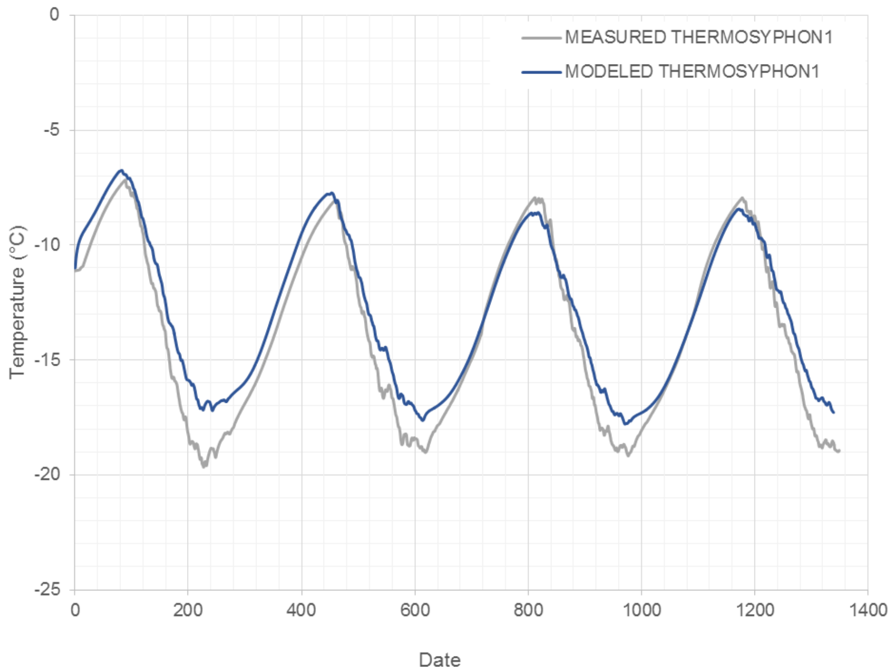
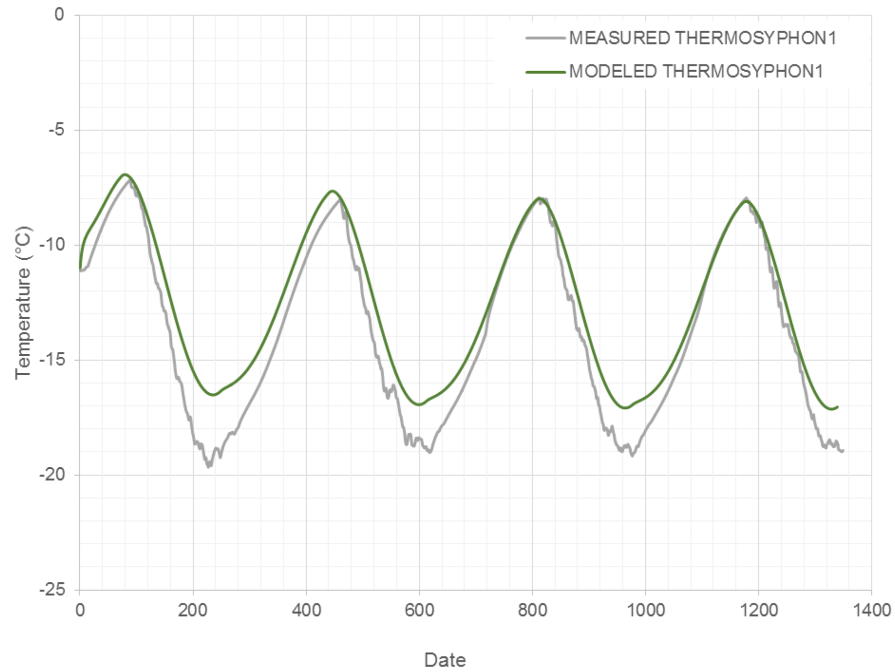
Model 1: Measured Air Temperature and Wind Speed



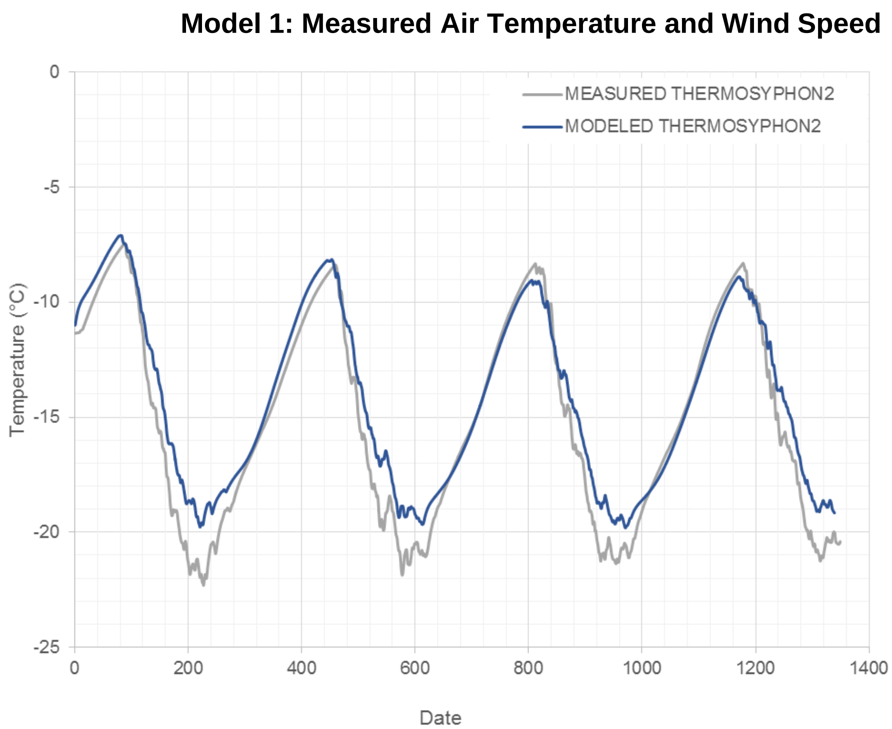
Model 2: Climate Boundary with Average Wind Speed

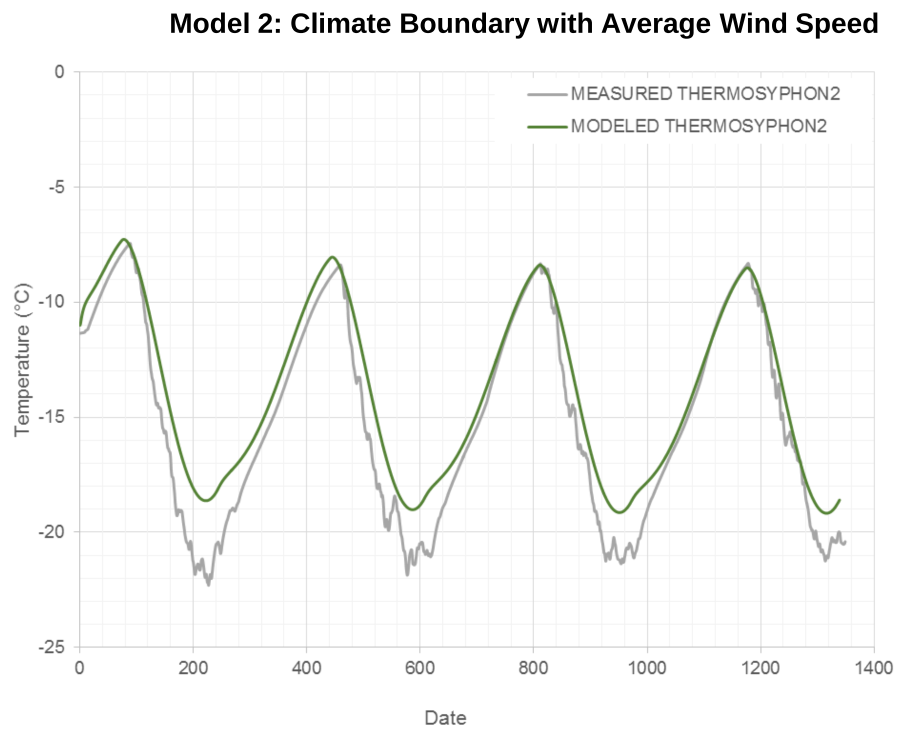


Notes:

1. Ground temperature measurements from thermistor string ND-HTS-040-31.5
2. Thermistor node located near thermosyphon evaporator 1, Dam Section 0+40

srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	**Model Calibration – Thermosyphon Evaporator 1 (0+40)**
		Date: 5/2/2016 · Approved: cws · Figure: **26**



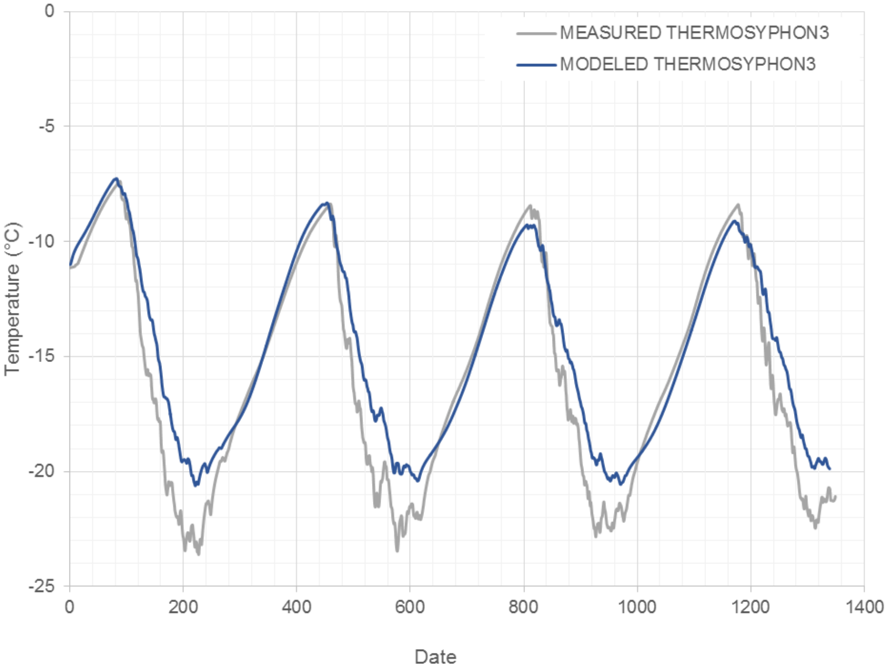


Notes:

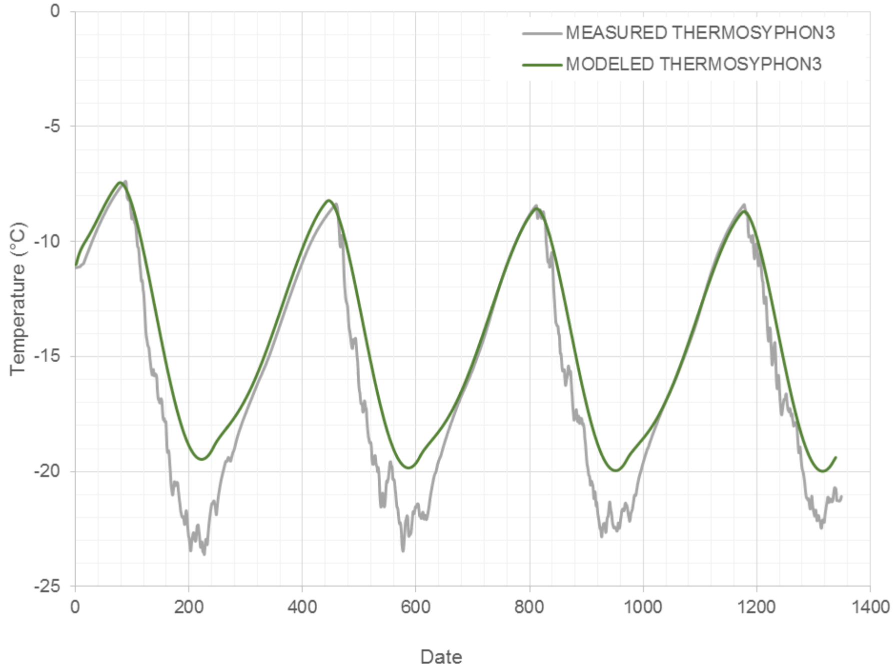
1. Ground temperature measurements from thermistor string ND-HTS-040-31.5
2. Thermistor node located near thermosyphon evaporator 2, Dam Section 0+40

srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling **Model Calibration – Thermosyphon Evaporator 2 (0+40)**
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 · Approved: cws · Figure: **27**

Model 1: Measured Air Temperature and Wind Speed



Model 2: Climate Boundary with Average Wind Speed

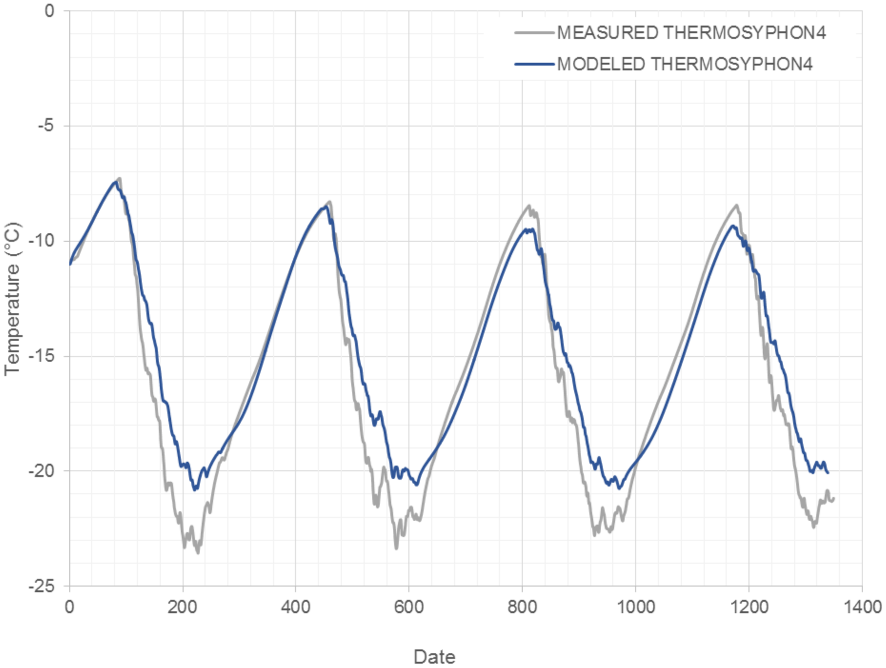


Notes:

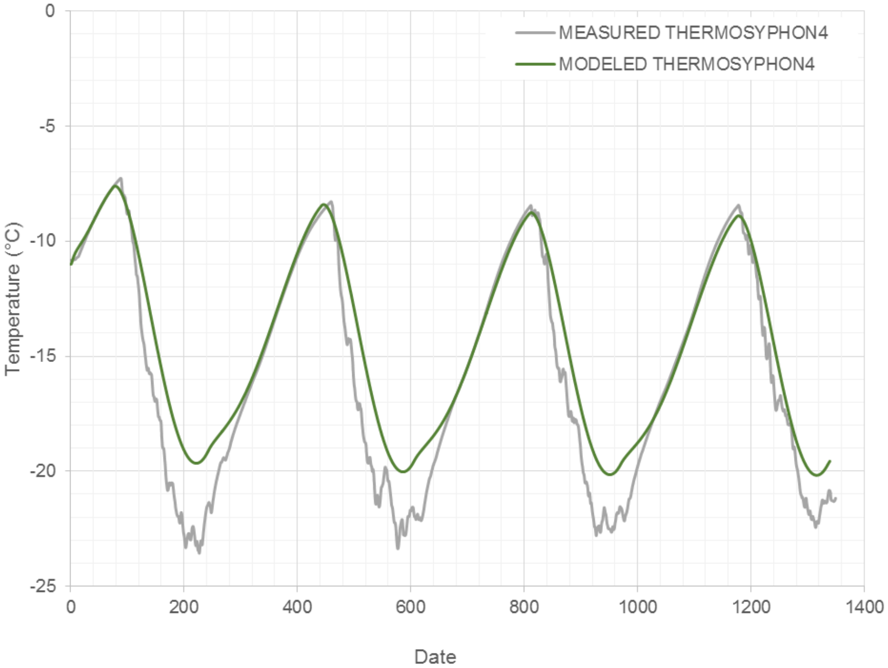
1. Ground temperature measurements from thermistor string ND-HTS-040-31.5
2. Thermistor node located near thermosyphon evaporator 3, Dam Section 0+40

srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling **Model Calibration – Thermosyphon Evaporator 3 (0+40)**
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 · Approved: cws · Figure: **28**

