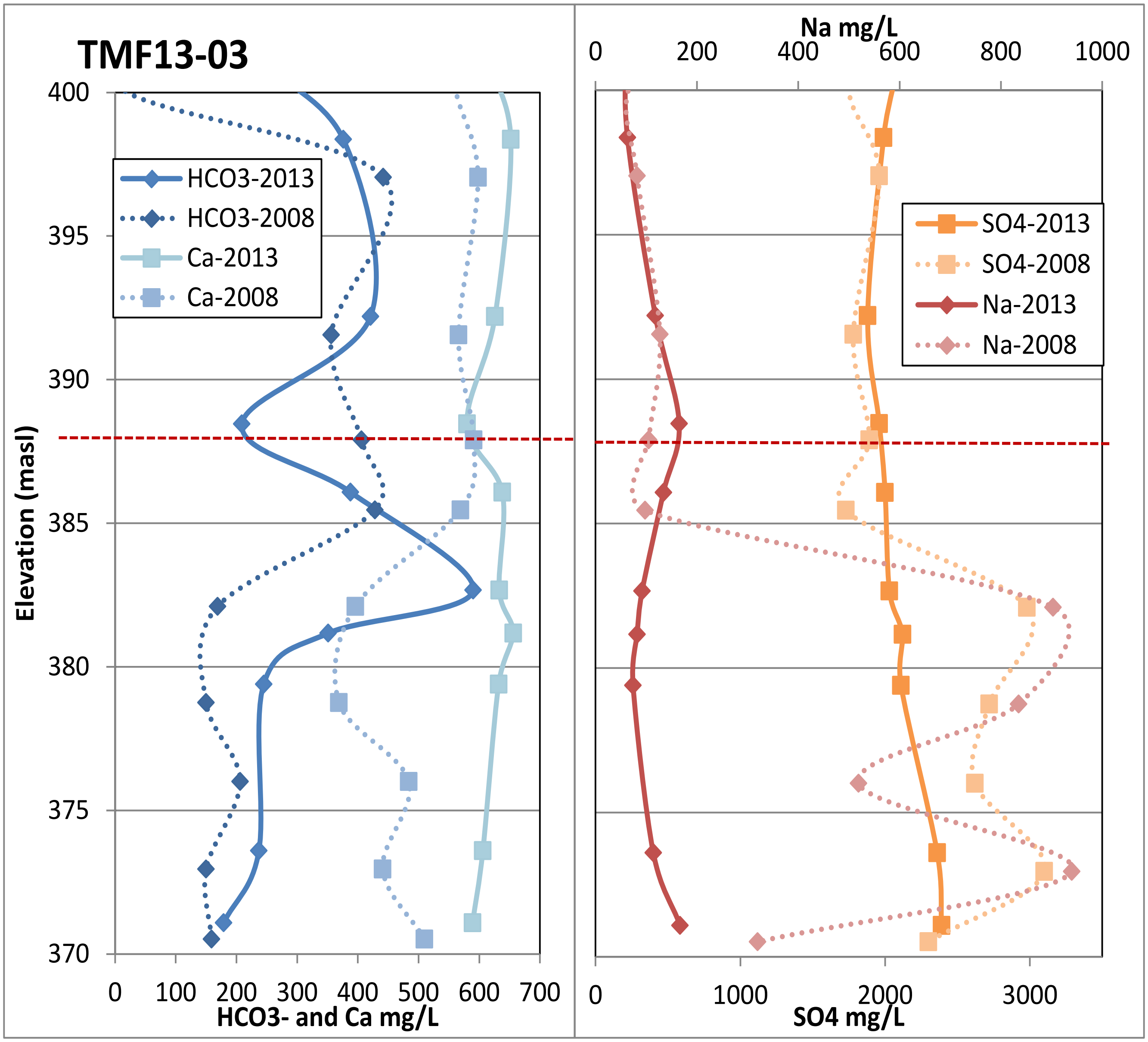


Figure 5.5-32: Major Ion Pore Water Concentrations in TMF-03 Indicating Calcite Precipitation at 388 mASL in 2018. The red line notes an area of carbonate precipitation that began to develop in 2013 became more pronounced in 2018

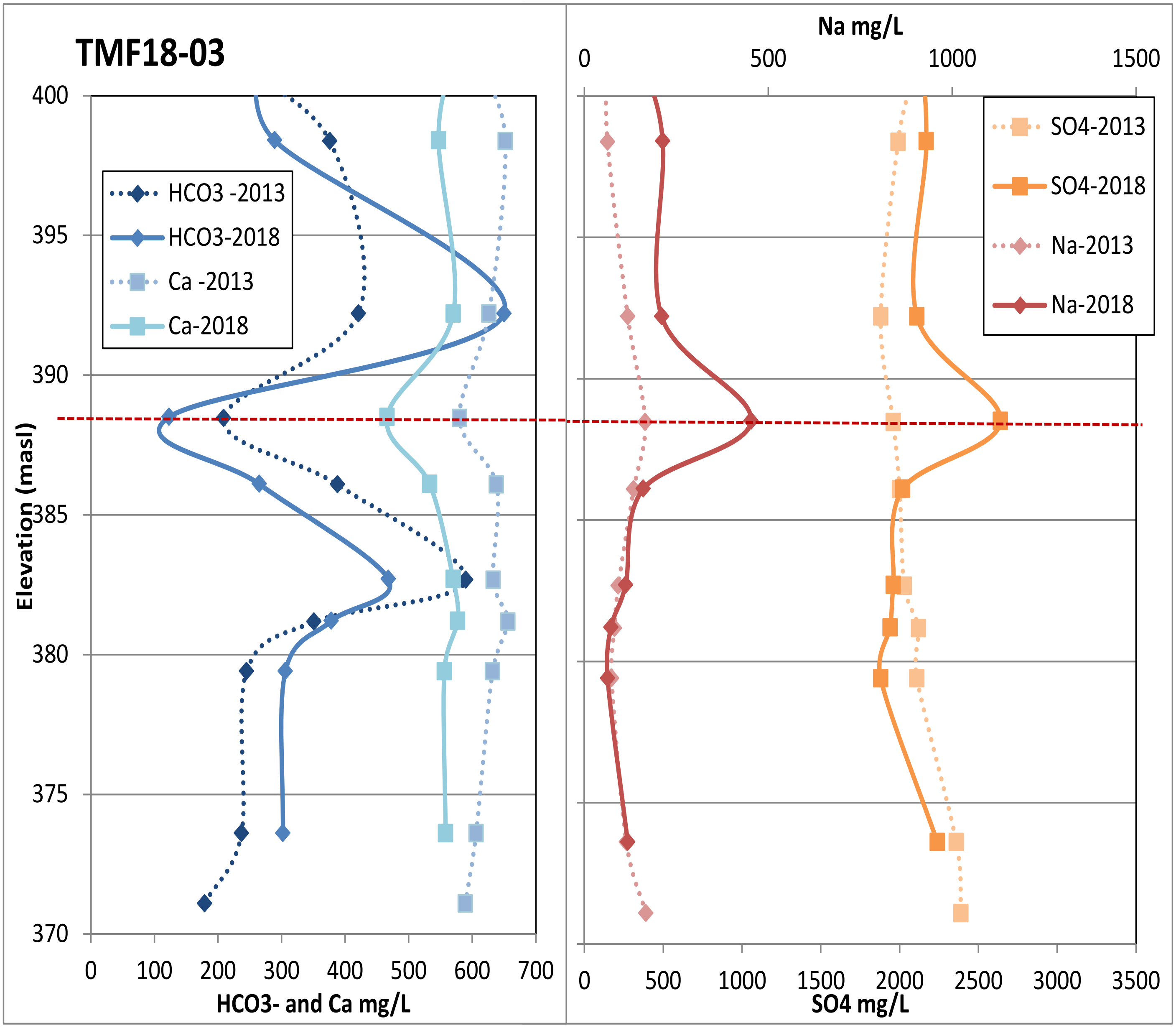


Figure 5.5-33: Major Ion Pore Water Concentrations in TMF-03 Indicating a rebound towards equilibrium conditions at 388 mASL in 2023. The red line notes an area of carbonate precipitation that began to develop in 2013 became more pronounced in 2018 and dissipated in 2023

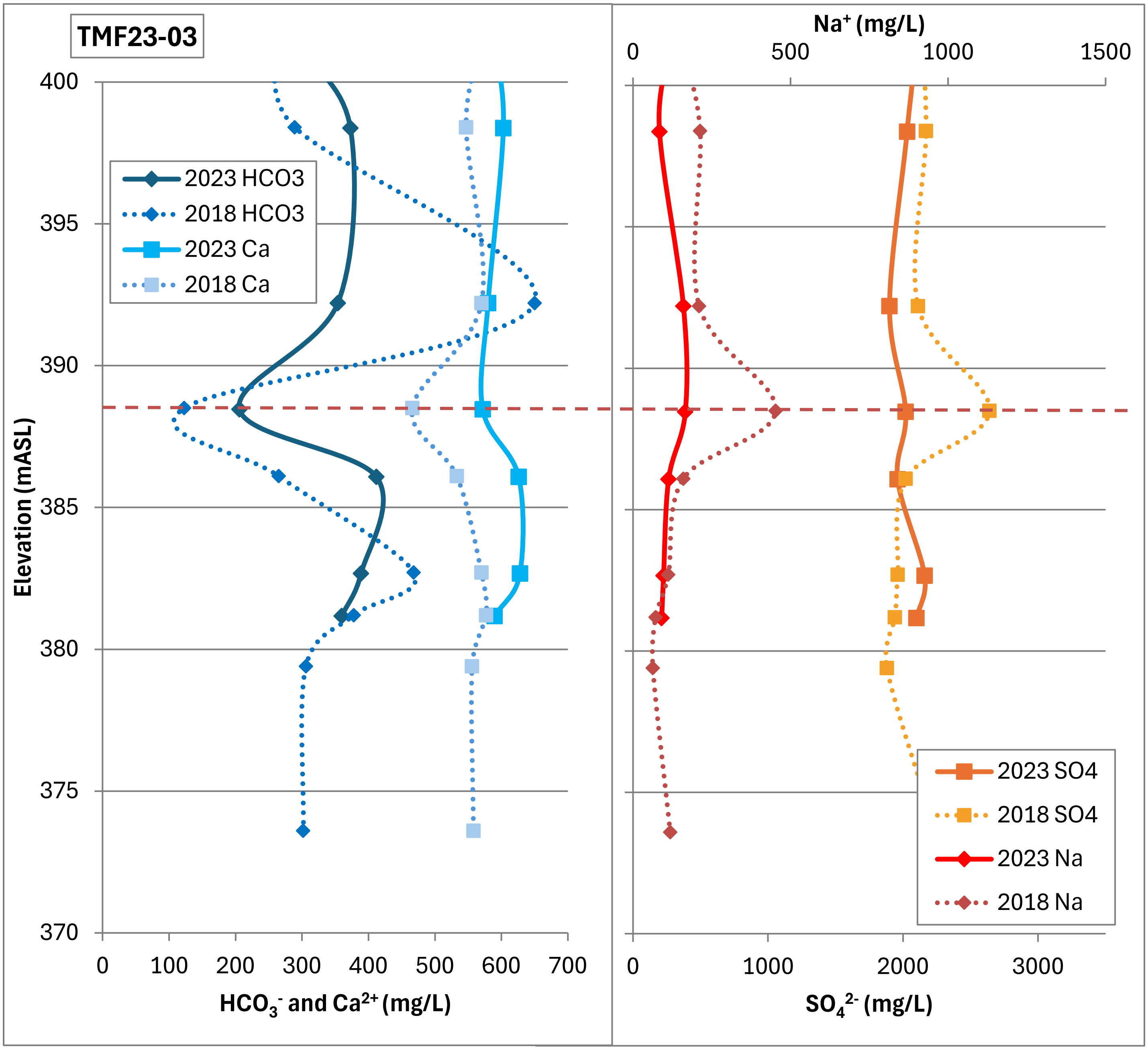


Figure 5.5-34 presents uranium concentrations in the tailings porewater averaged over three-meter intervals, and it is noted that at lower elevations in the oldest tailings, uranium values have remained consistently lower than peak values at higher elevations (approximately 385 -397 mASL). At higher elevations large increases were noted in the uranium concentration in the pore water first in 2008. Smaller increases were observed in concentration from 2008-2013, and since 2013, average concentrations in 2018 and 2023 have remained largely consistent. This stabilization in uranium concentrations may indicate peak values have been reached at 385-397 mASL but will need to be confirmed with further sampling. To evaluate what values the long-term uranium pore water concentrations may decrease towards at this location we look at the oldest tailings below 385 mASL, where it is likely conditions are further advanced towards equilibrium and Uranium values are low and controlled. Figure 5.5-35 shows changes in U and HCO_3^- concentrations over the same time period as described Figure 5.5-31, 32 and 33 above (2008-2023) in the lower elevations of borehole TMF-01. (note that for 2023, because samples of the lower elevations of TMF-01 borehole were not obtained, TMF-04 is substituted). In TMF-01 and TMF-04, uranium concentrations below 380 mASL have remained more stable between sampling campaigns and may be approaching equilibrium conditions. PHREEQC modelling supported a concentration of 168 mg/L for HCO_3^- in equilibrium with the carbonate mineral calcite, which corresponds to an observed U concentration of 8.5 mg/L. The predicted pore water uranium concentration of 8.5 mg/L is supported with measured concentrations found in the TMF (below 384 mASL in both TMF-01 and TMF-04) in 2008, 2013, 2018 and 2023, and was selected to represent the long-term uranium source concentration in tailings pore water (Appendix D, Section C). Although the pore water uranium concentration of 8.5 mg/L is well supported by TOVP in-situ results, and appears to be conservative while HCO_3^- values are more variable. For tailings in TMF-01 and TMF-04 below 380 mASL, uranium concentrations in the pore water remain low and stable, but HCO_3^- concentrations have risen slightly.

University of Saskatchewan Uranium Studies

In 2013, investigations at the University of Saskatchewan and Canadian Light Source were initiated on samples from the 2013 TOVP campaign. The studies began with the hypothesis that calcite was the most likely carbonate mineral to be precipitating as the principal solubility control on tailings pore water HCO_3^- concentrations.

The selection of calcite is based on the relatively high concentration of Ca^{2+} available in the tailings pore water in equilibrium with gypsum and supported by observations which showed that drawdowns in HCO_3^- concentrations were often accompanied by drawdowns in Ca^{2+} concentrations (Figure 5.5-32 and 5.5-33). The identification of calcite in the tailings is challenging, as it is difficult to resolve the small new calcite crystals against the much larger amount of gypsum present. Several techniques, both conventional and synchrotron-based, were used in an attempt to identify calcite against the gypsum background (Appendix D, Section D, Subsection E). The initial investigations, although informative, were not successful.

With knowledge gained from the initial investigations, a new technique was developed that combined X-ray fluorescence (XRF) elemental mapping with micro X-ray absorption near edge spectroscopy (μ-XANES). The methodology of the analysis was as follows:

- Samples were carefully selected from areas most likely to have the conditions required for the precipitation of carbonate minerals (i.e. pore water samples supersaturated with calcite based on saturated index modelling).

- Individual XRF maps were made for each sample to identify areas with high concentrations of Ca^{2+} and low concentrations of S, as these regions were less likely to contain gypsum (Figure 5.5-36).

- Each point of Ca^{2+} not associated with gypsum was further evaluated with μ-XANES and fit against a library of 34 possible mineral spectra (Figure 5.5-37 and Figure 5.5-38).

- At the end of the study, several different carbonate minerals in the tailings were subsequently identified (Table 5.5-8).

    - In particular, the mineral rapidcreekite ($Ca_2(SO_4)(CO_3)\cdot 4H_2O$) was identified more frequently than any other carbonate minerals.

    - Thermodynamic data for rapidcreekite is limited, and future work will involve a comprehensive literature search in order to model it and better predict equilibrium pore water values for HCO_3^-

    - As rapidcreekite contains sulfate, it will be more challenging than calcite to resolve against the large amounts of gypsum in the tailings. The technique used in the most recent U of S research sought to exclude areas of high S concentrations in the solids, which may have removed areas of rapidcreekite precipitation causing a potential underestimation of its prevalence.

    - To better estimate the concentration of rapidcreekite in the tailings, future work will involve a more detailed microprobe analysis of gypsum-rich areas to identify possible co-precipitation with rapidcreekite.

This research was continuing using samples of the 2018 TOVP but was significantly delayed due to the Covid -19 pandemic and two extended shutdowns of the Canadian Light Source Synchrotron Facility due to equipment failure. Currently a new research program is in progress to advance this work further.

Figure 5.5-34: Averaged uranium pore water values by three-meter interval presented for each in situ sampling campaign from 2004-2023. Noted is the large increase in U pore water values between 2004 and 2008 and subsequent stabilization in 2013 - 2023.

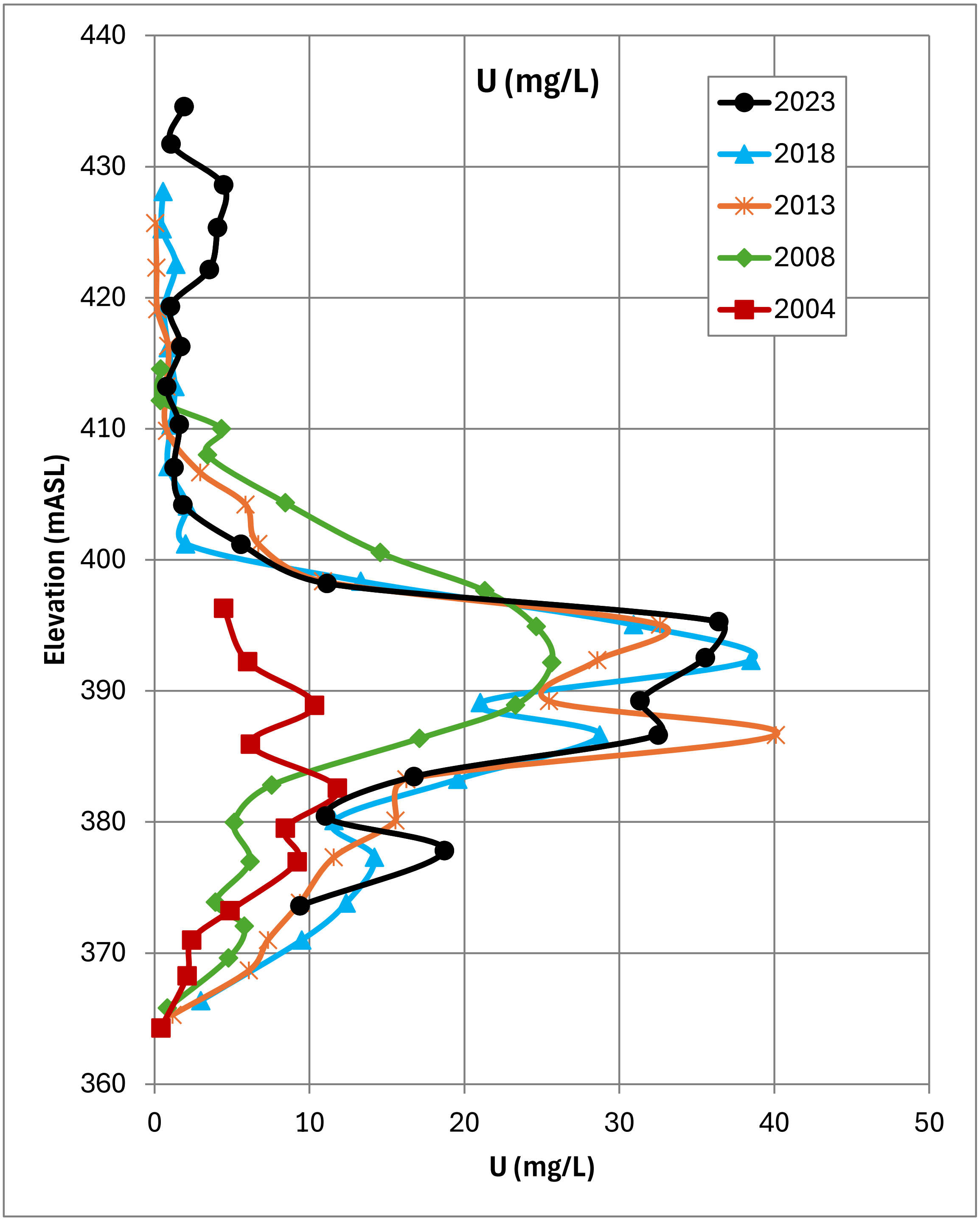
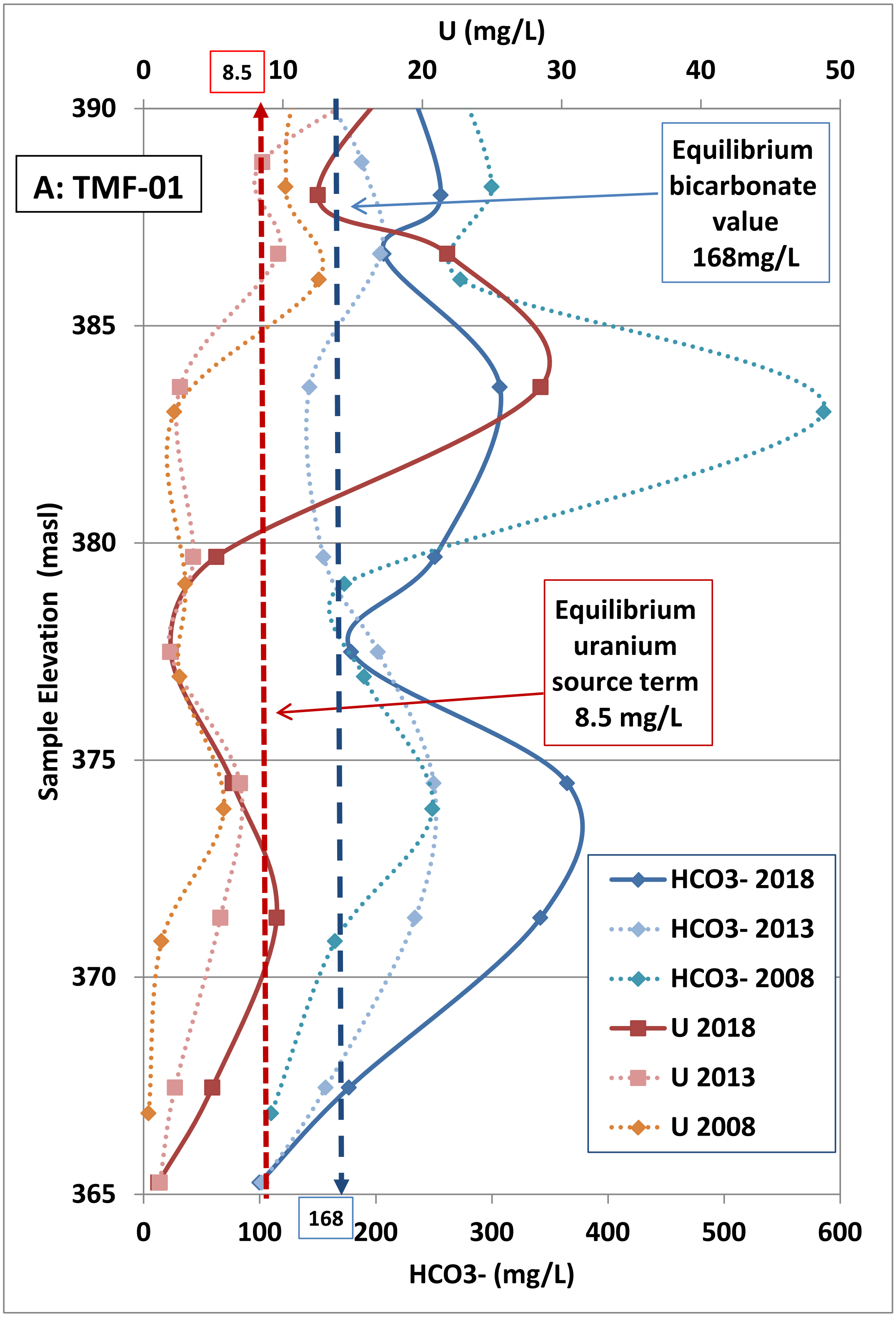


Figure 5.5-35: A) Example Equilibrium Conditions in Borehole TMF-01 Below 390 mASL from 2008 to 2018) B) Example of Equilibrium Conditions in Borehole TMF-04 Below 383 mASL from 2013 to 2023



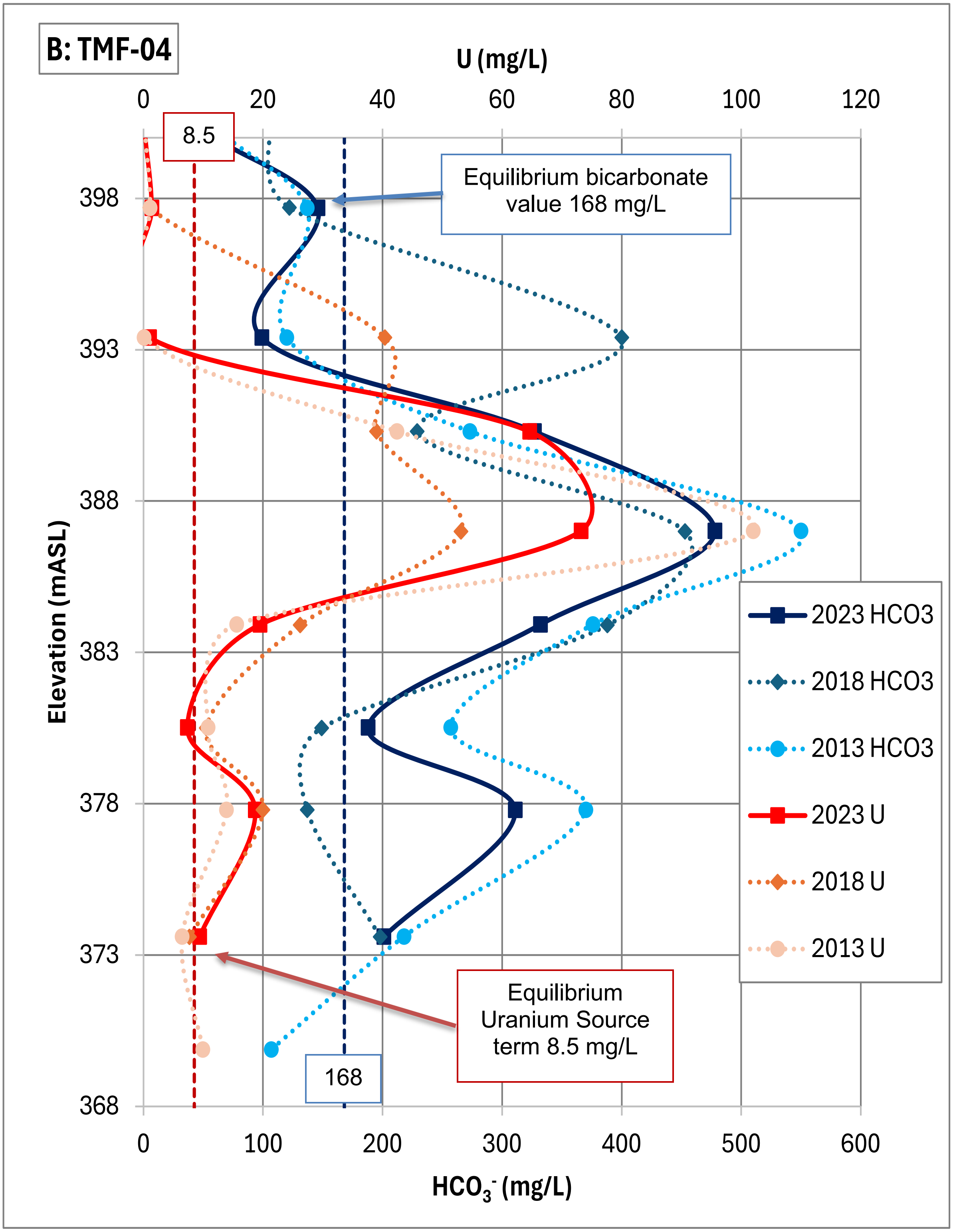

B: TMF-04
U (mg/L)
0
20
40
60
80
100
120
8.5
Equilibrium bicarbonate value 168 mg/L
398
393
388
383
378
373
368
Elevation (mASL)
2023 HCO3
2018 HCO3
2013 HCO3
2023 U
2018 U
2013 U
Equilibrium Uranium Source term 8.5 mg/L
168
0
100
200
300
400
500
600
HCO3- (mg/L)

Figure 5.5-36: XRF maps showing the distribution of Ca, S, U, Cl, P, Fe, Si and K collected from tailings sample TMF13-01 SA14 (a to h respectively). Each map is 500X500 µm. Spots where individual Ca K-edge µ-XANES spectra were collected are marked, scales are 50µm in length (from Situm et al. 2020)

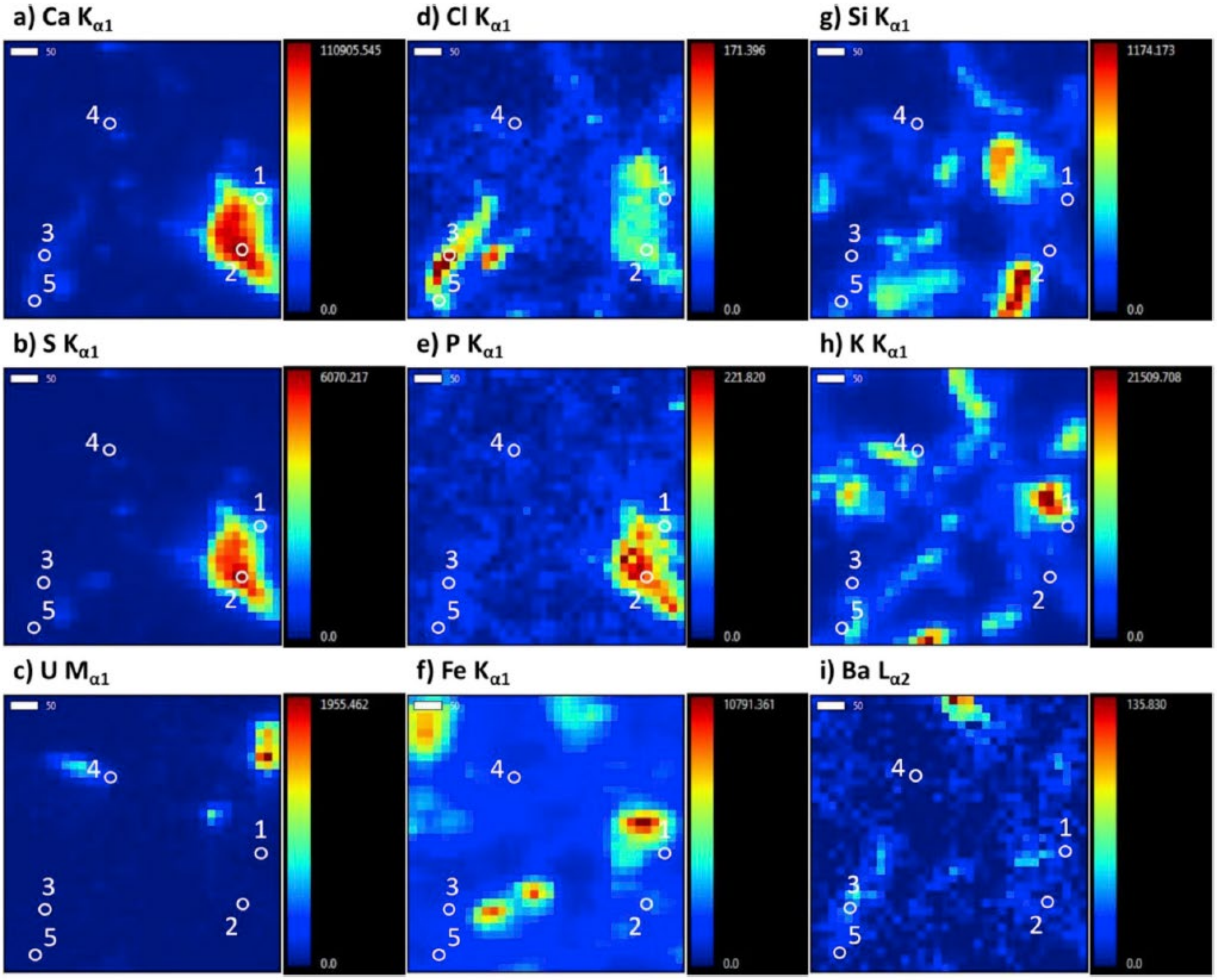


Figure 5.5-37: Ca K-edge XANES spectra from Ca standards collected for the U of S study (from Situm et al. 2020)

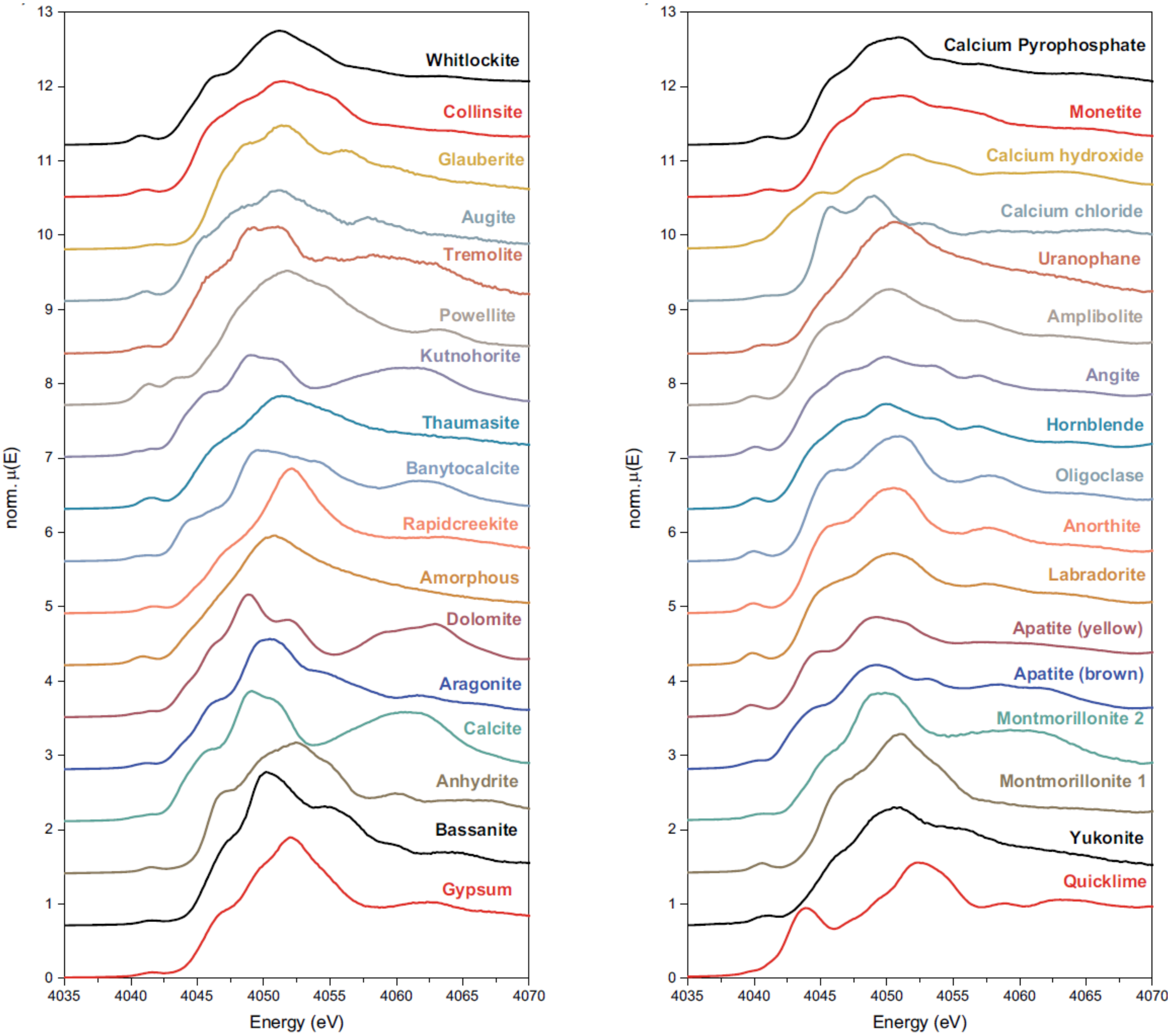


Figure 5.5-38: Examples of fitted C K-edge u-XANES spectra from TMF13-01 SA14 from spot 3 and 5 (Situm et al. 2020)

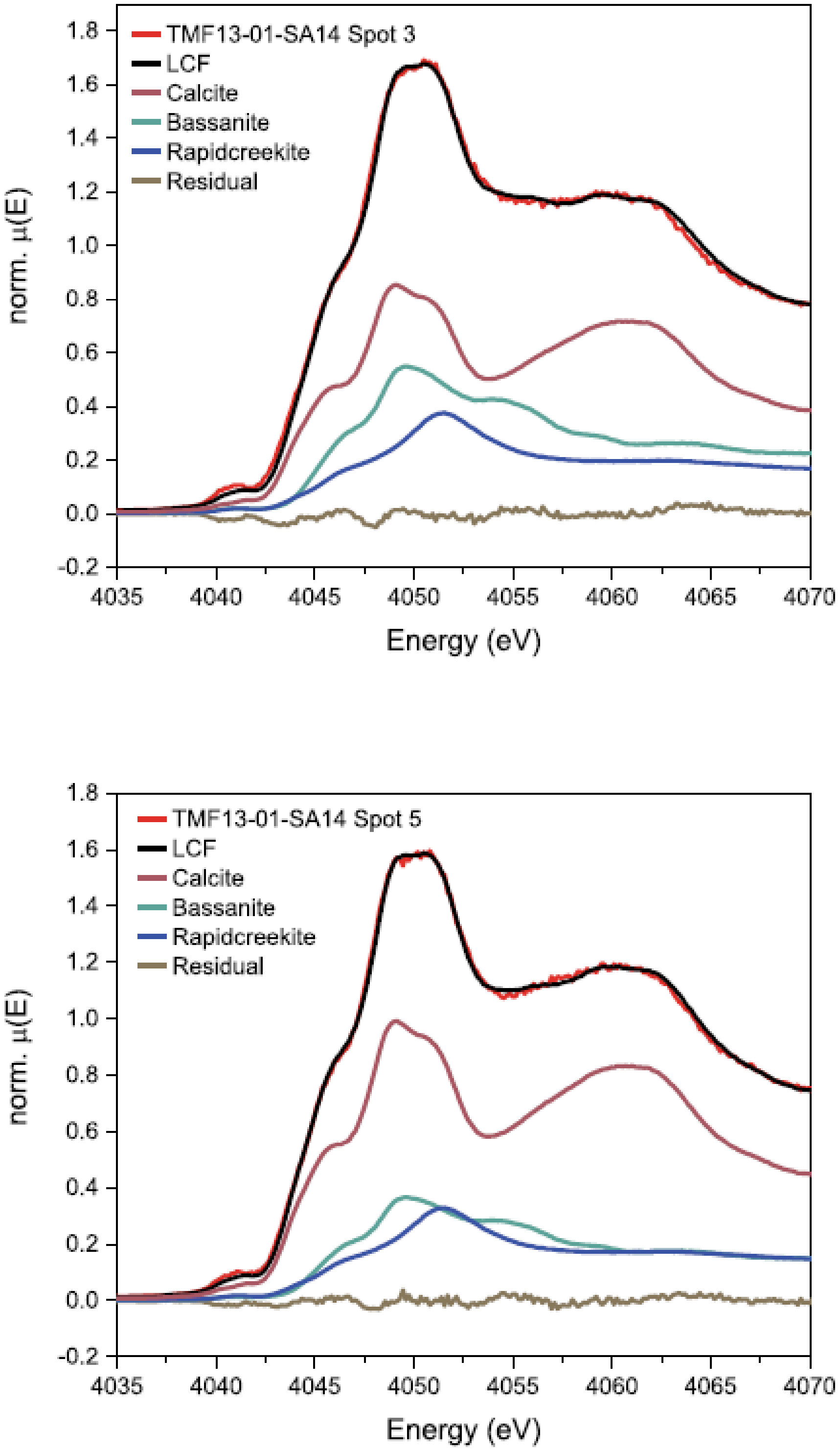


Table 5.5-8: Carbonate minerals identified in the tailings using combined XRF, μ-XANES analysis.

Mineral	Formula	# Discrete Identifications
Rapidcreekite	**$Ca_2(SO_4)(CO_3)\cdot 4H_2O$**	45
Aragonite	$CaCO_3$	6
Dolomite	$CaMg(CO_3)^2$	6
Calcite	$CaCO_3$	2
Amorphous calcium carbonate	$CaCO_3$	4
Thaumasite	$Ca_3Si(OH)^6(CO_3)(SO_4)\cdot 12H_2O$	1
Barytocalcite	$BaCa(CO_3)_2$	0
Kutnohorite	$CaMn(CO_3)_2$	0
Total		64

5.5.3.4 Conclusions – Uranium Geochemical Model

The current model for the U-HCO_3^--calcite system consists of two principal components:

1) The concentration of HCO_3^- in the tailings pore water is constrained to an upper limit by the solubility of carbonate minerals in the tailings solids.
2) Uranium in the tailings pore water occurs predominantly as UO_2CO_3 complexes, which in turn are controlled by the concentration of HCO_3^- in solution.

Since 2008, the hydrocarbon concentrations of the tailings solids has been uniformly low, with outlier values likely representing mill upset conditions. The low hydrocarbon concentrations in the tailings solids, combined with the observed stabilization of pore water HCO_3^- and U concentrations since 2018, suggest that the respective peak concentrations in the tailings pore water have been reached.

The investigations by the U of S and the Canadian Light Source has identified new carbonate minerals, in addition to calcite, which may act together to control the solubility of HCO_3^- in the tailings pore water.

The following future work is planned with respect to uranium investigations:

- Geochemical modelling to estimate equilibrium pore water concentrations of U and HCO_3^- will be revisited and refined based on the results of investigations to date.

- The previously planned study, in conjunction with the U of S and Canadian Light Source, will now occur to attempt to identify and characterize stable oxidized uranium mineral phases in the tailings solids. The development of synchrotron-based techniques to accomplish the research objectives has begun and initial work is summarized in the paper Situm et. al. (2020) which may be found in Appendix E.

5.6 Verification of Tailings Geotechnical Properties

5.6.1 Introduction

The geotechnical-related objectives of the TOVP are to:

1. Evaluate the segregation and stratification of placed tailings;
2. Determine the long term predicted permeability of placed tailings; and,
3. Assess the tailings consolidation behaviour.

Advances have been made regarding each of these objectives since the 2020 TID report was issued. Specific progress includes:

- Developing site-specific correlations that link easily measured geotechnical parameters with the hydromechanical properties of interest;
- Implementing a Bayesian network, which uses a graphical probabilistic network to quantify the site-specific correlations;
- Utilizing these tools to develop a "block" model that represents the JEB Pit TMF that will be used to perform consolidation modelling for predictions of long-term performance.

The following sections provide:

- An overview of the geotechnical design basis for the JEB Pit TMF (5.6.2.1),
- a brief summary of the conclusions from the previous TID report, (5.6.2.2)
- additional information on work completed since the last TID report
- Overview (5.6.2.3)
- 2021 TOVP (5.6.3)
- 2023/2024 TOVP (5.6.4)
- field investigation issues encountered since the last TID report (5.6.4.3), and
- an overview of proposed and ongoing work related to characterizing the geotechnical performance of the stored tailings in the JEB Pit TMF (5.6.5).

Results of the development of the site-specific correlations are discussed herein, however, the work related to the block model and consolidation modelling remains ongoing. No discussion of preliminary data has been included in this summary.

5.6.2 Background Information

5.6.2.1 JEB Pit TMF Geotechnical Design Basis

The hydraulic containment design for the JEB Pit TMF relies on the tailings' consolidated hydraulic conductivity being two orders of magnitude lower than the surrounding sandstone formation. Because the tailings are less permeable than the surrounding sandstone, the preferred groundwater flow path is through the sandstone, reducing the advective release of solute through the tailings, meaning that diffusion becomes the controlling rate of contaminant transport. The TMF features a granular drainage layer and raise well pumping system at the bottom of the pit, below the tailings. This is intended to create and maintain a hydraulic gradient towards the TMF as well as accelerate consolidation.

5.6.2.2 Summary of Conclusions From 2020 TID Report

The 2020 TID report summarized data from borehole sampling, dredge sampling, cone penetration testing (CPT), and laboratory testing conducted during two site investigations in 2017 and 2018. The focus of the laboratory testing in this report was on the Cigar Lake tailings, since these programs marked the first efforts to sample and characterize the Cigar Lake tailings. The associated laboratory program included the following tests (Table 5.6-1).

Table 5.6-1: Summary of 2018 TOVP Laboratory Testing

Test	Purpose
Atterberg Limits	Determine the plasticity of the fine-grained tailings and anticipate general behavior
Grain Size / Particle Size Distribution (PSD)	Quantify coarse/fine particles; assess segregation
Specific Gravity, Moisture Content, Dry/Bulk Density	Evaluate useful parameters (i.e. void ratio) through weight-volume relationships
Settling Tests	Build the compression curve at very low effective stresses (below 1 kPa)
Seepage Induced Consolidation (SIC) Tests	Determine the compressibility response of the tailings samples with high void ratios at low effective stresses and measure the vertical hydraulic permeability
Large Strain Consolidation (LSC) Tests	Determine the compressibility response of the tailings samples with high void ratios at various effective stresses and determine the vertical hydraulic conductivity.
Creep Test	Determine the amount of deformation of a sample under isotropic stress conditions

Key conclusions pertaining to the Cigar Lake tailings from the in-situ and laboratory testing include:

- Based on both borehole and dredge sampling, the subaqueous deposition method has not eliminated segregation of tailings during placement;
- Coarse tailings are generally observed in close proximity to deposition points. As distance from the deposition point increases, tailings become progressively finer until reaching approximately 40 meters, beyond which the grain size tends to stabilize and remains uniformly fine-grained.
- Due to the segregation that occurs during deposition, and the historic practice of depositing tailings near the centre of the facility, it may be assumed that there are predominantly fine tailings against the pit walls.
- The Cigar Lake tailings are generally finer than the underlying JEB/Sue tailings.
- The clay-sized content plays a significant role in defining the hydraulic conductivity of the Cigar Lake tailings.
- The fine tailings' hydraulic conductivity is generally two orders of magnitude less permeable than the surrounding sandstone formation, meeting its design objective.

5.6.3 New Programs Since the 2020 TID

5.6.3.1 Overview

Since the last TID report, four dredge sampling campaigns (2021, 2022, 2023 and 2024) and two site investigations (2021, 2023/2024) have been completed. Dredge sampling, on each occasion, was completed in a radial pattern originating from the most recent deposition points to characterize the tailings segregation during deposition. All dredge samples have only sampled Cigar Lake tailings.

Site investigations have featured a combination of borehole and dredge sampling, CPTu soundings, and laboratory testing. Laboratory testing for the 2023/2024 TOVPs remains ongoing but is expected to be completed by late summer of 2025 with analysis completed in early 2026. This report will be updated with an addendum to reflect that work. Given the large number of samples and testing completed to date on the JEB/Sue tailings, and their relatively well understood behaviour, the 2021, 2023/2024 campaigns have placed an emphasis on characterizing the Cigar Lake tailings.

Despite the 2021 and 2023/2024 TOVPs having similar sampling and testing procedures as past campaigns, a different framework was used to select and characterize samples. Previous programs combined Shelby tubes to develop composite samples and characterized these samples with the intention of assessing the “bulk material” performance. This method was not conducive to identifying trends between index testing and the hydromechanical properties. As opposed to characterizing composite samples and assuming those properties applied to the portion of the TMF where the sample was collected, the 2023/2024 TOVP, focused on understanding the segregation characteristics of the tailings, not creating composite samples, and instead grouping the segregated tailings into discrete “bins”, and characterizing each “bin” accordingly.

To characterize the tailings within each “bin”, easily measured index or CPTu parameters, such as the plasticity index or porewater pressure ratio from CPTu soundings, were linked with the hydromechanical properties, such as compressibility and hydraulic conductivity. The probabilities associated with these links were then quantified using a Bayesian network. Bayesian networks (also commonly referred to as ‘belief networks’ or ‘causal networks’) are a type of probabilistic model that apply Bayes Rule to calculate the conditional probability of an event or condition occurring (i.e., tailings hydraulic conductivities being less than $1x10^{-7}$ m/s) based on other observations that may be related (i.e., tailings having high plasticity or fines content).

By establishing a link between index, CPTu, and hydromechanical properties, disturbed samples coupled with index testing from around the facility may be used to provide a probabilistic estimate of whether the tailings will meet their hydraulic conductivity requirement (or other parameters of interest). This strategy improves the resolution of the pit characterization, as it is no longer limited to the small number of samples subjected to expensive laboratory testing.

Key aspects of the work completed between 2020 and 2025 regarding the three objectives of the TOVP are summarized below:

1. **Segregation:**

- Evidence of segregation during deposition has been found in each of the three field investigations, confirming the findings of the 2017 and 2018 programs

- Segregation characteristics have been evaluated using both dredge and borehole samples. In summary, the tailings become increasingly finer with increasing distance from the deposition point. Cigar Lake tailings become predominantly fine grained and poorly graded at approximately 50m from the deposition.

- Since tailings deposition has been limited to at least 30m from the pit edge, the segregation of the tailings during deposition is a benefit to the hydraulic containment of the facility as the finer tailings that deposit further from the deposition point have a lower conductivity than the coarser tailings deposited near the deposition point. Additional details regarding hydraulic conductivity estimates are provided in the following sections.

- Using the plasticity index, as opposed to the fines content, has been found to be a good indicator of tailings material type. Accordingly, the plasticity index is now used as the main criteria for assessing segregation.

- Cigar Lake Tailings were categorized into three different “bins” based on their plasticity index: “Low”, “Medium”, and “High”. In addition to the plasticity index, these bins correlate to several other geotechnical characteristics that will be discussed in the following sections.

2. **Hydraulic Conductivity**

- The hydraulic conductivity of the tailings has been found to range between 1x10^{-6} m/s to 1x10^{-8} m/s, which is consistent with previous programs.

- Tailings that have a low plasticity index are generally on the upper end of this range, while high plasticity tailings are at the lower end of this range.

- At this stage, the Bayesian network provides an estimate of whether the tailings have a hydraulic conductivity that is higher or lower than 1 x 10^{-7} m/s. The network incorporates information related to plasticity index, fines content, tailings type, overburden pressure, and porewater pressure ratio (Bq) as measured from the CPTu. Key conclusions pertaining to the findings of the Bayesian network are presented in a later section.

3. **Consolidation**

- The compressibility of the tailings has been evaluated using the “bin” strategy. In general, tailings with a higher plasticity index are more compressible than those with a lower plasticity index.

- Modelling to provide estimates of consolidation rates and settlement during and after operations is currently underway. Work related to this task is expected to be completed in early 2026.

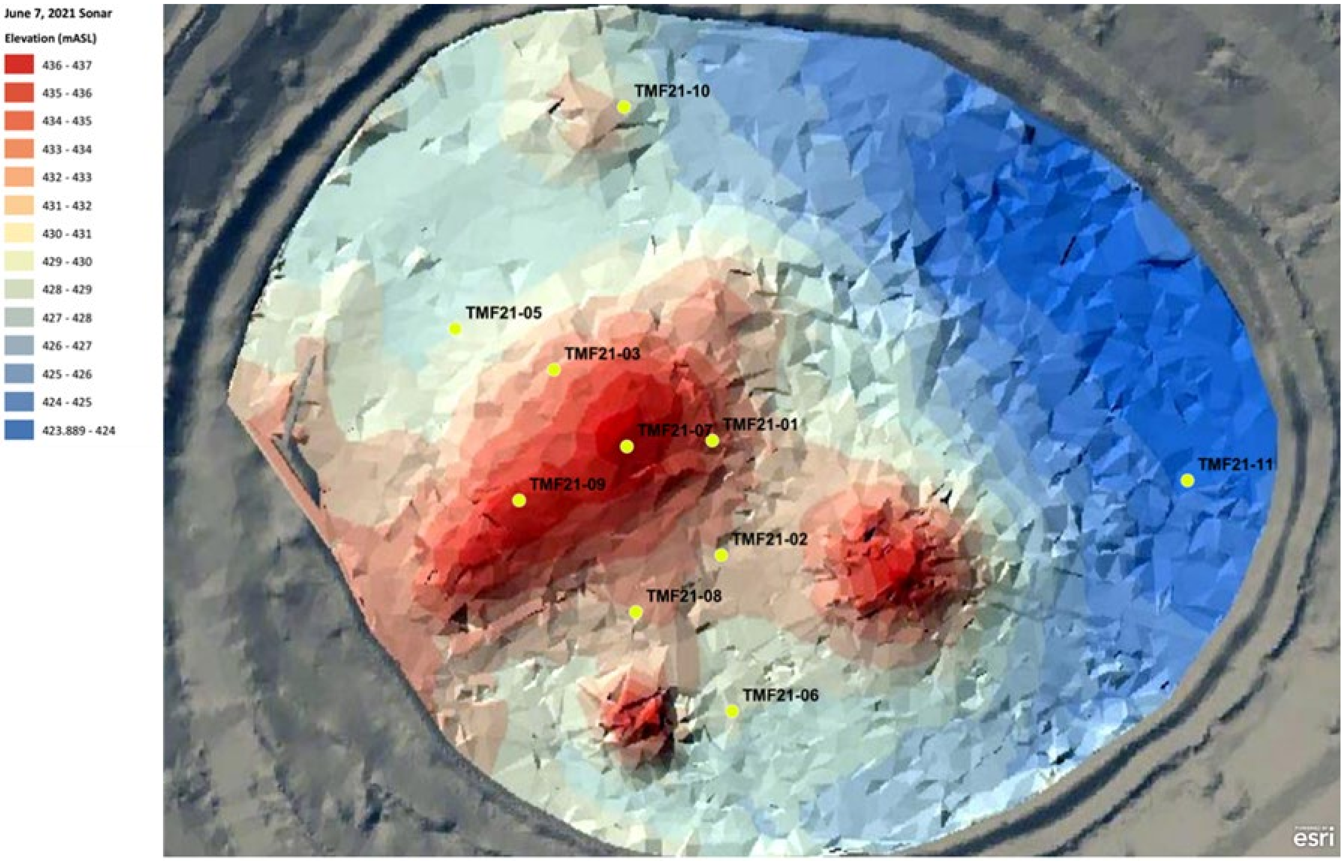
The following sections provide a chronological summary of the work completed between 2020 and 2025 that supports the findings discussed above. In addition, a discussion of issues encountered during the latest sampling campaigns is provided at the end.

