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Kiggavik Project

Environmental Impact Statement

Tier 3 Technical Appendix 5G

Thermal and Water Transport Modelling for the Waste Rock Piles and TMF

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Thermal and Water Transport Modelling for the Waste Rock Piles and TMF

Report Prepared for

Areva Resources Canada Inc.

Report Prepared by

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1 Introduction

Areva Resources Canada Inc. mandated SRK Consulting to complete a thermal and water transport modelling assessment for the waste rock piles and the covered tailings management facilities (TMF) for the Kiggavik Project. The work presented herein is based on our proposal dated August 13, 2010 and consists of the following tasks:

- Data review and compilation;
- Modelling of thermal conditions of the waste rock piles; and
- Evaluation of the water balance of the waste rock piles and the covered TMF.

The objectives of the assessment are to:

- Assess the thermal regime during the construction of the waste rock piles;
- Investigate whether persistent frozen conditions (permafrost) can be developed within the piles; and
- Estimate the rate of percolation through the pile and the covered TMF under unfrozen conditions.

The thermal and hydraulic conditions of the waste rock piles are important factors for controlling the migration of contaminants to surface and groundwater. Contaminant migration can be minimized by ensuring that the piles remain frozen for perpetuity.

This report provides a brief overview of the project's background followed by descriptions of the tasks and assessments listed above. Conclusions are provided at the end of the report.

1.1 Background

The Kiggavik Project site is located approximately 75 km west of Baker Lake in the Nunavut Territory. The proposed Kiggavik site currently includes three pits that will be mined: Main Pit, Centre Pit and East Pit. A purpose-built pit will be excavated specifically for water management. Waste rock piles will be constructed in the vicinity of the pits and will likely be covered at closure. The current mine plan is to use the pits for storing the tailings produced by the operation. The deposited tailings will subsequently be covered with waste rock to accelerate consolidation and to provide a physical barrier against the surrounding environment. This waste rock cover may also be covered with soil to support vegetation. Final closure concepts will be detailed in the Final Closure Plan for the site.

The site is well within the region of continuous permafrost, with the exception of probable taliks below large water bodies. At Kiggavik, the permafrost depth is approximately 210 m below ground surface. The mean annual air temperature (MAAT) is about -12°C and the mean annual surface temperature (MAST) is approximately -7°C. A weather station has been operating at the site but historical data has been developed using the dataset from Environment Canada weather station in Baker Lake.

2 Data Review and Compilation

Technical documents that were relevant to the work presented in this report were compiled and reviewed. Most of the documentation was provided by Areva. Other relevant papers and data were obtained from various public sources. The following list provides references that were consulted for this study:

- Areva (2010a): Climate Baseline (draft)
- Areva (2010b): Environmental Impact Statement (draft)
- Areva (2010c): Tailings Characterization and Management (draft)
- Golder (2010a): Estimated Inputs For Water Balances At Kiggavik – Revision
- Golder (2010b): Hydrology of Waste Rock Piles in Cold Climates (draft)
- Golder (2010c): Waste Rock Water Balance (draft)
- Neuner et al. (2009): Diavik Waste Rock Project: Unsaturated Water Flow
- Pham et al. (2009): Diavik Waste Rock Project: Heat transfer in experimental waste rock piles under permafrost environment

Historical climatic data was obtained from the Environment Canada weather station in Baker Lake. This dataset included the parameters to develop the boundary conditions for the thermal and water transport simulations. The data was adjusted to the Kiggavik conditions where applicable as per Areva (2010a). Environment Canada climatic data was downloaded from the following sites:

- Climate Data Online

http://climate.weatheroffice.gc.ca/climateData/canada_e.html

- Adjusted and Homogenized Canadian Climate Data

http://ec.gc.ca/dccha-ahccd/Default.asp?lang=En&n=B1F8423A-1

- Canadian Climate Normals 1971-2000

http://climate.weatheroffice.gc.ca/climate_normals/results_e.html?Province=NU%20%20&StationName=&SearchType=&LocateBy=Province&Proximity=25&ProximityFrom=City&StationNumber=&IDType=MSC&CityName=&ParkName=&LatitudeDegrees=&LatitudeMinutes=&LongitudeDegrees=&LongitudeMinutes=&NormalsClass=A&SelNormals=&StnId=1709&

- Canada Canadian Daily Climate Data (CDCD)

ftp://arcdm20.tor.ec.gc.ca/pub/dist/CDCD/

3 Thermal Conditions of the Waste Rock Piles

3.1 Introduction

The thermal model used for the assessment of the waste rock pile was configured to simulate thermal conditions during the construction of the pile as well as long term conditions. The objective of the modelling assessment was to evaluate the rate of permafrost development within the waste rock given different construction scenarios. This was achieved by varying the lift thickness, the sequence and season of deposition. The waste rock piles were modelled by placing two or five lifts with thicknesses of 5, 10 or 25 m. The lifts were placed at intervals of 6, 12 or 18 months; seasonal deposition varied between summer deposition (warmest) and winter deposition (coldest). For example, a simulation would evaluate the summer placement five lifts of 5 m at an interval of 12 months. The details for the thermal modelling is summarised in the following sections.

3.2 General Model Assumptions

It was assumed that the heat generation from the natural uranium and the oxidation process was too low to influence the thermal regime of the waste rock piles.

Convective cooling was considered to be negligible in this modelling assessment. The rate of convective heat transfer is dependent on several physical characteristics of the waste rock pile, in particular the permeability, which can be highly variable and difficult to estimate accurately. A modelling assessment completed in conjunction with the thermal modelling reported here confirmed that convective heat transfer would accelerate cooling of the waste rock. Therefore, the assumption of negligible convective cooling can be considered to be conservative in terms of predicting permafrost intrusion rates.

It was assumed that blasted rock would have reached thermal equilibrium when placed in the pile. The entire lift was assigned a constant temperature at the time of deposition.

3.3 Climate

The thermal modelling scenarios were based on the climatic conditions present at the Kiggavik and the ambient air temperature was fitted

as a sinusoidal function that represented seasonal fluctuations of the local air temperature according to the following expression:

$$Air\ temperature = MAAT + A\ \sin\left(\frac{2\pi * time}{365}\right)$$ [1]

The mean annual air temperature (MAAT) was set to -12°C and the mean annual air temperature amplitude (A) to 25°C. This equates to temperatures varying between+13 and -37 °C over one year (365 days).

The climate change was simulated by introducing a warming trend of 5°C over a 100 year period as per Areva (2010c). This warming represents the extreme case for climate change as presented in (SRK Consulting 2008). The magnitude of the climate change is however subject to great

[1] *Time in days*

uncertainties. This warming trend was divided into two segments. The initial segment was a constant warming of 3°C over the first 30 years following completion of the pile. This was followed by a 2°C warming distributed over the subsequent 70 years. The ultimate MAAT of -7°C was then maintained in perpetuity. The climate change scenario was applied after the pile was fully constructed, i.e. when all the lifts were placed.

3.4 Numerical Model

Thermal modelling was carried out using the finite element model SVHEAT version 6 developed by SoilVision Systems Ltd. and FlexPDE version 6.15 developed by PDE Solutions Inc.

SVHEAT models heat transport for both steady-state and time-dependent analyses using the FlexPDE solver. It incorporates the latent heat associated with phase changes of water. The model supports geometries in 1D, 2D or 3D. SVHEAT supports multiple boundary conditions as well as transient boundary conditions. Further details are available in the User's Manual of SVHEAT (SoilVision Systems 2009).

FlexPDE is a general purpose partial differential equation (PDE) solver that is based on the finite element method. FlexPDE can solve a multitude of PDE problems in 1D, 2D and 3D spaces. More information is available in the User's Manual of FlexPDE (PDE Solutions 2010).

3.5 Geometry

The construction of the waste rock pile was simulated using a 2D geometry with a 1 m width. The unit width was chosen to simulate a 1D model while enabling certain 2D features. The sequence of construction consisted of three scenarios:

- Two lifts of 25 m each
- Five lifts of 5 m each
- Five lifts of 10 m each

All waste rock geometries were placed on a 100 m thick bedrock layer. Each lift included a 0.5 m thick traffic zone at the top using the waste rock traffic material. Overburden was not included in these simulations.

3.6 Deposition sequence

The deposition sequence of the waste rock was simulated by placing a lift of waste rock using intervals of 6, 12 or 18 months. Lifts were incorporated instantaneously into the model. For example, a five lift pile with a deposition interval of 12 months took five years to complete, i.e. one lift per year. The deposition sequence is illustrated in the Figure 3.1 below.

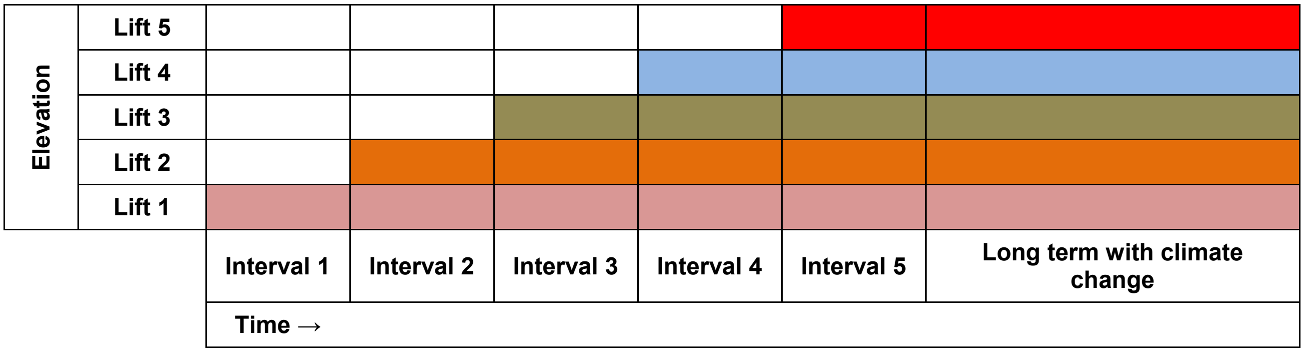

Figure 3.1: Schematic of modelled deposition sequence

Waste rock material placed in winter and summer were assigned constant temperatures of -25.9°C and 15.3°C, respectively. These temperatures correspond to the estimated ground temperatures at the time of deposition. The 6 and 18 month intervals alternated between winter and summer deposition.

3.7 Material Properties

Three material types were used in the simulations, namely coarse waste rock, waste rock subject to traffic, and bedrock. The thermal properties used in the simulations are summarised in Table 3 1. The properties of the bedrock are based on the values presented in Areva (2010c). The properties of the waste rock material were deducted from the properties of the bedrock as a granular material and on the observations reported by Neuner et al. (2009). Traffic zone waste rock has higher water content as a result of the higher fraction of fines.

Table 3.1: Thermal Properties of Waste Rock and Bedrock

Material	Thermal conductivity [kJ/(day m C)]		Volumetric heat capacity [kJ/(m^3 C)]		Porosity	Volumetric water content
	Unfrozen	Frozen	Unfrozen	Frozen		
Waste rock traffic	135	161	2099	1722	0.30	0.18
Waste rock	71	74	1597	1471	0.30	0.06
Bedrock	271.9	275.5	2314	2293	0.01	0.01

3.8 Boundary Conditions

Conductive heat transfer is a function of the surface temperature of the waste rock pile. Therefore, the boundary condition along the top surface of the model was resolved by converting the time dependent ambient temperature (discussed in Section 3.3) to surface temperatures. The temperature conversion relied on the freezing (nf) and thawing (nt) indices to represent the variation of heat transfer when the air temperature was above or below the freezing point (0°C). Calibrated thermal modelling performed for the Hope Bay Gold Mine Project (SRK Consulting 2005) with similar ground and climatic conditions as Kiggavik had a value of 0.7 for nf and 1.0 for nt. The nt value was adjusted to 1.18 to obtain a mean annual surface temperature (MAST) of -7°C that was observed at the Kiggavik site. The surface of the waste rock was assigned a value of 2 for nt to reflect the higher heat transfer during the summer months. Such nt values see the surface temperature peak at 15.3°C with a nt value of 1.18, and 26°C with a nt value of 2.0. The nf value was kept to 0.7 as it is controlled primarily by the snow cover in winter. The influence of nt and nf on the MAST was also assessed by calculating the MAST using the sinusoidal function described above.

The start value of the sinusoidal function was adjusted to reflect the season at which the deposition was initiated. The function would begin at the cold peak for winter deposition and at the warm peak for summer deposition. As mentioned previously, the waste rock material was assigned a constant temperature at placement.

The bottom boundary was assigned a constant geothermal heat flux of 8278 J day^{-1} m^{-2} that corresponded to the permafrost depth of 210 m when using the thermal properties of the bedrock listed in Table 3.1.

3.9 Simulations

The influence of the nf and nt indices combined with the warming effects of climate change was assessed prior to completing the modelling scenarios. It consisted of estimating the MAST using the sinusoidal function that was used for top boundary condition. The assessment provided some indication on the sensitivity of the MAST for various nf and nt values and climate conditions.

Ten different deposition scenarios were evaluated using the numerical model. The variables were:

- Lift thickness;
- Deposition season; and
- Time elapsed between placements of lifts.

Long term simulations with climate were performed for selected cases. Table 3.2 lists the simulations that were performed for this study.

Each lift placement had to be simulated individually. The initial condition for subsequent lifts was the end condition of the previous lift. This sequence of modelling was followed for all the lifts and the long term simulations.

Table 3.2: Simulations Performed

No. of lifts	Lift thickness (m)	Length of deposition cycle (month)	Season at deposition	Long term with climate change
5	5	12	winter	
5	5	12	summer	Yes
5	5	6	winter & summer	Yes
5	5	18	winter & summer	
5	10	12	winter	Yes
5	10	12	summer	Yes
5	10	6	winter & summer	
5	10	18	winter & summer	
2	25	12	winter	
2	25	12	summer	Yes

3.10 Results

3.10.1 Mean Annual Surface Temperature (MAST)

MAST values were calculated by varying the freezing and thawing indices, and by including climate change on selected cases as indicated in Table 3.3. The MAST was calculated with the sinusoidal function described in Section 3.3.

Table 3.3: Estimated MAST Values Under Various Conditions

MAAT (°C)	n_f	n_t	Estimated MAST (°C)	Comment
-12	0.7	1.00	-7.5	Calibrated model from other mine site
-12	0.7	1.18	-7.0	Natural ground at Kiggavik
-7	0.7	1.18	-2.6	Natural ground + warming
-12	0.7	3.09	-1.5	T < 0 °C at base of 50 m of waste rock, geothermal gradient of 30 °C/km
-12	0.7	3.26	-1.0	T < 0 °C at base of 50 m of waste rock, geothermal gradient of 20 °C/km
-12	0.7	3.43	-0.5	T < 0 °C at base of 50 m of waste rock, geothermal gradient of 10 °C/km
-7	0.7	1.41	-1.5	T < 0 °C over 50 m of waste rock, geothermal gradient of 30 °C/km + warming
-7	0.7	1.52	-1.0	T < 0 °C over 50 m of waste rock, geothermal gradient of 20 °C/km + warming
-7	0.7	1.62	-0.5	T < 0 °C over 50 m of waste rock, geothermal gradient of 10 °C/km + warming
-12	0.7	2.00	-4.6	Waste rock surface
-7	0.7	2.00	1.3	Waste rock surface + warming
-12	0.9	2.00	-7.6	Waste rock surface, higher n_f
-7	0.9	2.00	-1.1	Waste rock surface, higher n_f + warming

The initial freezing and thawing indices of 0.7 and 1.0 listed above are based on the Hope Bay Gold Mine Project (SRK Consulting 2008) that were obtained from a calibrated thermal model for climatic and ground conditions similar to Kiggavik. The thawing index was adjusted to obtain a MAST of -7°C to reproduce the MAST observed at Kiggavik. The warming effect of climate change over the long term was represented by increasing the MAAT from -12 to -7°C in the calculations. The estimated MAST values show that:

- Undisturbed ground surfaces (natural ground) will likely retain permafrost after a warming of 5°C;
- Permafrost would eventually develop in the waste rock piles if warming from climate change is excluded;
- Permafrost could become marginal or even disappear at the base of the pile if warming from climate change is applied, as indicated by the values of nt hovering around 1.5. The thermal regime associated with snow accumulation and the albedo of the ground surface could become critical. This assumes that the waste rock pile would be spread over a large area; and
- With an nt value of 2, permafrost would eventually disappear following a warming of 5°C from climate change.

Although approximate, the above calculations show that the waste rock piles may not maintain permafrost under certain conditions over the long term.

3.10.2 Deposition sequence

The results of the thermal modelling showed that the deposition season and sequence are important for the rate of permafrost development within the waste rock pile.

Figure 3.2 shows the temperature profile for individual lifts within a 50 m high waste rock pile with five 10 m lifts placed in the summer. Figure 3.3 shows the same scenario but with winter deposition. The corresponding long-term thermal profiles for the waste rock pile are shown in Figure 3.4 and Figure 3.5 (summer and winter placement, respectively).

Winter deposition establishes and maintains frozen conditions as the material is placed, while the summer deposition prevents the short-term development of frozen conditions in the waste rock because of the relatively slow rate of conductive cooling. Waste rock placed in the summer will gradually attain a steady state of freezing temperatures but the process will take several decades (Figure 3.4). For instance, the waste rock pile constructed during the summer months would require more than 15 years before the bottom lift would freeze. Similarly, the temperature of waste rock deposited in the winter will gradually increase to a steady state temperature over the course of several decades (Figure 3.5).

The time required to reach the steady temperatures in the waste rock pile is dependent on the thickness of the lifts. A waste rock pile constructed with 5 m lifts to an ultimate height of 25 m (Figure 3.6) reaches steady state temperatures after approximately 10 years following completion of construction. A 50 m pile constructed of two 25 m lifts (Figure 3.7) requires more than 30 years to reach steady state temperatures.

Figure 3.8 shows the effect of alternating summer and winter deposition on the thermal regime of the waste rock pile. The modelling scenario considered deposition intervals of 6 and 18 months for five lifts of 10 m. The waste rock material generally freezes within two deposition cycles. The equilibrium temperature attained when blending equal volumes of waste rock with winter and summer temperatures (-25.9°C and 15.3°C, respectively) is approximately -7.5°C. Therefore, alternating the deposition of waste rock with similar lift heights between summer and winter ensures that the net temperature within the pile remain at freezing conditions.

