GEOLOGICAL SURVEY OF CANADA

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Potential impact of global warming in permafrost in the Mackenzie Valley, Northwest Territories

Prepared by

Geo-Engineering (M.S.T.) Ltd.

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GEOLOGICAL SURVEY OF CANADA

POTENTIAL IMPACT OF GLOBAL WARMING IN PERMAFROST IN THE MACKENZIE VALLEY

**RESULTS
OF
GEOTHERMAL MODELLING**

Prepared by:

geo-engineering
(M.S.T.) LTD.

March 1992

FOREWORD

This report documents work undertaken as part of the Terrain Sciences Division's Mackenzie Valley Integrated Research and Monitoring Area (MIRMA). The study examines one approach that can be taken to determine the sensitivity and response of permafrost terrain to global warming. Site specific one-dimensional geothermal modelling of the transient response to a change from 1 X CO2 to 2 X CO2 climate is undertaken at three locations, representing the range from continuous through to discontinuous permafrost: MacKenzie Delta, Norman Wells and Fort Simpson. Several different functions were examined in the simulation of the transient response: step, linear and exponential.

At each location two boreholes are modelled, an ice-rich and an ice-poor. The boreholes were selected for the analysis on the basis of the availability of the following model input parameters: physical and thermal properties, lithology, ground temperature-depth measurements, snow cover data and air temperatures. A compilation of the pertinent geotechnical, geothermal and climate data for each site was forwarded to the contractor and can be made available upon request.

Funding for this project was provided by the Panel on Energy Research and Development (PERD) and the Green Plan.

Margo Burgess

Scientific Authority
Terrain Sciences Division
Geological Survey of Canada

POTENTIAL IMPACT OF GLOBAL WARMING IN PERMAFROST IN THE MACKENZIE VALLEY

RESULTS

OF

GEOTHERMAL MODELLING

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EXECUTIVE SUMMARY

The phenomena of global warming will likely have dramatic and adverse effects to permafrost along the Mackenzie Valley as the result of a doubling of the carbon dioxide in our atmosphere. Climatic changes provided from Global Circulation Models, suggest that increases of between +4.2 and +5.0°C will likely occur over the next 50 years within the Mackenzie Valley.

This study summarizes the results of a series of geothermal analyses undertaken on six soil profiles from three areas within the Mackenzie Valley; the Mackenzie Delta (near Tuktoyaktuk), Norman Wells and Fort Simpson. The analyses were undertaken with the end value climatic conditions provided from Atmospheric Environment Services Global Circulation Model.

Based on the results of the analyses, warm discontinuous permafrost zones, such as Fort Simpson, will likely either have no permafrost in 50 years, or thaw depths anywhere from 2.3 to 8 m. It is possible that in very local areas, where micro-climatic conditions are ideal, some permafrost may exist. However, it is not likely this will occur on a widespread basis. Permafrost within the Norman Wells area will experience almost the same type of impact, although it is likely more isolated pockets of permafrost will exist at Norman Wells than for Fort Simpson.

The results of the analyses for the Mackenzie Delta suggest that permafrost conditions will likely exist even under sustained 2 x CO_2 Scenario climatic conditions, although the permafrost would be warm and discontinuous.

The time period of all simulations was 50 years. In most cases, the changes were very subtle in the first 10 years but, depending on the surface function applied, tended to accelerate with time.

The likely impacts of warming of the permafrost or complete degradation would be characterized by any of the following:

- thickening of the active layer,

- thaw settlement,
- thermokarst feature development, such as thaw lakes, etc.,
- warming of ground temperature,
- decrease in permafrost thickness,
- instability of some foundations on ice-rich permafrost, and
- instability of slopes in ice-rich permafrost.

In summary, the impact of global warming on permafrost within the Mackenzie Delta will likely be dramatic and should be addressed in any future nothern work, if the present Global Circulation Model predictions are considered correct.

1.0 INTRODUCTION

Geo-Engineering (M.S.T.) Ltd. was retained by the Terrain Sciences Division of the Geological Survey of Canada (GSC) to undertake a geothermal modelling study of the potential impacts of global warming on permafrost within the Mackenzie Valley. The Mackenzie Valley is one of the key focal areas of the Integrated Research Monitoring Areas (IRMA) program and, as such, is an area of multidisciplinary research. The phenomena of global warming potentially has a widespread effect on climate, vegetation, geological conditions, etc. The geothermal modelling presented in this study therefore, reflects a very specific area of research which forms a part of a more complete overall evaluation of the problem being undertaken by the GSC.

Terms of reference for this study were established in our proposal of December 2, 1991, and are briefly restated below:

- review available geotechnical and meteorological conditions for three study areas in the Mackenzie Valley,
- establish equilibrium, steady-state permafrost conditions for six soil/permafrost profiles,
- perform a series of geothermal simulations using meteorological conditions which reflect a doubling in the carbon dioxide level in our atmosphere; and
- prepare a report summarizing the results of all the geothermal simulations and a discussion of the potential impact on permafrost in the Mackenzie Valley.

Three general areas along the Mackenzie Valley were selected for consideration by the GSC, one at each of the following locations:

- Mackenzie Delta near (Tuktoyaktuk),
- Norman Wells, and
- Fort Simpson.

Two soil profiles for each general area were also investigated, typically representing ice-poor and ice-rich conditions. The wide range of latitudes of the three sites, as well as the differences in soil/permafrost conditions, were selected to represent reasonable bounds to the anticipated permafrost conditions found along the Mackenzie Valley. The locations of the general study areas are shown in Figure 1 (Appendix A).

All work performed on this study was under Contract 032SS.23397-1-1424.

2.0 BACKGROUND

Over the past decade, the effect of increased carbon dioxide levels in our atmosphere on global weather patterns has been the topic of much discussion and research. The general consensus to-date (although not universally accepted by all scientific authorities) is that an increase in carbon dioxide emissions will tend to result in an overall global warming. The mechanism by which this warming occurs is commonly referred to as the "greenhouse effect." In simplistic terms, this theory proposes that as carbon dioxide levels increase, additional solar radiation will be trapped within the atmosphere that normally would reflect back into space, thus causing an increase in the earth's atmospheric temperature.

Presently, the most sophisticated means to predict global weather patterns is with highly sophisticated models referred to as Global Circulation Models (GCM). Climatologists not only attempt to predict the impact of increases in carbon dioxide levels on weather patterns with these models, but also model existing and historical weather patterns. For the purposes of our study, only one possible scenario (ie. GCM prediction) was selected as the endpoint for all geothermal modelling, and this was the doubling of the carbon dioxide level in our atmosphere. This condition is referred to in this report as the 2 x CO_2 Scenario.

The meteorological data for the 2 x CO_2 Scenario was transmitted to us by the GSC from the Canadian Climate Centre of Atmospheric Environmental Services (AES) and is enclosed in Appendix C. This information was provided in a format that consisted of mean-monthly air temperatures and monthly total precipitation for various weather station locations in the Mackenzie Valley. The time for the 2 x CO_2 event was estimated to be approximately 50 years. Some estimate of maximum snow depths were also provided but were not used directly in this study as will be discussed in a later section.

As the end conditions for the geothermal modelling and the time over which the event is to occur were assumed fixed, several alternate ways of reaching this point from present-day, relatively stable permafrost conditions, were evaluated. This included an instantaneous step to the 2 x CO_2 Scenario, a linear increase and an exponentially increasing function. Details of the design approach are presented in the following sections.

3.0 STUDY LOCATIONS

3.1 GENERAL

Three general study areas were selected for consideration by the Geological Survey of Canada at locations shown in Figure 1. These locations represent a broad range of latitudes and include zones of very warm discontinuous permafrost near Fort Simpson to cold continuous permafrost in the Mackenzie Delta near Tuktoyaktuk. Two soil profiles were selected at each site for typically ice-rich and ice-poor conditions.

A compilation of all pertinent geotechnical, geothermal and historical meteorological data was provided by the Geological Survey of Canada, in a document entitled "Documentation Provided by the Terrain Sciences Division, Geological Survey of Canada for Contract 032SS.23397-1-1424." This data was reviewed and used where applicable as input parameters for the geothermal model. In some instances, minor adjustments were made to ensure stability of the permafrost existed for present-day meteorological conditions.

Specific conditions at each of the sites are discussed individually in the following sections.

3.2 MACKENZIE DELTA - SITE A

Site A is located along the Geological Survey of Canada's Lousy Point Transect. Two soil profiles were considered for analysis; one consisting of massive ice underlying a thin glaciofluvial layer and the other consisting of a relatively ice-poor glaciofluvial deposit.

The massive ice profile is referred to as A.1, and is based approximately on soil and permafrost conditions encountered in GSC Borehole 91-11. The simplified soil profile, and selected geotechnical and geothermal properties are summarized in Table 3.1.

Table 3.1 Geotechnical and Geothermal Properties for Site A.1
Mackenzie Delta - Massive Ice Underlying Thin Glaciofluvial Deposit

Layer no.	Depth Range (m)		Soil Description	w (%)	Dry Density (kg/m^3)	Ku (W/mK)	Kf (W/mK)	P	Q
1	0.0	0.80	Sand/silt	35	340	1.7	3.3	5	5
2	0.8	1.8	Ice w/ silt	60	-	1.7	3.3	0.5	10
3	1.8	3.2	Silt	36	-	1.2	2.1	8	4
4	3.2	5.0	Ice w/ till	500	-	1.2	2.0	0.1	20
5	5.0	8.0	Ice w/ till	500	-	1.2	2.0	0.1	20
6	8.0	12.0	Ice w/ till	500	-	1.2	2.0	0.1	20
7	12.0	20.0	Ice w/ till	500	-	1.2	2.0	0.1	20
8	20.0	100.0	Ice w/ till	500	-	1.2	2.0	0.1	20

[shaded box] Denotes measured parameter

Soil conditions at Site A.1 consist of a thin ice-rich glaciofluvial layer of silts and sands extending to a depth of approximately 3.2 m. Below a depth of 3.2 m, massive ice or ice with soil (till) inclusions extends to the base of the borehole at a depth of 30 m. No surficial organic layer was identified on the borehole log. This is considered reasonable, considering the location of Borehole 91-11 near the crest of a ridge along the transect.

Based on the thermistor data shown in Figure 2, the ground temperature at a depth below the seasonal effects is approximately -7.0 to -7.3°C, consistent with continuous permafrost we would anticipate in the Mackenzie Delta area. Permafrost thickness was assumed to be between 450 and 600 m (Pelletier, 1987). Therefore, based on prevailing permafrost temperatures and thicknesses, a geothermal gradient of 0.012°C was used in our modelling for both the Mackenzie Delta sites.

The ice-poor, glaciofluvial profile is referred to as A.2 in the analysis, and is based on soil and permafrost conditions encountered in GSC Borehole 91-12. The simplified soil profile, and selected geotechnical and geothermal properties are summarized in Table 3.2.

Soil conditions at Site A.2 consist primarily of silts and sands which extend from 0.8 m to the base of the borehole at 30 m. A surficial layer of peat and organics was encountered to a depth of 0.8 m. Based on the location of Borehole 91-12 in a terrain depression on the transect, the existence of relatively thick organics appears explainable.