5.6.3.2 2021 TOVP

2021 TOVP Overview

The 2021 field investigation involved a barge-based drilling program that included the completion of 10 boreholes, 11 cone penetration soundings (CPTu), and 68 porewater dissipation tests. The location of these boreholes and CPTu soundings are shown in Figure 5.6-1.

Figure 5.6-1: Location of CPTu soundings and boreholes completed within the JEB Pit TMF during the 2021 TOVP (July 7, 2021 Sonar).



The laboratory testing program for the 2021 TOVP was divided into two phases. The first phase consisted of index testing – which was used to select samples for the second phase of testing. Phase 1 testing included:

- Visual Soil Description (ASTM 2488);
- Particle Size Distribution via Laser Diffraction (ASTM C1070);
- Atterberg Limits (ASTM D 4318);
- Specific Gravity (ASTM D854).

After the first phase of laboratory testing, relationships between these index parameters were explored and samples were grouped into characteristic “bins”. Representative samples from each bin were then subjected to Phase 2 testing, which included:

- Flexible wall permeameter testing; and,
- Additional index testing including:

- Particle Size Distribution (with hydrometer);
- Atterberg Limit; and,
- Specific Gravity.

2021 TOVP – Phase 1 Laboratory Testing

Table 5.6-2 and Figure 5.6-2 to Figure 5.6-5 provide a summary of the results, particle size distributions, and Atterberg limits from the Phase 1 testing, respectively.

As indicated in Figure 5.6-2, samples ranged from having 15% to 95% of their particles being < 0.0075mm (the conventional cut off for fine-grained material), while clay sized particles ranged from ~4% to ~28%. These findings are relatively consistent with testing completed during the 2017 and 2018 programs and support the conclusion that the Cigar Lake tailings are highly heterogeneous. A comparison of these results to the 2017 and 2018 programs is shown in Table 5.6-3.

Although the Cigar Lake tailings were found to be non-plastic during the 2017 and 2018 programs, Atterberg limits were conducted on 2021 samples. Unlike the 2017 and 2018 data, large variations in the plasticity of each sample were observed. As shown in Figure 5.6-3, plasticity indexes ranged from non-plastic (0) to 46. Samples with a higher plasticity index tended to have a higher fines content, although there was significant scatter observed for samples with a high fines content. This variation between the 2017/2018 results and the 2021 results likley reflects the two factors. First samples taken in 2017 and 2018 represent some Cigar Lake tailings produced under start-up commissioning conditions which is a significantly different condition than tailings sampled later produced during normal operations. Second, as discussed in section 5.3.2 the Cigar lake tailings are significantly variable due to the lack of blending in the mill.

As shown in Figure 5.6-4, samples with similar silt or clay contents were observed to be anywhere from non-plastic to having a plasticity index > 40. Accordingly, it was determined that categorizing the Cigar Lake tailings by plasticity index, as opposed to fines content, would provide a better resolution in differentiating material behaviour. As shown in the following section, this observation was subsequently validated when comparing measured hydraulic conductivities to fines content and plasticity index, respectively.

Table 5.6-2: Index Properties from Phase 1 Laboratory Testing

Sample Name	Tailings Source	Gs	Plastic Limit	Liquid Limit	Plasticity Index	Fines Content (%)
TMF21-01-SA01	Cigar Lake	2.58	23.1	31.8	8.7	84.0
TMF21-01-SA02	Cigar Lake	2.68	44.3	61.6	17.3	90.6
TMF21-01-SA03	Cigar Lake	2.60	52.3	65	12.7	93.5
TMF21-01-SA04	Cigar Lake	2.67	21.2	30.1	8.9	53.6
TMF21-01-SA05	Cigar Lake	2.69	27.9	33.6	5.6	69.8
TMF21-02-SA01	Cigar Lake	2.74	52.7	87.9	35.2	96.2
TMF21-02-SA04	Cigar Lake	2.99	48.5	60.5	12	94.2
TMF21-03-SA01	Cigar Lake	2.54	29.1	46.5	17.4	91.9
TMF21-03-SA02	Cigar Lake	2.55	60.4	78.7	18.2	90.1
TMF21-03-SA03	Cigar Lake	2.63	73.1	98.7	25.7	92.2
TMF21-03-SA04	Cigar Lake	2.58	59.8	76.5	16.7	98.2
TMF21-03-SA05	Cigar Lake	2.69	0	0	0	44.8
TMF21-05-SA02	Cigar Lake	2.68	0	0	0	97.1
TMF21-05-SA03	Cigar Lake	2.77	65.6	111.7	46	95.2
TMF21-06-SA01	Cigar Lake	2.70	56.8	89.8	33	91.3
TMF21-06-SA03	Cigar Lake	2.50	45.3	65.6	20.3	84.0
TMF21-06-SA04	Cigar Lake	3.04	26.8	40.5	13.7	94.2
TMF21-06-SA05	Cigar Lake	2.67	46.7	69.3	22.6	97.2
TMF21-07-SA02	Cigar Lake	2.87	0	0	0	48.7
TMF21-07-SA03A	Cigar Lake	2.87	20.2	24.2	4	25.3
TMF21-07-SA04	Cigar Lake	2.51	53.7	59.6	6	89.2
TMF21-07-SA05	Cigar Lake	2.79	21.4	25.5	4.1	28.9
TMF21-07-SA06	Cigar Lake	2.80	0	0	0	16.4

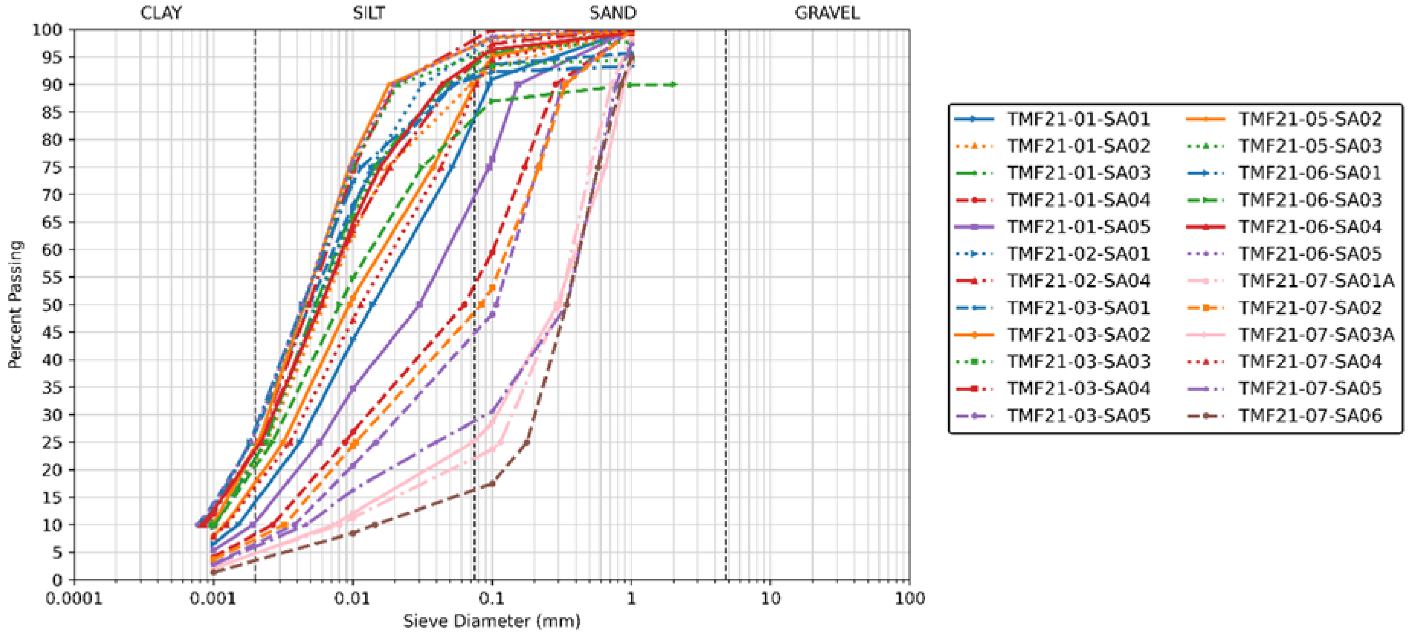


Figure 5.6-2: Particle Size Distribution (PSD) from 2021 TOVP Phase 1 Testing

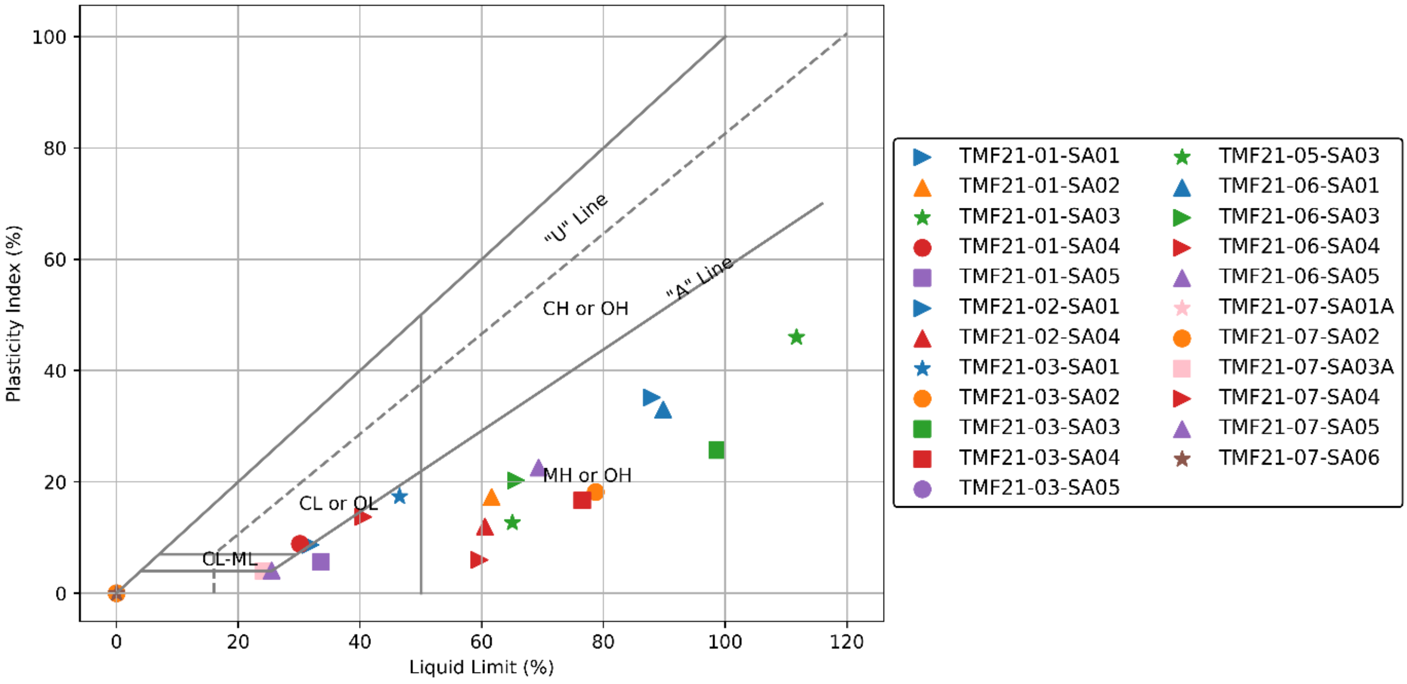


Figure 5.6-3: Atterbergs Limits from 2021 TOVP Phase 1 Testing

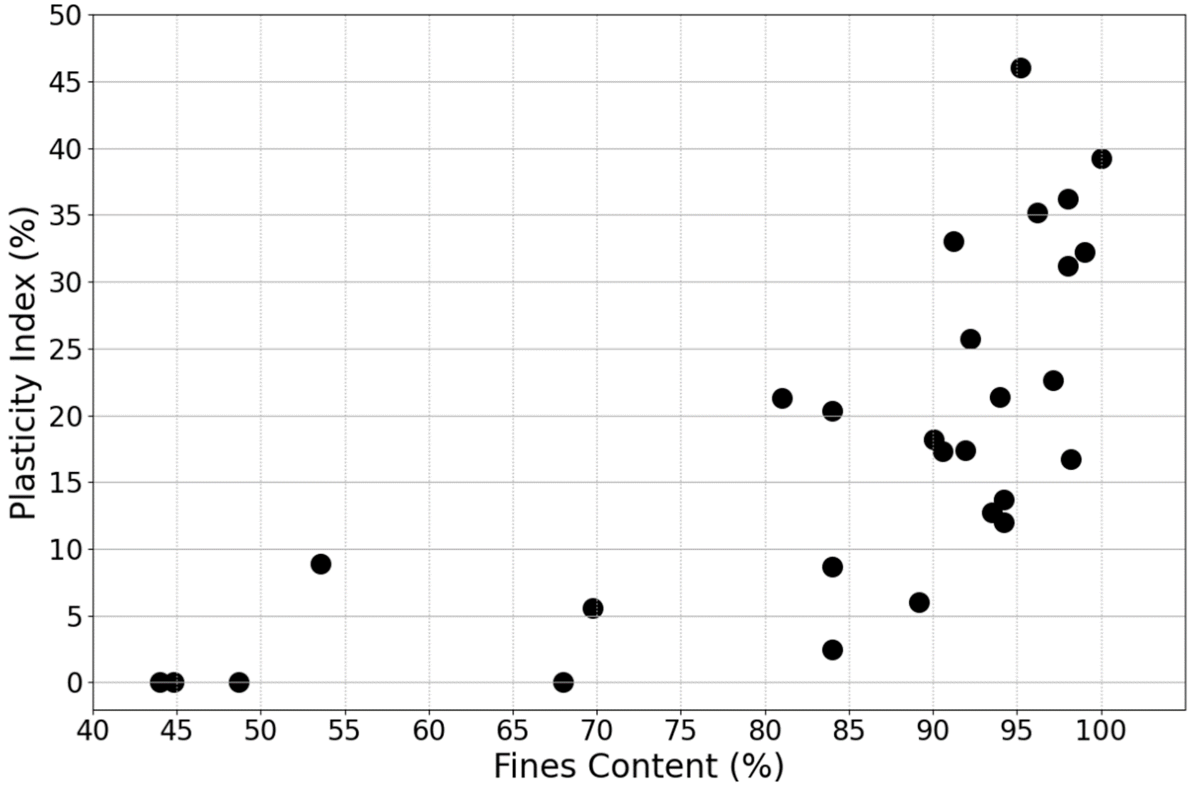


Figure 5.6-4: **Fines Content vs. Plasticity Index for all Cigar Lake Tailings Samples**

Table 5.6-3: **Summary PSD Comparison from 2017, 2018 and 2021 TOVPs**

Program Year (%)	Fines Content (%)	Clay Content (%)
2017	41 to 100	5 to 18
2018	53 to 100	2 to 10
2021	15 to 95	4 to 28

Based on these results, tailings were grouped into “bins” and selected representative samples from each bin for more advanced testing. The sample selection and conceptual framework is visualized in Figure 5.6-5.

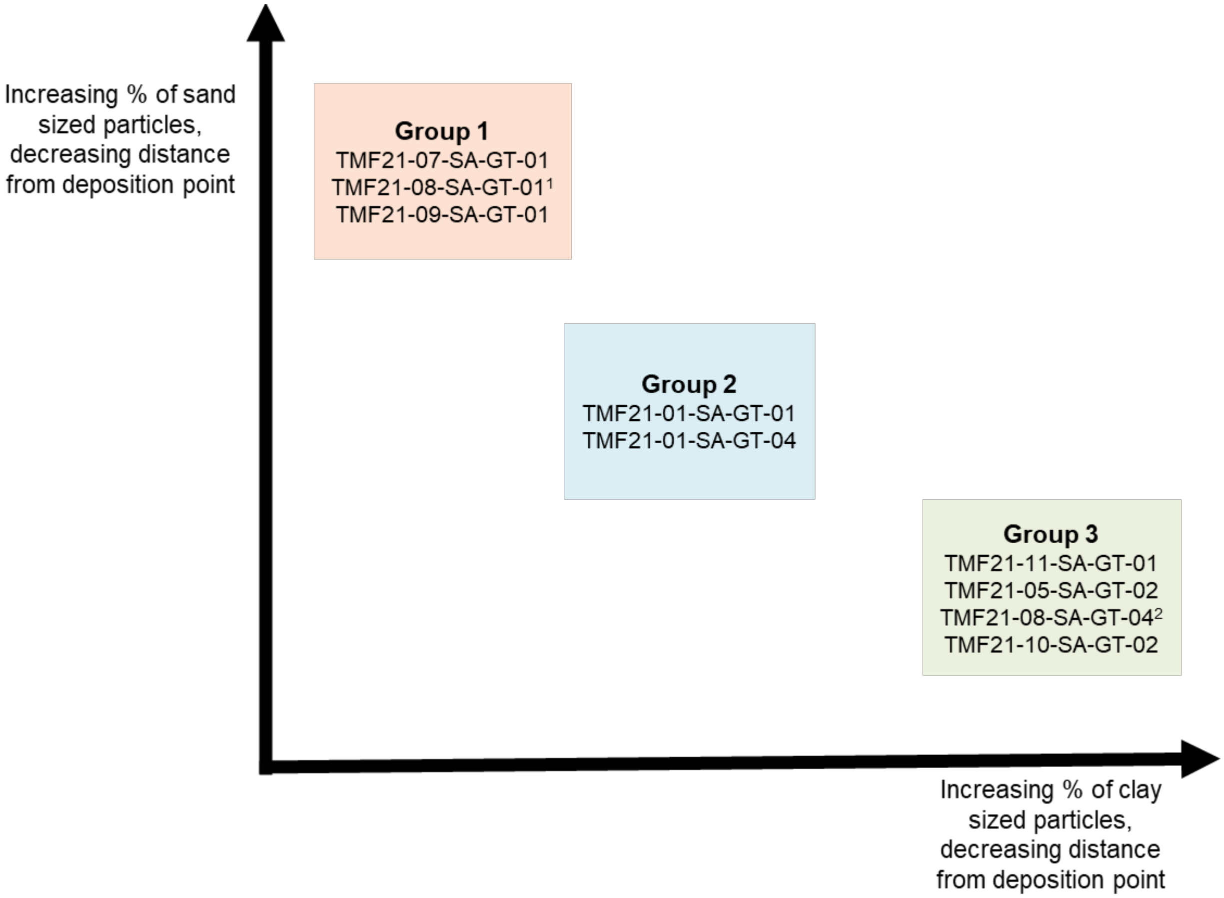


Figure 5.6-5: Samples Selected for Phase 2 Testing

2021 TOVP – Phase 2 Laboratory Testing

The results of the Phase 2 testing are summarized in Table 5.6-4. As previously discussed, the strategy for characterization was to find a link between index and/or CPTu parameters and the hydromechanical properties, such as hydraulic conductivity. To find a link, an exploratory analysis was performed, and the hydraulic conductivities were compared to fines content (Figure 5.6-6), plasticity index (Figure 5.6-7) and a ratio of plasticity index to fines content (Figure 5.6-8).

From this assessment, the following observations were made:

- The plasticity index was confirmed to provide a higher resolution of the change in hydraulic conductivity and reduces scatter relative to the relationship between hydraulic conductivity and fines content;
- Material categories should be based on plasticity index, rather than fines content, due to the wide range of potential plasticity index associated with similar high fines content, and better representation of the range of hydraulic conductivities.

- There is a trend of decreasing hydraulic conductivity with increasing fines content and plasticity index; more specifically:

- Tailings with a fines content greater than 95% are likely to have a hydraulic conductivity less than $1x10^{-7}$ m/s;

- Tailings with a plasticity index greater than 25% are likely to have a hydraulic conductivity less than $1x10^{-7}$ m/s;

- The ratio of plasticity index to fines content provides a clear semi-log relationship for tailings with some plasticity, but not for non-plastic tailings (plasticity index / fines content > 0);

- There is a trend of decreasing hydraulic conductivity with increasing effective stress (indicated by the colour of the symbols in Figure 5.6-6 to Figure 5.6-8);

- The change in hydraulic conductivity between 10 kPa and 400 kPa effective confining pressures is typically less than one magnitude for all sample types (low, medium, high plasticity);

Since the 2017 and 2018 tailings were deemed non plastic, the “bin” categories based on plasticity index are not applicable to the historic samples. However, a look at the trend between fines content and hydraulic conductivity is shown in Figure 5.6-9. As shown, the historic data follows the same trend as the 2021 data, with a similar level of scatter.

Figure 5.6-10 provides a plot of plasticity index / fines content vs the dynamic porewater pressure ratio measured from the CPTu (Bq). The samples selected for Phase 2 testing are indicated by yellow ‘X’s. There is a trend of increasing Bq with increasing ratio of plasticity index / fines content. This trend is more apparent in the Phase 2 samples. The clearer trend between Phase 2 samples relative to Phase 1 samples is likely due to the careful subsampling procedure used for Phase 2 samples.

Table 5.6-4: Summary of Phase 2 Results

Post Laboratory Classification	Sample Name	Plasticity Index (%)	Specific Gravity, Gs	Sand Content 2mm < x < 0.075mm (%)	Fines Content <0.075mm (%)[1]	Clay Content, <0.002mm (%)	Stress, σ (kPa)	Void Ratio, e	Hydraulic Conductivity, k (m/s)
Coarse / Non-plastic	TMF21-07-SA-GT01	0 (NP)	3.07	55.8	44.2	1.7	(initial)	2.46	-
							10	1.94	2.1×10^{-6}
							100	1.65	2.1×10^{-6}
							400	1.44	9.9×10^{-7}
							10 (unload)	1.61	-
	TMF21-09-SA-GT-01	0 (NP)	3.14	16.4	83.6	0.4	(initial)	4.19	-
							22	2.72	2.0×10^{-6}
							100	1.77	1.0×10^{-6}
							400	1.32	9.9×10^{-7}
							10 (unload)	2.44	-
	TMF21-10-SA-GT-01	0 (NP)	2.75	31.6	68.4	0.5	(initial)	2.52	-
							16	1.82	5.1×10^{-7}
							100	1.67	1.3×10^{-7}
							400	1.56	8.7×10^{-8}
							10 (unload)	1.63	-
Medium	TMF21-08-SA-GT-04	21.3	3.17	19.2	80.8	0.4	(initial)	3.11	-
							47	2.65	1.4×10^{-7}
							100	2.42	8.6×10^{-8}
							400	2.02	3.8×10^{-8}
							10 (unload)	2.42	-
	TMF21-01-SA-GT-01[2]	21.4	3.05	6.0	94.0	5.7	(initial)	4.60	-
							10	3.40	5.5×10^{-7}
							100	2.67	1.9×10^{-7}
							400	2.07	7.3×10^{-8}
							10 (unload)	2.22	-
Fine / High Plasticity	TMF21-05-SA-GT-02	31.2	2.97	1.6	98.4	0.3	(initial)	4.14	-
							30	3.26	4.7×10^{-8}

Post Laboratory Classification	Sample Name	Plasticity Index (%)	Specific Gravity, Gs	Sand Content 2mm < x < 0.075mm (%)	Fines Content <0.075mm (%)[1]	Clay Content, <0.002mm (%)	Stress, σ (kPa)	Void Ratio, e	Hydraulic Conductivity, k (m/s)
							100	2.82	3.4×10^{-8}
							400	2.41	1.4×10^{-8}
							10 (unload)	2.99	-
	TMF21-08-SA-GT-01[2]	32.2	2.96	0.7	99.3	2.3	(initial)	4.15	-
							14	3.13	7.9×10^{-8}
							100	2.55	5.4×10^{-8}
							400	1.91	1.9×10^{-8}
							10 (unload)	2.13	-
	TMF21-01-SA-GT-03[2]	36.2	3.04	1.8	98.2	1.8	(initial)	4.06	-
							36	3.46	5.9×10^{-8}
							100	3.09	4.9×10^{-8}
							400	2.25	1.9×10^{-8}
							10 (unload)	2.47	-
	TMF21-11-SA-GT-01[2]	39.2	2.98	0.3	99.7	1.6	(initial)	4.10	-
							18	3.09	2.8×10^{-8}
							100	2.68	2.2×10^{-8}
							400	2.10	8.9×10^{-9}
							10 (unload)	2.32	-

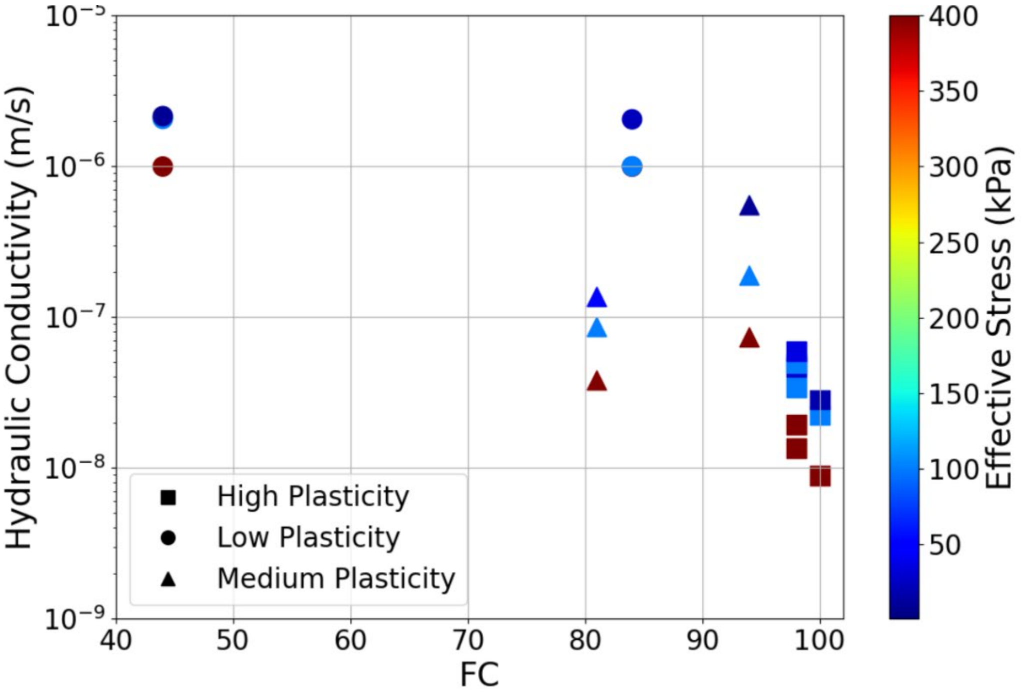


Figure 5.6-6: Fines Content (<0.0075mm particle size) vs. Hydraulic Conductivity.

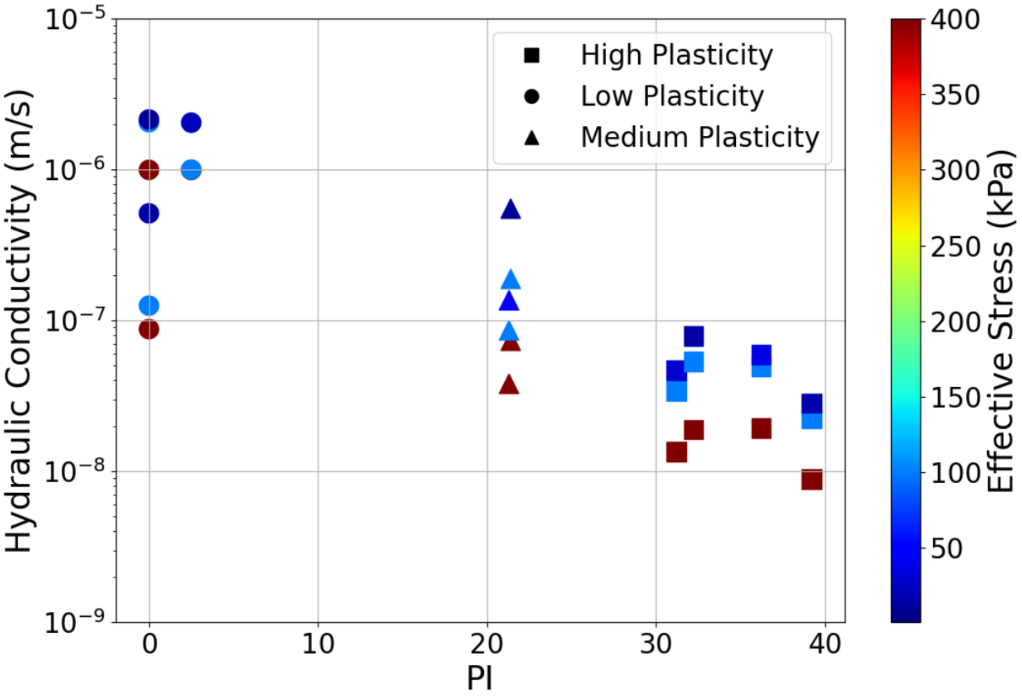


Figure 5.6-7: Plasticity Index vs. Hydraulic Conductivity.

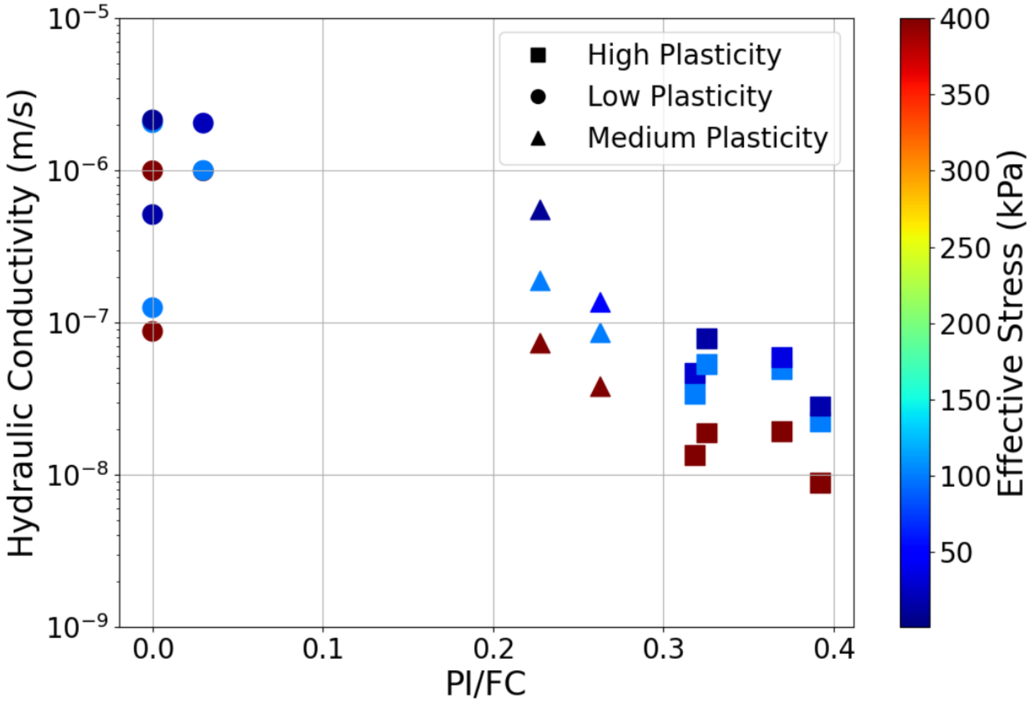


Figure 5.6-8: Plasticity Index (PI) / Fines Content (FC) vs. Hydraulic Conductivity.

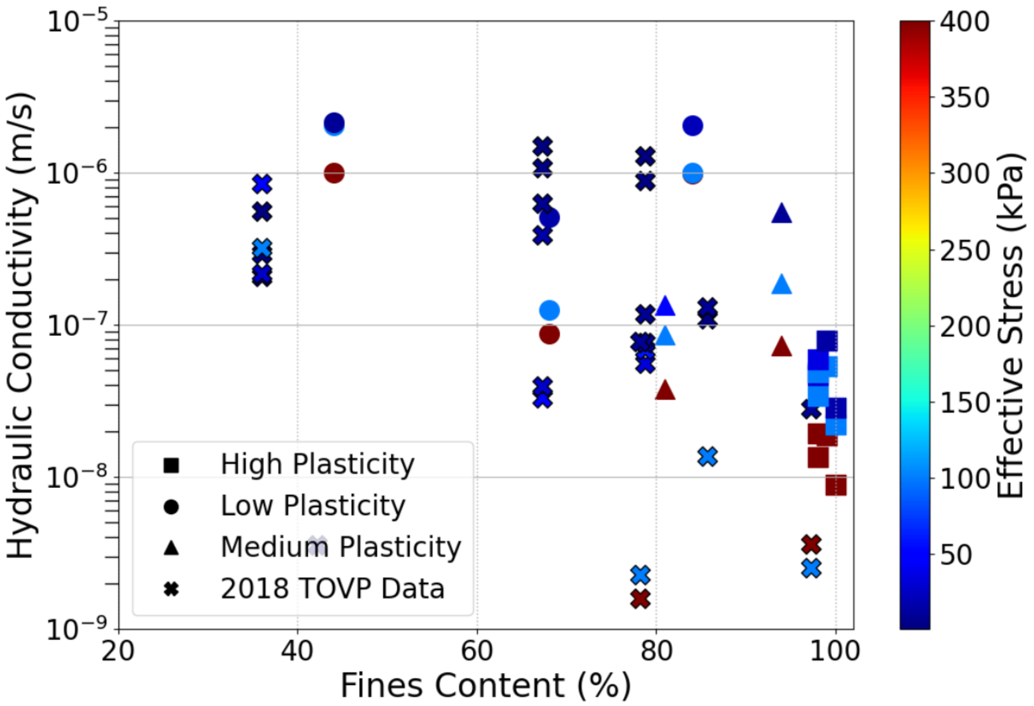


Figure 5.6-9: Comparison of 2018 TOVP Data with 2021 TOVP Data.

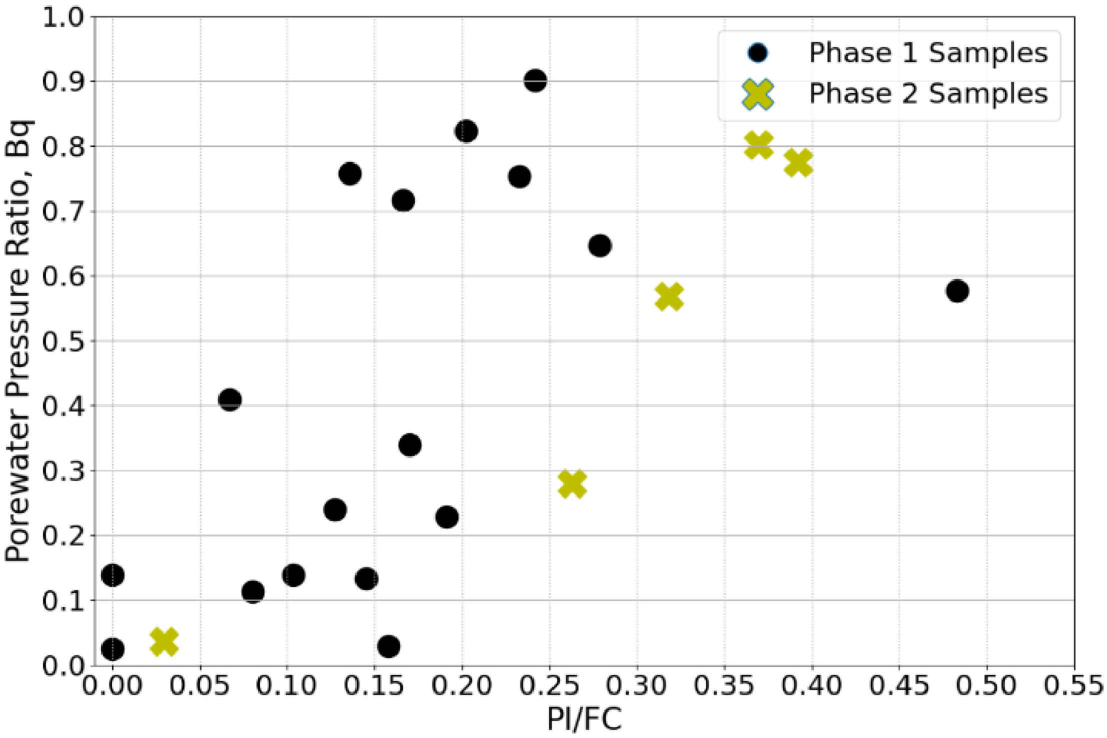


Figure 5.6-10: **Plasticity index (PI) / Fines Content (FC) vs. Porewater Pressure Ratio.**

2021 TOVP – Bayesian Network Development / Quantifying Linkages

Bayesian networks (also commonly referred to as 'belief networks' or 'causal networks') are a type of probabilistic model that apply Bayes Rule to calculate the conditional probability of an event or condition occurring (i.e., tailings hydraulic conductivities being less than $1x10^{-7}$ m/s) based on other observations that may be related (i.e., tailings having high plasticity or fines content). This method was selected in lieu of a traditional deterministic relationship between index and/or CPTu parameters and hydromechanical properties because:

- The relative number of samples to the total volume of tailings is not significant enough to develop reliable deterministic conclusions;
- Different types of data with varying levels of importance and reliability can be combined to enhance the estimate of a parameter; and,
- The results of a Bayesian network model directly address a key objective of the TOVP (what is the probability of tailings hydraulic conductivity meeting the required conductivity?) rather than providing a single-value deterministic estimate that requires further interpretation.

The steps in developing the Bayesian network for the Orano tailings were as follows:

1. Define the network structure using arrows to show relationships between variables (the direction of the arrows indicate causality, in other words A→ B indicates A causes B);
2. Discretize the variables into representative bins;
3. Incorporate data to fit the network; and,
4. Run scenarios and evaluate the performance.

Steps 1 and 2 involved exploring the results of the Phase 1 and 2 laboratory programs to identify important linkages and filling in gaps using expert judgement. The adopted Bayesian network structure is shown in Figure 5.6-11 and was developed based on available data and interpretation. Key rationale for the network, from top down, is as follows:

- The tailings' origin (either JEB/Sue or Cigar Lake) may cause different index properties, fines content and plasticity index. Note that there were only a few JEB/Sue samples available for use in the network, therefore the network should only be considered useful for the Cigar Lake tailings at this time;

- These index properties are a direct indication of the type of material;

- The index properties themselves are also interrelated (a higher fines content could be associated with a higher plasticity index, for example);

- Bq readings from CPTu and estimated distance from the deposition point may give less direct information about the type of material (these do not cause the material type, but are rather indicators that a certain type of material may be present); and,

- The type of material combined with its in-situ condition (stress state) will determine its hydromechanical response in terms of coefficient of volume compressibility (Mv) and hydraulic conductivity (k).

- Note that although Mv is shown in the network below, discussion herein is limited to hydraulic conductivity.

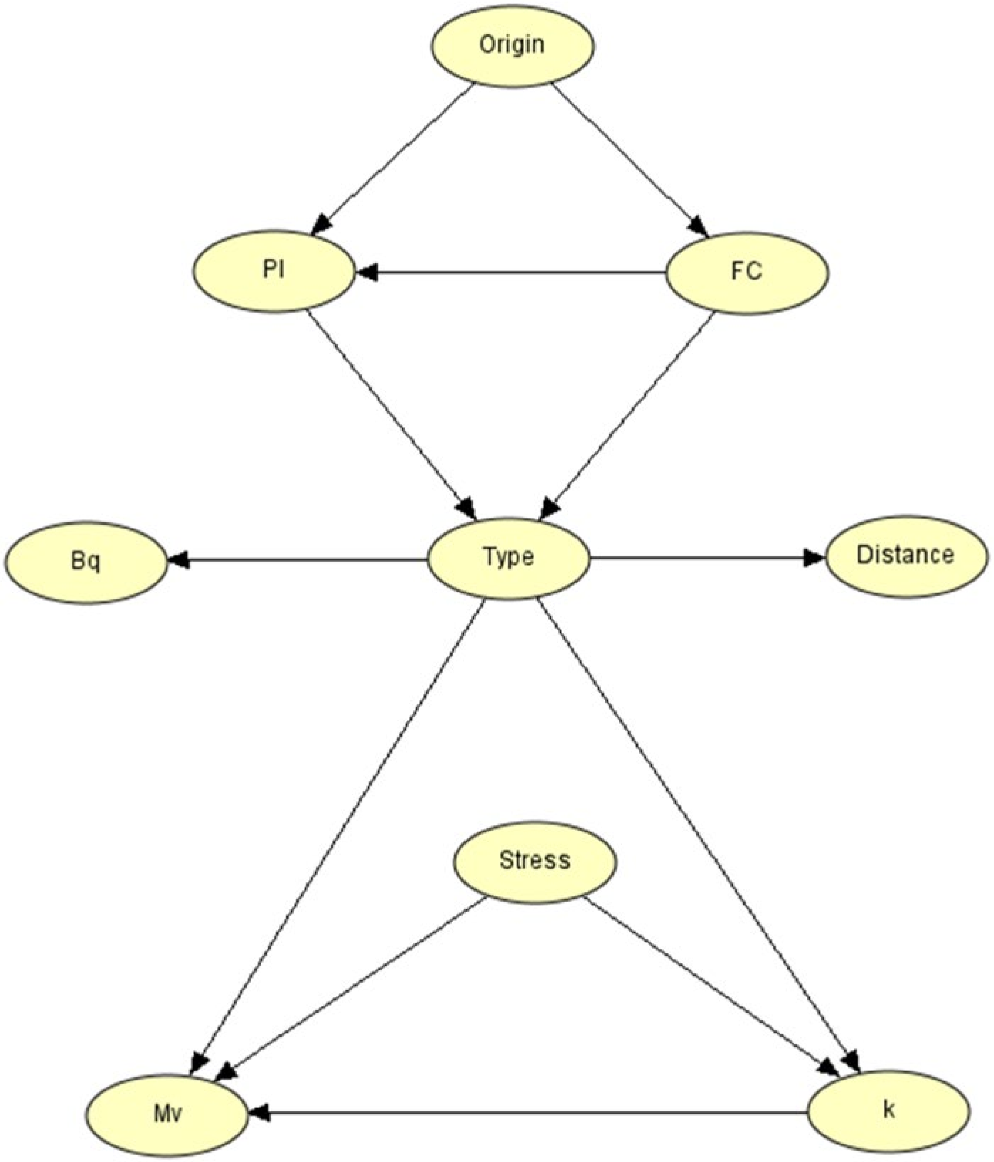


Figure 5.6-11: Adopted Bayesian Network

Variables were discretized based on natural thresholds visible in the data, which required some expert judgement. Five of the variables (fines content, plasticity index, tailings type, stress, and Bq) were discretized into three bins representing “Low”, “Medium” and “High” categories, as shown in Table 5.6-5 and Table 5.6-6. The adjectives “Low” “Medium” and “High” are relative terms for each variable. Hydraulic conductivity was split into two bins: whether it is above or below $1x10^{-7}$ m/s (Table 5.6.6). The value $1x10^{-7}$ m/s represents the geometric mean of the range of hydraulic conductivities obtained from historic testing ($1x10^{-6}$ to $1x10^{-8}$).

Table 5.6-5: Bayesian Network Parent Variable Bins

Variable	Low	Medium	High
Fines Content (FC)	FC < 75%	75% < FC < 95%	FC > 95%
Plasticity Index (PI)	PI < 10%	10% < PI < 25%	PI > 25%
Material Type (Type)	PI = Low	PI = Medium	PI = High
Effective Stress	Stress< 15 kPa	15 kPa < stress < 100 kPa	Stress > 100 kPa
CPTu (Bq)	Bq < 0.2	0.2 < PI < 0.5	Bq >0.5

Table 5.6-6: Bayesian Network Hydraulic Conductivity Variable Bins

Variable	Conductivity Less Than	Does not meet requirements
Hydraulic conductivity, k	< 1 x 10^{-7} m/s	> 1 x 10^{-7} m/s

Table 5.6-7 to Table 5.6.9 show the conditional probability of a variable for a given set of known (input) variables. All tables have the same generic structure where the values represent the joint or conditional probabilities of a variable (leftmost column) based on the states of its parent variables (other columns). Using Table 5.6-7 as an example, it shows the probability of hydraulic conductivity being less than or exceeding a threshold value of 1x10^{-7} m/s based on material type and in-situ stress. For 'medium'-type materials, there is a 60% of meeting targets when in-situ stresses are 'low'(<10KPa), a 70% chance when in-situ stresses are 'medium' (between 10 and 100 kPa), and an 83% chance when in-situ stresses are 'high' (greater than 100 kPa).

Table 5.6-7: Conditional Probability of Hydraulic Conductivity (k) by Material Type and Stress

Type	Fine			Medium			Coarse		
Stress	Low	Medium	High	Low	Medium	High	Low	Medium	High
k < 1x10-7	14%	32%	15%	60%	70%	83%	32%	100%	100%
k > 1x10-7	86%	68%	85%	40%	30%	17%	68%	0%	0%

Table 5.6-8: Conditional Probability of Plasticity Index (PI) by Origin and Fines Content (FC)

Origin	JEB / Sue			Cigar Lake		
FC	Low	Medium	High	Low	Medium	High
Low: PI < 10	100%	0%	0%	100%	24%	0%
Medium: 10 < PI < 25	0%	0%	100%	0%	66%	13%
High: PI > 25	0%	100%	0%	0%	10%	88%
Number of Observations	8	6	4	44	52	34

Table 5.6-9: Conditional Probability of Hydraulic Conductivity (k) by Material Type and Stress

Type	Fine	Medium	Coarse
Bq < 0.2	0%	9%	80%
0.2 < Bq < 0.5	0%	55%	10%
Bq > 0.5	100%	36%	10%

The benefits of the Bayesian network are that it can make use of incomplete information and data with varying levels of confidence to provide an estimate of a parameter of interest. Some key findings from the network are illustrated in Table 5.6-10 via different scenarios to show how different information affects predictions pertaining to whether the threshold hydraulic conductivity is being met. Example outputs for two scenarios are shown in Figure 5.6-12

- Scenario 1: knowing nothing specific about the tailings, there is only a 52% chance that the hydraulic conductivity will meet the requirements.

- Scenario 2: only having some CPT results that shows favourable (high) Bq values improves the probability to 74% (showing the potential value of CPT data alone).

- Scenario 3: only having some index testing showing favourable (high) FC or PI values improves the probability to 81% (showing the increased value of index laboratory work).

- Scenario 4: knowing that the in-situ stresses are medium to high (>10 kPa) combined with some index testing showing favourable (high) fines content results in a probability of 95% (showing the influence of the in-situ condition).

- Scenario 5: Scenario 4 plus the addition of favourable CPT data increases the confidence to 98% (showing the value of multiple sources of data).

- Scenario 6: knowing that the in-situ stresses are medium to high (>10 kPa) combined with favourable (high) plasticity index results in a probability of 100%[2]. This emphasizes that high plasticity index is a more direct indicator of hydraulic conductivity than the combination of fines context and CPTu Bq values.

Table 5.6-10: Summary of Conditional Probability of Hydraulic Conductivity Meeting Requirements for Different Scenarios

Scenario	Probability k < 1x10-7 given…	CPT - Bq	Index Property: FC or PI	In-situ condition: Stress
1	52%	Unknown	Unknown	Unknown
2	74%	High	Unknown	Unknown
3	81-84%	Unknown	FC or PI=High	Unknown
4	95%	Unknown	FC=High	Equally likely to be ‘medium’ or ‘high’
5	98%	High	FC=High	Equally likely to be ‘medium’ or ‘high’
6	100%	Unknown	PI=High	Equally likely to be ‘medium’ or ‘high’

---

[2] This does not imply that there is a 0% chance of having hydraulic conductivities less than targets. These probabilities reflect the within-model uncertainty based on the data available. There is always the potential that our model is wrong, or the collection of new data would identify new ranges or combinations not present in the model ‘training’ data.

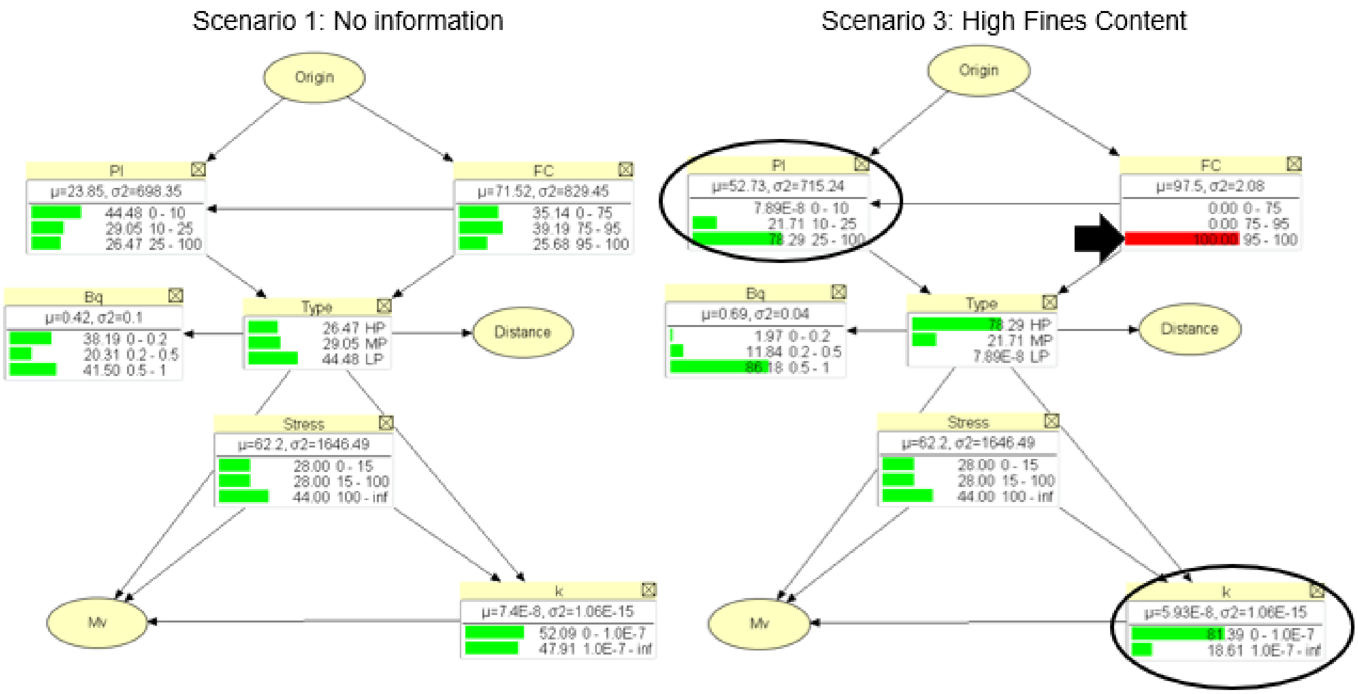


Figure 5.6-12: Comparison of Visual Results from Scenario 1 – no information (left) and 3 – high fines content (right).

The scenarios described above are representative examples to illustrate the concept of how predictions can be updated and improved with different types of information. One main advantage of the Bayesian network model is that it is a live, flexible tool that can be used to rapidly evaluate any scenario of interest. Some limitations of the initial Bayesian network and potential areas for improvement include:

- Small sample size:

- Some of the probabilities may be unrepresentative due to the small sample size. The conditional probability tables are estimated based on the number of examples it sees. There are combinations that show close to zero probabilities, but this is likely due the absence of that specific combination of properties in the examples and not because that combination is close to impossible.

- Incorporation of expert experience and judgement:

- Experience and judgement were applied to define the structure of the network and discretize the variables, but the conditional probability tables were purely statistically driven. Incorporating experience-based prior probability assumptions could help smooth out some of the cases described above where data is lacking.

- Missing variables:

- The Bayesian network does not currently consider distance from the deposition point as a variable; however, this variable may be a useful indicator of material type and hydraulic conductivity and will be explored in future programs.

In light of these identified deficiencies, the 2023/2024 site investigation had the objective of addressing these limitations and areas for enhancement.

5.6.3.3 2023 / 2024 TOVP

2023 / 2024 TOVP Overview

The 2023/2024 TOVP was completed over two summers, with all samples for geochemical testing collected in 2023 and all samples for geotechnical testing collected in 2024. Issues with borehole stability were encountered during the geochemical sampling program and will be discussed at the end of this section which caused the program to take place over two years rather than being completed in 2023. The following sections are specific to the geotechnical sampling program and associated laboratory testing.

Considering the absence of the variable "distance from deposition point" in the Bayesian network, the 2023/2024 TOVP investigation strategy aimed to characterize a single deposition cone in the northeast corner of the facility and three locations at the perimeter of the facility. The intent of this approach was to enhance the understanding of how Cigar Lake tailings particles segregate and to validate that tailings deposited against the perimeter will meet hydraulic conductivity requirements. It has been assumed that Cigar Lake tailings will exhibit consistent segregation characteristics during deposition, and that conclusions drawn from studies at one depositional point could be applicable to other points within the pit.

Ongoing work involves combining Orano's tailings deposition records with the segregation characterisation of this cone to develop a 3D model of the JEB Pit TMF. Data obtained from past programs is being used to validate the model, specifically the laboratory testing from the 2021 TOVP. Since this work is ongoing, details regarding the 3D model development will not be provided herein.

Eleven geotechnical sampling locations were completed as part of the 2023/2024 TOVP. Each sampling location was combined with CPTu soundings. The sampling and CPTu sounding locations are shown in Figure 5.6-13.