Model 1: Measured Air Temperature and Wind Speed



Model 2: Climate Boundary with Average Wind Speed

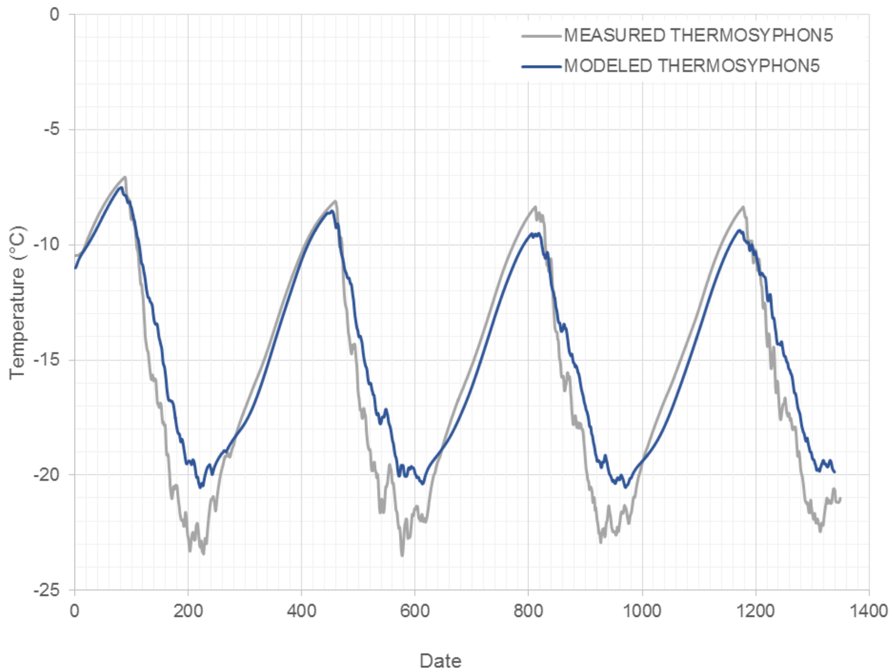


Notes:

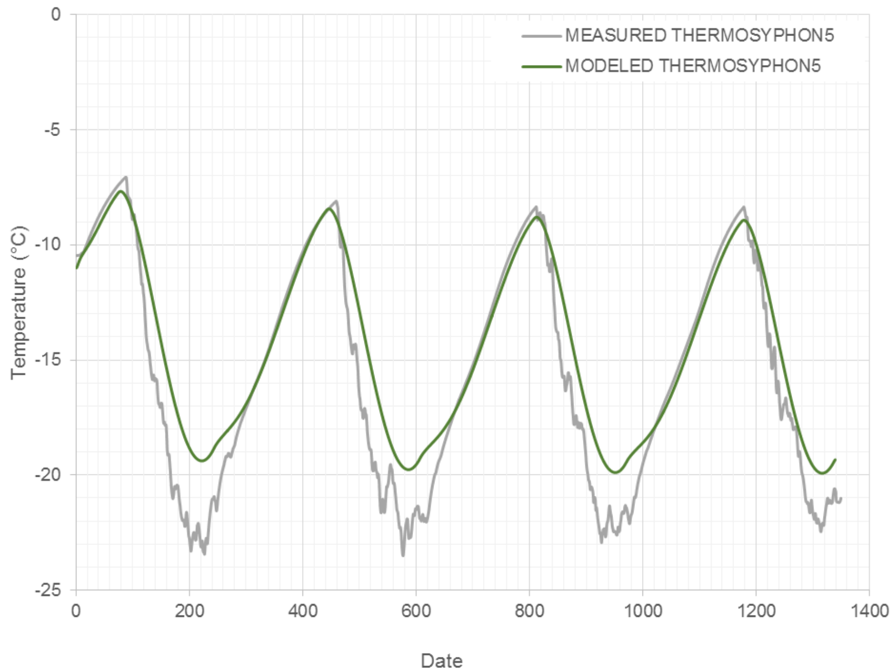
1. Ground temperature measurements from thermistor string ND-HTS-040-31.5
2. Thermistor node located near thermosyphon evaporator 4, Dam Section 0+40

srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling
		Model Calibration – Thermosyphon Evaporator 4 (0+40)
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 · Approved: cws · Figure: **29**

Model 1: Measured Air Temperature and Wind Speed



Model 2: Climate Boundary with Average Wind Speed

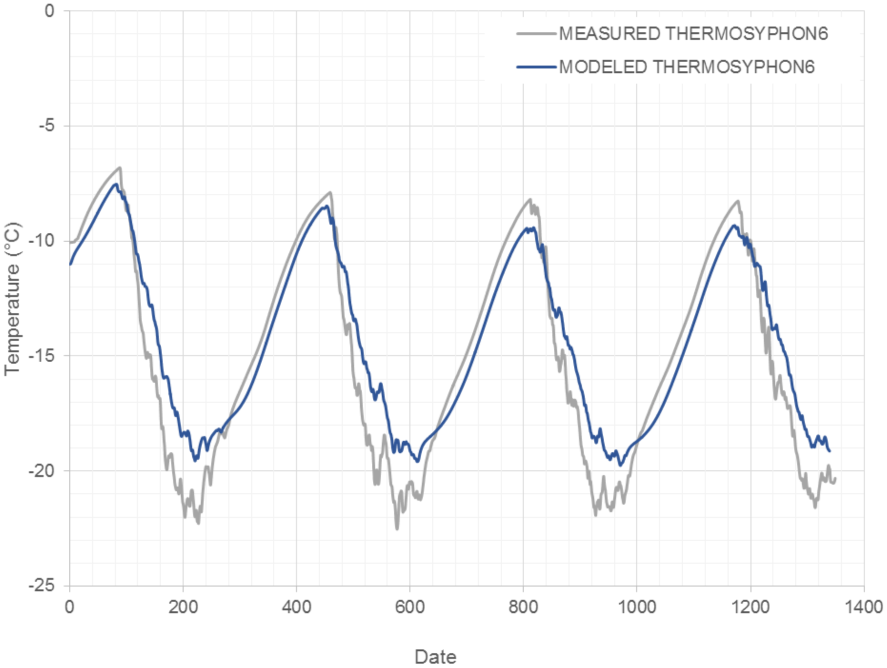


Notes:

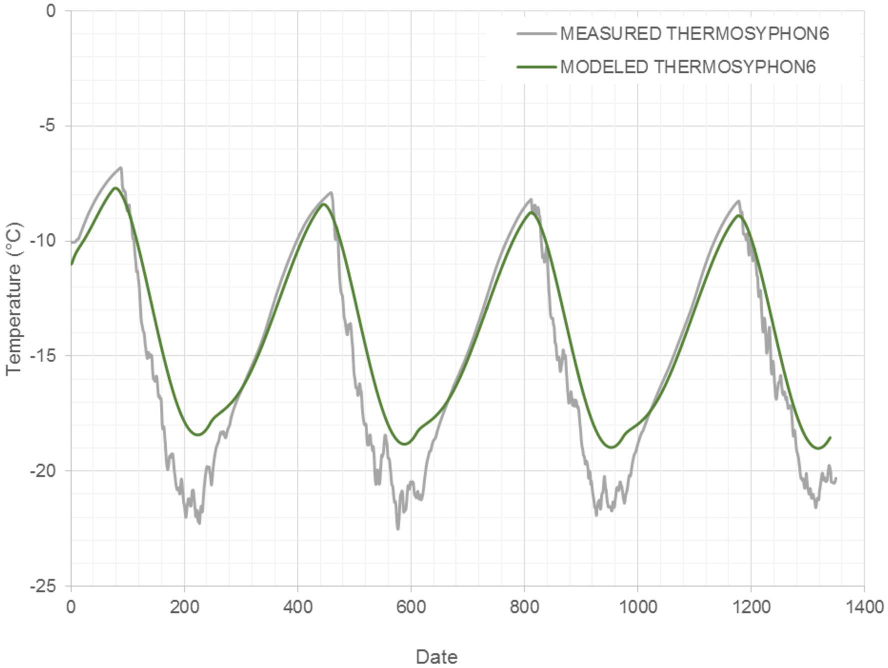
1. Ground temperature measurements from thermistor string ND-HTS-040-31.5
2. Thermistor node located near thermosyphon evaporator 5, Dam Section 0+40

srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling
		Model Calibration – Thermosyphon Evaporator 5 (0+40)
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 · Approved: cws · Figure: **30**

Model 1: Measured Air Temperature and Wind Speed



Model 2: Climate Boundary with Average Wind Speed

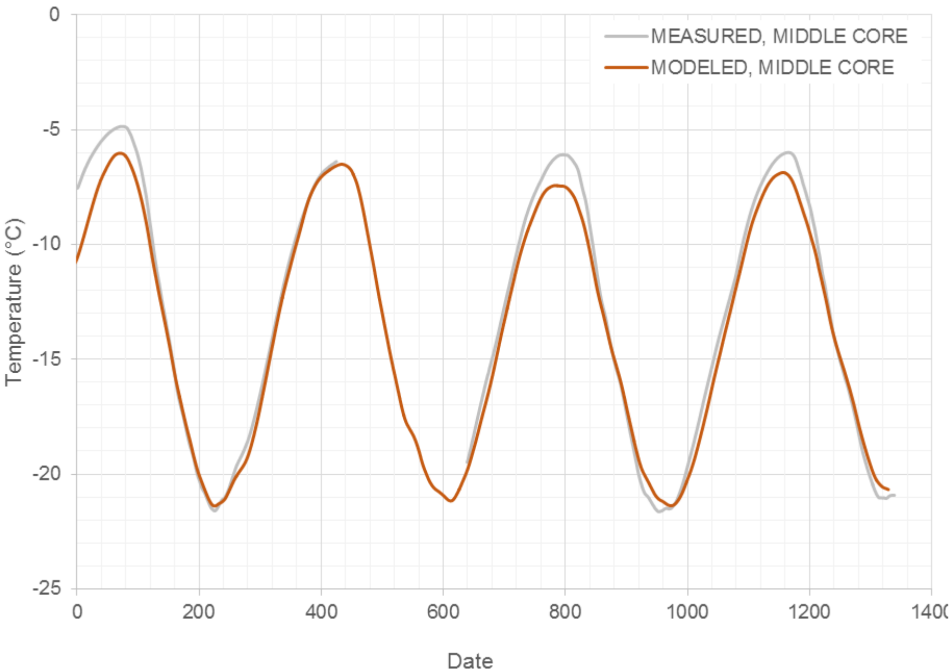


Notes:

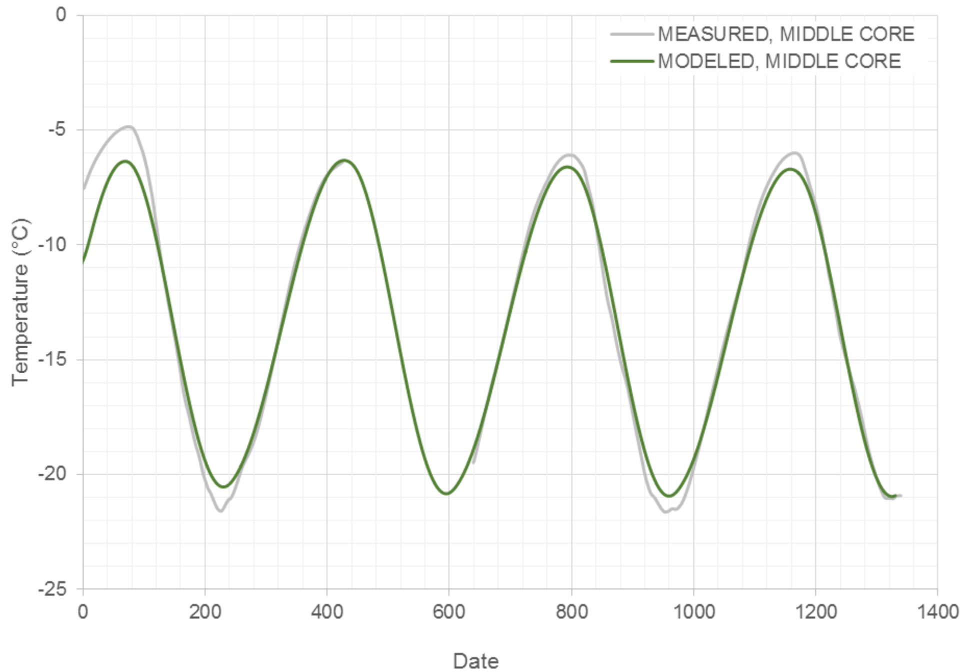
1. Ground temperature measurements from thermistor string ND-HTS-040-31.5
2. Thermistor node located near thermosyphon evaporator 6, Dam Section 0+40

srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling
		Model Calibration – Thermosyphon Evaporator 6 (0+40)
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 | Approved: cws | Figure: **31**

Model 1: Measured Air Temperature and Wind Speed



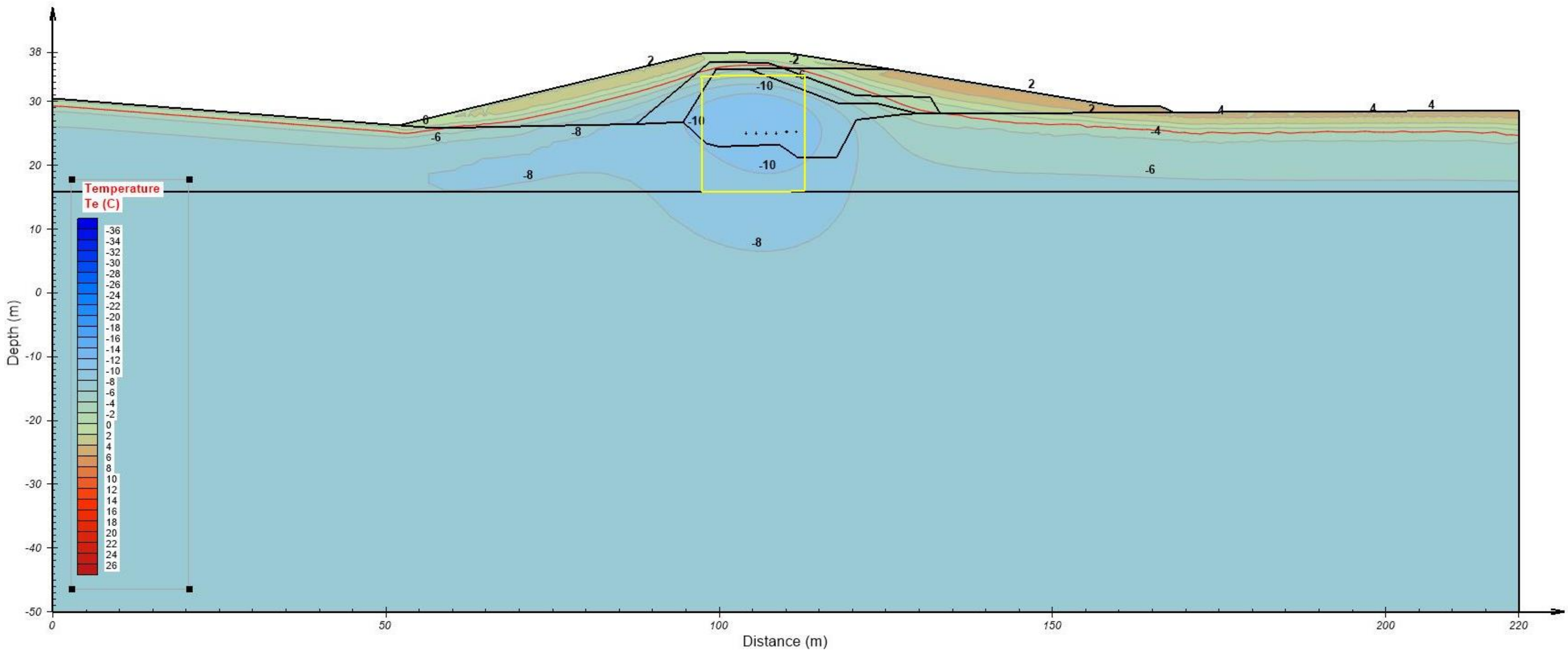
Model 2: Climate Boundary with Average Wind Speed



Notes:

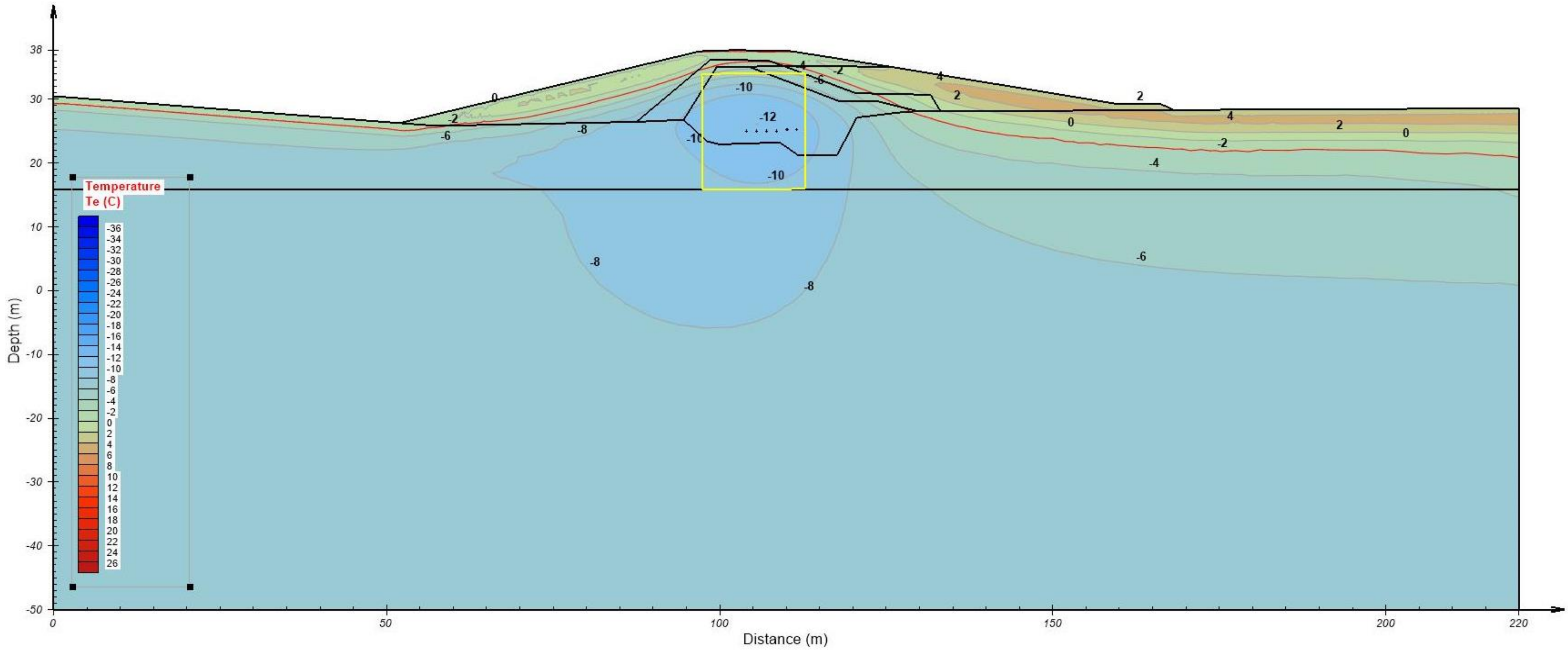
1. Ground temperature measurements from thermistor string ND-HTS-040-33.5
2. Thermistor string is located near the middle of the frozen core, Dam Section 0+40

srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling
		Model Calibration – Middle Core (0+40)
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 · Approved: cws · Figure: **32**



Notes:
1. Model results for year 2, maximum position of -2°C isotherm
2. Yellow bounding box indicates critical section based on thermal design criteria
3. Dam Section 0+85 with clay foundation
4. Five working thermosyphons

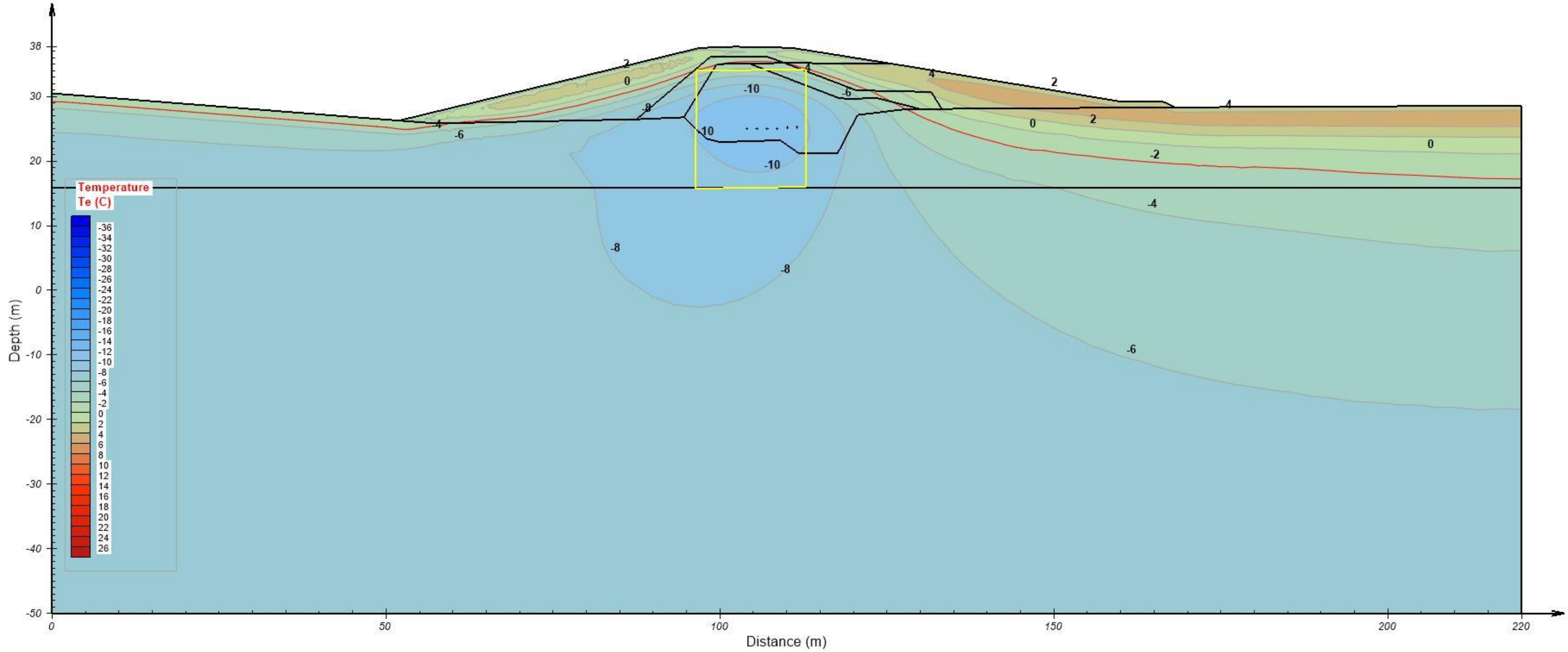
srk consulting	MAC RESOURCES	Doris North Dam Thermal Modeling
		North Dam – Year 2 (Section 0+85)
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 · Approved: cws · Figure: 33



Notes:

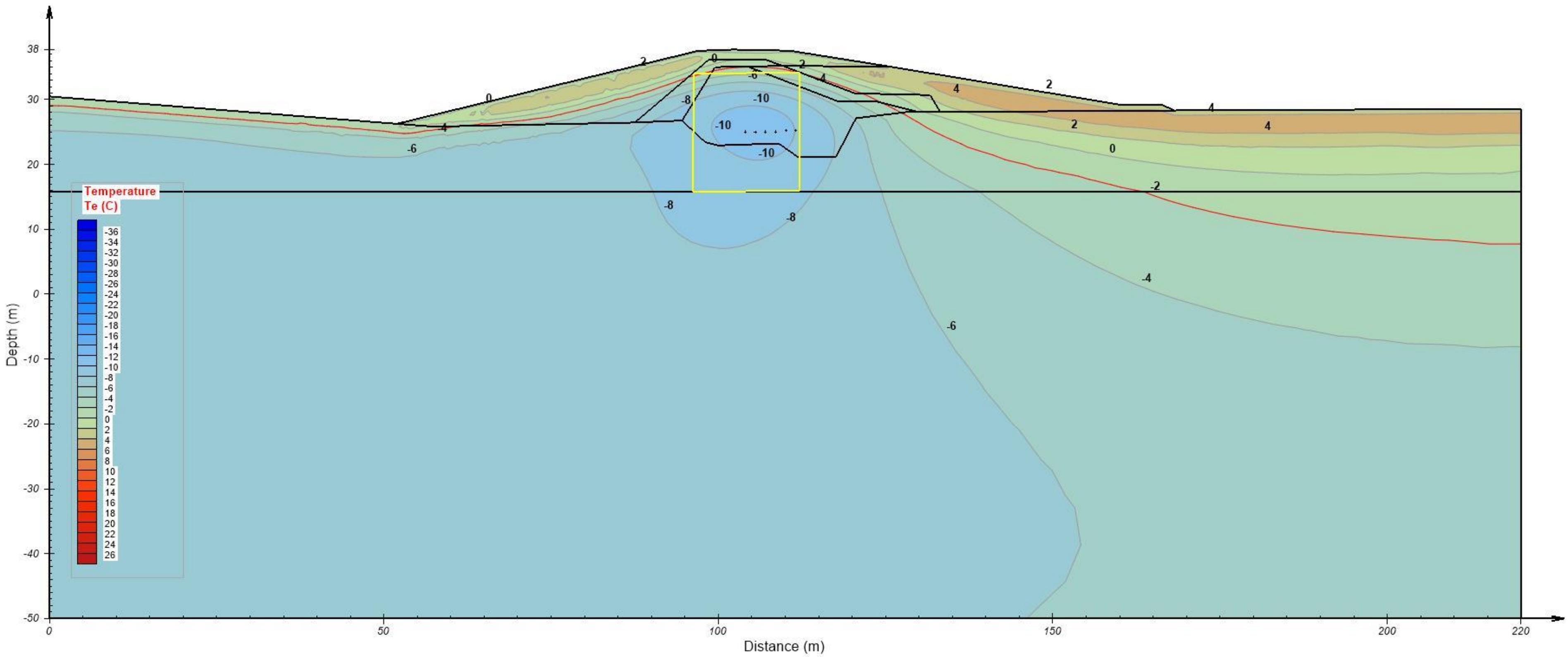
1. Model results for year 10, maximum position of -2°C isotherm
2. Yellow bounding box indicates critical section based on thermal design criteria
3. Dam Section 0+85 with clay foundation
4. Five working thermosyphons

srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling
		North Dam – Year 10 (Section 0+85)
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 | Approved: cws | Figure: 34



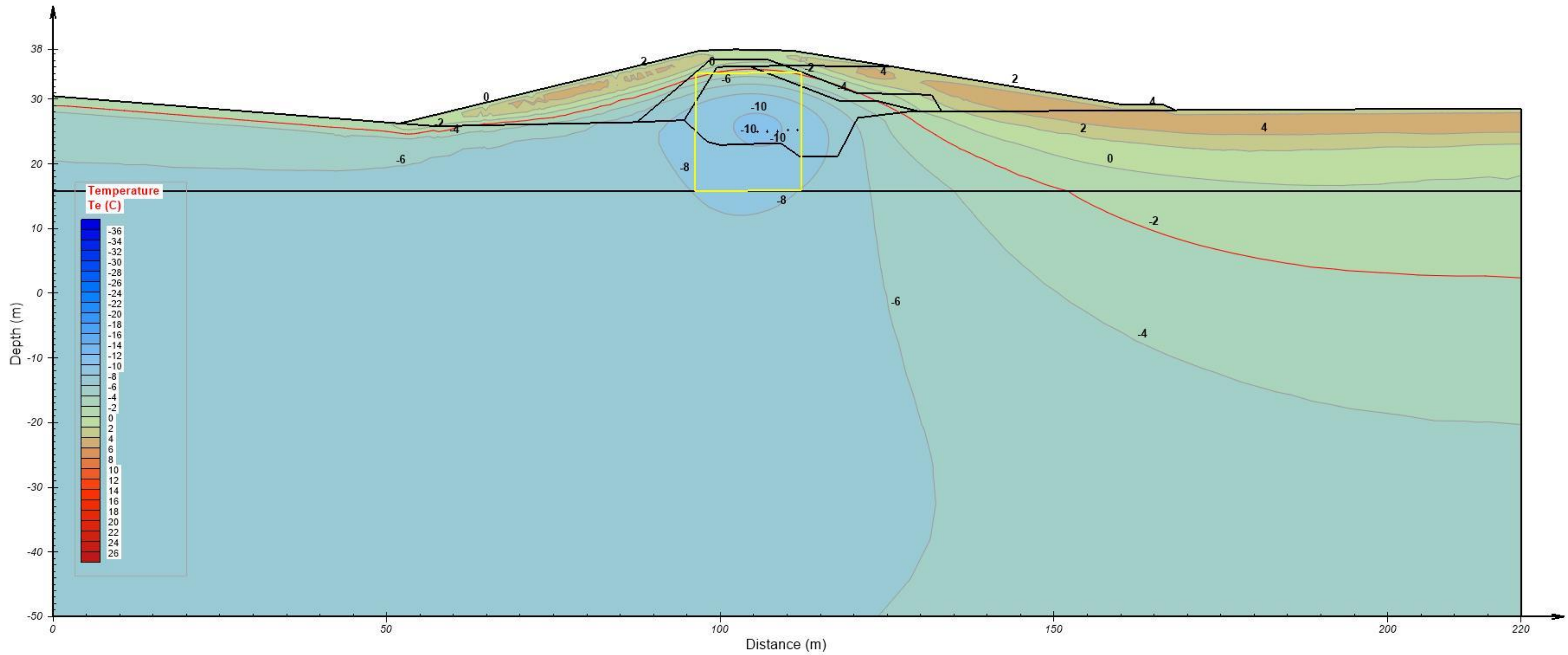
Notes:
1. Model results for year 20, maximum position of -2°C isotherm
2. Yellow bounding box indicates critical section based on thermal design criteria
3. Dam Section 0+85 with clay foundation
4. Five working thermosyphons

srk consulting	MAC RESOURCES	Doris North Dam Thermal Modeling
Job No: 1CT022.004	HOPE BAY PROJECT	**North Dam – Year 20 (Section 0+85)**
Filename: NorthDam.pptx		Date: 5/2/2016 · Approved: cws · Figure: 35



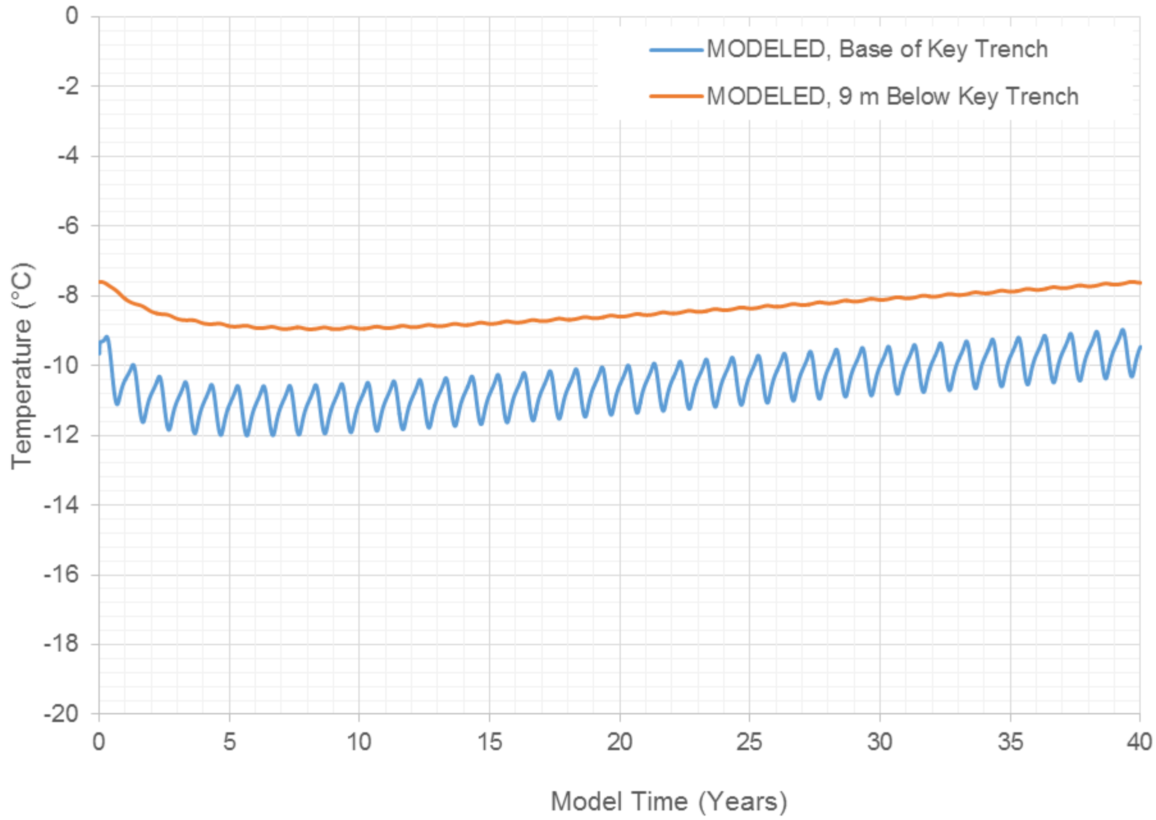
Notes:
1. Model results for year 30, maximum position of -2°C isotherm
2. Yellow bounding box indicates critical section based on thermal design criteria
3. Dam Section 0+85 with clay foundation
4. Five working thermosyphons

srk consulting	MAC RESOURCES	Doris North Dam Thermal Modeling
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	**North Dam – Year 30 (Section 0+85)**
		Date: 5/2/2016 · Approved: cws · Figure: **36**