Ground temperatures below the seasonal effects are typically between -6.0 and -6.5°C, also consistent with continuous permafrost conditions we would expect in the area. Thermistor data for Site A.2 is shown in Figure 3.

Geotechnical and geothermal information for both locations on the Lousy Point Transect were the least extensive of all the areas considered in this study. This information consisted primarily of natural water contents, but also included some frozen bulk densities and frozen thermal conductivities. Additional information as noted in Tables 3.1 and 3.2 was supplemented based on our past experience from projects with similar soil conditions and as required to achieve a stable permafrost soil profile.

Table 3.2 Geotecnical And Geothermal Properties for Site A.2
Mackenzie Delta - Ice-poor Glaciofluvial Deposit

Layer no.	Depth Range (m)		Soil Description	w (%)	Dry Density (kg/m^3)	Ku (W/mK)	Kf (W/mK)	P	Q
1	0.0	0.8	Peat	250	340	0.5	1.8	5	5
2	0.8	2.0	Silt	25	-	1.5	2.0	8	4
3	2.0	3.0	Silt	30	-	1.5	2.0	8	4
4	3.0	5.0	Sand	35	-	1.5	4.0	5	10
5	5.0	8.0	Sand	26	-	1.9	4.4	5	10
6	8.0	12.0	Sand	26	-	1.9	3.8	5	10
7	12.0	20.0	Sand	26	-	1.9	3.8	5	10
8	20.0	100.0	Sand	26	-	1.9	3.8	5	10

(shaded) Denotes measured parameter

Historical meteorological data for this area was available for two Tuktoyaktuk weather stations and Inuvik. This data was provided to Geo-Engineering in the form of computer files from the Atmospheric Environmental Services Archive System. Upon review of the information, it was decided that data for Tuktoyaktuk would most closely resemble conditions along the Lousy Point Transect. Specific information used in this study consisted of the 30-year normal mean-monthly air temperature and precipitation data for the period 1951 to 1980, and the daily snowfall on ground measurements from 1963 to 1980.

Mean-monthly air temperatures and snow depth thickness as derived from the meteorological data are presented in Figures 4 and 5 respectively. The figures also show the 2 x CO_2 Scenario end values. The method by which the of the 2 x CO_2 Scenario snow depths were derived will be discussed in a later section.

In order to achieve steady-state permafrost conditions, the snow depth values shown in Figure 5 were further adjusted for each site. The snow depths for Site A.1 were reduced by 18 percent and the snow depths at Site A.2 were increased by 50 percent. These adjustments appear reasonable given the topographical setting of the two sites and that Site A.2 is in a terrain depression that potentially could collect more snowfall than Site A.1.

3.3 NORMAN WELLS - SITE B

The Norman Wells study area consists of two separate sites; one near the Town of Norman Wells and the other on the north side of Canyon Creek. Both sites are on the east side of the Mackenzie River, near the Norman Wells to Zama (IPL) Pipeline.

Site B.1, near the Norman Wells townsite, is situated on an ice-rich lacustrine plain just north and east of Seepage Lake. Soil and permafrost conditions are based approximately on the Hardy Associates (1978) Ltd. Borehole 80-1, drilled for the Norman Wells to Zama Pipeline. The simplified profile and selected geothermal properties are summarized in Table 3.3.

Soil conditions at Site B.1 consist of a 0.3 m layer of peat overlying a medium to high plastic clay extending to a depth of approximately 6.0 m. Although not encountered in Borehole 80-1, it is our understanding shallow bedrock consisting of clay shale is encountered frequently in this area. For purposes of our analysis, therefore, shale has been assumed to exist below a depth of 6.0 m.

Table 3.3 Geotechnical And Geothermal Properties for Site B.1
Norman Wells - Ice-rich Lacustrine Plain

Layer no.	Depth Range (m)		Soil Description	w (%)	Dry Density (kg/m^3)	Ku (W/mK)	Kf (W/mK)	P	Q
1	0.0	0.3	Peat	200	340	0.5	1.1	5	5
2	0.3	1.3	Clay	38	-	1.2	2.1	8	2.3
3	1.3	2.0	Organic Silt	38	-	1.2	2.1	3	4
4	2.0	4.0	Clay	48	-	1.0	2.1	8	2.3
5	4.0	6.0	Clay	42	-	1.1	2.1	8	2.3
6	6.0	8.0	Clay	42	-	1.1	2.1	8	2.3
7	8.0	20.0	Shale	20	1800	0.6	0.6	8	2.3
8	20.0	100.0	Shale	20	1800	0.6	0.6	8	2.3

Denotes measured parameter (shaded)

Ground temperatures for Site B.1 were based primarily on thermistor monitoring data from off the right of way at the Norman Wells Pump Station as shown in Figure 6. The ground temperature was around -2.0°C at a depth of 15 m. Based on a geothermal gradient of 0.05°C/m measured in the deep instrumentation at Canyon Creek, permafrost thicknesses of approximately 40 to 50 m were estimated for this site.

Site B.2 is located at KMP 19 of the Norman Wells Pipeline on the north side of Canyon Creek. Soil and permafrost conditions are based approximately on those encountered in GSC/INAC Borehole 84-2A. The simplified soil profile and selected geotechnical and geothermal properties are summarized in Table 3.4.

Although not reflected in the log for Borehole 84-2A, approximately 0.4 m of organic silt/peat existed off the right of way at Site B.2. In order to maintain stable permafrost in the Norman Wells area, it has been our experience this organic layer must be present. It has been well-documented that the disturbance of the organic cover in discontinuous warm permafrost areas can result in degradation of permafrost or at least an increase in the surficial active layer.

Below the assumed 0.4 m of organic material, the soil profile consisted of a relatively low-ice content glacial silt or clay till to a depth of approximately 9 m. Clay shale was encountered below 9 m and is assumed to extend to depth in the profile.

Ground temperatures for Site B.2 were determined from the thermistor string in Borehole 84-2A as shown in Figure 7. The ground temperature at Site B.2 is warmer than at Site B.1, and is approximately -0.6°C at 15 m. Based on the measured geothermal gradient in a deep borehole in the area of 0.05°C/m, a permafrost thickness of 26 m was estimated for this site.

More geotechnical and geothermal material properties were available for the Norman Wells sites than for the Mackenzie Delta, and consisted primarily of natural moisture contents, frozen bulk densities and frozen thermal conductivities. Data, where unavailable, was assumed, based on our experience for typical soils in the area. In addition, minor changes in soil/meteorological data were made to ensure steady-state permafrost conditions were maintained for base conditions.

Table 3.4 Geotechnical and Geothermal Properties for Site B.2
Norman Wells - Low-ice Glacial Till Deposit

Layer no.	Depth Range (m)		Soil Description	w (%)	Dry Density (kg/m^3)	Ku (W/mK)	Kf (W/mK)	P	Q
1	0.0	0.5	Organic silt	200	340	0.5	1.1	5	5
2	0.5	1.0	Clay (till)	19	-	1.8	2.0	8	2.3
3	1.0	3.0	Clay (till)	19	1800	1.8	2.0	8	2.3
4	3.0	5.0	Clay (till)	19	-	1.8	2.0	8	2.3
5	5.0	7.0	Silt (till)	13	-	2.0	2.1	3	4
6	7.0	9.0	Silt (till)	13	-	2.0	2.1	3	4
7	9.0	20.0	Shale	20	-	2.2	2.5	8	2.3
8	20.0	100.0	Shale	20	-	2.2	2.8	8	2.3

[shaded box] Denotes measured parameter

Historical meteorological data for this area was derived from the airport weather station at Norman Wells. This data was available on computer file from the Atmospheric Environmental Services Archive System. Specific meteorological information used in this study consisted of the 30-year normal mean-monthly air temperature, precipitation data for the period 1951 to 1980 and the daily snowfall on ground measurements from 1955 to 1980.

Mean-monthly air temperatures and snow depth thicknesses derived from the historical meteorological data for Norman Wells are presented as Figures 8 and 9, respectively. Snow depths for Site B.1 and Site B.2 were reduced by 30 and 20 percent respectively from the values measured for the Norman Wells weather station in order to obtain equilibrium conditions.

3.4 FORT SIMPSON - SITE C

The Fort Simpson study area consists of two separate sites approximately 50 km apart. Both sites are located south of the Liard River and the Town of Fort Simpson.

Site C.1 is located near the Norman Wells to Zama Pipeline near Jean-Marie Creek, and is situated in an ice-rich peat plateau. Soil conditions are based approximately on GSC/INAC Borehole 85-12B. A simplified soil profile and selected geothermal properties are summarized in Table 3.5.

Based on borehole information, the soil profile at Site C.1 consists of approximately 3 m of peat overlying a low plastic clay or clay till. Below 10 m, a glaciofluvial gravel was encountered to the bottom of the borehole at 16.8 m.

Based on the thermistor string installed in Borehole 85-12B, permafrost at the site is very thin, being around 5 to 6 m (Figure 10). The geothermal gradient measured in this borehole was relatively steep and had a value of around 0.07°C/m.

This type of permafrost is considered "sensitive" and exists only due a unique micro-climate and local vegetation.

Table 3.5 Geotechnical and Geothermal Properties for Site C.1
Fort Simpson - Ice-rich Thick Organics (Peat Plateau)

Layer no.	Depth Range (m)		Soil Description	w (%)	Dry Density (kg/m^3)	Ku (W/mK)	Kf (W/mK)	P	Q
1	0.0	0.5	Peat	300	100	0.5	1.3	5	5
2	0.5	1.0	Peat	650	100	0.5	1.3	5	5
3	1.0	3.0	Peat	1300	50	0.3	1.2	5	5
4	3.0	6.0	Clay	50	1150	1.0	2.7	8	2.3
5	6.0	10.0	Clay	35	1150	1.2	2.7	8	2.3
6	10.0	15.0	Gravel	15	-	2.8	4.0	1	15
7	15.0	20.0	Gravel	15	-	2.8	4.0	1	15
8	20.0	100.0	Gravel	15	-	2.8	4.0	1	15

[shaded box] Denotes measured parameter

Site C.2 is located near the Norman Wells to Zama Pipeline in the Manners Creek drainage basin on a lacustrine plain. The soil and permafrost conditions were based approximately on GSC/INAC Borehole 85-8A and are summarized in Table 3.6.

The soil profile for Site C.2 consists of 5 m of silts and sands overlying ice-rich medium to high plastic clay. The site is overlain by approximately 0.5 m of peat.

Thermistor data from Borehole 85-8A, shown in Figure 11, indicates a steep geothermal gradient exists below a depth of 20 m and has a value as high as 0.10°C/m. The thickness of permafrost is relatively thin at this site, being approximately 12 m thick.

Geotechnical and geothermal material properties were readily available for both the Fort Simpson profiles. Information typically consisted of full moisture content and density profiles, in-situ frozen thermal conductivity profiles, laboratory frozen thermal conductivity tests, unfrozen water content curves, etc. Data where unavailable was assumed, based on our experience for typical soils in the area. Minor adjustments were made as required to maintain steady-state permafrost conditions for the 1951 to 1980 meteorological information.