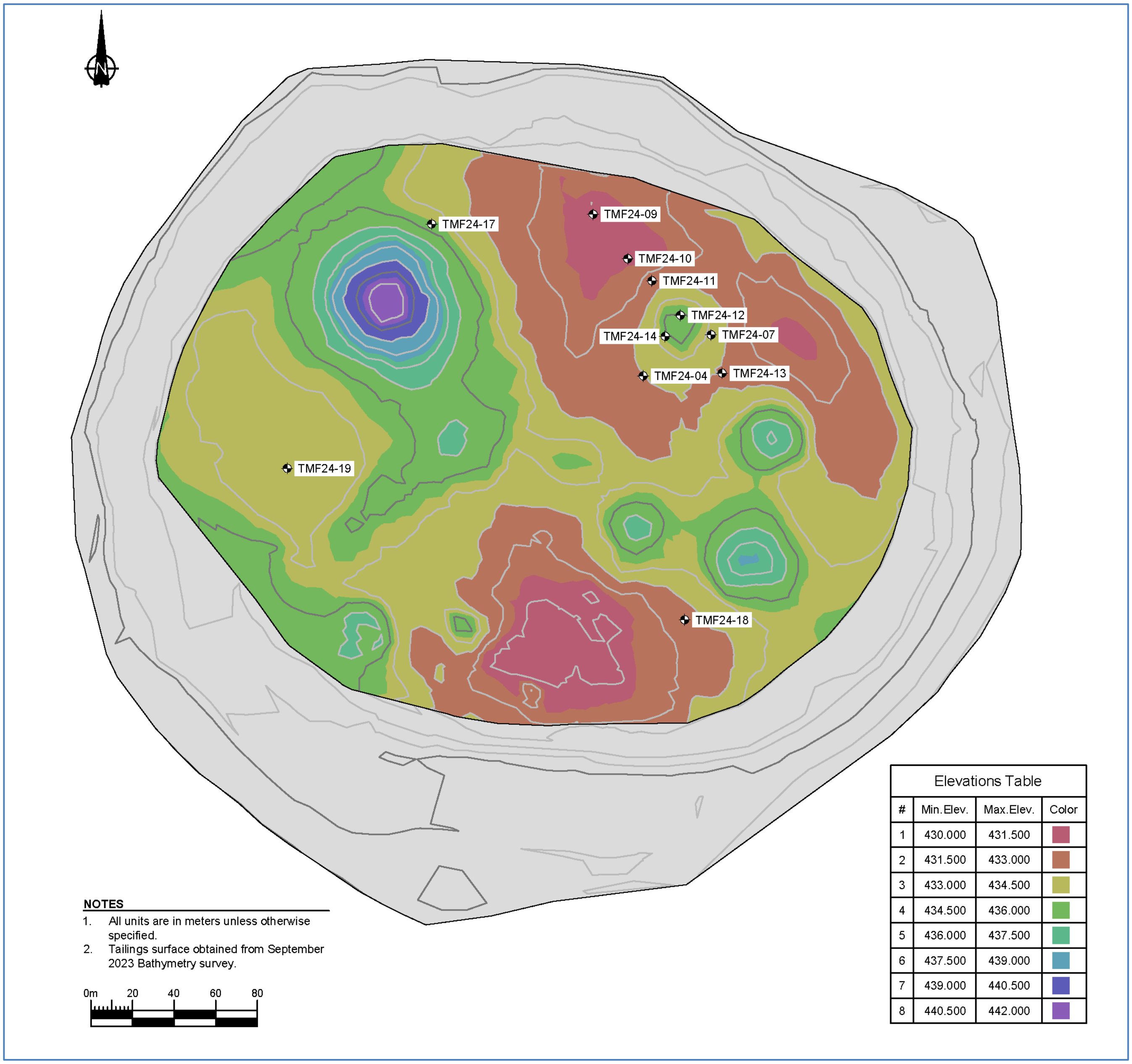


Figure 5.6-13: 2023/2024 TOVP Geotechnical Sampling Locations

2023/2024 Laboratory Testing

Geotechnical laboratory testing for the 2023/2024 TOVP remains ongoing; however, it is following a similar procedure as the 2021 TOVP whereby index testing is performed as the first phase to identify which samples should be targeted for more advanced testing in Phase 2. Table 5.6-11 provides a summary of the laboratory testing status. Unlike the 2021 campaign, the 2023/2024 program included characterisation of the JEB/Sue and Cigar Lake tailings. Note that the JEB/Sue testing is intended to be confirmatory as this material has been well characterised by previous consultants (Golder 2010).

Table 5.6-11: Summary of 2023/2024 Laboratory Testing

Phase	Test	Status	Purpose
1	Water Content	JEB/Sue Completed Cigar Lake Completed	To obtain information necessary for calculating the in-situ bulk density of the tailings To improve datasets in Bayesian network to inform advanced testing / To improve segregation characterisation
	Specific Gravity		
	Particle Size Distribution		
	Atterberg Limits		
2	Consolidation with Falling Head Hydraulic Conductivity	JEB/Sue Complete Cigar Lake Ongoing	To pair with index testing as part of advancing the Bayesian network To provide inputs for consolidation modelling
	Seepage Induced Consolidation	No JEB/Sue samples selected Ongoing for Cigar Lake	

Results from the Atterberg limit and Particle Size Distribution testing are presented in Figure 5.6-14 and Figure 5.6-15, respectively. As shown in Figure 5.6-14, the Atterberg limits are consistent with the 2021 data, and the resolution of data points has been improved. Like the Atterberg limits, the particle size distributions were found to generally be within the range of the results from 2021 and appear to improve the resolution of data. Note that hydrometer analyses were not completed for any of the 2023/2024 samples, as only sieves were completed. This decision was made based on the efficacy of performing multiple hydrometers, and since the plasticity index appears to be a better indicator of geotechnical behaviour.

Figure 5.6-15 shows that the particle sizes of JEB/Sue and Cigar Lake tailings span similar ranges of fines contents. Thus, the conclusion drawn from the 2017 and 2018 testing that Cigar Lake tailings are finer than the JEB/Sue tailings may not be accurate. However, it would be more accurate to state that the mineralogy of the tailings is different, and that the Cigar Lake tailings contain more clay minerals. This statement is based on the observation that for similar fines contents, the Cigar Lake tailings are generally more plastic.

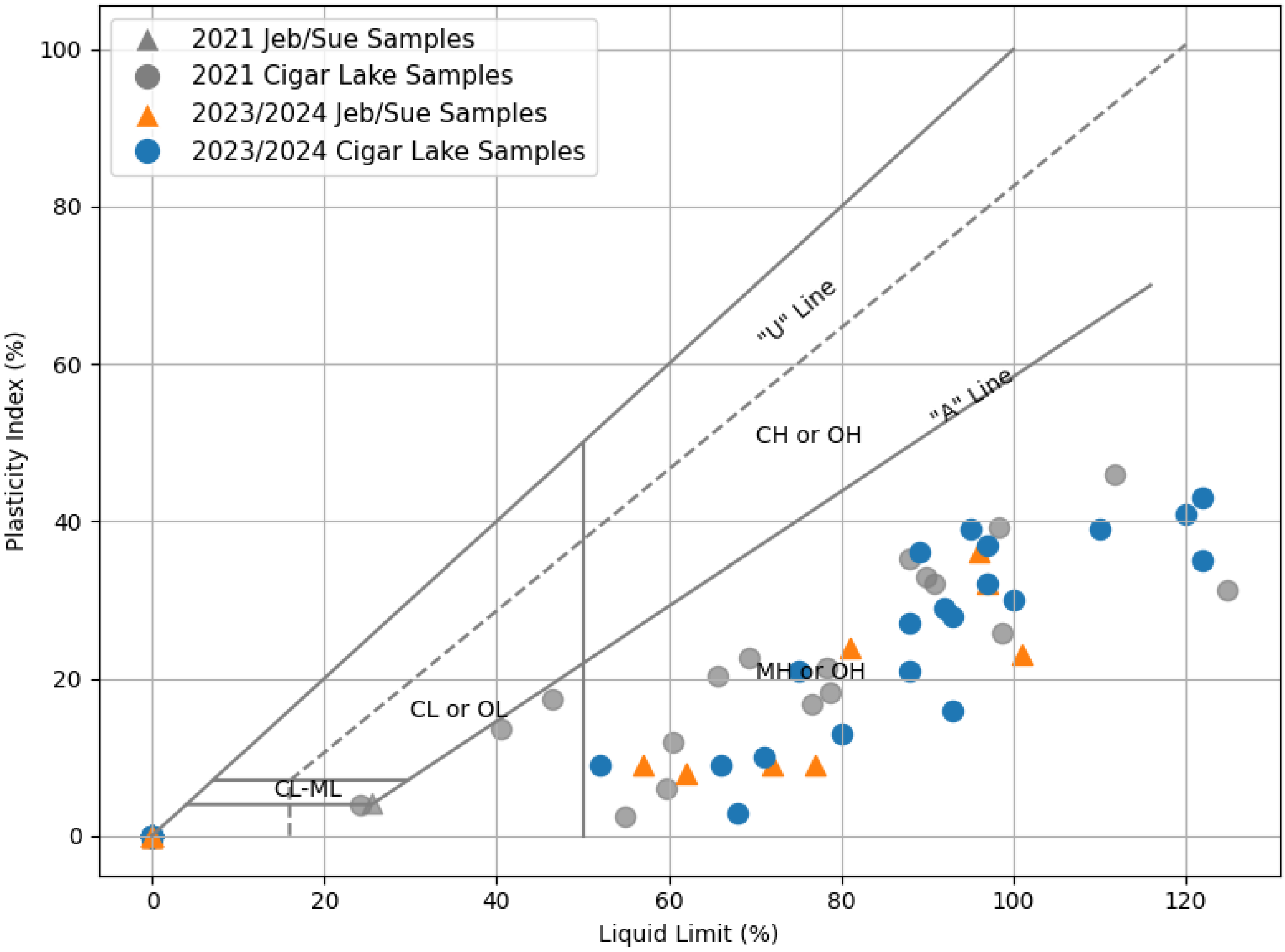


Figure 5.6-14: **Atterberg Limits from 2023/2024 TOVP. Grey markers represent 2021 TOVP data for comparison.**

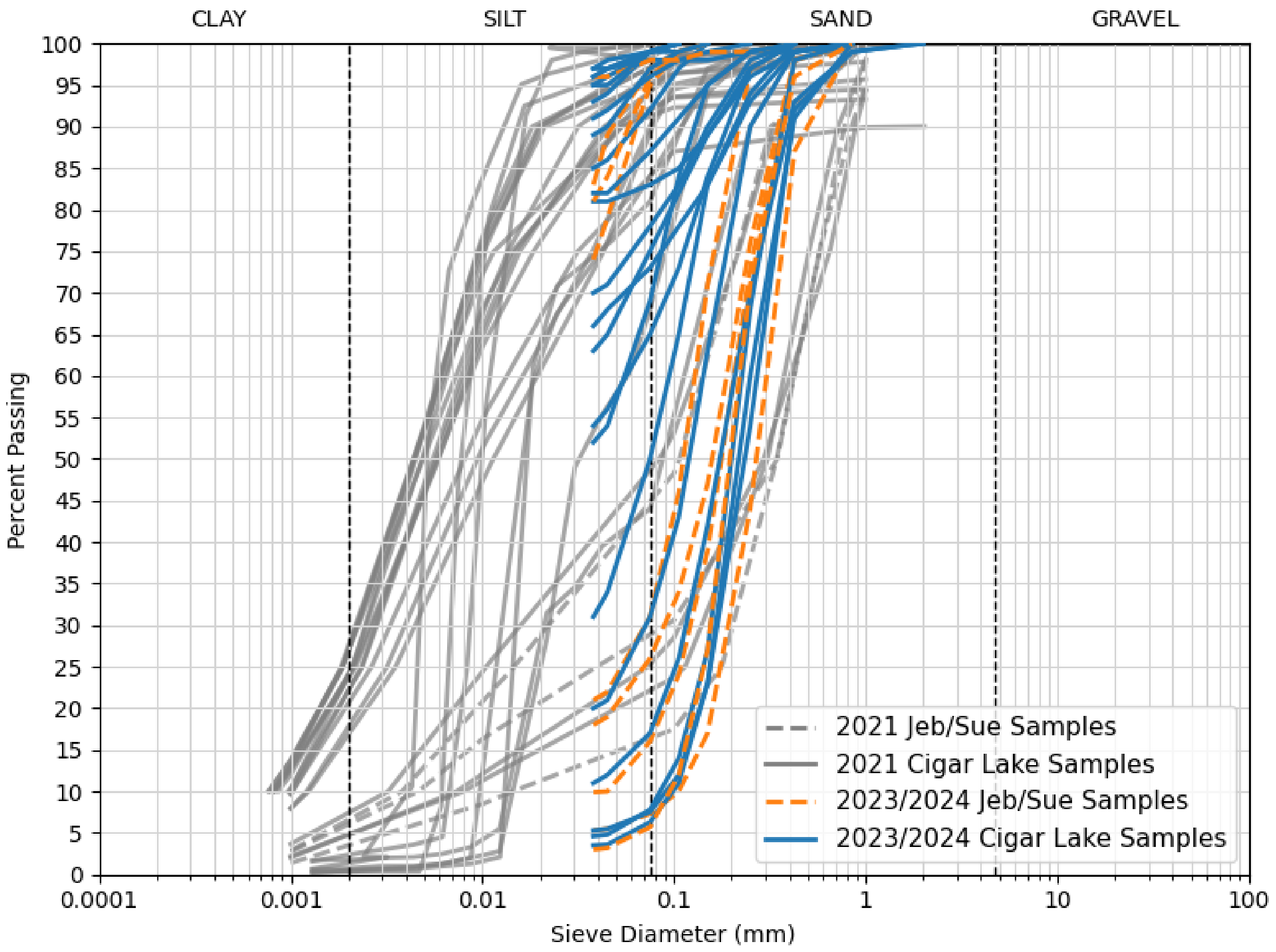


Figure 5.6-15: **Particle Size Distributions from 2023/2024 TOVP samples. Grey lines represent 2021 TOVP data for comparison.**

Hydraulic conductivity and consolidation testing data is only available for the JEB/Sue tailings, for which three samples were selected. Figure 5.6-16 provides a plot of the void ratio vs. pressure for the three samples tested and shows how they compare to historic testing. As indicated in the legend of the plot, samples were grouped into three bins using a similar strategy described in the sections pertaining to the 2021 TOVP; however, fines content was used to group materials since plasticity index was not available. Bins used for categorizing the JEB/Sue tailings are displayed in Table 5.6-12. Note that values separating the bins are different than those previously developed primarily for the Cigar Lake tailings, and the Bayesian network has been updated to utilise the appropriate set of values given the tailings origin (JEB/Sue or Cigar Lake) is known.

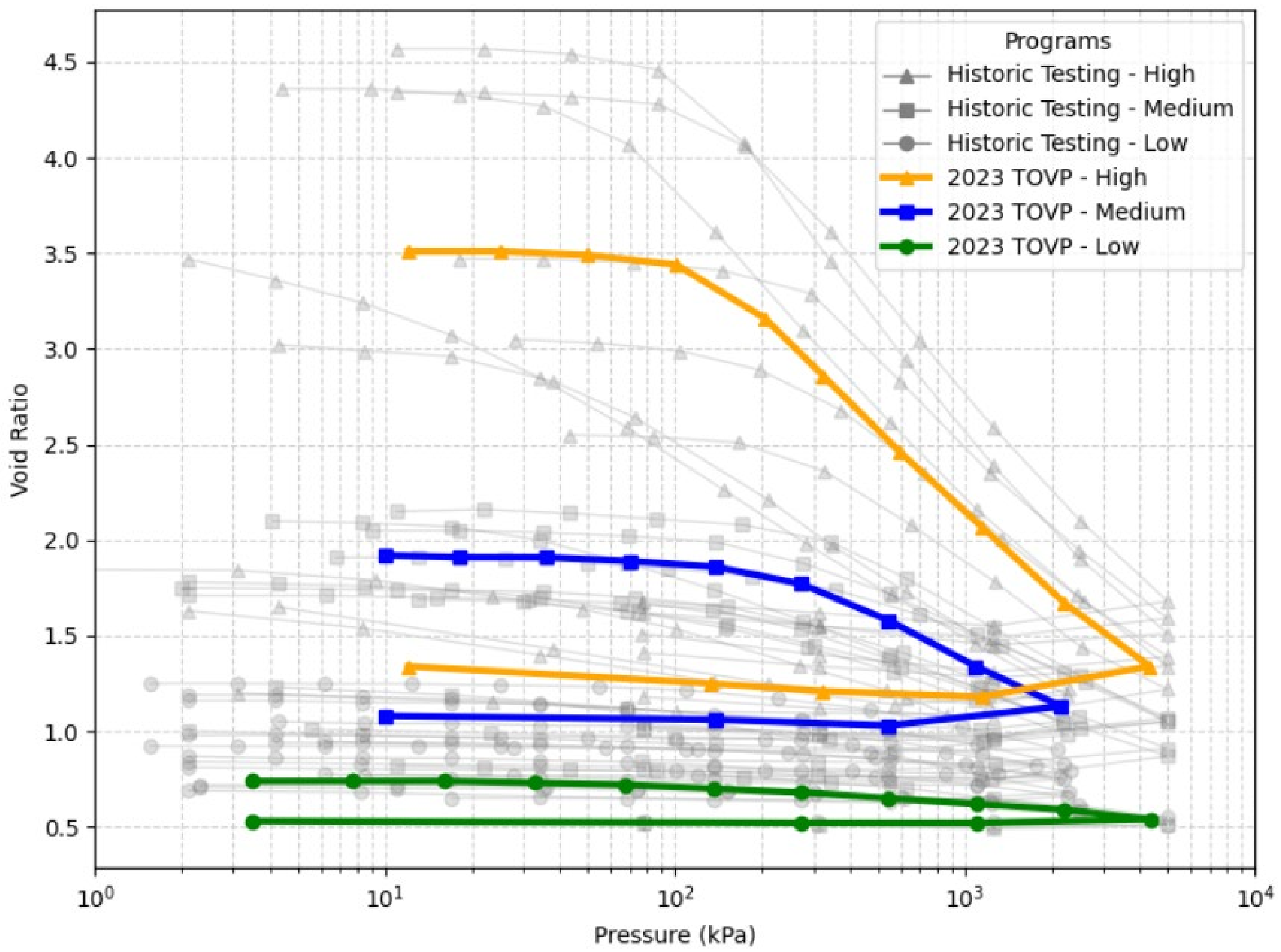


Figure 5.6-16: **Oedometer testing results for JEB/Sue tailings. Colored lines represent recently collected samples. Grey lines represent historical testing for reference.**

Table 5.6-12: **Bins Used for Grouping JEB/Sue Tailings Based on Fines Content (FC)**

Low	Medium	High
0% < FC < 45%	45% < FC < 75%	FC < 100%

Figure 5.6-17 presents a plot of hydraulic conductivity determined from falling head tests for the same three consolidation samples. As shown, the hydraulic conductivity of the new samples is within the range of the historic samples for each respective sample group.

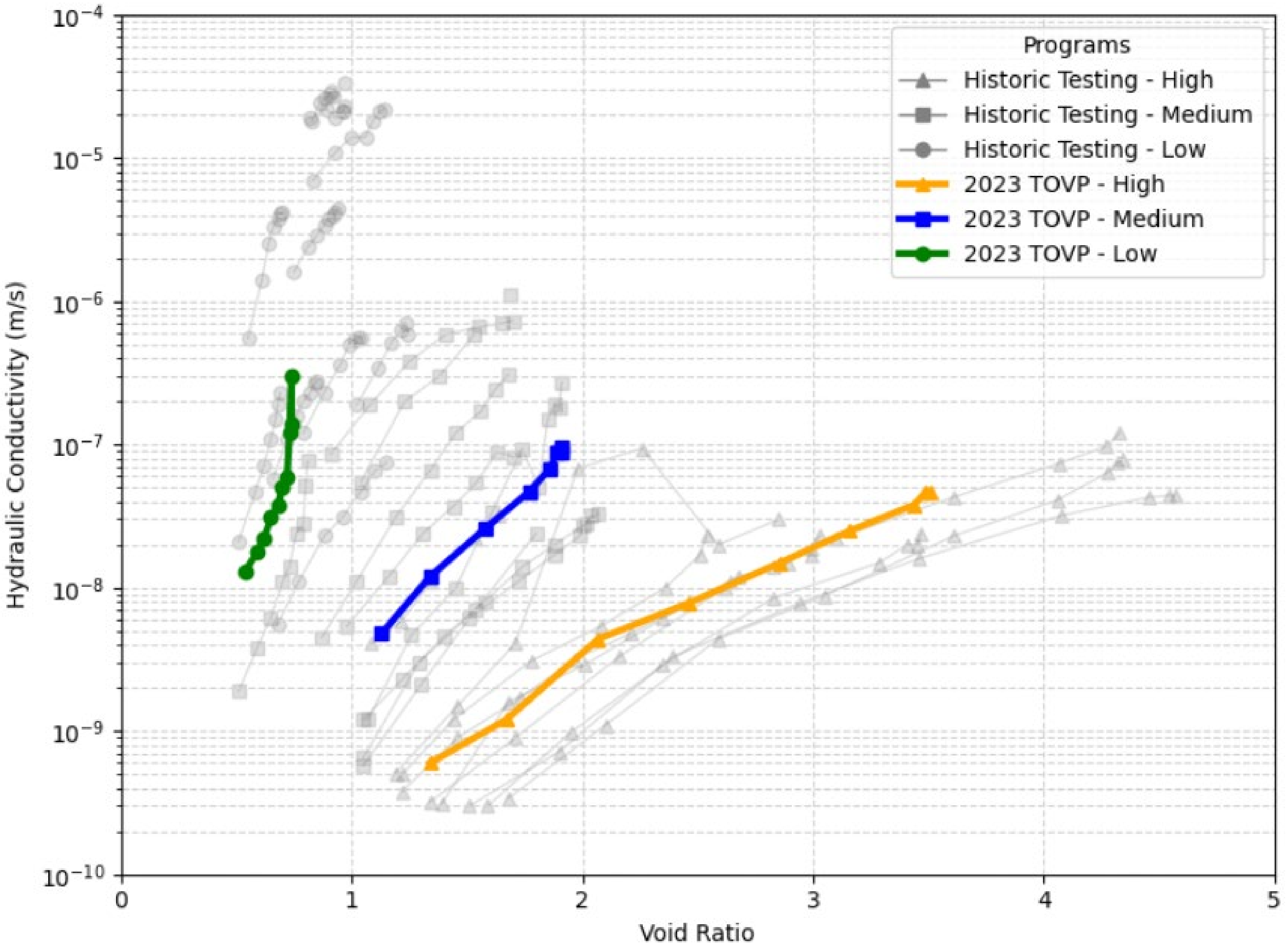


Figure 5.6-17: Hydraulic conductivity testing results for JEB/Sue tailings. Colored lines represent recently collected samples. Grey lines represent historical testing for reference.

Testing of the Cigar Lake tailings remains ongoing, and there are no results available for presentation at this time. Once analysis of the test work in completed in Q1 of 2026 an addendum will be included in this document.

Borehole Instability Issues

During the 2023/2024 sampling program, borehole instability (slough) was a major issue and impacted drilling efficiency when attempting to sample the JEB/Sue tailings. Slough refers to material that entered the steel casing, which prevented the sampler from reaching its intended elevation. In situations where slough prevented the sampler from reaching its target depth, multiple attempts were required to “clean” or “flush” the borehole casing down to the fully cased (target) depth. Slough depths ranged from a few inches to 40 feet.

It was hypothesized that the cause of the slough inside the casing is due to collapse of the tailings around the casing after water pressure being used to advance the casing is turned off and the high hydrostatic pressure of the pond is allowed to act on the newly drilled borehole. Figure 5.6-18 provides a schematic depicting the hypothesized phenomenon.

Water pressure from the drill rig is used to flush the casing while it is advanced. When the tailings collapse around the casing, a "jet" of water is sent back into the casing, carrying tailings that have been disturbed /loosened by the drilling process. This "jet" of water was visible at surface (Figure 5.6-19). A few minutes after stopping casing advancement, slough would be present inside the drill casing.

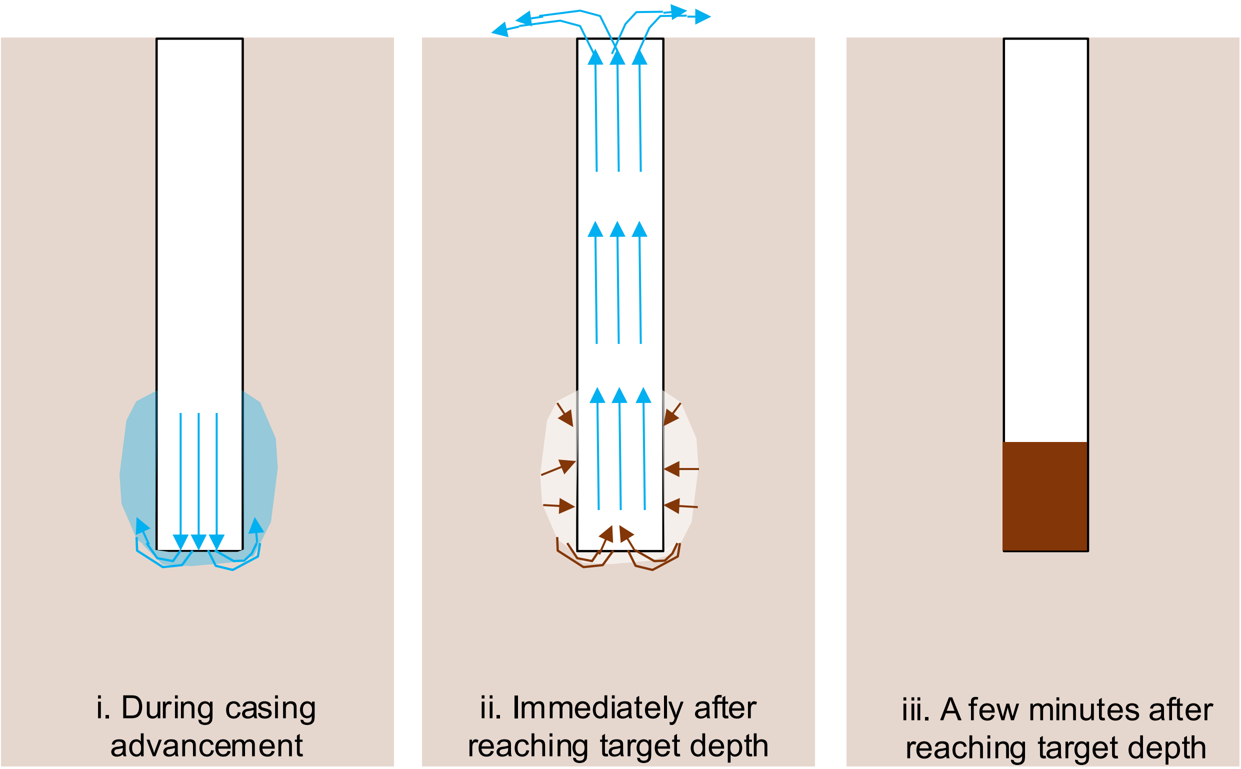


Figure 5.6-18: **i.) Water pressure from drill rig creates small zone of displacement around the base of the boring while advancing casing. ii.) Immediately after the target depth is reached and the water pressure being using during drilling is stopped, the tailings collapse around the casing and enter at the base. The collapse of the tailings creates a "jet" of water that is observed at surface. iii.) A few minutes after drilling is stopped, the tailings fully collapse around the casing and "slough" is accumulated inside the base of the casing.**

Figure 5.6-19: **A "jet" of water observed at surface after stopping casing advancement. Note that the artesian flow was temporary and typically stopped within a couple minutes.**

Multiple strategies were trialed to mitigate the sloughing issues encountered; however, none of the strategies below were overly successful. Ultimately, repeated cleaning of the drill hole was the only way to reach the target depth in most cases. Future sampling programs may require an alternative drilling method to allowed sampling of the deeper portions of the JEB/Sue tailings.

Responses Geotechnical comments on the Geotechnical aspects of the Drill Campaign

CNSC Comment #1 – Challenges to drilling and sampling

Tailings are typically silty and are known to be highly prone to liquefaction when subject to seismic disturbance or cyclic loading. Tailings deposited sub-aqueously (which is how tailings were deposited in TMF) appears to be stable in static conditions, but will experience loss of shear strength, stiffness, and ability to withhold even self-weight when disturbed by cyclic loadings. The vibration to adjacent body of tailings caused by drilling, especially when samplers were repeatedly hammered for sampling, could cause tailings to liquify, and flow towards the bottom opening of the borehole. This process causes sloughing of deposition to the hole, sometimes several feet thick.

The submitted report identified a phenomenon of jet water flow after drill rig stopped advancement. The report interpreted this phenomenon as a result of borehole collapse that pushes water out of the rig pipe. CNSC staff recommend Orano to consider whether the collapse of the borehole could be a consequence of liquefaction, rather than borehole instability. The root cause of the borehole instability might be liquefaction of tailings induced by drilling or hammering of samplers.

Once the root cause of the borehole instability is identified, it is possible to develop countermeasures to address the technical challenges. Orano could consider following potential engineering measures that are able to:

- reduce the vibrational disturbance to the in-situ tailings during drilling and sampling (e.g., by reducing the rotational speed of drills, using static press instead of hammering to advance sampler etc.), in order to improve stability of the boreholes.
- develop new drill head that can prevent tailings from entering the borehole during drilling but can be opened for sampler to advance during sampling.

Expectations to Address Comment #1 – The licensee is recommended to consider whether borehole collapse could be a consequence of liquefaction. Additionally, Orano is recommended to consider to develop countermeasures to address the technical challenges, including:

- **reducing the vibrational disturbance to the in-situ tailings during drilling and sampling (e.g., by reducing the rotational speed of drills, using static press instead of hammering to advance sampler etc.), in order to improve stability of the boreholes.**
- **developing new drill head that can prevent tailings from entering the borehole during drilling but can be opened for sampler to advance during sampling.**

Orano Response:

The drilling method used in 2024/2024 involves rotating a cutting edge bit attached to the base of drill casing, and jetting water from the base of the borehole. During the 2023 program, the drill head was rotated as slowly as possible and balanced advancing the drill casing versus frication along the outside of the casing, such that the casing did not become stuck. The feed water pressure within the casing was recorded as being near 0 kPA at almost all times. Considering the limitations of the current drilling method, all efforts were taken during drilling to reduce the amount of disturbance in the tailings mass adjacent to the borehole.

Once the target sample depth is reached, the water that was being used to advance the casing is turned off, and the drill head is no longer rotated. During the 2023 drilling program it was routinely observed that immediately after reaching the target depth, before beginning to send the sampler down the hole, a large amount of water would flow freely from the annulus of the casing on the drilling barge. After waiting for this water to stop flowing from the top of the casing, a reel tape would be sent to the bottom of the hole, and it was at this time that the slough was measured. Therefore, slough entered the borehole prior to advancing the sampler. Accordingly, the “hammering” on the SPT split spoon, was not the cause for the slough.

The next step in the sampling process is to string together multiple sampling rods (AWJ) together and send them down the hole with the split spoon sampler on the end. Note that during periods of sloughing, use of the GUS piston sampler was not feasible. In the event that the sampler was able to get near the target depth, the sampler was hammered to the desired depth, after passing through some accumulated slough. The hammer was used because the drill was not capable of producing enough force via static press to advance the split spoon. For materials susceptible to liquefaction, it is common for uncorrected SPT N-values to be less than ~30. Uncorrected N-values recorded during the 2023 campaign were routinely greater than 100, indicating the presence of dense materials. Furthermore, in most situations the sampler could not be advanced more than 200mm into the formation, despite the hammer being used. Based on these findings, it is not believed that mass liquefaction of the tailings is a root cause to the sloughing.

Since the slouging issue was only encountered at significant drilling depths, it has been hypothesized that the horizontal earth pressure of the tailings is high enough to collapse the space between the soil formation and the outer casing that develops during casing advancement. Due to the cohesionless nature of the tailings, the material is incapable of bridging around the casing to maintain borehole stability. Attempts to use drilling mud modifiers were made to improve the borehole stability were made, but they were unsuccessful. In lieu of forming a barrier of negative pressure between the drill casing and the surrounding soil mass, when casing advancement stops, the soil collapses around the casing. This process forces water that was previously between the soil formation and the casing along the path of least resistance, which is into the base of the casing. This phenomenon results in the jet of water observed at surface. Due to the cohesionless nature of the tailings, when this jet of water begins, it draws previously in-situ tailings up into the casing, which results in the observed slough.

Developing a new drill head may be one potential solution to the problem; however, it would likely be a novel solution and would require a significant amount of research and testing to be considered feasible, and is unlikely to be validated in time to reliably be used in the 2028 TOVP. In general this a key challenge currently facing the mining industry in regards to collecting undisturbed samples of loose tailings within tailings impoundments. Significant success drilling through soft, loose tailings without the need to add water as a drilling lubricant, has been had using the sonic drilling method, which collects a disturbed sample as the casing is advanced. While it can be argued that the sonic vibrations disturb the in-situ state of the tailings, the projects objective is not to collect completed undisturbed samples as this is an unrealistic expectation considering the current state of practice. Sonic drilling may prove to be a more expedient and cost-effective solution of achieving the project goal of collecting in-situ samples while mitigating the sloughing problem. Implementation of this drilling method is being considered for future TOVPs.

As a final statement regarding liquefaction of the tailings: Evaluating liquefaction susceptibility of the JEB TMF tailings is not the objective of the TOVP due to the nature of the facility. These tailings are considered susceptible to liquefaction, but should liquefaction occur, this will result in a reorientation of the particles, and in many cases, the post-liquefaction state can be more dense than the pre-liquefaction state. In the case of the JEB Pit TMF, this would be a positive outcome for closure cover construction.

CNSC Comment #4 - Potential effects of sonic drilling on sample disturbance and its impacts on tailings geotechnical properties

In order to address borehole instability and improve drilling efficiency, the licensee plans to use sonic drilling method for the 2024 geotechnical sampling campaign. While sonic drilling provides some advantages for sampling, it is understood that vibration of the sonic drill head may result in disturbances of tailings to be sampled, which could impact on assessment of tailings geotechnical performance.

Expectations to Address Comment 4 – The licensee is expected to assess the potential impacts of the sample disturbance on the geotechnical properties of the 2024 sampling campaign.

Orano Response:

Please note that because no deep boreholes were planned for drilling in 2024, Orano made the decision to proceed using the same drilling technique as in 2023 which had been very successful in sampling the Cigar Lake tailings. Solic drilling will be again carefully considered for use in the 2028 TOVP to enable sampling the deepest tailings. The initial assumptions/ known limitations around the use of sonic drilling are presented below.

Sonic drilling will cause some degree of disturbance to the samples collected through the core, and may result in the disturbance of in-situ samples collected with the GUS piston sampler, although it is noted that GUS piston samples collected of loose, soft materials are also considered to be disturbed in general. Although some understanding of the structure and fabric of the tailings may be sacrificed, is not the key objective of the sampling program. Orano will consider this trade off against the possibility that collecting deep tailings samples may not be possible without employing a different technique. Orano is confident that developing a relationship between void ratio, hydraulic conductivity, and compressibility will provide the most insight in the long-term geotechnical properties of the tailings and developing this relationship may be done using remoulded samples.

Sonic drill rigs are routinely used to successfully characterise tailings deposits in other locations. It is likely that an intact sonic core that is properly packaged after retrieval is likely to undergo less disturbance than samples collected using an SPT split spoon.

5.6.3.4 Dredge Sampling

Dredge sampling is conducted annually in a radial pattern originating from the relevant deposition points at the JEB Pit TMF. Figure 5.6-20 shows a summary of results from the dredge sampling completed in the current reporting period. Figures 5.6-21 to 5.6-26 show the dredge sampling locations in the TMF. Figure 5.6-20 provides plots of clay sized particles, silt size particles, and coefficient of uniformity vs. distance to the relative deposition point. Silt and clay sized particles correspond to materials finer than 0.05mm and 0.002mm, respectively. The coefficient of uniformity is a measure of how well a soil is graded, and is determined using equation 1, where D_{60} is sieve size for which 60% of the particles are finer and 40% of the particles are coarser; and D_{10} is sieve size for which 10% of the particles are finer and 90% of the particles are coarser.

$$Cu = \frac{D_{60}}{D_{10}}$$

As shown, there is a clear relationship between Cu and the silt sized particles with increasing distance from the deposition point, while the trend with clay sized particles is less evident. As indicated in the plots, it appears as though materials become uniformly graded (or well sorted) and have high fines contents (>95%) at distances greater than 50m from the deposition point. Tying this information to the known relationships between fines content and hydraulic conductivity suggests that material that is deposited 50 or more metres from the deposition point is likely to have a hydraulic conductivity of at 1 x 10^{-7} m/s or lower.

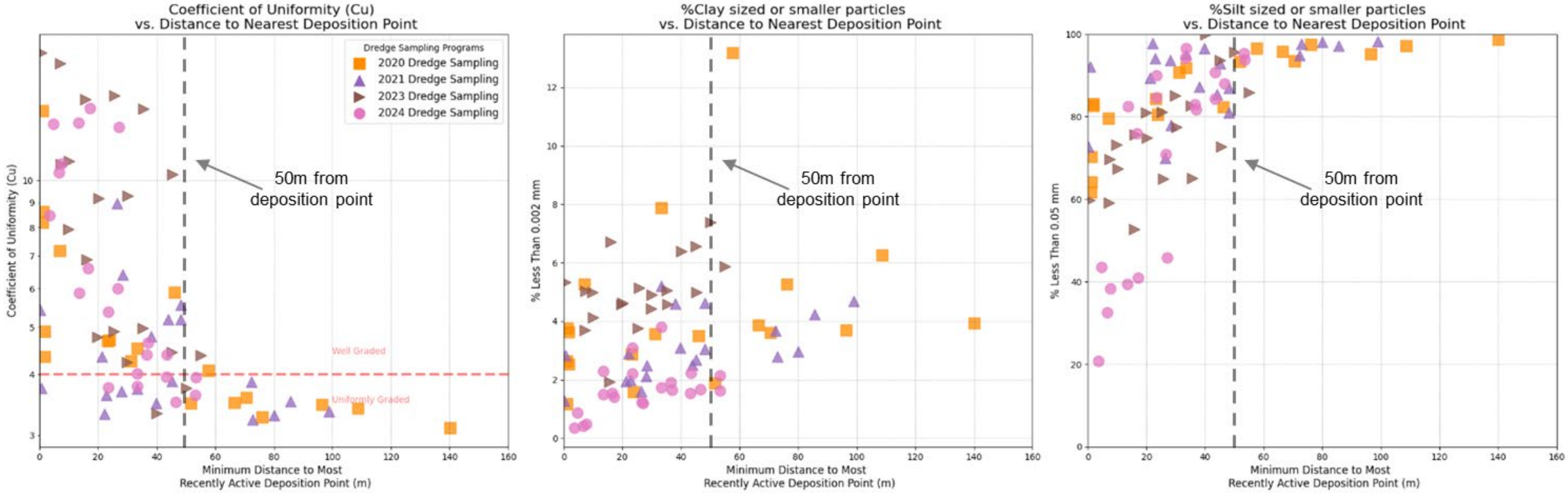


Figure 5.6-20: Summary of Dredge Sampling Completed Since Last TID Report (2020, 2021, 2023, 2024)

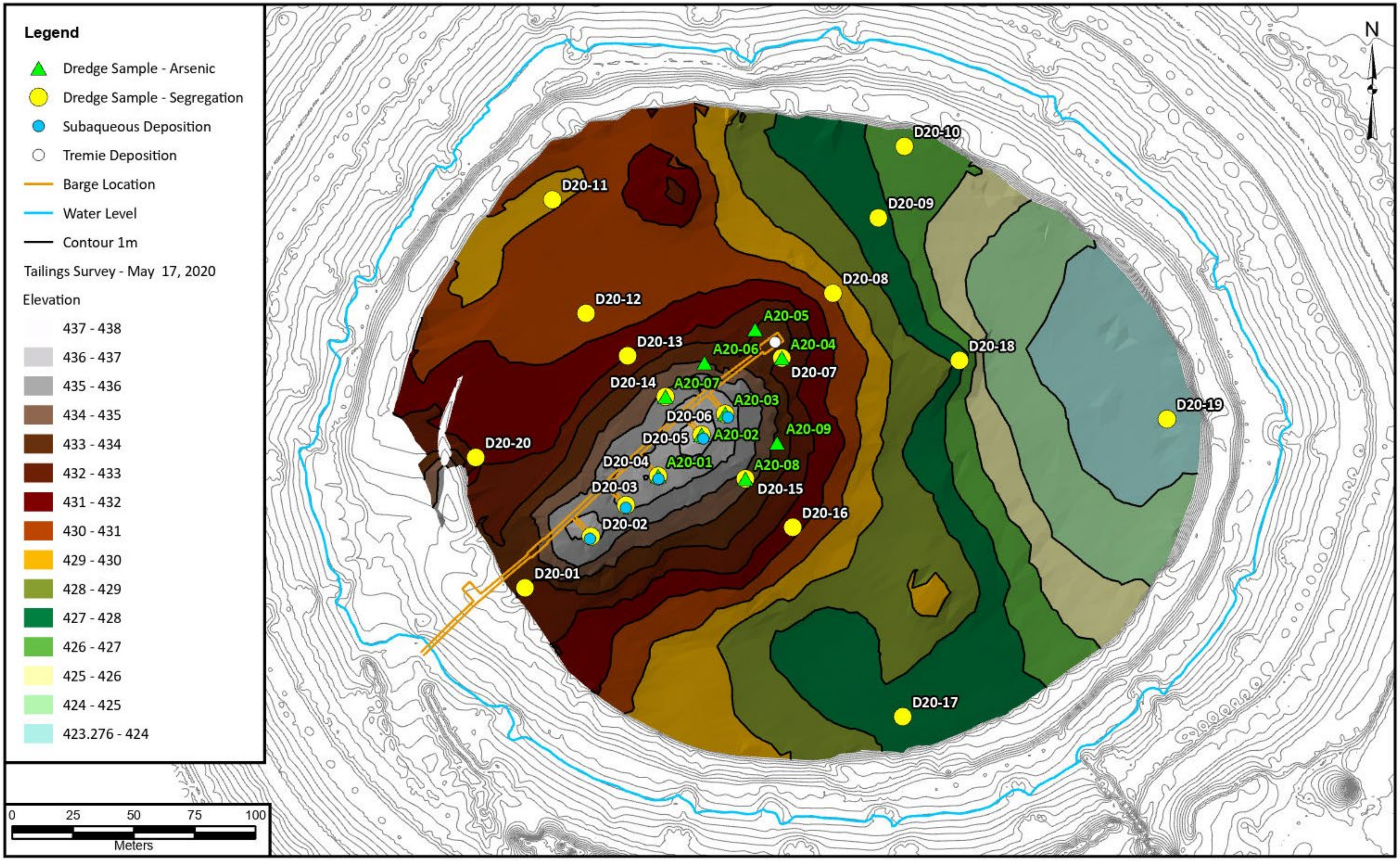


Figure 5.6-21: Dredge Sampling Locations in 2020

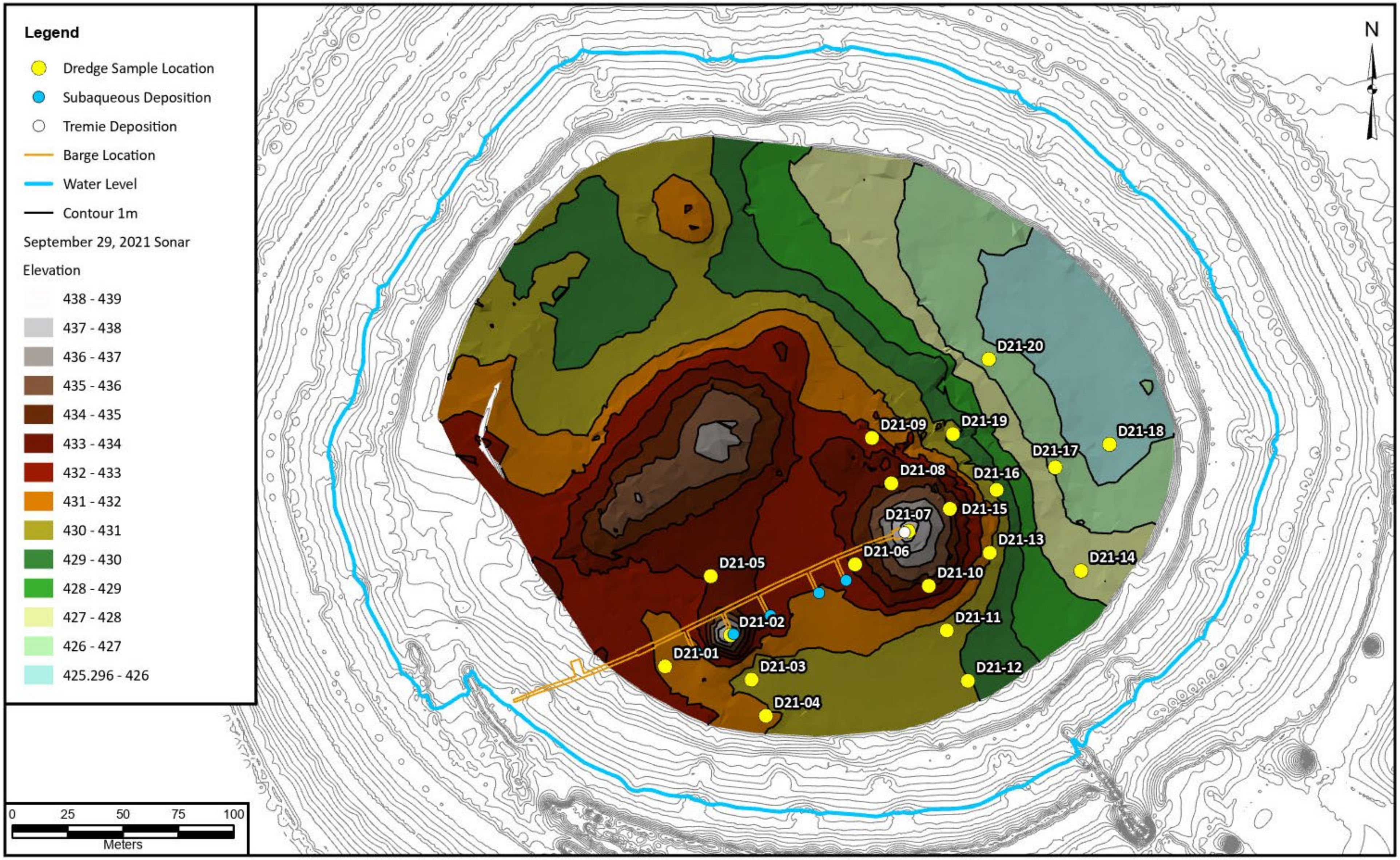


Figure 5.6-22: Dredge Sampling Locations in 2021

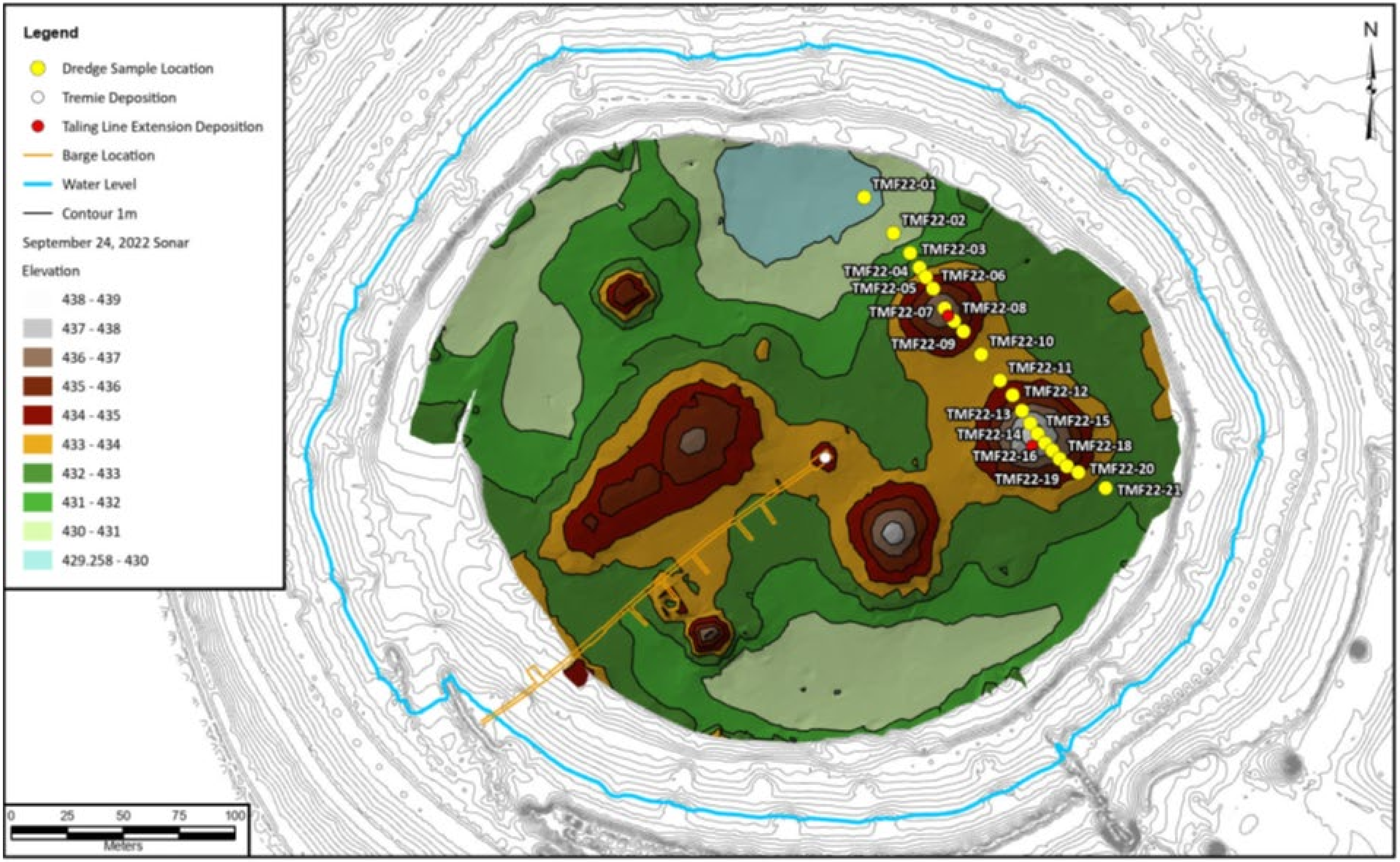


Figure 5.6-23: **Dredge Sampling Locations in 2022**

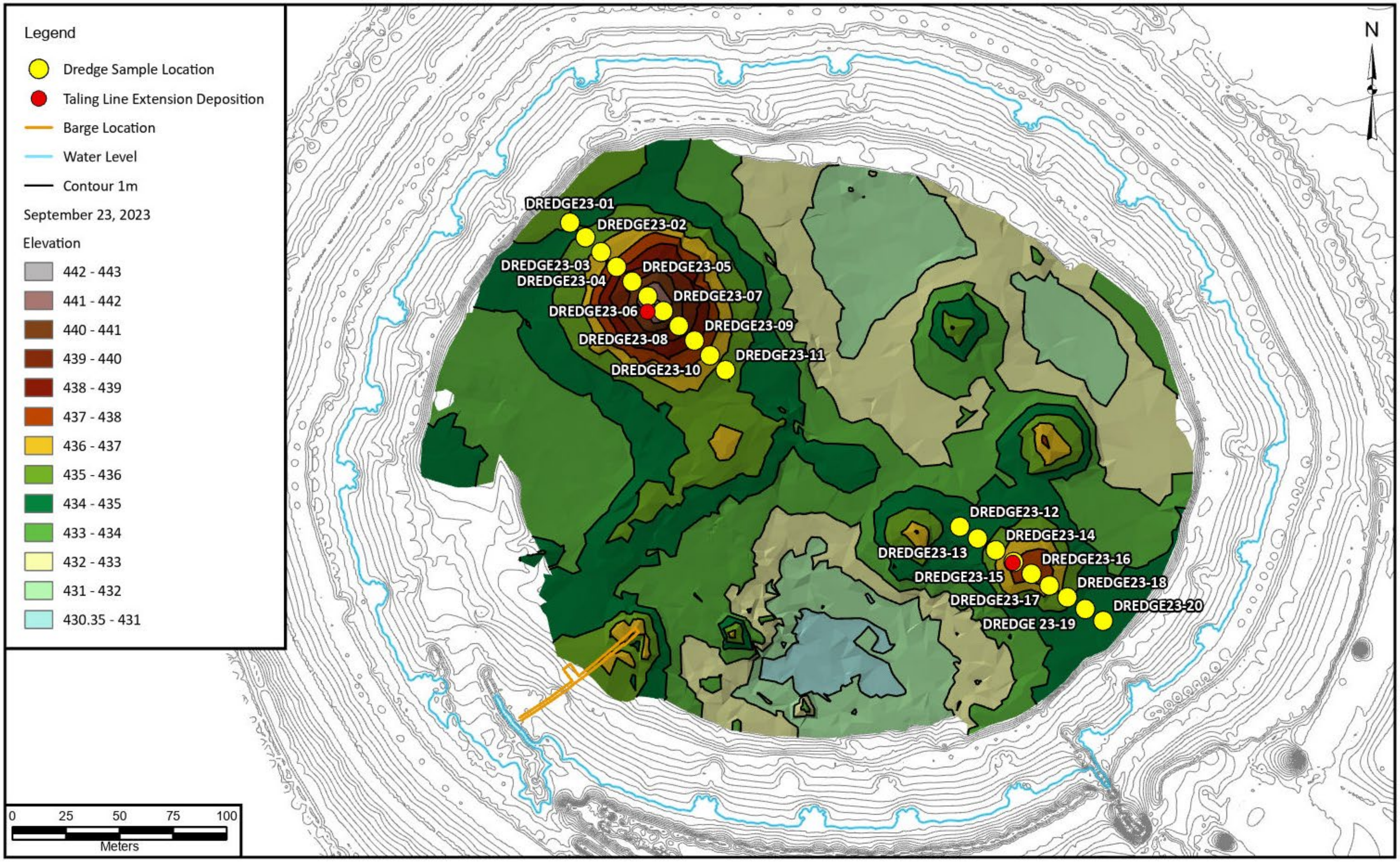


Figure 5.6-24: **Dredge Sampling Locations in 2023**

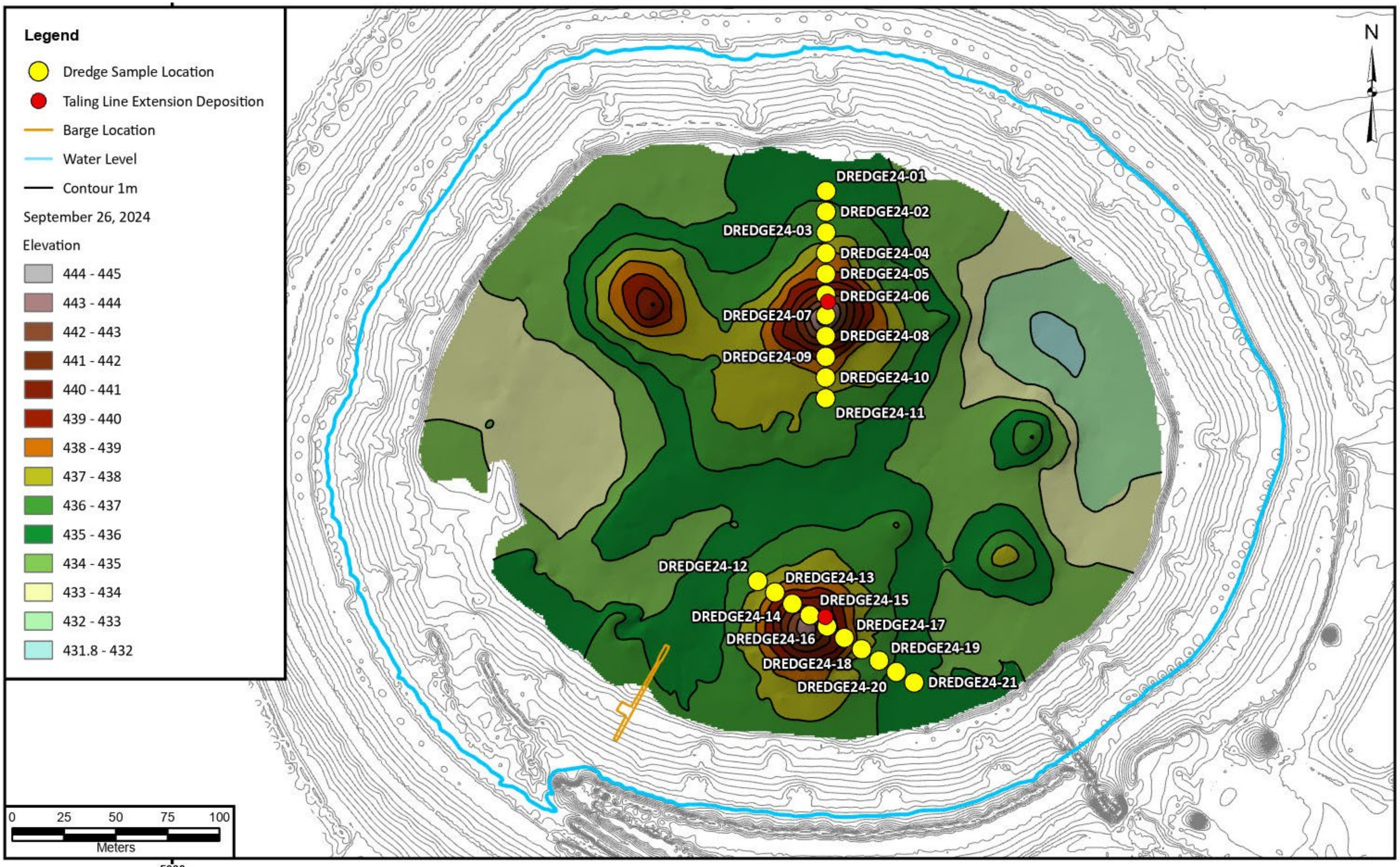


Figure 5.6-25: Dredge Sampling Locations in 2024

5.6.4 **Conclusions – Geotechnical Analysis**

5.6.4.1 **Segregation**

The findings across the various TOVP campaigns confirm that the subaqueous tailings deposition method has not eliminated segregation during placement but has instead demonstrated predictable patterns of particle distribution. Specifically, tailings are observed to become increasingly fine-grained as the distance from deposition points increases, stabilizing approximately 50 meters away. The finer tailings that accumulate against the pit perimeter are beneficial for hydraulic containment due to their lower hydraulic conductivity. Figure 5.6-26 shows fines content of samples taken to characterize a tailings deposition cone during the 2023/2024 sampling campaign. Samples near the center of the cone contained almost 0% fines content while samples near the pit wall on the edge of the cone contained ~40% fines. Advances in segregation analysis, such as the introduction of the plasticity index as a primary indicator of material behavior, have improved classification and modeling accuracy, enabling the characterization of tailings into discrete bins based on segregation characteristics. This approach has enhanced the resolution of tailings characterization and provides insights into material behavior relevant to long-term containment strategies.