The presence of the traffic zones had insignificant effects on the thermal regime, although their presence would reduce with the effectiveness of convective cooling because of their lower permeability. A complete set of figures is included in Appendix 1 of this report.

As noted above, convective effects were not included in the modelling. They are expected to further cool the rock, and could be used to compensate for summer deposition.

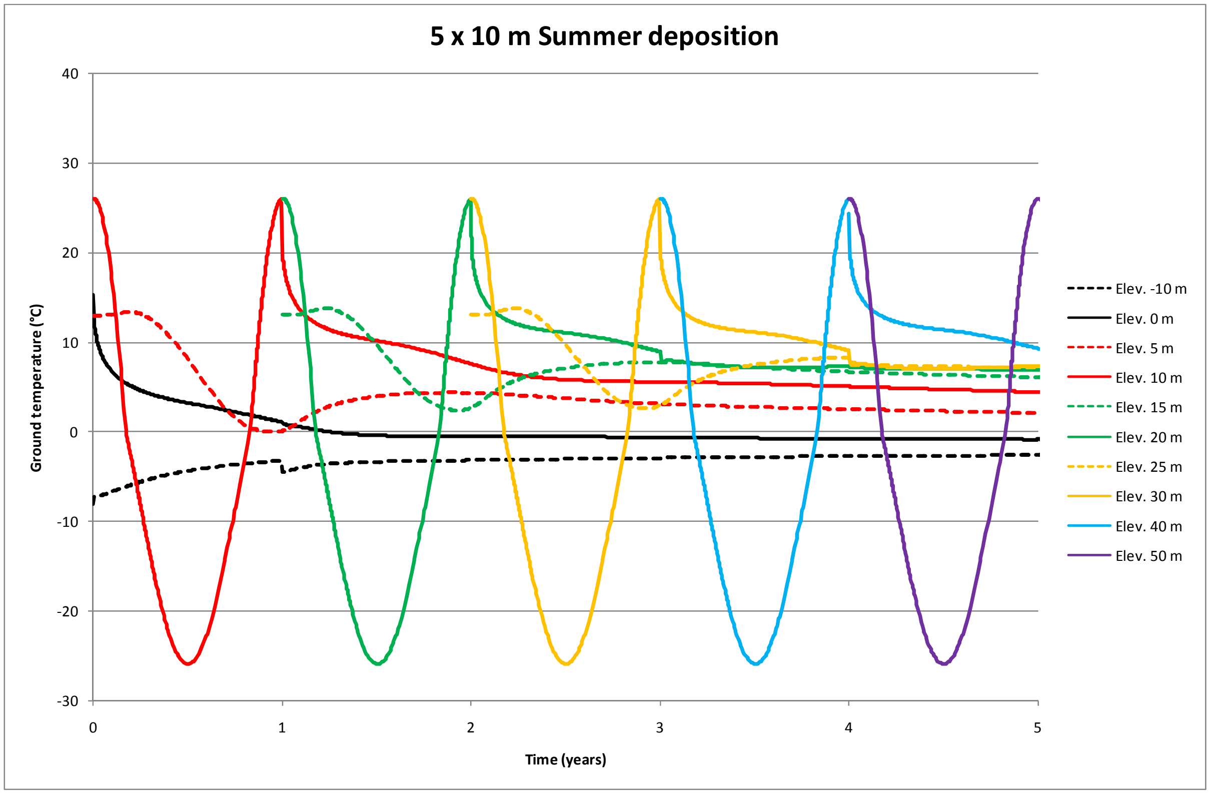

Figure 3.2: 50 m High Waste rock Pile (5 lifts of 10 m), Summer Deposition, 0 to 5 Years

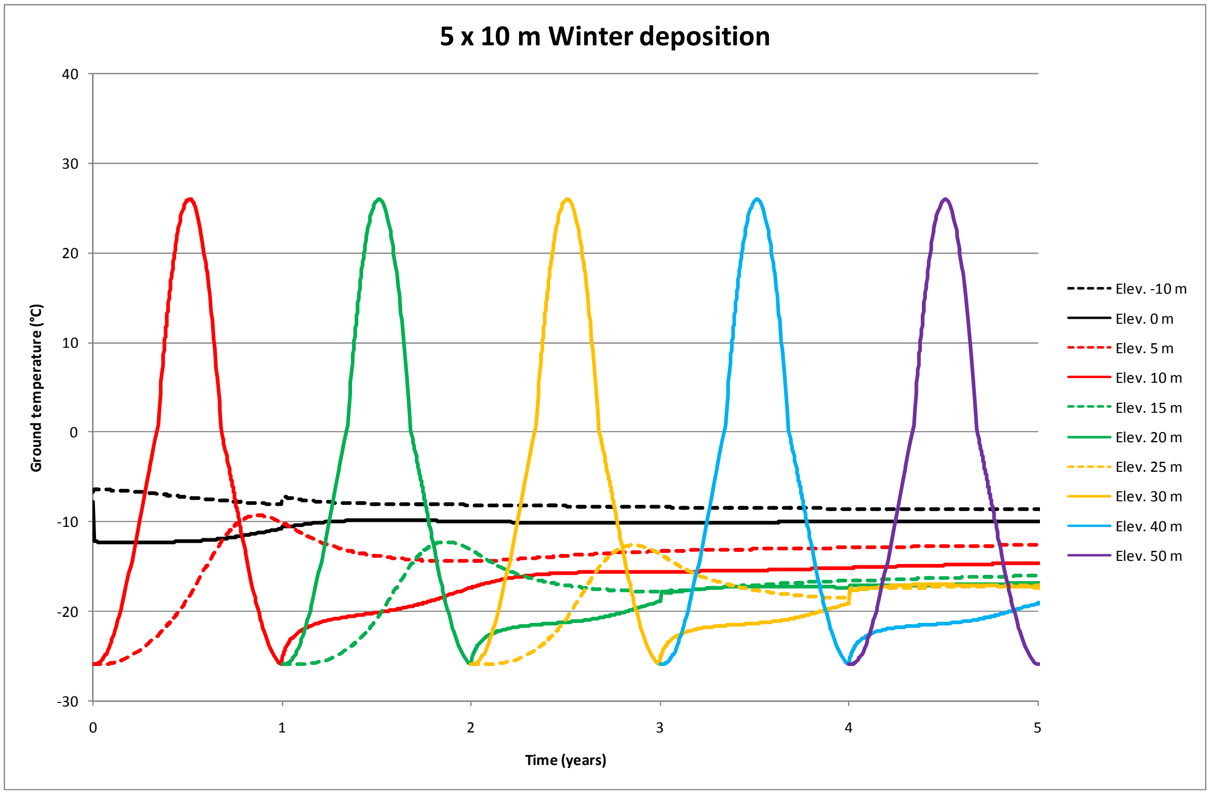

Figure 3.3: 50 m High Waste rock Pile (5 lifts of 10 m), Winter Deposition, 0 to 5 Years

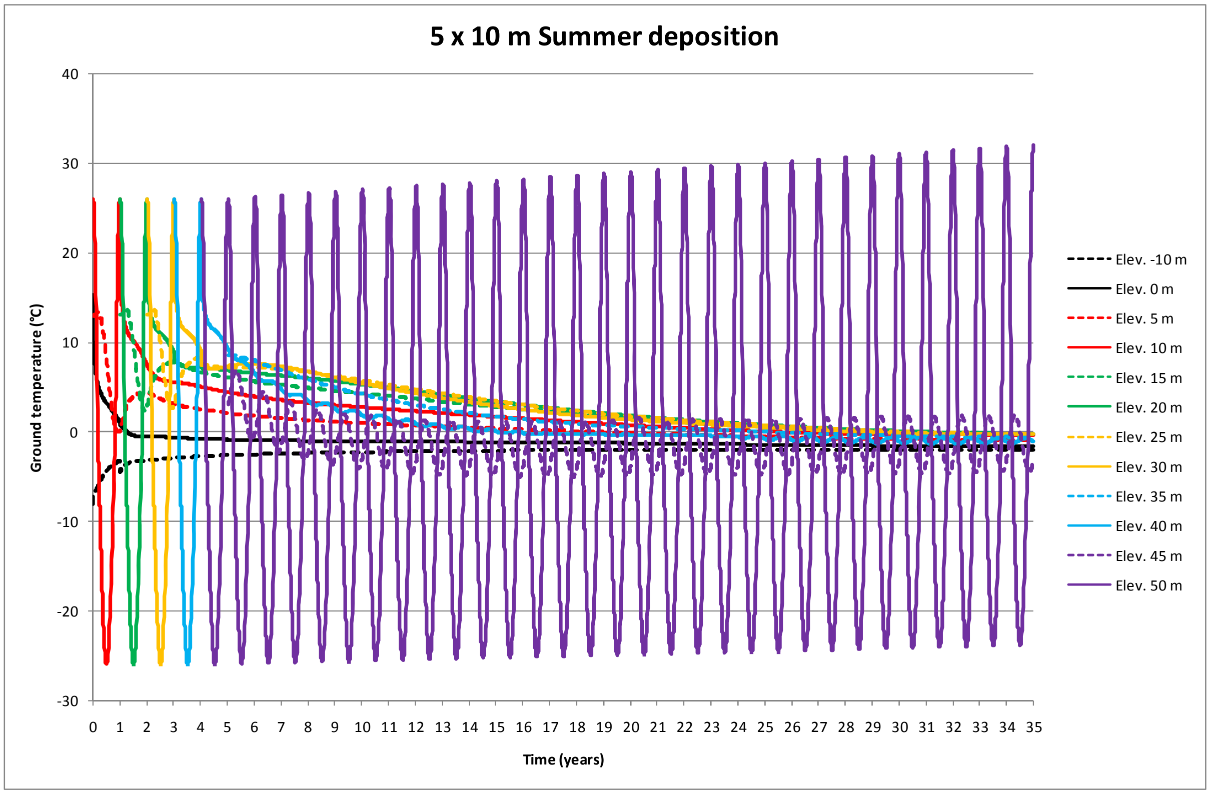

Figure 3.4: 50 m Waste Rock Pile (5 lifts of 10 m), Summer Deposition, 0 to 35 years

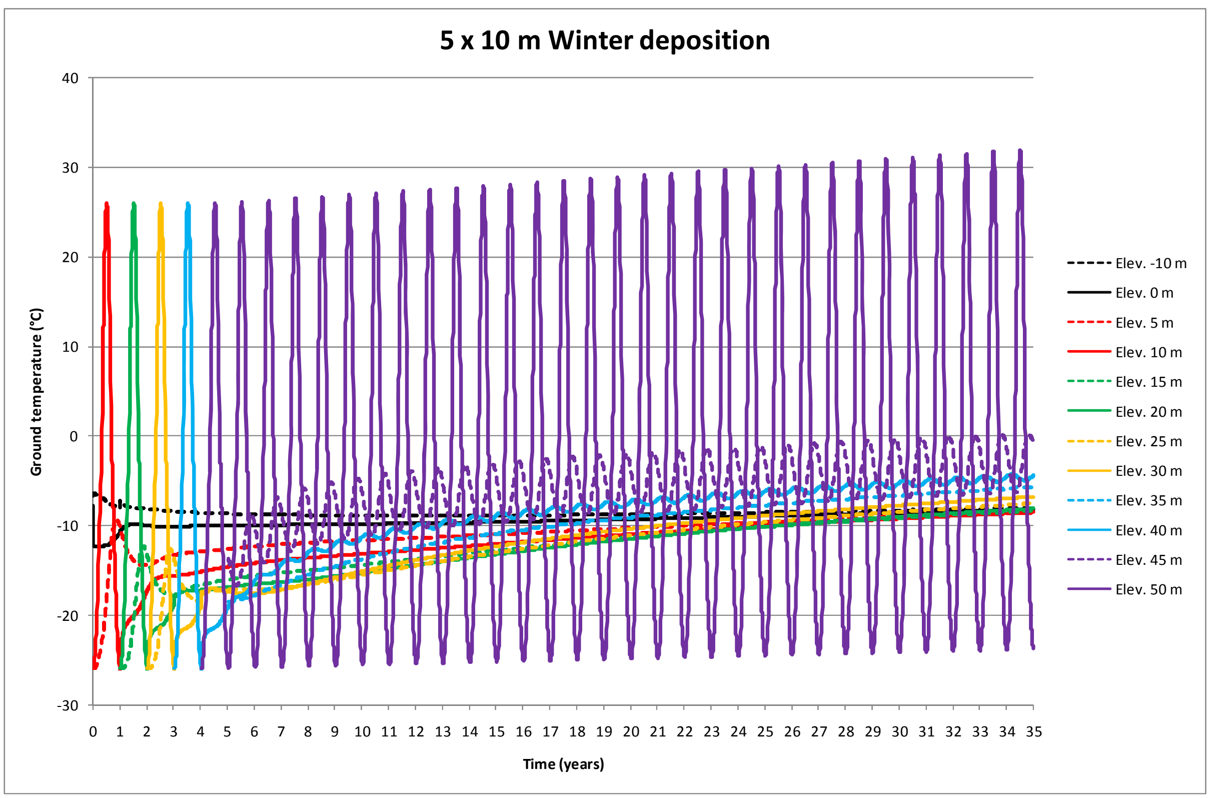

Figure 3.5: 50 m Waste Rock Pile (5 lifts of 10 m), Winter Deposition, 0 to 35 years

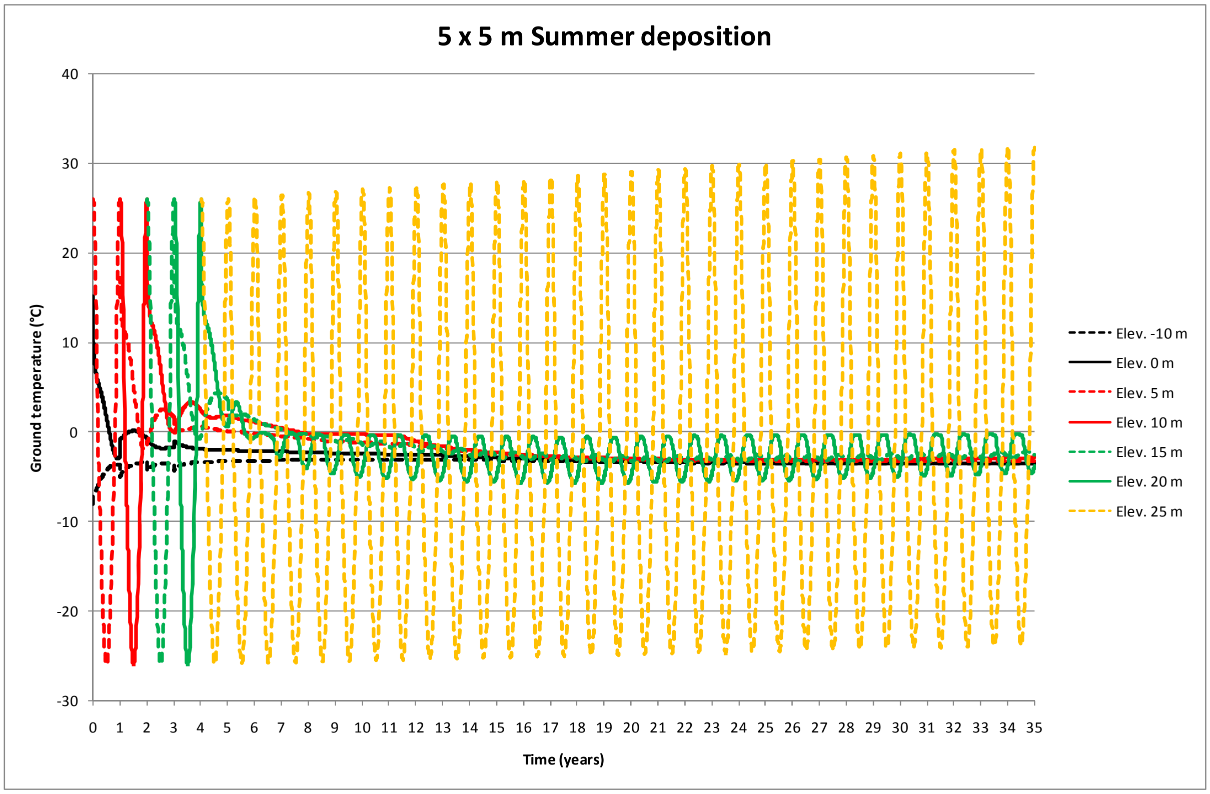

Figure 3.6: 25 m Waste Rock Pile (5 lifts of 5 m), Summer Deposition, 0 to 35 years