Historical meteorological data was derived from two airport weather stations near Fort Simpson. This data was available on computer files from the Atmospheric Services Archive System. Specific meteorological information used in this study consisted of the 30-year normal mean-monthly air temperature and precipitation data for the period 1951 to 1980, and the daily snowfall on ground measurements from 1955 to 1980.

Mean-monthly air temperature and snow depth thicknesses derived from the historical meteorological data for Fort Simpson are presented as Figures 12 and 13, respectively. Snow depths for Site C.1 did not have to be adjusted to obtain steady-state permafrost conditions, while a reduction in snow depth of 20 percent was required at Site C.2.

Table 3.6 Geotechnical and Geothermal Properties for Site C.2
Fort Simpson - Lacustrine Deposit - Ice-poor in the Top 5m; Ice-rich Below

Layer no.	Depth Range (m)		Soil Description	w (%)	Dry Density (kg/m^3)	Ku (W/mK)	Kf (W/mK)	P	Q
1	0.0	0.5	Peat	200	340	0.5	1.1	5	5
2	0.5	1.0	Sand/silt	28	1320	1.4	2.2	8	4
3	1.0	3.0	Sand	25	1460	1.8	4.0	5	10
4	3.0	5.0	Silt	28	1410	1.4	3.6	8	2.3
5	5.0	7.0	Clay	30	1510	1.4	2.5	8	2.3
6	7.0	11.0	Clay	42	1190	1.1	1.9	8	2.3
7	11.0	20.0	Clay (unfrozen)	35	-	1.2	2.0	8	2.3
8	20.0	100.0	Clay (unfrozen)	35	-	1.2	2.0	8	2.3

(shaded) Denotes measured parameter

4.0 THE 2 x CO_2 SCENARIO

4.1 GLOBAL CIRCULATION MODEL PREDICTIONS

The Global Circulation Model 2 x CO_2 Scenario predictions used in this study consisted of mean-monthly air temperature and monthly total precipitation estimates for a doubling of the carbon dioxide level in our atmosphere for the same weather stations that the historical meteorological information came from. Only three of the weather stations were used specifically in this study. Table 4.1 summarizes the annual 30-year climatic normal and the 2 x CO_2 Scenario values for the Mackenzie Delta (Tuktoyaktuk), Norman Wells and Fort Simpson areas and the relative changes at each location.

In general, the GCM predictions suggest an increase of between 4.2 and 5.0°C on the mean-annual air temperature will occur for the study area under consideration. In addition, increases in total precipitation of between 20 and 56 mm are also predicted. However, as discussed in the next section, increased total precipitation does not necessarily mean increased snowfall.

As it is our understanding that temperature predictions from the GCM have the highest level of confidence, total precipitation being next and estimates of snow cover the least, it was felt that the historical information could be more useful in predicting some of the end-point parameters for the model, such as snow depth.

A description of the method to predict snow depth is discussed in the next sections.

4.2 ESTIMATIONS OF SNOW DEPTH FOR ANALYSIS

Snow depth information is extremely difficult to estimate, for a specific site due to the potential for dramatic variations locally from aspect, tree cover, elevation, etc. While it can be argued the temperature is also affected by these same factors, generally it can be demonstrated that this amounts to a only few degrees (Smith and Riseborough, 1985). In the case of snowfall, however, an open area can be swept clean of snow, a treed area may collect average snowfall depths and, in some cases where conditions are right, even accumulate huge snow drifts.

Table 4.1 Summary of Climatic Changes

LOCATION	MEAN-ANNUAL AIR TEMPERATURE (C)			TOTAL PRECIPITATION (mm)		
	30 yr Normals	2XCO2 Scenario	Difference	30 yr Normals	2XCO2 Scenario	Difference
Tuktoyaktuk	-10.9	-5.9	+5.0	138	157	+19
Norman Wells	-6.4	-2.2	+4.2	328	356	+28
Fort Simpson	-4.2	-0.0	+4.2	355	411	+56

The GCM predictions provided an estimate of maximum snow depth thickness in March only and did not provide information for other months. For this reason, it was decided to use historical data to predict snow depths.

The snow depth information used in this study come from actual monitoring data collected at specified weather stations within the Mackenzie Valley. As the location of the actual monitoring sites greatly influences the amount of snow depth measured, this parameter obviously is extremely site-dependent and, consequently, snow depth became the input parameter in the geothermal runs that was adjusted to obtain steady-state permafrost conditions.

The snow data on ground information originally was in form of daily records. These records were averaged by month for the period of time which closely-matched our desired base case interval (i.e. 1951 to 1980). However, as most of the weather stations in the area did not begin actively recording this information until between 1955 and 1963, we have assumed the information available for the partial time period approximates the 30-year normal values.

Using the snow depth thicknesses calculated for the three general study areas for climatic normal conditions, the next step was to devise a reasonable means of predicting snow depth on the ground in the 2 x CO_2 Scenario. Following discussions with Ms. M. Burgess of the Geological Survey of Canada, a method of estimating snow depth from total precipitation and temperature data was proposed, based on correlations from the historical snow depth records.

In this method, the first step involved an estimation of the percentage of total precipitation that fell in the form of snow versus temperature. The 30-year normal precipitation data was plotted against temperature for the Tuktoyaktuk, Norman Wells and Fort Simpson weather stations, as shown in Figures 14 to 16, inclusive. As can be seen for each area, above a certain temperature, all precipitation fell in the form of rain, and below a certain temperature, all precipitation fell in the form of snow. For temperatures in between these limits, precipitation was a mixture of snow and rain. Based on these relationships, estimates of snowfall for each month for each of the three study areas were made using the 2 x CO_2 Scenario temperature and total precipitation values.

The next step involved modelling the accumulation/ablation behavior of a typical snow pack. Normally, in the general Mackenzie Valley area, a snow pack develops in the early fall and a large percentage of the snowfall received goes to increasing the snow depth. Then in the early spring, with longer days and warmer air temperatures, the snow pack begins to decrease. Snowfall during the spring is often wet, and generally there appears to be no significant net increase to the snow pack beyond March. A two-stage correlation of first increasing and then decreasing the snow pack versus temperature and snowfall was then derived for each study area as discussed below.

Between the first snowfall and the end of March, relationships of percentages of snowfall contributing to snow depth as a function of temperature were established. These correlations are shown in Figures 17 to 19 for each of the three study areas. Between April and the last day of snow on the ground, relationships between the percentage decrease in snow pack as a function of temperature were also established. These decreasing correlations are shown in Figures 20 to 22 for each study area. Using this two-step approach, snow depths for each weather station were derived from the temperature and snowfall values of the 2 x CO_2 Scenario. These snow depth predictions are shown in Figures 5, 9 and 13 for Tuktoyaktuk, Norman Wells and Fort Simpson, respectively.

Although the above method may seem highly subjective, it matches the existing data quite well. As the method incorporated both the effects of precipitation and temperature, it was felt the technique was a reasonable approximation to what conditions may be like with the 2 x CO_2 Scenario. As previously discussed snow depths at specific sites were further either increased or decreased to obtain steady-state permafrost conditions with the 1951 to 1980 mean monthly air temperatures. The same factor used to adjust the base case snow depth values at each site were also used to adjust the 2 x CO_2 Scenario values.

5.0 GEOTHERMAL MODELLING

5.1 ANALYTICAL APPROACH

The analytical approach used to model the potential impacts of global warming on permafrost involved running several series of one-dimensional geothermal simulations reflecting steady-state permafrost as the start condition and then varying surface conditions with time. The end-point of the simulations in all cases was the 2 x CO_2 Scenario predicted by the Global Circulation Model.

Snow depths for the 2 x CO_2 Scenario were normally assumed to be less than the 30-year climatic normals as derived in the previous section, with the exception of one series of analyses where the end snow depth values were assumed to be 10 percent greater than the climatic normals. This series of analyses was included to investigate the sensitivity of snow depth on the analysis and assumed both temperature and snow depth increased linearly with time.

As it was felt that equilibrium climatic conditions may not exist at present-day, and some global warming effects may have already occurred, the 1951 to 1980 climatic normal meteorological values were selected as the base conditions for steady-state permafrost rather than the 1961 to 1990, 30-year normals.

The geothermal analyses were performed using the one-dimensional finite difference program THERM1 under license from Nixon Geotech Ltd. This one-dimensional geothermal simulator has been used on many projects and its use is well-documented (Nixon, 1983). Geotechnical and geothermal properties used in the geothermal model were as presented in Section 3.0.

All geothermal modelling was performed on a 100 m deep soil profile, with a large mass of soil in the bottom of the finite difference mesh, to act as a heat sink. Had such a large mesh not been used, the effects of the increased surface temperatures from global warming would have been exaggerated.

Boundary conditions for the geothermal model consisted of surface temperatures and snow depths. As the GCM model provided mean-monthly air temperatures rather than surface temperatures, it was felt the best way to apply these temperatures to the ground was by the use of n-factors. Although much more sophisticated means of applying boundary conditions to the geothermal model exist, the information required to input into the model is not available and would have had to be assumed. In addition, as the intent of the study was to observe the effect of changes in air temperature, it was felt that this method was best-suited for the purpose.

Surface temperatures were applied to the top of the snow pack in winter and directly to the ground surface in summer. Based on our experience and published literature values, an n-factor of 1.0 was considered appropriate for both freezing and thawing conditions (Andersland and Anderson, 1978). This assumed the surface of the ground in summer was turf (i.e. vegetated) and in winter was snow.

For each of the six sites/soil profiles, steady-state permafrost conditions were established by a trial and error method until negligible variations were measured between the start and end conditions in a 50-year time period. The input parameter, which was varied most significantly to achieve steady-state conditions, was the snow depth on the ground. The criteria used for establishing equilibrium conditions for this study over a 50-year period were when the following conditions were reasonably approximated:

- ground temperature below the depth of seasonal effects, matched the thermistor data,
- active layer thickness was reasonable, and
- base of permafrost was reasonable for the area or as measured by thermistor data.

5.2 SURFACE FUNCTIONS

The end values for the 2 x CO_2 Scenario were discussed in Section 4.0. Although the GCM model was able to estimate what the end result would be, there was very little indication on how fast or at what rate these changes would occur. To establish some bounds to this problem, four cases or surface functions were investigated, as follows:

- base case (stable permafrost conditions),
- step case (instantaneous application of the 2 x CO_2 end values),
- linear case (linear increase of temperature/linear decrease of snow depth), and
- exponential case (exponential increase of temperature/exponential decrease of snow depth).

The bounds to the problem for a given set of end conditions, therefore, are the base case (no change) and the step case (instantaneous change). The probable solution, therefore, would likely be somewhere in the middle, which would be most closely represented by either the linear or the exponential case. Figure 23 illustrates the relative shape of each of the surface functions. Base conditions are reflected by "0", while 2 x CO_2 Scenario end values are reflected by "1" on the y-axis in Figure 23.

Figures 24 to 47, inclusive, summarize the actual surface functions for each of the general study areas for temperature and snow depth for the 2 x CO_2 Scenario that assumed temperatures will increase and snow depth will decrease.