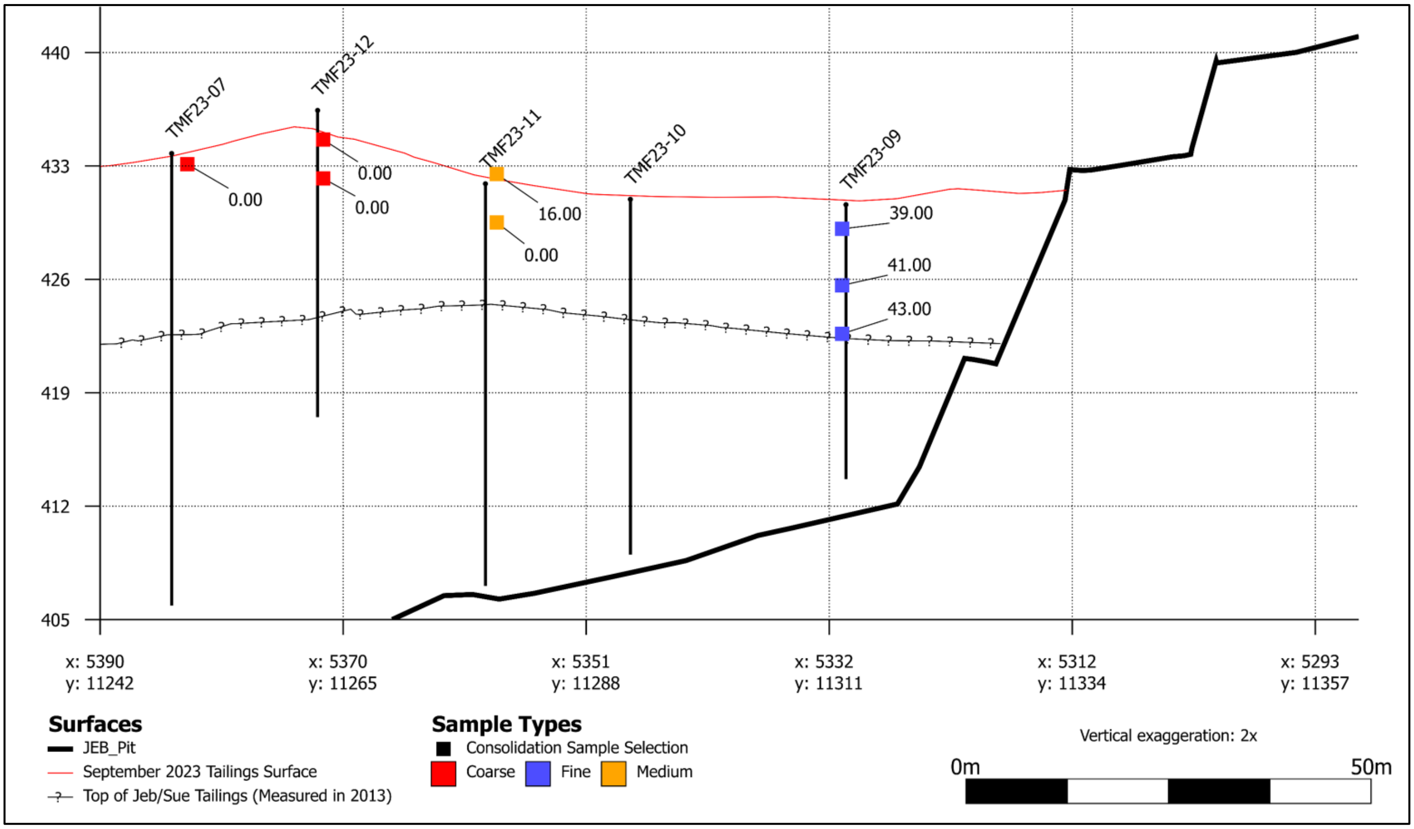


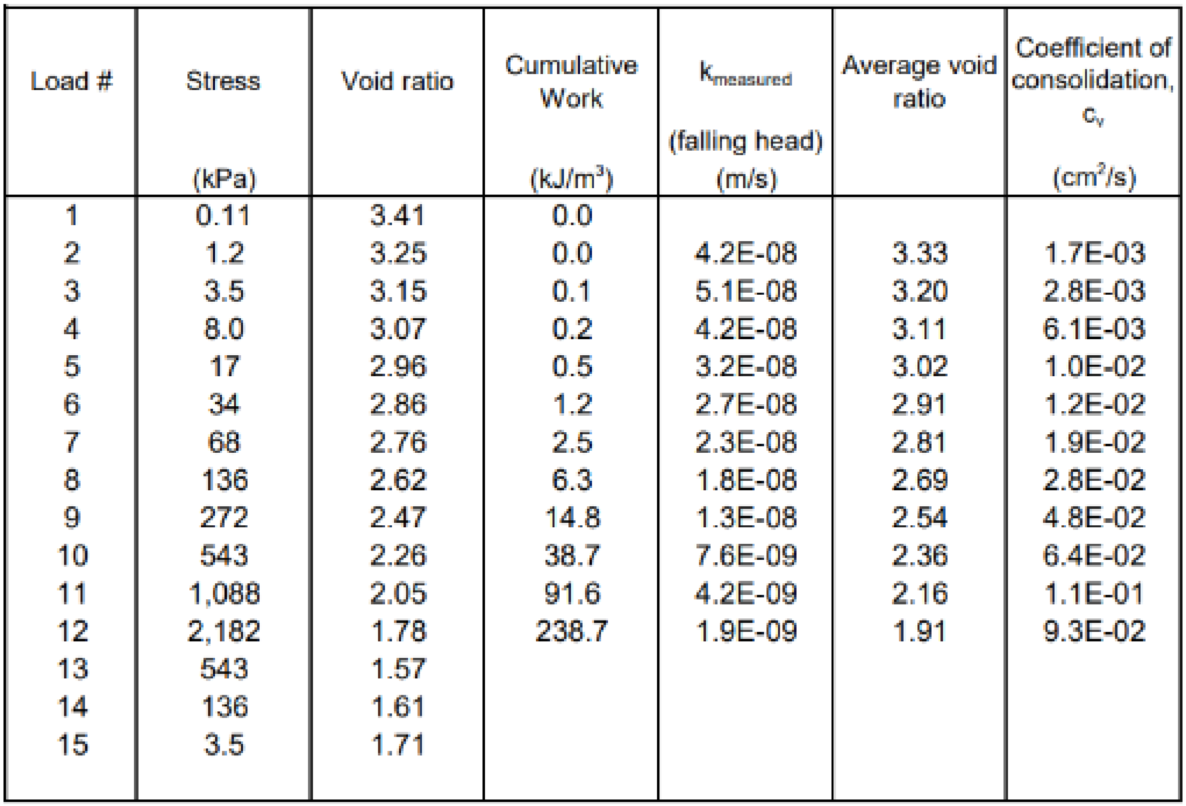
Figure 5.6-26: Segregation of Grain Size in a Tailings Deposition Cone Shown Through % Fines of Each Samples

5.6.4.2 **Hydraulic Conductivity and Consolidation Behaviour**

The hydraulic conductivity of tailings has been found to vary between 1x10⁻⁶ m/s and 1x10⁻⁸ m/s, with low plasticity materials displaying higher conductivity values and high plasticity materials demonstrating lower conductivity. A key advance is the development a Bayesian network to probabilistically estimate hydraulic conductivity. This network incorporates parameters like plasticity index, fines content, stress conditions, and CPTu porewater pressure ratios. Hydraulic conductivity results show clear trends of decreasing values with higher plasticity indices and increased consolidation pressures. Overall, the hydraulic conductivity of the tailings along the pit edge meets the design objectives.

Regarding consolidation behavior, tailings with higher plasticity indices are generally more compressible, while lower plasticity tailings are less compressible. Ongoing work utilizes the "bin" classification and Bayesian methodologies to refine consolidation modeling and settlement predictions. Future consolidation modeling, expected to conclude by late 2025 with reporting in Q1 2026, will provide further insights into settlement dynamics and long-term geotechnical performance. Preliminary results from the ongoing consolidation testing are provided in Table 5.6-23. In this test on a fine-grained Cigar Lake sample, at an effective stress of 136 kPa (representing a sample 13.6m deep) the hydraulic conductivity is 1.8x10^{-08} m/s. At just 8kPa the hydraulic conductivity is 4.2x10^{-08} m/s which demonstrates that fine grained Cigar Lake tailings samples can be predicted to consolidate to acceptably low values of hydraulic conductivity to limit advective groundwater flow through the tailings after decommissioning.

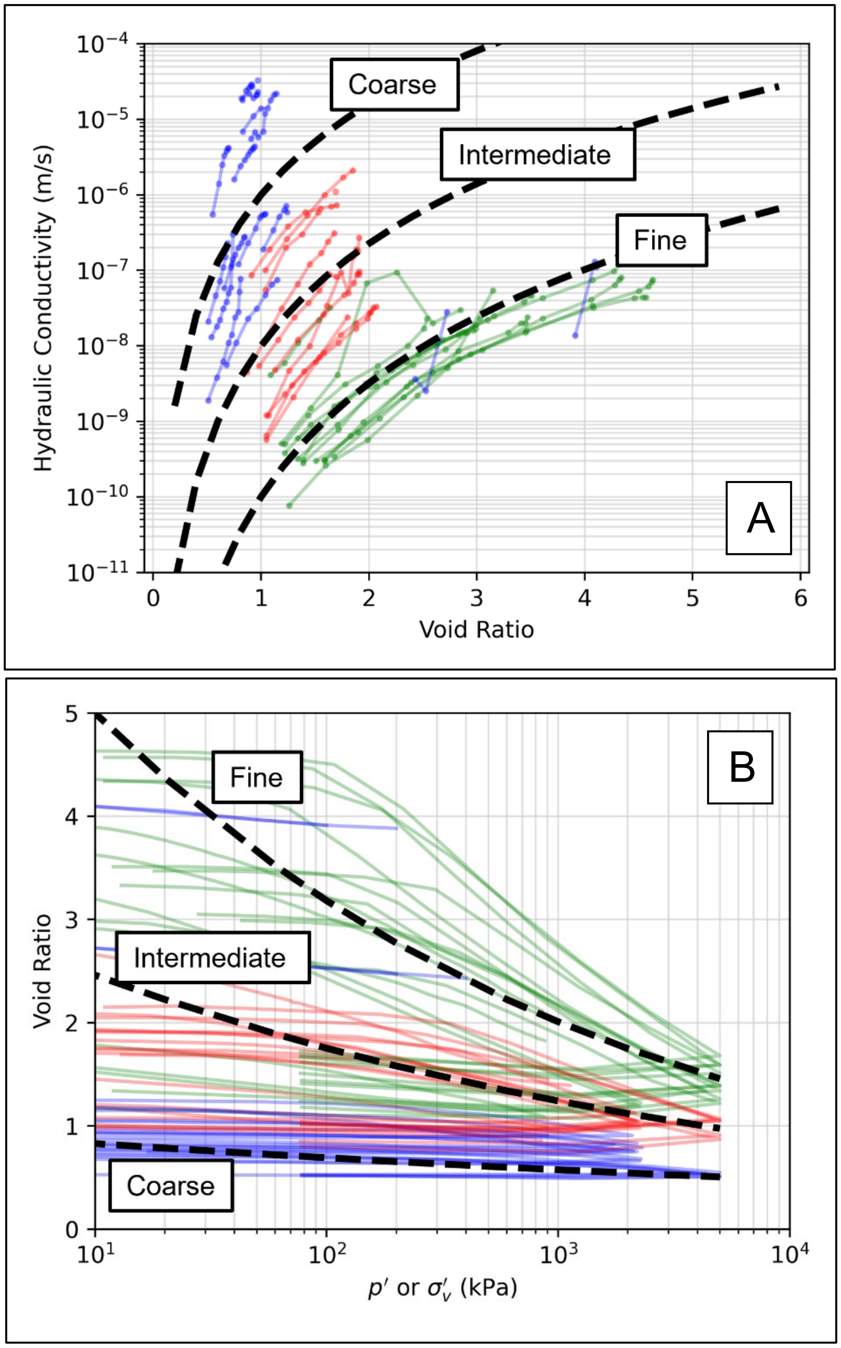
Table 5.6-13: Preliminary Consolidation Testing Results from A Fine-Grained Cigar Lake Tailings Sample



Load #	Stress (kPa)	Void ratio	Cumulative Work (kJ/m^3)	$k_{measured}$ (falling head) (m/s)	Average void ratio	Coefficient of consolidation, c_v (cm^2/s)
1	0.11	3.41	0.0			
2	1.2	3.25	0.0	4.2E-08	3.33	1.7E-03
3	3.5	3.15	0.1	5.1E-08	3.20	2.8E-03
4	8.0	3.07	0.2	4.2E-08	3.11	6.1E-03
5	17	2.96	0.5	3.2E-08	3.02	1.0E-02
6	34	2.86	1.2	2.7E-08	2.91	1.2E-02
7	68	2.76	2.5	2.3E-08	2.81	1.9E-02
8	136	2.62	6.3	1.8E-08	2.69	2.8E-02
9	272	2.47	14.8	1.3E-08	2.54	4.8E-02
10	543	2.26	38.7	7.6E-09	2.36	6.4E-02
11	1,088	2.05	91.6	4.2E-09	2.16	1.1E-01
12	2,182	1.78	238.7	1.9E-09	1.91	9.3E-02
13	543	1.57				
14	136	1.61				
15	3.5	1.71				

Predicted post-decommissioning hydraulic conductivities of the JEB/Sue tailings can be estimated using data from 25years of geotechnical sampling data. Figure 5.6-27 shows consolidation testing results of JEB/Sue data categorized based on grainsize. In this case a hydraulic conductivity of 1x10^{-7}m/s occurs at a void ratio of ~4 (Figure 5.6-27a) for the fine-grained material. The fine-grained data trend line for void ratio vs stress (Figure 5.6-27b) tells us that the void ratio will be ~4 under ~20 kPA stress, which is representative of approximately 2m of overlying material. The JEB/Sue tailings will be consolidated by ~ 20+ m of material, which corresponds to a void ratio of ~3 and a hydraulic conductivity of 1X10^{-8}m/s.

Figure 5.6-27: Interpretation of historical JEB/Sue Consolidation Data by Grain Size and Void Ratio



5.7 Verification of Long-term Tailings Geochemistry

5.7.1 Introduction

The principal objectives of the geochemical portion of the 2023 TMF sampling program were three-fold:

- to compare pore water concentrations of COPCs sampled from placed tailings pore water with those predicted by pre-operational laboratory aging tests;
- to assess the relationship between the mineralogy of the tailings solids and the soluble COPC concentrations in the pore water in contact with the solids; and
- to evaluate the tailings produced through the milling of ore from the Cigar Lake mine and compare their geochemistry with the previous understanding of tailings generated from the JEB and Sue open pits at the McClean Lake Operation.

These objectives were accomplished by focusing investigative efforts on the pore water and solid samples extracted by the in-situ sampling campaigns, primarily along two lines of inquiry:

- ***Pore Water Summary and Mill Operations*** – characterization and trends in the pore water, including general water quality parameters, major ion concentrations, minor constituents, and radionuclides, were documented, summarized, and evaluated with an understanding of large-scale changes in the mill; and
- ***Pore Water Concentrations and Solids Age*** – as minerals evolve with time, they invoke changes in the concentrations of certain constituent species in the pore water. These changes in constituent concentration in the pore water have been identified and quantified, and the factors affecting their magnitude and duration determined.
- A summary and discussion of the pore water concentrations found in the 2023 sampling campaign is presented below.

5.7.1.1 Data Presentation

To facilitate comparisons to analytical data from previous campaigns, the reporting format and data management used in the previous status reports has been retained. Vertical sample locations within the tailings mass are defined with respect to a fixed reference point and expressed as meters above sea level (mASL). The Figures presented in this section have the independent variable (sample elevation) on the y-axis rather than the conventional x-axis. This provides a “drill log” type presentation to visualize evolutionary changes with respect to tailings deposition depth (or age) within the TMF.

In graphs presenting average data, the geochemical samples have been grouped into 3 m vertical intervals by elevation. The analytical data within each 3 m interval has been averaged for all boreholes for presentation in the figures. Individual borehole data is presented, and identified as such, for additional context in select cases.

Not all data is presented in all graphs, for the sake of clarity in graphs which present the weighted average data over the history of the TOVP earlier TOVP campaign data may be omitted if it is not material to the conclusions. This data can be found in the respective TOVP reports in Appendix F.

5.7.1.2 Sampling Locations

The data presented in this report includes findings from eight boreholes, four original TOVP boreholes (TMF-01, TMF-02, TMF-03, and TMF-04), three additional boreholes first sampled in 2013 (TMF-05, TMF-06 and TMF-07) and one new location sampled in 2023 (TMF-08). The three boreholes added in 2013 were included to represent tailings closer to the edges of the TMF and further from the initial (tremi) point of deposition. Over the distance from the deposition point, some segregation has occurred in the JEB/Sue tailings and the JEB/Sue tailings at these TMF-05, TMF-06 and TMF07 are in general finer grained, which decreases the hydraulic conductivity of the tailings and slows the rate of geochemical reactions and contaminant transport. The finer grained JEB/Sue tailings also contain higher percentages of precipitates, sludges, clays, and amorphous hydrous ferric oxides, which adsorb other chemical species more readily. Borehole TMF-08 is sampled only through the Cigar Lake tailings to look at one particular deposition location (subaqueous) of tailings known to have been composed of ore with higher arsenic content.

5.7.1.3 Tailings by Sampling Depth

This section presents information on the source ore of the tailings by depth. The purpose of examining the source ore is to provide context to some of the variability noted in the tailings pore water results. Except for major interfaces (i.e. JEB/Sue), the exact locations of ore sources prior to the milling of Cigar Lake are difficult to determine due to consolidation and the processing of blended ores. Therefore, the depths assigned to the deposits are approximate. The Cigar Lake ore has never been blended, and key differences in geochemistry make the Cigar Lake tailings easily distinguishable from the preceding Sue ores. Figure 5.7-1 presents the approximate depths of the tailings assigned to each ore source in the same “drill-log” format as the pore water data for comparison. Table 5.7-1 presents the ore source assignment for each 2023 sample for reference.

Figure 5.7-1: Approximate Correlation of Source Ore Deposit with Tailings by Depth

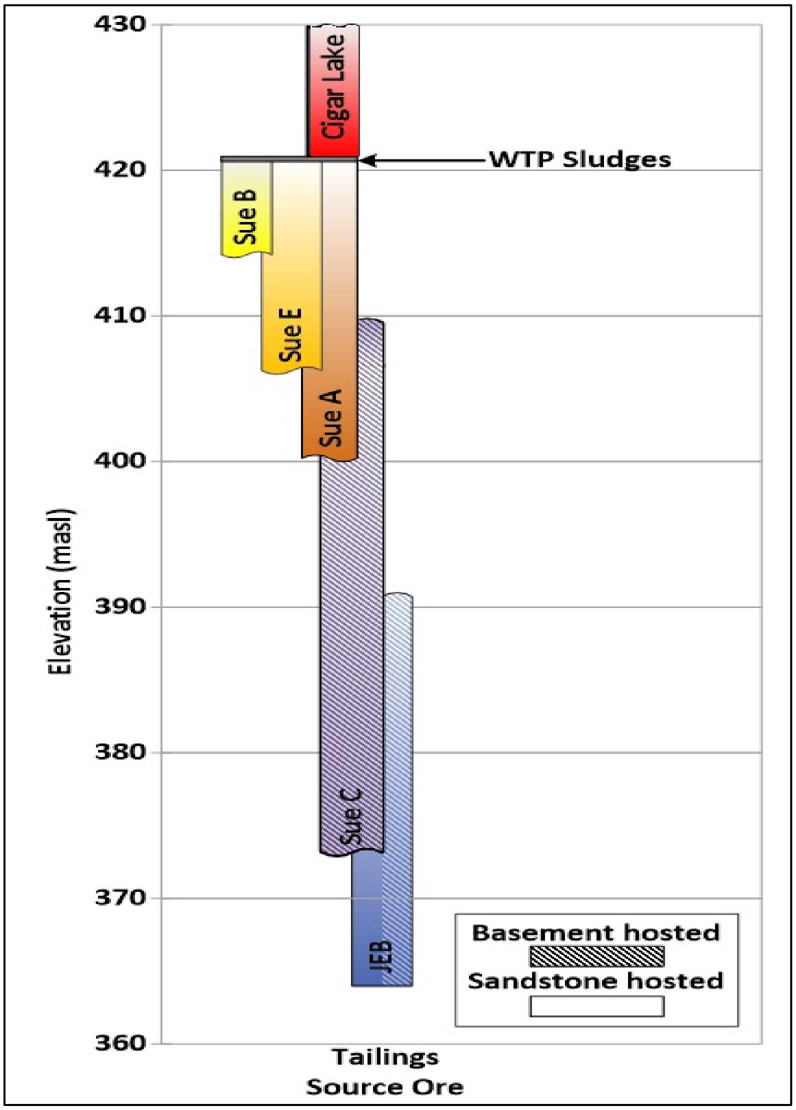


Table 5.7-1: Approximate 2018 In-Situ Sample Correlations with Initial Parent Ore

	Boreholes TMF23							
Ore	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**
Cigar Lake	01-05	01-05	01-06	01-03	01-07	01-06	01-06	01-07
Sue E, B and A	06-13	06-12	07-15	04-13	08-13	07-11	07-13	n/a
Sue C	14-19	13-19	16-21	14-19	14-17	12-17	-	n/a
JEB	n/a	n/a	n/a	20,21	-	-	-	n/a

*Columns denote hole and sample numbers. For example, Borehole TMF23-01, samples 01 to 05 originate from Cigar Lake (i.e. TMF23-01 SA01, SA02, SA03, SA04, SA05). n/a indicates deeper samples were not obtained while "-" indicates that no tailings exist at those depths at those locations.

JEB Deposit

Background: The first ore processed by the McClean Lake Mill was from the JEB deposit, and upon completion of mining the JEB pit was converted into the current JEB TMF. The JEB deposit was relatively small, and JEB high grade ore was processed through the mill without the blending in of other ores for only a limited time. After the processing of JEB high-grade ore was complete, JEB low-grade ore was blended with the initial Sue C ore. Samples of exclusively JEB material can be found at the lowest depths in holes TMF-01, -02, -03 and -04 (Table 5.7-1).

Key Characteristics: Due to their position at the bottom of the TMF, the JEB tailings are the most consolidated in the TMF and it is expected that additional geochemical changes in the JEB tailings will occur at a slower rate than in tailings at higher elevations. JEB tailings have a controlled arsenic source term and a higher percentage of clays as noted in the QEMSCAN analysis presented in Orano 2020, Section 5.3.2. Note that as the tailings consolidate obtaining samples of the JEB tailings will become increasingly challenging. In 2023 reaching the bottom of the tailings using the conventional drilling method used in past campaigns was not effective. Only two likely samples of the JEB tailings were obtained from the bottom of borehole TMF23-04 SA20 and SA21.

Sue C Deposit

Background: The Sue C deposit was mined directly following the JEB deposit, and provided several important lessons learned going forward at the McClean Lake Operation. The Sue C ore contained a low arsenic mineral content, which was resistant to leaching and resulted in unleached reduced arsenic being deposited in the TMF. The nature of the arsenic in the deposit left the Sue C tailings with less arsenic in the tailings solids than the JEB tailings, but with a relatively larger percentage of that arsenic being in the reduced form. As it was believed that the arsenic content was low and sufficient iron was present in the ore, a limited amount of ferric iron was added to the tailings preparation circuit (TPC) during processing.

Key Characteristics: The Sue C tailings present a characteristically higher arsenic source term as discussed in section (5.5.1). The Sue C deposit was partially basement hosted, which gives it distinctive characteristics (i.e. the aforementioned low arsenic content with a larger percentage of reduced arsenic).

Sue *E, A and B*

Background: The Sue E, A, and B deposits were closely co-located and primarily hosted in the Athabasca sandstone, resulting in similar mineralogy between the deposits. The Sue E, A, and B deposits were routinely blended together to achieve an average uranium feed grade to the mill. The deposits are difficult to distinguish geochemically due to blending and are considered as one tailings unit in this assessment.

Key Characteristics: During the milling of Sue E, A, and B, lessons learned from the production of the Sue C tailings were implemented. Additional ferric iron was added through the TPP to ensure sufficient control of arsenic pore water values. Additionally, at approximately 400 mASL, hydrogen peroxide was added to the TPP to oxidize residual hydrocarbons and control uranium pore water values as discussed in detail in Section (3.3.2.4). Prior to the temporary mill shutdown in 2010, low grade Sue A ore was fed through the mill at a higher rate to achieve production targets. As a result, sufficient retention time was not achieved in the TPP and, although the tailings leaving the mill were adjusted to the correct pH, various chemical reactions did not have time to go to completion as they normally would. The shortened retention times resulted in the continuation of these incomplete reactions (neutralization reactions, caused by lime addition) within the deposited tailings. A noticeable depression of the pH values in 2013 and an increase in nickel concentration in the resulting pore water from 2013 to 2023 is observed due to this activity (Section 5.7.4.1,)

Cigar Lake

Background: After an extended shutdown from 2010 – 2014, the restart of the McClean Lake Mill marked the beginning of the milling of the Cigar Lake deposit. Extensive upgrades were completed to the McClean Lake Mill to accommodate the much higher uranium grade of the Cigar Lake ore and a higher tonnage throughput. The geochemical principals applied throughout the mill, and in the TPC in particular, remain the same as described in previous TIDs. Physical changes to the tailings preparation circuit are described in detail in Section 2. This report focuses on the comparison of the geochemical properties of the new Cigar Lake tailings to the JEB/Sue tailings, to demonstrate that the long-term pore water quality will be controlled to expected levels.

Key Characteristics: The 2018 TOVP field campaign provided the first opportunity to sample the Cigar Lake tailings, and a preliminary understanding of the key Cigar Lake tailings properties was developed. The 2023 TOVP campaign has allowed a refinement of the assumptions around the Cigar Lake tailings with a larger number or samples to draw conclusions from. There are several characteristics that distinguish Cigar Lake tailings from JEB/Sue tailings:

- As noted in Section 5.6, the Cigar Lake tailings have a higher clay content than the JEB/Sue tailings which has a much larger percentage of quartz from the Athabasca sandstone.

- Deposition of the Cigar Lake tailings has occurred at multiple deposition points to maximize TMF pit capacity, and borehole TMF-01 is no longer considered universally closest to the point of deposition for assessments of the Cigar Lake tailings.

- The Cigar Lake ore is observed to have higher uranium grades, and also higher grades of COPCs such as arsenic, nickel, lead, and copper. The presence of these higher concentrations of COPCs in the solids will be closely compared with pore water concentrations, in order to identify key COPCs for potential additional study.

5.7.2 General Water Quality Parameters

This section considers the evolution of general water quality parameters, such as pH, redox potential, and specific conductivity in the context of ore source (i.e. depth, borehole location). Historical observations and trends are discussed, followed by a focus on the most recent 2023 data.

5.7.2.1 pH

The JEB TMF tailings pore water pH values are plotted against sample elevation for the 2004, 2008, 2013, 2018, and 2023 sample campaigns in Figure 5.7-2.

Historical Observations: The average pH value has changed relatively little over the life of the TMF, as shown in Table 5.7-2. In the past, the observed average pH decreased slightly at the lower elevations over time, which is consistent with observed redox activities (Figure 5.7-2). This observation can be attributed to ongoing geochemical processes in the tailings. For example: the precipitation of calcite from saturated bicarbonate solution would release hydrogen ions, and the oxidation of residual arsenide minerals in the tailings solids is also acid generating. Both of these reactions would tend to reduce the pH slightly in this strongly buffered system. A draw down in average pH values was observed in 2013 in newly placed tailings, which likely represents their temporary continued reactivity, pH values rebounded in 2018 to higher, circumneutral values, indicating that the draw down in pH was a short-term phenomenon.

2023 Observations: As part of the tailings preparation of the new Cigar Lake ore, pH adjustment of the as-discharged tailings is carefully maintained at a slightly higher pH (8-8.5). The pH control acts as a buffer from the continued reactivity of the tailings upon placement in the TMF, and no decrease in pH has been observed so far. The trend of pH values at higher elevations (which represent newly placed tailings) is slightly increasing which reflects the adjusted discharge pH. Variation in pH is observed in individual boreholes, representing areas where ongoing geochemical reactions temporarily draw down the pH; however, values are generally well controlled at circumneutral.

5.7.2.2 Redox Potential and Related Activity

Historical Observations: TOVP results demonstrate that ongoing redox reactions are the major geochemical feature of the aging process in the tailings pore water as the system moves towards equilibrium. COPCs involved in redox reactions include, but are not limited to, arsenic, iron, manganese, carbon, and potentially nitrogen. The historical average Eh ranges for the 2001 to 2023 sampling campaigns are presented in Figure 5.7-3. In general, Figure 5.7-2 shows the Eh values at pH 7 that correspond to different oxidation-reduction reactions at chemical equilibrium. The range of averaged Eh measurements completed in 2023 for TMF pore waters is indicated on the Figure by a green box and is compared to representations of the field measured Eh values for past sampling campaigns. Redox species, found in the pore water are also shown for context at their critical Eh values including: NO_2^-, NH_4^+, $[UO_2(CO_3)_2]^{2-}$, Mn^{2+}, MoO_4^{2-}, AsO_4^{3+}, Fe^{3+}, SO_4^{2-}, and HCO_3^-.

Reduced primary minerals such as pyrite, chalcopyrite, gersdorffite and rammelsbergite, not completely dissolved during the mill leaching process, have been observed in the tailings solids, particularly noted in the Cigar Lake tailings. Organic carbon-based materials, such as kerosene, tricapryl amine, and various flocculants are consumed during the milling process and occasionally report to the tailings solids. Within the oxidizing Eh range measured in the TMF pore waters, none of the above species are thermodynamically stable in the solids. In the pore water, a mixture of thermodynamically stable and unstable redox-sensitive species is observed. The pore water analytical data shows evidence that supports the oxidation of these reduced species to more stable oxidized forms over time.

The JEB TMF tailings pore water redox potential (Eh) values are plotted against sample elevation for the 2004, 2008, 2013, 2018, and 2023 sampling campaigns in Figure 5.7-2. The average of Eh values measured since 2001 in each sampling campaign is presented in Table 5.7-2.

Table 5.7-2: Overall weighted average general water quality parameters for each intrusive sampling campaign

	2001	2002	2003	2004	2008	2013	2018		2023	
							JEB/Sue	Cigar Lake	JEB/Sue	Cigar Lake
pH	7.51	7.77	7.60	7.79	7.49	6.88	7.43	7.74	7.27	7.95
Eh (mV)	364	357	317.7	367	329	270	222	291	206	237
Conductivity (µS/cm)	3245	2617	2801	3027	2777	3321	3508	5384	4656	5798

An oxidized environment has been maintained within the TMF over time. A slight decreasing trend with depth/age was observed in the 2013 data and again in 2018 (more obvious in tailings from approximately 380 to 400 mASL). The tailings between 380 to 400 mASL are principally from the milling of Sue C ore where insufficient oxidant (ferric iron) was added. Lower Eh values are consistent with on-going redox geochemical processes within the tailings mass as discussed previously within this report (Sections 5.5). There was evidence in 2018 to suggest that the geochemical reactions of arsenic and uranium were nearing their peak in key locations representing the problematic Sue C tailings and Eh values were expected to begin to be stable or recover in the Sue C tailings zone.

2023 Observations: The averaged 2023 Eh values ranged from 175 to 338 mV with an overall average of 236.53 mV for the Cigar Lake tailings and 206.5 mV for the JEB/Sue tailings. A key change in the 2023 data shows that, as predicted in 2018, Eh values have recovered significantly from approximately 380-400 mASL which supports the earlier interpretations in the arsenic and uranium geochemical models that reactions oxidizing reduced species are slowing. At higher elevations (above 400 mASL) Eh values have decreased since 2008. In the 2023 data the most significant decrease was in the newly placed Cigar Lake tailings. A decrease in Eh is not unexpected as the newer tailings are significantly out of equilibrium, and the Cigar Lake tailings contain a higher loading of reactive sulfide minerals which are likely to drive down redox values as the oxidize in the tailings. The uppermost data points in the 2023 data are influenced by the inclusion of 1) newly deposited tailings which have not yet begun to further oxidize since their placement and 2) tailings samples at the top of the column potentially influenced by the TMF pond water.

Figure 5.7-2: Sample Elevation vs pH and Eh

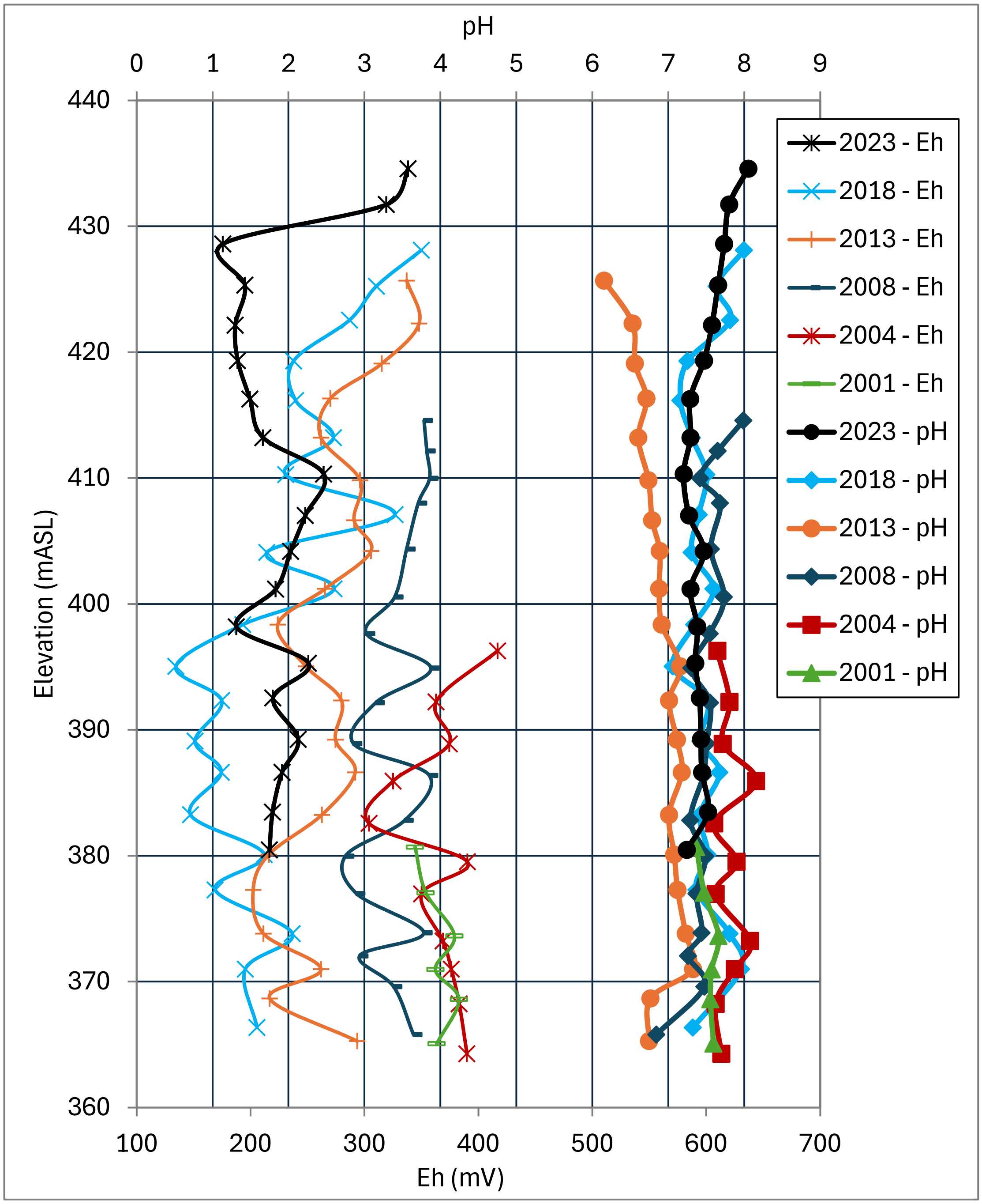
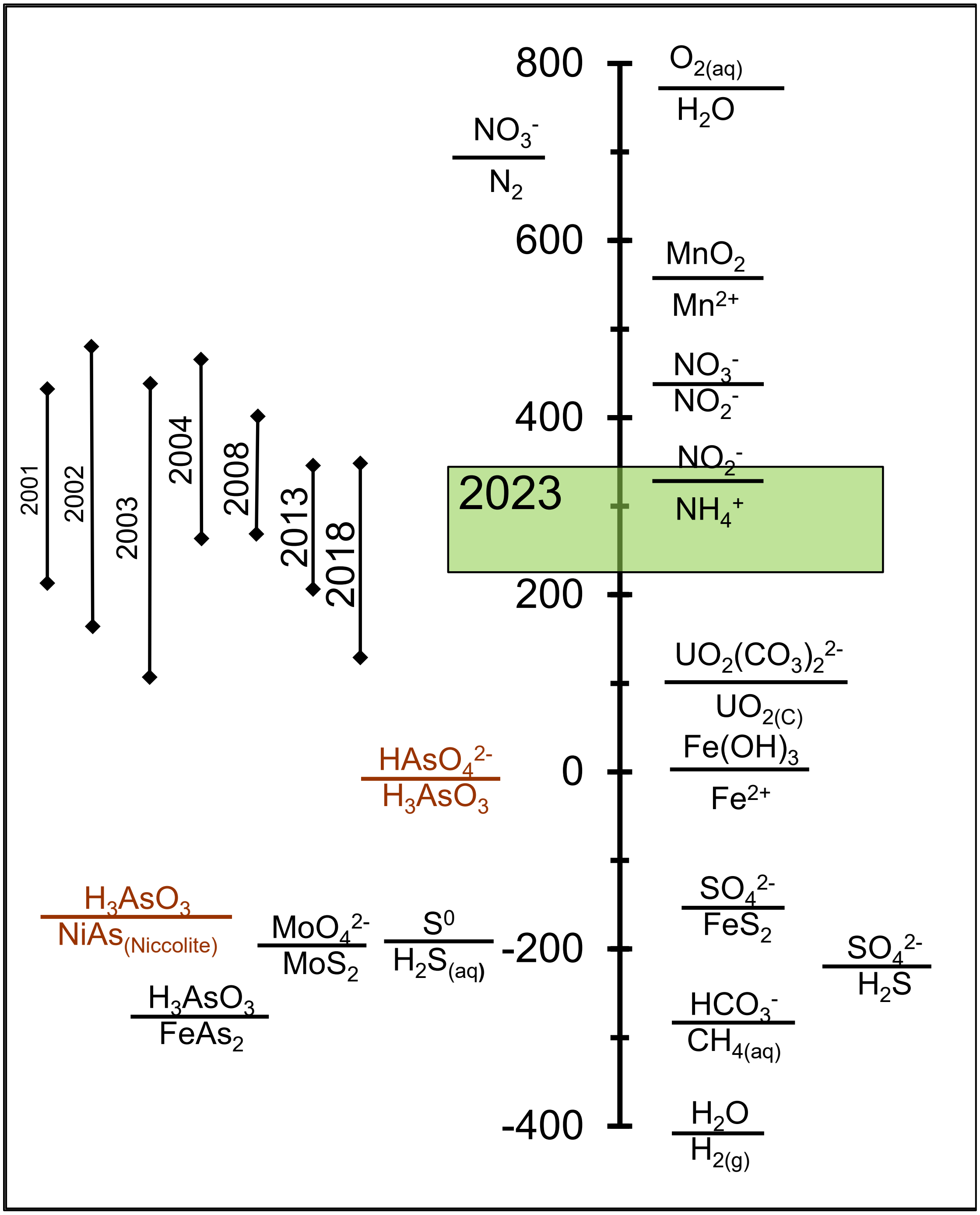


Figure 5.7-3: **Eh Ladder Diagram for Important Redox Sensitive Species in the TMF Pore Water Showing Approximate Redox Conditions of the TMF by Sampling Year (after Drever, 1997)**

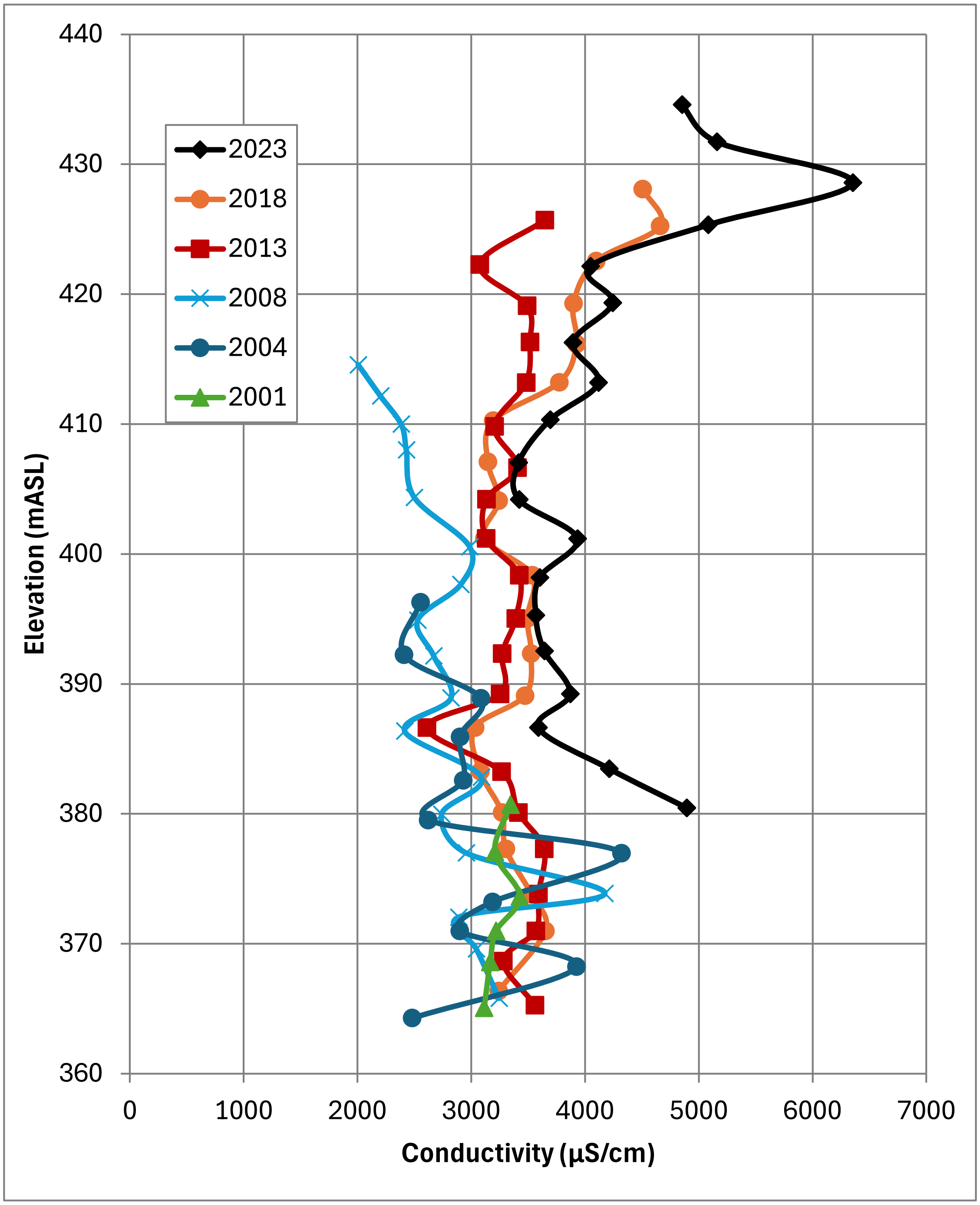


5.7.2.3 Specific Conductivity

Historical Observations: Changes in specific conductivity values generally reflect variations in major ion concentrations, particularly those ions that are smaller, of higher charge, and therefore more mobile. Figure 5.7-4 compares the sample elevation with specific conductivity for 2001 to 2023. Average values from each sampling campaign are presented in Table 5.7-2. As rapidly formed impure amorphous precipitates from the TPP age in the TMF, impurities will be expelled, and a greater structural order and crystallinity will the achieved. A rise in specific conductivity is expected to develop slowly over time as a signal of this aging process.

2023 Observations: Overall, the conductivity data shows a gradual increase over time from 2008 to 2023, particularly in the upper tailings. As observed in the pH values, there has been a greater increase in conductivity at higher elevations in 2023 compared to past campaigns. Much of the increase likely reflects the high clay content of the Cigar Lake ore, which has increased the major ion concentrations in all Cigar Lake pore water samples. At depth, the 2023 pore water also shows increases in conductivity, which is attributed to increases in major ions, particularly magnesium and chloride which show variability similar to the 2008 and 2004 campaign data.

Figure 5.7-4: Sample Elevation vs Specific Conductivity



5.7.3 Major Ions

The major cations dissolved in the tailings pore water are Ca^{2+}, Na^{+}, K^{+}, and Mg^{2+}. These are approximately electrically charge balanced with the anion concentrations for SO_4^{2-}, Cl^{-}, and HCO_3^{-}. The concentrations for Cl^{-}, Mg^{2+}, and K^{+} for the 2002, 2004, 2008, 2013, 2018, and 2023 TOVP campaigns by averaged interval are plotted against sample elevation in Figures 5.7-5, 5.7-6 and 5.7-7. Historical observations and trends are discussed in the sections below, followed by a focus on the most recent 2023 data.

5.7.3.1 Potassium *(K^{+})* and Magnesium *(Mg^{2+})*

Historical Observations: In previous reporting (COGEMA, 2003; COGEMA, 2004a; AREVA, 2005a) and initial laboratory test work (Langmuir et.al., 1999), K^{+} concentrations demonstrated a slight decrease with depth/age below 400 mASL. Mg^{2+} concentrations in the pore water were observed to rise with depth/age (COGEMA, 2002, Appendix A).

2023 Observations: The K^{+} and Mg^{2+} trends with depth/age noted above continue to be observed in 2023, with Mg^{2+} concentrations now considerably higher than those measured in 2001. Mg^{2+} concentrations at the lower elevations are similar to 2018 values but are still variable with an increasing trend in 2023. In the Cigar Lake tailings placed prior to 2018, Mg^{2+} and K^{+} concentrations decreased significantly in 2023, while concentrations in tailings placed after 2018, concentrations increased relative to newly placed tailings in 2018. The observed decrease is likely related to the initial flush of ions from freshly placed tailings which are significantly out of equilibrium, which quickly decreases over time. At higher elevations, the large increase in Mg^{2+} in particular, is responding to the requirement to charge balance the elevated SO_4^{2-} concentrations in the pore water. The increased arsenic mineral content in the Cigar Lake ore has resulted in the need to add a larger quantity of ferric sulfate in the TPP than previous ores. Additionally, increased volumes of sulphuric acid are used in the mill process due to the increased mill throughput. This trend of elevated SO_4^{2-} concentrations in the upper tailings is similar for most major ions and can be attributed to the influence of the Cigar Lake ore.

5.7.3.2 Chloride *(Cl^{-})*

Historical Observations: Previous TOVP Status Reports (e.g. COGEMA, 2003; COGEMA, 2004a; AREVA, 2005a), found that the concentration of Cl^{-} appeared to be unaffected by the aging process. The principal source of Cl^{-} in the tailings pore water historically was the quantity of barium chloride added in the TPC for radium control. In the years before the upgrade of the McClean Lake Mill, the uranium content in the ore steadily declined and therefore required less barium chloride for radium treatment.

2023 Observations: Cl^{-} concentrations in the JEB/ Sue tailings continue to be largely stable and similar to the results of past sampling campaigns. In the Cigar Lake tailings, there was a decrease in Cl^{-} concentration in Cigar Lake pore water at tailings elevations previously sampled in 2018, and a large increase in Cl- concentrations in tailings placed since 2018. The significantly high uranium ore grade from Cigar Lake has required a large increase in barium chloride addition to treat associated radium in the TPC. As discussed in section 5.6, the Cigar Lake ore also has a larger proportion of clays than the JEB/Sue tailings and so, being more chemically diverse than the quartz of the JEB/Sue tailings, will liberate more major ions into the pore water.