Notes:
1. Model results for year 40, maximum position of -2°C isotherm
2. Yellow bounding box indicates critical section based on thermal design criteria
3. Dam Section 0+85 with clay foundation
4. Five working thermosyphons

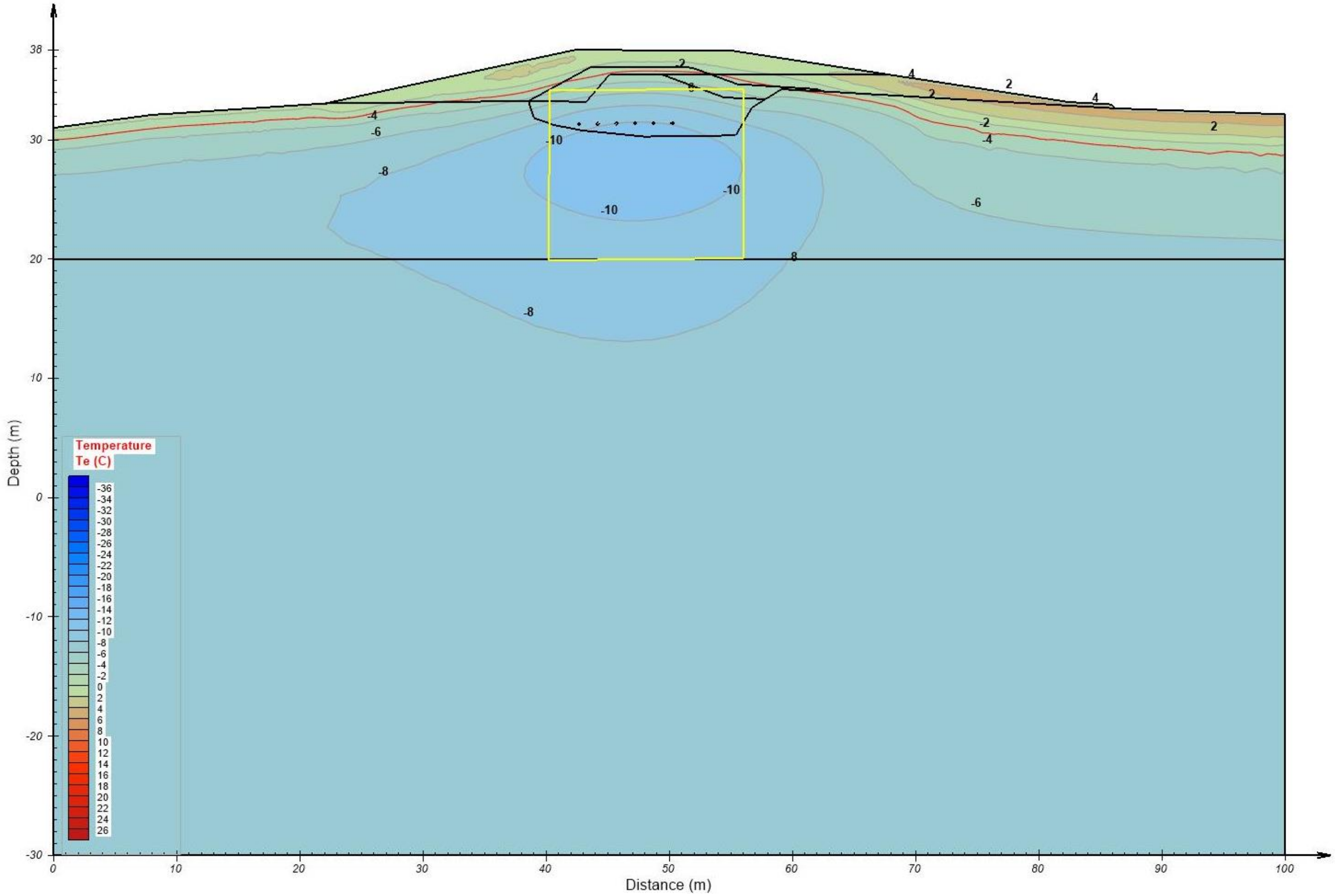
srk consulting	MAC RESOURCES	Doris North Dam Thermal Modeling **North Dam – End of Design Life (Section 0+85)**
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 · Approved: cws · Figure: **37**



Notes:

1. Model results for base of key trench and 9 m below key trench within the foundation
2. Dam Section 0+85

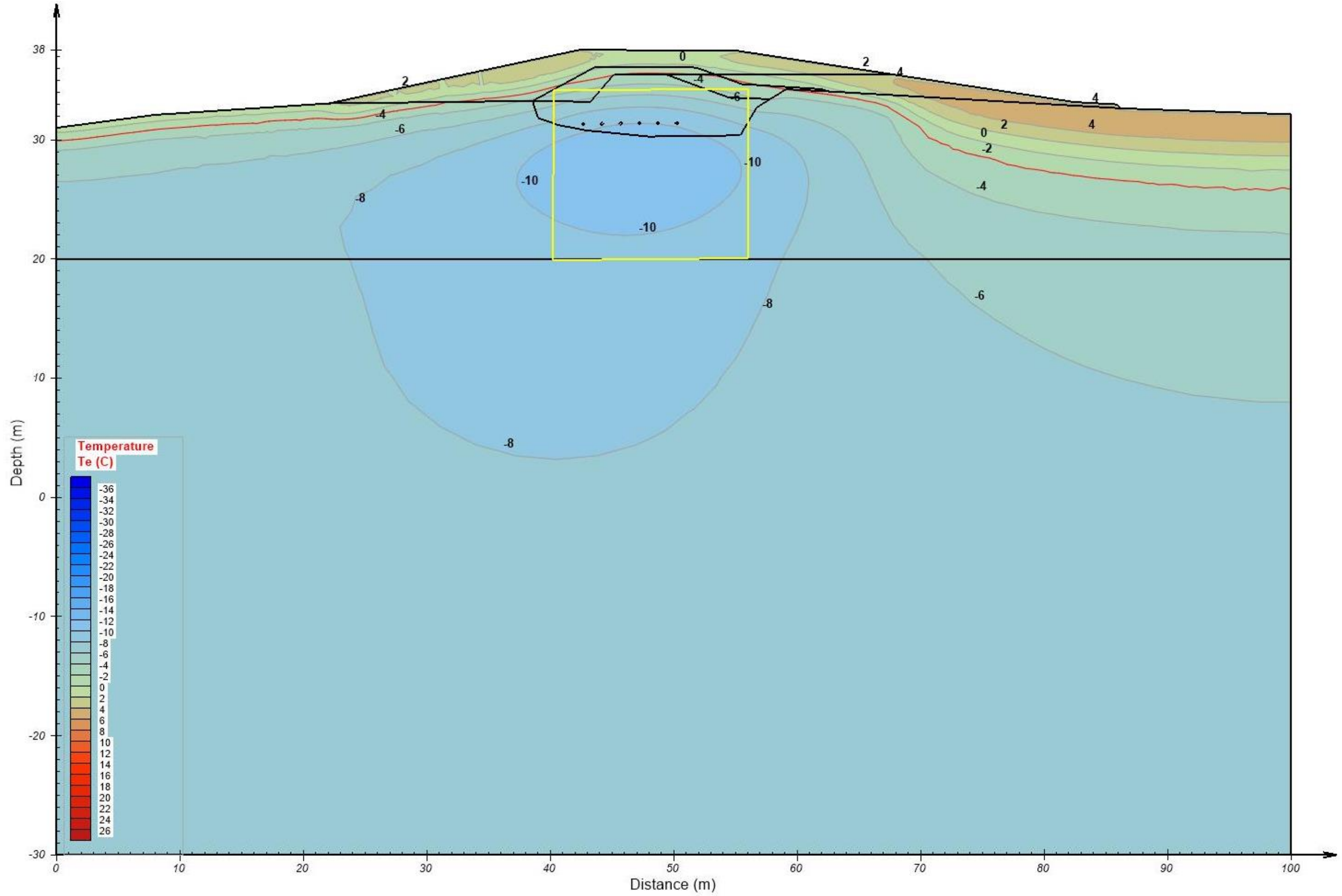
srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling **North Dam – Design Life, Key Trench and Foundation (0+85)**
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 / Approved: cws / Figure: **38**



Notes:

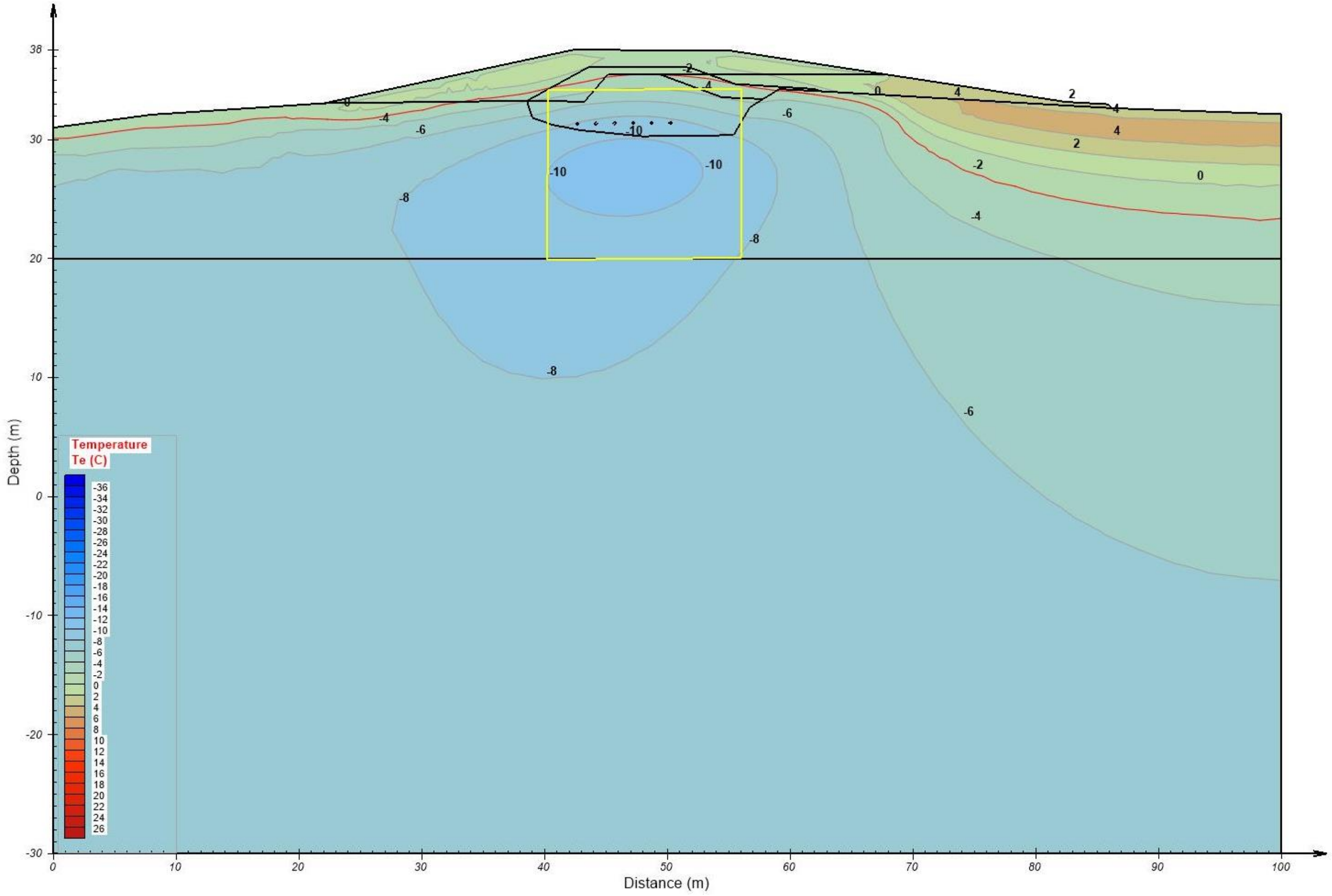
1. Model results for year 2, maximum position of -2°C isotherm
2. Yellow bounding box indicates critical section based on thermal design criteria
3. Dam Section 0+85 with clay foundation
4. Five working thermosyphons

srk consulting	MAC RESOURCES	Doris North Dam Thermal Modeling
		North Dam – Year 2 (Section 0+40)
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 · Approved: cws · Figure: 39



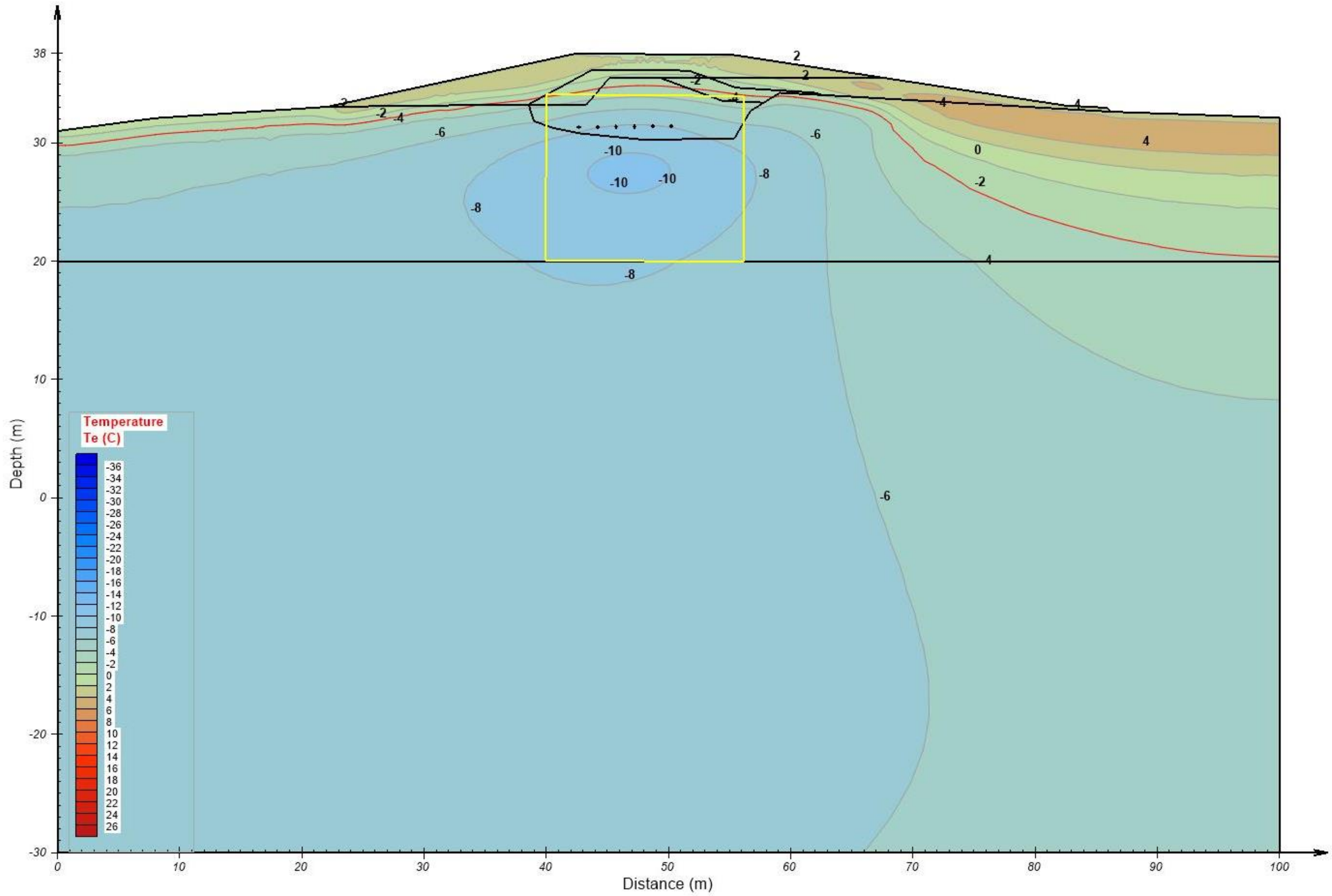
Notes:
1. Model results for year 10, maximum position of -2°C isotherm
2. Yellow bounding box indicates critical section based on thermal design criteria
3. Dam Section 0+85 with clay foundation
4. Five working thermosyphons

srk consulting	MAC RESOURCES	Doris North Dam Thermal Modeling
		North Dam – Year 10 (Section 0+40)
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 Approved: cws Figure: **40**