As the end temperature conditions for the 2 x CO_2 Scenario were not assumed to vary, but the end snow depth values were estimated by an empirical method only, a further series of analyses reflecting a different set of end conditions was undertaken. In this case, temperature was assumed to increase linearly as before, but snow depth was assumed to also increase linearly to a 2 x CO_2 Scenario where snow depth was 10 percent greater than the 30-year climatic normals. This combination of increased snow pack and increased temperatures reflects more adverse end conditions than those modelled above.

Figures 48 to 50 show the linearly-increasing snow depth factors for Tuktoyaktuk, Norman Wells and Fort Simpson, respectively, for this special series of analyses.

6.0 RESULTS

6.1 GENERAL

The results of all the geothermal analyses are presented in Appendix B. As the results represent a sizeable amount of information, the order in which it is presented is discussed below.

All analyses have been grouped according to the specific site locations, which then are broken down to specific surface functions, and finally to the specific graphs themselves. The site groupings are A.1 to C.2, inclusive, as previously discussed. The surface functions for each site are presented in the following order:

- base case conditions (steady-state permafrost),
- exponential case conditions (exponentially-increasing temperature/ exponentially-decreasing snow depth),
- linear case conditions (linearly-increasing temperature/linearly-decreasing snow depth),
- step case conditions (instantaneous application of 2 x CO_2 Scenario end values), and
- linear case with an increased snow pack (linearly-increasing temperature/ linearly decreasing snow depth).

For each geothermal simulation represented above, there are also an accompanying series of four figures which include the following:

- temperature profile (consisting of trumpet curves for years 10 and 50 and base conditions),
- thaw depth versus time (which may include the base of permafrost when the thickness of permafrost was less than 30 m),
- surface temperature versus time (which reflects temperatures just below the ground surface), and
- ground temperatures versus time (reflecting temperatures at three discrete depths which vary with each soil profile and supplement the trumpet curve information regarding changes in the ground thermal regime).

In addition to the individual results, Table 6.1 summarizes some of the more important aspects of the analyses. One of the parameters summarized in the table is a comment on whether the permafrost is degrading. For the purposes of this study, degrading refers to a condition where the depth of thaw continues to increase with time following a surface perturbation, with little chance of regaining equilibrium. It does not refer to an increase in thaw depth with time alone if the thaw depth is a function of a transient surface boundary condition.

In most cases, the decision of whether the permafrost will likely regain equilibrium if the surface boundary conditions stabilize, is a judgment call, based on our experience with the

Table 6.1 Summary of Geothermal Analyses

SITE	SURFACE FUNCTION	ACTIVE LAYER THICKNESS (m)			PERMAFROST CONDITION	
		t = 0 yrs	t = 10 yrs	t = 50 yrs	Is Permafrost Degrading (yes/no)	Time for complete degradation
A.1	Base	0.9	0.9	0.9	No	-
	Exponential	0.9	0.9	1.2	No	-
	Linear	0.9	0.95	1.2	No	-
	Step	1.2	1.2	1.2	No	-
	Linear+10%	0.9	0.95	1.3	No	-
A.2	Base	0.4	0.4	0.4	No	-
	Exponential	0.4	0.4	0.55	No	-
	Linear	0.4	0.4	0.55	No	-
	Step	0.55	0.55	0.55	No	-
	Linear+10%	0.4	0.4	0.65	No	-
B.1	Base	0.9	0.9	0.9	No	-
	Exponential	0.9	0.9	1.3	Yes	-
	Linear	0.9	1.0	1.4	Yes	-
	Step	1.1	1.3	1.7	Yes	-
	Linear+10%	0.9	1.0	3.1	Yes	-
B.2	Base	1.1	1.1	1.1	No	-
	Exponential	1.1	1.1	3.5	Yes	-
	Linear	1.1	1.3	4.7	Yes	-
	Step	1.4	4.2	12.0	Yes	-
	Linear+10%	1.1	1.3	7.8	Yes	-
C.1	Base	0.9	0.9	0.9	No	-
	Exponential	0.9	0.9	2.3	Yes	-
	Linear	0.9	0.95	-	Yes	48
	Step	1.0	1.8	-	Yes	26
	Linear+10%	0.9	0.95	-	Yes	41
C.2	Base	1.1	1.1	1.1	No	-
	Exponential	1.1	1.1	6	Yes	-
	Linear	1.1	1.2	8	Yes	-
	Step	1.3	4.9	-	Yes	30
	Linear+10%	1.1	1.1	-	Yes	50

geothermal model. A discussion of the results of each site are presented in the following sections.

6.2 SITE A.1 - MACKENZIE DELTA
Massive Ice Underlying a Thin Glaciofluvial Deposit

The results of the geothermal analyses for Site A.1 are presented as Plates B.1 to B.20, inclusive (Appendix B) and as summarized in Table 6.1.

Active layer thicknesses predicted for all the surface functions for this soil profile were larger than average for such a northern site, but is explainable by the absence of a surface organic layer. An active thaw depth of 0.9 m was predicted for the average or base conditions. This thaw depth increased to 1.2 m when the 2 x CO_2 Scenario end values were imposed as an instantaneous step. The greatest depth of thaw occurred at 50 years in the extreme case of an increased snow pack and, even then, the value was still only 1.3 m.

Active layer thicknesses quickly went into a quasi-steady-state condition, which strongly suggests that even under long-term exposure to the 2 x CO_2 Scenario end values, permafrost conditions will likely be maintained.

However, what is not apparent in the plots of active layer or surface thaw, is the overall warming of the permafrost. For example, in the case of the step surface function, the ground temperature in the upper 5 m had shifted approximately 3°C and the variation between the 10-year and 50-year trumpet curves was minor nearsurface (Plate B13). The warming trend is slower at depth and is heavily-damped by the presence of several hundred meters of permafrost. Given sufficient time, however, it is likely the temperature profile for Site A.1 would resemble a profile from a more southern discontinuous permafrost zone.

The exponentially- and linearly-increasing surface functions suggest that in 10 years, little change to the ground temperature will have occurred, but by the end of 50 years, significant warming would have begun in them as well (Plates B5 and B9).

6.3 SITE A.2 - MACKENZIE DELTA - Ice-Poor Glaciofluvial Deposit

The results of the geothermal analyses for Site A.2 are presented in Plates B21 to B40, inclusive, and summarized in Table 6.1.

The results of the analyses for Site A.2 were very similar to the results of Site A.1, except the actual thickness of the active layer was predicted to be substantially less at Site A.2, due to the moderately-thick surface organic layer. Based on the average or base surface conditions, only 0.4 m of thaw was predicted for this soil profile.

Ground temperature response to the various surface functions was approximately the same for Site A.2 as for Site A.2. The exponentially- and linearly-increasing surface temperature functions (and decreasing snow pack) suggest little change in ground temperatures will occur in 10 years, but by 50 years, the change will be significant (Plates B25 and B29).

The most significant impact on permafrost of any of the surface functions investigated for this soil profile was the linearly-increasing temperature and snow depth case. As can be seen in Plate B37, a mean-temperature shift of 5 or 6 degrees nearsurface is predicted at year 50, when both temperature and snow depth conditions are most adverse. It is difficult to ascertain whether this profile is stable or not without running a simulation for additional time without further increasing the temperature or snow cover. If permafrost conditions are stable for this profile, the permafrost would likely be very warm (-0.5 to -1.0°C).

6.4 SITE B.1 - NORMAN WELLS - Ice-Rich Lacustrine Plain

The results of the geothermal analyses for Site B.1 are presented on Plates B41 to B60, inclusive, and summarized in Table 6.1.

The active layer thickness for this site, as predicted for base case conditions, was approximately 0.9 m. When the same profile was subjected to an instantaneous increase in temperature (and decrease in snow depth), thaw depth began to increase with time. This response is significant in that it suggests that under the 2 x CO_2 Scenario end values, permafrost conditions cannot be maintained. Within 50 years, the active thaw depth increased from 0.9 to 1.7 m (Plate B54). Although less dramatic, the results of the exponentially- and linearly-increasing temperature surface functions predicted active thaw depths of 1.3 and 1.4 m by the end of 50 years.

Ground temperatures in most of the analyses typically rose between 1 and 1.5°C within the permafrost within 50 years. Given the original permafrost temperature was between -2.0 and -2.5°C, the potential for adverse ramifications are obvious.

6.5 SITE B.2 - NORMAN WELLS - Low-Ice Glacial Till Deposit

The results of the geothermal analyses for Site B.2 are presented in Plates B61 to B80, inclusive, and as summarized in Table 6.1.

The active layer thickness for the base climatic conditions was predicted to be 1.1 m. When an instantaneous step temperature increase was imposed on the soil profile, the permafrost began to degrade quickly and, by year 50, thaw depth had reached 12 m.

The exponentially- and linearly-increasing temperature functions (and decreasing snow depth) cases both produced degrading permafrost scenarios. By year 50, thaw depths of 3.5 and 4.7 m, respectively, were predicted by the model.

The linearly-increasing temperature and snow depth case also produced degrading permafrost, predicting a thaw depth of approximately 7.8 m by year 50. It is interesting to note that at Site B.1, the linearly-increasing temperature and snow depth scenario predicted more thaw than the step case, yet in the Site B.2 analyses, the linearly-increasing temperature and snow depth case produced less thaw than the step case. This difference in trend illustrates the complex interaction of transient boundary conditions and the actual properties of the soil profile.

Ground temperatures in all the analyzed profiles for Site B.2 show the dramatic shift of the trumpet curves to above freezing at nearsurface depths by year 50. The lag that occurs as a result of latent heat effects near the 0°C isotherm is very evident in most profiles. If the geothermal simulation had been continued for additional time, all of the surface functions investigated (except the base case) would have resulted in a complete thawing of the permafrost and a shift of the trumpet curves above 0°C.

6.6 SITE C.1 - FORT SIMPSON - Ice-Rich Organics - Peat Plateau

The results of the geothermal analyses for Site C.1 are presented in Plates B81 to B100, and are summarized in Table 6.1.

The active layer thickness predicted for the average or base case conditions was 0.9 m. When an instantaneous step temperature increase was imposed on the soil profile, complete permafrost degradation had occurred by year 26.

In the case of the exponentially-increasing temperature (and decreasing snow depth) case, complete permafrost degradation had not occurred by year 50, but a thaw depth of 2.3 m had developed. With an original permafrost thickness of between 5 and 6 m, this kind of surface thaw is very significant. In all other geothermal simulations, complete permafrost degradation occurred before year 50.

Based on our experience with permafrost in southern latitudes, they are extremely sensitive to minor surface changes. The existence of permafrost at all these locations is generally a result of a combination of local vegetation and micro-climatic conditions. Given the very thin nature of the original permafrost layer, it is not surprising to see the results of the geothermal model's predictions. It is interesting to note, however, that in both the exponentially- and linearly-increasing temperature (and decreasing snow depth) cases, by year 10, the changes to the ground temperature profiles are subtle (Plates B85 and B89, respectively). This suggests it may be difficult to actually observe the early impacts of global warming in a real monitoring situation when the normal seasonal variations exceed the global warming effects.