Figure 5.7-5: Sample Elevation vs Major Ions – K^+

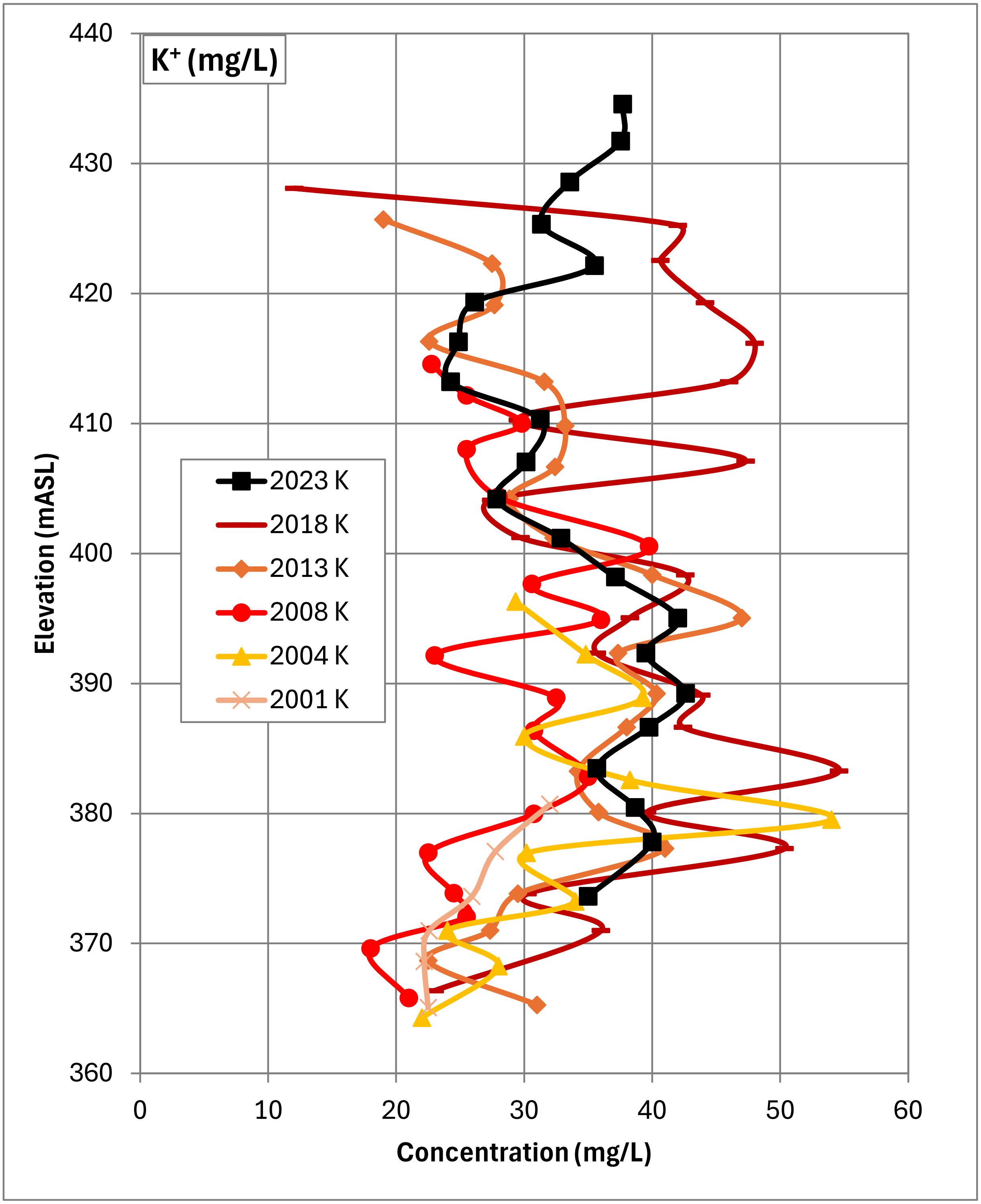


Figure 5.7-6: **Sample Elevation vs Major Ions – Mg^{2+}**

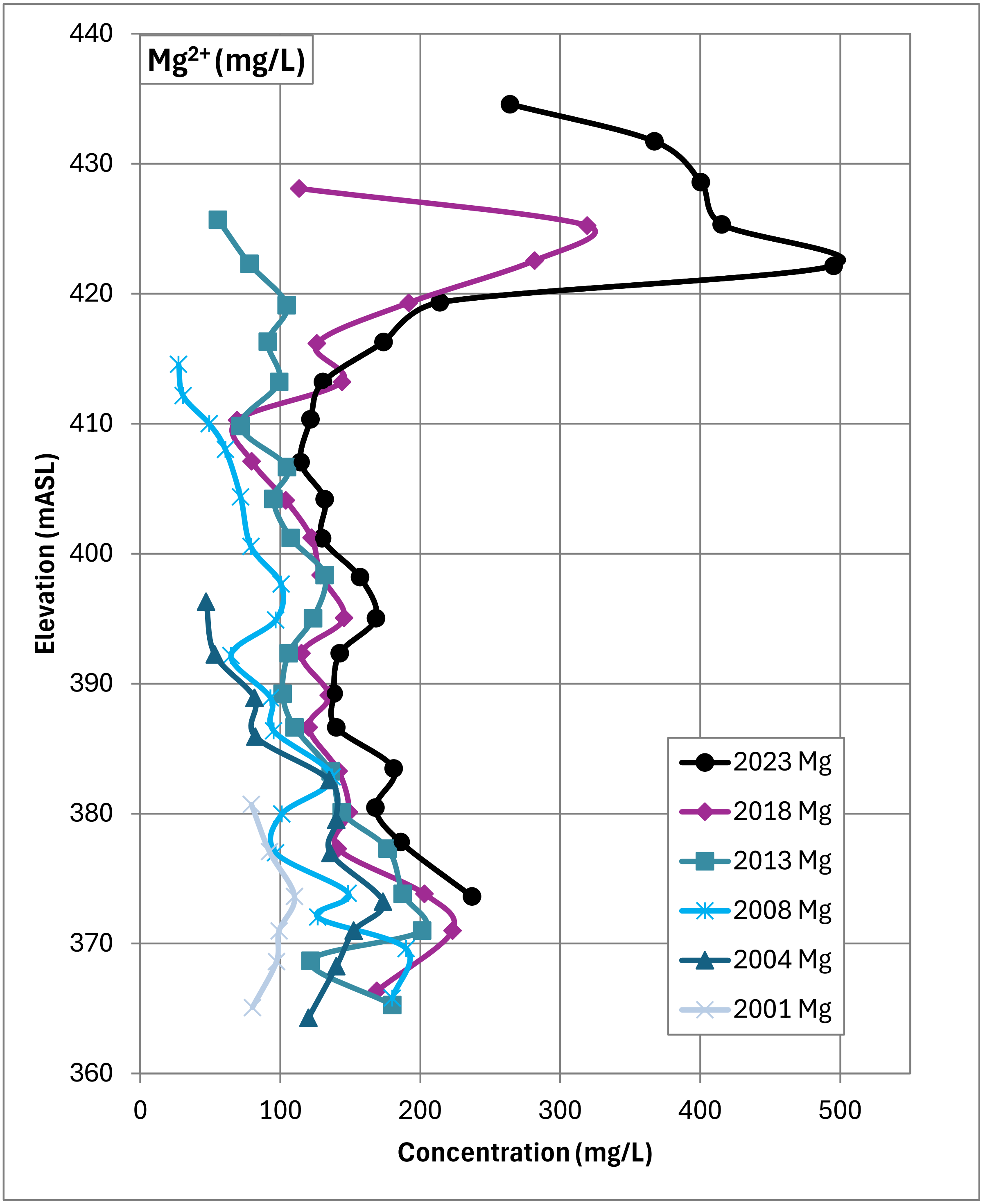
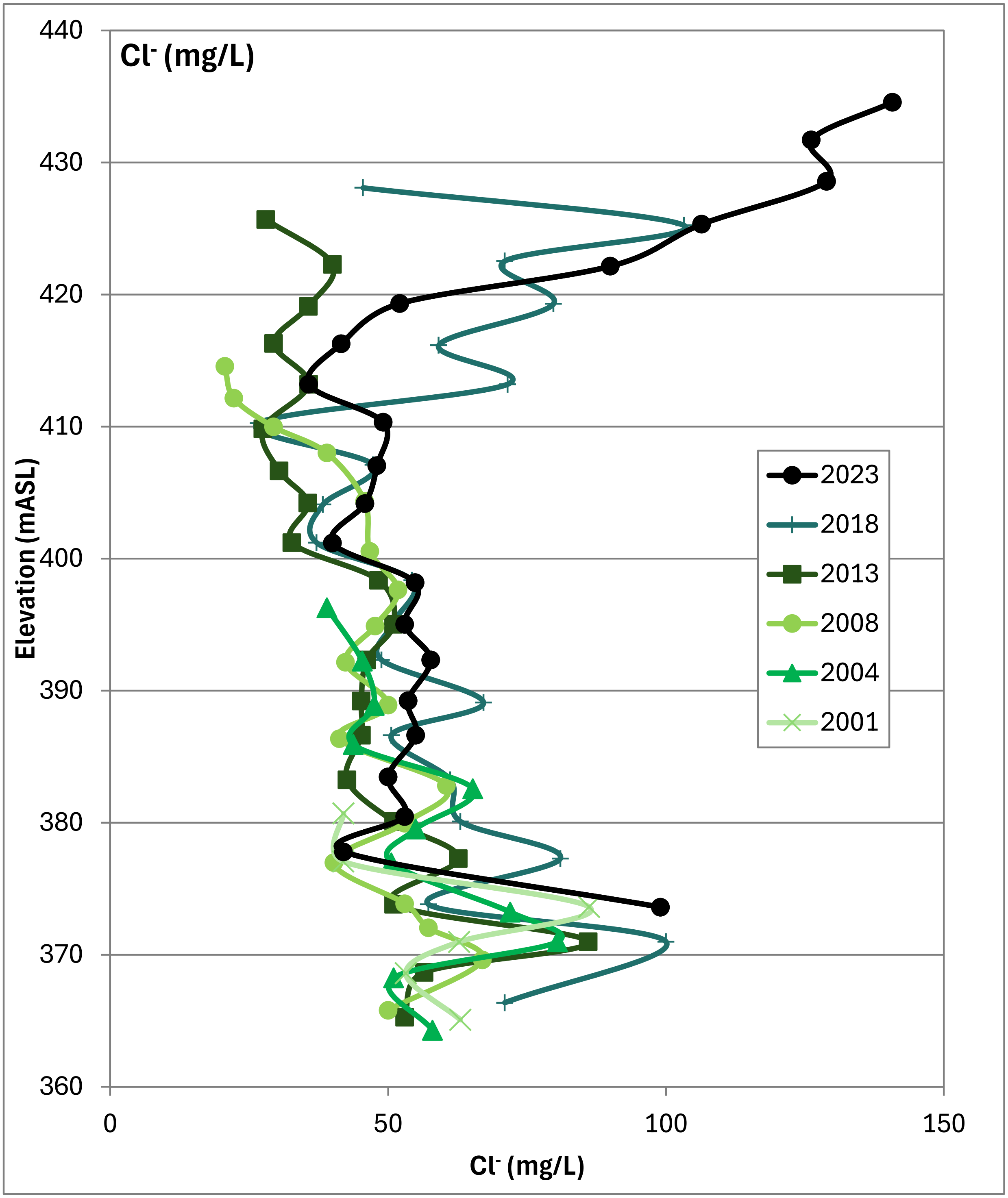


Figure 5.7-7: Sample Elevation vs Major Ions – Cl^-



5.7.3.3 Bicarbonate *(*HCO_3^-) and Calcium (Ca^{2+})

Historical Observations: Prior studies have noted an increased concentration of HCO_3^- at depth below ~400 mASL. Increases in HCO_3^- concentration in the pore water are driven by the oxidation of hydrocarbons deposited with the tailings and has implications for the pore water concentrations of other constituents related to the precipitation of secondary carbonate minerals (e.g. U, Ca^{2+}, Na^+ and SO_2^-), which has been discussed in Section 5.5.3. For major ions, the effects of increases in HCO_3^- concentrations are presented in Figures 5.7-8, 5.7-9, and 5.7-10. The weighted average concentrations of HCO_3^- and Ca^{2+} in tailings pore water at 3 m depth intervals for the 2001, 2004, 2008, 2013, and 2023 TOVP campaigns are compared in Figure 5.7-8. In the 2008 data, averaged HCO_3^- pore water concentrations exceeded 300 mg/L at several elevations having risen from below 100 mg/L at the time of initial tailings placement. In 2013 and 2018, HCO_3^- concentrations remained elevated and exceeded 300 mg/L in several locations, but no increases in the average values were observed. In previous TOVP Status Reports (e.g. 2001(COGEMA 2002) and 2004 (COGEMA 2005a)), Ca^{2+} concentrations appeared to be at saturation with respect to gypsum (approximately 550 mg/L) however in 2008 concentrations of Ca^{2+} were noted to be undersaturated in samples below ~400 mASL. Ca^{2+} concentrations in samples below ~400 mASL rebounded significantly in 2013 an then in 2018 concentrations again showed significant undersaturation in the same locations as 2008. These large changes in Ca^{2+} concentrations suggests that the system swings over time from periods of carbonate mineral precipitation to periods of rebound, during which small amounts of the total gypsum dissolves in the tailings and Ca^{2+} is replenished in the liquid phase.

2023 Observations: HCO_3^- and Ca^{2+} concentrations in individual samples from the 2023 TOVP campaign are shown in Figure 5.7-9. In 2023 HCO_3^- average values remained elevated but stable below ~400 mASL, even showing some evidence of decreasing concentrations in the lowest depth intervals sampled, suggesting that the process of oxidizing hydrocarbons has peaked. If carbonate minerals are now slowly being formed in the tailings, as the cyclical nature of the Ca^{2+} concentrations suggests, bicarbonate values will continue to decrease over time. In 2023, Ca^{2+} concentrations at locations corresponding to high HCO_3^- concentrations, have rebounded (similar to what was observed in 2013) relative to the 2018 results. A period of gypsum dissolution can be identified by an accompanying increase of SO_4^{2-} concentration in the pore water (discussed further in Section 5.7.3.4, Figure 5.7-10).

5.7.3.4 Sodium and Sulfate (Na^+ and SO_4^{2-})

Historical Observations: As with HCO_3^- and Ca^{2+} **c**ontrol over both Na^+ and SO_4^{2-} concentrations in solution is divided at approximately 400 mASL, when hydrogen peroxide addition began in the TPC to fully oxidize all organic carbon in the tailings. The addition of hydrogen peroxide was initiated to control uranium concentrations in the pore water; however, it had a cascade of effects through various major and minor ions in solution.

In the case of Na^+ and SO_4^{2-}, changes in concentration over time are generally observed below 400 mASL as SO_4^{2-} comes into solution through gypsum dissolution. Na^+ is drawn into solution as a charge balance to SO_4^{2-}. Figure 5.7-10 shows that, beginning in 2008, observed Na^+ and SO_4^{2-} concentrations below 400 mASL supported carbonate mineral precipitation, as discussed in the uranium geochemical model in Section 5.5.3, with the same large increases and decreases in concentrations as noted above for HCO_3^- and Ca^{2+}. Both

Na^+ and SO_4^{2-} concentrations were several hundred mg/L higher at elevations where carbonate mineral precipitation was thought to be occurring in 2008, reflecting the secondary dissolution of gypsum, while the same increases were not observed in 2013. In 2018 SO_4^{2-} concentrations were again variable although Na^+ concentrations were not, likely demonstrating the sequential nature of the process where the dissolution of gypsum releasing SO_4^{2-} precedes Na^{2+} coming into solution to charge balance. This data also suggests that these two steps occur at different rates and so the 2018 data is reporting either a reaction just beginning or nearing completion. In 2018 Cigar Lake tailings samples increases in concentration were noted for both SO_4^{2-} and Na^+ over average JEB/Sue tailings concentrations as is expected based on the chemistry of the Cigar Lake ore (previously described in section 5.7.3.1 and 5.7.3.2)

2023 Observations: The 2023 averaged concentration data for Na^+ and SO_4^{2-} in JEB/Sue tailings was similar to the system observed in 2013 without large increases in concentrations (Figure 5.7-10) although more variability is noted when looking at individual sample results (Figure 5.7-11). Results for the Cigar Lake tailings increased over 2018 concentrations as previously noted in other major ions, which is predicted due to the increased need to treat high arsenic grades with additional sulphuric acid (in leaching) and ferric sulfate (in the TPP). Additionally, elevated amounts of sulphide minerals are present in the Cigar Lake ore (principally pyrite, galena and chalcopyrite) which, upon oxidation, will release SO_4^{2-} into solution. Na^+ is pulled into solution to charge balance SO_4^{2-} sourced from the increased clay content in the Cigar Lake tailings.

Figure 5.7-8: **Sample Elevation vs Major Ions – Ca^{2+} and HCO_3^-**

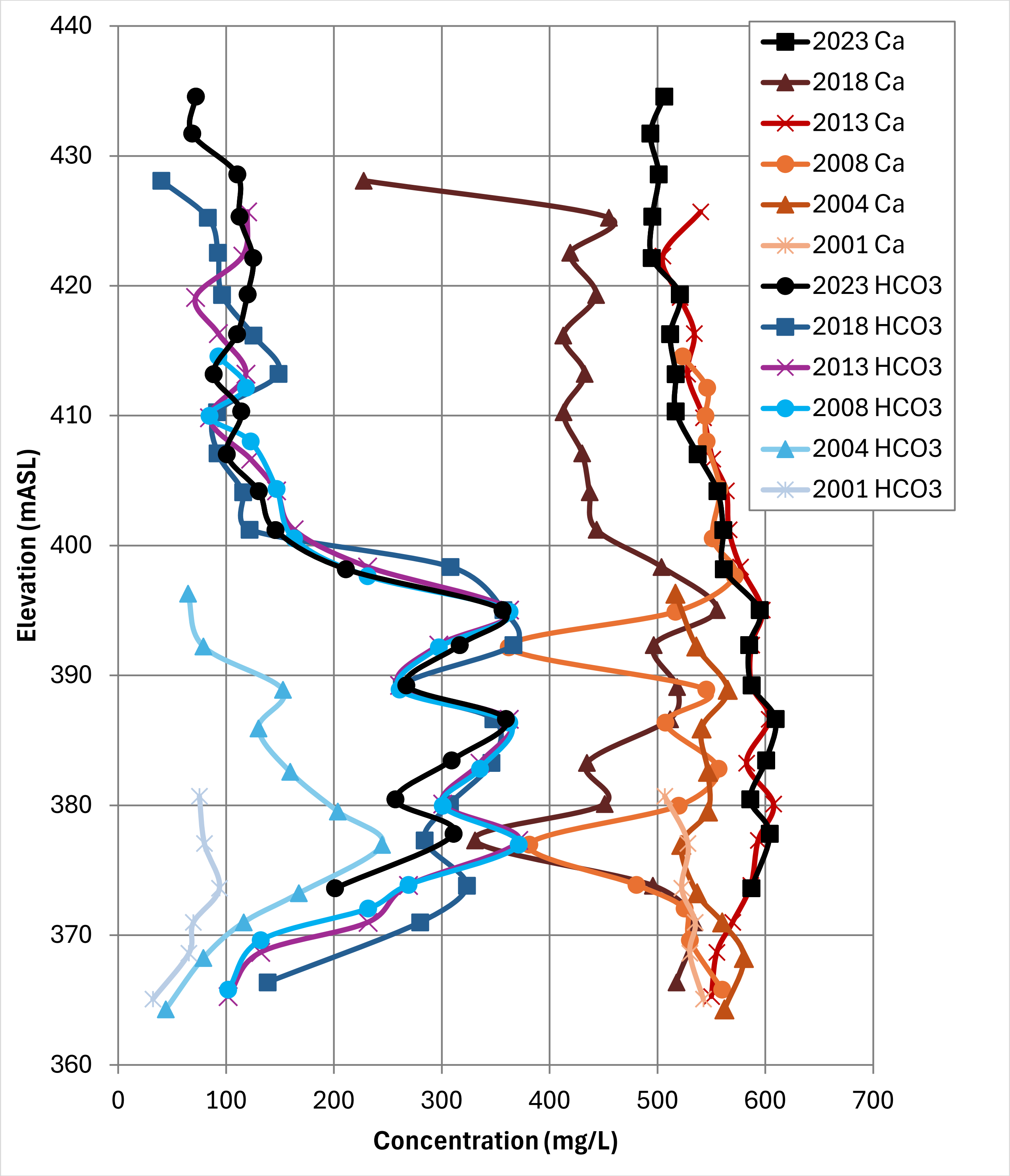


Figure 5.7-9: Sample Elevation vs Major Ions – Ca^{2+} and HCO_3^- by borehole 2023

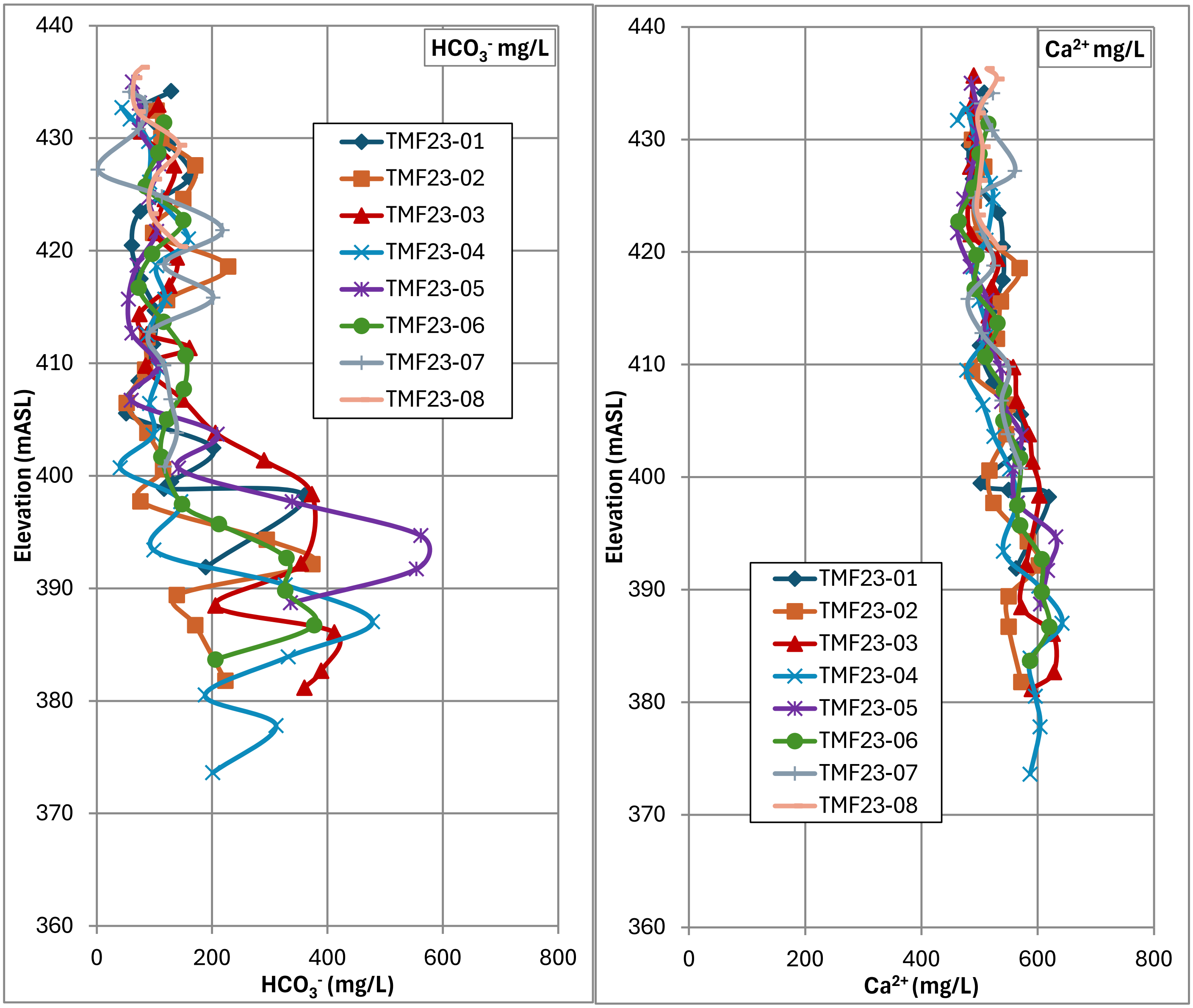


Figure 5.7-10: Sample Elevation vs Major Ions – Na^+ and $SO4^{2-}$

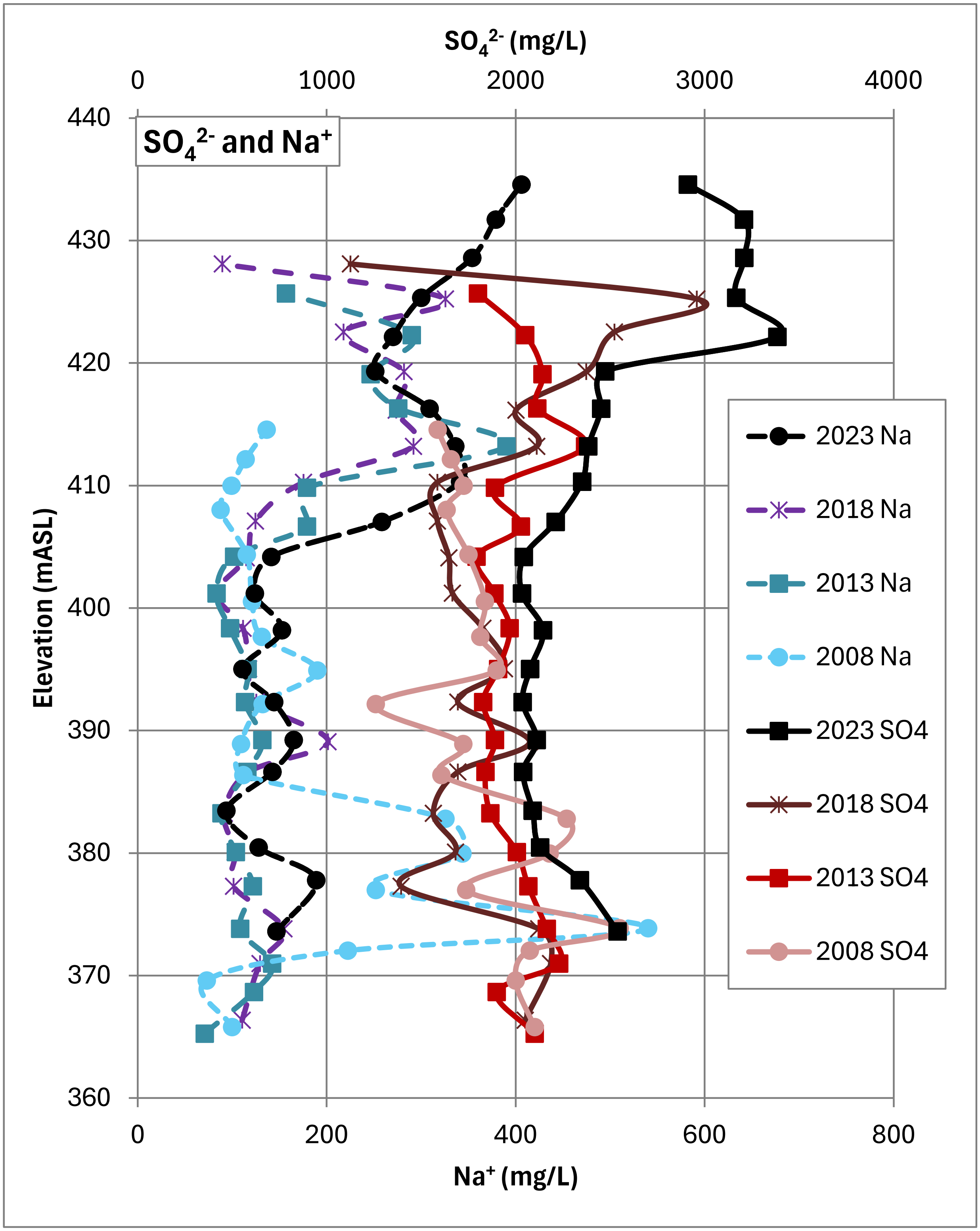
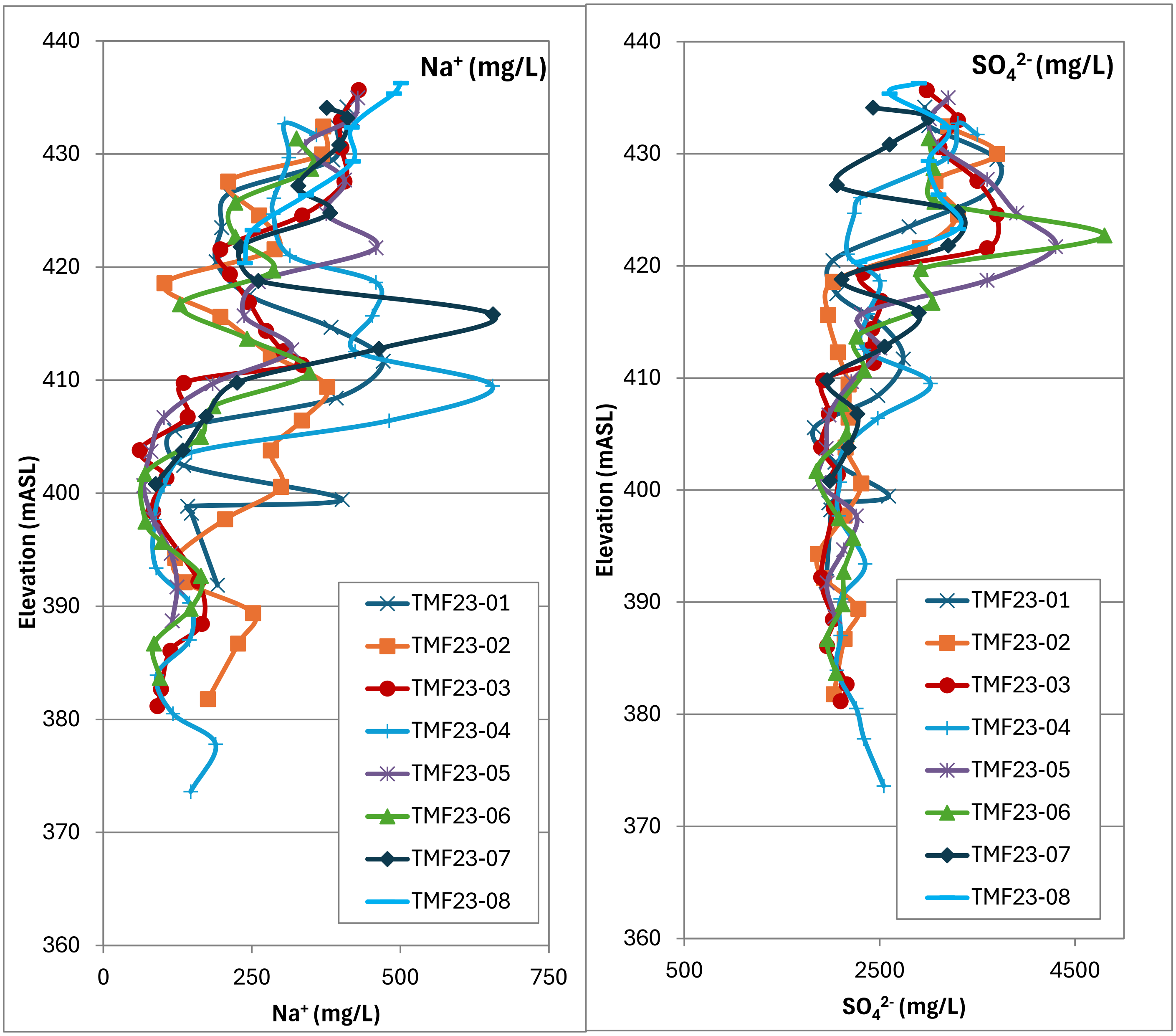


Figure 5.7-11: Sample Elevation vs Major Ions – Na^+ and $SO4^{2-}$ by borehole 2023



5.7.4 Minor Constituents

The concentrations of several COPCs, present in relatively small amounts, have trends of interest with elevation in the TMF. These include nickel, molybdenum, selenium, copper, lead and arsenic. Historical observations and trends are discussed in the sections below, followed by a focus on the most recent 2023 data and the path forward for further understanding.

5.7.4.1 Nickel (*Ni*)

Historical Observations: Early laboratory aging test work conducted before the start of tailings deposition (Appendix C, Section C) suggested that Ni concentrations in the placed tailings pore water had the potential to increase during aging. Figure 5.7-12 follows average Ni concentrations with elevation for 2004, 2008, 2013, and 2018 TOVP campaigns showing that increases in Ni have been minor. Nickel concentrations have remained low in the JEB/ Sue tailings, with an average value of 2.37 mg/L and minor variability in the uppermost Sue tailings over time. Above 409 mASL, the Ni pore water concentrations reflect a period of increased mill throughput during the processing of lower grade Sue A ore. Oxidation reactions of reduced minerals were completed in the placed tailings rather than the TPC, which resulted in nickel being incompletely removed from the tailings pore water. The 2013 results shows that nickel concentrations had increased in response to the increased tonnage rate in the mill during the Sue A processing period but decreased in the 2018 sampling results.

Cigar Lake tailings results in 2018 demonstrated low and controlled pore water nickel concentrations.

2023 Observations: Samples representing the Sue A tailings again showed a decrease in concentration over time, while Cigar Lake nickel concentrations remain low and controlled.

Path Forward: Additional test work into the final stable oxidized nickel mineralogy in the tailings has been initiated, in order to better understand controls on the final pore water nickel concentration. Initial results for the new Cigar Lake tailings demonstrate very low pore water concentrations (weighted average 0.17 mg/L) despite higher nickel concentrations present in the ore. As the processing of the Cigar Lake ore continues, the amount of nickel reporting to the tailings solids is expected to increase and corresponding pore water concentrations will be tracked to identify any evolution with time. Nickel pore water values remain well controlled, and the initiation of additional nickel mineralogy studies is proactive. The work will support a strong geochemical understanding of nickel, by identifying solubility controls and providing a basis for validation through future sampling campaigns.

5.7.4.2 Molybdenum *(Mo)*

Historical Observations: The geochemical model of molybdenum is discussed in Section 5.5.2

2023 Observations: In 2023, it was again noted, as in 2013 and 2018, that the newly deposited tailings have lower Mo values than previously observed likely due to reduced retention time in the TPC (Figure 5.7-12). Normally, up to 25% of the ferrimolybdite formed in the tailings preparation process has time to redissolve, resulting in higher Mo concentrations in the newly placed tailings. A shorter retention time in the TPC means that dissolution of ferrimolybdite occurs later in the placed tailings, and therefore initial Mo values are relatively low although the same rise and fall in molybdenum concentrations is expected over time.

Path Forward: Overall, the observations provide verification of laboratory aging tests and the research work conducted by the University of Saskatchewan which predicted that Mo pore water concentrations will stabilize to lower levels with time. Future sampling results will continue to be monitored to validate that molybdenum geochemistry is evolving as expected in the TMF.

5.7.4.3 Selenium (*Se*)

Historical Observations: Average pore water Se concentration data is presented from 2008 to 2023 in Figure 5.7-13. Selenium data is limited as it was first collected in 2008. Overall, the Se concentrations remained very low throughout the depth of the tailings with minor variability. Although a small increase in Se values was noted at one depth interval in the Cigar Lake tailings in 2018, the concentrations continued to be very low.

2023 Observations: Average Se pore water concentrations in the newly placed Cigar Lake tailings are noted to be low and stable in the 2023 results. Slightly more variability in the data is noted in the JEB/Sue tailings however the relative concentrations remain low.

Path Forward: Geochemical modelling was initiated to determine the most stable selenium mineral phase(s) in the tailings but was then delayed due to the Covid-19 pandemic. This work is again underway with preliminary work undertaken in 2025. The study will advance over the coming years and be reported on in the next submission of the Tailings Management TID. In the past, it has not been possible to identify selenium phase(s) in the tailings solids, as concentrations were too low for speciation analysis. The concentrations of selenium in Cigar Lake ore may make speciation analysis possible, and this analysis will be investigated through a research partnership with the University of Saskatchewan.

5.7.4.4 Copper and Lead (*Cu and Pb*)

Historical Observations: Throughout the history of the McClean Lake (JEB/Sue) tailings, copper and lead have not been considered important COPCs as their respective concentrations have been consistently low and controlled (Figure 5.7-13). In the JEB and Sue tailings, only very minor amounts of Cu and Pb sulphide minerals were present in the ores, limiting potential sources for increased solubility in the tailings pore water. Pb and Cu concentrations from the Cigar Lake tailings first sampled in 2018 showed slightly elevated concentration in one depth interval, however the relative concentrations were still very low.

2023 Observations: With the processing of the Cigar Lake ore, the potential for an increased loading of copper and lead to the tailings pore water exists, principally from potential oxidation of chalcopyrite ($CuFeS_2$) and galena (PbS); however, in 2023 average concentrations of Pb and Cu remained low and controlled in the Cigar Lake tailings. A small area of increasing values was noted in Pb concentrations in the lower Sue C tailings however the relative concentrations remain low.

Path Forward: A research program with the University of Saskatchewan, which was substantially delayed by the Covid-19 pandemic has been re-initiated to examine Cu and Pb to better understand their final geochemically stable endpoints in the TMF. The program is designed to follow the same approach that was previously taken for the development of the molybdenum geochemical model. Geochemical modelling of thermodynamic equilibrium reactions will be undertaken using PHREEQC to identify possible stable mineralogical endpoints. Upon completion of this initial work, tailings samples will be analyzed using various microanalytical techniques to identify possible minerals which have precipitated. The study will advance over the coming years and be reported on in the next submission of the Tailings Management TID.

Figure 5.7-12: Sample Elevation vs Minor Elements – Ni and Mo

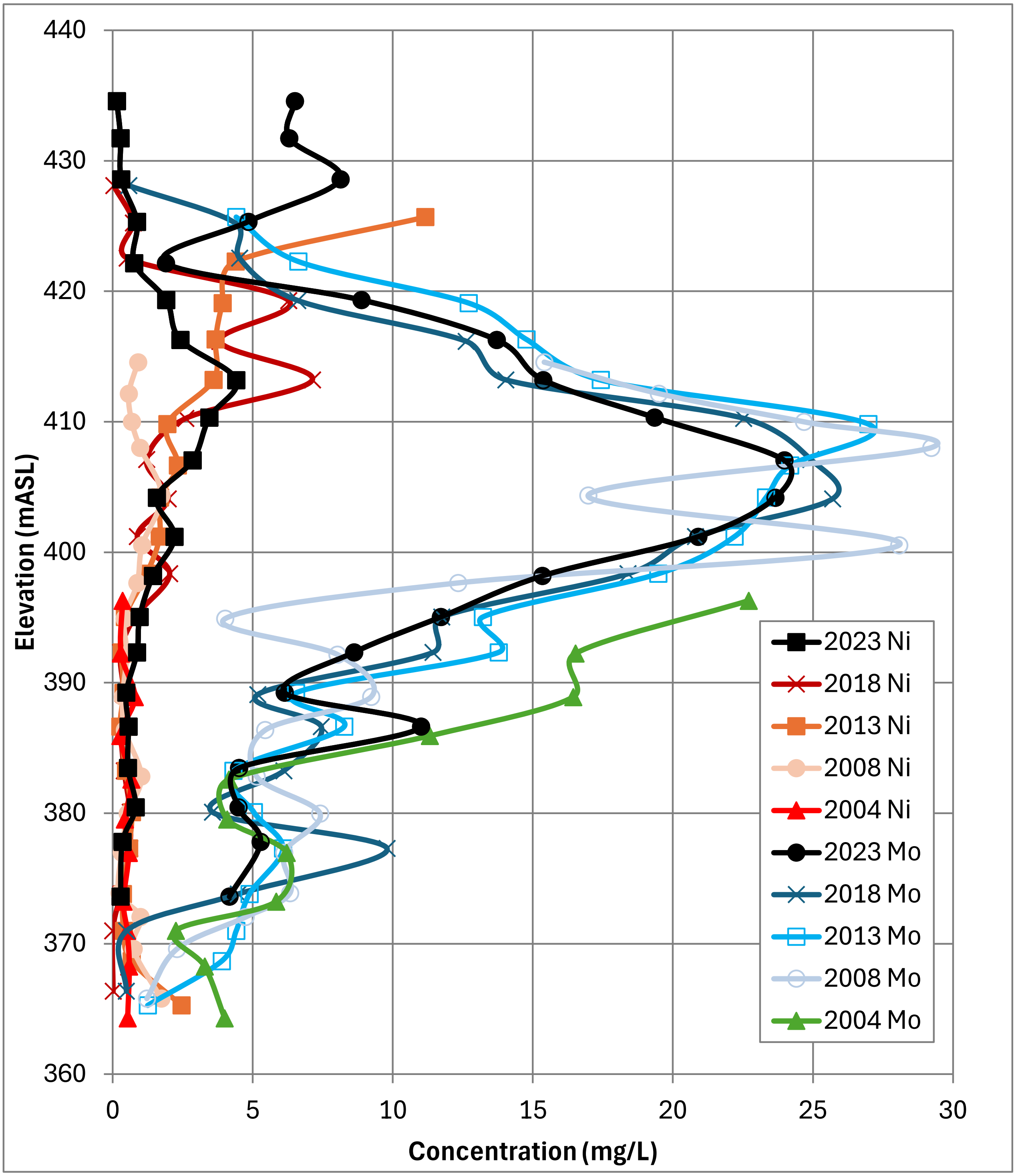


Figure 5.7-13: Sample Elevation vs Minor Elements – Se

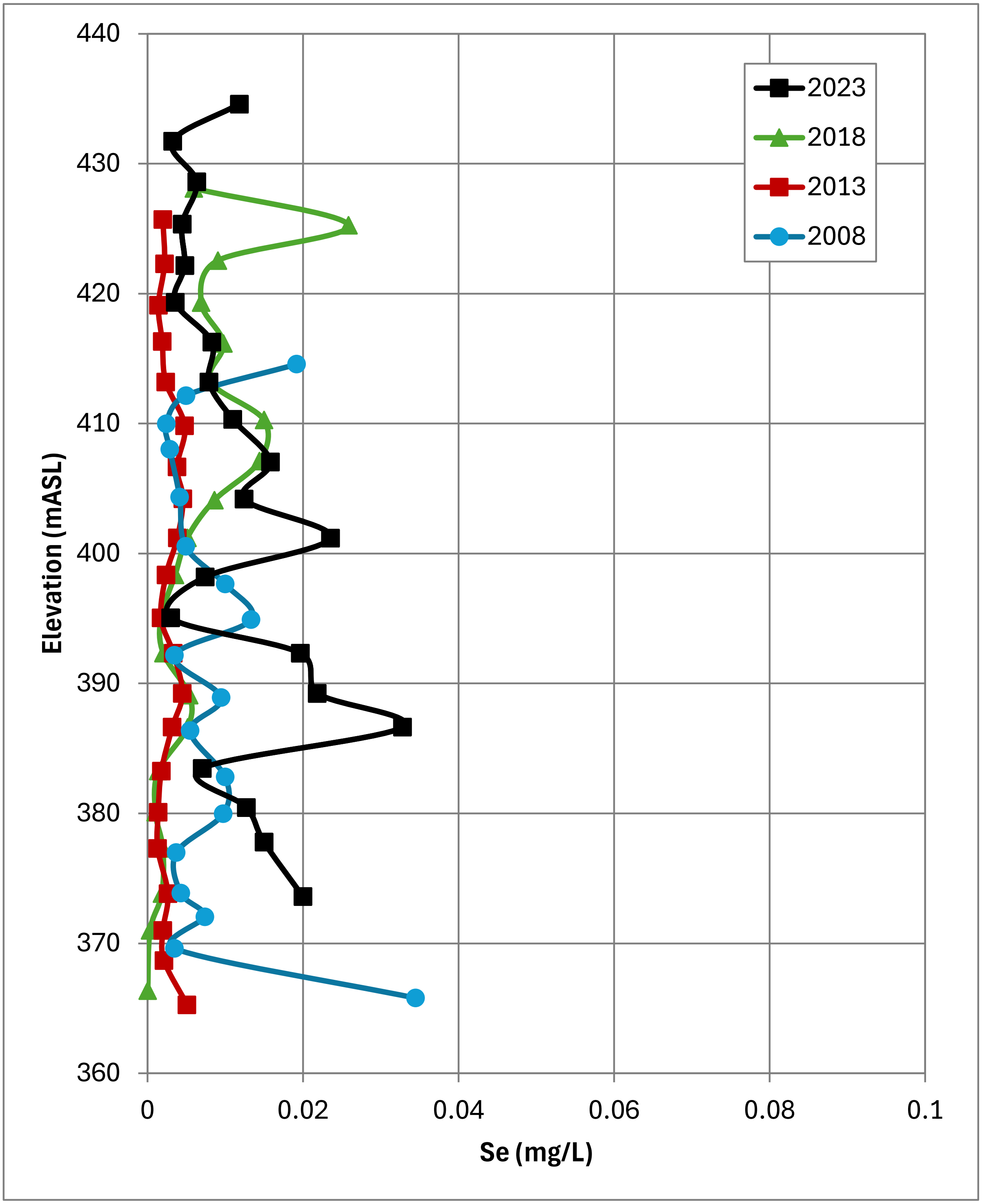
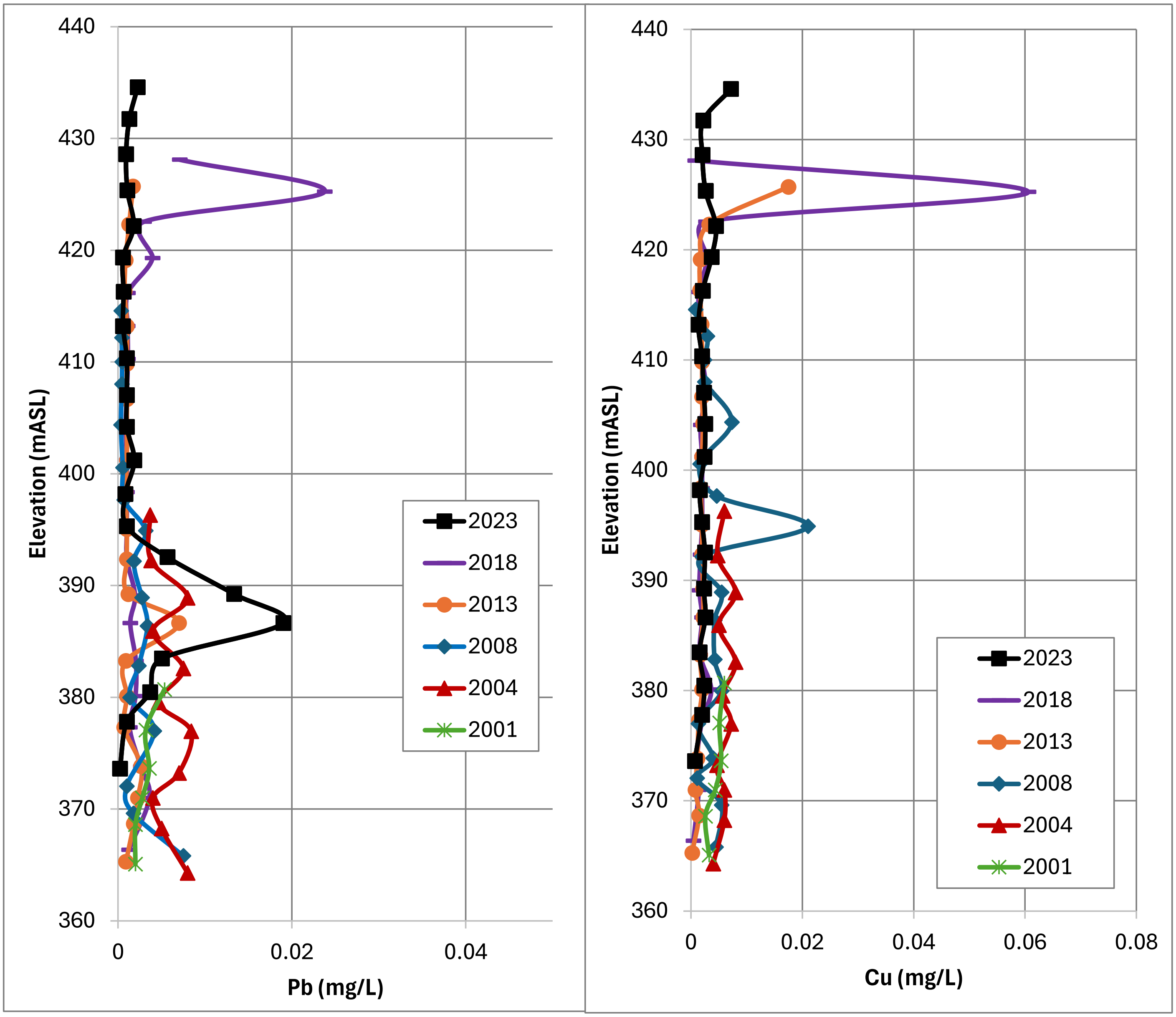


Figure 5.7-14: Sample Elevation vs Minor Elements - Pb and Cu



5.7.4.5 Arsenic

Historical Observations: In the TMF pore waters, historical sampling results show that arsenic concentrations rise and then fall at lower elevations below ~400mASL (Figure 5.7-15, Figure 5.7-16). The results are consistent with observations from TOVP arsenic aging test work (Appendix D, Section D, Subsection E) and are explained by the arsenic aging geochemical model (Section 5.5.1). In the long-term, arsenic in the tailings will be driven towards As^{5+} by the oxidizing conditions in the tailings. Over several sampling campaigns, As^{5+} in the pore water has been found to occur at average concentrations consistently less than 1.5 mg/L with no particular trend by sample elevation (Appendix D, Section B). As the arsenic is fully oxidized, As^{5+} will be the dominant arsenic pore water species.

The zone from 373-398 mASL contains tailings produced from Sue C ore (Section 5.5.1, Figure 5.5-8). In this zone, primary arsenic mineralization was not fully oxidized in the mill before tailings placement. In comparison to other tailings, it is expected that the Sue C tailings will require more time to achieve full oxidation of all arsenic species and reach equilibrium. While oxidation is occuring the arsenic content in solution will be controlled by the intermediate soluble As^{3+} phase.

The arsenic concentration in the pore water of the Sue C tailings from the centre borehole (TMF-01) is observed to have risen to a high point in 2003, followed by a decrease over time until 2008. The behaviour observed in TMF-01 is consistent with the geochemical model (Figure 5.7-16). In 2013 arsenic values increased again in TMF-01, however in 2018 they remained similar to 2013 concentrations. The cause of the increase is likely the continued oxidation of more recalcitrant forms of primary arsenic mineralization that have taken longer to oxidize under TMF conditions.

The experience of under dosing Sue C tailings with ferric has provided several important lessons with respect to tailings preparation. The TPP was modified after the Sue C experience by 1) adjusting the Fe^{3+}/As ratio to take into account total arsenic in all waste streams reporting to the TPC, and 2) the addition of hydrogen peroxide to TPC for tailings ≥ 400 mASL. As a result, low and controlled pore water arsenic concentrations have been observed above approximately 400 mASL.

Prior to Cigar Lake ore processing, the Fe^{3+}/As ratio was further refined as described in section 3.2.4, to account for all residual reduced arsenic in the tailings solids. The adjustment accounts for the significantly higher grades of arsenic in the Cigar Lake ore in comparison to previous ores. A percentage of reduced arsenic reports, unleached, to the TMF in the tailings solids, and so additional ferric iron is being added to the TPP to account for the eventual oxidation and precipitation of arsenic associated with primary arsenic mineralization in the placed tailings.

2018 provided the first opportunity to evaluate arsenic concentrations sampled from the Cigar Lake ore treated with the updated Fe^{3+}/As ratio defined in the ferric calculator. Arsenic concentrations were low and controlled supporting the changes made to ferric addition in the TPP.

2023 Observations: 2023 data below ~400 mASL, arsenic porewater concentrations remained stable or decreased at several locations including a notable decrease in TMF-01(Figure 5.7-15 and Figure 5.7-16). This follows 2018 observations where weighted average pore water arsenic data for the zone below ~400 mASL did not significantly increase over 2013. The lack of increase in 2018 was interpreted as an indication that arsenic concentrations may have peaked in the Sue C tailings, which is further supported by the following decrease in 2023 concentrations. The larger decrease in concentrations in TMF-01 is consistent with the geotechnical properties of the tailings from TMF-01 which may enable reactions there may occur more quickly relative to other areas of the tailings. TMF-01 was originally the central deposition point in the TMF for the JEB/Sue tailings and due to grain size segregation upon deposition it contains some of the coarsest tailings in the TMF. These tailings have larger pore spaces available to allow for greater interaction between the pore water and tailings solids.

Significantly more samples of the Cigar Lake tailings were taken in 2023. These samples show that the Cigar Lake tailings have low and controlled pore water arsenic concentrations even in areas with higher amounts of arsenic in the solid phase (5.7-16)

Path Forward: Arsenic grades from Cigar Lake are anticipated to increase and be highly variable. The behaviour of arsenic in the tailings pore water and solids will continue to be monitored, in order to validate the arsenic geochemical model and ensure that the source term remains low and controlled as predicted.