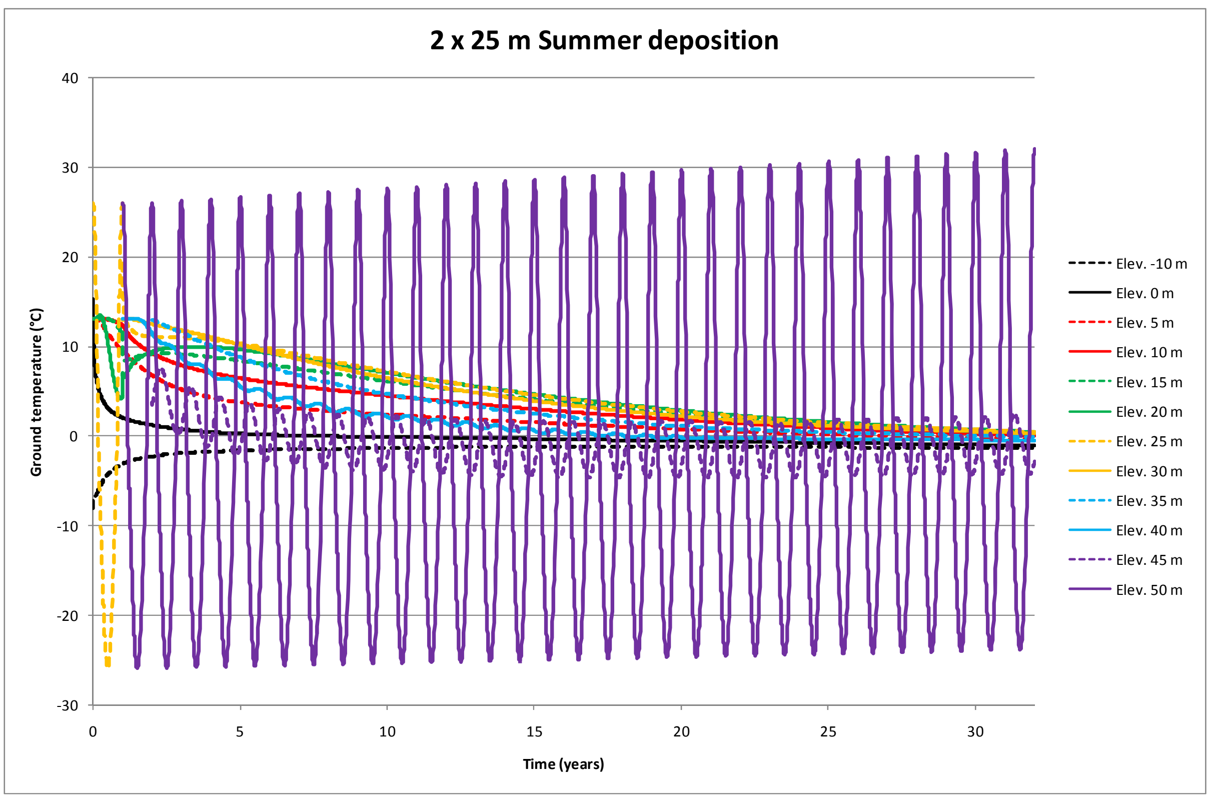

Figure 3.7: 50 m Waste Rock Pile (2 lifts of 25 m), Summer Deposition, 0 to 35 years

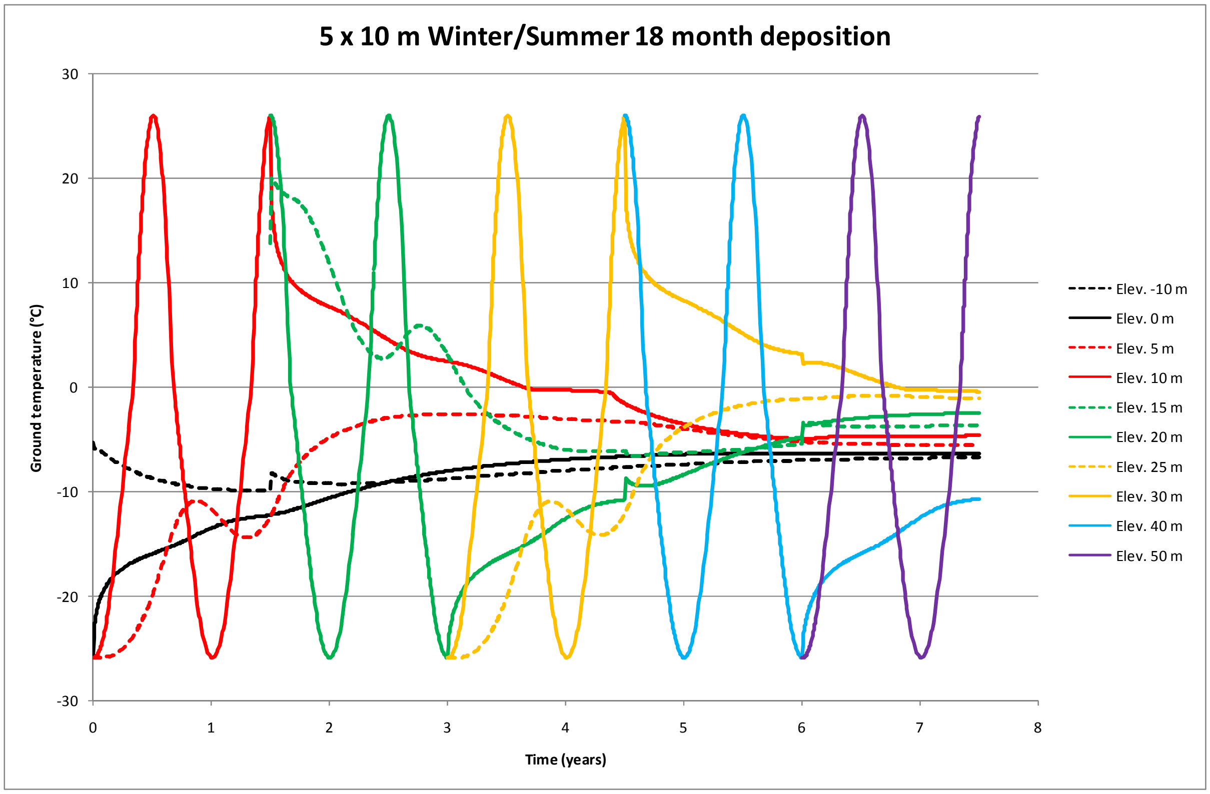

Figure 3.8: 50 m Waste rock pile (5 lifts of 10 m), winter/summer deposition at 18 month intervals, 0 to 7.5 years

4 Water Balance at the Waste Rock Piles and Covered TMF

4.1 Introduction

The water balance of the waste rock piles and the covered TMF was assessed using a water transport model that incorporated the climatic conditions at the Kiggavik site. The objective was to estimate the net percolation through the entire profile. The simulations were applied to uncovered and covered waste rock profiles.

As mentioned earlier, the tailings will be stored in the depleted pits and then covered with 10 m or more of waste rock. The thick waste rock cover is intended to accelerate the consolidation of the tailings and to provide a barrier at the ground surface. The water table will likely be 10 m or more below the surface of the cover. Such condition is essentially equivalent to having a 10 m high waste rock profile with a water table at the bottom.

The terms “infiltration” and “percolation” are used interchangeably in some literature, but other literature distinguishes the “infiltration” of water through the soil surface from the “percolation” of water downwards through the soil profile. That distinction is important in arid regions, where water that has penetrated the soil surface can subsequently be removed by a number of processes, meaning that “percolation” can be much less than “infiltration”. To avoid confusion, the term “net percolation” will be used herein to refer to the water that continues to move into the soil and ultimately reports to groundwater.

4.2 Diavik Mine Research on Waste Rock

The research work at the Diavik Mine (Neuner et al. 2009, Pham et al. 2009, and Golder 2010b) provides valuable information on the water balance and thermal aspects of the waste rock material under climatic conditions that are similar to Kiggavik. Their measurements indicate that the net percolation is about 39 percent of total precipitation. The work also provides an excellent description of water transport in waste rock material. The hydraulic properties of the waste rock material were measured and are used in the water transport model presented herein.

4.3 Numerical Model

The soil water modelling was performed using Hydrus-1D software Version 4.14. (Simunek et al. 2008). Hydrus-1D numerically solves Richard’s equation for variably saturated water flow, subject to a range of user input material properties and boundary conditions. The model was developed as a cooperative effort of the U.S. Salinity Laboratory and the University of California at Riverside. It is one of the most widely used models for simulating unsaturated water flow in soils.

4.4 Geometry

Two waste rock profiles were modelled. The main profile consisted of a 25 m thick vertical profile that included 0.5 m zones to represent traffic zones. This profile was to represent a waste rock pile constructed in five lifts of 5 m each, with the top 0.5 m of each lift being composed of finer material to represent traffic zones. A soil cover was incorporated in some of the simulations, and consisted of adjusting the hydraulic properties of the top traffic zones to represent the cover material. Figure 4.1 illustrates the geometry that was modelled with Hydrus-1D.

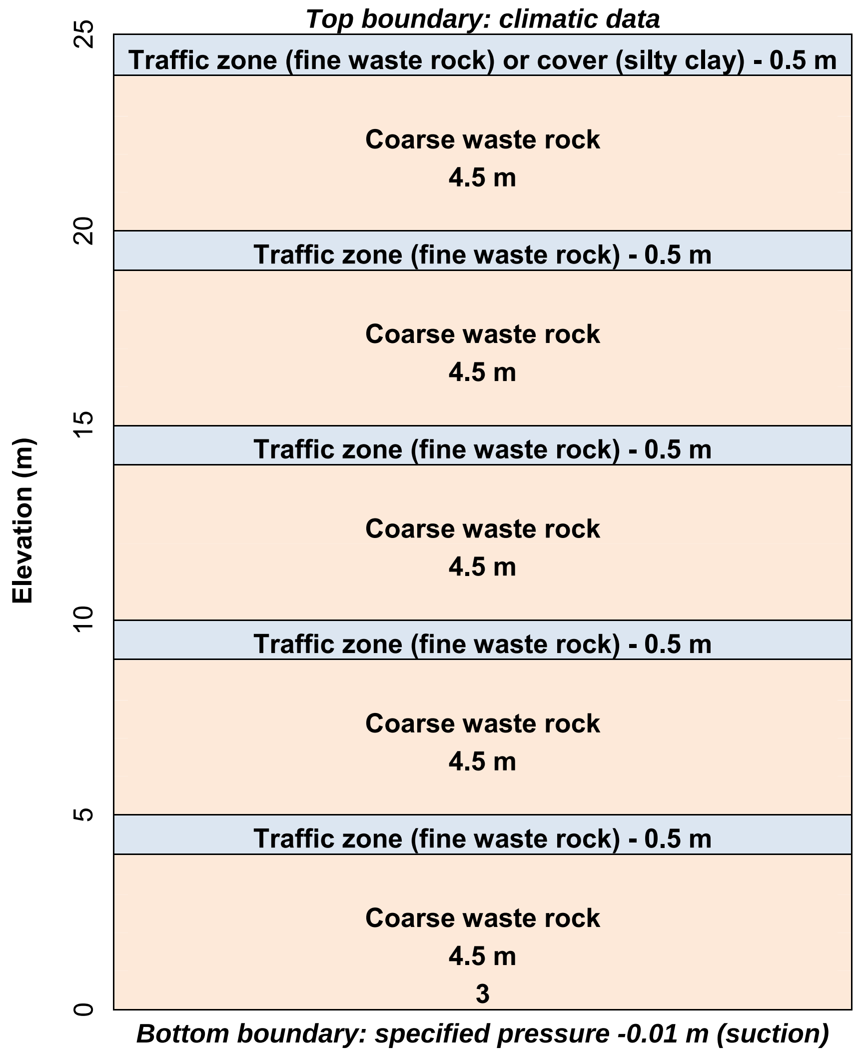

Figure 4.1: Geometry modelled in Hydrus-1D.

A few simulations were performed with a 10 m thick profile for representing the waste rock cover on top of the TMF. This 10 m profile was based on two 5 m lifts with a top 0.5 m zone for the traffic zones in both lifts.

4.5 Material Properties

Three material types were used in the simulations: coarse waste rock, fine waste rock and silty clay. The silty clay was used in some simulations to represent the inclusion of a soil cover over the waste rock profile. The properties of the waste rock material (fine and coarse) are based on the values presented in Neuner et al. (2009) for the Diavik Mine. The hydraulic properties of the silty clay were selected from Hydrus-1D (Simunek et al. 2008). The hydraulic properties were modelled according to the van Genuchten-Mualem model with the air entry value limited to 0.02 m of suction. The parameters used to define the hydraulic properties of the materials are listed in Table 4.1.

Table 4.1: Hydraulic Properties

	Volumetric water content		Saturated hydraulic conductivity	α	η	l
	Residual	Saturated	(m/s)	(1/m)		
Fine waste rock	0.01	0.25	9.0E-06	5.9	1.45	0.5
Coarse waste rock	0.01	0.25	1.0E-02	1.6	4.00	0.5
Silty clay	0.07	0.36	5.6E-08	0.5	1.09	0.5

The parameters α and η are for the soil water retention function while l is the tortuosity parameter in the hydraulic conductivity function.

4.6 Boundary and Initial Conditions

The boundary condition at the surface is based on the data presented in Golder (2010c) and Areva (2010a). The climatic data is based on the dataset collected in Baker Lake and adjusted to the Kiggavik site. The dry and wet years developed by Golder (2010c) were used as the basis for the climate conditions for the top boundary. The average climatic year was not used in the simulations. The selected dry year is based on the climate data collected in 1999 which has a total precipitation of 263 mm. The selected wet year is 2004 and has a total precipitation of 530 mm. The average total precipitation for the dataset is 387 mm.

The dataset used in the model was reconstructed using data from Environment Canada and using the adjustments presented in Golder (2010c) and Areva (2010a) to obtain the climatic conditions at Kiggavik.

The top boundary condition consisted of specifying daily values of climatic parameters that were dependent on the scenario being modelled. The parameters used for the water transport modelling are as follow:

- Air temperature: daily average data provided by Environment Canada (2011b) and adjusted to Kiggavik.
- Total precipitation (rain + snowfall water equivalent “SWE”): based on daily values provided by Environment Canada (2011b), adjusted according to Environment Canada (2011a) to obtain corrected daily values and then adjusted to Kiggavik.
- Wind speed: daily average calculated from hourly data provided by Environment Canada (2011b) and adjusted to Kiggavik.
- Relative humidity: daily average calculated from hourly data provided by Environment Canada (2011b) and adjusted to Kiggavik.
- Radiation: based on monthly averages for Baker Lake over the period between 1969 and 2003 (Golder 2010c).
- Potential evaporation: (PE) based on the curves presented in Golder (2010c) for the wet and dry years. The total potential evaporation used in the model was 164 mm for the dry year and 287 mm for the wet year. The alternative is to let Hydrus-1D calculate the potential evaporation based on Penman-Monteith combination equation (Simunek et al. 2009).

Most of the modelling scenario consisted of varying the top boundary conditions. The main variants are as follow:

- Climate: dry or wet
- Potential transpiration: specified or calculated
- Total precipitation: Total, no infiltration when air temperature > -2 °C and > 0 °C
- Intensity of precipitation: daily precipitation distributed over 6 and 24 hours

The adjustments applied to total precipitation were to compensate for the minimal snow cover that will be expected on the top of the waste rock piles prior to the snowmelt at Kiggavik (Golder 2010c). Most of the snow is expected to be blown away. Snow will however accumulate along the side slopes of the piles but most of it will be lost to sublimation/evaporation and surface runoff. The boundary condition consisted of having precipitation only when the ambient air temperature was above -2 or 0°C. The table below provides the annual total for those precipitation scenarios.

Table 4.2: Annual precipitation values for boundary conditions

	Precipitation (m)		Ratio Over Total	
	Wet year	Dry year		
Total precipitation	0.530	0.263		
Precipitation when T > -2°C	0.253	0.142	48%	54%
Precipitation when T > 0°C	0.303	0.170	57%	65%

The intensity of the precipitation was arbitrarily set by distributing the daily precipitation over a period of 6 hours instead of 24 hours.

The bottom boundary consisted of specifying a constant suction of 0.01 m simply to avoid saturation at the bottom for numerical aspects. This is equivalent to have a water table 0.01 m below the bottom of the waste rock pile.

The influence of the initial conditions was avoided by running the scenarios over several years until the water balance was relatively constant over subsequent years. The results presented herein were taken at the end of cycled scenarios.

4.7 Results

The modelling results show that 30 to 50 percent of the total precipitation will percolate through uncovered waste rock piles under the climatic conditions at Kiggavik. These results are consistent with the research work at Diavik (Pham et al. 2009, Neuner et al. 2009). As summarised in Table 4.3, the net percolation will likely vary between 50 and 150 mm under unfrozen conditions. The net percolation from the 10 m profile was essentially identical to the 25 m profile.

The water transport reported herein assumes that the porous media would not be obstructed by frozen pore water, i.e. the effective porosity was not reduced by frozen pore water. The thermal modelling demonstrated that the waste rock material will freeze under the current climatic conditions. This means that percolating water will freeze inside the waste rock pile. The amount of frozen pore water will accumulate over time and it can be expected that this accumulation of frozen pore water will eventually block the flow paths. The percolation values mentioned above would eventually be limited to the freeze-thaw zone near the surface (active zone). The bulk of the waste rock pile would consequently be isolated from percolating water, and therefore, restrict the transport of contaminants that could be present in the waste rock material. The obstruction of the flow paths at the base of the active zone will likely create perched groundwater conditions, induced ponded water in depressions, and increase lateral flow along sloped areas. Large cavities within the waste rock profile would obviously delay the development of the frozen “seal”. The configuration of the waste rock piles should include those aspects in their design, in particular for post-closure.

The percolation was reduced to 5 percent or less when a 0.5 m thick silty clay was placed on top of the waste rock profile. These simulations did not include the presence of vegetation. The inclusion of vegetation would have reduced further the net percolation through the profile. The simulations clearly demonstrated that a fine grained soil cover would reduce the net percolation in addition to isolate the waste rock material.

The influence of the traffic zones is clearly visible in the volumetric water content profile shown in Figure 4.1 and the corresponding degree of saturation in Figure 4.2. The finer particles present in the traffic zones will retain more pore water up to 40 percent of saturations. The results were similar for the wet and dry climates. Those traffic zones will restrict and eventually act as barriers to downward water movement once the waste rock profile freezes as shown previously. They would also restrict the movement of oxygen once the frozen pore space is filled with sufficient ice.

The amount of water stored within the 25 m high profile is in the order of 0.7 m, or alternatively a volumetric water content of about 3 percent (0.7m/25m) for the 25 m high profile. If we assume an average climatic year with a total precipitation of 387 mm and an average percolation of 40 percent, the net percolation would be about 150 mm per year. It would require 4.5 years or more to fill the pore space with that amount of water in a dry waste rock profile. This would be under “ideal” conditions, i.e. fully homogenous. The “real” behaviour of the pile will obviously be different. For instance, the waste rock will likely be placed with some moisture; the heterogeneity of the waste rock material will involve preferential flow paths; the frozen traffic zones will restrict water flow or even isolate certain zones of the pile; etc. Nonetheless, it can be expected that the time to reach a form of “hydraulic equilibrium” would be measured in terms of several years. The frozen conditions could however encapsulate large dry zones within the pile, and consequently maintain zones that will be deficient in water but isolated from percolating pore water.

The net percolation was essentially the same when the water table was set to either 10 or 25 m below surface. This pattern indicates that the interpretation of the results for the waste piles is also valid for the cover of the TMF.