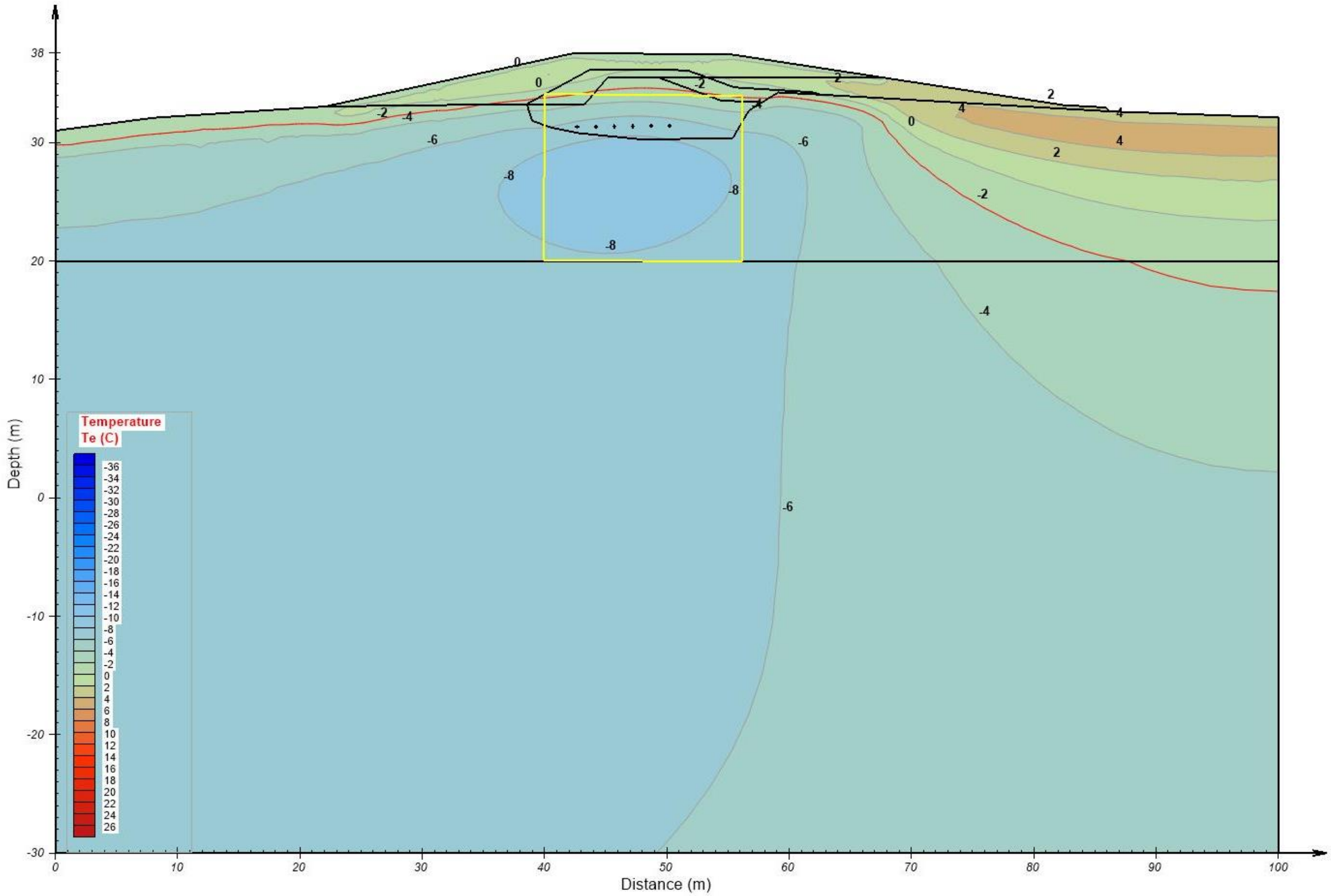
Notes:
1. Model results for year 20, maximum position of -2°C isotherm
2. Yellow bounding box indicates critical section based on thermal design criteria
3. Dam Section 0+85 with clay foundation
4. Five working thermosyphons

srk consulting	MAC RESOURCES	Doris North Dam Thermal Modeling **North Dam – Year 20 (Section 0+40)**
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 · Approved: cws · Figure: **41**



Notes:
1. Model results for year 30, maximum position of -2°C isotherm
2. Yellow bounding box indicates critical section based on thermal design criteria
3. Dam Section 0+85 with clay foundation
4. Five working thermosyphons

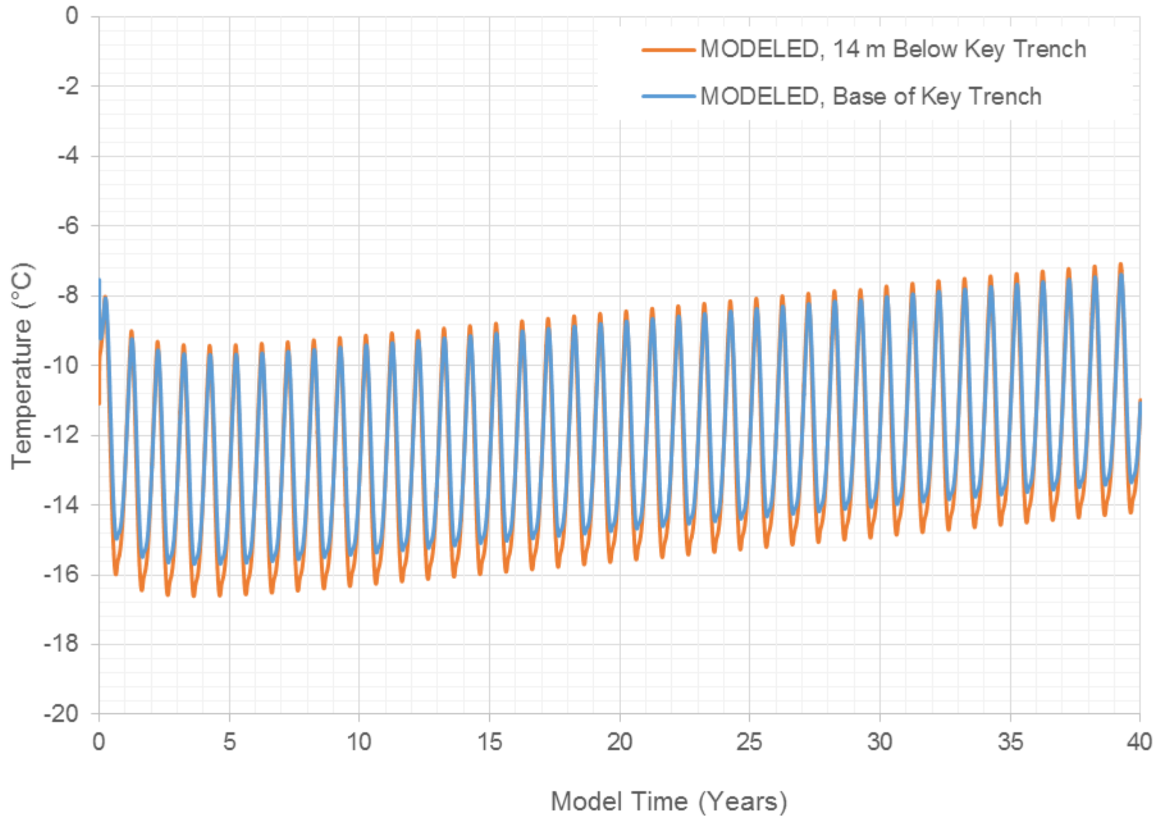
srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling
		North Dam – Year 30 (Section 0+40)
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 / Approved: cws / Figure: **42**



Notes:

1. Model results for year 40, maximum position of -2°C isotherm
2. Yellow bounding box indicates critical section based on thermal design criteria
3. Dam Section 0+85 with clay foundation
4. Five working thermosyphons

srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling
		North Dam – End of Design Life (Section 0+40)
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 · Approved: cws · Figure: **43**



Notes:

1. Model results for base of key trench and 14 m below key trench within the foundation
2. Dam Section 0+40

srk consulting	TMAC RESOURCES	Doris North Dam Thermal Modeling
		North Dam – Design Life, Key Trench and Foundation (0+40)
Job No: 1CT022.004 Filename: NorthDam.pptx	HOPE BAY PROJECT	Date: 5/2/2016 · Approved: cws · Figure: **44**

Appendix D – Hope Bay Project: Phase 2 Doris Tailings Impoundment Area Creep Analysis

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Memo

To:	John Roberts, PEng, Vice President Environment	**Client:**	TMAC Resources Inc.
From:	Arcesio Lizcano, PhD	**Project No:**	1CT022.004
Reviewed By:	Maritz Rykaart, PhD, PEng	**Date:**	December 5, 2016
Subject:	Hope Bay Project: Doris Tailings Impoundment Area North Dam Creep Deformation Analysis		

1 Introduction

1.1 General

The Hope Bay Project (the Project) is a gold mining and milling undertaking of TMAC Resources Inc. The Project is located 705 km northeast of Yellowknife and 153 km southwest of Cambridge Bay in Nunavut Territory and is situated east of Bathurst Inlet. The Project comprises of three distinct areas of known mineralization plus extensive exploration potential and targets. The three areas that host mineral resources are Doris, Madrid, and Boston.

The Project consists of two phases: Phase 1 (Doris project), which is currently being carried out under an existing Water Licence, and Phase 2, which is in the environmental assessment stage. Phase 1 includes mining and infrastructure at Doris only, while Phase 2 includes mining and infrastructure at Madrid and Boston located approximately 10 and 60 km due south from Doris, respectively.

Phase 1 tailings are deposited subaerially in the Doris tailings impoundment area (TIA), formerly Tail Lake, located approximately 5 km from the Doris Mill. Containment would be provided by three retention structures: a water retaining frozen core dam (North Dam), a frozen foundation tailings containment dam (South Dam), and an Interim Dike situated at approximately the midpoint of the facility. Tailings would be deposited subaerially between the South Dam and Interim Dike, and the Reclaim Pond will be contained between the Interim Dike and the North Dam.

The North Dam was constructed over two winters (2011 and 2012) and has impounded water since 2011 (Figure 1). The South Dam and Interim Dike are scheduled for construction in 2017. Phase 2 tailings deposition would include a continuation of the Doris TIA with raising of the South Dam and construction of a new West Dam (SRK 2016a). Thermal analysis completed for the North Dam is reported in SRK (2016b).

The North Dam relies on a frozen ice-saturated core and foundation to achieve the required water retention properties for a water full supply level of 33.5. A geosynthetic clay liner (GCL) was installed along the upstream side of the frozen core to provide secondary water-retaining capability in case cracks develop in the core caused by thermal expansion or creep deformation. To ensure adequate performance of the dam, it is imperative to maintain the frozen state of the core and foundation over the design life.

The original design life of the North Dam was 25 years (SRK 2007). As part of Phase 2 tailings deposition, the North Dam design life would be extended to 2041 (30 years from 2011). This timeline assumes a period of nominal water impoundment prior to the start of tailings deposition in 2017, active tailings deposition between 2017 and 2032 and a one-year post-closure period prior to breaching the dam in 2033.

1.2 Objective of the Creep Deformation Analysis

The objective of the creep deformation analysis is to anticipate if long-term strains occurring over the dam design life can affect the performance or compromise the stability of the North Dam. The analysis also confirms whether the integrity of frozen ice-saturated core and underlying saline foundation will be affected by creep deformations occurring in these two zones, and if the level of the core crest remains above the full supply level (FSL) throughout the dam design life.

2 North Dam Details

2.1 As-Built Overview

2.1.1 General

The North Dam is located across the Tail Lake outlet and extends approximately 200 m long and 11 m high, with upstream and downstream slopes of 6H:1V and 4H:1V, respectively (Figure 1 through Figure 3). The dam as-built report, drawings, and quality control and quality assurance documentation is provided in SRK (2012).

2.1.2 Foundation

The overburden soils are up to 20 m thick at the base of the valley and thin out at the dam abutments. About two-thirds of the dam longitudinal section is characterized by ice-saturated sand of approximately 10 to 15 m thick. The sand deposit is overlain by a silt and clay layer less than 3 m thick. The remaining one-third portion of the dam alignment is characterized by marine clayey silt that is up to 15 m thick. The fine-grained materials are also ice-saturated and contain excess ground ice. At the North Dam, the average pore water salinity is 39 parts per thousand (ppt), with a freezing point depression of −2.2°C (geometric mean of 30 ppt and −1.7°C). The average site-wide freezing point depression is −0.8°C for sand and −2.2°C for silt and clay, with an average of −2.1°C for all samples collected at the Project site (SRK 2016c). Bedrock is generally competent basalt.

2.1.3 Dam Construction

The North Dam was constructed over the winters of 2011 and 2012 and consists of three major regions: the frozen core, transition zone, and dam shell (Figure 3).

The key trench was excavated in 2011 using drill and blast methods. A hyper-saline zone comprised of clayey silt with an average pore water salinity of 45 ppt and a freezing point of −2.6°C was encountered between key trench Station 1+00 and Station 1+20. The trench was over excavated to remove as much hypersaline material as practical. Further detail of key trench excavation, testing, and conditioning of the surface for material placement is provided in SRK (2012).

The central frozen ice-saturated core was constructed of a 2:3 blend of 20 mm minus material to fines (SRK 2012). This blend was tested on-site to obtain the moisture retention required for placement during construction. The blend material was moisture conditioned in the frozen core mixing plant using freshwater sourced from Doris Lake, with routine testing to ensure no elements in the water would affect the frozen material. A GCL was installed over the upstream side of the frozen core to function as a secondary water retention system. The crest of the frozen central core is at an elevation of 35 m.

The transition zone was constructed of 150 mm (6 inch) minus crushed material and placed over the top of the frozen core and GCL (SRK 2012). The transition material was observed to be clean with little fines and no sand and gravel.

The external dam shell (Shell) was constructed of run-of-quarry material. Finer crushed rock transition material was placed over a portion of the dam crest to serve as an access road.

2.1.4 Ground Temperature Cables

A total of 24 ground temperature cables (*aka* thermistor strings) were installed within the North Dam during construction. They monitor temperature every six hours to ensure the dam core and foundation remain within the design operating temperature. The cables include horizontal thermistor strings installed in the upper (Upper Core), middle (Middle Core), and lower (Lower Core) regions of the frozen core. Details of ground temperature cable locations in the North Dam are included in SRK (2016b).

2.1.5 Thermosyphons

Thermosyphon evaporator pipes located at the base of the key trench provide passive cooling during the winter to ensure that the core and foundation remain frozen throughout the year.

Thermosyphons are pressurized sealed pipes, charged with a two-phase working gas that vaporizes and condenses to move heat without the need of a mechanical pump. A typical passive thermosyphon consists of an evaporator pipe buried in the ground and radiator exposed at the surface. The radiator section is manufactured with fins attached to the radiator pipe to enhance heat transfer with the atmosphere.

North Dam thermosyphons were procured and installed by Arctic Foundations of Canada Inc. Thermosyphon installation included one series of six evaporator pipes installed from the north end of the key trench and another six installed from the south end. The evaporator pipes extend to Section 0+85 which is the lowest point of the key trench. The north and south evaporator pipes are sloped at 4.6° and 8°, respectively.

Two thermosyphon radiators were attached to each evaporator pipe, with a total radiator surface area of 39 m^2. The North and South radiators are exposed at the surface and unobstructed by surface infrastructure to allow for effective heat loss from the radiator (Figure 1). Each pipe is charged with a carbon dioxide working gas and considered to have similar performance. General function of the thermosyphons is assessed in the winter by comparing the temperature differential between the air and the evaporator pipe directly below the ground surface.