Figure 5.7-15: Redox Activity – Sample Elevation vs Average Arsenic Concentration by Year

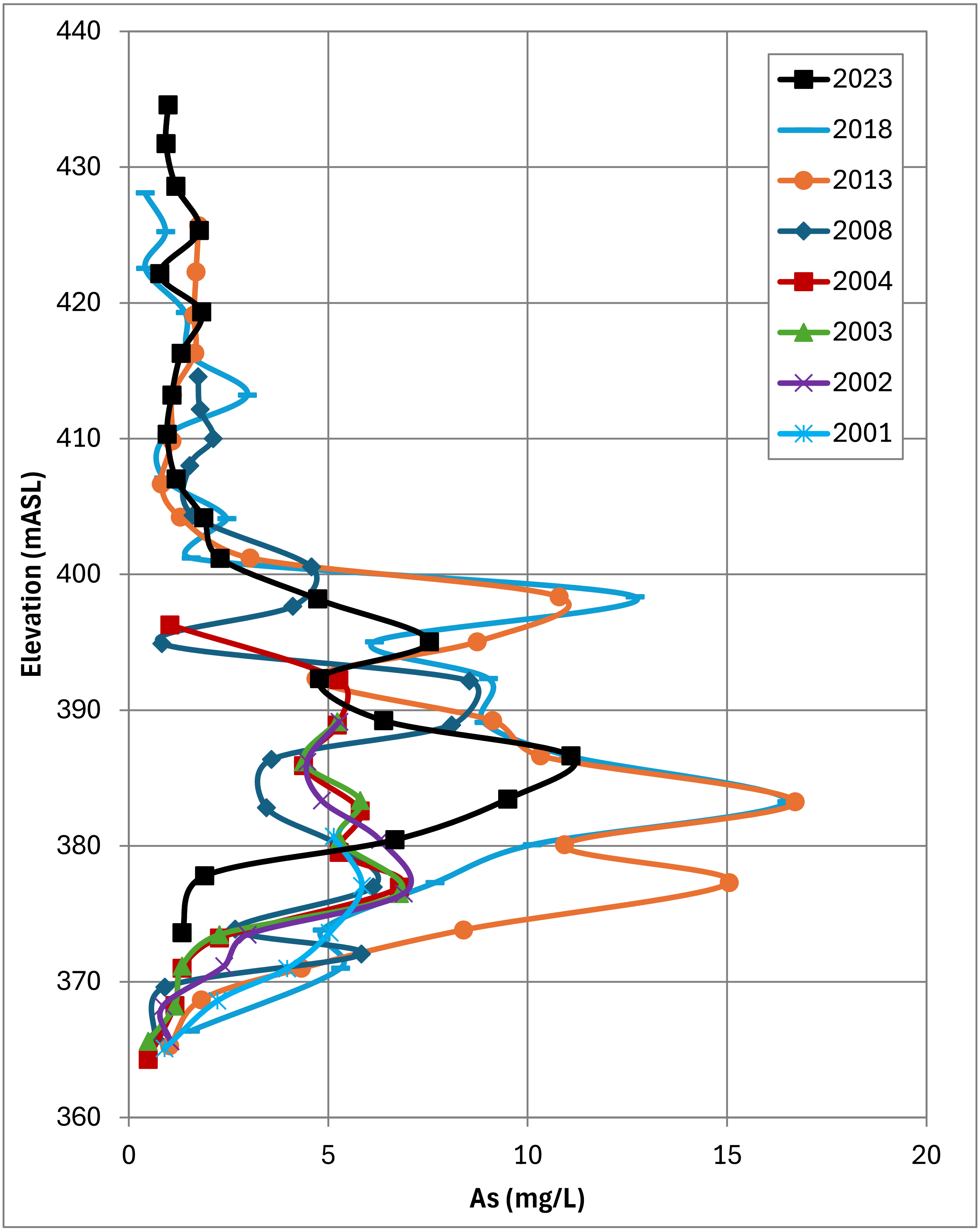
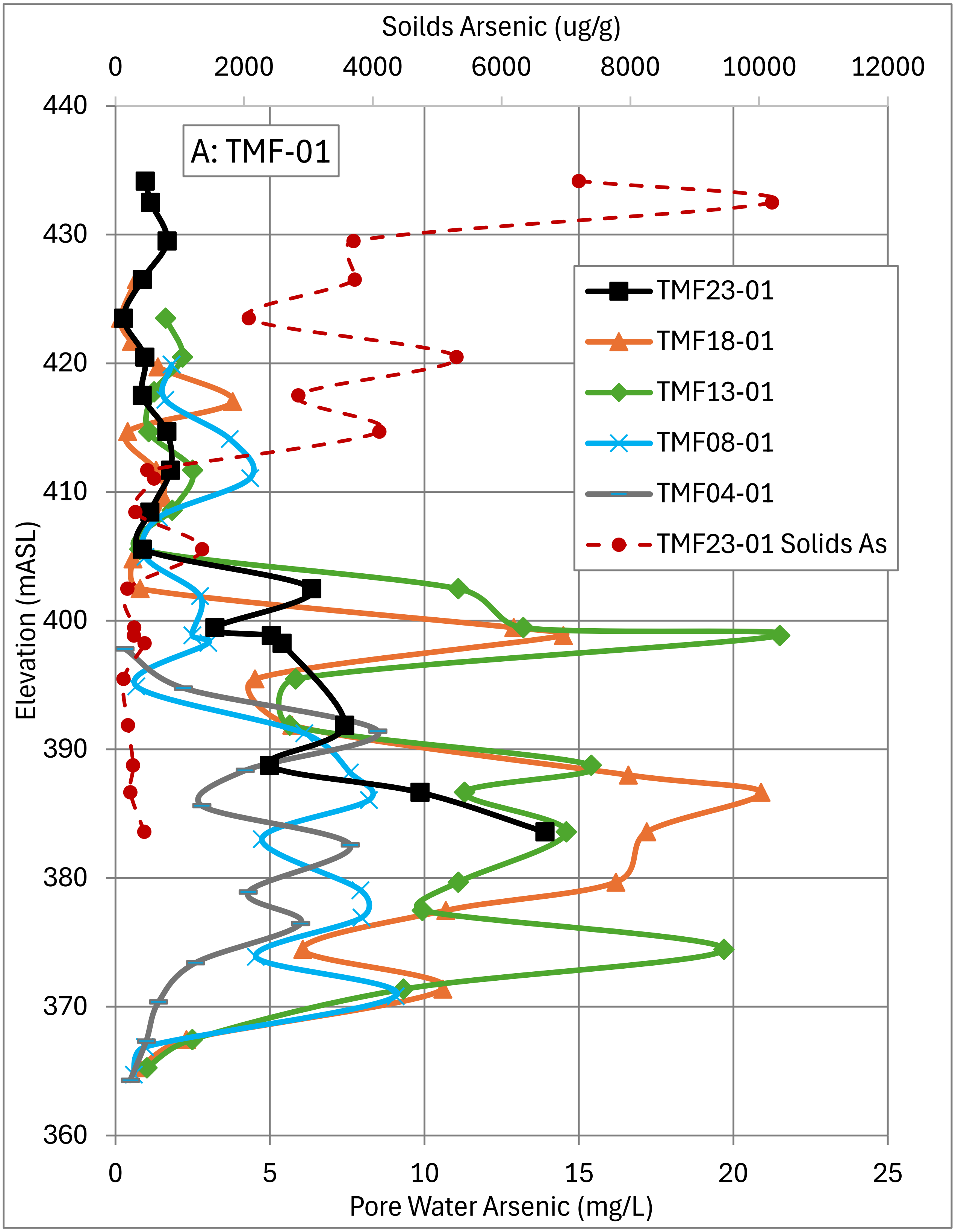
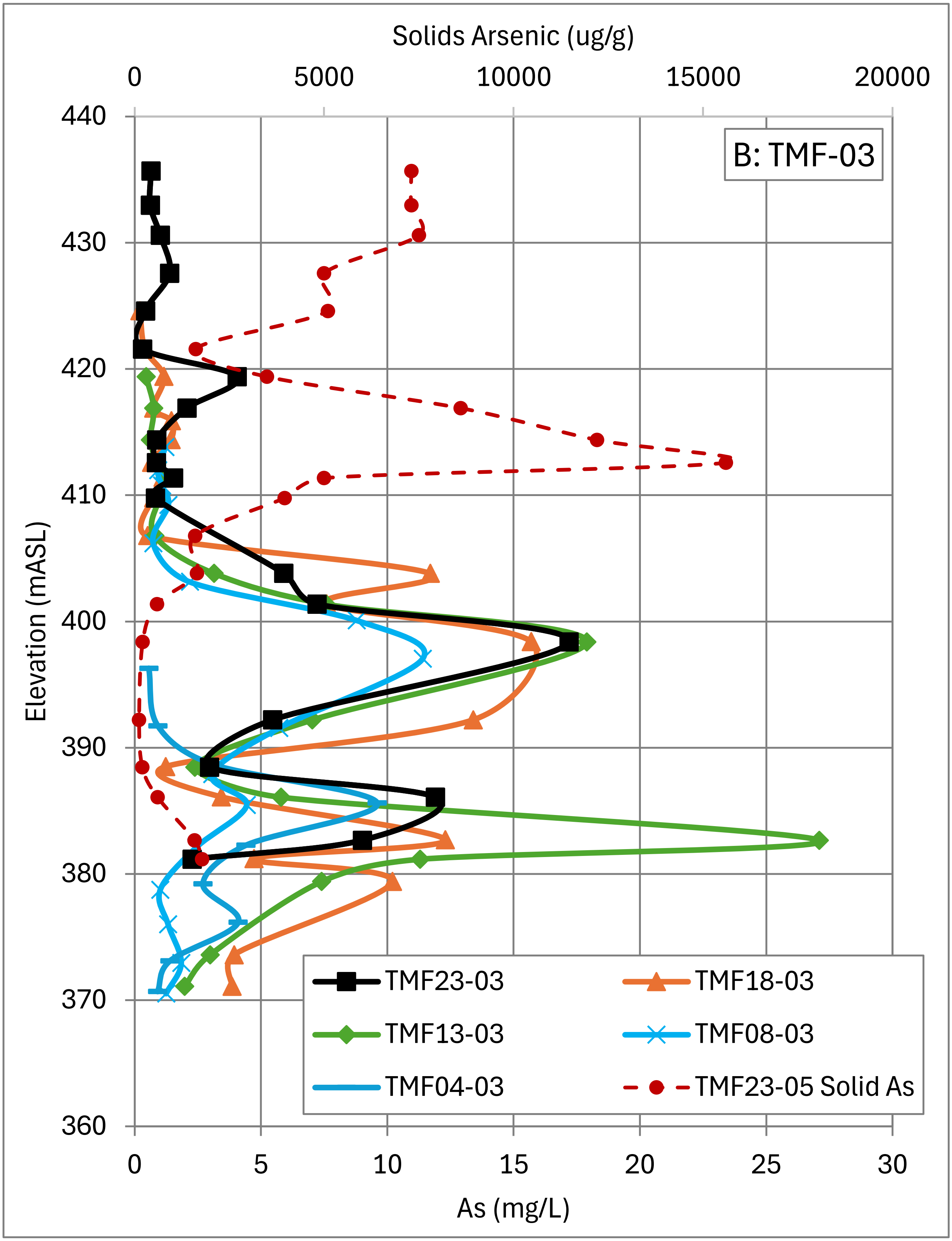
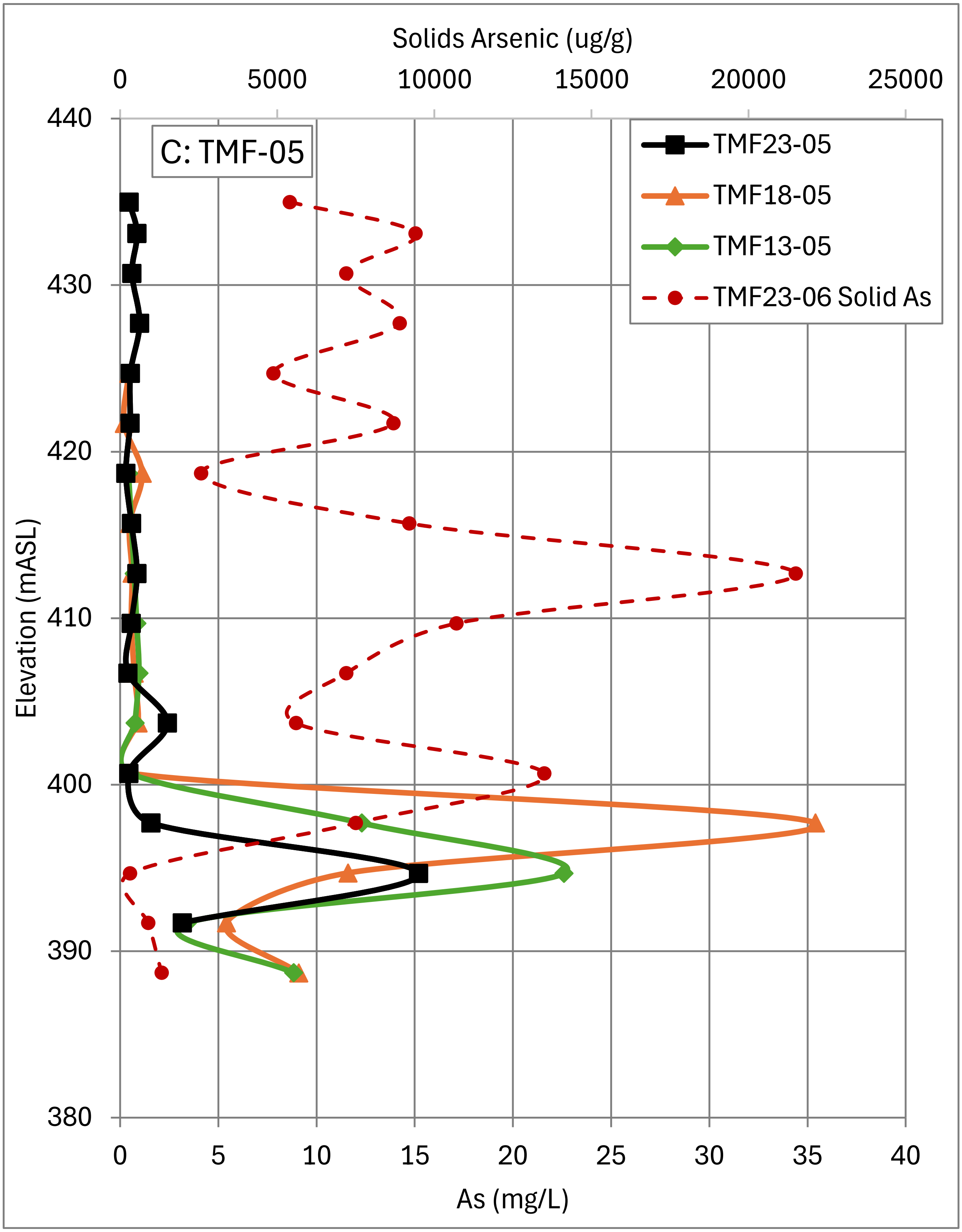


Figure 5.7-16: Sample Elevation vs As Concentration A: TMF-01; B: TMF-03; C: TMF-05




Solids Arsenic (ug/g)
0
5000
10000
15000
20000
B: TMF-03
Elevation (mASL)
440
430
420
410
400
390
380
370
360
0
5
10
15
20
25
30
As (mg/L)
TMF23-03
TMF18-03
TMF13-03
TMF08-03
TMF04-03
TMF23-05 Solid As


Solids Arsenic (ug/g)
0
5000
10000
15000
20000
25000
C: TMF-05
TMF23-05
TMF18-05
TMF13-05
TMF23-06 Solid As
Elevation (mASL)
440
430
420
410
400
390
380
0
5
10
15
20
25
30
35
40
As (mg/L)

5.7.5 Radionuclides

Of the radionuclides, radium-226 (^{226}Ra) and uranium (U) have historically been the key COPCs of interest in the McClean Lake tailings. This assessment continues to focus on ^{226}Ra and U as the main radionuclides of interest as they have the highest concentrations in both the solid and liquid phases of the tailings.

Concentrations of other radionuclides have typically been low in tailings such as 230Th (half life 75.380 years) which is consistently measured at or near detection levels. Lead 210 and Polonium 210 are less of a concern due to both their lower concentrations, and shorter half-lives. (^{210}Po and ^{210}Pb, 138 days and 22.3 years respectively). With the change in ore source to Cigar Lake in 2014, special note has been taken of radionuclide values, however uranium and radium-226 continue to have the most significant concentrations in the tailings pore water (Table 5.7-3). ^{230}Th, ^{210}Po and ^{210}Pb will continue to be monitored through future TOVP campaigns to validate these findings.

Table 5.7-3: Weighted average concentrations of radionuclides in the tailings Pore water 2023

	Uranium (mg/L)	Radium 226 (Bq/L)	Thorium 230 (Bq/L)	Lead 210 (Bq/L)	Polonium 210 (Bq/L)
Cigar Lake	3.1	4.11	1.05	2.29	0.51
JEB/Sue	9.4	4.63	1.11	2.20	0.75

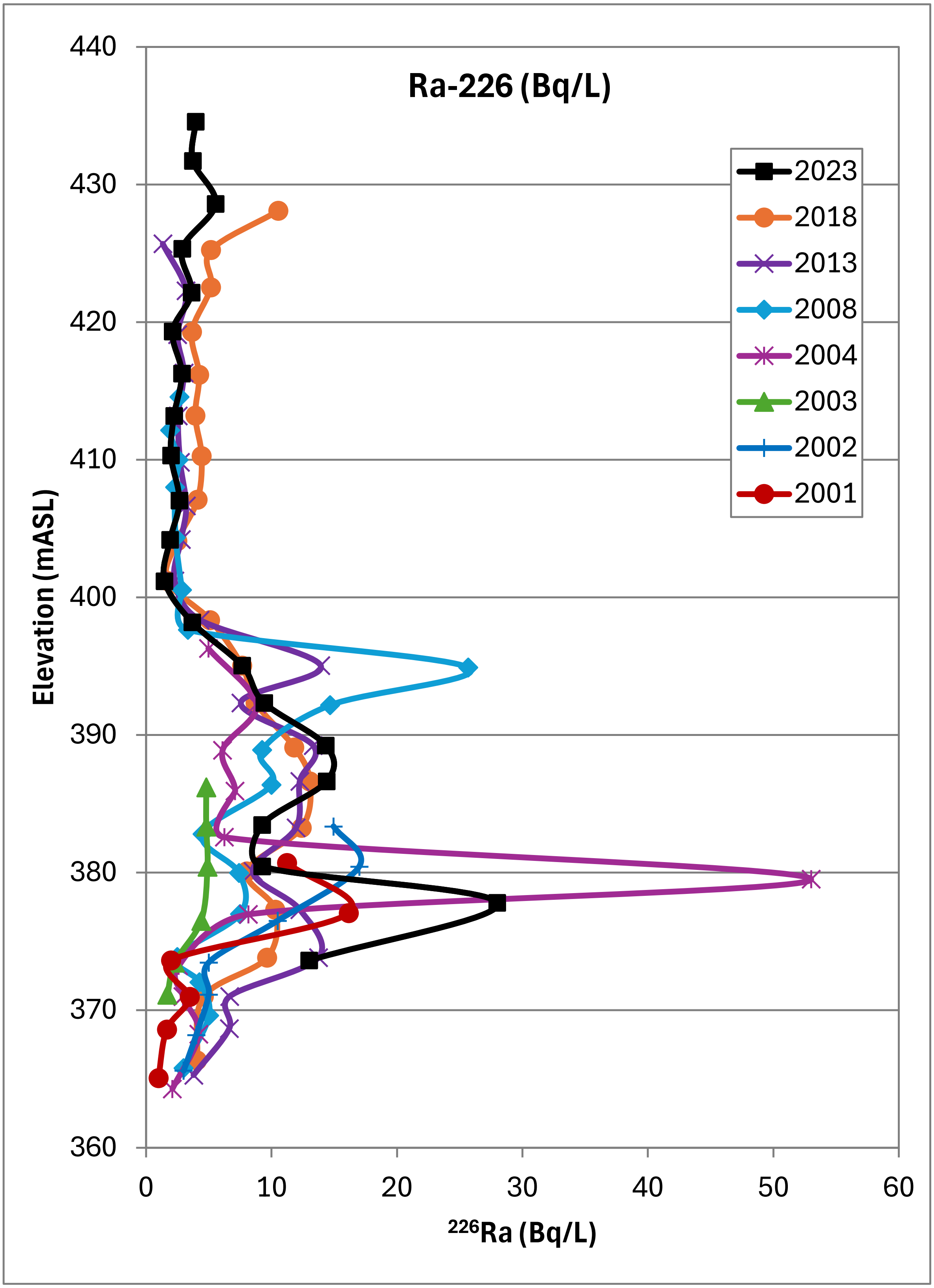
5.7.5.1 Radium-226 (^{226}*Ra*)

Historical Observations: Average pore water ^{226}Ra concentrations for the 2001, 2004, 2008, 2013, and 2018 sampling campaigns are plotted with sample elevation in Figure 5.7-20. Concentrations of ^{226}Ra have typically been low and controlled. Occasional noted spikes in concentration (at 379 mASL in 2004, 395 mASL in 2008, and to a lesser extent 401 mASL in 2013) were temporary outliers and do not reflect long-term trends. At each previously noted spike location, pore water concentrations of ^{226}Ra returned to average values during the following sampling campaign. These increases likely represent locations where primary uranium mineralization has oxidized in the tailings, co-releasing ^{226}Ra to solution. The pore water values then decrease in time as the ^{226}Ra partitions to the tailings solids.

In 2018, a small increase was observed in pore water ^{226}Ra concentrations in the Cigar Lake tailings samples. As with many other COPCs (e.g. Ni, As, Pb, and Cu), the Cigar Lake ore is expected to contain higher concentrations of ^{226}Ra than past deposits milled at McClean Lake. In the case of ^{226}Ra, the increase in concentration was linked with the high uranium grades; however, ^{226}Ra concentrations remained low and controlled.

2023 Observations: Weighted average ^{226}Ra concentrations remained stable and controlled throughout the tailings, including in the newly placed Cigar Lake tailings. The recent data supports the ongoing observation that ^{226}Ra is well controlled in the TMF.

Figure 5.7-17: Radionuclides – Sample Elevation vs ^{226}Ra



Research Partnership: In 2022, work was undertaken in partnership with the research group of Orano France to model the effect of barite (barium sulfate) on the contaminant transport of ^{226}Ra from the JEB TMF. This work was completed using samples from the 2018 and 2021 tailings sampling campaigns and published in (Besancon et. al. 2025). A summary is presented here:

^{226}Ra activities in the JEB TMF have activities of up to 3000 Bq/g. ^{226}Ra is treated through the addition of barium chloride ($BaCl_2$) to precipitate ^{226}Ra in barite as a solid solution (radiobarite). The purpose of the study was to provide experimental verification of the ^{226}Ra bearing phases. ^{226}Ra in the tailings liquid phase is generally considered to be sequestered in barite and sorbed onto ferrihydrite based on the porewater source terms derived from TOVP sampling and analysis. However, radium as a cation is known to sorb on the surface of many minerals including:

- clays,
- iron oxyhydroxides
- manganese oxides,
- organic matter and
- some silicates, including quartz.

Radium can also replace other earth-alkaline elements in solid solutions such as sulfates and some carbonates; Therefore, it is necessary to confirm the method of immobilization of ^{226}Ra in the tailings to determine its long-term stability. To assess the stability of ^{226}Ra in the tailings, an extensive study of its retention potential was performed. Characterizations included:

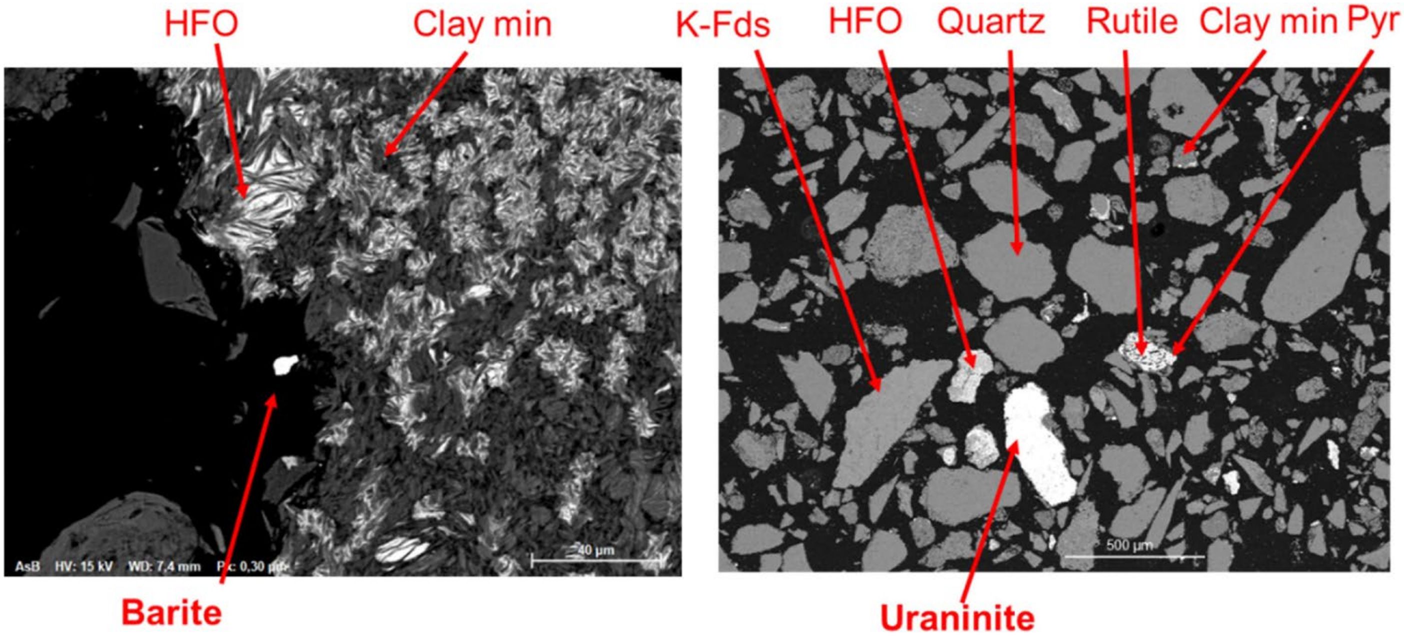
- assessment of tailings pore water and solids chemistry,
- tailings mineralogy,
- cation exchange capacity measurement,
- scanning electron microscopy and energy-dispersive x-ray spectroscopy (SEM/EDS),
- and alpha-autoradiography analyses supplemented with thermodynamic modelling.

Chemical analyses were completed on selected tailings samples from various depths of the TMF. Generally, barite was a minor phase and difficult to distinguish using standard XRD but was identified using both High Resolution (HR)-XRD (synchrotron based) and SEM/EDS analysis (Figure 5.7-18). Additional testing was done to measure the Cation Exchange Capacity (CEC) of the samples to identify the availability of sorption sites on clay minerals which provided data for geochemical modelling. Clay rich samples of tailings, as expected, had higher CEC capacity than more quartz dominated samples. Using the accumulated geochemical data, a geochemical model was developed using PHREEQC. The best fit to of the data to the model showed that 85-100% of the ^{226}Ra in the tailing solids is held by barite, with residual amounts being held on the surface of uranium minerals. Sorption was found to be a minor contributor (<1%).

Imaging of the tailings samples was also conducted to map the distribution of alpha particle activity in the samples. A comparison of alpha-autoradiography and, EDS and WDS mapping was used to confirm the modelling results using visual identification of ^{226}Ra bearing minerals. Residual uranium minerals, barite, iron oxy-hydroxides and clays were all targeted using elemental mapping and alpha-autoradiography. Results were overlain to identify alpha particle emitters (Figure 5.7-19). Barite was identified using a combination of Ba and S elemental maps (Figure 5.7-20). This technique confirmed that in most samples more than 75% of ^{226}Ra was trapped in barite, while an additional fraction (0-7%) was associated with uranium minerals.

This work presents a novel approach to the confirmation of a geochemical model and provides evidence of the control of ^{226}Ra in the tailings through the formation of a ^{226}Ra solid solution with barite.

Figure 5.7-18: SEM-EDS imagery of tailings sample identifying important mineral phases



This work confirms that barite is the main ^{226}Ra binding-phase, in agreement with the ^{226}Ra concentration measured in the porewater (6 Bq/L) resulting from a coprecipitation reaction. A $(Ba,Ra)SO_4$ solid solution regulates the average ^{226}Ra concentration now and over the long term, through a distribution coefficient which is subject to a gradual shift towards a recrystallisation equilibrium. Recrystallisation causes an increase in the long-term concentration of ^{226}Ra in the tailing water to 10 Bq/L. The study, conducted to assess the management strategy of the tailings, allowed us to ensure that the tailings have no significant effects on the downstream environment over the long-term.

Path Forward: ^{226}Ra will continue to be monitored in future TOVP campaigns to confirm that concentrations are low and controlled in the Cigar Lake tailings. Additional work in partnership with Orano France has been proposed in the development a reactive transport model for ^{226}Ra to understand it's fate in the environment post decommissioning of the JEB TMF.

Figure 5.7-19: Alpha radiography and WDS element maps showing locations where alpha activity was detected A: TMF18-11 SA03; B: TMF18-01 SA24

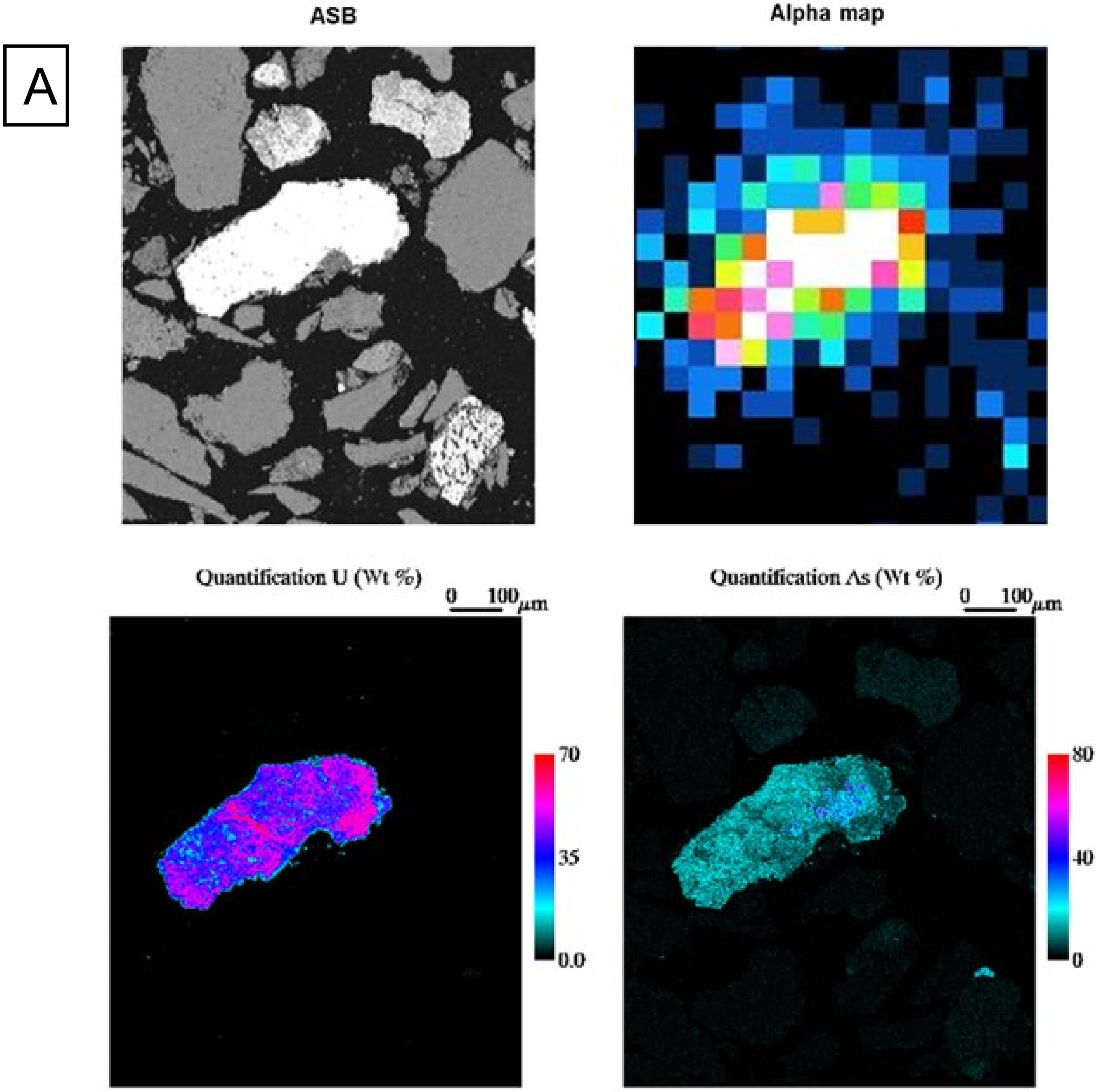
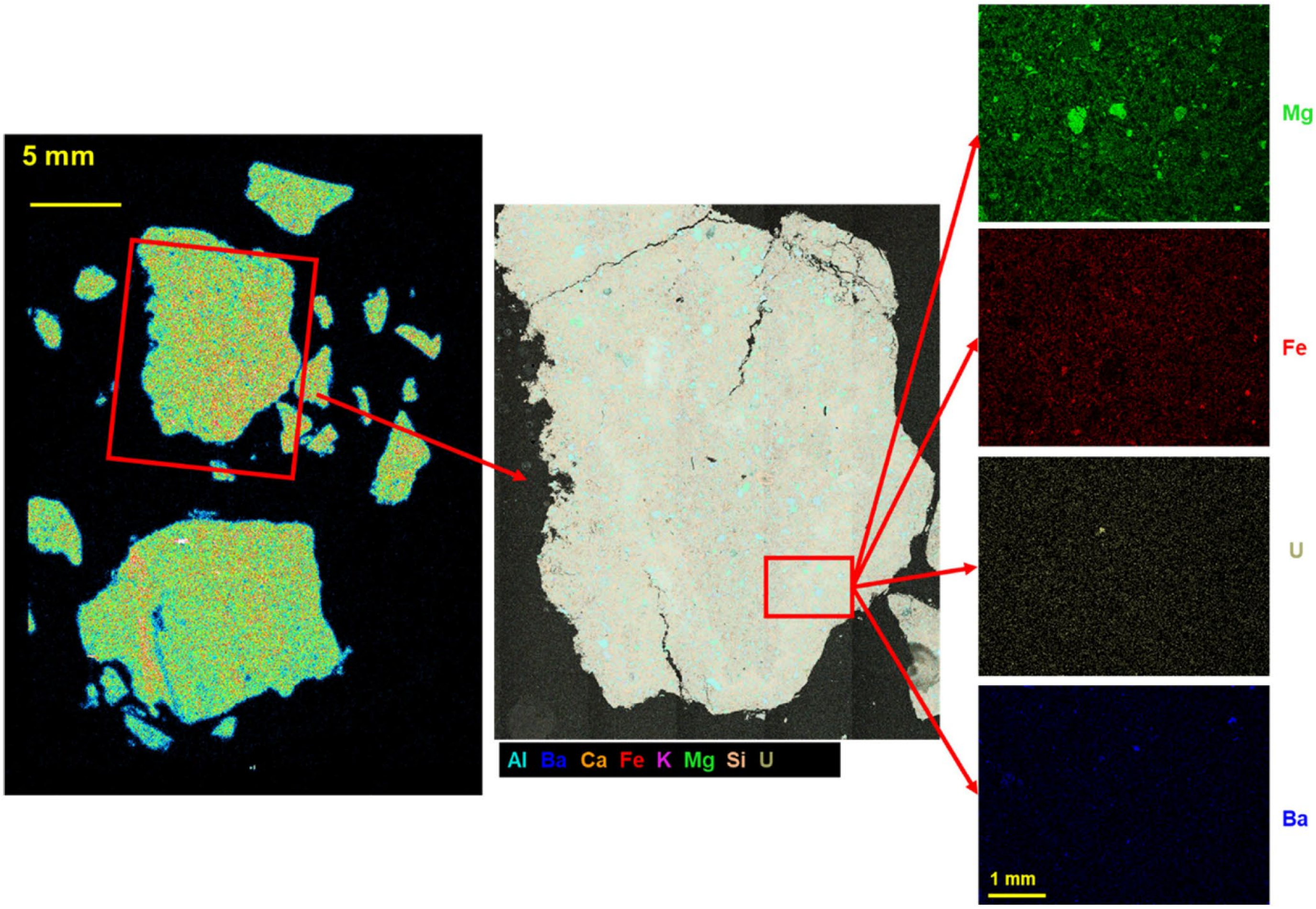


Figure 5.7-20: **Left: alpha autoradiographs for sample TMF18-01 SA01. Centre: EDS image of part of the same sample from the same thin section. Right: Extractions of the qualitative EDS maps for Mg, Fe, U and Ba.**



5.7.5.2 Uranium (*U*)

Overview: Observations of uranium are understood in the context of the geochemical model which is discussed in detail in Section 5.5.3. Uranium in the pore water is controlled by the solubility of uranyl carbonate complexes formed with bicarbonate ions (Figure 5.7-21). The model concludes that, within the TMF, the HCO_3^- concentrations will reach an equilibrium value of 168 mg/L and U concentrations will reach an equilibrium value of approximately 8.5 mg/L through saturation with carbonate minerals. 2013 was the first time that a uranium decrease was identified in coordination with a decrease in HCO_3^-. The 2018 results for TMF-01 continue to be lower in HCO_3^- and U than 2008 concentrations. Past sampling campaigns had established that increases in HCO_3^- cause an increase in uranium in solution, and now the opposite is observed which as well (Table 5.7-4) validates the relationship between the two COPCs.

Historical Observations: The weighted average pore water concentrations of uranium from the 2001 to 2023 in-situ sampling campaigns are presented in Figure 5.7-22. With the exception of tailings below approximately 383 mASL, uranium concentrations rose significantly between the 2004 and 2008 TOVP sampling campaigns. Increases were noted again between the 2008 and 2013 campaigns, but the magnitude of the increase was generally much smaller. Weighted average pore water uranium concentrations from 2013 to 2018 were generally stable and increased at only one depth interval which is a notable decrease in the rate of uranium accumulation in the pore water.

Uranium in the pore water of the Cigar Lake tailings was observed for the first time in 2018 and remained low and controlled.

2023 Observations: As observed in 2018 weighted average uranium concentrations, the tailings below ~400 mASL (produced before hydrogen peroxide was added to the TPP) did not show significant increases over 2013 concentrations (Figure 5.7-21). In individual boreholes some local areas of increased pore water uranium concentrations were identified, however, these samples are limited and in general, uranium values are stable or decreasing (Figure 5.7-23).

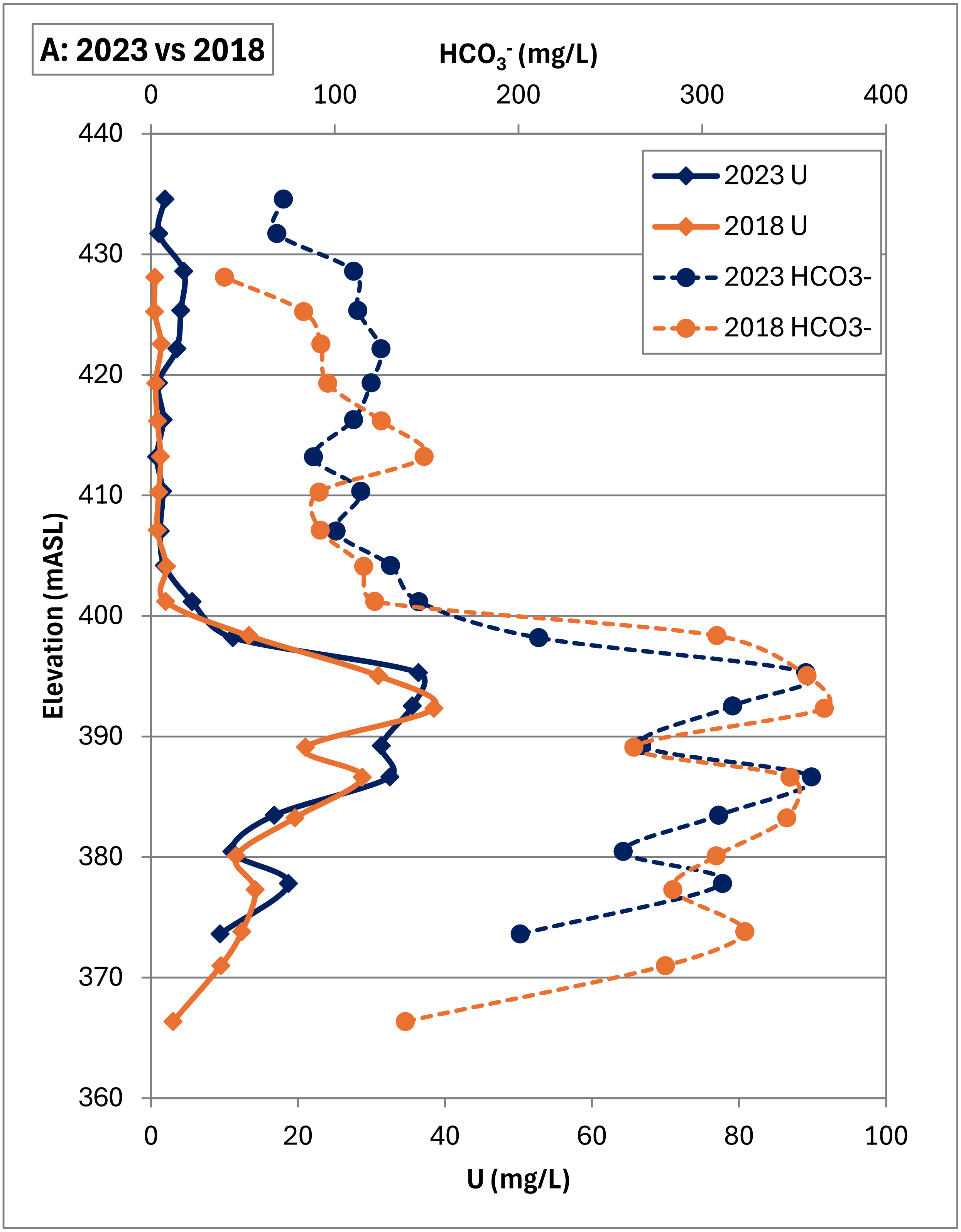
Uranium in the Cigar Lake tailings remains well controlled through the addition of hydrogen peroxide in the TPP. There are individual locations with small increase in pore water uranium concentrations which are likely related to mill upset conditions where high organic wastes were released to the tailing without being treated with additional hydrogen peroxide. These events create discrete horizons in the tailings where small elevations in uranium source term are expected, however they will have a negligible impact on the overall source term of the TMF.

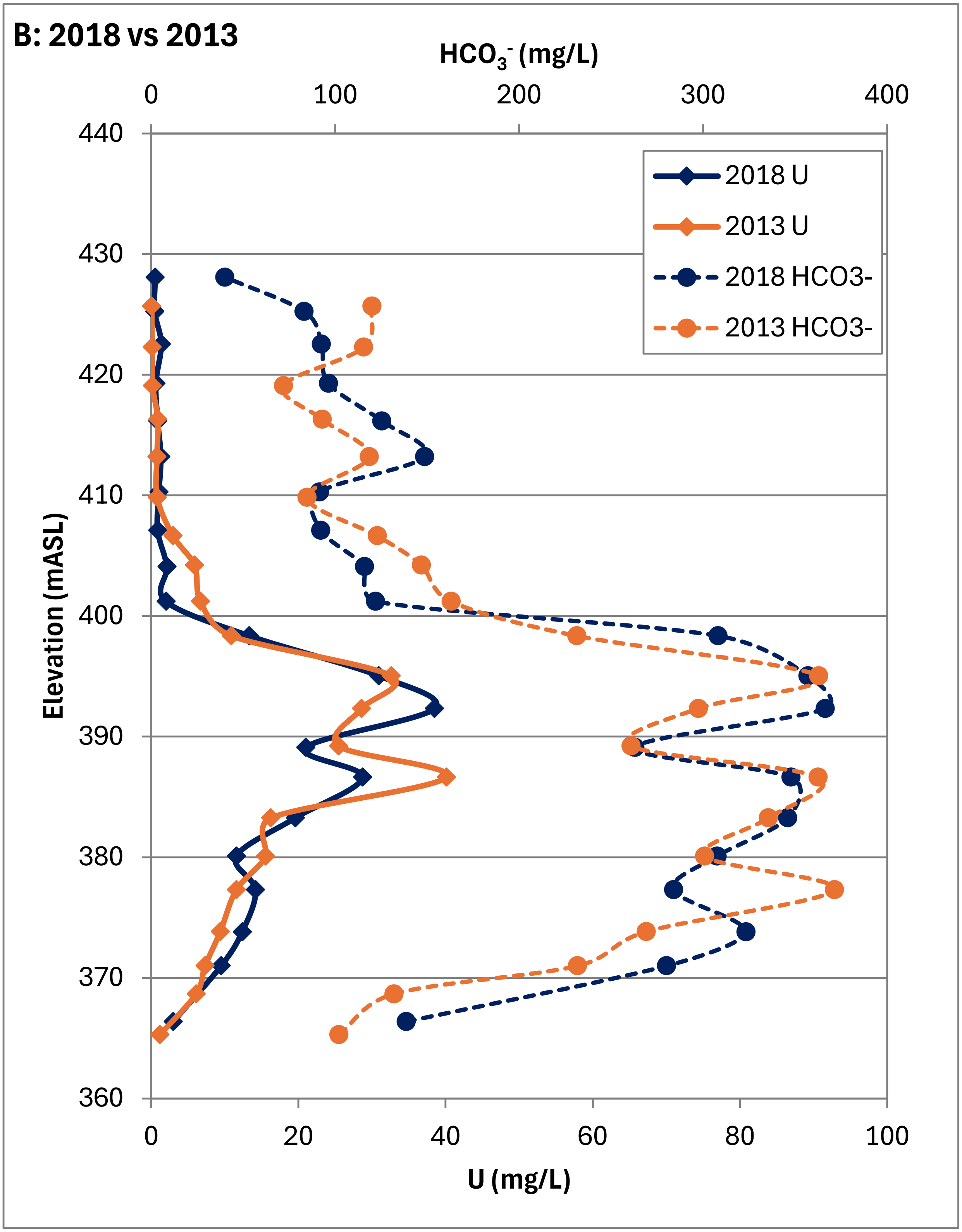
Table 5.7-4: Averaged observations from TMF-01:365 to 400 mASL showing uranium values increasing and decreasing with HCO_3^- values.

Year	# of Weighted Average Intervals	HCO_3^- (mg/L)	U (mg/L)
2004	12	121	4.6
2008	12	274	15.9
2013	13	176	9.9
2018	13	250	12.90
2023*	10	288	22.53
Note that the lowest three depth intervals were not samples in 2023 due to difficulties encountered with sluffing of the boreholes. The lowest depth intervals, in the past have shown the lowest uranium pore water values so the average values in 2023 are considered to be artificially high.			

Path Forward: The uranium grade in ore from Cigar Lake is known to be higher than previous ores milled at McClean Lake and research is ongoing with the University of Saskatchewan regarding solubility controls on uranium in the tailings. This work was significantly delayed due to the Covid-19 pandemic and equipment outages at the Canadian Light Source; however, the program is now progressing. Results of the work in progress will be presented in the update of the tailings TID in 2030.

Figure 5.7-21: Comparison of Uranium and Bicarbonate Concentrations in the Tailings over Time A: 2023 vs 2018, B: 2018 vs 2013, C: 2013 vs 2008




B: 2018 vs 2013
HCO$_3^-$ (mg/L)
0
100
200
300
400
440
430
420
410
400
390
380
370
360
Elevation (mASL)
0
20
40
60
80
100
U (mg/L)
2018 U
2013 U
2018 HCO3-
2013 HCO3-

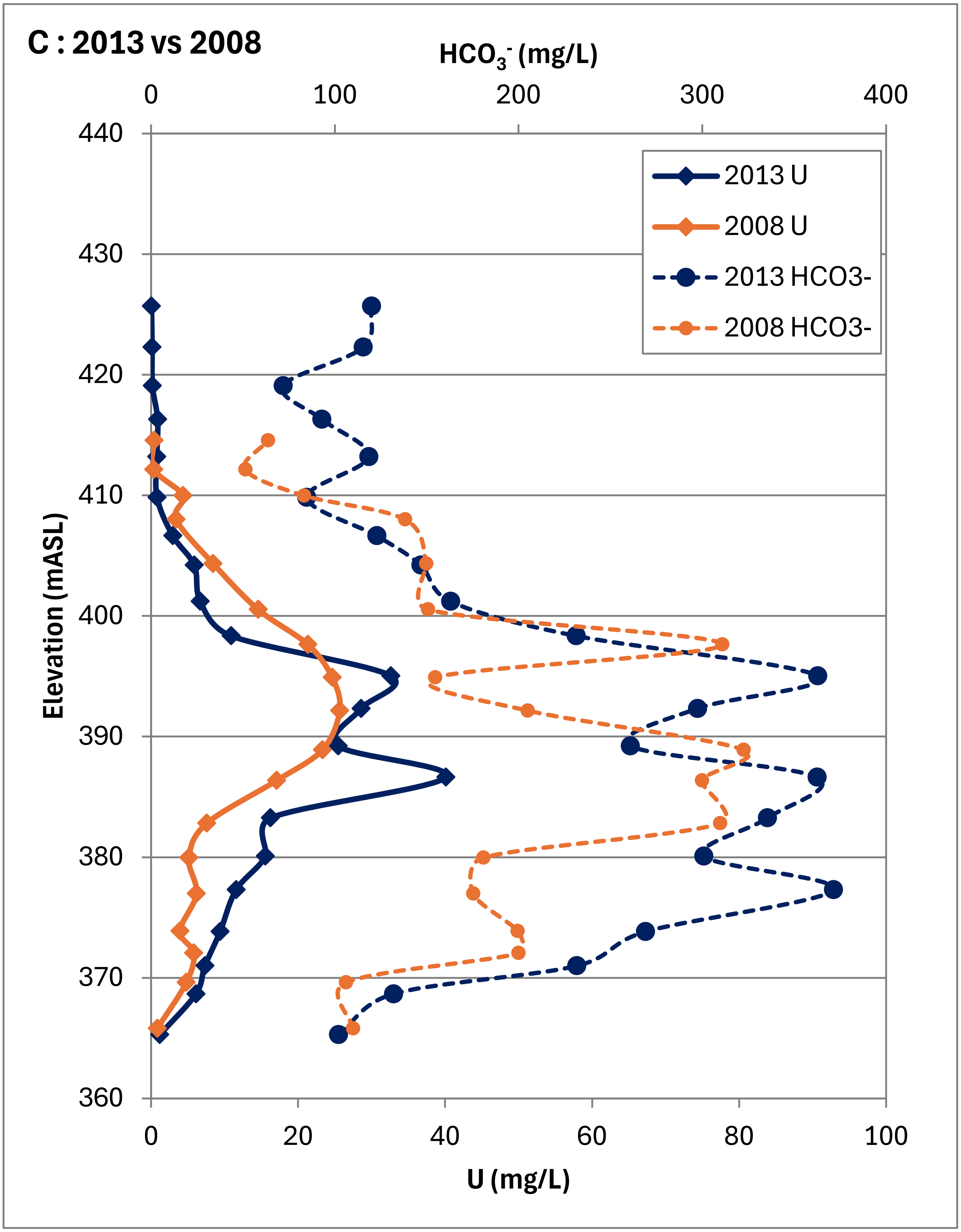
C : 2013 vs 2008
HCO_3^- (mg/L)
0
100
200
300
400
440
430
420
410
400
390
380
370
360
Elevation (mASL)
0
20
40
60
80
100
U (mg/L)
2013 U
2008 U
2013 HCO3-
2008 HCO3-

Figure 5.7-22: Weighted Average Uranium Concentration by Sample Elevation

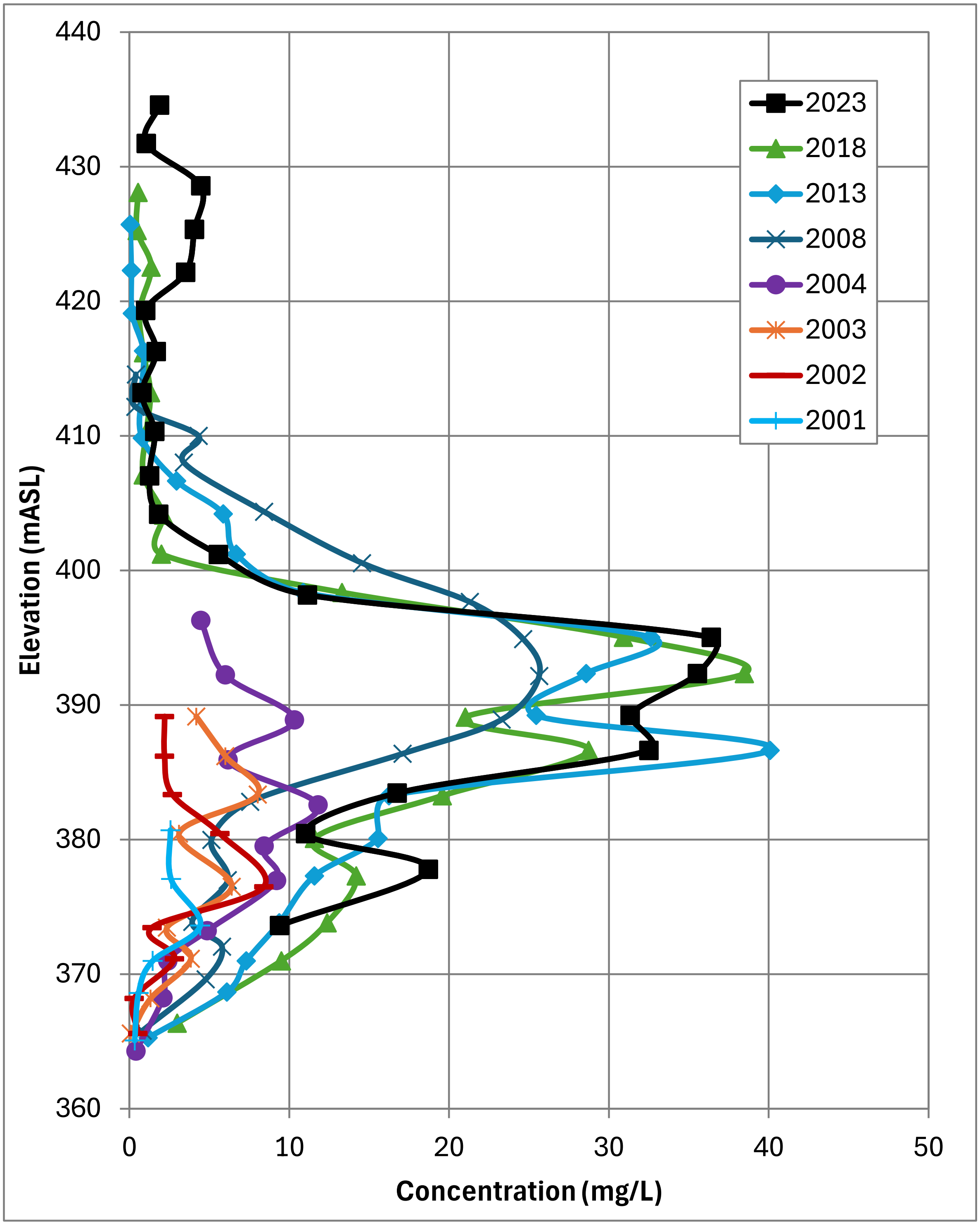
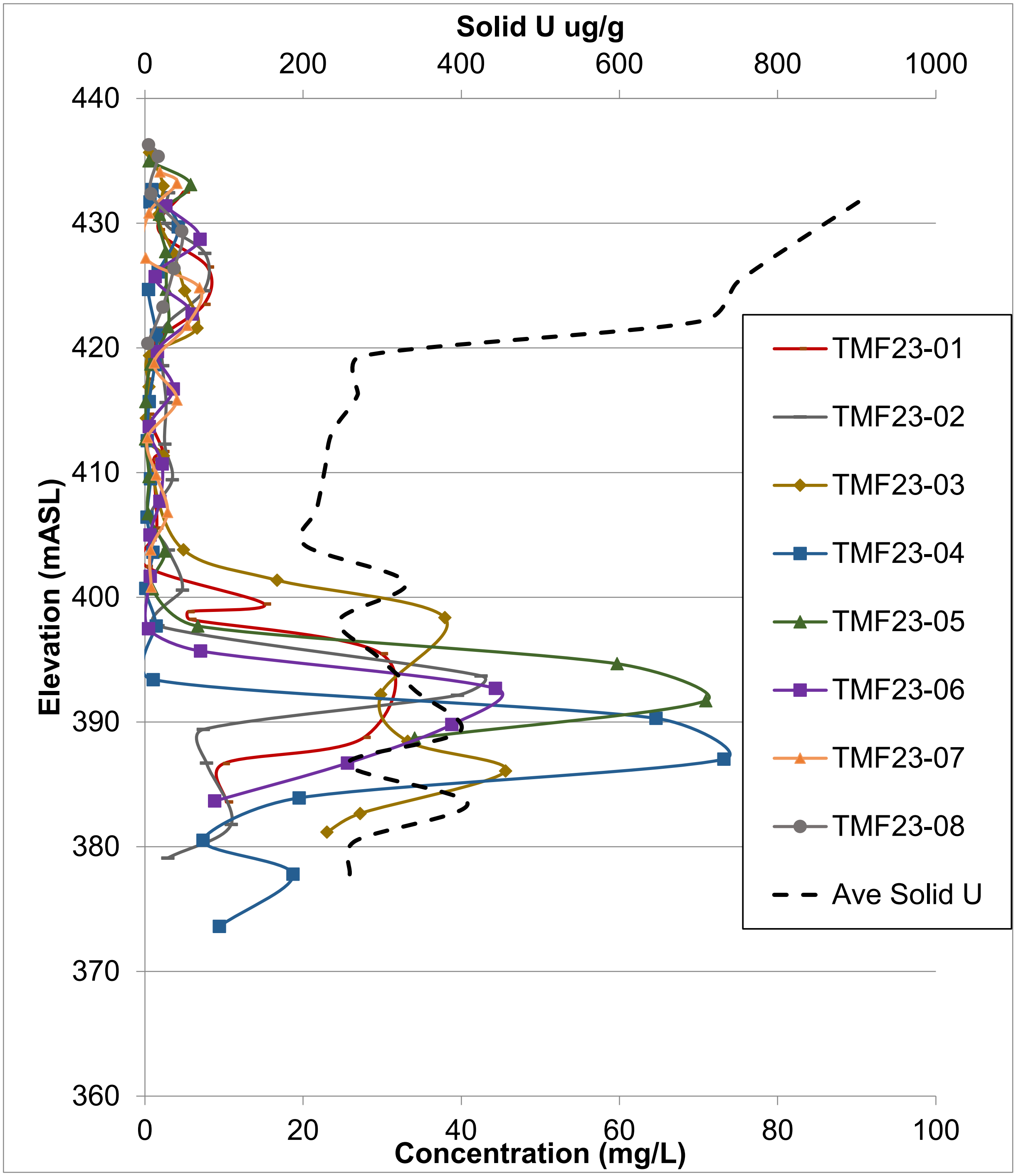


Figure 5.7-23: Uranium Concentration by Borehole 2023



5.7.6 Conclusions – Long-term Tailings Geochemistry

The following is a summary of conclusions and observations from the 2023 geochemical program:

- JEB/Sue tailings:
  - Overall, the general trends in tailings pore water geochemistry have developed as expected, following trends observed in past sampling campaigns.
  - The JEB/Sue tailings from approximately 385–400 mASL continue to demonstrate the effects of insufficient addition of ferric iron during the milling of the Sue C ore.
  - Lessons learned from the Sue C experience have been applied, and the TPC has been upgraded and commissioned to support the milling objectives for high-grade ore from Cigar Lake. The results of this work are evident in the low and controlled pore water source terms in the subsequent tailings deposited.
  - COPCs described by existing geochemical models (As, Mo and U) have evolved in the pore water within the expectations of the individual model parameters.
  - Overall increases were not observed for weighted average arsenic and uranium concentrations in pore water in 2023, indicating that peak values have possibly been achieved for these COPCs. Arsenic concentrations in individual boreholes were stable or reducing in the key area of the Sue C tailings. Uranium concentrations in individual boreholes increased only in a few of samples, and in general remained stable.
  - Pore water molybdenum concentrations continue to evolve as predicted, with the added observation that faster tailings throughput is causing less Mo to be released into the tailings pore water upon initial deposition. This evolution is now predicted to occur more slowly as the tailings age.
- Cigar Lake tailings:
  - The 2023 campaign provided the second opportunity to examine the efficacy of the TPP and tailings performance with respect to Cigar Lake but with a greater number of samples than in 2018 and considering almost a full decade of aging for the earliest Cigar Lake tailings.
  - The behaviour of key COPCs is well controlled and in accordance with current geochemical models and past JEB/Sue tailings performance.
  - Small increases in Cu, Pb, noted in the tailings pore water associated with Cigar Lake tailings in 2018 are not observed in 2023. Although some increases in pore water concentration are expected

    based on the current understanding of the Cigar Lake ore mineralogy and solids analysis. It is likely that the increases observed in 2018 were the result of the tailings being newly placed and subsequently areas of initially elevated source terms have dissipated as ions solubilised in the TPP have been absorbed or precipitated into the solid tailings phase.