6.7 SITE C.2 - FORT SIMPSON
Lacustrine Deposit - Ice-Poor in Top 5 m; Ice-Rich Below

The results of the geothermal analyses for Site C.2 are presented in Plates B101 to B120, and are summarized in Table 6.1.

The active layer predicted for average or base case conditions was 1.1 m. When an instantaneous temperature increase (and decrease in snow depth) was imposed to the soil profile, complete degradation of the permafrost layer occurred by year 30. The only other analyses to produce complete permafrost degradation within 50 years was the linearly-increasing temperature and snow depth case.

In the exponentially- and linearly-increasing temperature (and decreasing snow depth) cases, thaw depths of 6 and 8 m were predicted by year 50, respectively. With an original permafrost thickness of approximately 12 m, this magnitude of thaw depth is highly significant.

In all the geothermal simulations undertaken for Site C.2, only the base case conditions resulted in a situation where the permafrost was not degrading. Again, as in the results of Site B.1, the changes in the ground temperature profiles by year 10 were subtle, but by year 50, they were dramatic.

7.0 DISCUSSION AND CONCLUSIONS

The results of the geothermal analyses presented in the previous section, suggest that the temperature increases of +4 to +5°C of the mean-annual air temperature will likely result in significant degradation of permafrost along the Mackenzie Valley. The hardest hit areas obviously would be the furthest south regions, typified by very warm discontinuous permafrost. Based on a surface function that reasonably predicts what likely will occur in the next 50 years, such as an exponentially- or linearly-increasing temperature (and decreasing snow depth) condition, depths of thaw between 2.3 and 8 m were predicted for the Fort Simpson area.

The Norman Wells area, although slightly better than Fort Simpson, is still presently in an area of warm discontinuous permafrost. Based on the exponentially- or linearly-increasing temperature (and decreasing snow depth) cases, depths of thaw of between 1.3 to 4.7 m are predicted for this region over a 50-year period. It would also appear the likelihood of permafrost being maintained in any of the profiles analyzed for either the Norman Wells or Fort Simpson area is low. This does not mean all permafrost will disappear, but rather the occurrence of these areas may be significantly reduced. Permafrost will still likely exist locally at Norman Wells, but it could be more sporadic and resemble conditions near the NWT-Alberta/British Columbia borders.

The results of the analyses also suggest that dramatic warming of the permafrost will occur in the Mackenzie Delta, but it is likely that equilibrium can be regained in the profiles analyzed under the 2 x CO_2 Scenario of increased temperature and decreased snowfall. However, permafrost temperatures would likely be very warm (possibly between -2° to 0°C). This will also result in a very slow process of a thinning of the permafrost layer as the surface temperature of the earth regains equilibrium with the ground at depth. This process could take centuries or thousands of years.

The majority of the analyses presented in this report have assumed that snow depth will decrease with time. This combination of end values would tend to produce a buffering effect of the increases in temperature that have been predicted. If, however, snow depths remain the same or actually increase, the effects of global warming would be even more adverse to permafrost in the Mackenzie Valley. The series of analyses that explored this possibility resulted in the complete degradation of all permafrost in the Fort Simpson area in less than 50 years. For the Norman Wells area, thaw depths of between 3.1 and 7.8 m were also predicted. For the Mackenzie Delta, thaw depths were still very small, although the ground temperature profiles were shifted very close to the 0°C isotherm.

The ramifications of the above on permafrost could result in some or all of the following conditions:

- thickening of the active layer,
- thaw settlement,
- thermokarst feature development,
- ground temperature warming,
- decreases in permafrost thicknesses,
- instability of some foundations on ice-rich permafrost, and
- instability of slopes in ice-rich permafrost.

In summary, the results of the geothermal modelling suggest the potential impact on permafrost in the Mackenzie Valley is high and, based on the soil profiles analyzed, steady-state permafrost conditions are likely only achievable on a widespread basis in the Mackenzie Delta, or in the zone that presently is referred to as continuous permafrost by today's standards.

Respectfully submitted,

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G443

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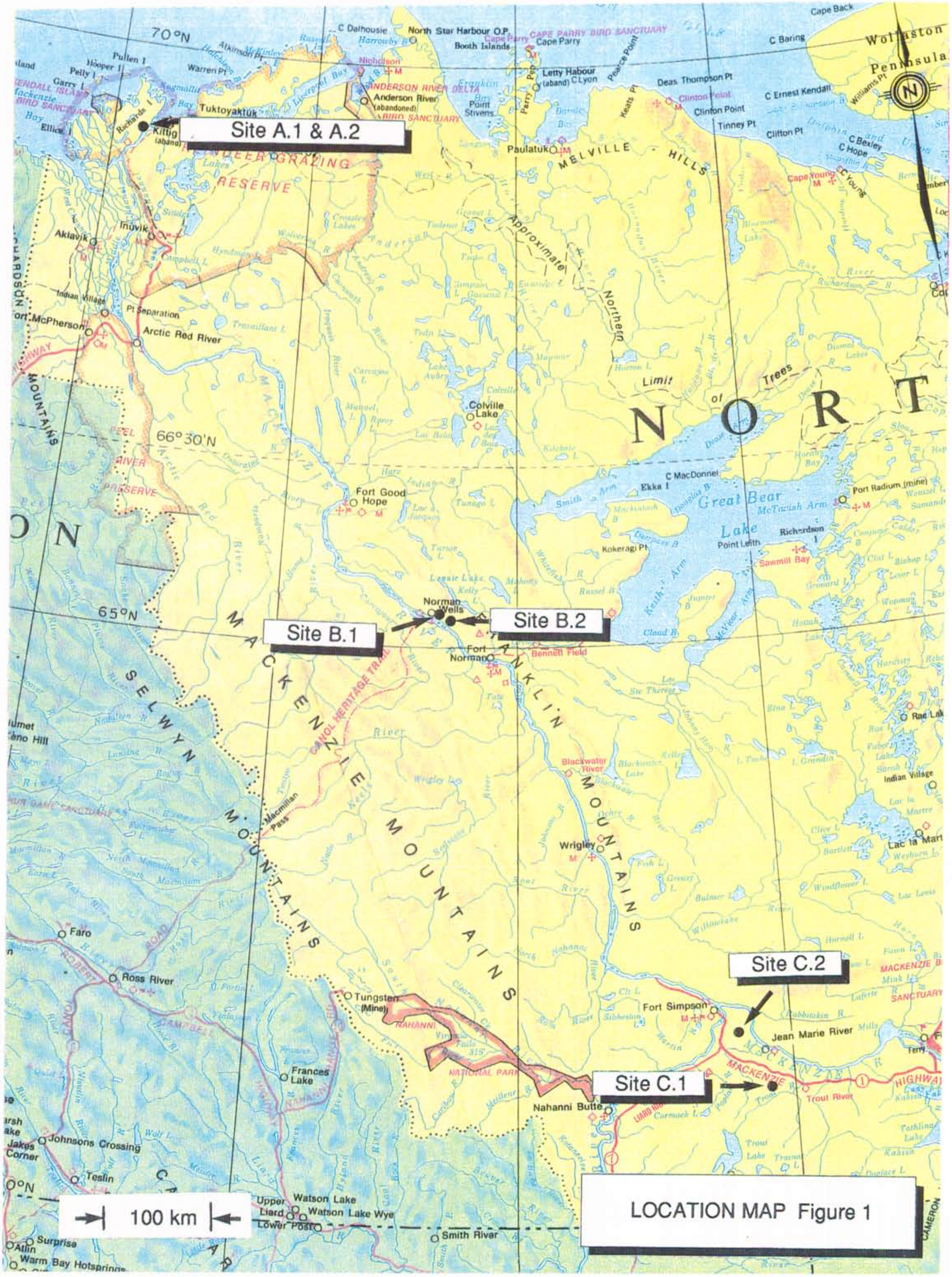
APPENDIX A

FIGURES



LOCATION MAP Figure 1

SITE A.1 - MACKENZIE DELTA

Massive Ice Underlying Thin Glaciofluvial Layer

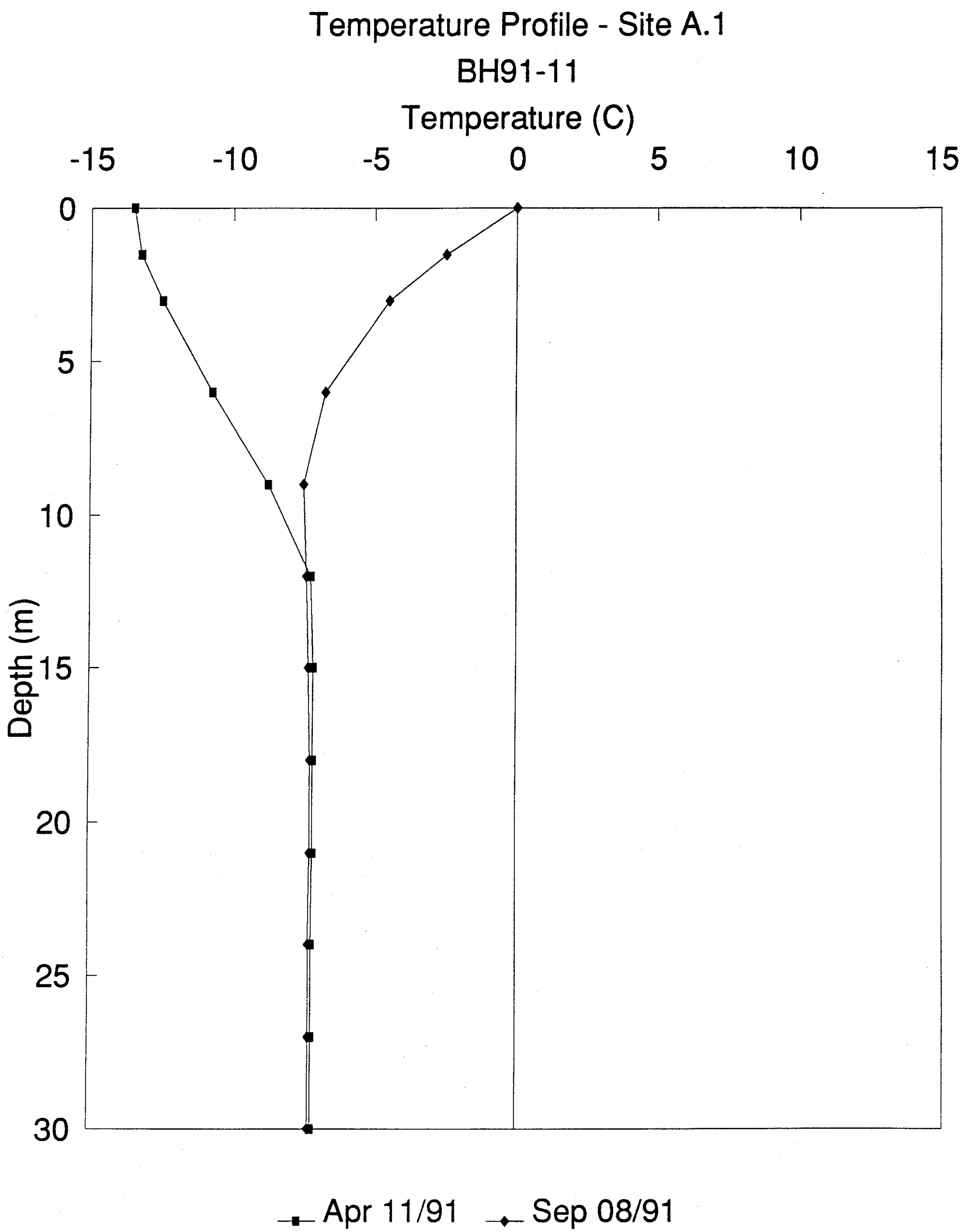

Temperature Profile - Site A.1
BH91-11
Temperature (C)
-15
-10
-5
0
5
10
15
Depth (m)
0
5
10
15
20
25
30
Apr 11/91
Sep 08/91