2.1.6 Survey Monitoring

A series of 14 crest survey monitoring points, 3 deep settlement points, and 18 surface survey points were installed in the North Dam upon completion (Figure 4). These monitoring points were installed to monitor any surface movement of the dam crest, downstream face, and deep settlement of the downstream foundation of the dam.

2.2 Creep Deformation Evaluation Criteria

Creep deformation evaluation criteria for the frozen core and foundation establish limits to insure long-term integrity of the frozen core and foundation. The criteria guarantee long-term strains occur slowly and in a ductile manner. The criteria are based on the original design criteria proposed by EBA (2006) and require:

- The frozen core maintains the long-term shear strains at or below 2% and the maximum shear strain rate at or below 1.0E-05 sec^{-1} (3.2E+02 $year^{-1}$).
- The frozen foundation underneath the core maintain the long-term shear strain at or below 10% and the maximum shear strain rate at or below 1.0E-05 sec^{-1} (3.2E+02 $year^{-1}$).

2.3 Current Conditions

Annual inspections and review of monitoring data suggest the dam is performing in accordance with the design expectations. The North Dam has had impounded water since the first winter of construction in 2011. The operating water level impounded against the upstream face of the dam has averaged 29.0 m, with a maximum level of 29.5 m over the period from September 2011 to September 2015. The original water level of Tail Lake prior to construction of the North Dam was 28.3 m. Core and foundation temperatures have been below the design temperatures of −2ºC and −8°C, respectively.

Annual review of displacement monitoring data collected at the North Dam indicates (SRK 2016e):

- The maximum vertical displacement at the crest is 0.07 m measured at ND-SMP-120-DS, with a change of 0.02 m in the last three years.
- The maximum horizontal displacement measured at the crest is 0.10 m measured at the ND-SMP-120-US, with a change of 0.06 m in the last three years.
- The maximum vertical displacement measured at the downstream face of the dam is 0.21 m measured at ND-SSP-065-2, with a change of 0.01 m in the last three years.
- The maximum horizontal displacement measured at the downstream face of the dam is 0.20 m at ND-SSP-110-3, with a change of 0.07 m in the last three years.

3 Creep Deformations Analysis

3.1 Model Setup

Creep deformations were assessed by plane strain conditions using the two-dimensional non-linear finite difference code, Fast Lagrangian Analysis of Continua (FLAC 2-D), by Itasca (2012). The analysis was carried out along the cross sections 0+85 located at the thickest section of the dam (Figure 2). Thermal modelling was completed for the same cross section (SRK 2016b).

As-built survey information was used for the 2-D model sections of the dam. Section 0+85 was modelled with a 14 m wide crest, 11 m height, upstream slope of 6H:1V, and downstream slope of 4H:1V. Five material regions were considered in the model: shell, transition zone, core, foundation, and bedrock. The 5 mm GCL liner was not represented in the model, which is presented in Figure 5.

3.2 Basis for the Assessment

The ice-saturated granular material in the frozen core is a dense material with a void ratio around 0.35 (SRK 2016b). The deviatoric strength (peak or residual) of the frozen core material is expected to be above 1 MPa based on published results from laboratory tests conducted on frozen sand samples under constant temperatures around −5°C and constant strain rates around 1E-07 sec^{-1} (Bragg and Andersland 1981 and Arenson 2002). Considering the height of the North Dam (11 m), the level of deviatoric stresses within the frozen core is anticipated to be low relative to the expected deviatoric strength of the frozen material in the core. According to Andersland and Landanyi (2004), medium to high-density ice-saturated sands under low stress levels exhibit only primary creep (i.e., decreasing strain rates). Therefore, the creep deformation analysis assumed the frozen core will exhibit only primary creep.

Secondary creep (i.e., constant creep strain rate) were assumed for the frozen marine clayey silt in the foundation. This type of soils exhibits a short primary-creep period and a prolonged secondary-creep phase (Andersland and Landanyi 2004).

Based on the Bailey-Norton law (Norton 1929 and Bailey 1935), creep strains rates ($\dot{\varepsilon}$) of frozen soils due to the deviatoric part of the stresses ($\bar{\sigma}$) can be described by the following general equation:

$$\dot{\varepsilon} = (A\bar{\sigma}^n) \cdot mt^{m-1} \tag{1}$$

where A is a creep parameter that depends on soil type and temperature, n and m can be considered temperature independent parameters, and t is the elapsed time after load application.

Secondary creep is commonly described by Equation (1) with $m = 1$. In this case, the equation can be rewritten as

$$\dot{\varepsilon} = A\bar{\sigma}^n \tag{2}$$

With Equation (2), frozen soils are always predicted to creep for any given deviatoric stress. Even for very small stresses, frozen soil will be predicted to creep. This may lead to overestimating actual long-term displacements. A threshold stress (σ_{th}) for frozen soils likely exists, as for metals (Norton 1929), below which creep cannot be measured and Equation (2) no longer applies. Equation (2), as most constitutive equations for creep, is however formulated without a threshold stress.

In the performed analysis, creep strains were evaluated using a constitutive relation represented by Equation (2) implemented in FLAC, described as “The Two-Components Power Law” (Itasca 2012). For the analysis, a temperature independent threshold stress of 30 kPa was selected for all frozen materials based on published laboratory testing results (Landanyi 1971, Nixon and Lem 1984, Wijeweera and Joshi 1991, and Arenson, 2002) and engineering judgment. No creep strains were predicted ($\dot{\varepsilon} = 0$) for $\bar{\sigma} < \sigma_{th} = 30$ kPa. This stress is considered to be low relative to the expected peak deviatoric strength. The assumed stress was not a threshold for the deviatoric part of the stresses as introduced by Norton (1929). In this latter case, the deviatoric part of the stresses ($\bar{\sigma}$) in Equation (2) is reduced by σ_{th}, or $\dot{\varepsilon} = (\bar{\sigma} - \sigma_{th})^n$. Likely thresholds for other creep mechanisms in frozen soil (e.g., temperature) were not considered in the analysis.

Equation (2) can therefore be written as follows:

$$\frac{\dot{\varepsilon}}{\dot{\varepsilon}_r} = \left(\frac{\bar{\sigma}}{\sigma_r}\right)^n \tag{3}$$

where $\dot{\varepsilon}_r$ and σ_r are reference values for the strain rate and stress. According to Equation (3), the creep parameter A in Equation (2) is:

$$A = \frac{\dot{\varepsilon}_r}{(\sigma_r)^n} \tag{4}$$

Based on the experimental work from Nixon and Lem (1984) on saline fine grained frozen soils, Andersland and Landanyi (2004) proposed the following empirical expression for σ_r in kPa as a function of temperature and salinity:

$$\sigma_r = 0.323(1-T)^2\left(\frac{59.505-S}{8.425+S}\right) \quad (5)$$

where T is the temperature in Celsius degrees and S is the salinity in ppt.

The parameter A $(\mathrm{kPa}^{-n}\cdot\mathrm{year}^{-1})$ can be then calculated with Equation (4) as a function of temperature and salinity using the Equation (5) for σ_r and a reference strain rate of $\dot{\varepsilon}_r = 10^{-4}\ \mathrm{year}^{-1}$ (Anderson and Landanyi 2004). For the analysis, the parameter A was determined with Equation (4) at different temperatures for the reported average salinity of 39 ppt (Section 3.4.3).

3.3 Methodology

The creep analysis used in the ground thermal conditions were predicted by thermal modelling at cross section 0+85 (SRK 2016b). It is expected that the creep behavior of the frozen core and foundation changes as the temperature changes over the dam design life. An accurate prediction of long-term creep deformations therefore requires a thermomechanical coupled constitutive model. However, an efficiently implemented coupled thermo-mechanical model is not available in commercial codes. Hence, long-term creep behavior was evaluated for the ground temperature distribution predicted ten years after dam construction (Figure 6). This time interval is considered as representative for the long-term creep deformation in the North Dam.

The analysis followed the following steps:

1. Initial state: The initial stresses of the dam embankment and foundation was achieved in the model by using elastic properties for all materials and turning gravity on.
2. Elasto-plastic phase: Dam shell, transition zone, and foundation zone over the isotherm −2°C (thawed clayey silt) predicted by the thermal modelling (Figure 6) were changed from elastic to Mohr-Coulomb materials, and the model was brought again to equilibrium.
3. Creep phase: Temperature dependent elastic and creep properties were assigned to the frozen core and foundation based on the predicted temperature ten years after dam construction. The model was allowed to deform for 30 years.

3.4 Material Properties

Elastic and creep material properties from laboratory tests are not available. Elastic and creep properties used in the deformation analysis were estimated based on previous reports (e.g., in EBA (2006)), published data in the literature, and engineering judgment.

3.4.1 Elastic Properties

Elastic properties for the initial state were taken from EBA (2006). SRK adjusted the elastic modulus of the frozen foundation. Table 1 presents the material elastic properties used for achieving the initial state in the model.

Table 1: Elastic Properties for the Initial State[1]

Model Region	Material	Unit Weight (kN/m^3)	Elastic Modulus (kPa)	Poisson's Ratio (-)
Shell	Run-of-Quarry	22	1.0E+05	0.35
Transition	150 mm minus	21	1.0E+05	0.30
Core	20 mm minus: 5 mm minus (2:3 blend by volume)	22	1.0E+05	0.25
Foundation	Clayey Silt	17	6.4E+05[2]	0.35
Bedrock	Basalt	26	1.0E+08	0.25

Notes:
1. Source: EBA 2006
2. Adjusted by SRK. EBA Elastic Modulus: 5 x 10^{-4} kPa

3.4.2 Shear Strength Properties

Shear strength properties were taken from EBA (2006). SRK believes these Mohr-Coulomb properties are suitable for the elasto-plastic phase of the analysis. Table 2 includes the shear strength properties.

Table 2: Shear Strength Properties

Model Region	Cohesion (kN/m^2)	Friction Angle (º)
Shell	-	40
Transition	-	35
Foundation (Thawed Clayey Silt)	40	-
Bedrock	1000	-

3.4.3 Creep Parameters

Table 3 summarizes the parameter used for the creep phase of the analysis. Parameters n, m, and A (Equation (1)) for the frozen core were estimated based on the laboratory testing results from Ottawa sand (Sayles 1968) and an average temperature of −9˚C in the core ten years after dam construction. For the frozen foundation, $n,$ (Equation (2)) was estimated based on published laboratory testing results from saline fine grained soils (Nixon and Lem 1984 and Wijeweera and Joshi 1993). Temperature dependent A values for the frozen foundation were calculated with equations (3) and (4) for a constant salinity of 39 ppt. For reference, Figure 7 plotted equations (3) and (4) for different temperatures and salinities. The figure includes values from Nixon and Lem (1984) for a salinity of 35 ppt and those used by EBA (2006) for a salinity of 45 ppt.

Table 3 includes the estimated temperature dependent elastic moduli of the frozen core and foundation required for the elastic strains. Since the creep is considered to be a constant volume process, the analysis used a Poisson's ratio of 0.5 for the frozen core and foundation.

Table 3: Creep and Elastic Properties of the Frozen Core and Foundation[1]

Model Region	***b*** (-)	***n*** (-)	***A***	**Elastic Modulus** (kPa)
	(-)	(-)	$\mathrm{kPa}^{-n}\mathrm{year}^{-b}$	(kPa)
Core (-9^{0}C)	0.26	1.32	2.0E-07	3.0E+05
Foundation[2]				
-3^{0}C	1	3	9.6E-05	1.0E+04
-4^{0}C	1	3	2.5E-05	3.2E+04
-5^{0}C	1	3	8.4E-06	6.6E+04
-6^{0}C	1	3	3.3E-06	1.4E+05
-7^{0}C	1	3	1.5E-06	2.8E+05
-8^{0}C	1	3	7.4E-07	5.7E+05
-9^{0}C	1	3	3.9E-07	1.2E+06
-10^{0}C	1	3	2.2E-07	2.4E+06

Notes:
1. Constant volume deformation; Poisson's ratio $\nu = 0.5$
2. Salinity 35 ppt

4 Results

Table 4 summarizes the predicted creep strains and stresses in the frozen core and underlying frozen foundation 10 and 30 years after dam completion. Table 5 presents the predicted displacements for the same time intervals.

Table 4: Creep Strains and Stresses in the Frozen Core and Foundation

	Maximum Shear Strain Rate (Fig. 8 and 9)		**Maximum Shear Strain** (Figs. 10 and 11)		**Maximum Deviatoric Stress** (Figs. 12 and 13)		**Shear Stress** (Figs. 15 and 16)	
	(year^{-1})		(m/m)		(kPa)		(kPa)	
	Core[1]	Foundation[2]	Core[1]	Foundation[2]	Core[1]	Foundation[2]	Core[1]	Foundation[2]
10 years after dam construction	5.0E-08	1.0E-07	5.0E-02	~1.0E-01	100[3] (300)[4] (400)[5]	50	20 (50)[5]	20
30 years after dam construction	2.0E-08	4.0E-08	1.0E-01	~2.0E-02	50[3] (300)[4] (450)[5]	50	20 (70)[5]	20

Notes:
1. Within the frozen core
2. Underneath the frozen core
3. At the top of the frozen core
4. At the bottom of the frozen core
5. Localized at the upstream lower corner of the core

Table 5: Creep Displacements in the Frozen Core and Foundation

	Maximum Horizontal Displacement (Fig. 18 and 19)		**Maximum Vertical Displacement** (Figs. 20 and 21)		**Vertical Displacement** (Fig. 22)
	(m)		(m)		(m)
	Core[1]	Foundation[2]	Core[1]	Foundation[2]	Core Crest
10 years after dam construction	0.4	0.4	0.6	0.6	0.24
30 years after dam construction	0.8	0.6	1.0	1.0	1.0

Notes:
1. Within the frozen core
2. Underneath the frozen core

4.1 Shear Strain Rates and Shear Strains

The analysis predicts shear strain localization at the downstream side of the dam mainly (Figures 9 to 11). The shear localization zone is almost circular and goes along the transition zone and through the saline frozen foundation. This surface can be considered as a likely failure surface in the event that the material strength is mobilized along this surface.

In general, the predicted shear strain rates are very low in all zones of the dam and foundation compared with strain rates usually used in laboratory tests with frozen soils (Sayles 1968, Wijeweera and Joshi 1991 and Arenson 2002). The maximum shear strain rates are 3.5E-07 year^{-1} and 1.E-07 year^{-1}, 10 and 30 years after dam completion, respectively (Figures 8 and 9). The maximum shear strains are 4.0E-01 m/m (40%) and 6.0E-01 m/m (60%) for the same periods of time (Figures 10 and 11). Maximum shear strain rates and shear strains are predicted to occur in points within the shear localization zone (i.e., outside the frozen core and underlying foundation).

In the frozen sandy core and underlying foundation (Table 4), the maximum rate of shear strain meets the design criteria for ductile material behavior (Section 2.2), while the shear strains *themselves* exceed the criteria. However, for the frozen sandy core, ductile material behavior is expected because the maximum rate of shear strain is predicted to be very low (~ 1E-08 year^{-1}). Based on Bragg and Andersland (1981) and Arenson (2002), a brittle mode of failure can be excluded in frozen sands that deform under a shear strain rate below < 1E-05 sec^{-1} (3.2E+02 year^{-1}). Nevertheless, the lower the strain rate, the lower the strength of the frozen material.

4.2 Principal stresses Difference

Creep strain rates were evaluated as a response to induced deviatoric stresses by the dam weight. Maximum principal stresses differences of around 75 and 300 kPa are predicted to be almost constant at the crest and bottom of the frozen core, respectively, throughout the dam design life (Table 4). In the frozen saline foundation, underneath the frozen core, an almost constant principal stress difference below 50 kPa is predicted over the design life (Figures 12 and 13). Figure 14 presents histories of principal stresses difference for two points located at the crest and within the low zone of the frozen core (Points A and B, Figure 5).

The predicted stress differences at the bottom of the frozen core can be considered as intermediate compared with the expected peak deviatoric stress. In the remaining areas of the frozen core and underlying foundation, low stresses difference will prevail.

4.3 Shear stresses

In general, the shear stresses in the frozen core and foundation are predicted to be relatively low over the design life of the dam compared with the expected shear strengths of these materials (Figures 15 and 16). Figure 17 shows shear stress histories for two points located at the core crest and within the low zone of the frozen core (Points A and B, Figure 5).

4.4 Displacements

Based on the thermal modelling, a greater frozen area is predicted in the foundation at the downstream side than at the upstream side (Figure 6 and SRK 2016b). Therefore, the maximum creep displacements due to the frozen foundation will be expected at the downstream side of the dam.