  - Modelling and research were proactively initiated for Cu, Pb, Ni, and Se, which are known to be present in the Cigar Lake ore in greater abundance. This research program was significantly delayed by the Covid-19 pandemic and equipment outages at the Canadian Light Source. In 2024 this research was re-started to establish an understanding of how these COPCs may be expected to evolve over time, and the results will continue to be validated against future, Cigar Lake tailings sampling results with lessons learned applied as the milling of Cigar Lake ore continues.

- A research program was conducted which validated geochemical modelling of ^{226}Ra retention in the tailings with physical investigations of tailings samples. The results from the study have shown that the majority of ^{226}Ra is bound in the tailings solid as barite solid solution. The results of this work can be used to validate the source term for ^{226}Ra from the tailings.

- TOVP data is a uniquely complete data set observing the evolution of tailings in the TMF. Because of the number of sampling campaigns, and the effort taken to obtain samples from similar locations year over year, it is possible to track the evolution of the tailings pore water concentrations of COPCs over time.

  - The data presented in this section identifies many COPCs which show similar patterns of pore water concentration between multiple sampling campaigns (e.g. Molybdenum; Figure 5.7-12 and Chloride; Figure 5.7-7). In response to CNSC Comment #3 from Table 5.1-1 (Section 5.1.2): The geochemical data set supports the overall integrity of the sampling method and provides strong additional information to support Orano's assertion that additives in the drilling mud did not influence the geochemical results.

5.8 Overall Conclusions and Modelling Inputs

The goal of the Tailings Optimization and Validation Program (TOVP) is to optimize and validate long-term performance of the tailings management system at the McClean Lake Operation. The information within this document represents the 9th presentation of data obtained under the TOVP in-situ sampling campaigns. The most recent in-situ sampling results from the 2023 field program have been used in this assessment. Principal conclusions related to the specific objectives of the program are summarized below:

During the past five years, the results of various investigations have continued to provide evidence for the presence and identification of chemical/mineral phases containing COPCs produced by the TPP. Research will continue into aging effects and validation of geochemical models to further support understanding, in addition to advancing knowledge for other COPCs in the tailings. Guided by the TOVP, Orano will continue to consider optimizations to mill processes while maintaining downstream performance that is suitably protective of the environment.

Monitoring and subsequent studies of placed tailings within the JEB TMF have yielded results that further delineate tailings solids aging characteristics and demonstrate compliance with Action Levels set for concentrations of arsenic in the placed tailings pore water:

- Long-term pore water arsenic (As) will be controlled to <2 mg/L through the precipitation of the mineral scorodite. Current elevated arsenic pore water values are temporary and reflect the incomplete process of oxidizing primary arsenic mineralization still in progress in the tailings. The current understanding of arsenic geochemistry explains TOVP observations and provides confidence in the mechanisms for long-term control of arsenic concentrations in pore water.

- Long-term pore water molybdenum (Mo) concentration will be controlled to <8 mg/L through the precipitation of the mineral powellite. Current elevated molybdenum pore water values are temporary and reflect the dissolution of an unstable molybdenum phase formed during the TPP in the mill. Molybdenum is liberated into the placed tailings pore water which is then sequestered as the mineral powellite.

- Long-term pore water uranium (U) concentration will be controlled to < 8.5mg/L through the precipitation of carbonate minerals. Current elevated pore water uranium concentration reflects uranium complexation with bicarbonate (HCO_3^-). HCO_3^- is liberated as hydrocarbons in the tailings are oxidized, and pore water concentration of HCO_3^- will decline as all the hydrocarbons are consumed. In tailings deposited above 400 mASL, hydrogen peroxide was added to oxidize the bulk of the hydrocarbons in the TPC so that excess HCO_3^- will not be produced in the placed tailings.

New areas of monitoring and study have been identified for continued evaluation, including understanding the long-term geochemical evolution of nickel, lead, and copper in the tailings pore water.

Geotechnical studies have confirmed that the tailings placed at the edges of the TMF are predominantly fine grained. The consolidated tailings will provide a hydraulic conductivity contrast to the surrounding sandstone that enables preferential flow of groundwater around the decommissioned facility.

The above conclusions demonstrate that the design and operation of the TPC and the TMF are validated with respect to protection of the receiving environment.

5.8.1 TOVP Findings Used for Contaminant Transport Modelling

5.8.1.1 Source Terms

A table of pore water concentrations for 18 COPCs is presented below adapted from Appendix D, Section C (Table 5.8-1). The pore water COPC concentrations in this table are used to predict potential long-term environmental effects in Pat and Fox Lakes, through groundwater contaminant transport modelling, as described in Section 7. Fifteen of 18 COPCs in this table are observed to be stable under TMF conditions and the concentrations in the table are calculated using a weighted average of pore water concentrations throughout the tailings as described in Appendix D, Section C. Three COPCs – arsenic, molybdenum, and uranium - are observed to change over time through aging processes (see Section 5.5) indicating that the respective mineral phases acting as solubility controls are evolving to more stable forms in the TMF solids. These three pore water source terms are derived through modelling, as summarized above.

Table 5.8-1: Groundwater and Contaminant Transport Modelling Source Term Inputs from 2023 Tailings Sampling

		Current predicted concentration based on 2023 in-situ sampling			
		JEB/Sue		Cigar Lake	
Parameter	Units	Base Case	Bounding Case	Base Case	Bounding Case
CATEGORY 1	Weighted Average				
Chloride	mg/L	43.86	82.70	118.12	145.15
Sulfate	mg/L	2205.84	2578.00	3292.61	4325.00
$NH_3^+ + NH_4^+$	mg/L	11.69	24.40	13.29	35.55
Cadmium	mg/L	0.00090	0.0022	0.00041	0.0011
Cobalt	mg/L	0.15	0.47	0.047	0.27
Copper	mg/L	0.0019	0.0046	0.004	0.017
Lead	mg/L	0.0021	0.0142	0.0009	0.007
Nickel	mg/L	2.37	8.11	0.168	0.63
Selenium	mg/L	0.0095	0.052	0.007	0.032
Vanadium	mg/L	0.021	0.18	0.0043	0.0077
Zinc	mg/L	0.026	0.7	0.008	0.032
Lead-210	Bq/L	2.20	4.00	2.29	6.25
Polonium-210	Bq/L	0.75	3.55	0.51	0.62
Radium-226	Bq/L	4.63	16.00	4.11	7.70
Thorium-230	Bq/L	1.11	1.55	1.00	1.10
CATEGORY 2	See Section 5.5				
Arsenic	mg/L	1.27	2.98	0.76	1.78
Molybdenum	mg/L	8.00	14.09	5.34	13.68
Uranium	mg/L	9.37	53.36	3.08	7.59

5.8.1.2 Hydraulic Conductivity

A table of hydraulic conductivity values for the JEB/Sue and Cigar Lake tailings is presented below with inputs from Section 5.6.3.2 (Table 5.8-2). The hydraulic conductivity values in this table are used to predict the transport of COPCs and potential long-term environmental effects in Pat and Fox Lakes, through groundwater contaminant transport modelling, as described in Section 7. A detailed evaluation of the potential hydraulic conductivity of the consolidated tailings, based on in-situ tailings CPT measurements, and laboratory testing of tailings samples (consolidation tests) concludes that $1X10^{-8}$ m/s is a reasonable value, which both the JEB/Sue and Cigar Lake tailings will achieve when they are fully consolidated. As the JEB/Sue tailings are older, this value has been achieved at many depths already. Because the Cigar Lake tailings are new and less consolidated, a sensitivity case of $1X10^{-7}$ m/s was chosen to include in a parametric sensitivity analysis to determine the effect of poorly consolidated tailings. Results of the sensitivity analysis are presented in Section 7 and Appendix D, Section E.

Table 5.8-2: Groundwater and Contaminant Transport Modelling Hydraulic Conductivity Inputs from 2023/24 Tailings Sampling

Source Tailings	Modelling Input Hydraulic Conductivities	
	Base Case	Sensitivity
JEB/Sue	1X10^{-8} m/s	1X10^{-7} m/s
Cigar Lake	1X10^{-8} m/s	1X10^{-7} m/s

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6 Decommissioning

6.1 Planning and End-State

Orano's overarching decommissioning objective is to remove, reduce, and control potential sources of constituents of potential concern, thereby reducing the potential for adverse environmental effects associated with the decommissioned properties. The McClean Lake Preliminary Decommissioning Plan (PDP) (Orano, 2025) contains the plans that are designed to achieve an end-state for the McClean Lake Operation that will be safe for human and non-human biota, to be chemically and physically stable, and ultimately to facilitate the return of the land to the Crown through the provincial institutional control program (RISA 2006).

As summarized in Section 2.3.1, eventual decommissioning technical feasibility, environmental protection, public acceptability, and ease were considered at the TMF design stage. Over time with changes in processed ore, process upgrades, advancing science, and other influences, the continued validity of tailings management is assessed through the TOVP (Section 5) and revisions are made to the PDP on a five-year frequency.

For the McClean Lake JEB TMF, decommissioned end-state objectives will be met by:

- controlling the release of contaminants over the very long term through geochemical and geotechnical controls; and
- placement of a cover on the JEB TMF, grading to blend into the existing topography, and re-vegetating.

6.2 Decommissioning Design Basis

The natural surround design of the JEB TMF, combined with control of the tailings geotechnical and geochemical properties during tailings preparation, is employed as a passive method to limit the long-term release of constituents of potential concern from the decommissioned facility.

6.2.1 Geochemical Controls and Decommissioned TMF Source Terms

Long-term solute concentrations within the tailings pore water are of importance as they represent the portion of constituents of potential concern available for transport from the tailings mass and into the receiving environment. The tailings preparation process in the McClean Lake mill manufactures tailings such that the tailings geochemical characteristics provides for long term control of constituents of potential concern. Long-term control of soluble arsenic in the tailings has been the primary environmental concern. Optimized control parameters for the existing tailings preparation circuit produce arsenic bearing secondary minerals with the lowest solubility (Section 3.5). The McClean Lake Operation is capable of processing ores with highly variable arsenic concentrations and successfully produce tailings which meet design criteria for arsenic concentrations in tailings pore water.

Orano undertakes geochemical studies for the purpose of predicting long-term solute concentrations within the tailings pore water. The results of the most recent detailed intrusive sampling campaign assessments are presented in Appendix D of this report and discussed in detail in Section 5.

The geochemical and geotechnical controls over pore water migrating through the tailings are incorporated into the contaminant transport modelling completed in conjunction with each iteration of the TOVP. The most current modelling is presented in Section 7.

6.2.2 Geotechnical Controls and Decommissioned Groundwater Flow

6.2.2.1 Tailings Consolidation

The long-term control of groundwater flow through the tailings is dependent on site-specific factors related to the physical characteristics of the tailings compared with those of the local Athabasca sandstone. The tailings, as produced during mill operations, contain a significant amount of fine-grained materials. Consolidation of these materials produces a tailings mass with a hydraulic conductivity lower than that of the surrounding sandstone. An understanding of the current geotechnical parameters of the placed tailings which are used to estimate an end-state hydraulic conductivity can be found in Section 5.6.

Under these conditions for the long term, the consolidated tailings mass represents a low-permeability plug in the sandstone which groundwater will preferentially flow around, through the surrounding host rock. Advective flow of groundwater through the tailings will be very limited, and the small residual amount of flow can be predicted through appropriate groundwater flow models and established material properties (Section 7).

6.2.2.2 Engineered Cover

The control of the vertical infiltration of meteoric water through the tailings at the time of decommissioning will be limited through cover design features. Landform design to divert runoff, the use of low-permeability materials, the establishment of a vegetative cover, compaction of surface materials, and the installation of drain layers all serve to reduce infiltration and limit advective transport.

A conceptual cover design has been developed and is presented in the 2019 TMF Expansion submission (Orano 2019b). The base and upper bound cover net percolation rates of 10 mm/yr and 20 mm/yr, respectively, from this conceptual design inform the groundwater and contaminant transport modelling in Section 7. Net percolation through the cover is the primary contributor of advective flux, as advective flow of groundwater through the tailings is limited by TMF design as described above through tailings consolidation.

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7 Validation of Operational Hydraulic Containment and Prediction of Long-Term Environmental Effects

7.1 Introduction

Groundwater flow and contaminant transport modelling is updated routinely to predict potential effects downstream of the JEB TMF. Long-term performance predictions incorporate the results of knowledge acquired during nearly 25 years of operating the McClean Lake Mill and TMF.

Numerical modelling is an iterative process with model assumptions and inputs revisited frequently based on new information. TMF contaminant transport modelling updates typically occur every five years coinciding with the TOVP, using refined inputs derived from the TOVP field program. The TMF models are occasionally updated outside of this schedule to support specific project work(s).

The groundwater flow and contaminant transport modelling for the TMF was most recently updated in early 2025 using the geochemical and geotechnical inputs developed using the results from the 2023/24 TOVP field program and reflecting the content of this Tailings TID submission. The modelling is summarized within this Tailings TID for completeness, with a full report provided in Appendix D, Section E. This section contains a summary of the modelling approach, key inputs, and both operational and long-term performance predictions.

7.2 Approach to Modelling

7.2.1 Conceptual Model

The conceptual hydrogeological model for the TMF was initially developed in 2004 and has been refined over time. A summary of the key features of the conceptual model is included in this section, with further detail in Appendix D, Section E.

7.2.1.1 JEB Pit

The mining of the JEB pit began in October 1995 with overburden stripping and it continued through to the completion of ore mining in July 1997. The JEB pit is approximately 120 m deep from the lowest point at the bottom of the pit (342 mASL) to natural ground surface near the raise pump house (462 mASL). The dimensions of the top of the pit are approximately 350 m in the north-south direction and 460 m in the east-west direction.

During earlier mining operations, pit dewatering was accomplished using a combination of perimeter dewatering wells and an operations sump (i.e. base drain) at the base of the pit. The purpose of the dewatering system was to intercept clean groundwater before it entered the pit and to control water levels within the TMF. Any water that seeped past the dewatering ring was collected by the operation sump and pumped to treatment. After 2014, pumping from the dewatering wells was discontinued and now the TMF water level is maintained via pumping from the base drain (Section 2.2.2).

During operations, the TMF pond water level was maintained at a given working level for extended periods of time and adjusted periodically as required to provide additional volume for tailings placement. The hydraulic head in the drain at the bottom of the pit was maintained at or slightly below the TMF pond water level by pumping water from the dewatering drift via the raise wells. Daily dewatering rates were collected since the beginning of mining operations in March 1996 and throughout TMF operations to the present.

The monitoring data from this operational period provides useful data for calibrating the groundwater model over several operational time frames. The integration of monitoring data and the calibration are described in Section 7.2.2 and Section 7.3.3, respectively.

7.2.1.2 Hydrostratigraphic Units

The general hydrostratigraphy encountered at the JEB TMF area, in descending order of elevation, includes the following units:

- Overburden;
- Upper Sandstone;
- Lower Sandstone;
- Basement Regolith; and
- Intact Basement.

The overburden, approximately 5 to 20 m thick, is heterogeneous with hydraulic conductivity varying by several orders of magnitude from one location to another depending on the clay content and the abundance of boulders and large cobbles. The sandstone unit, approximately 60 to 200 m thick, has a relatively low permeability matrix, but is fractured on both the local and regional scales. Both the upper and lower units of the sandstone are affected by major faults that influence the distribution of hydraulic heads. The basement rock includes a variety of crystalline rocks. Overlying the more competent basement rock is a layer of paleo-weathered basement rock (regolith). The thickness of the regolith varies from a few metres to approximately 50 m. In general, the regolith has permeability much lower than the sandstone, either equal or slightly greater than the permeability of the basement.

7.2.1.3 Groundwater Flow Directions

The topography of the JEB area was formed by tectonics, glacial depositions of tills, sands and gravels, and differential weathering. The relief of the area is defined by muskeg-covered, poorly drained terrain. Near the JEB pit, the muskeg layer is generally 1.0 to 1.5 m thick. The lowest elevation corresponds to Pat Lake at approximately 443.5 mASL, while the highest elevation corresponds to two drumlins at approximately 470 mASL, located directly to the northeast and southeast of the JEB pit. Near the JEB TMF, ground elevation varies from 450 to 460 mASL.

The JEB area includes a series of lakes, including Fox, Pat, Isis, Osiris, and Johannes lakes, which influence both surface water and groundwater flow. Local topographic features are the main control for the flow of shallow groundwater within the overburden units. In general, the direction of shallow groundwater flow in the JEB area is inferred to be east to west, with recharge in highlands and discharging to low lying bogs and lakes such as Fox Lake and Pat Lake. Deep groundwater flow is influenced to a greater degree by regional topographic and stratigraphic features. The topography is poorly drained and slopes gently to the south from the JEB area to Collins Creek. The surface of the basement rock confining unit slopes significantly to the south from the JEB TMF. Head contours indicate the southerly flow of deep groundwater from the JEB TMF toward Collins Creek, indicating strong influence of the structural base of the sandstone on deep groundwater flow.

7.2.2 Integration of Monitoring Data

7.2.2.1 Dewatering and Base Drain Pumping Rates

Dewatering well pumping rates were monitored throughout operations. Pumping rates varied significantly among the dewatering wells, from 0 m^3/day up to 956 m^3/day.

Daily dewatering rates were collected since the beginning of mining operations in March 1996 and throughout TMF operations to the present. Groundwater inflow into the pit was estimated by performing a water balance for the facility based on monitored inflows and outflows, estimated precipitation runoff, evaporation from the TMF pond, and the change in storage within the TMF. The groundwater inflow to the TMF, calculated from the water balance, varied in a narrow range, from 2,300 m^3/day (fully dewatered) to 1,200 m^3/day (pond elevation of 426.75 mASL).

Table 7.2-1 presents a summary of groundwater collected by the dewatering wells as well as that reporting to the TMF. Total groundwater inflow to the dewatering wells and TMF varied from 10,700 m^3/day (fully dewatered) to 4,000 m^3/day (pond elevation of 426.75 mASL).

Table 7.2-1: Summary of Groundwater Inflow to Operation Sump and Dewatering Wells

Operational Conditions	Period		Dewatering Rates (m^3/day)		
	From	To	Inflow to Dewatering Wells	Inflow to TMF Operation Sump	Total Groundwater Inflow
Fully Dewatered	1 May 1998	1 May 1999	8,400	2,300	10,700
Pond 374.0 m	30 June 1999	10 September 1999	7,300	2,600	9,900
Pond 392.5 m	13 August 2000	30 April 2002	6,300	2,300	8,600
Pond 410.0 m	15 October 2002	6 May 2006	4,300	2,600	6,900
Pond 426.75 m	1 July 2007	30 June 2009	2,800	1,200	4,000

7.2.2.2 Hydraulic Properties

Several testing programs have been undertaken since 1989 to characterize the hydraulic properties of the various hydrostratigraphic units in the JEB TMF area. Laboratory and field tests conducted include laboratory falling head testing, single borehole packer tests, single borehole response tests, and pumping tests. Field hydraulic conductivity data was used to inform the calibration, by providing initial hydraulic conductivity values and confirming the reasonableness of the calibrated values.

The hydraulic properties of tailings are one of the key passive controls on downstream performance. The tailings properties are consistently monitored through the TOVP and are derived from a combination of in-situ and laboratory testing of tailings (Section 5.6.3).

7.2.2.3 Hydraulic Head

In general, hydraulic head data were collected monthly across a network of piezometers and/or monitoring wells surrounding the JEB TMF. Hydraulic head distributions were generated from the data, and are included in Appendix D, Section F and summarized in Section 7.2.1.3.

Hydraulic head data provided calibration targets for the groundwater modelling, described further in Section 7.3.3.

7.2.2.4 Tailings Geochemistry

Tailings geochemistry is also a key control on downstream performance. Tailings geochemistry is monitored routinely through the TOVP as described in Section 5. The base case and upper bound source terms calculated in Appendix D, Section C are inputs to the source term model in the contaminant transport analysis (Section 7.4). The source terms are derived from in-situ sampling and are recalculated with each TOVP.

7.2.3 Identification of Constituents of Potential Concern (COPCs)

The TOVP (Section 5) provides the means for identifying the key COPCs to be modelled. The primary COPCs of concern are arsenic, uranium, and molybdenum, with nickel, selenium, copper, lead, and and radium-226 as minor constituents.

For completeness, and consistency with other groundwater modelling assessments performed at McClean Lake, a large suite of COPCs have been modelled, and include the following: chloride, sulfate, ammonia, arsenic, cadmium, cobalt, copper, lead, molybdenum, nickel, selenium, vanadium, zinc, polonium-210, lead-210, radium-226, thorium-230, and uranium.

7.2.4 Numerical Modelling Software

7.2.4.1 FEFLOW

The three-dimensional finite element numerical code FEFLOW (V8) was selected for the groundwater flow model, based on its ability to represent the key components of the conceptual hydrogeologic model. This included large contrasts in hydraulic conductivity (e.g., the drain filter material vs. underlying bedrock), complex geometry, and unsaturated conditions that exist in the overburden and bedrock near the TMF during operations.

7.2.4.2 GoldSim

The GoldSim software package (GTG 2025) was used to simulate the transport of solutes from the tailings through the groundwater flow system to downgradient surface water receptors (i.e. Fox Lake and Pat Lake).

GoldSim was used to solve standard one-dimensional differential equations for each aquifer pathway, with source term information from the TOVP (Appendix D, Section C) and travel distance and velocity distributions for each pathway (i.e. FEFLOW outputs) as key inputs.

7.2.5 Spatial and Temporal Boundaries

The extent of the hydrogeologic model was based on the limits of Orano's local JEB MODFLOW model, which was extracted from a larger calibrated three-dimensional regional model to be published in the forth comming Colins Creek Regional Groundwater Technical Information Document (Orano 2026) which is an update of the 2011 version of the regional groundwater model (AREVA 2011).

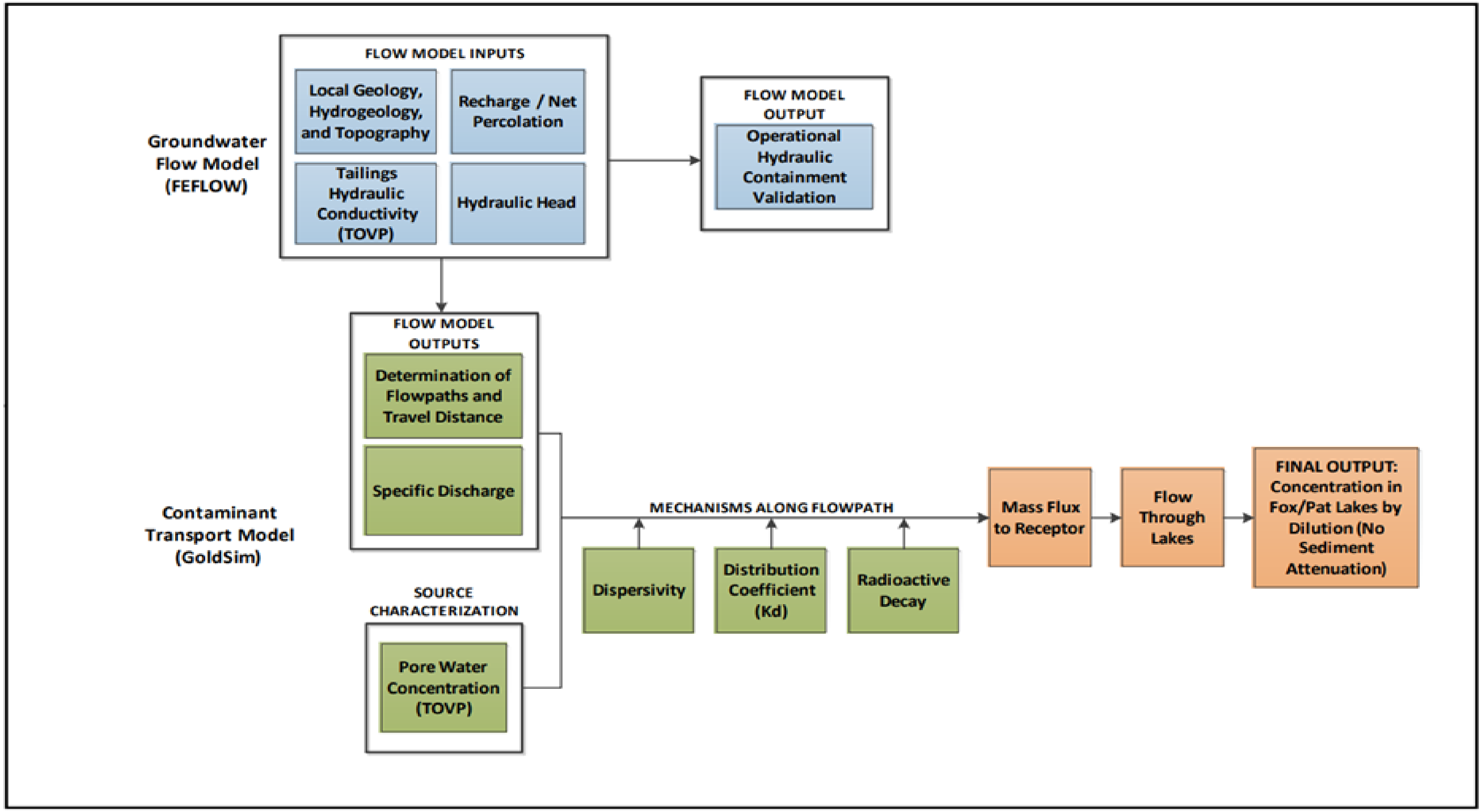
The lateral model boundaries are set sufficiently far from the TMF to allow adequate representation of pre-mining and operational conditions, and the sufficiency is confirmed during calibration. The model is approximately centred on the TMF area and extends up to 15 km in the east-west direction and 14 km in the north-south direction. The planar area of the model domain was about 130 square kilometers.

The model mesh consisted of approximately 828,000 triangular elements with a spacing of approximately 5 to 10 m in the area of the TMF to approximately 100 m along the model perimeter. Vertically, the model was discretized into 14 layers of variable thickness, with an additional layer added in this model update to refine the representation of the liner. The top of layer one set to ground surface elevation (from 410m to 500m), and the bottom of layer 14 was set to a constant elevation of 200 m (approximately 150 m below the base of the TMF).

Mass flux calculations were run for 20,000 years post-decommissioning.

7.2.6 Roadmap

Figure 7.2-1 presents a roadmap to the groundwater and contaminant transport modelling. The various inputs and outputs of the model are highlighted and described further in this section.



Projection:
Compiled: T.Lohman Drawn: T.Lohman
Date: 4/21/2020 Scale:
Data Sources: ORANO Canada Inc.

McCLEAN LAKE OPERATION

FIGURE 7.2-1
GROUNDWATER AND CONAMINANT TRANSPORT MODEL ROADMAP

TAILINGS MANAGEMENT TID

orano

Figure 7.2-1: Groundwater and Contaminant Transport Model Roadmap

7.3 Groundwater Flow Model

7.3.1 Overview

Groundwater flow modelling for the JEB TMF is conducted for two purposes:

1) To validate that hydraulic containment of the JEB TMF will be maintained throughout the operating period, including as TMF Expansion plans progress; and

2) To determine the transport pathways from the TMF to receptor lakes and associated transport times, for later input into a contaminant transport model to assess post-decommissioning performance.

The currently approved case for the expanded JEB TMF is an embankment height of 468 mASL. The model update described in this section primarily focuses on the impact of this higher level of placed tailings in the JEB TMF.

7.3.2 Model Development

7.3.2.1 Hydrostratigraphy and Model Parameters

The hydrostratigraphy of the model was developed based on the conceptual hydrogeological model (Section 7.2.1). Layers were assigned for the overburden, upper and lower sandstone, basement regolith, and intact basement. The TMF was subdivided into the following units: cover and berms, tailings, sand filter material, and gravel and rock drain material. Initial values of hydraulic properties were assigned based on either field data (Section 7.2.2.2) or knowledge gained from previous modelling and assessments.

7.3.2.2 Boundary Conditions

Four types of boundary conditions were used in the model: head dependent, specified head, specified flux, and no-flow. The location of these boundaries is described in detail in Appendix D, Section F and described below.

Head dependent boundaries were assigned to nodes in layer 1 to layer 6 to represent all watercourses within the model domain. The boundaries were set equal to the reported average water level elevation (AREVA 2011b) or to ground surface elevation if the water level elevation was unknown. Groundwater flow through these boundaries was inferred to be impeded by lower permeability sediments at the base of the lakes and creeks, with the conductance set through previous model calibration (Golder 2019).

Specified head boundaries were assigned to the base of the base drain and to the top of the tailings to simulate the tailings pond. The head was varied according to the simulated pond elevation for the calibration stage: 360 m (fully dewatered), 374 m, 392.5 m, 410 m, and 426.75 m.

Specified flux boundaries were assigned to the top of layer one to represent recharge from precipitation. Initial recharge rates were adopted from previous modelling and were later adjusted during model calibration to 58 mm/yr. Specified flux boundaries were used to simulate the dewatering wells. The rates assigned to the dewatering wells varied for each calibration stage according to the production rates measured during operation (Section 7.2.2.1).

No-flow boundaries were used to represent inferred groundwater flow divides at the lateral extents of the model. A no-flow boundary was assigned along the bottom of the model at 200 m elevation. Groundwater flow below 200 m elevation was expected to have negligible effect on model predictions due to the inferred low permeability of the intact bedrock.

7.3.3 Model Calibration

7.3.3.1 Calibration Parameters

During calibration, the model was run repeatedly and the following parameters were iteratively adjusted until a reasonable agreement between simulated and observed hydraulic heads and inflow measurements was obtained (i.e. calibration targets, Section 7.3.3.2):

- Recharge;
- Conductance of lake and creek bed sediments; and
- Hydraulic conductivity of the various stratigraphic layers.

7.3.3.2 Calibration Targets

The With incorporated changes in the model, the ability of the model to reproduce previous calibration stages from the past modelling was checked. The check was completed for 4 calibration scenarios with site data that was collected prior to mining and during mine operation. This data included hydraulic head measurements and inflow measurements for the following operating conditions:

- Pre-mining conditions (December 1995)
- Fully dewatered conditions (May 1999)
- TMF water level at 426.75 mASL (June 2009)
- Field pumping trials (inflows for stage 3 and 4, January 2021)

The data used in the calibration process consisted of hydraulic heads measured in piezometers installed in the overburden, sandstone, regolith and/or basement, and measured groundwater inflows to the TMF operation sump (except for field pumping trials). Water levels recorded in the overburden were generally reviewed but not used in the model calibration. During operational conditions, perched groundwater conditions and partial dewatering is inferred to have occurred in the overburden, which could not be accurately reproduced by the numerical model. In addition, the screen lengths in the overburden wells were relatively long, which makes it difficult to assess what elevation the hydraulic head measurement represents. This is especially important during operational conditions when vertical gradients likely developed in overburden.

7.3.3.3 Calibration Statistics

Figures 7.3-1 and 7.3-2 present a summary of the model predicted and measured hydraulic head for each of the calibration stages. Predicted and measured hydraulic head values are also presented in Table 5 of the 2025 Modelling Update (Appendix D, Section F). Overall, the normalized root-mean-square error in the calibration stages ranged from 8% to 11%. These values are near the upper end of the range normally used in hydrogeological studies; however, given the complexity of the geology and enhanced permeability features near the pit, and the reasonable match to measured inflows, these results were considered acceptable. Considering the reasonable calibration match to pre-operational and multiple operational scenarios, and the fact that the calibrated parameters are well within bounds established during in-situ testing, the calibrated model is considered to be capable of predicting future inflows to the TMF within the level of accuracy required for this assessment.

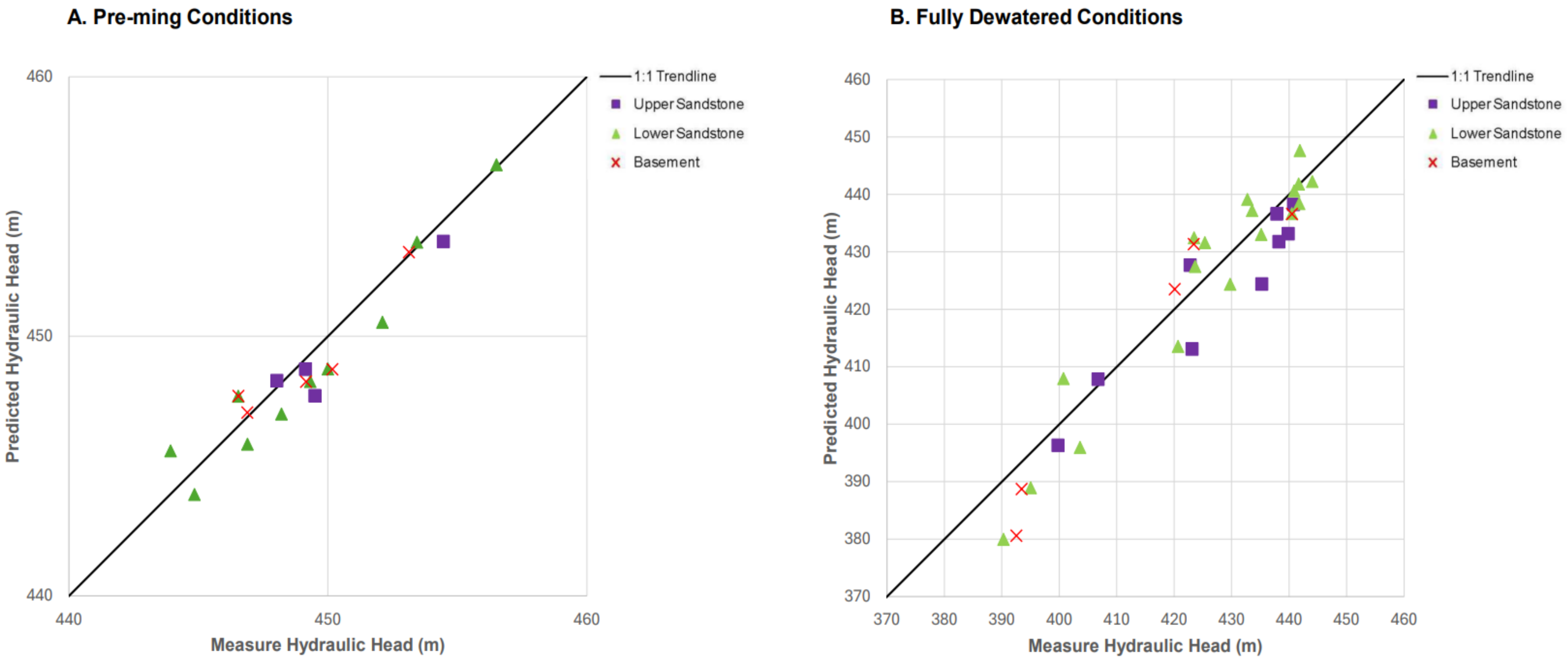
7.3.3.4 Calibration Check – Pumping Test Trial

A field trial pumping test was conducted at the TMF between December 1, 2020, and February 6, 2021 to evaluate hydraulic response and TMF pumping rates. During the field trial pumping test, the pumping rates were varied between 1,809 m^3/day and 776 m^3/day. Full data from the pumping test is provided in Appendix D, Section F).

Consistent with previous modelling in 2021, the groundwater model was configured to evaluate two states of the field pumping trial, including

- Stage 3, where the groundwater elevation in the base drain was at elevation 440.0 mASL. At this stage in the field pumping trials, the base drain pumping rate was approximately 1,500 m3/day.
- Stage 4, where the groundwater elevation in the base drain was at elevation 442.5 mASL. At this stage in the field pumping trials, the base drain pumping rate was approximately 930 m3/day.

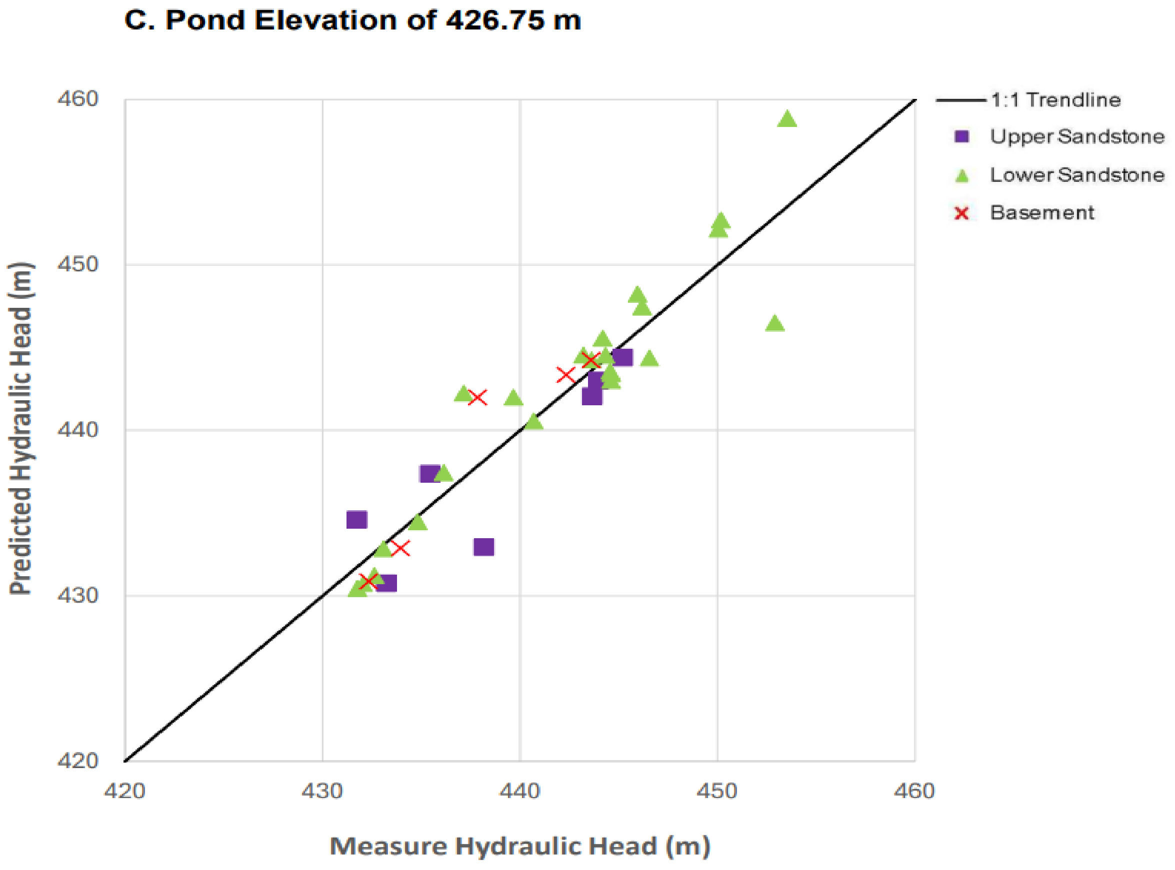
Results of the simulations were compared to the base drain pumping rates observed during the field pumping trial. For Stage 3 of the pumping trials, the simulated groundwater inflow to the drain was approximately 1,550 m^3/d, which compares well to the average measured value of 1,502 m^3/d. For Stage 4, the simulated groundwater inflow to the drain was 1,200 m^3/d, which compares well to the average measured value of 934 m^3/d. The updated model therefore still reasonably reproduces measured data.



Mean Absolute Error (m)	0.90
Normalized Mean Absolute Error (m)	7.18%
Root Mean Square Error (m)	1.05
Normalized Root Mean Square Error	8.32%
Mean Error (m)	-0.39

Mean Absolute Error (m)	5.28
Normalized Mean Absolute Error (m)	9.83%
Root Mean Square Error (m)	6.10
Normalized Root Mean Square Error	11.35%
Mean Error (m)	-1.54

Figure 7.3-1: Measured vs. Predicted Hydraulic Heads for Various Conditions (Page 1 of 2)


C. Pond Elevation of 426.75 m

Mean Absolute Error (m)	1.92
Normalized Mean Absolute Error (m)	8.80%
Root Mean Square Error (m)	2.46
Normalized Root Mean Square Error	11.27%
Mean Error (m)	0.17

Figure 7.3-2: Measured vs. Predicted Hydraulic Heads for Various Conditions (Page 2 of 2)

7.3.4 Flow Model Results and Outputs

7.3.4.1 Full Build Capacity

As described in Section 2.2.2, pumping from the TMF dewatering wells ceased in 2014 and containment is now maintained by pumping from the TMF base drain. The model was used to assess the operating base drain elevations required to maintain groundwater capture with the JEB TMF operating at full build capacity after the 468 Expansion in order to validate that containment will be maintained by base drain pumping throughout the life of the project. The model was configured to include tailings to an elevation of 465.5 mASL, a pond elevation of 467 mASL and a berm crest elevation of 468 mASL.

The following steps were taken to evaluate the groundwater capture:

- The model was run using a base drain elevation with a head differential relative to the surface water elevation of Fox Lake (445.65 mASL). The simulation was run to steady-state conditions.
- The degree of groundwater capture was evaluated by completing a particle tracking analysis, where groundwater flow particles were released from the TMF pond and tailings and forward tracked through the groundwater flow system to their ultimate point of discharge.
- If the groundwater particle tracking analysis indicated that containment was not achieved (i.e., groundwater particles discharged from the model anywhere except the base drain) then the model was re-run using a lower base drain elevation and the particle tracking analysis was repeated.

Results of the predictive simulations indicate that containment is achieved when the base drain elevation is specified at an elevation of 439.7 mASL (i.e., 6 m lower than Fox Lake) or lower. Figures A1 and A2 in Appendix A of the 2025 Modelling Update (Appendix D, Section E) illustrate the groundwater particle traces drain elevations of 439.7 mASL and 438.7 mASL, respectively. As shown in the figures, the particle traces generally follow a path directly towards the drain. A small portion of particles travel towards the west along by the east-west trending conductive feature in the sandstone that intersects the south side of the JEB TMF before returning to the drain.

In addition to the base case scenario above (scenario using the calibrated model parameters), four additional simulations were completed to evaluate the potential sensitivity of model outcomes with the base drain elevation set at 7 m below the Fox Lake water elevation:

- The hydraulic conductivity was increased in the overburden by a factor of 10.
- The anisotropy (vertical permeability) was reduced in the sandstone by a factor of 10.
- The hydraulic conductivity of the liner was increased by a factor of 10 (i.e., from 1×10^{-9} m/s to 1×10^{-8} m/s).

Hydraulic containment was maintained for each sensitivity scenario except when the liner hydraulic conductivity was increased by a factor of 10. The same scenarios were run with the base drain elevation set at 8 m below the Fox Lake water elevation and hydraulic containment was maintained for all scenarios. Sensitivity runs for both base drain elevations are illustrated in Figures A2 to A9 in Appendix A of the 2025 Modelling Update (Appendix D, Section E)

Settings of 438.7 mASL (7 m head differential) and 437.7 mASL (8 m head differential) would cause a groundwater inflow in the base case of 2,050m^3/d and 2,250m^3/d, respectively.

7.3.4.2 Post Closure Scenarios

For the post closure scenarios, pumping from the base drain was considered to remain inactive following mine closure, and it was considered that the top of the TMF is covered by a low permeability barrier. The infiltration (i.e., net percolation) through the low permeability barrier was assessed as part of the soil cover design report (Golder 2011) and was estimated to be 10 mm/yr. The soil cover design in this report is conceptual and intended to demonstrate the feasibility of the construction of a cover to limit net percolation to these values, as required to ensure the overall performance of the decommissioned TMF.

Two post closure scenarios were simulated. In the first scenario, the expected infiltration of 10 mm/yr was assigned to layer one in the area of the expanded TMF to represent net percolation of precipitation through the soil cover. In the second scenario the infiltration was increased to 20 mm/yr. In addition to the two post closure scenarios varying the net percolation rate, two sensitivity simulations were completed to support the solute transport assessment (Section 7.4) where the hydraulic conductivity of the tailings was adjusted by an order of magnitude above and below the base case value (i.e., from 1x10-9 m/s for the low hydraulic conductivity scenario to 1x10-7 m/s for the high hydraulic conductivity scenario).

7.3.4.3 Pathline Analysis

Figure 7.3-3 presents the predicted advective transport pathway for the base case net percolation rate of 10 mm/yr. Seepage pathways for the higher net percolation rate are similar to the 10 mm/yr scenario. Discharge from the TMF is predicted to migrate south-west towards Fox Lake and Pat Lake. Approximately 68% of the predicted flow discharges to Fox Lake Basin and 32% of the flow discharges to Pat Lake.

The model results indicated that, in general, the discharge from the TMF originates from the net percolation of precipitation through the soil cover (5.8 to 11.6 m3 /day) (Figure 7.3-4). Precipitation that infiltrates through the cover is predicted to migrate through the tailings and discharge to the sandstone and to the base drain. A small portion (approximately 2%) of the simulated groundwater flow through the tailings originates from the surrounding environment and liner, typically in the upper portions of the Cigar Lake tailings.

Sensitivity runs were conducted to examine the effect of varying the tailings hydraulic conductivity on the post-decommissioning TMF water balance (Figure 7.3-4). The results indicate that negligible changes to the total outflow from the tailings occurred for the case where the hydraulic conductivity of the tailings was reduced by an order of magnitude, and that a greater portion of the flow occurred through the Cigar Lake tailings. For the case where the tailings hydraulic conductivity was increased by an order of magnitude, the total flow out of the tailings mass increased by approximately 5%. An additional sensitivity simulation was completed to evaluate the influence of removing the liner from the TMF. Results of this simulation indicate that removal of the liner resulted in an approximate 5% increase in the groundwater flow through the Cigar Lake tailings, which originated as lateral flow from the surrounding environment.

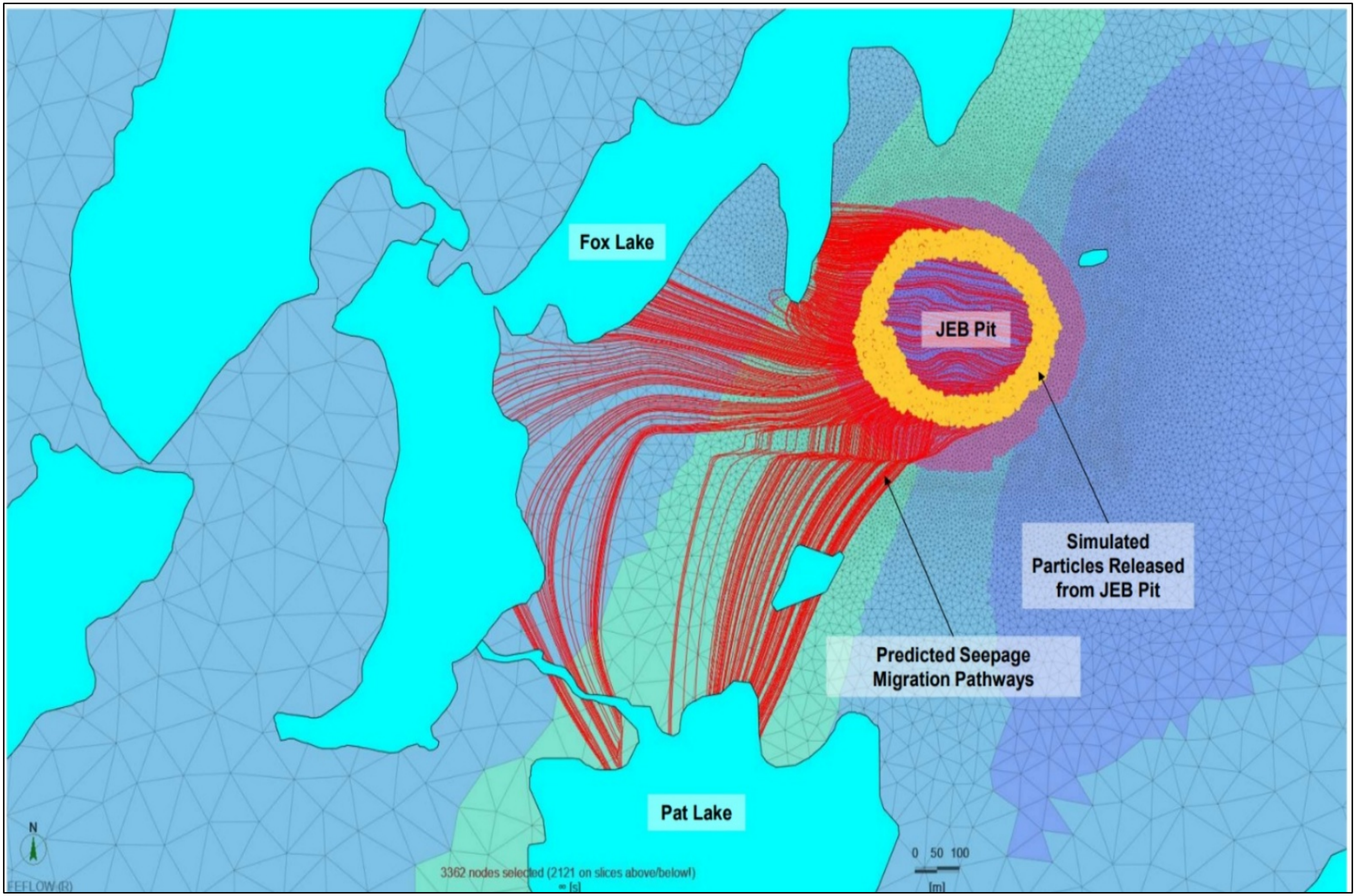


Figure 7.3-3: Predicted Advective Contaminant Transport Pathways From the Tailings Management Facility Postclosure

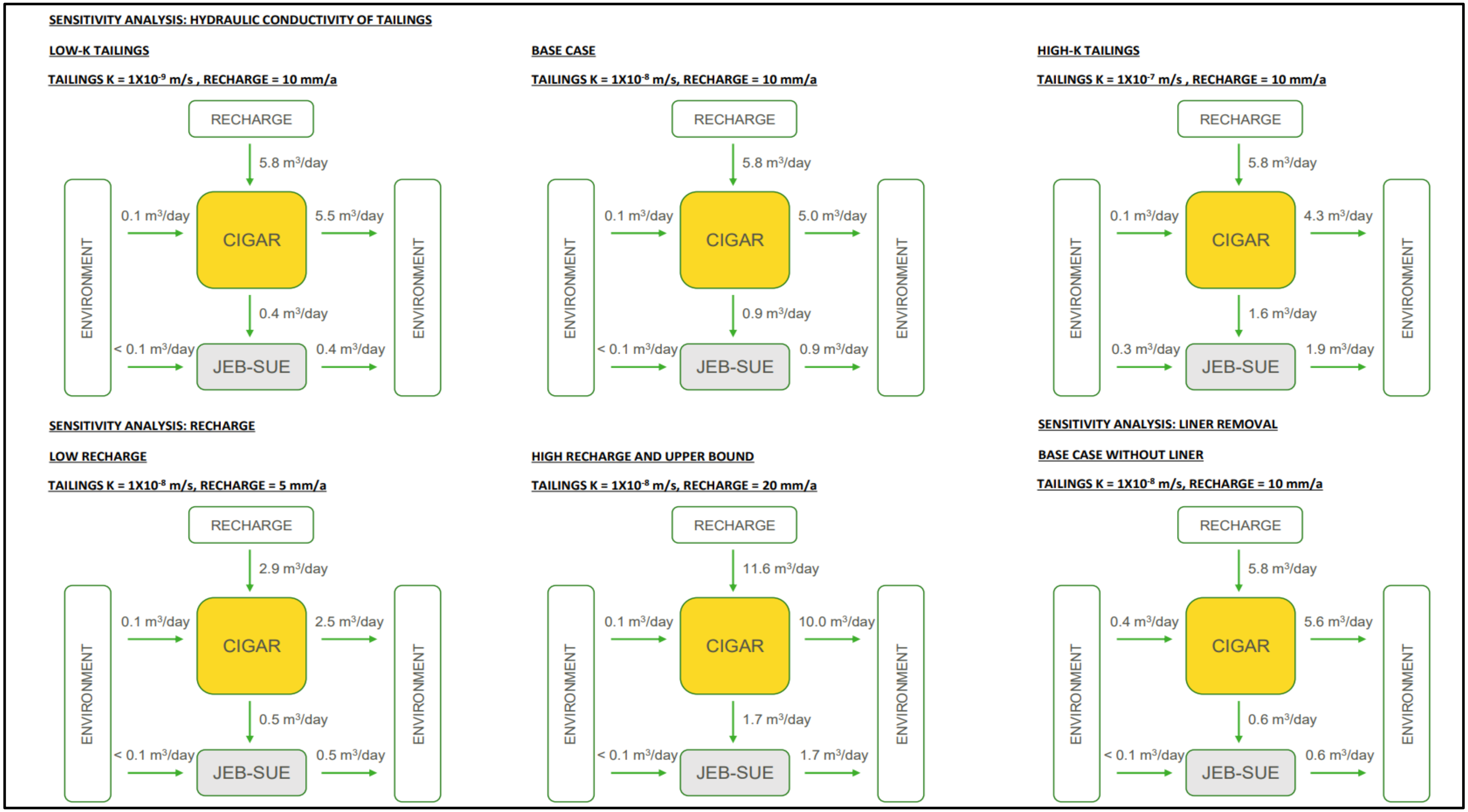


Figure 7.3-4: Water Balance Components of the JEB TMF

7.4 Contaminant Transport Model

Solute transport analyses describe the migration of solute in groundwater between a source and receptor, considering advective and diffusive transport mechanisms, and attenuation due to sorption behaviour and decay in transit. Solute release may be due to advection, which is a function of groundwater movement, and/or molecular diffusion, which is a function of chemical gradients. As such, factors that may influence solute mass flux out of the source include the groundwater flow in and around the source, the development of chemical gradients and the chemical properties of the solute.