FIGURE 2

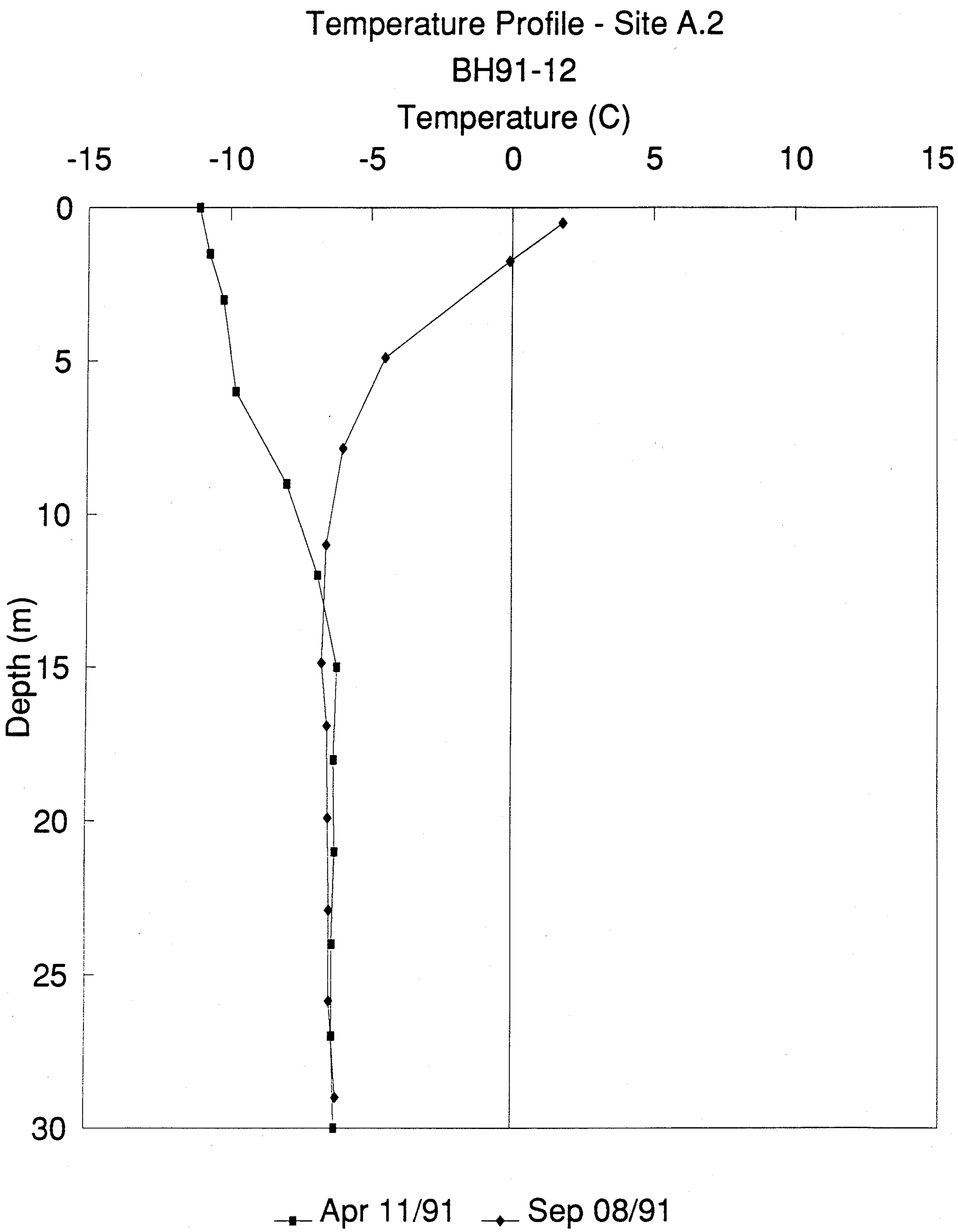
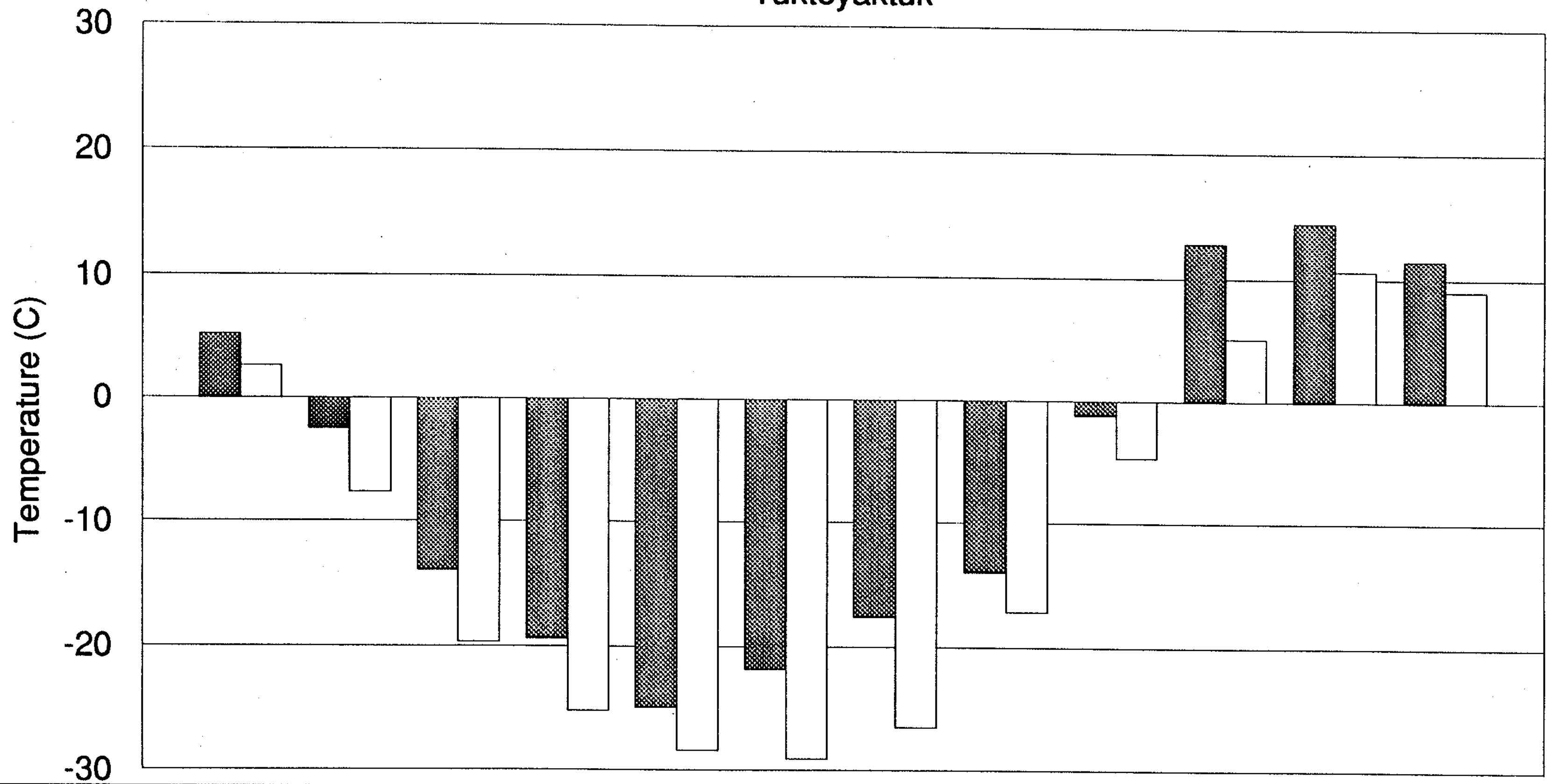

Temperature Profile - Site A.2
BH91-12
Temperature (C)
-15
-10
-5
0
5
10
15
0
5
10
15
20
25
30
Depth (m)
Apr 11/91
Sep 08/91

FIGURE 3

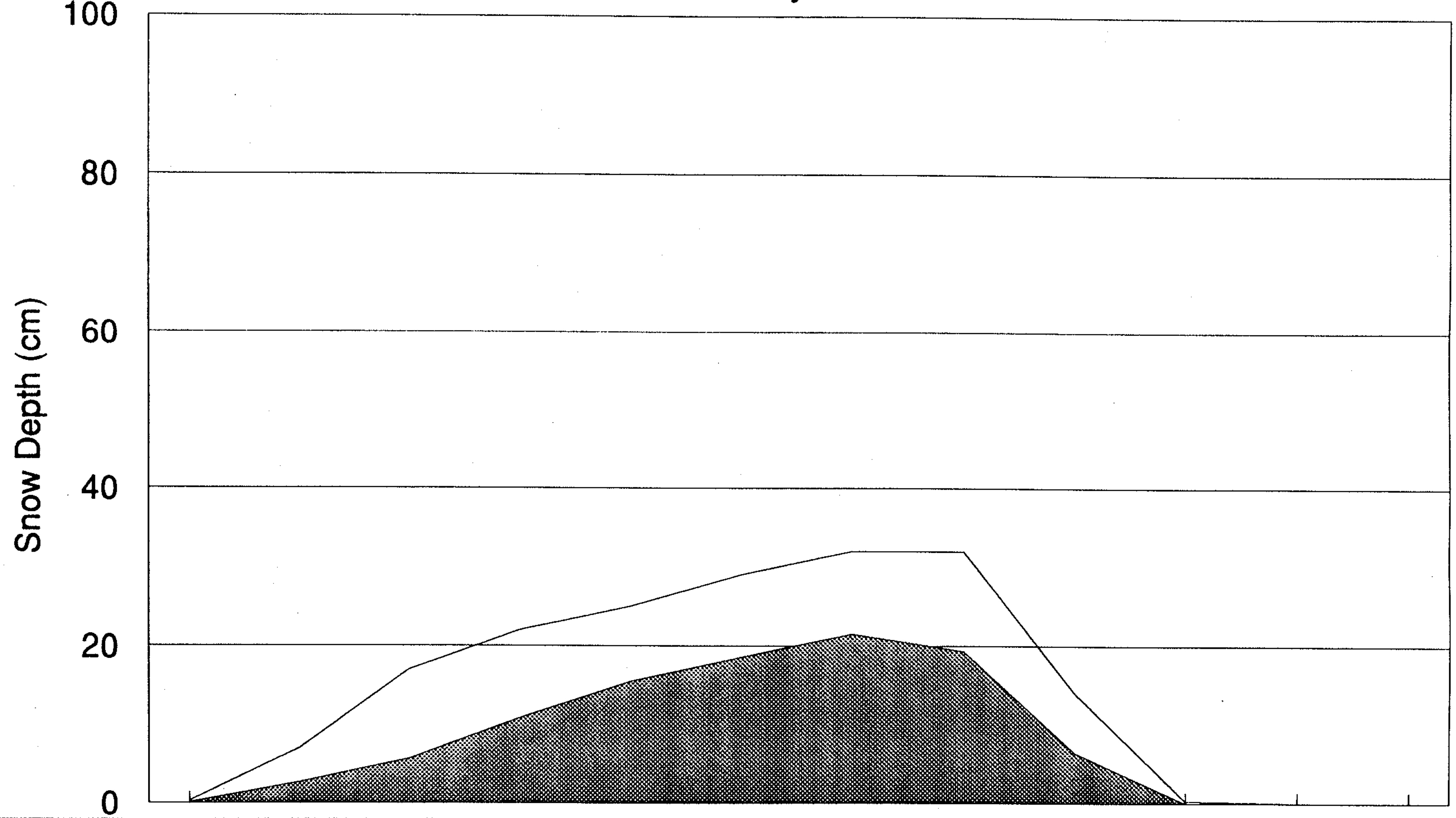
Mean-Monthly Air Temperatures
Tuktoyaktuk