Table 4.3: Modelling Results, Net Percolation

Case No.	Climate	Case	Precipitation Total (mm)	Precipitation Duration (hour)	Potential Evaporation PE (mm)	PE Method	Infiltration (mm)	Actual Evaporation AE (mm)	Snow Water Equivalent SWE (mm)	Surface Runoff (mm)	Net percolation (mm)	Ratio Net percol./ Precip.
1	Wet	Daily precipitation over 24 hours with evaporation	530.0	24.0	287.0	Golder	530.0	154.5	0.0	0.0	375.5	71%
2	Wet	Same as Case 1 with precipitation over 6 hours	530.0	6.0	179.4	Golder	530.0	123.1	0.0	0.0	406.9	77%
3	Wet	Same as Case 2 with evapo calculated with Penman-Montheith	530.0	6.0	813.3	Golder	530.0	222.8	0.0	0.0	307.3	58%
4	Wet	Same as Case 3 but with thermal heat transfer	510.1	6.0	735.0	Model	372.1	196.5	138.0	0.0	313.6	61%
5	Wet	Same as Case 2 with winter precip. spread over 7 days once T ambient > 0°C	530.0	6.0	179.4	Golder	530.0	134.2	0.0	0.0	395.8	75%
6	Wet	Same as Case 3 with winter precip. spread over 7 days once T ambient > 0°C	275.0	6.0	813.3	Model	275.0	79.2	0.0	0.0	195.8	71%
7	Dry	Daily precipitation over 24 hours with evaporation	263.0	24.0	287.0	Golder	263.0	95.1	0.0	0.0	167.9	64%
8	Dry	Same as Case 1 with precipitation over 6 hours	263.0	6.0	179.4	Golder	263.0	85.6	0.0	0.0	177.4	67%
9	Dry	Same as Case 2 with evapo calculated with Penman-Montheith	263.0	6.0	755.0	Golder	263.0	116.4	0.0	0.0	146.6	56%
10	Dry	Same as Case 3 but with thermal heat transfer	234.3	6.0	638.3	Model	163.3	105.5	71.0	0.0	128.8	55%
11	Dry	Same as Case 2 with winter precip. spread over 7 days once T ambient > 0°C	262.9	6.0	179.4	Golder	262.9	94.4	0.0	0.0	168.5	64%
12	Dry	Same as Case 3 with winter precip. spread over 7 days once T ambient > 0°C	117.9	6.0	755.0	Model	117.9	58.5	0.0	0.0	59.4	50%
13	Wet	Same as Case 2 with silty clay cover	528.9	6.0	-69.2	Golder	281.3	123.0	0.0	247.6	158.3	30%
14	Wet	Same as Case 3 with silty clay cover	521.7	6.0	592.4	Model	309.1	197.2	0.0	212.6	111.9	21%
15	Dry	Same as Case 8 with silty clay cover	269.4	6.0	111.4	Golder	195.0	98.8	0.0	74.3	96.2	36%
16	Dry	Same as Case 9 with silty clay cover	261.8	6.0	682.3	Model	190.3	126.0	0.0	71.5	64.3	25%
17	Wet	Same as Case 9 with silty clay cover	523.3	6.0	592.8	Model	309.5	198.6	0.0	213.8	110.9	21%
18	Wet	Same as Case 2 but with rain only when T < -2°C	303.2	6.0	179.4	Golder	303.2	122.7	0.0	0.0	180.6	60%
19	Wet	Same as Case 2 but with rain only when T < 0°C	253.2	6.0	179.4	Golder	253.2	117.2	0.0	0.0	136.0	54%
20	Wet	Same as Case 19 but with evapo calculated with Penman-Montheith	253.2	6.0	813.3	Model	253.2	172.4	0.0	0.0	80.8	32%
21	Wet	Same as Case 19 but with silty clay cover	252.2	6.0	58.9	Golder	132.7	119.2	0.0	119.5	13.5	5%
22	Wet	Same as Case 21 but with evapo calculated with Penman-Montheith	246.7	6.0	713.4	Model	153.3	156.9	0.0	93.4	-3.5	-1%
23	Wet	Same as Case 20 but water table at 10 m depth	253.2	6.0	813.3	Model	253.2	171.6	0.0	0.0	81.6	32%
24	Dry	Same as Case 19 but dry climate	141.6	6.0	179.4	Golder	141.6	77.6	0.0	0.0	64.0	45%
25	Dry	Same as Case 20 but dry climate	141.6	6.0	755.0	Model	141.6	90.6	0.0	0.0	51.0	36%
26	Dry	Same as Case 21 but dry climate	141.5	6.0	131.5	Golder	93.7	90.9	0.0	47.8	2.8	2%
		Diavik	351.0		270.0	Measured					140.4	40%

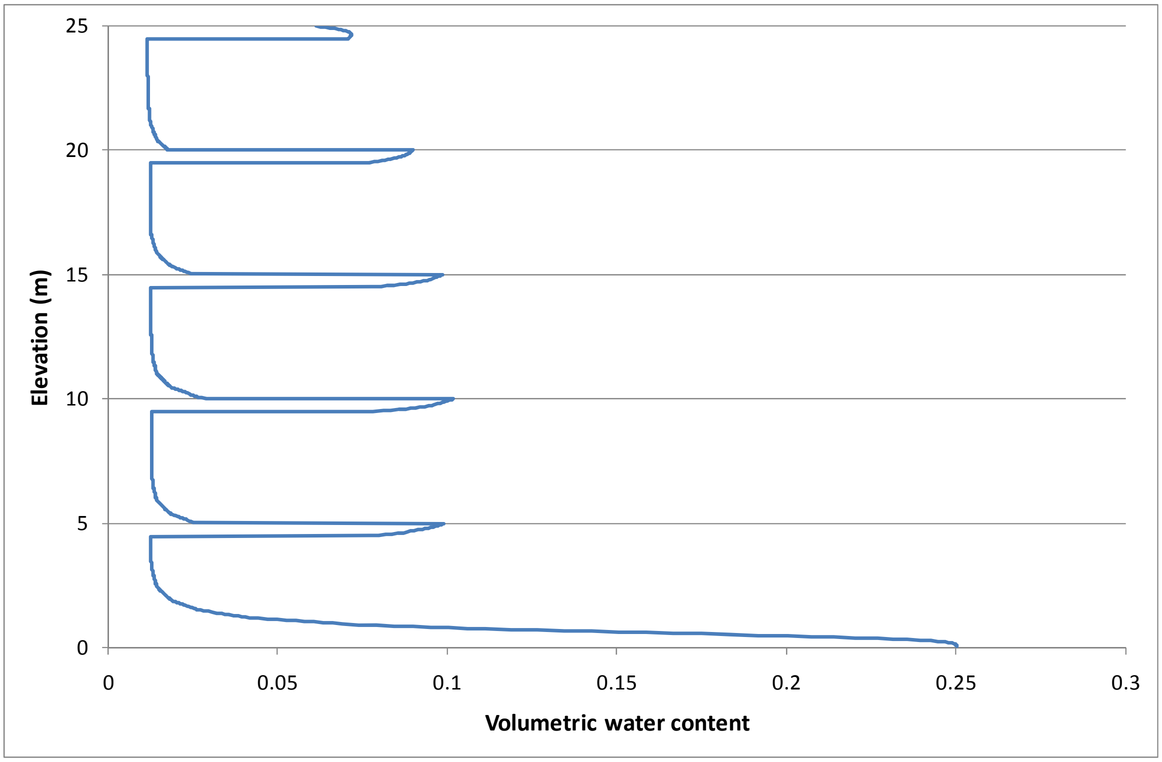

Figure 4.2: Volumetric water content over 25 m waste rock profile, wet climate, potential evaporation using Penman-Montheith (Case 20 in Table 4.3)

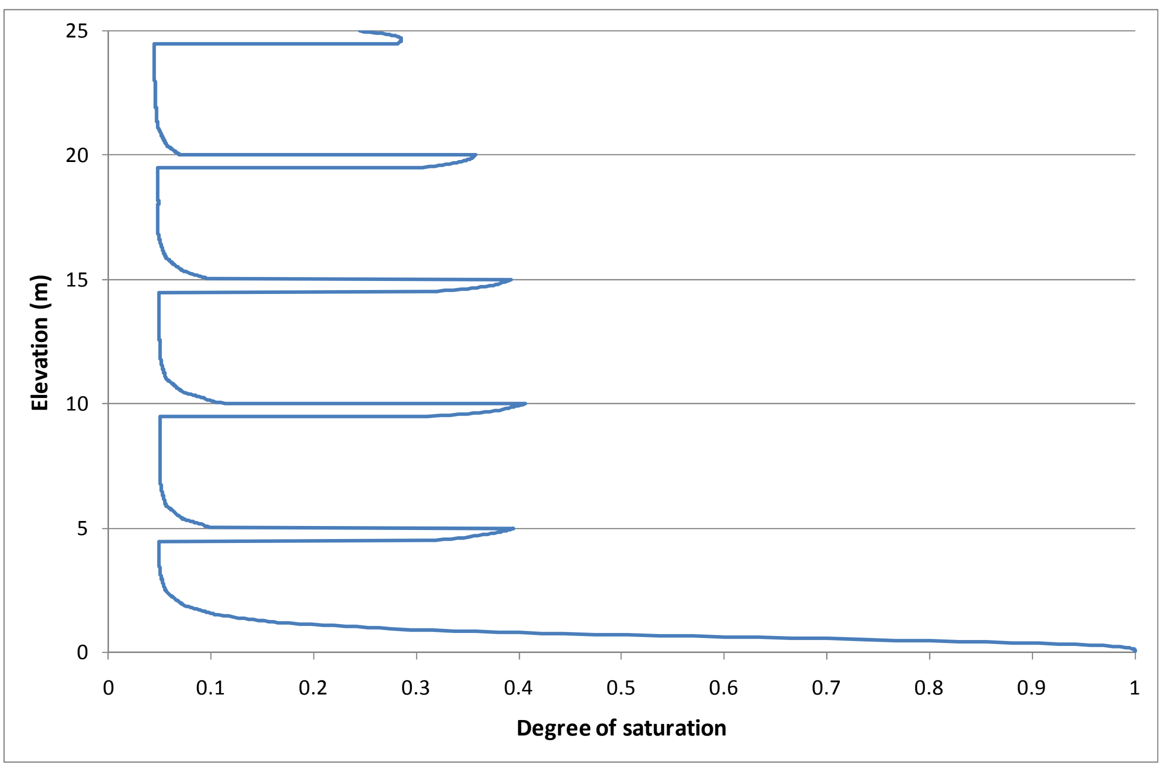

Figure 4.3: Degree of saturation over 25 m waste rock profile, wet climate, potential evaporation using Penman-Montheith (Case 20 in Table 4.3)

5 Conclusions

The results of the thermal modelling indicated that:

- Undisturbed ground surfaces (natural ground) will likely retain permafrost after a warming of 5°C;
- Permafrost will likely develop and be maintained within the waste rock piles and the covered TMF under the current climatic conditions;
- Permafrost could become marginal or disappear at the base of the pile when certain surface conditions are considered (high nt value) and that warming from climate change is considered (5 °C over 100 years);
- Winter deposition of waste rock material in the pile will promote development of frozen conditions, while summer deposition will delay it. The time difference would be in the order of several decades before reaching similar thermal conditions;
- Frozen conditions could be promoted by depositing alternating lifts of waste rock in the summer and winter; the equilibrium temperature of equal volumes of summer and winter waste rock is approximately -7.5°C; and
- Traffic zones have negligible effects on the thermal regime, but their presence will promote the development of water barriers once frozen, thus restricting percolation through the pile.

The results of the water transport modelling indicated that:

- Net percolation through waste rock material will likely be in the order of 30 to 50 percent of the annual total precipitation under unfrozen conditions. For frozen waste rock piles, the percolating water will also freeze and eventually block the flow paths. The bulk of the waste rock material would consequently be isolated from percolating water and restrict the transport of contaminants that could be present in the waste rock material. The percolation values mentioned above would eventually be limited to the freeze-thaw zone near the surface (active zone).
- Fine grained soil covers has the potential of reducing the net percolation to less than 5 percent of the annual total precipitation;
- The traffic zones (finer particles) will retain more water, thus acting as barriers to water transport once the pile is frozen. The zones could encapsulate and maintain large dry zones within the pile that would be deprived from percolating water. It could also act as a barrier to oxygen transport and consequently limit the oxidation of the waste rock material;
- The net percolation did not vary between the 10 and 25 m high profiles, thus confirming that the uncovered waste rock pile and the TMF will have similar behaviour in regards to net percolation; and
- The water storage of the waste rock pile profile could take years to stabilise as the waste rock material will be deficient in pore water when placed in the pile.

This report, "**Thermal and Water Transport Modelling for the Waste Rock Piles and TMF**", has been prepared by SRK Consulting (Canada) Inc.

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All data used as source material plus the text, tables, figures, and attachments of this document have been reviewed and prepared in accordance with generally accepted professional engineering and environmental practices.

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Appendix 1
Thermal Modelling Results, Waste Rock Pile