Contaminant transport was conservatively assumed to be steady-state (i.e. non-depleting source) in this assessment. For the case of steady-state transport from a source to a receptor with no decay in transit, the mass flux from the source defines the peak rate of solute loading to the receptor when the increase achieves a steady-state. Therefore, in this case, the mass flux from the source is conservative - the peak concentration is sustained rather than declining back to background (as would occur as the mass is depleted over time).

Predicted and upper bound mass flux from the expanded JEB TMF were calculated with the GoldSim model based on the results of the groundwater flow model for the expanded JEB TMF and updated tailings pore water source concentrations (Appendix D, Section C). Values were calculated using predictions of net percolation rates from a conceptual soil cover design (Golder 2011) and source concentrations determined from the TOVP Program (Section 5). The upper bound values were calculated using the combination of a soil cover net percolation sensitivity case and the calculated upper bound pore water concentrations (Appendix D, Section C).

This section describes the conceptual source term model used in this assessment, a summary of the model inputs, and the base and bounding case results.

7.4.1 Source Term Model

The conceptual source term model in this assessment considers low-permeability tailings in direct contact with a high-permeability host rock. Advection (transport resulting from mean fluid flow) is limited in this scenario, as groundwater preferentially flows around the decommissioned tailings mass, limiting flow through the tailings. Net percolation through the decommissioned cover and into the tailings mass provides the main component of advective flux. As groundwater flows past the tailings mass, a concentration gradient exists between the placed tailings and the surrounding materials. Transport occurs in this scenario through molecular diffusion, a process by which a solute in water will move from an area of higher concentration to an area of lower concentration. The diffusive flux of solutes occurs across the tailings/host rock interface into the active flow zone. Chemical gradients develop until equilibrium is reached between the mass flux out of the tailings and the rate of removal by groundwater flow.

Figure 7.4-1 provides a graphical representation of the conceptual model.

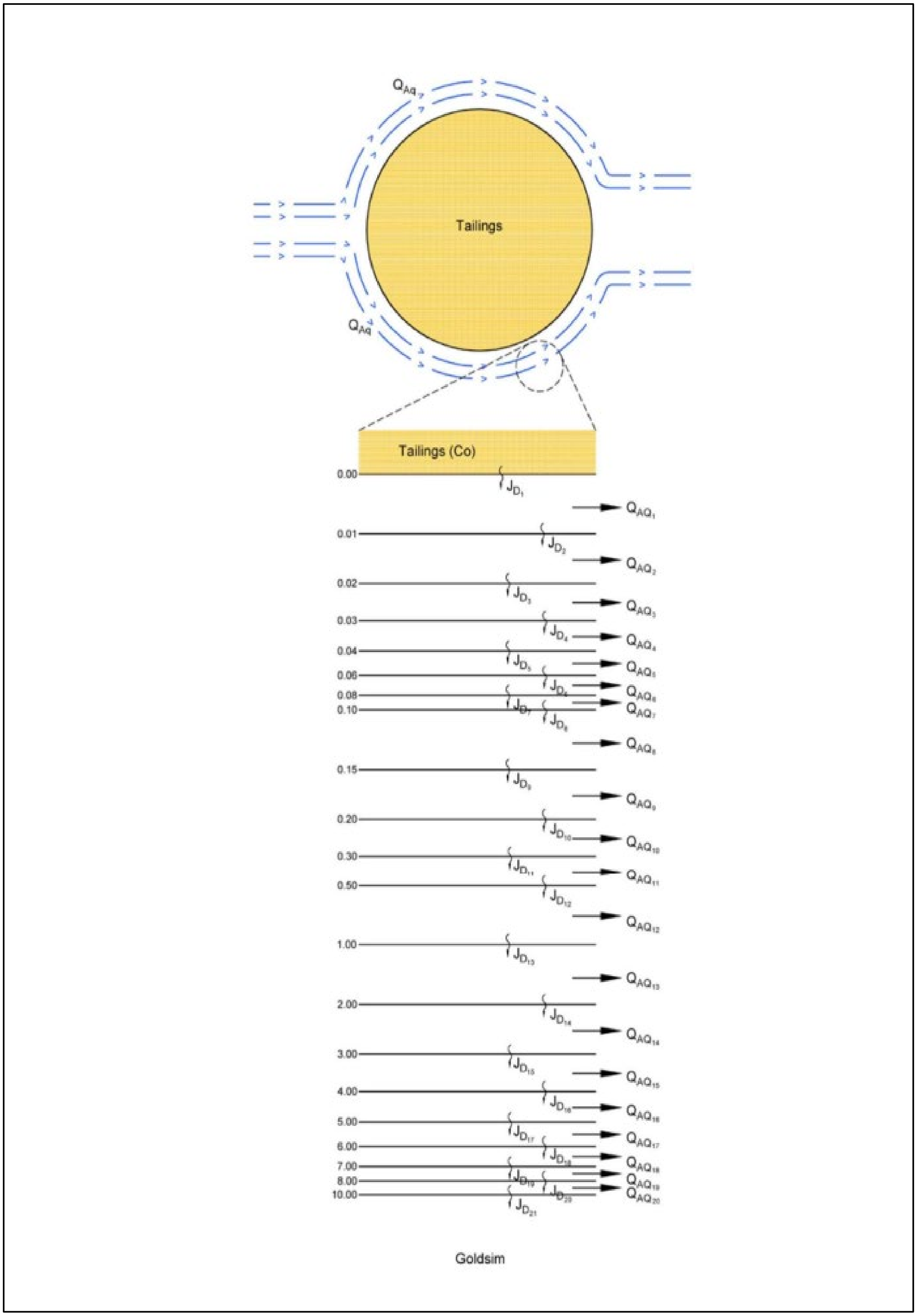


Figure 7.4-1: Source Term Conceptual Model

7.4.2 Model Inputs

Input parameters applied to mass flux calculations are summarized in Table 7.4-1, while solute transport calculation inputs are summarized in Table 7.4-2.

Table 7.4-1: Mass Flux Calculation Input Parameters

Parameter	Model Input	Source
Elevation Tailings Surface (JEB-Sue)	~422 mASL	As-built tailings survey data; TOVP sampling results
Elevation Tailings Surface (Cigar Lake)	~422 mASL to 465.5 mASL	JEB TMF Expansion Design (Orano 2019b)
Effective porosity (n_e)	11% (sandstone)	Site-specific laboratory testing
Effective Diffusion Coefficient (D^*)	3x10^{-11} m^2/s	Site-specific radial diffusion tests conducted on sandstone
Tailings Lateral Surface Area (Cigar Lake, lined portion)	127,600 m^2	As-built survey data for the JEB TMF; JEB TMF Expansion Design (Orano 2019b)
Tailings Lateral Surface Area (Cigar Lake, unlined portion)	41,300 m^2	
Tailings Lateral Surface Area (JEB-Sue)	82,100 m^2	
Tailings Lateral Surface Area (Total; A_L)	251,000 m^2	
Tailings Top Surface Area (A_T; *applies to Cigar Lake Tailings*)	211,500 m^2	
Cover Net Percolation Rate (q_i)	10 mm/year to 20 mm/year	Conceptual soil cover design (Orano 2019b)
Specific Discharge Sandstone (q_{SS})	0.04 m/day	Conservatively selected as greatest value predicted by FEFLOW model (Section 7.3)

Table 7.4-2: Solute Transport Calculation Input Parameters

Parameter	Model Input	Source
Travel Distance (x)	Fox Lake Pathway: 280 m; Pat Lake Pathway 790 m	FEFLOW model pathline analysis (Section 7.3.4.3)
Groundwater Velocity (v)	Fox Lake Pathway: 0.06 m/day; Pat Lake Pathway 0.005 m/d	Calculated using particle paths from FEFLOW model, specific discharge and porosity (Table 7.4-1)
Specific Discharge (q)[4]	Fox Lake Pathway: 0.0066 m/d; Pat Lake Pathway: 0.00056 m/d	Greatest value (i.e., 0.04 m/day through sand filter) predicted by the flow model
Seepage Pathway Width	Fox Lake Pathway: 100 m; Pat Lake Pathway: 500 m	FEFLOW model pathline analysis (Section 7.3.4.3)
Units Thickness	Overburden: 20 m; Sandstone: 80 m	FEFLOW model
Dispersivity (α)[1]	0.1x	Scale-dependent parameter that accounts for mechanical mixing during transport of solute through an aquifer - set as 10% of the travel distance (literature review)
Distribution Coefficient (k_d)[2]	^{230}Th, ^{210}Pb, ^{210}Po, As: 1 L/kg Ni: 2 L/kg ^{226}Ra: 50 L/kg	Site-specific testing at Cigar Lake, Key Lake, and Midwest sites; literature review; COPCs with limited data conservatively applied 1 L/kg
First order decay constant (λ)[3]	U: 1.55 E-10 1/year ($T_{1/2}$ = 4.5E9 year; A = 1.24 E4 Bq/g) ^{230}Th: 8.7 E-5 1/year ($T_{1/2}$ = 8000 year; A = 7.19 E9 Bq/g) ^{226}Ra: 4.3 E-4 1/year ($T_{1/2}$ = 1620 year; A = 3.62 E10 Bq/g) ^{210}Pb: 3.1 E-2 1/year ($T_{1/2}$ = 22.3 year; A = 2.83 E12 Bq/g) ^{210}Po: 1.83 1/year ($T_{1/2}$ = 0.378 year; A = 1.67 E14 Bq/g)	Calculated based on representative half-life of each COPC

[1] Scale dependent parameter that accounts for mechanical mixing during transport through an aquifer
[2] Partitioning of solute between liquid and solid phases along the pathway; used to describe attenuation (sorption) behaviour along the flowpath. In a steady state assessment, sorption behaviour simply delays the breakthrough time of solute at a receptor but does not affect the steady-state concentration or mass flux where decay does not occur along the pathway.
[3] Used to determine radioactive decay rate based on element half-life.
[4] Specific discharge is calculated using the porosity of sandstone, which is 0.11
TMF = Tailings Management Facility; m = metre; m/day = metres per day; L/kg = litres per kilogram; Bq/g = Becquerel per gram

7.4.3 Parametric Sensitivity Analysis

While the groundwater model is calibrated against measured data, the same process cannot be completed for the contaminant transport model. As the TMF has been hydraulically contained throughout operations, contaminant transport has not yet occurred and downstream monitoring wells cannot serve as calibration targets. Instead, a parametric sensitivity analysis is conducted to identify the input parameters exerting the greatest influence on calculated mass loading rates from the decommissioned JEB TMF, and therefore long term performance. The parametric sensitivity analysis identifies whether adjustments to a parameter will be material or immaterial to final results and bounds possible future performance.

Mass flux calculations were performed while varying each input parameter individually over the selected range (Table 11, Appendix D, Section E). Figure 7.4-2 presents the results of the sensitivity analysis and indicates the range applied to each parameter. The results presented are generalized and reflect relative magnitudes of sensitivity for all key COPCs. Based on the results of the sensitivity analysis, it is apparent that the cover net percolation rate and tailings pore water source concentrations exert the greatest control over the predicted mass flux from the decommissioned JEB TMF. Predicted values are relatively insensitive to the rate of groundwater flow within the host sandstone adjacent to the tailings.

Based on the results of the sensitivity analysis, base case and upper bound scenarios were developed for the calculation of peak mass flux to receptors. The base case considered expected input parameter values for net percolation and measured pore water concentrations. The base case provides the expected future performance. The upper bound case considered the compounding effects of increasing the cover net percolation from the base case value of 10 mm/year to an upper bound rate of 20 mm/year (values from the conceptual cover design) and applying the upper bound source concentrations in tailings pore water defined at the 95th percentile and described further in Appendix D, Section C. The bounding case can be compared to the base case to gauge the extent of potential future performance, keeping in mind that the sensitivity case inputs represent low likelihood and compounding scenarios of net percolation and source term.

7.4.4 Contaminant Transport Model Results

Base case and upper bound case mass fluxes of pore water constituents are presented in Table 7.4-3. The total mass loadings out of the JEB TMF were applied to Pat Lake as Fox Lake reports to Pat Lake by surface flow.

The incremental concentrations for each receptor lake were calculated based on the predicted mass loadings and the average annual flows through the north basin of Fox Lake (5,763 m^3/day), Fox Lake (14,743 m^3/day), and Pat Lake (18,465 m^3/day; AREVA 2011b). Tables 7.4-4 and 7.4-5, respectively, present base case and upper bound incremental COPC concentrations for Fox Lake and Pat Lake.

Base case COPC concentrations in receiving waters are marginally above baseline concentrations and remain lower than Canadian Water Quality Guidelines (CWQG) and Saskatchewan Environmental Quality Guidelines (SEQG) at peak values. Calculated cadmium, cobalt, and lead concentrations marginally exceed SEQG criteria; however, this is an artifact of the guideline being lower than the baseline concentrations for these constituents. In each case, the incremental concentration is negligible in relation to the baseline concentration.

Figure 7.4-3 graphically presents the predicted long-term water quality in Fox Lake, where the greatest effects are predicted to occur for key COPCs. The elevation of 465.5 mASL noted in the figure corresponds to the unconsolidated top of placed tailings in the 468 mASL Expansion case, which was conservatively used in the assessment. The resulting concentrations of solutes are compared to baseline concentrations and SEQG. Predicted long-term water quality is within SEQG for all COPCs. Arsenic and uranium appear to be the most sensitive constituents with predictions approaching 28% of objective values and upper bound values approaching 72% of the surface water arsenic guideline and exceeding the surface water uranium guideline.

Solute transport calculations were performed for the predicted rates of constituent loading from the JEB TMF to the active groundwater flow zone. The results of the solute transport analysis are presented in terms of mass flux to surface water receptors as a function of time. The results of the solute transport analysis are presented in terms of mass flux to surface water receptors as a function of time and are plotted for arsenic, nickel, uranium and radium-226 in Figure 7.4-4 for Fox Lake and Pat Lake. Predicted and upper bound steady state mass fluxes to receptors for all constituents are presented in Table 7.4-4 and Table 7.4-5.

The average arrival time of a solute plume at a given point along the pathway may be defined as the time at which the solute concentration reaches half of the ultimate steady-state value. The arrival time will vary from one solute to another depending on the degree of attenuation. For unattenuated species, the average arrival time to Fox Lake is approximately 20 years. Moderately attenuated species such as arsenic and nickel show breakthrough at receptors in 280 to 540 years. Arrival time for radium-226 is expected to occur in approximately 6,520 years with peak radium-226 loadings occurring after approximately 20,800 years.

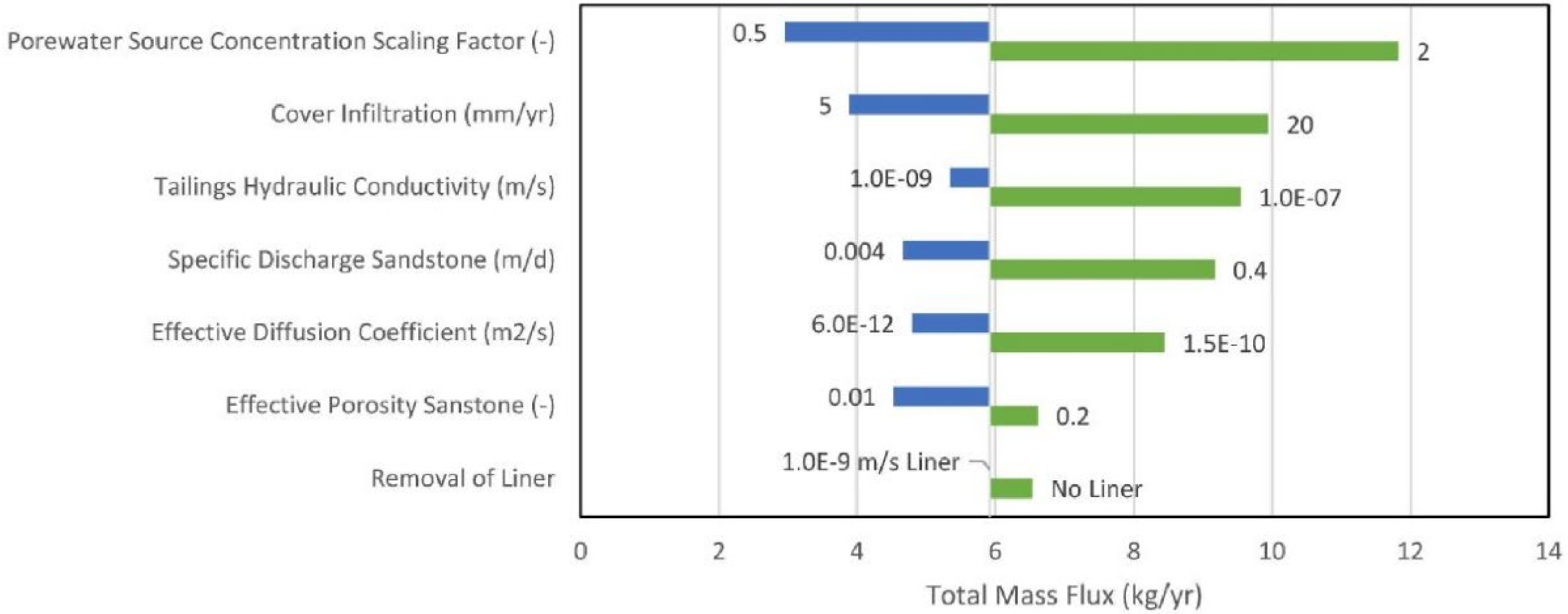


Figure 7.4-2: Parametric Sensitivity Analysis

Table 7.4-3: Expanded JEB TMF Predicted Peak Mass Flux

Constituent	Cigar Lake Tailings Pore Water Concentration (mg/L or Bq/L)		JEB-Sue Tailings Pore Water Concentration (mg/L or Bq/L)		Mass Flux Out of Tailings (kg/a or MBq/a)		Mass Flux To Fox Lake (kg/a or MBq/a)		Mass Flux To Pat Lake (kg/a or MBq/a)	
	Prediction	Upper Bound	Prediction	Upper Bound	Prediction	Upper Bound	Prediction	Upper Bound	Prediction	Upper Bound
Chloride	118.12	145.15	43.86	82.7	259	622	181	435	259	622
Sulphate	3292.61	4325	2205.84	2578	7706	18612	5394	13029	7706	18612
Ammonia	13.29	35.55	11.69	24.4	33	156	23	109	33	156
Arsenic	0.76	1.78	1.27	2.98	2.16	9.19	1.52	6.44	2.16	9.19
Cadmium	0.00041	0.0011	0.0009	0.0022	0.00128	0.00597	0.00089	0.00418	0.00128	0.00597
Cobalt	0.047	0.27	0.15	0.47	0.17	1.41	0.12	0.99	0.17	1.41
Copper	0.004	0.017	0.0019	0.0046	0.01	0.07	0.01	0.05	0.01	0.07
Lead	0.0009	0.007	0.0021	0.0142	0.003	0.038	0.002	0.027	0.003	0.038
Molybdenum	5.34	13.68	8	14.09	14.7	63.6	10.3	44.5	14.7	63.6
Nickel	0.168	0.63	2.37	8.11	1.54	8.89	1.08	6.23	1.54	8.89
Selenium	0.007	0.032	0.0095	0.052	0.02	0.16	0.01	0.11	0.02	0.16
Vanadium	0.0043	0.0077	0.021	0.18	0.019	0.173	0.01	0.12	0.019	0.173
Zinc	0.008	0.032	0.026	0.7	0.03	0.68	0.02	0.48	0.03	0.68
Polonium-210[a]	0.51	0.62	0.75	3.55	15.6	46.4	13	48	13	49
Lead-210[a]	2.29	6.25	2.2	4	20	69	13	48	13	49
Radium-226[a]	4.11	7.7	4.63	16	10.2	41.2	0.13	0.47	0.15	0.50
Thorium-230[a]	1	1.1	1.11	1.55	2.56	5.45	1.79	3.80	2.5	5.3
Uranium	3.08	7.59	9.37	53.36	11	72	8	50	11	72

[a] Polonium-210, Lead-210, Radium-226 and thorium-230 are expressed as Bq/L or Bq/a.

mg/L = milligrams per litre; Bq/L = Becquerel per litre; kg/a = kilograms per year; MBq/a = Megabecquerel per year.

Table 7.4-4: Expanded JEB TMF Predicted Receptor Surface Water Quality

Constituent	Units	Baseline Concentration			Incremental Concentration			Resulting Concentration			Water Quality Criteria
		Fox Lake North Basin	Fox Lake	Pat Lake	Fox Lake North Basin	Fox Lake	Pat Lake	Fox Lake North Basin	Fox Lake	Pat Lake	SEQG- Fresh Water Aquatic Life
Chloride	mg/L	0.133	0.133	0.12	8.60E-02	3.36E-02	3.83E-02	0.22	0.17	0.16	120 (b,e)
Sulfate	mg/L	0.633	0.633	0.71	2.56E+00	1.00E+00	1.14E+00	3.20	1.64	1.85	128-429(c)
Ammonia	mg/L	0.021	0.021	0.014	1.08E-02	4.23E-03	4.82E-03	0.032	0.025	0.019	1.54(a,e,f)
Arsenic	mg/L	0.00052	0.00052	0.00074	7.20E-04	2.81E-04	3.19E-04	0.00124	0.00080	0.00106	0.005(a,b,e)
Cadmium	mg/L	0.001	0.001	0.001	4.25E-07	1.66E-07	1.89E-07	**0.0010**	**0.0010**	**0.0010**	0.00004 – 0.00037(b,e)
Cobalt	mg/L	0.001	0.001	0.001	5.66E-05	2.21E-05	2.52E-05	**0.0011**	0.0010	0.0010	0.001(d)
Copper	mg/L	0.002	0.002	0.002	2.98E-06	1.17E-06	1.33E-06	0.0020	0.0020	0.0020	0.002 – 0.004(a)
Lead	mg/L	0.005	0.005	0.006	9.53E-07	3.73E-07	4.25E-07	**0.0050**	**0.0050**	**0.0060**	0.001(a)
Molybdenum	mg/L	0.005	0.005	0.005	4.90E-03	1.92E-03	2.19E-03	0.0099	0.0069	0.0072	0.073- 31(a,b,e)
Nickel	mg/L	0.003	0.003	0.003	5.12E-04	2.00E-04	2.03E-04	0.0035	0.0032	0.0032	0.025-0.15(a)
Selenium	mg/L	0.001	0.001	0.001	6.26E-06	2.45E-06	2.79E-06	0.0010	0.0010	0.0010	0.001(a)
Vanadium	mg/L	0.01	0.01	0.01	6.40E-06	2.50E-06	2.86E-06	0.010	0.010	0.010	-
Zinc	mg/L	0.006	0.006	0.006	9.71E-06	3.80E-06	4.33E-06	0.0060	0.0060	0.0060	0.030(a)
Polonium-210	Bq/L	0.008	0.008	0.006	6.07E-03	2.37E-03	1.98E-03	0.014	0.010	0.008	-
Lead-210	Bq/L	0.022	0.022	0.02	6.01E-03	2.35E-03	1.95E-03	0.028	0.024	0.022	-
Radium-226	Bq/L	0.005	0.005	0.006	6.37E-05	2.49E-05	2.20E-05	0.0051	0.0050	0.0060	0.11(b)
Thorium-230	Bq/L	0.012	0.012	0.013	8.50E-04	3.32E-04	3.68E-04	0.013	0.012	0.013	-
Uranium	mg/L	0.0006	0.0006	0.0006	3.63E-03	1.42E-03	1.62E-03	0.0042	0.0020	0.0022	0.015(a,b,e)

(a) SSWQO – Saskatchewan Surface Water Quality Objective for the Protection of Aquatic Life (Water Security Agency 2015)

(b) SEQG – Saskatchewan Environmental Quality Guidelines (GS: as reported on April 24, 2025)

(c) BC – British Columbia Water Quality Guideline (BCMOE 2025)

(d) FEQG – Federal Environmental Quality Guideline (EC 2017)

(e) CWQG – Canadian Water Quality Guidelines (CCME: as reported on April 24, 2025)

(f) Ammonia guidelines are temperature and pH dependent. Value shown for pH = 7.5 and temperature = 20oC

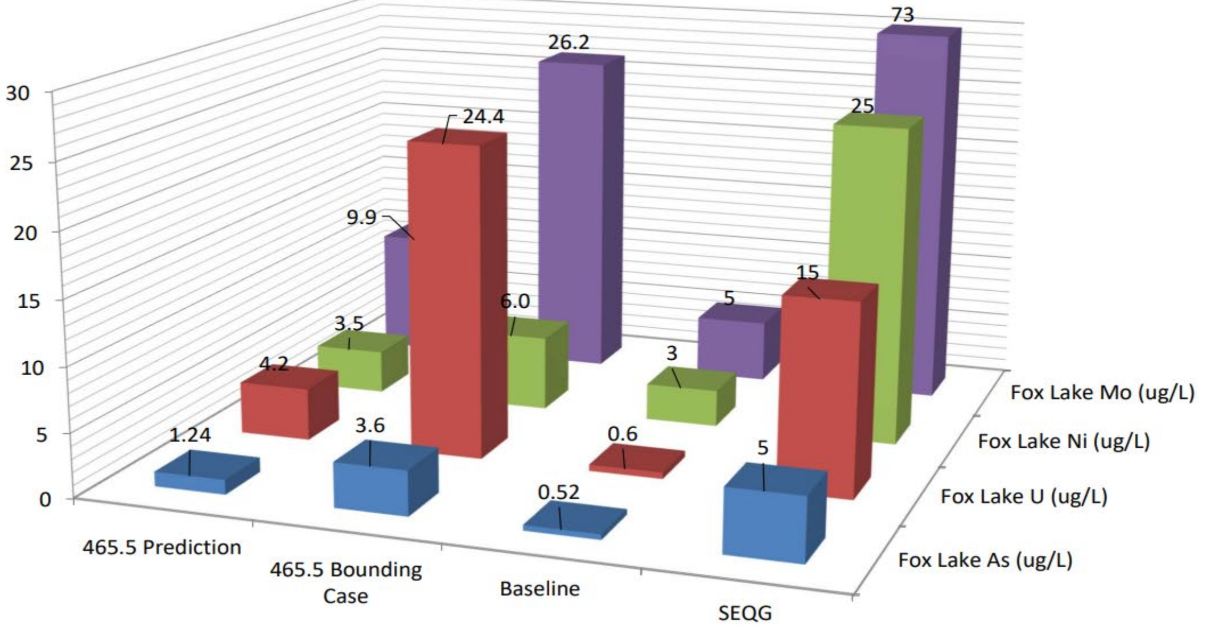
Bold indicates an exceedance of SEQG

mg/L = milligrams per litre; Bq/L = Becquerel per litre; CCME = Canadian Council of Ministers of the Environment; SEQG = Saskatchewan Environmental Quality Guidelines

Table 7.4-5: Expanded JEB TMF Upper Bound Receptor Surface Water Quality

Constituent	Units	Baseline Concentration			Incremental Concentration			Resulting Concentration			Water Quality Criteria
		Fox Lake North Basin	Fox Lake	Pat Lake	Fox Lake North Basin	Fox Lake	Pat Lake	Fox Lake North Basin	Fox Lake	Pat Lake	SEQG- Fresh Water Aquatic Life
Chloride	mg/L	0.133	0.133	0.12	2.07E-01	8.08E-02	9.22E-02	0.34	0.21	0.21	120 (b,e)
Sulfate	mg/L	0.633	0.633	0.71	6.19E+00	2.42E+00	2.76E+00	6.82	3.05	3.47	128-429(c)
Ammonia	mg/L	0.021	0.021	0.014	5.17E-02	2.02E-02	2.31E-02	0.073	0.041	0.037	1.54(a,e,f)
Arsenic	mg/L	0.00052	0.00052	0.00074	3.06E-03	1.20E-03	1.35E-03	0.00358	0.00172	0.00209	0.005(a,b,e)
Cadmium	mg/L	0.001	0.001	0.001	1.99E-06	7.76E-07	8.85E-07	**0.0010**	**0.0010**	**0.0010**	0.00004 – 0.00037(b,e)
Cobalt	mg/L	0.001	0.001	0.001	4.69E-04	1.83E-04	2.09E-04	**0.0015**	**0.0012**	**0.0012**	0.001(d)
Copper	mg/L	0.002	0.002	0.002	2.29E-05	8.94E-06	1.02E-05	0.0020	0.0020	0.0020	0.002 – 0.004(a)
Lead	mg/L	0.005	0.005	0.006	1.27E-05	4.96E-06	5.66E-06	**0.0050**	**0.0050**	**0.0060**	0.001(a)
Molybdenum	mg/L	0.005	0.005	0.005	2.12E-02	8.27E-03	9.43E-03	0.0262	0.0133	0.0144	0.073- 31(a,b,e)
Nickel	mg/L	0.003	0.003	0.003	2.96E-03	1.16E-03	1.17E-03	0.0060	0.0042	0.0042	0.025-0.15(a)
Selenium	mg/L	0.001	0.001	0.001	5.46E-05	2.13E-05	2.43E-05	**0.0011**	0.0010	0.0010	0.001(a)
Vanadium	mg/L	0.01	0.01	0.01	5.77E-05	2.25E-05	2.57E-05	0.010	0.010	0.010	-
Zinc	mg/L	0.006	0.006	0.006	2.27E-04	8.87E-05	1.01E-04	0.0062	0.0061	0.0061	0.030(a)
Polonium-210	Bq/L	0.008	0.008	0.006	2.29E-02	8.94E-03	7.29E-03	0.031	0.017	0.013	-
Lead-210	Bq/L	0.022	0.022	0.02	2.27E-02	8.86E-03	7.21E-03	0.045	0.031	0.027	-
Radium-226	Bq/L	0.005	0.005	0.006	2.24E-04	8.74E-05	7.42E-05	0.0052	0.0051	0.0061	0.11(b)
Thorium-230	Bq/L	0.012	0.012	0.013	1.81E-03	7.07E-04	7.82E-04	0.014	0.013	0.014	-
Uranium	mg/L	0.0006	0.0006	0.0006	2.38E-02	9.32E-03	1.06E-02	**0.0244**	0.0099	0.0112	0.015(a,b,e)

(a) SSWQO – Saskatchewan Surface Water Quality Objective for the Protection of Aquatic Life (Water Security Agency 2015)
(b) SEQG – Saskatchewan Environmental Quality Guidelines (GS: as reported on April 24, 2025)
(c) BC – British Columbia Water Quality Guideline (BCMOE 2025)
(d) FEQG – Federal Environmental Quality Guideline (EC 2017)
(e) CWQG – Canadian Water Quality Guidelines (CCME: as reported on April 24, 2025)
(f) Ammonia guidelines are temperature and pH dependent. Value shown for pH = 7.5 and temperature = 20oC
Bold indicates an exceedance of SEQG
mg/L = milligrams per litre; Bq/L = Becquerel per litre; CCME = Canadian Council of Ministers of the Environment; SEQG = Saskatchewan Environmental Quality Guidelines



	465.5 Prediction	465.5 Bounding Case	Baseline	SEQG
🟦 Fox Lake As (ug/L)	1.24	3.6	0.52	5
🟥 Fox Lake U (ug/L)	4.2	24.4	0.6	15
🟩 Fox Lake Ni (ug/L)	3.5	6.0	3	25
🟪 Fox Lake Mo (ug/L)	9.9	26.2	5	73

Figure 7.4-3: Predicted and Bounding Case Long Term Effects to Fox Lake

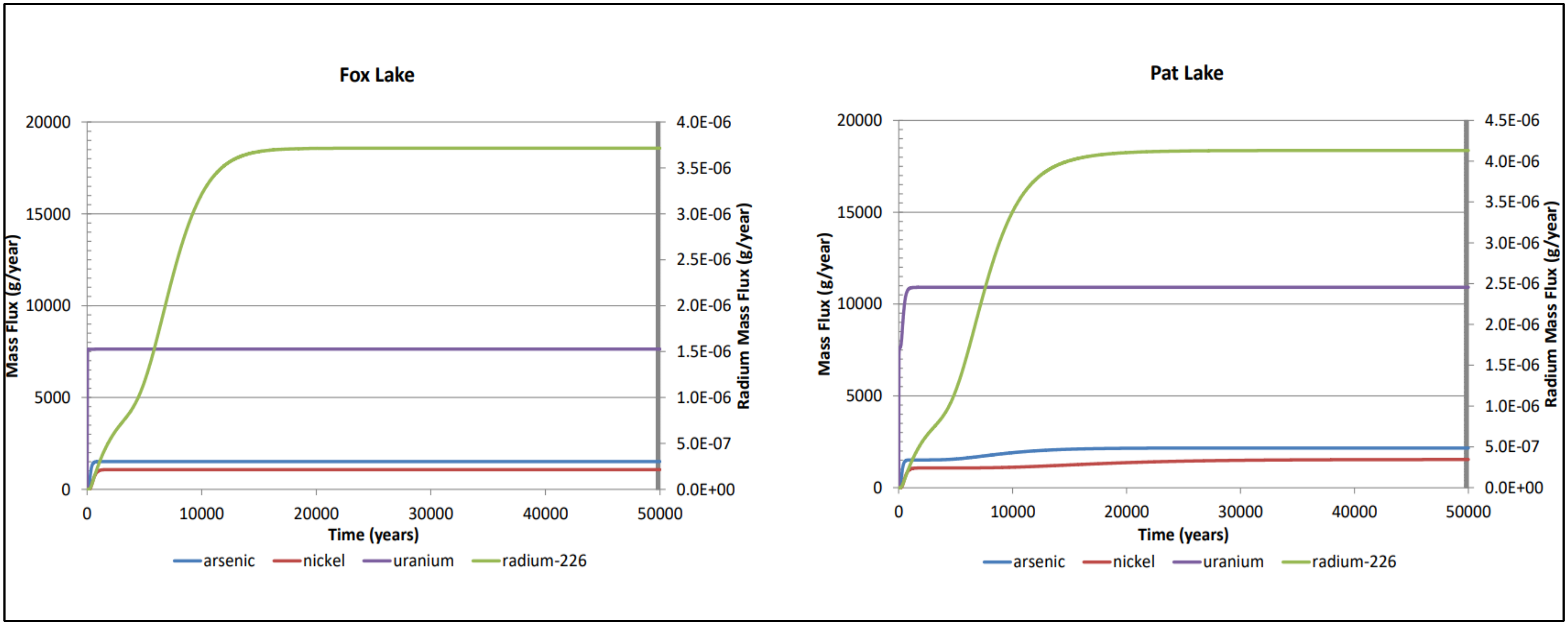


Figure 7.4-4: Mass Flux to Receptors vs Time

7.5 Summary and Conclusions

7.5.1 Validation of Hydraulic Containment

The updated model was used to complete predictive simulations of the 468 Expansion and to predict solute transport pathways from the TMF following mine closure. For full build 468 Expansion (tailings elevation of 465.5 mASL and ≤467 mASL TMF pond elevation), hydraulic containment was maintained in each sensitivity scenario if the base drain elevation is maintained 8 m or more below the Fox Lake elevation.

7.5.2 Validation of TMF Performance Predictions

The key monitoring data that support hydraulic containment continues to be water elevation data used for head differential determination; therefore, the JEB TMF pond, Fox Lake and drift monitoring well water elevations will continue to be monitored regularly to validate these inputs. Discharge from the TMF following mine closure is predicted to migrate east and south towards Fox and Pat Lake. In general, the volume of discharge from the TMF is mainly derived from the net percolation of precipitation through the low permeability cover with a small component from groundwater inflow. Approximately 68% of the TMF flow discharges to Fox Lake and 32% discharges to Pat Lake.

Arsenic and uranium appear to be the most sensitive constituents (Figure 7.4-3) with predictions approaching 28% of objective values and upper bound values approaching 72% of the surface water arsenic guideline and exceeding the surface water uranium guideline. The uranium upper bound was calculated using an extremely conservative 95th percentile case which excluded no outlier data. This approach conservatively included a small number of elevated uranium pore water values that increased the upper bound calculation over past predictions but are not anticipated to be representative of the long-term uranium pore water concentrations. Aging effects on uranium pore water values are discussed in detail in Section 5.5.3. Predicted long-term cadmium, cobalt, lead and selenium concentrations exceed surface water quality guidelines because they reflect baseline concentration values and are not due to mass loading from the TMF.

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8 Conclusions, Compliance, and Recommendations

8.1 Conclusions

The Tailings Management Technical Information Document (Tailings Management TID) provides a comprehensive, current understanding of the design, operation, and future decommissioning of the JEB Tailings Management Facility (JEB TMF) at the McClean Lake Operation. The design and operational features of the TMF have been assessed and validated through routine monitoring programs and technical studies, most notably the Tailings Optimization and Validation Program (TOVP).

The goal of the TOVP is to optimize and validate long term performance of the tailings management system at the McClean Lake Operation. The decommissioned end state of the TMF and long-term environmental performance rely on the establishment of geochemical and geotechnical passive controls, which will control contaminant transport in the long term.

The TOVP results contained in this document represent the fifth five-year major review of tailings performance since 2004. The field program conducted in 2023/2024 provided the second opportunity to validate the performance of placed Cigar Lake tailings, and the first opportunity to observe how they have aged once placed.

Principle conclusions related to the overall performance of tailings are summarized below:

- **Geochemical Validation**
  - From initial start-up in 1999 to the present, the performance of the tailings preparation process (TPP) has consistently demonstrated compliance with applicable Action Levels for tailings pore water quality at the point of discharge from the mill (Figure 2.2-1).
  - During the past five years, the results of various laboratory investigations have continued to provide evidence for the presence and identification of chemical/mineral phases containing COPCs produced by the TPP.
  - Monitoring and subsequent studies of placed tailings within the JEB TMF have yielded results that further delineate geochemical tailings aging characteristics and demonstrate compliance with Action Levels set for concentrations of arsenic in the placed tailings pore water:
    - Arsenic (As) long term pore water values will be controlled to < 2 mg/L through the precipitation of the mineral scorodite. Current elevated As pore water values are temporary and reflect the incomplete process of oxidizing primary arsenic mineralization still in progress in the tailings.
    - Molybdenum (Mo) long term pore water values will be controlled to < 8 mg/L through the precipitation of the mineral powellite. Current elevated Mo pore water values are temporary

    and reflect the dissolution of an unstable Mo phase created in the mill. Mo is liberated into solution which is then sequestered as powellite.

    - Uranium (U) long term pore water values will be controlled to < 8.5 mg/L through the precipitation of carbonate minerals. Current elevated U pore water values reflect U complexation with bicarbonate (HCO_3^-). HCO_3^- is liberated as hydrocarbons in the tailings are oxidized, and pore water values of HCO_3^- will decline as all the hydrocarbons are consumed. In tailings deposited above 400 mASL, hydrogen peroxide was added to oxidize the bulk of the hydrocarbons so that excess HCO_3^- will not develop.

  - On-going areas of monitoring and study involve the understanding of the long-term geochemical evolution of nickel, lead, copper and radium-226 in the tailings pore water.

- **Geotechnical Validation**

  - Geotechnical studies have confirmed that the tailings placed at the edges of the TMF are predominantly fine grained, allowing for tailings to consolidate sufficiently to provide a hydraulic conductivity contrast to the surrounding sandstone that enables preferential flow of groundwater around the decommissioned facility.

  - A new initiative has begun to build a Bayesian graphical probabilistic network to quantify site-specific correlations between tailings geotechnical properties. This model uses the gathered TOVP geotechnical data to understand the relationships between various properties of the tailings in the JEB TMF. Using a Bayesian network will allow for the inference of criteria that are generally more difficult to evaluate based on simpler, more available tests. This work will leverage the tailings geotechnical data to build a stronger ongoing understanding of the evolution of the geotechnical properties of the tailings while allowing for more targeted sampling programs in the future.

  - During the 2023/2024 TOVP sampling campaign, for the first time, obtaining tailings samples from the full depth of the TMF was not possible at some locations. This difficulty reflects the changing, more consolidated nature of the tailings. Based on this experience new methods of sampling will be investigated to be applied to the 2028 TOVP sampling campaign to reach the full depth of the tailings.

- **Contaminant Transport Modelling**

  - The long-term environmental effects of tailings placement are continually assessed through an iterative process, using measured in-situ data from the TOVP and numerical models. The most recent assessment in this document validates that surface water quality objectives downstream of the TMF will be achieved over the long term.

The above conclusions, in conjunction with the prediction of long-term environmental effects, demonstrate that the design and operation of the TPP and the TMF are validated with respect to protection of the receiving environment.

8.2 Compliance with Licence Requirements

8.2.1 Overview

The following section discusses compliance with licence requirements over the last reporting period (2020-2025). Key performance and compliance indicators are discussed in Section 2.2, along with a summary of historical performance.

8.2.2 Properties of Production Tailings

The compliance objectives associated with production tailings are outlined in Section 2.2.1.1. (Table 2.2-2) Action Levels are applied to the as-discharged tailings pore water concentration for arsenic.

As shown in Figure 2.2-1, the arsenic concentrations in tailings pore water have consistently been maintained within Action Levels identified in the McClean Lake Operation's Environmental Protection Code of Practice (Orano 2023), including this reporting period.

In 2015, the McClean Lake Operation began continuously processing Cigar Lake ore exclusively, and in 2017 the expanded Tailings Preparation Process was commissioned. Table 8.2-1 presents an evaluation of the performance of the old and new TPPs while processing Cigar Lake ore. Administrative Levels have not been exceeded using both facilities.

Table 8.2-1: Evaluation of Administrative Level Compliance in the Original and Expanded TPPs While Processing Cigar Lake Ore

Parameter (Units)	Administrative Level	Original TPP	Expanded TPP	
	Daily Composite	Ave. Daily Composite (April 2015 – March 2017)	Ave. Daily Composite (April 2017 – March 2019)	Ave. Daily Composite (April 2019 – March 2024)
Arsenic (mg/L)	1.0	0.20	0.41	0.607
Nickel (mg/L)	1.0	0.07	0.10	0.612
pH	7.5<pH<8.5	7.75	7.85	8.00
Radium-226 (Bq/L)	200	14.0	9.55	7.70
Density (% solids)	25<% solids	24.6	24.7	22.4

8.2.3 TMF Hydrodynamic Containment

The compliance objectives associated with hydrodynamic containment are outlined in Section 2.2.2 and Table 2.2-3.

Hydraulic containment is assessed in each McClean Lake quarterly and annual report. The assessments completed over this reporting period (2020-2025) have determined that head differentials were consistently above the minimum head differential Action Levels, indicating that hydraulic containment was maintained.

8.2.4 TMF In-Situ Tailings Pore Water

Since the McClean Lake Operation received its initial licence in 1999, the TOVP has been the mechanism to confirm contaminant transport assumptions and evaluate model uncertainties, with arsenic as the primary contaminant of concern. Administrative and Action Levels have been established for concentrations of soluble arsenic in tailings pore water, to ensure acceptable long term source concentrations.

In conjunction with iterative evaluation of the evolution of arsenic pore water concentrations in the placed tailings, and the evolution of the groundwater flow and contaminant transport framework, the in-situ tailings arsenic pore water Action Levels have also evolved over the previous reporting period (2015-2020) as described below. No further revisions are proposed for the current reporting period (2020-2025).

8.2.4.1 2017 Revisions

Prior to 2017, the TOVP Document served as the authoritative document regarding the compliance and licensing requirements for in-situ tailings pore water quality (Section 2.1.1). In 2017, the TOVP Document was removed from the list of licensing basis documents, going forward long-term tailings pore water quality requirements will be defined and evaluated within this section of the Tailings Management TID, which is the authoritative document regarding tailings within the licensing basis documents identified in the McClean Lake Operation Licence Conditions Handbook.

8.2.4.2 2020 Revisions

Building upon the historical timeline described in Section 2.2.4.1 for arsenic pore water Action Levels, the following occurred during the 2015-2020 reporting period and the preparation of the 2020 Tailings Management TID:

- Source terms were determined separately for JEB/Sue and Cigar Lake tailings, to account for the notably different mineralogy of the Cigar Lake ore and the recent upgrades to the McClean Lake Mill. This was part of a continual improvement initiative to improve accuracy in the source term for contaminant transport modelling.

- The previously calculated Tier 2 Action Level for arsenic (20 mg/L) was updated to reflect the currently approved case in the licensing basis with top of consolidated tailings at an elevation of 448 mASL. The Tier 2 Action Level was recalculated using the groundwater and contaminant transport model described in Orano 2020, Section 7 and the same methodology as previously used in 1999 and 2010 (Section 2.2.4.1). The resulting value is 7 mg/L and is tied to the achievement of SEQGs in Fox Lake north basin. The recalculated value reflects the overall average of all tailings placed in the TMF, including JEB/Sue and Cigar Lake, considering the approved top of consolidated tailings at an elevation of 448 mASL.

- The calculation is made using the following conservative assumptions:

  - The resulting concentration of arsenic in the lake is calculated assuming a fully mixed lake, and

  - The tailings source term is assumed to be steady-state (i.e. non-depleting source), meaning that the peak concentration is sustained rather than declining to background (as will occur when mass is depleted over time).

- The Tier 1 Action Level of 5 mg/L for arsenic was maintained and approximates the calculated “All Tailings” arsenic pore water value for JEB/Sue of 4.55 mg/L in the 2020 Tailings Management TID (Table 8.2-2). The “All Tailings” value does not reflect modified tailings inputs and adaptive management process controls that were implemented in response to the observed arsenic pore water evolution in placed Sue C tailings (Section 2.2.4.1; Section 5.5.1.3). The TOVP arsenic program, described in Section 5.5.1, outlines the success of mill optimizations implemented in 2004 in response to the monitoring results of Sue C placed tails. The “All Tailings” value therefore represents an upper bound of performance that has not been observed above the Sue C tailings horizon. The value of 4.55 mg/L was the upper bound case modelled in contaminant transport modelling as the overall average of JEB/Sue tailings.

8.2.4.3 Compliance in the Current Reporting Period (2020-2025)

Table 8.2-2 shows the evolution of TMF pore water compliance and license requirements over time, with the inclusion of data from this reporting period (2020-2025). The measured pore water values of arsenic from the 2023 TOVP sampling campaign are reported as follows:

- **JEB/Sue tailings**: When considering the “All Tailings” the Jeb/SUE tailings arsenic pore water values fall below the Tier 1 Action Level (2.98 mg). When considering the Jeb/SUE tailings after the modification of tailings input in the adaptive management process the arsenic pore water values fall below the Administrative Level (1.27 mg/).
- **Cigar Lake Tailings**: The Cigar Lake tailings weighted average arsenic pore water values fall below the administrative level (0.76 mg/L).

Table 8.2-2: Summary of TMF Pore Water Compliance and Licence Requirements (1999 to Present)[1]

Authoritative Program Document	TOVP Validation Report	Average Weighted Pore Water Concentration As (mg/L)			Administrative Level[2] As (mg/L)	Tier 1 Action Level[3] As (mg/L)	Tier 2 Action Level[4] As (mg/L)
		All Tailings[8]		Modified tailings inputs, adaptive management process controls[9]			
TOVP Program Document/Validation Reports (1999-2015)							
TOVP Rev. 2, March 1999[5]	September 2005	4.3		1.5	n/a	**2**	**5**
TOVP Rev. 3, July 2007	April 2011	3.8		1.9	n/a	**2**	5
TOVP Rev 4, October 2010[6]	n/a	n/a		n/a	**2**	**5**	**20**
Tailings Management TID (2015-Present)							
May 2015		4.38		2.37	**2**	**5**	**20**
		J/S[10]	**CL[11]**	**J/S[10]**	▨	▨	▨
May 2020[7]		4.55	0.28	1.69	**2**	**5 [12]**	**7 [13]**
November 2025		2.98	**0.76**	**1.27**			

1. Administration Level, Tier 1 Action Level, and Tier 2 Action Level are currently applied following each 5-year TMF in-situ sampling campaign in the Tailings Management TID. Prior to 2017, the levels were applied in the TOVP Validation Report/Program Document.
2. Administration Level, if exceeded, requires an internal investigation and remedial action plan. An Administrative Level was established in 2010.
3. Tier 1 Action Levels (referred to as “Action Level” prior to 2010), if exceeded, require regulatory agency notification together with submission of a remedial action plan.
4. Tier 2 Action Level (referred to as “Limit” prior to 2010), if exceeded, requires suspension of mill production activities until such time as the remedial action plan has received regulatory agency approval and all steps required by Orano have been completed.
5. TOVP Rev. 1 document was revised prior to mill start-up.
6. The submission of the 2010 Program Document did not coincide with a TOVP Validation Report; therefore, an average pore water concentration was not presented at that time.
7. Authoritative document currently in force in the licensing basis, to be replaced by this submission.
8. All tailings results included in average with outliers included beginning for 2025.
9. When higher arsenic source terms were first identified, an interim source term was adopted considering 3 years of tailings aging based on preliminary aging tests which indicated that arsenic pore water values would decrease over time.
10. JEB/Sue tailings – the modified tailings inputs/adaptive management process controls value of 1.27 mg/L is the value compared to compliance requirements.
11. Cigar Lake tailings – modified tailings inputs/adaptive management process controls apply only to JEB/Sue; therefore, the “All Tailings” value of 0.76 mg/L is the value compared to compliance requirements.
12. Reflects the “All Tailings” value for JEB/Sue of 2.98 mg/L, prior to the implementation of process controls –upper bound in the contaminant transport model.
13. Reflects the overall average of all tailings placed in the TMF in the 457.5 mASL expansion case, to meet SEQGs in Fox Lake north basin with conservative assumptions.

8.2.4.4 Summary of Performance

Taking aging effects into account, and considering mitigative measures to minimize potential effects, arsenic pore water concentrations are consistent with the McClean Lake Operation licensing requirements. Based on monitoring and modelling to date, long term tailings arsenic pore water concentrations continue to be consistent with the range predicted during pre-operational laboratory test work.

The current understanding of arsenic geochemistry explains TOVP observations and provides confidence in the mechanisms for long term passive control of arsenic concentrations in pore water. Research will continue into aging effects and validation of the arsenic geochemical model to further support understanding, in addition to advancing knowledge for other key COPCs. Guided by the TOVP, Orano will continue to consider optimizations to mill processes while maintaining downstream performance that is protective of the environment.

8.3 Recommendations

8.3.1 Monitoring

In accordance with *CSA Standard 288.4-19 – Environmental Monitoring Programs at Nuclear Facilities and Uranium Mines and Mills* (CSA 2019), the Tailings Management TID was used as an opportunity to evaluate the effectiveness of current monitoring related to tailings performance.

8.3.1.1 Properties of Production Tailings

No changes are identified at this time. Samples of pore water in as-discharged tailings will continue to be collected and analyzed.

8.3.1.2 TMF Hydrodynamic Containment

Operational Period

The most recent changes to monitoring of the TMF hydrodynamic containment are described in section 2.2.2 and included in the ECOP (Version 4, Orano 2023). In the future, as tailings and water elevations increase in accordance with the JEB TMF Optimization and Expansion projects, monitoring will be reviewed and revised as needed for the validation of hydraulic containment.

Post Decommissioning Controls

Operational controls are in place to ensure the placement of fine-grained tailings at the edges of the TMF. The current placement of fine-grained tailings ensures an appropriate post-closure hydraulic contrast is maintained between the tailings and the host rock. No changes are identified at this time.

8.3.1.3 In-Situ Tailings Properties (TOVP)

Sampling Frequency: The sampling program provided sufficient understanding and analysis and met the needs of the tailings geochemical and geotechnical programs. There is no change at this time to the 5-year sampling frequency of the TOVP.

Sampling Methodology: Sampling methodology will be reviewed for the 2028 TOVP campaign to consider different drilling and/or sampling methods to enable the sampling of the lowest most consolidated tailings. As the tailings further consolidated it will also be contemplated that sampling of the lower tailings may become increasingly difficult.

Number of Sampling Locations: The understanding that the lower tailings may become increasingly difficult to access can be balanced by improving the understanding of the properties of the Cigar Lake tailings. The Cigar Lake tailings will have an ever-increasing influence over in the definition of the source term as their volume increases. For the 2028 TOVP sampling campaign additional sampling locations will be proposed to sample only the Cigar Lake tailings.

Dredge Sampling: Dredge sampling to inform assessments of tailings segregation will continue to occur annually or semi-annually, coinciding with tailings deposition point moves. The placement of fine-grained tailings at the edges of the TMF will continue to be validated in consideration of the new subaqueous placement system and preliminary geotechnical results for Cigar Lake tailings.

8.3.1.4 Tailings Placement Elevation

No changes are identified at this time. Tailings surface surveys and routine depth measurements at deposition points will continue.

8.3.1.5 Geotechnical Inspections

The TMF Expansion embankment is be monitored for geotechnical stability and inspected on a routine basis. The requirements for stability monitoring were established in accordance with industry best practices and guidelines and governed by the Tailings Operation, Maintenance and Surveillance manual.

8.3.2 Administrative and Action Levels

The compliance indicators for 1) production tailings and hydrodynamic containment as presented in the McClean Lake Operation's Environmental Protection Code of Practice (ECOP, Orano 2023); and 2) in-situ tailings pore water as presented in this document were reviewed in order to identify if changes were required.

8.3.2.1 Properties of Production Tailings (ECOP)

Administrative Levels: No changes at this time.

Action Levels: No changes at this time.

8.3.2.2 TMF Hydrodynamic Containment (ECOP)

Administrative Levels: No changes at this time.

Action Levels: No changes at this time.

8.3.2.3 In-Situ Tailings Properties (TOVP/Tailings Management TID)

Administrative Level: No changes at this time.

Action Levels: Arsenic Tier 1 – No proposed change; Arsenic Tier 2 – No proposed change.

Future adjustments to the Action Levels will reflect a level of conservatism that is commensurate with remaining uncertainties. In the interim, the previous conservative approach is maintained.

Through a long history of sampling, research, and monitoring, the long-term behaviour of arsenic in the TMF is well understood and proactively managed. Assessments of pore water compliance will continue to be conducted on a five-year frequency in the Tailings Management TID, and operational controls will be continually validated and optimized to ensure tailings performance that is protective of the environment in the long-term.

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