	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
2XCO2	5.2	-2.5	-13.9	-19.4	-24.9	-21.8	-17.6	-14.0	-1.2	12.8	14.5	11.5
1951-1980	2.6	-7.7	-19.7	-25.2	-28.4	-29.1	-26.5	-17.2	-4.7	5.1	10.6	9.0

FIGURE 4

Snow Depth Distribution
Tuktoyaktuk



	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
2XCO2	0.1	2.7	5.6	10.9	15.5	18.6	21.5	19.4	6.4	0.0	0.0	0.0
1963-1980	0.3	7.0	17.0	22.0	25.0	29.0	32.0	32.0	14.0	0.3	0.0	0.0

FIGURE 5

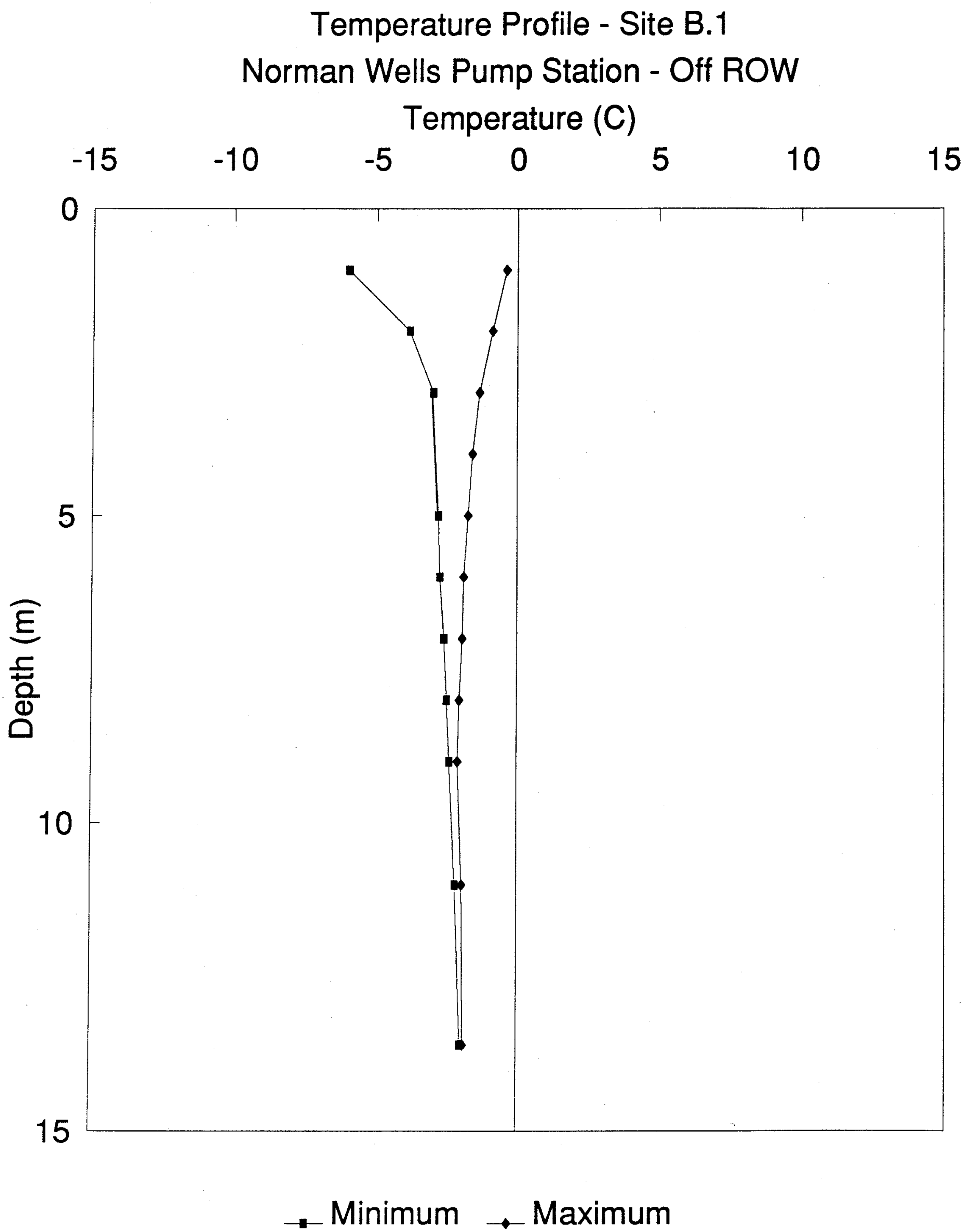

Temperature Profile - Site B.1
Norman Wells Pump Station - Off ROW
Temperature (C)
-15
-10
-5
0
5
10
15
0
5
10
15
Depth (m)
Minimum
Maximum

FIGURE 6

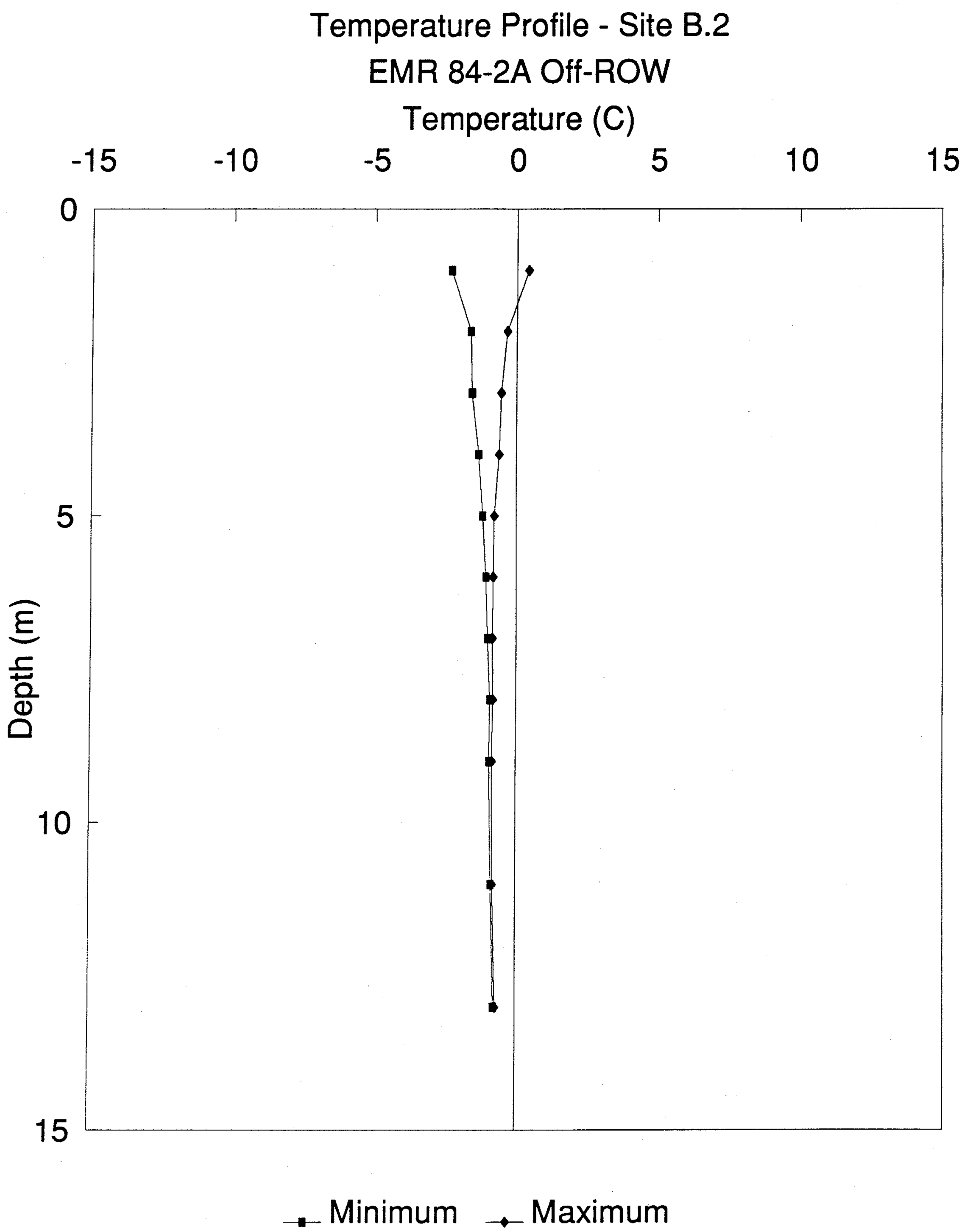
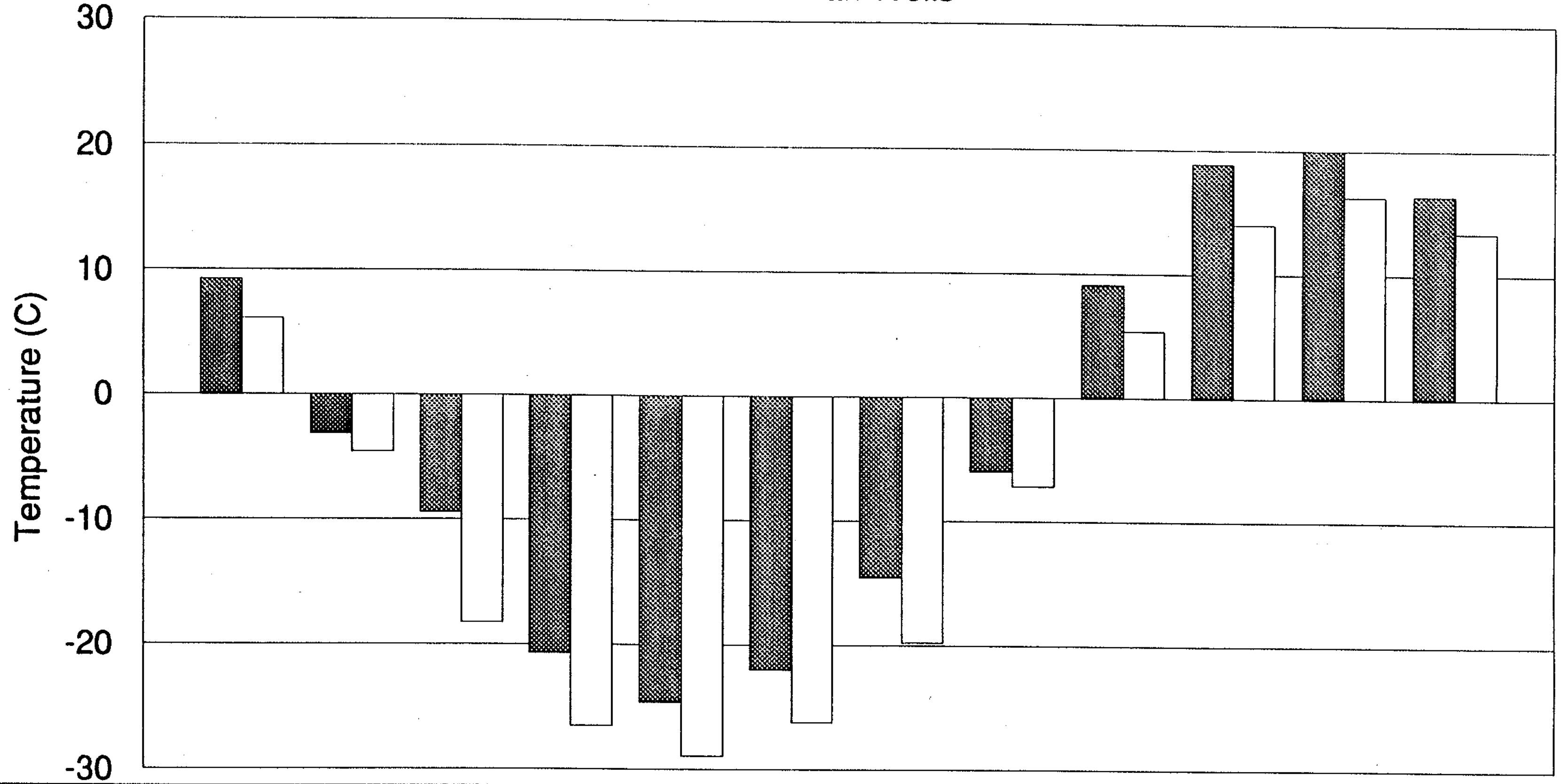