Figure 18 and 19 show the distributions of horizontal creep displacements. Maximum horizontal displacements of 2.8 and 4.2 m are predicted to occur 10 and 30 years after dam construction, respectively, in a small zone of the foundation at the downstream side. Within and underneath the frozen core, the horizontal displacements remains under 0.8 m over the design life of the dam (Table 5).

The distribution of the vertical displacements 10 and 30 years after dam construction are presented in Figures 20 and 21. Figure 22 shows the vertical displacement history of a point located on the frozen core crest determined for a threshold stress of 30 kPa and pore water salinity of 30 ppt. At the end of the planned design life, the core crest is predicted to settle around 1.0 m.

As a reference for the predicted vertical displacements, Figure 22 includes the maximum measured vertical displacements. These displacements were measured at the downstream part of the dam crest in station 1+20 (ND-SMP-120-DS in Figure 4) over the first four years after dam completion.

To show the impact of threshold stresses and salinities on the creep deformations analysis, Figure 22 also includes predictions of core crest settlements obtained with thresholds stresses of 0 and 35 kPa, and salinities of 39 and 35 ppt. The lower the threshold stress and higher the salinity, the greater the core crest settlement will be. For a salinity of 39 ppt and without threshold stress ($\sigma_{th} = 0$ kPa), the core crest is predicted to settle around 1.4 m at the end of the dam design life, i.e., the core crest will settle up to the water full supply level of 33.5 m. However, this result is considered an overestimation of vertical displacements for the reasons outlined in Section 3.2.

5 Conclusions

Main conclusions from the creep deformation assessment are as follows:

- A long-term ductile behavior is predicted for the materials in the ice-saturated frozen core and underlying frozen foundation. Creep shear strains in these zones will occur very slowly and remain below the strain rate for brittle failure modes.

- Vertical creep displacements will not compromise the long-term integrity of the frozen core and underlying foundation. Shear and deviatoric stresses in these zones caused by creep strains will remain well below the expected peak strengths of the materials. No shear strain localization is predicted within and underneath the frozen core.

- Long-term performance of the frozen core is not expected to be compromised throughout the dam design life. Thirty years after dam construction, the total settlement of the core will be around 1.0 m, i.e., 0.5 m above the full supply level (33.5).

- Shear strains are predicted to localize at the downstream side of the dam. Thirty years after dam completion, high shear strains (~ 60%) with very low strain rates (~1.0E-08 $year^{-1}$) can be expected in few points within the localization surface. However, shear stresses and principal stress differences will remain well below the expected peak deviatoric stress of the materials (> 1 MPa).

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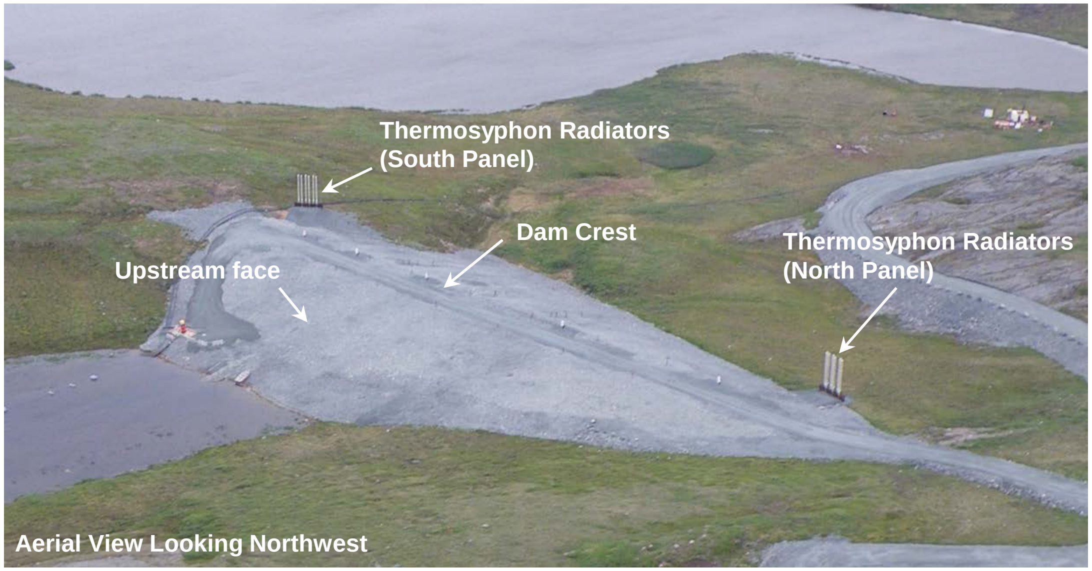
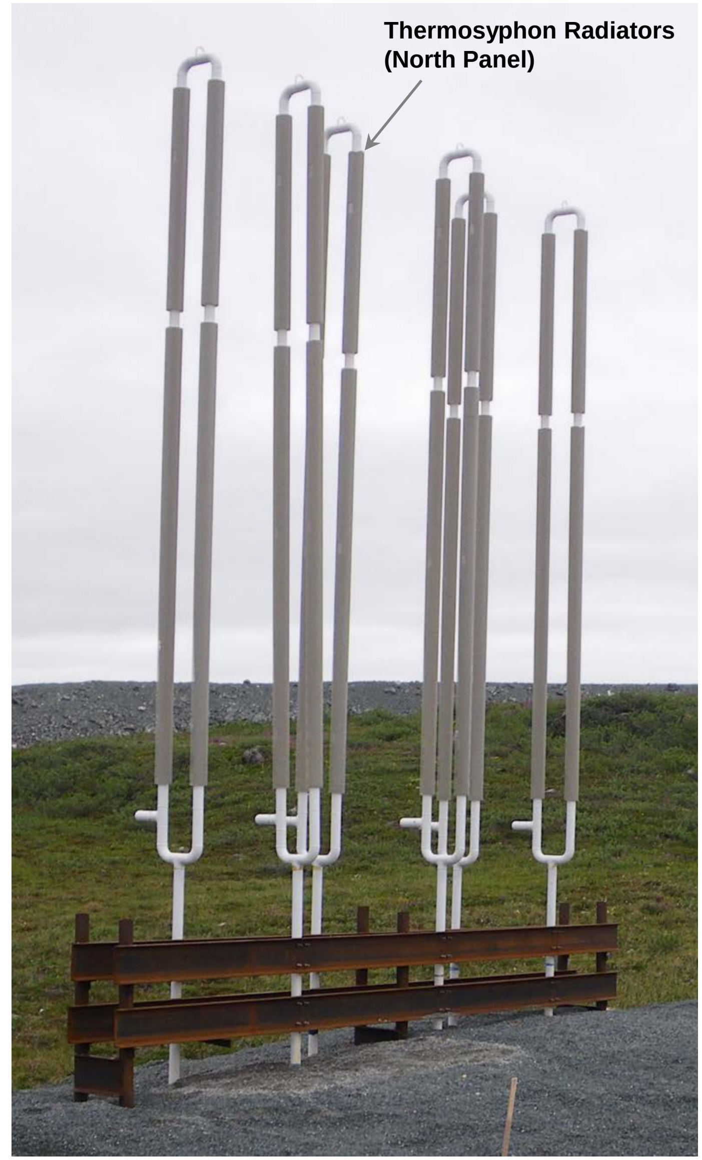
Figures

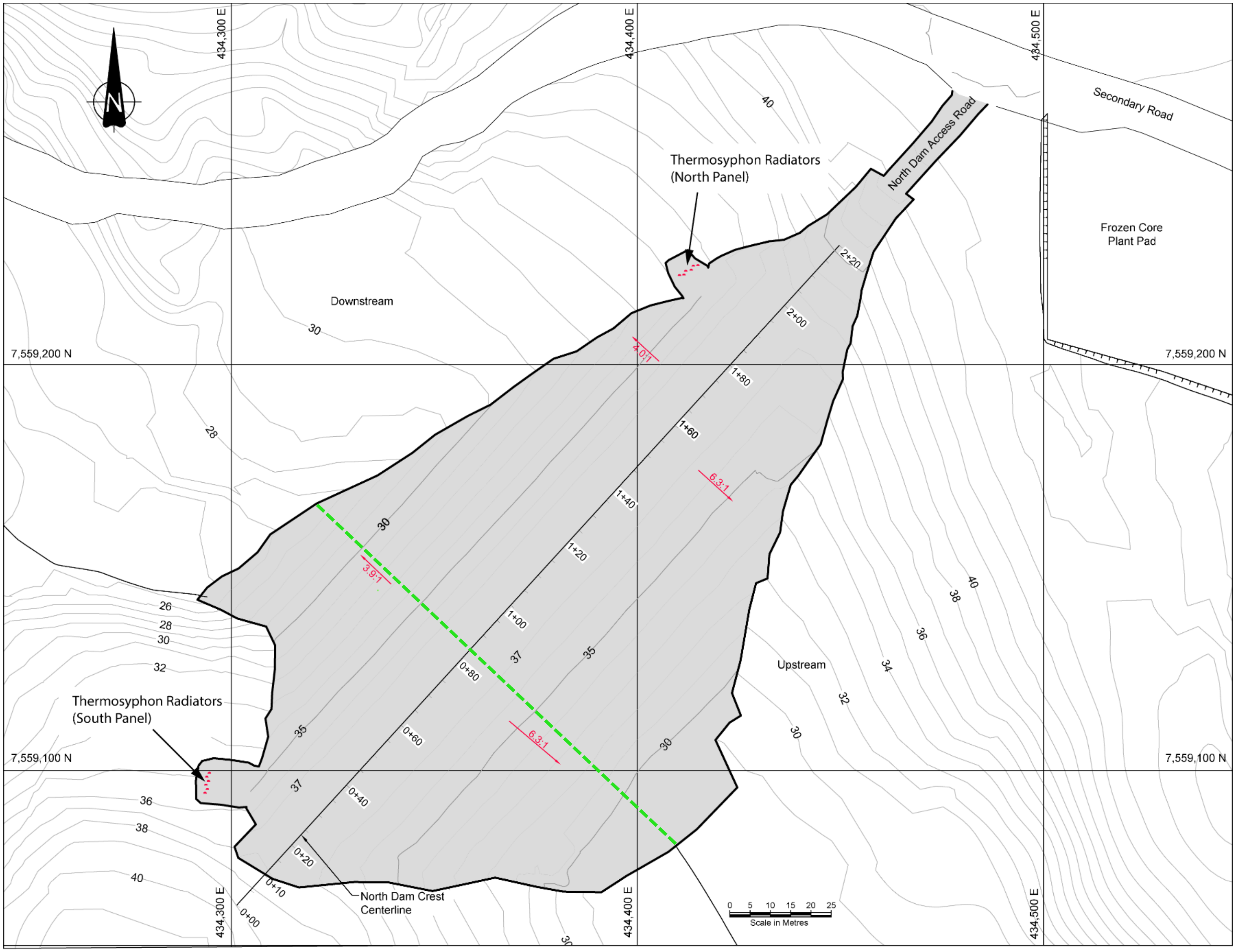




Notes:

1. Field photographs taken July 18th and July19th of 2014

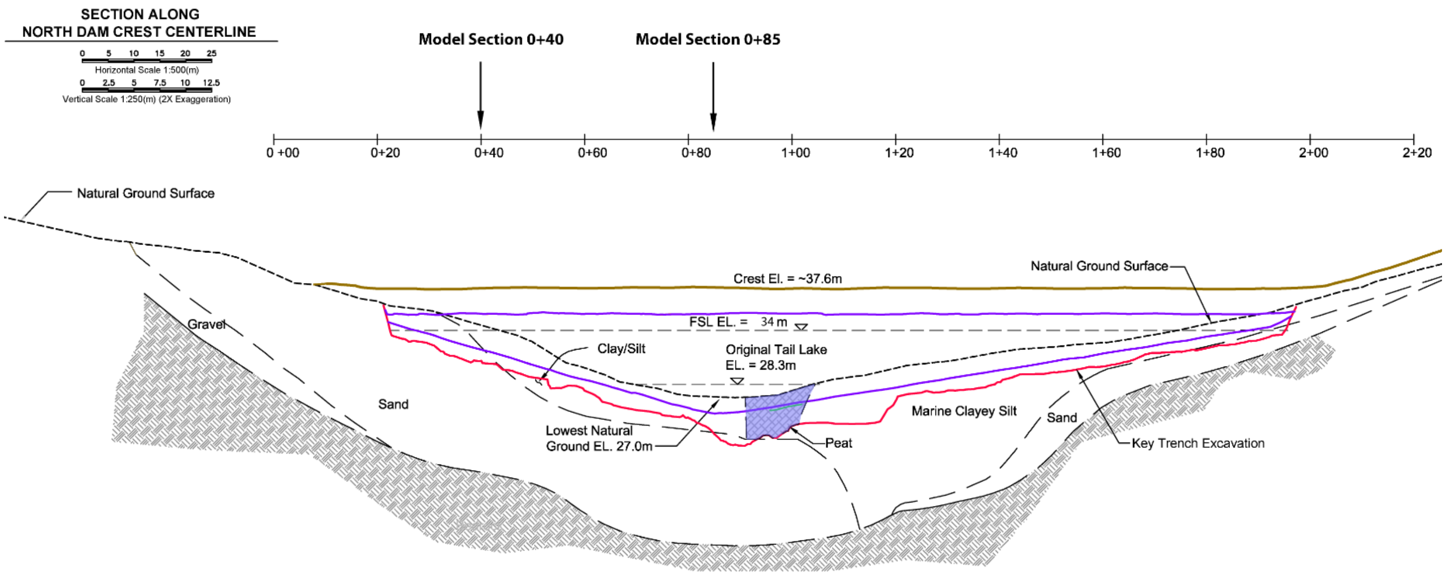
srk consulting	MAC RESOURCES	North Dam Creep Deformation Analysis
		North Dam – Field Photograph
Job No: 1CT022.004 Filename: NorthDam_CreepAnalysis.pptx	HOPE BAY PROJECT	Date: 8/17/2016 · Approved: AL · Figure: 1



Notes:

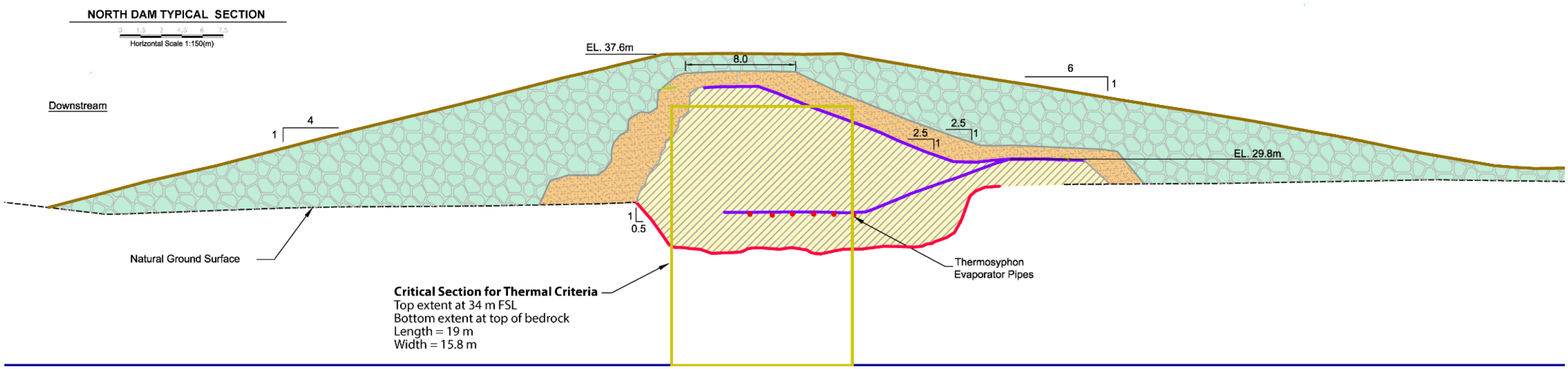
1. Dashed green line indicates Dam Section 0+85

srk consulting	TMAC RESOURCES	North Dam Creep Deformation Analysis
		North Dam General Arrangement
Job No: 1CT022.004 Filename: NorthDam_CreepAnalysis.pptx	HOPE BAY PROJECT	Date: 8/17/2016 · Approved: AL · Figure: 2



LEGEND

- Natural Ground
- Stratigraphic Boundary
- Core Material (Frozen Core)
- Transition Material (Transitional Zone)
- Run of Quarry (ROQ) (Dam Shell)
- Bedrock
- Peat
- Critical Section
- Thermosyphon Evaporator Pipe
- Geosynthetic Clay Liner (GCL)
- Base of Key Trench
- Top of Bedrock



Notes:

1. The subsurface geology has been extrapolated from a series of geotechnical investigations and geological unit contacts are therefore likely to vary somewhat.