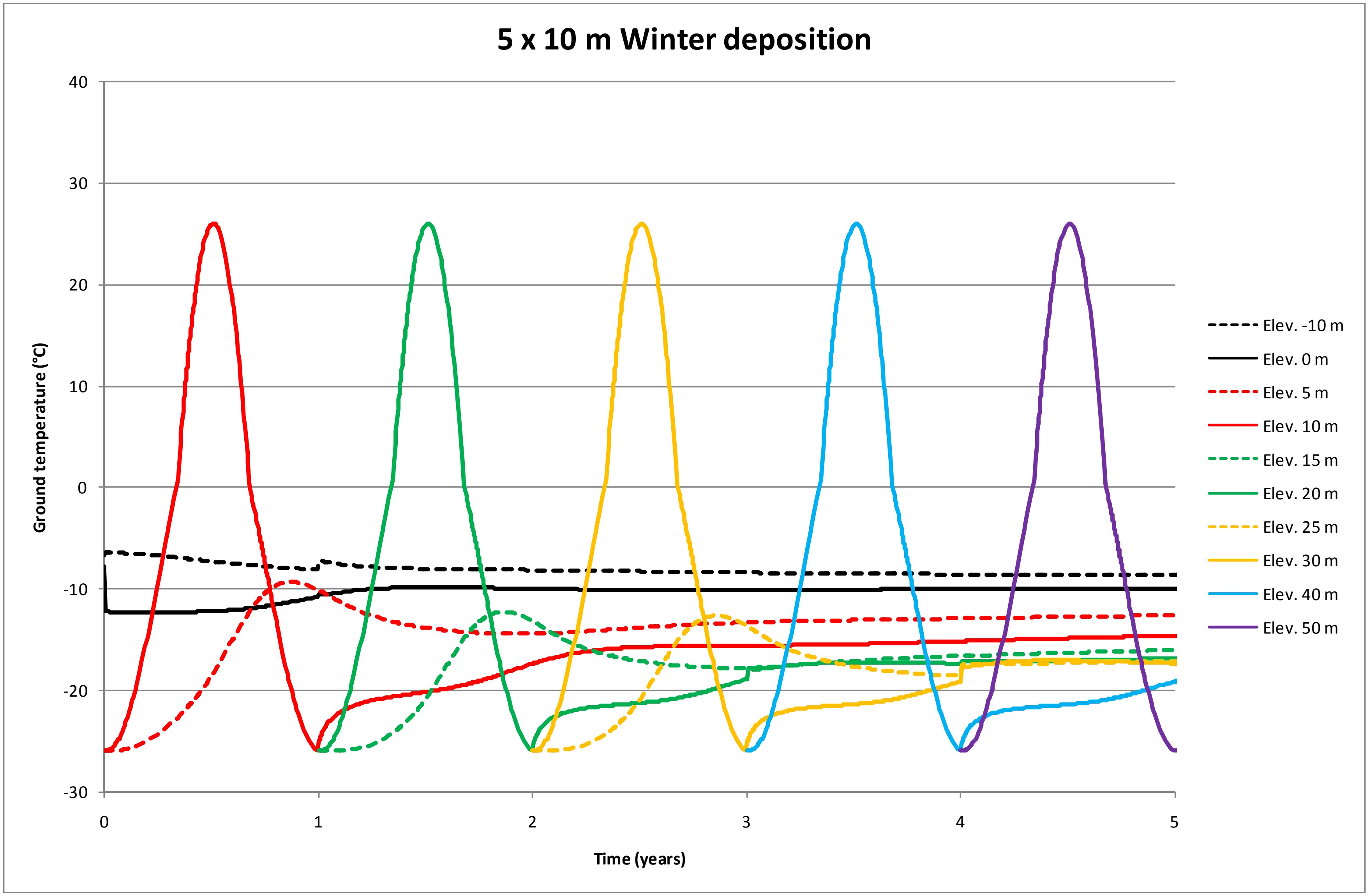

Figure 1: 5 lifts of 10m, winter deposition - 0 to 5 years

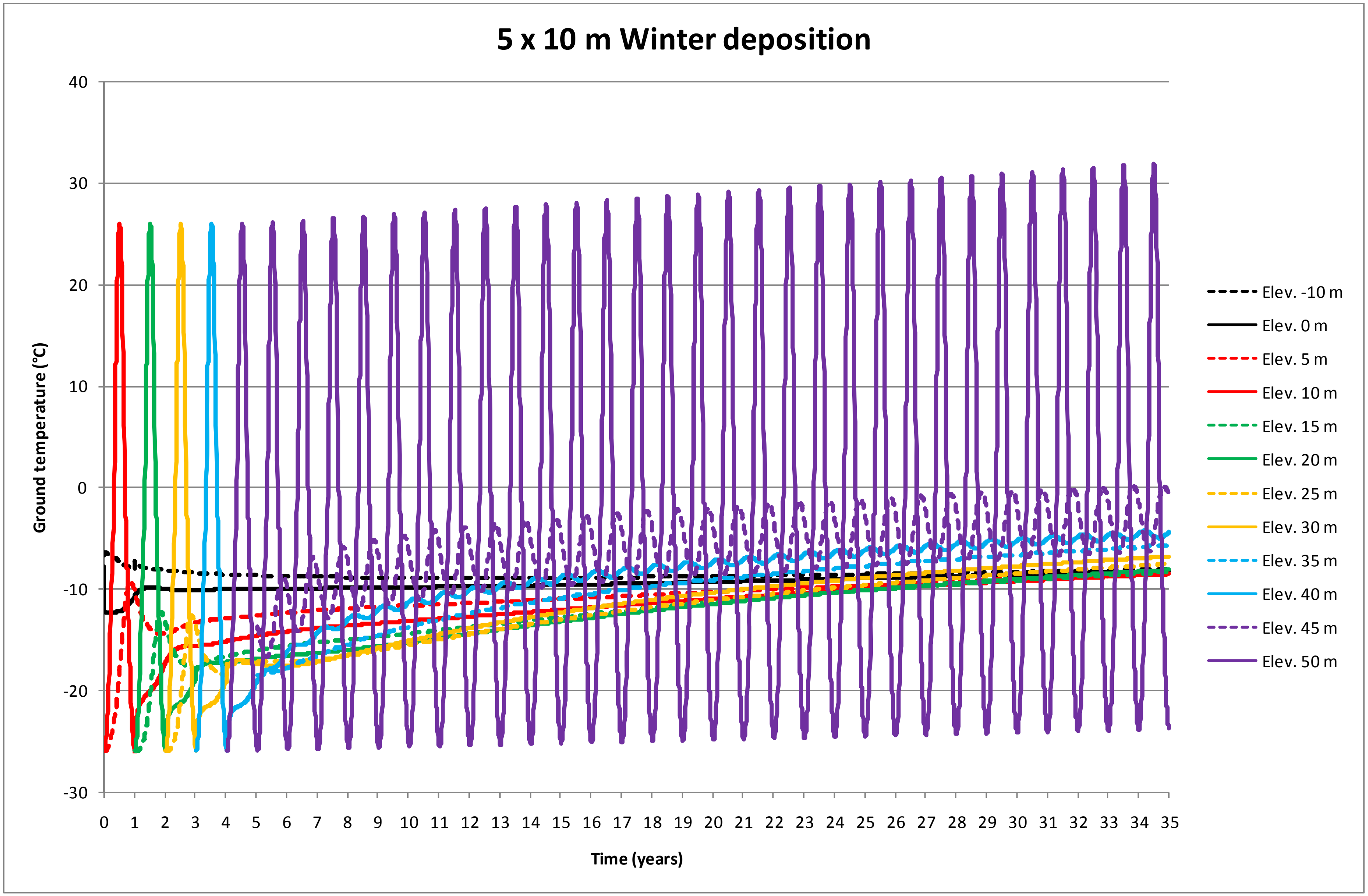

Figure 2: 5 lifts of 10m, winter deposition - 0 to 35 years

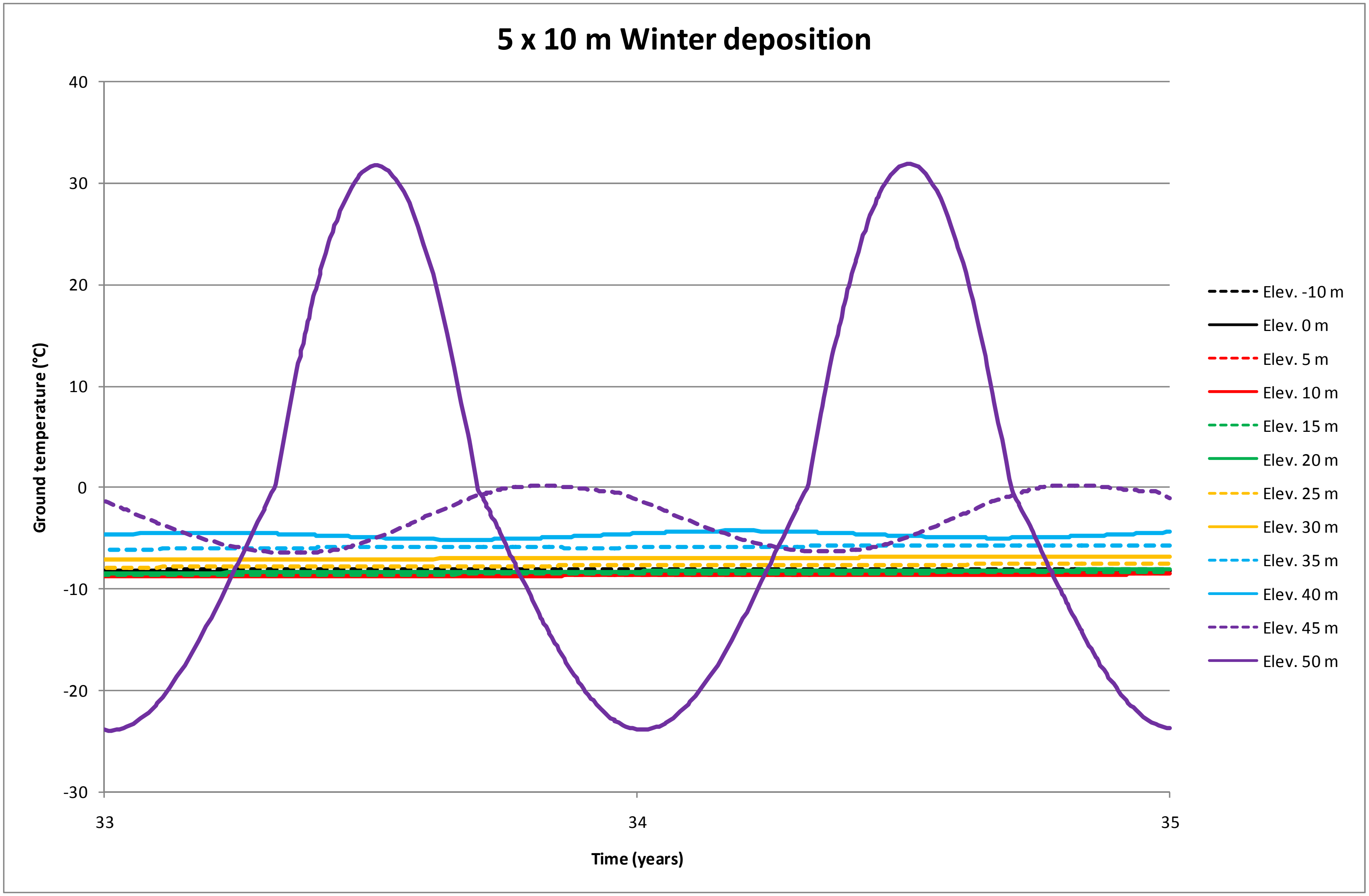

Figure 3: 5 lifts of 10m, winter deposition - 33 to 35 years

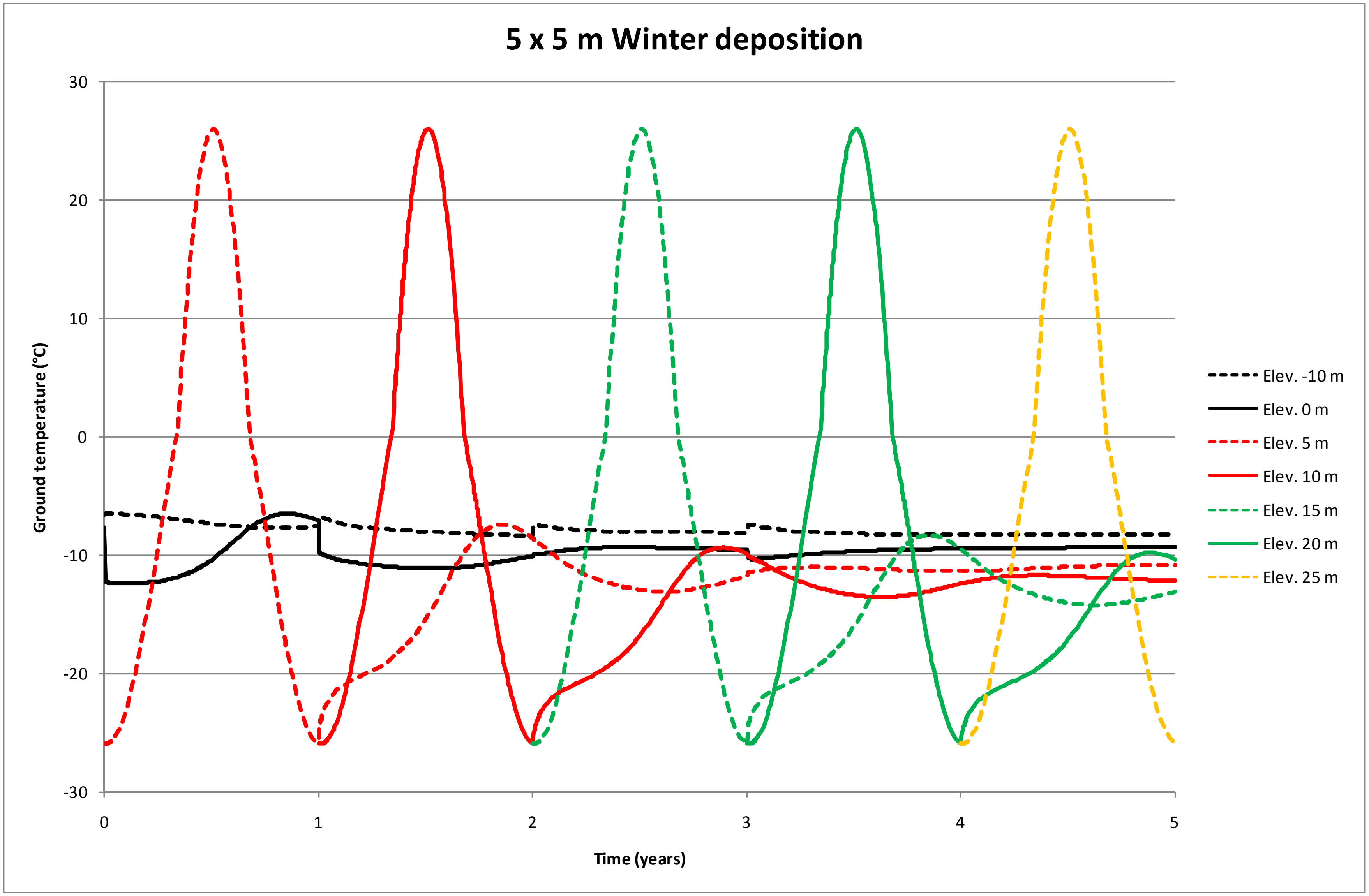

Figure 4: 5 lifts of 5m, winter deposition - 0 to 5 years

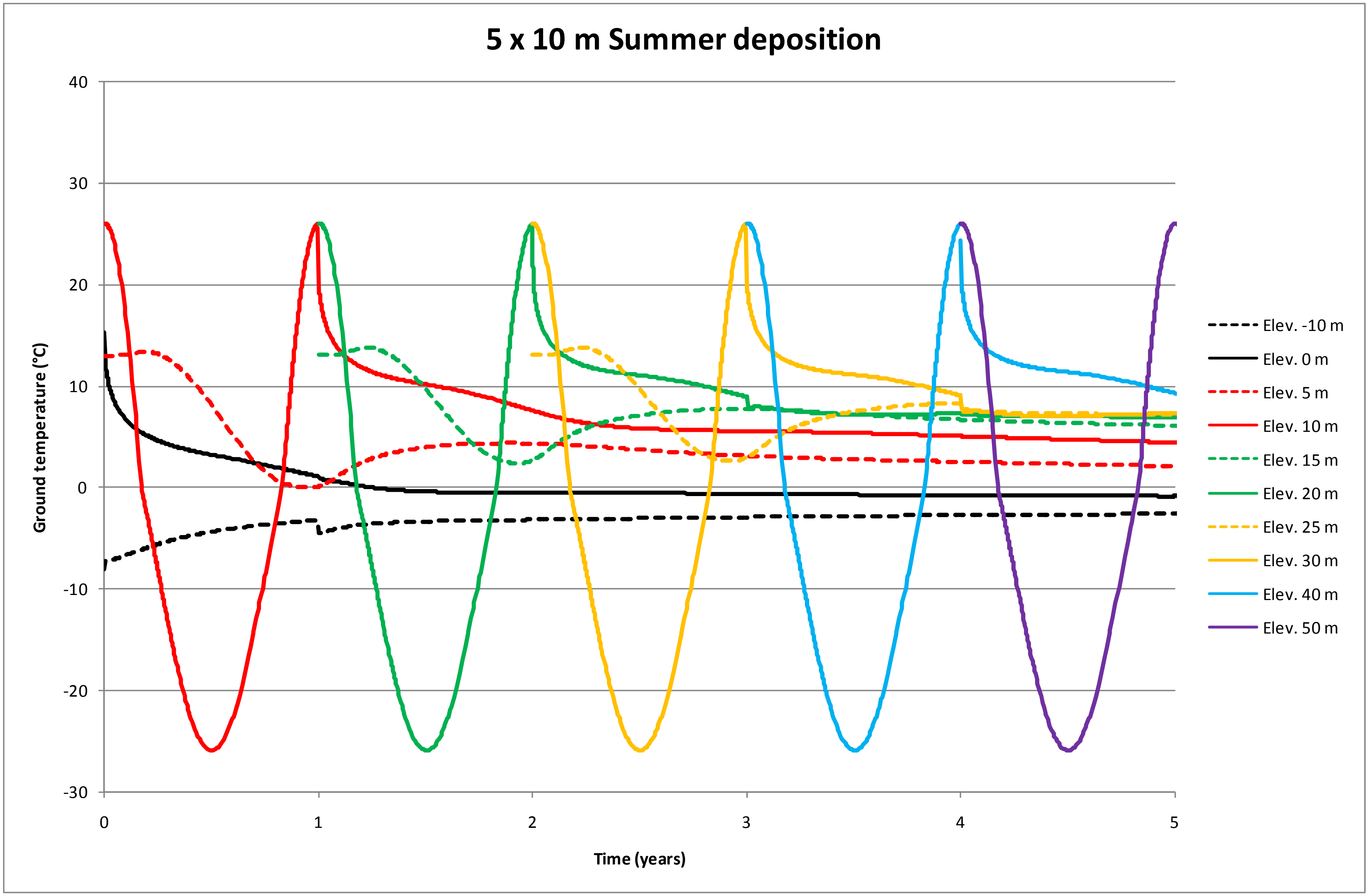

Figure 5: 5 lifts of 10m, summer deposition - 0 to 5 years

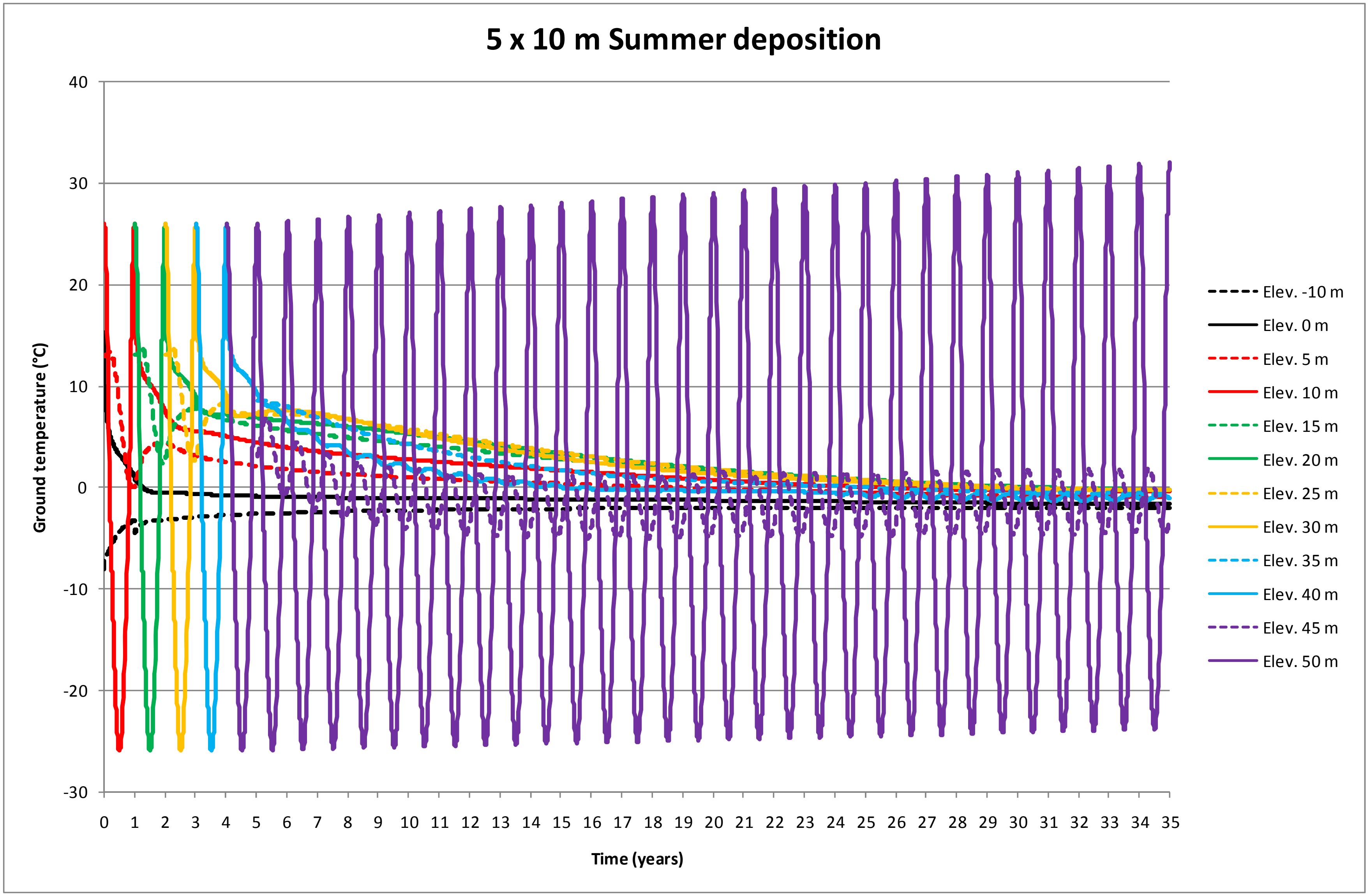

Figure 6: 5 lifts of 10m, summer deposition - 0 to 35 years

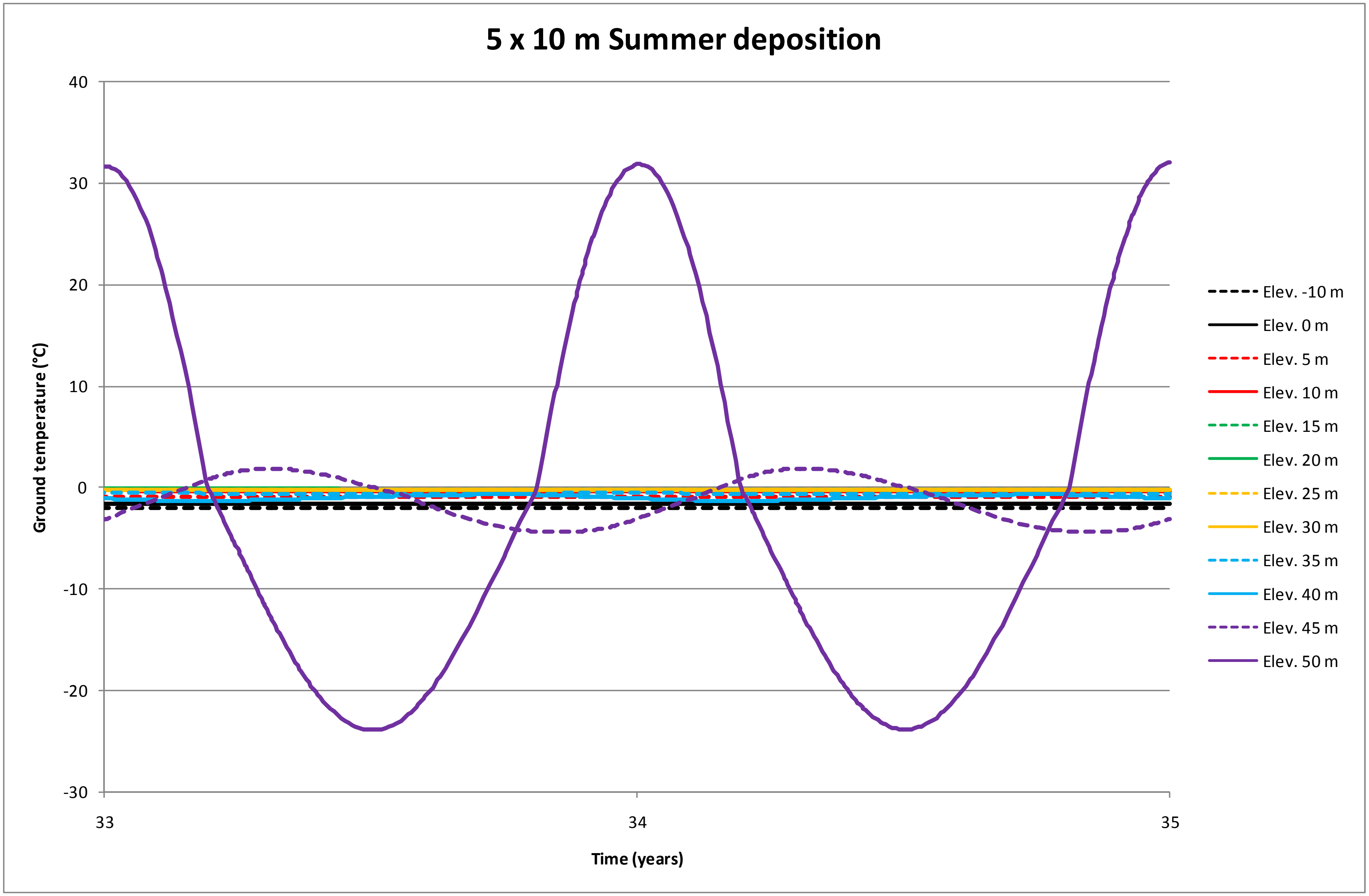

Figure 7: 5 lifts of 10m, summer deposition - 33 to 35 years

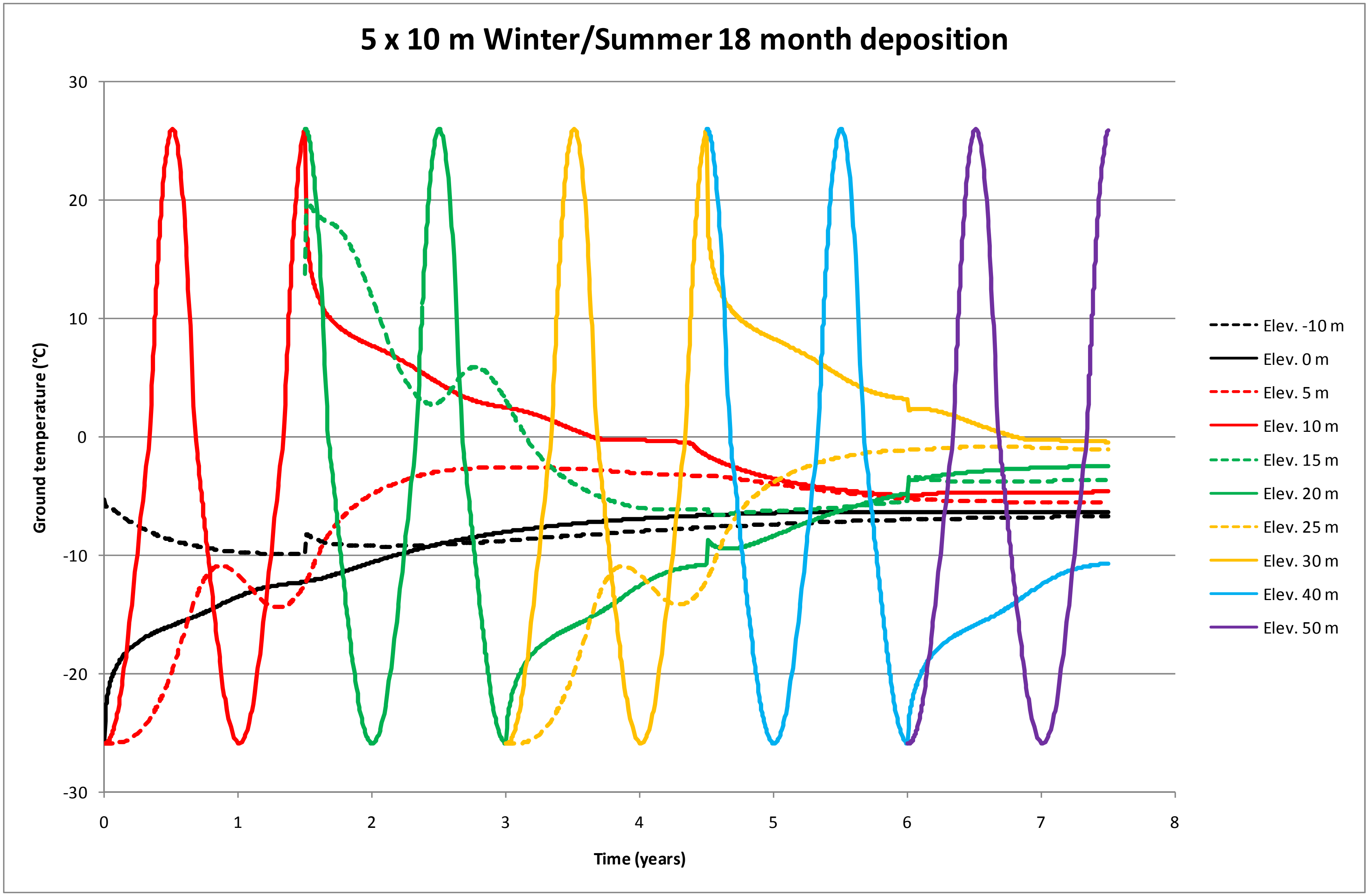

Figure 8: 5 lifts of 10m, winter/summer 18 month deposition - 0 to 8 years

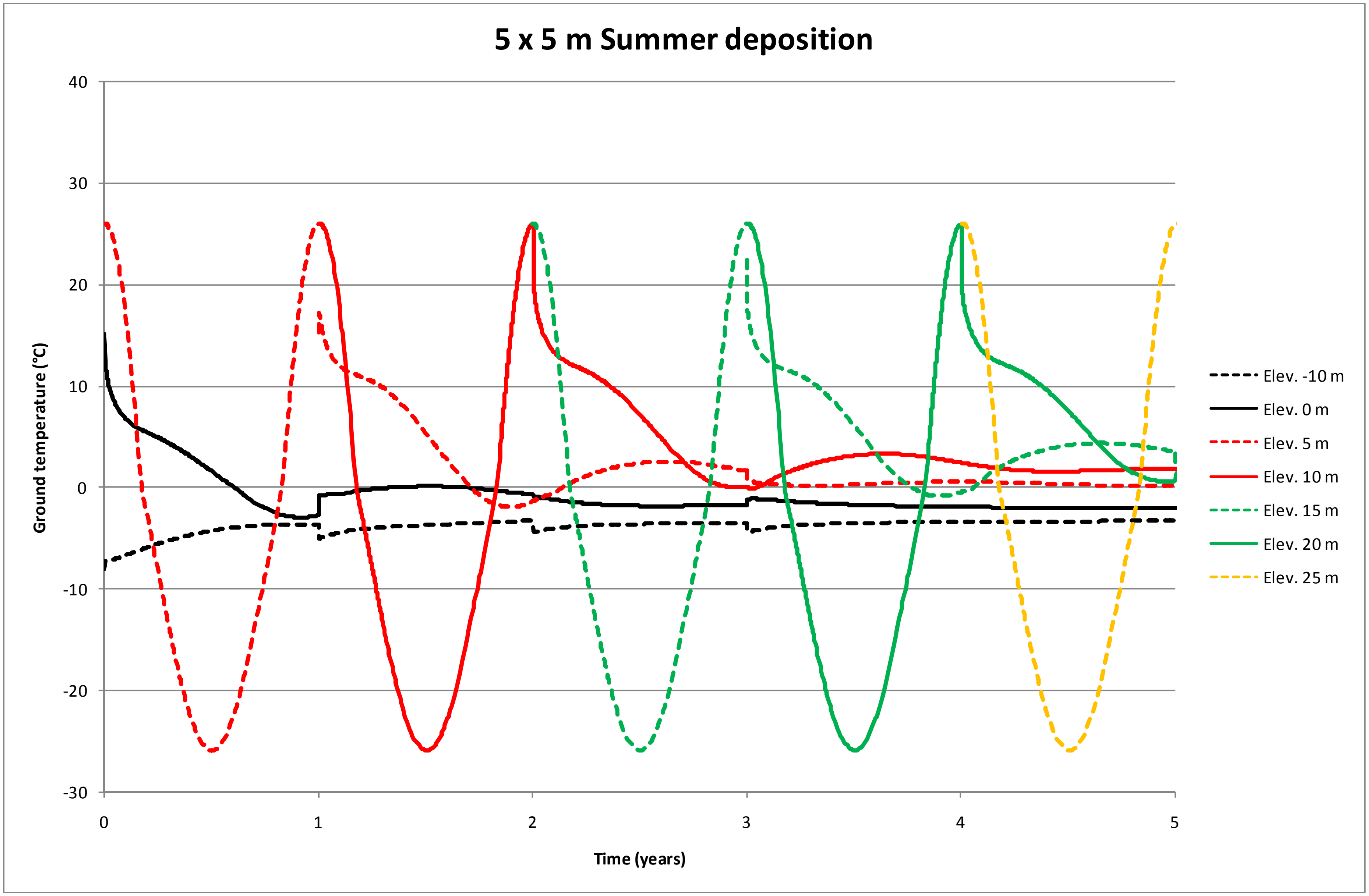

Figure 9: 5 lifts of 5m, summer deposition - 0 to 5 years

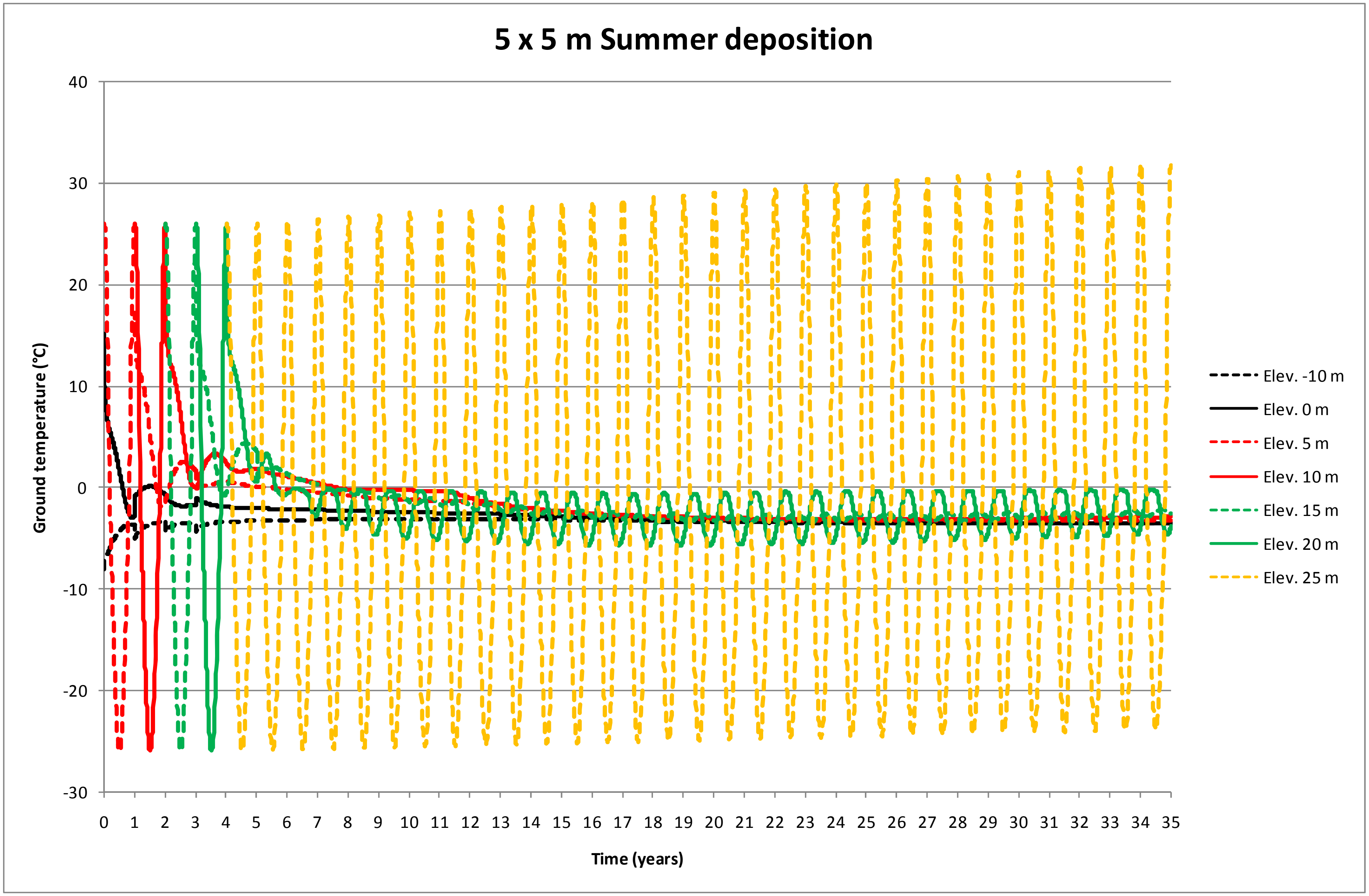

Figure 10: 5 lifts of 5m, summer deposition - 0 to 35 years

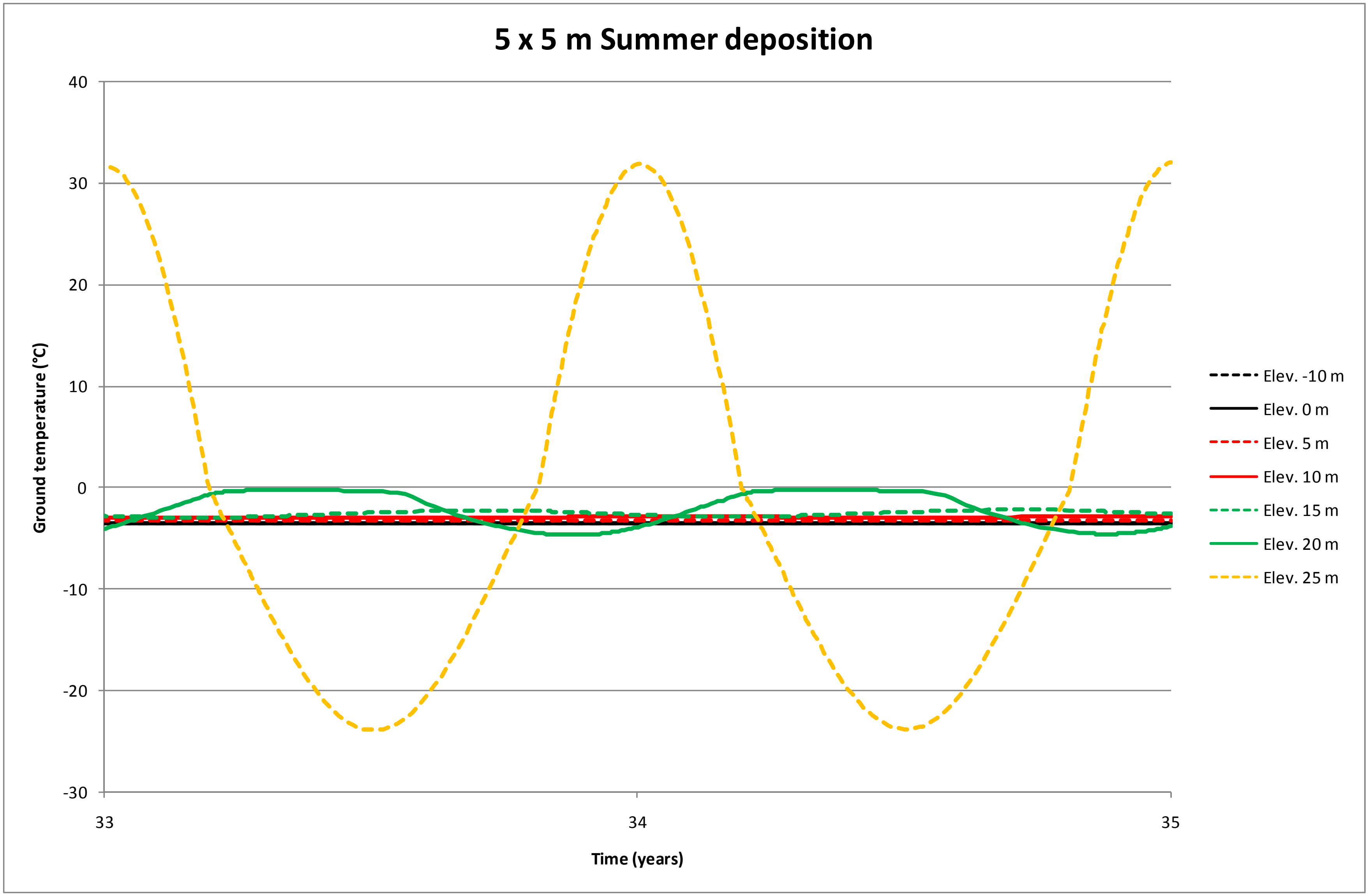