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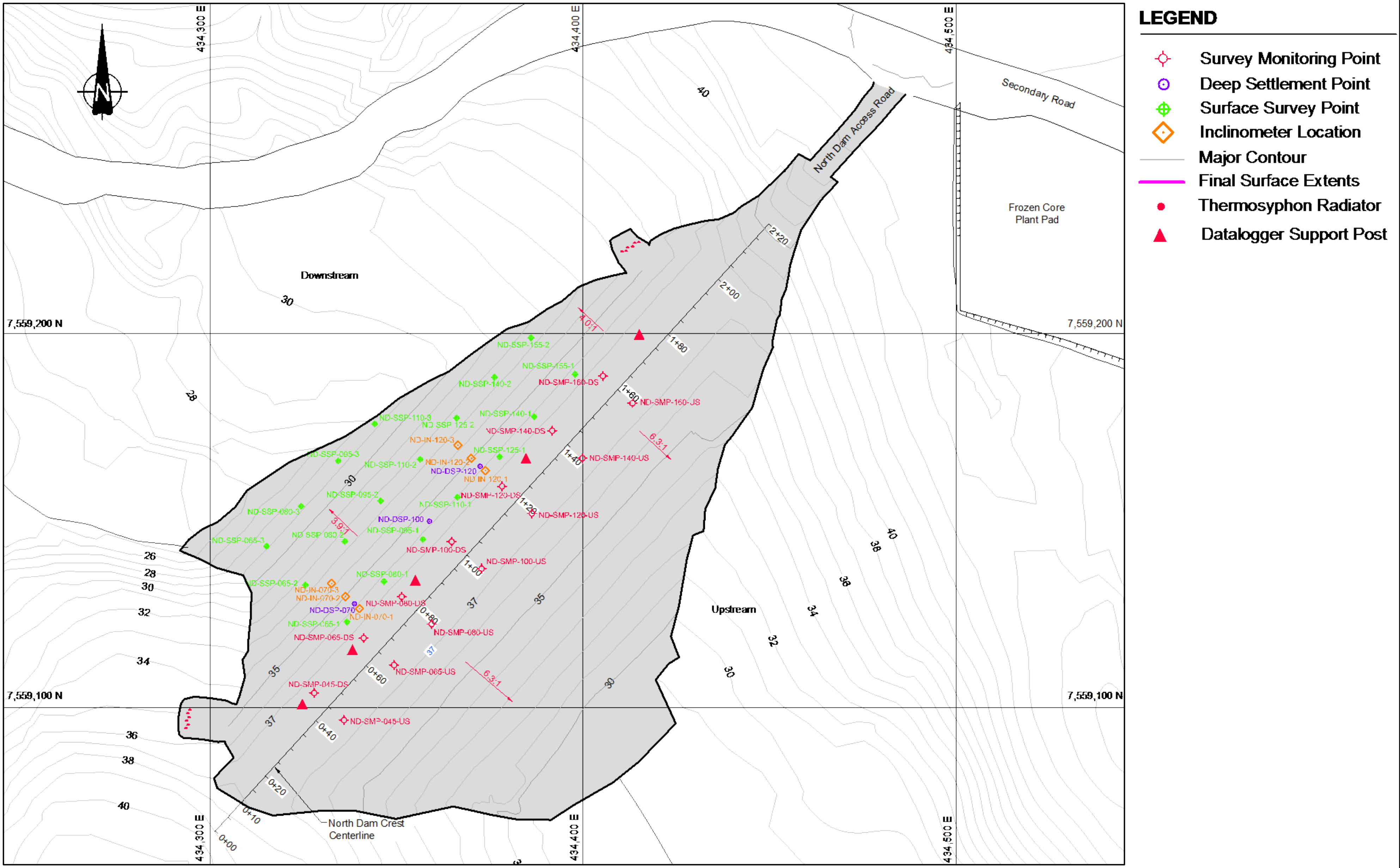
North Dam Creep Deformation Analysis

North Dam
Typical As-Built Section

Job No: 1CT022.004
Filename: NorthDam_CreepAnalysis.pptx

HOPE BAY PROJECT

Date:	Approved:	Figure:
8/17/2016	AL	3



NOTES

1. Topographic contour data for the terrain model was provided by the Contractor.
2. The co-ordinate system is UTM NAD 83, Zone 13.

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North Dam Creep Deformation Analysis

North Dam
Survey Monitoring Points

Job No: 1CT022.004

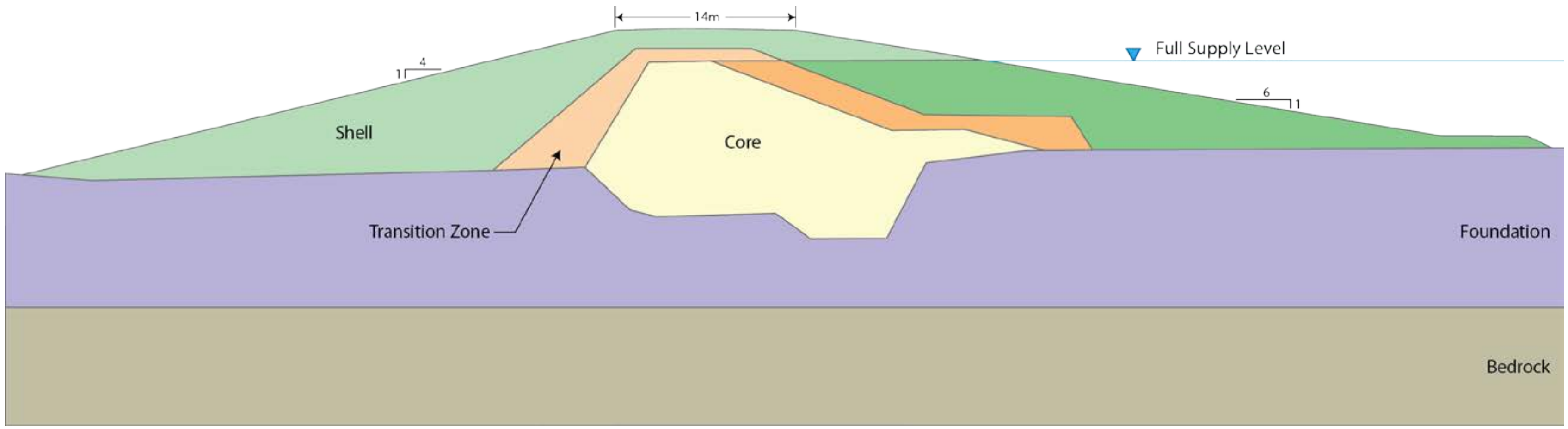
Filename: NorthDam_CreepAnalysis.pptx

HOPE BAY PROJECT

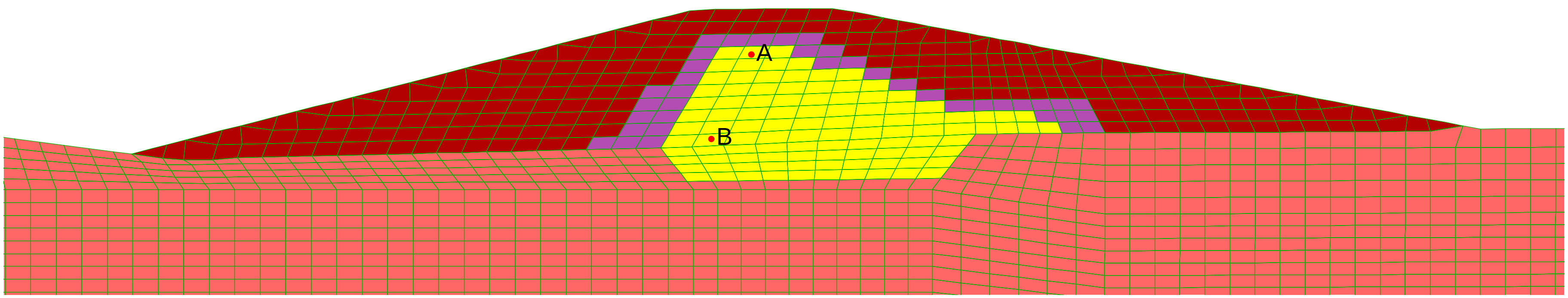
Date: 8/17/2016

Approved: AL

Figure: 4



Model Regions



Finite Difference Mesh

Notes:
1. Foundation layer in the FLCA mesh is shown until bedrock
2. Points A and B for stress history; see Figures 14 and 17

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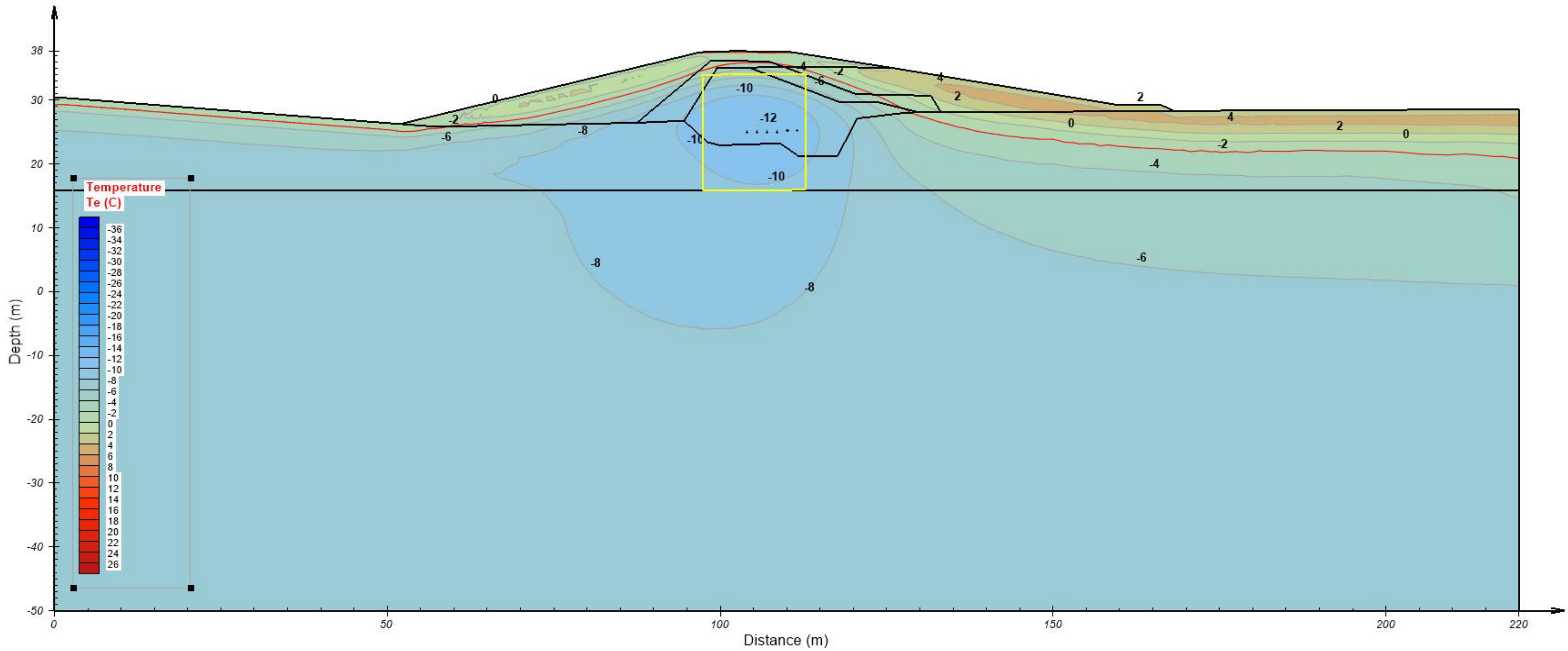
North Dam Creep Deformation Analysis

Model Set up – Section 0+85

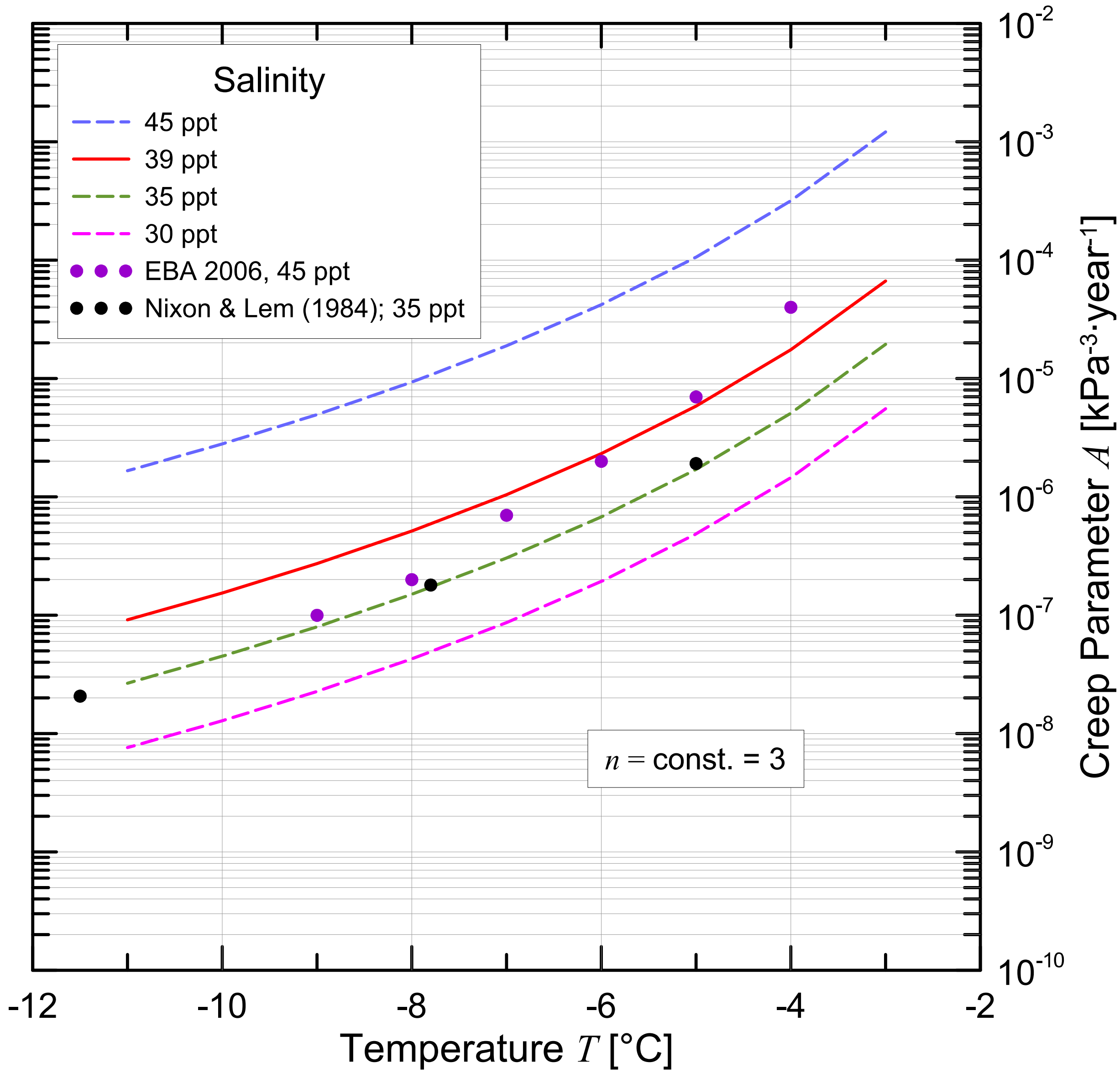
Job No: 1CT022.004 Filename: NorthDam_CreepAnalysis.pptx	HOPE BAY PROJECT	Date: 8/17/2016	Approved: AL	Figure: **5**



Notes:

1. Model results for year 10, maximum position of -2°C isotherm
2. Yellow bounding box indicates critical section based on thermal design criteria
3. Dam Section 0+85 with clay foundation
4. Five working thermosyphons
5. Source: SRK 2016b

srk consulting	MAC RESOURCES	North Dam Creep Deformation Analysis
		North Dam – Year 10 (Section 0+85)
Job No: 1CT022.004 Filename: NorthDam_CreepAnalysis.pptx	HOPE BAY PROJECT	Date: 8/17/2016 | Approved: AL | Figure: 6



srk consulting	TMAC RESOURCES	North Dam Creep Deformation Analysis **Creep Parameter *A* for the Marine Clayey Silt**
Job No: 1CT022.004 Filename: NorthDam_CreepAnalysis.pptx	HOPE BAY PROJECT	Date: 8/17/2016 · Approved: AL · Figure: 7