Figure 11: 5 lifts of 5m, summer deposition - 33 to 35 years

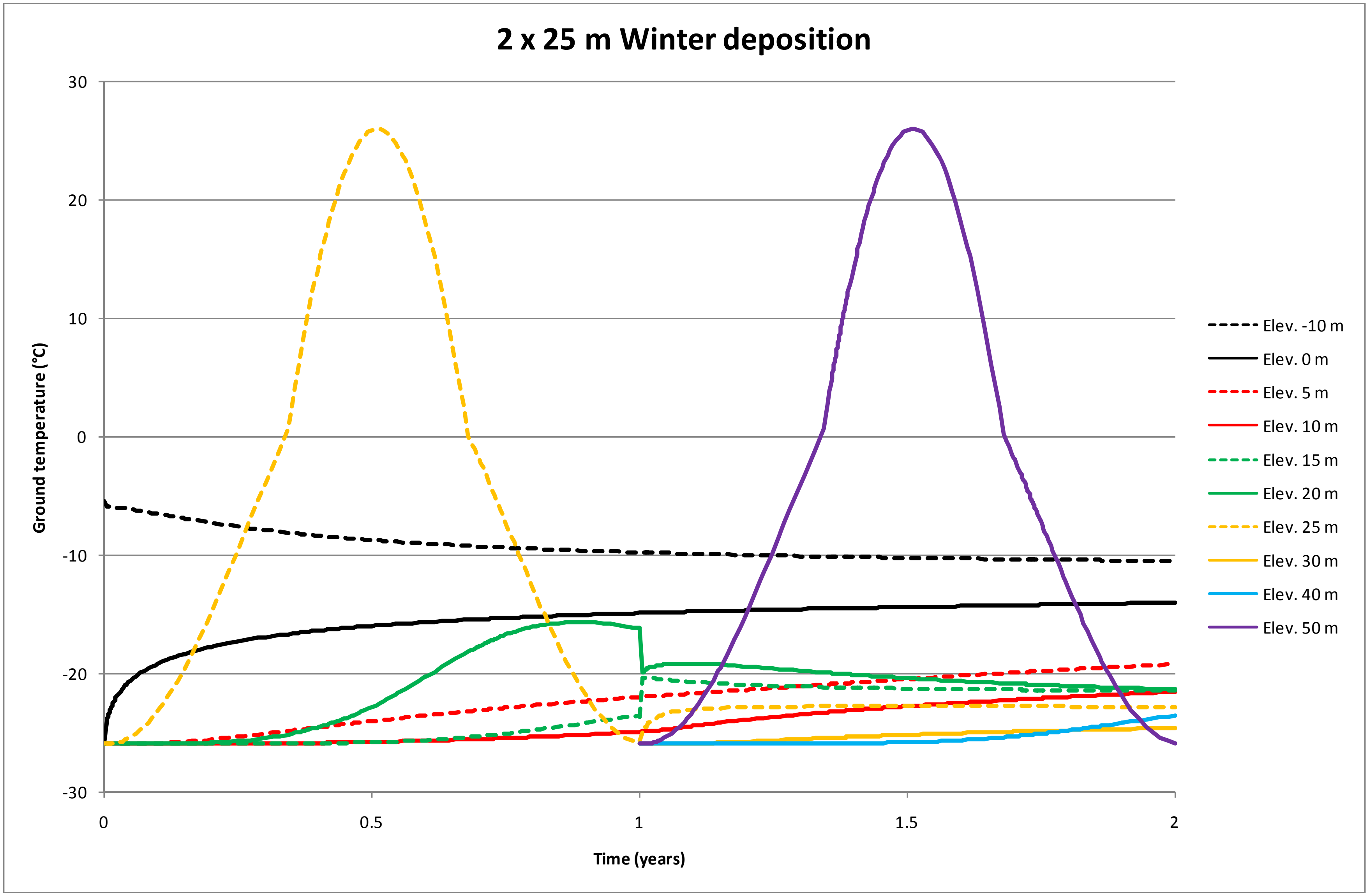

Figure 12: 2 lifts of 25m, winter deposition - 0 to 2 years

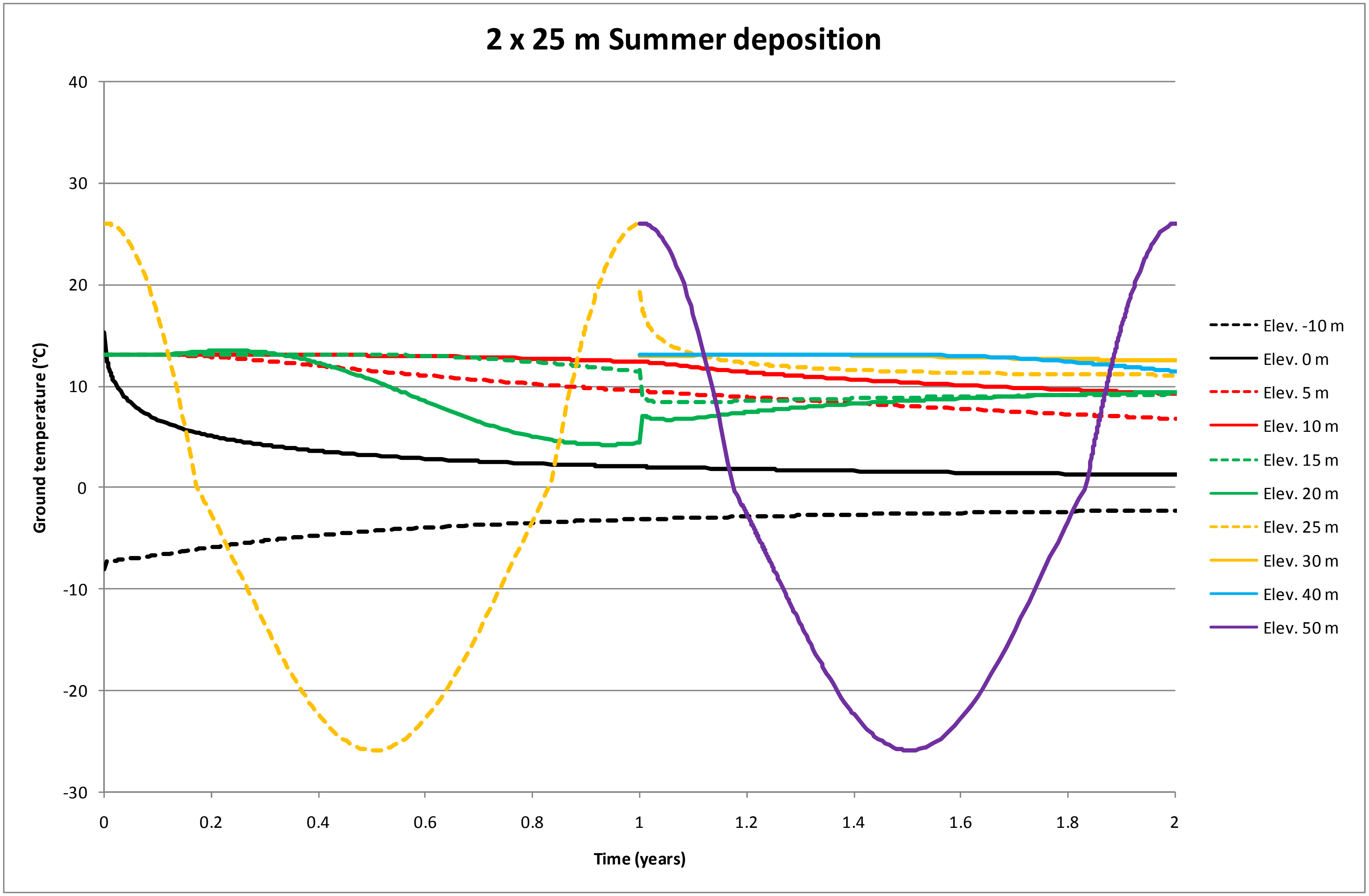

Figure 13: 2 lifts of 25m, summer deposition - 0 to 2 years

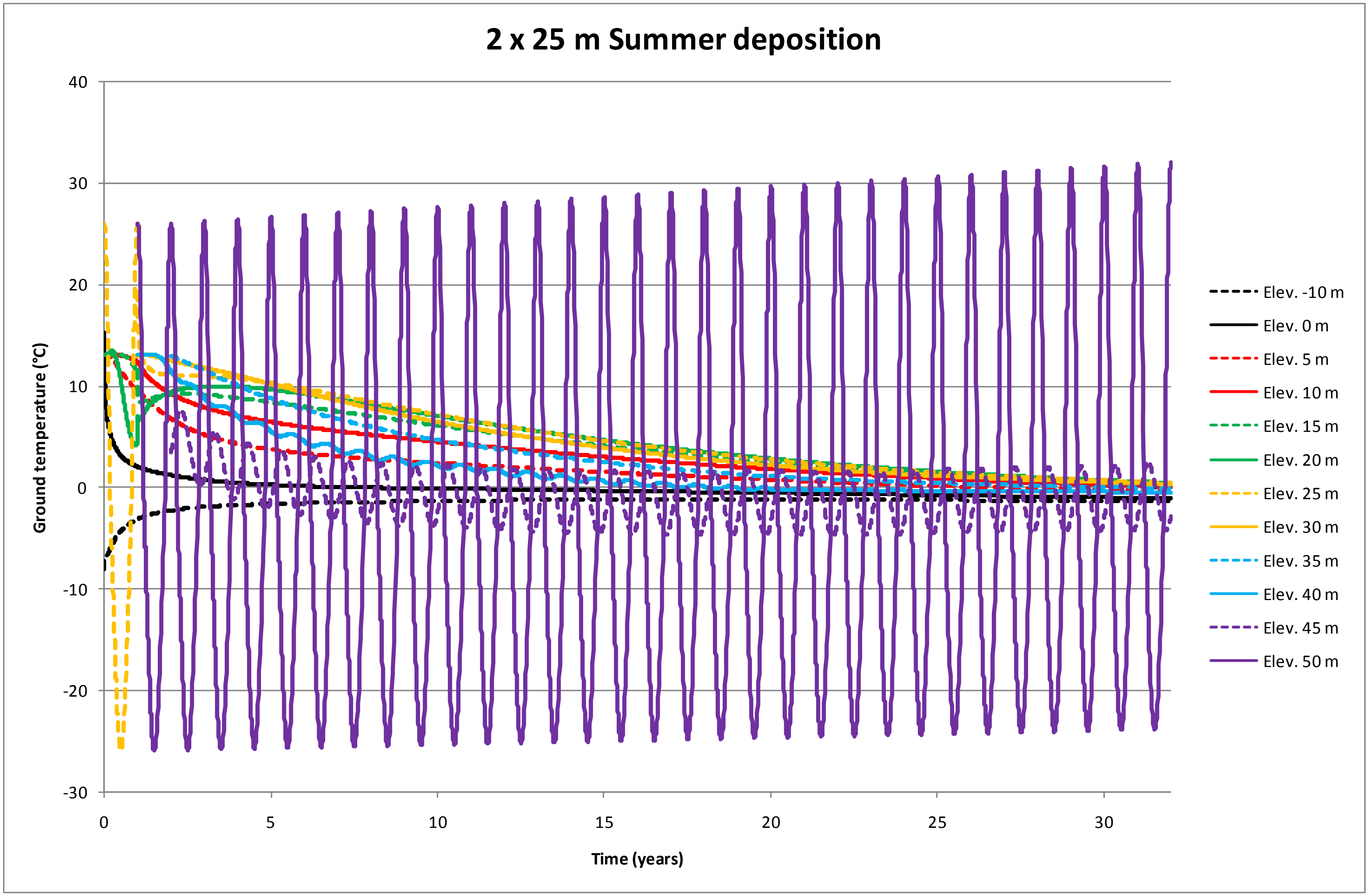

Figure 14: 2 lifts of 25m, summer deposition - 0 to 32 years

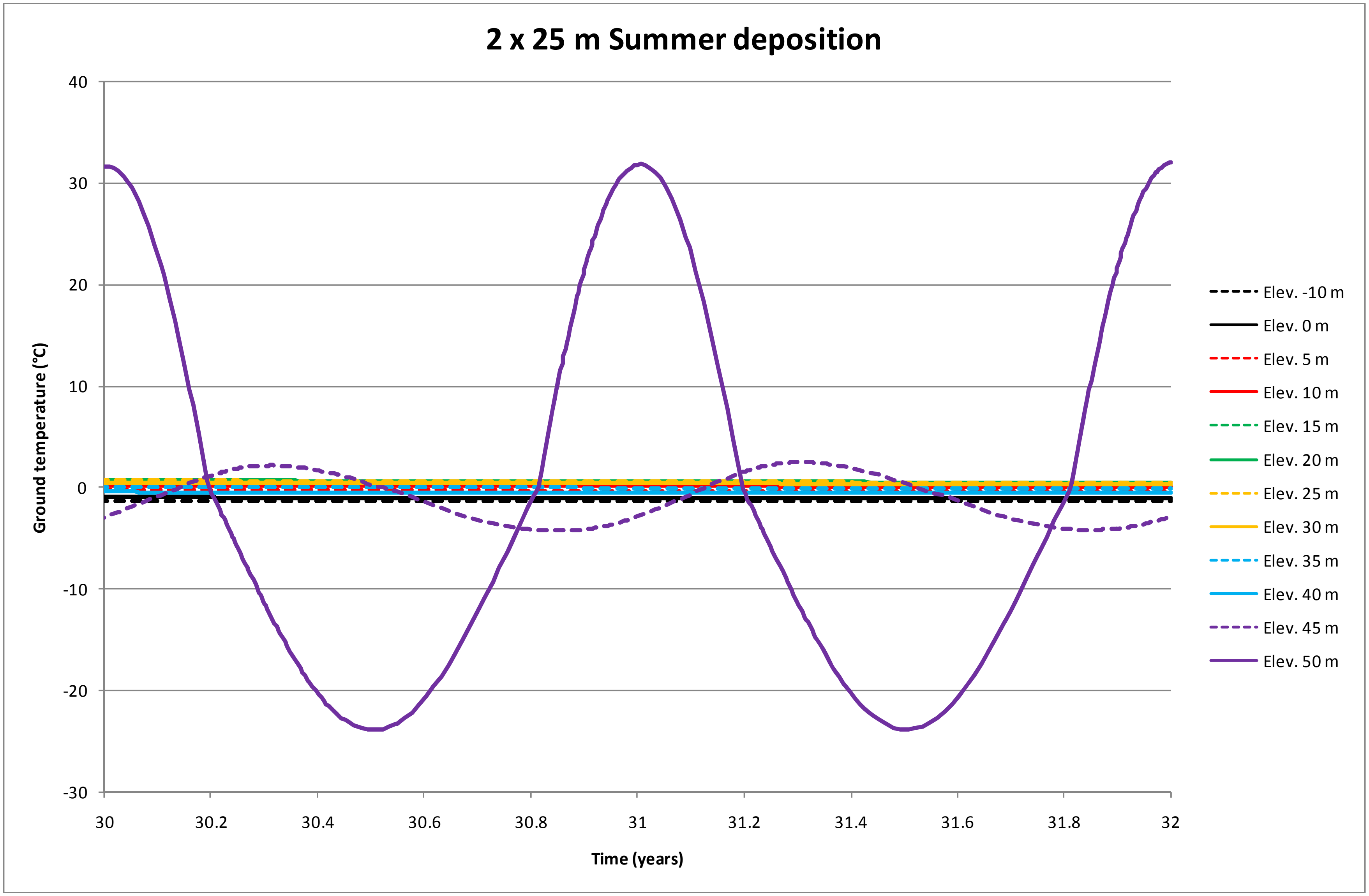

Figure 15: 2 lifts of 25m, summer deposition - 30 to 32 years

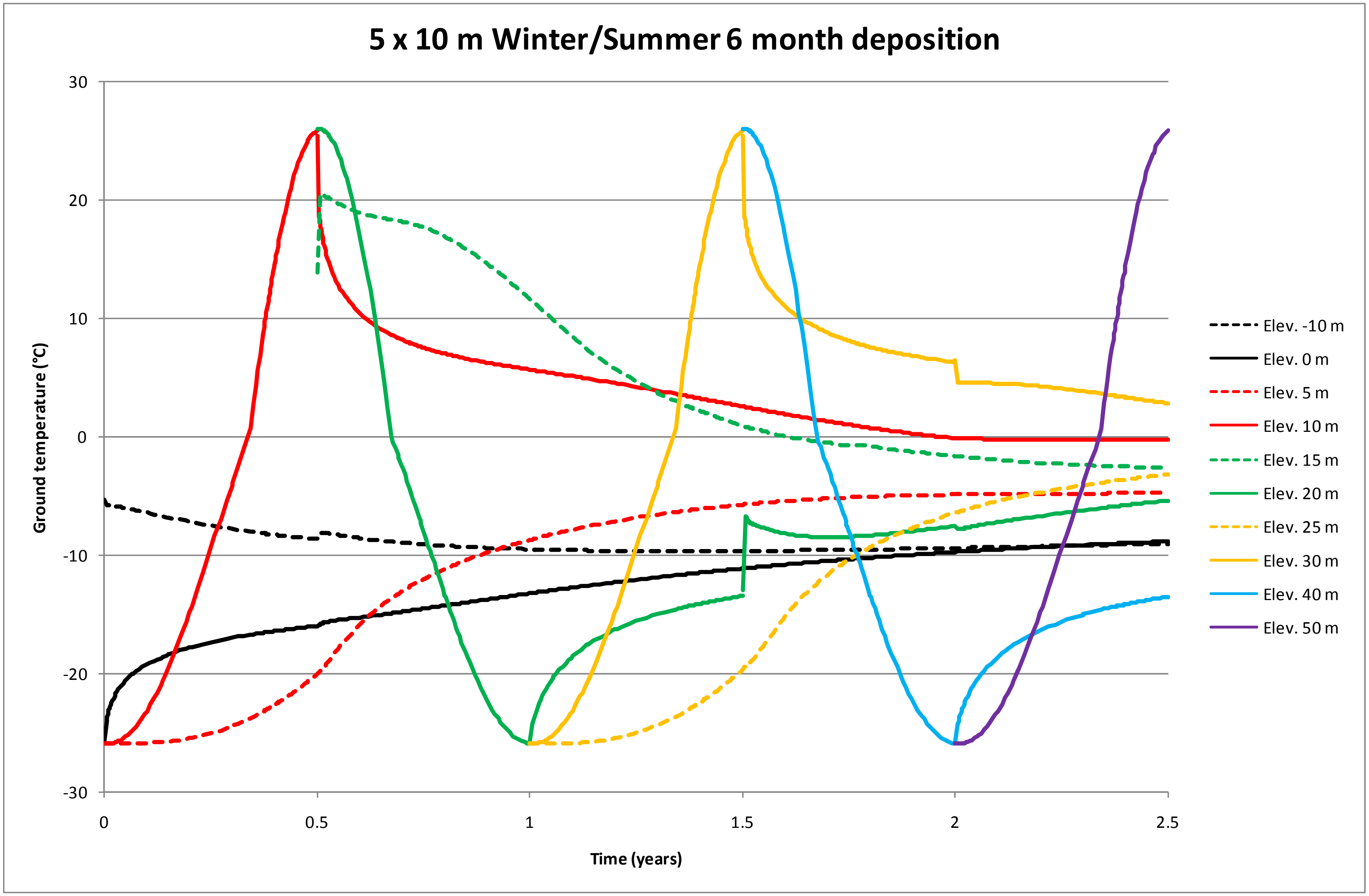

Figure 16: 5 lifts of 10m, winter/summer 6 month deposition - 0 to 2.5 years

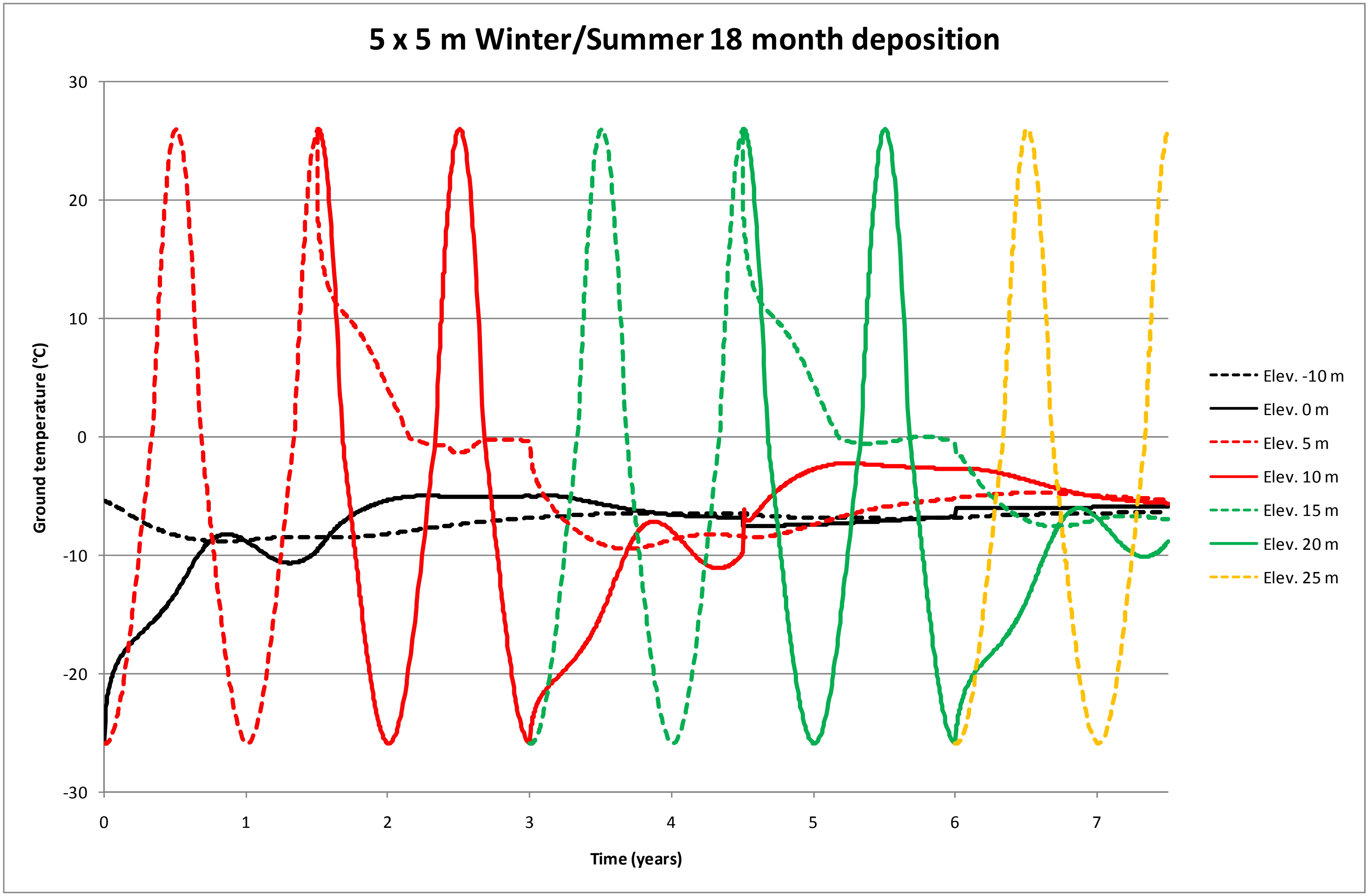

Figure 17: 5 lifts of 5m, winter/summer 18 month deposition - 0 to 7.5 years

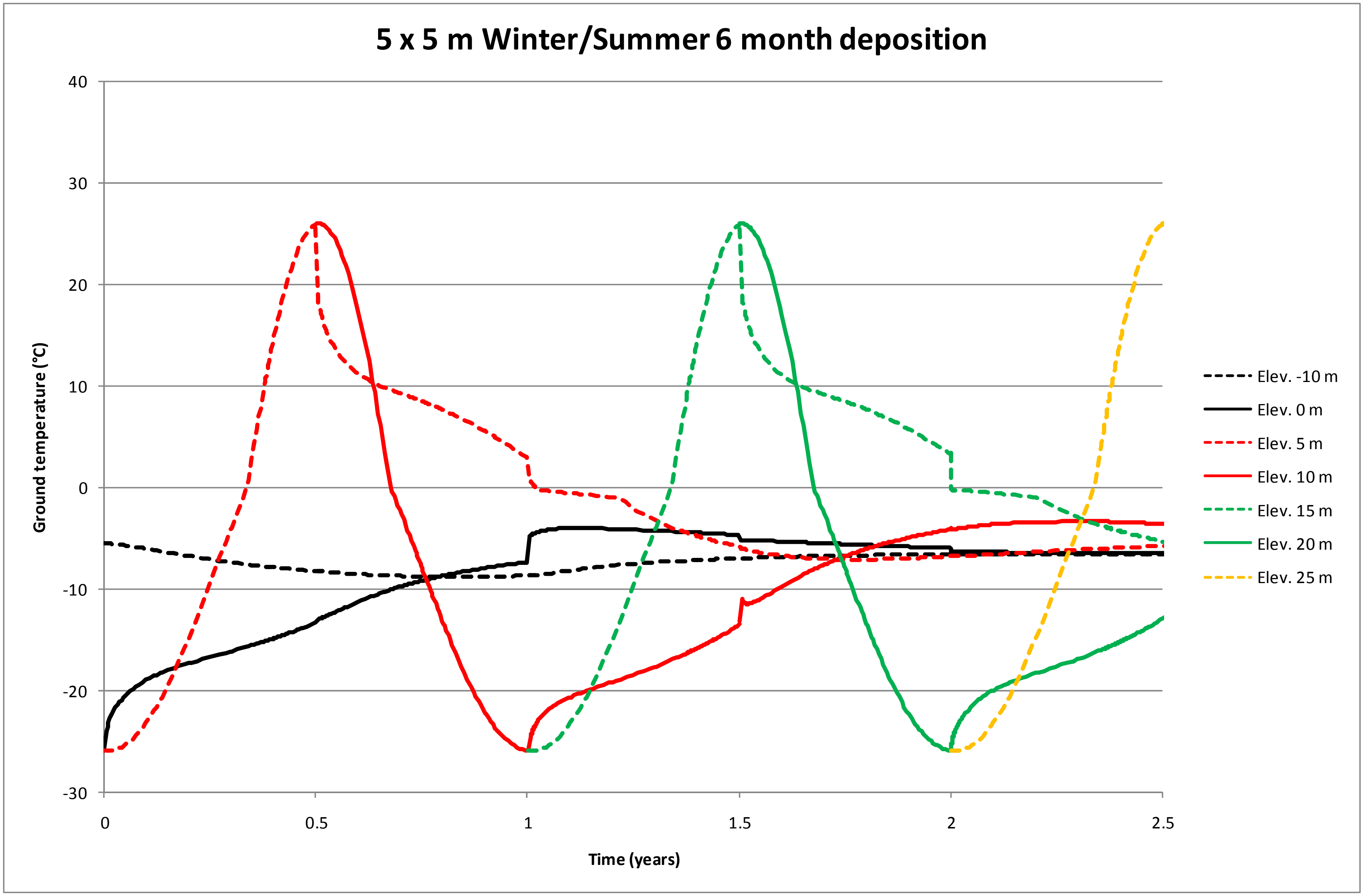

Figure 18: 5 lifts of 5m, winter/summer 6 month deposition - 0 to 2.5 years

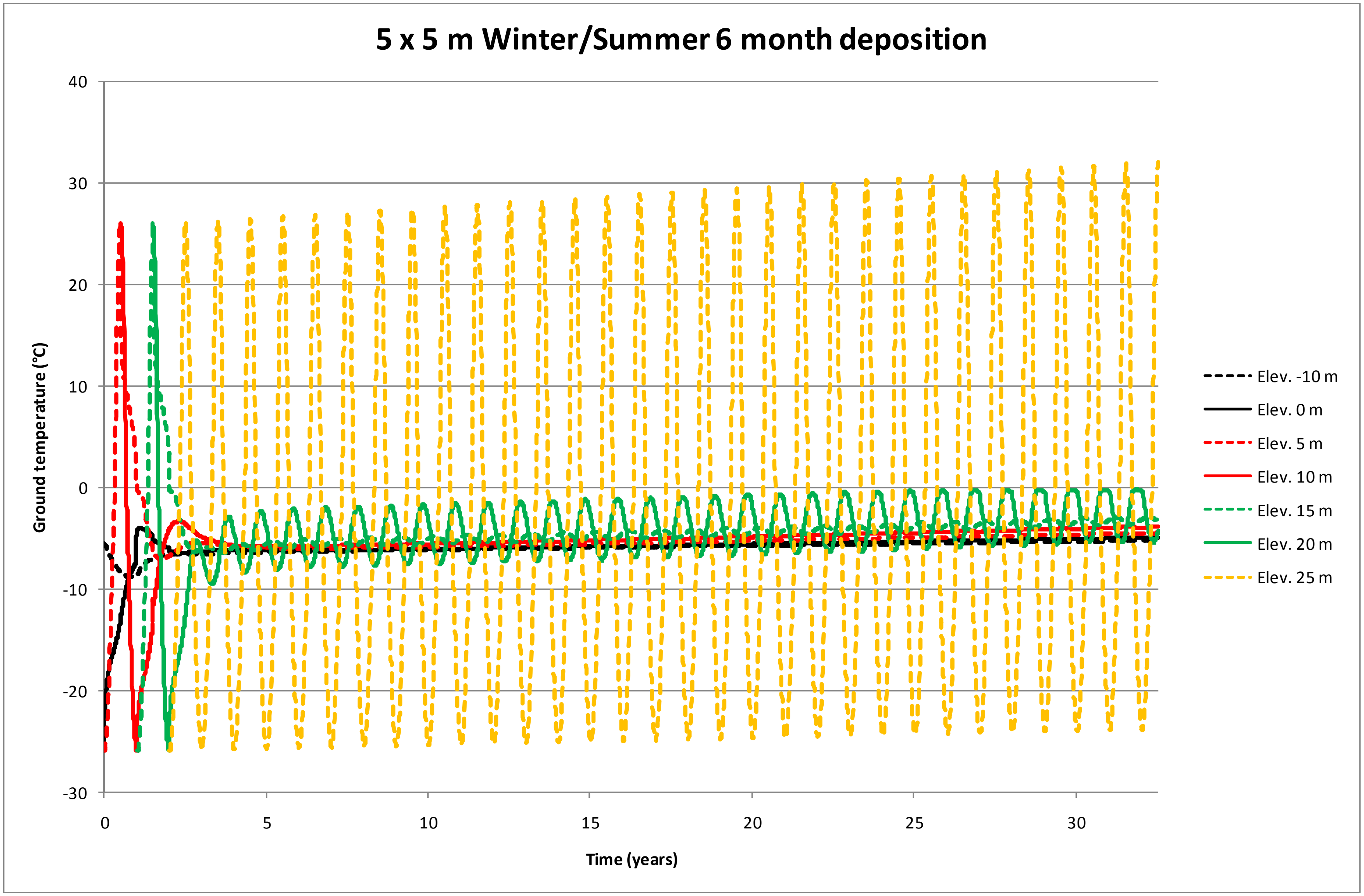

Figure 19: 5 lifts of 5m, winter/summer 6 month deposition - 0 to 32.5 years

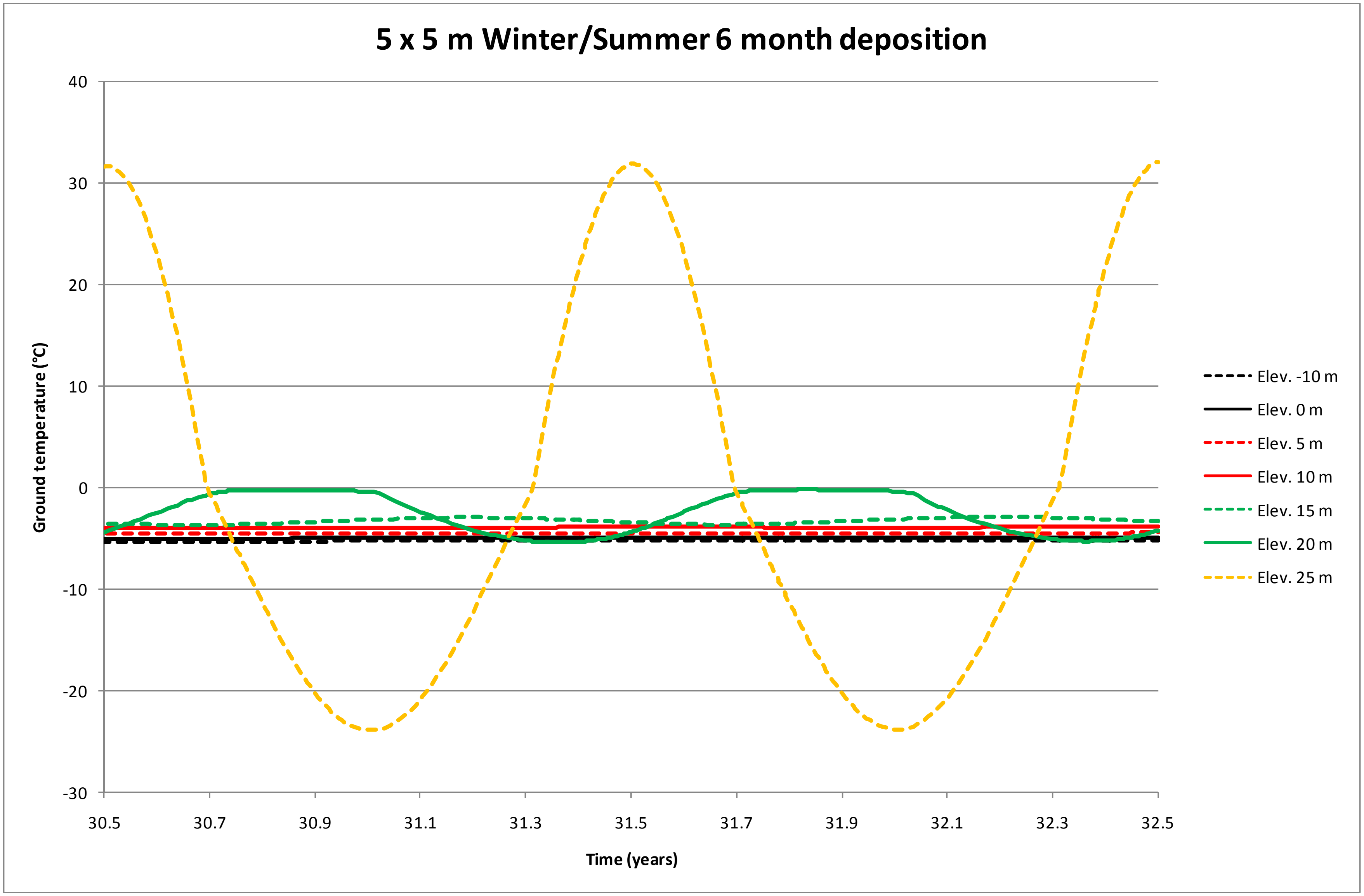

Figure 20: 5 lifts of 5m, winter/summer deposition - 30.5 to 32.5 years