Temperature Profile - Site B.2
EMR 84-2A Off-ROW
Temperature (C)
-15
-10
-5
0
5
10
15
0
5
10
15
Depth (m)
Minimum
Maximum

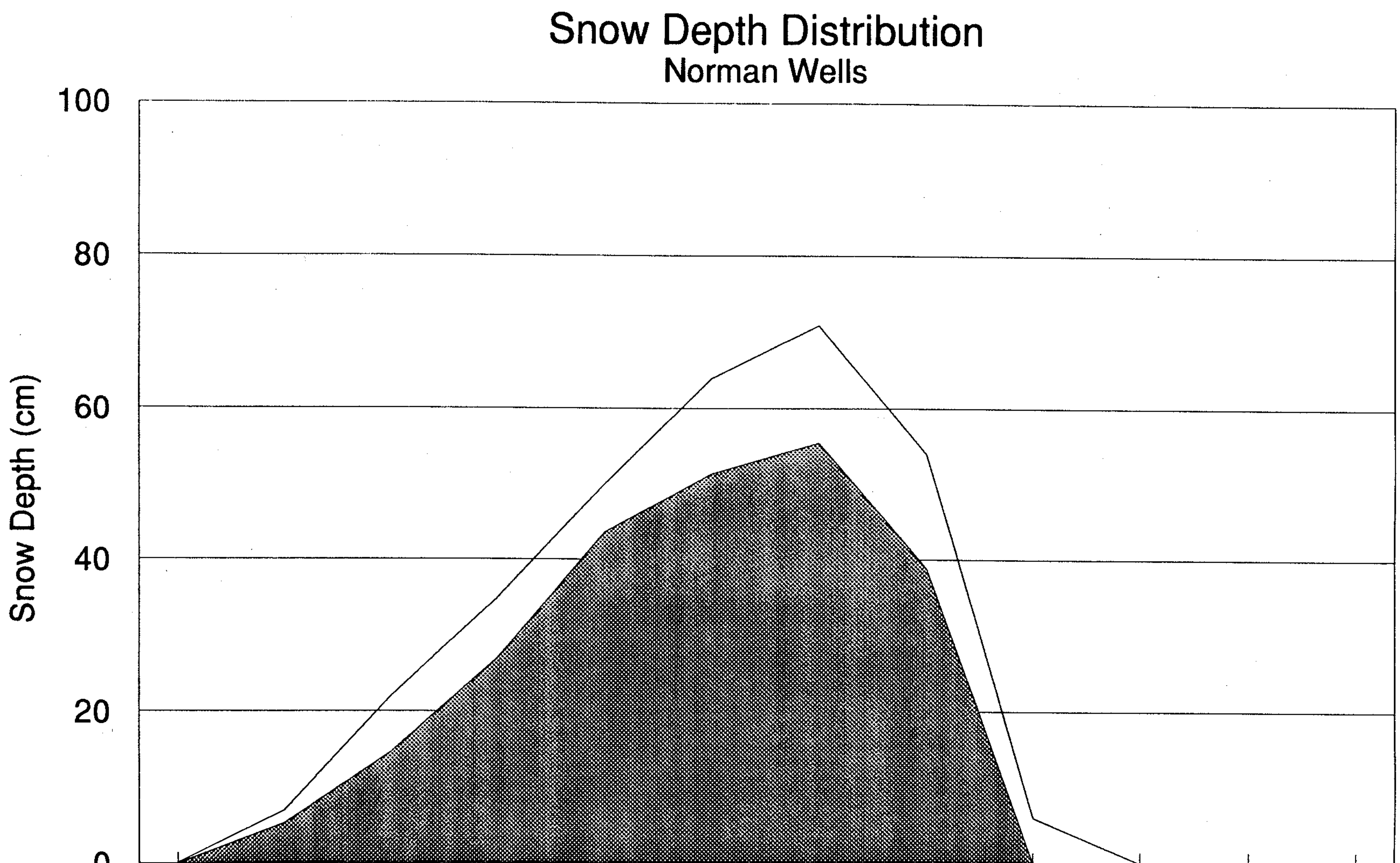
FIGURE 7

Mean-Monthly Air Temperatures
Norman Wells



	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
2XCO2	9.2	-3.1	-9.4	-20.7	-24.6	-22.0	-14.5	-6.0	9.1	18.9	20.0	16.4
1951-1980	6.1	-4.6	-18.2	-26.5	-28.9	-26.2	-19.8	-7.2	5.4	14.0	16.3	13.4

FIGURE 8



	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
2XCO2	0.0	5.3	14.6	27.1	43.6	51.4	55.5	38.9	0.0	0.0	0.0	0.0
1955-1980	0.1	7.0	22.0	35.0	50.0	64.0	71.0	54.0	6.0	0.0	0.0	0.0

FIGURE 9

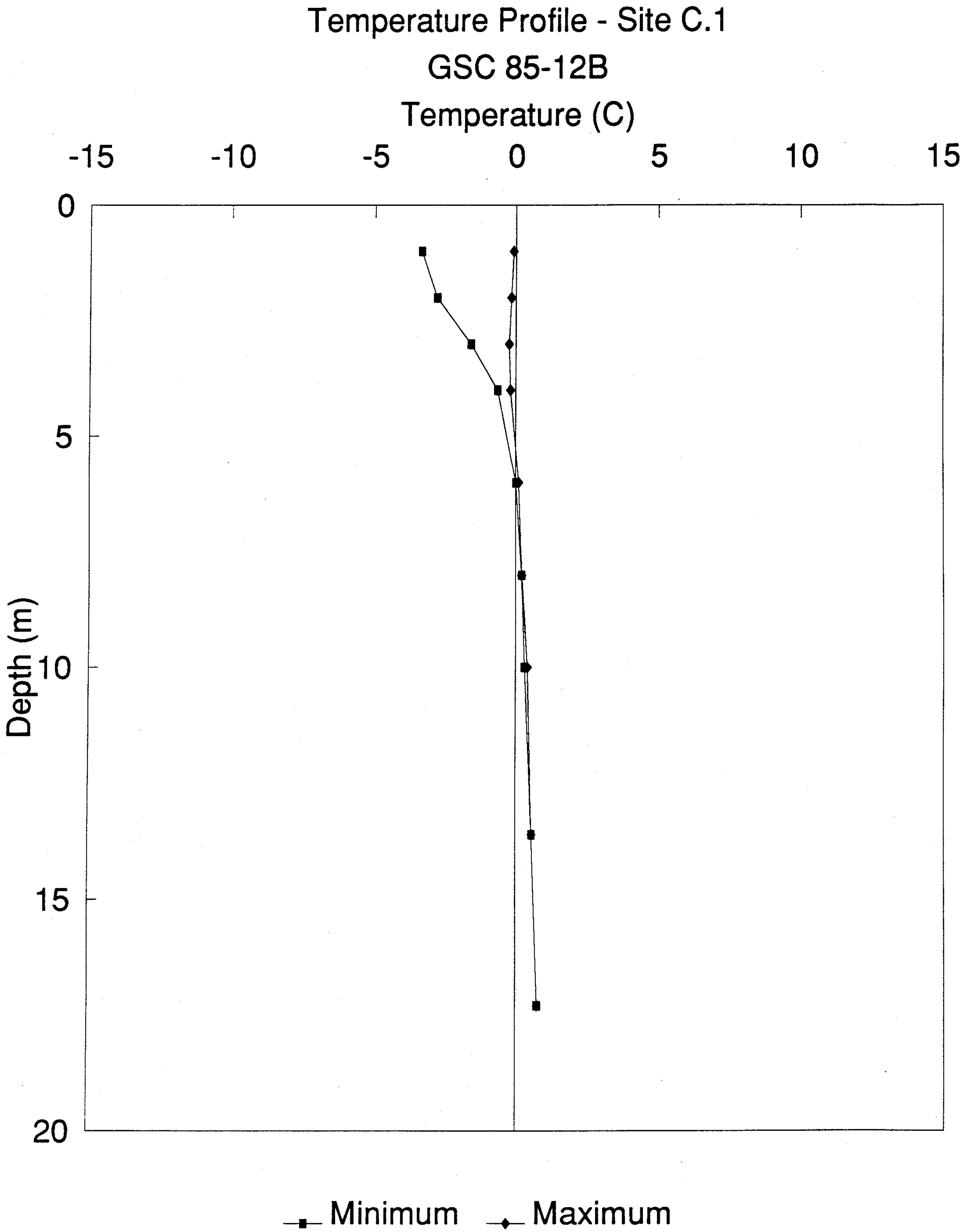
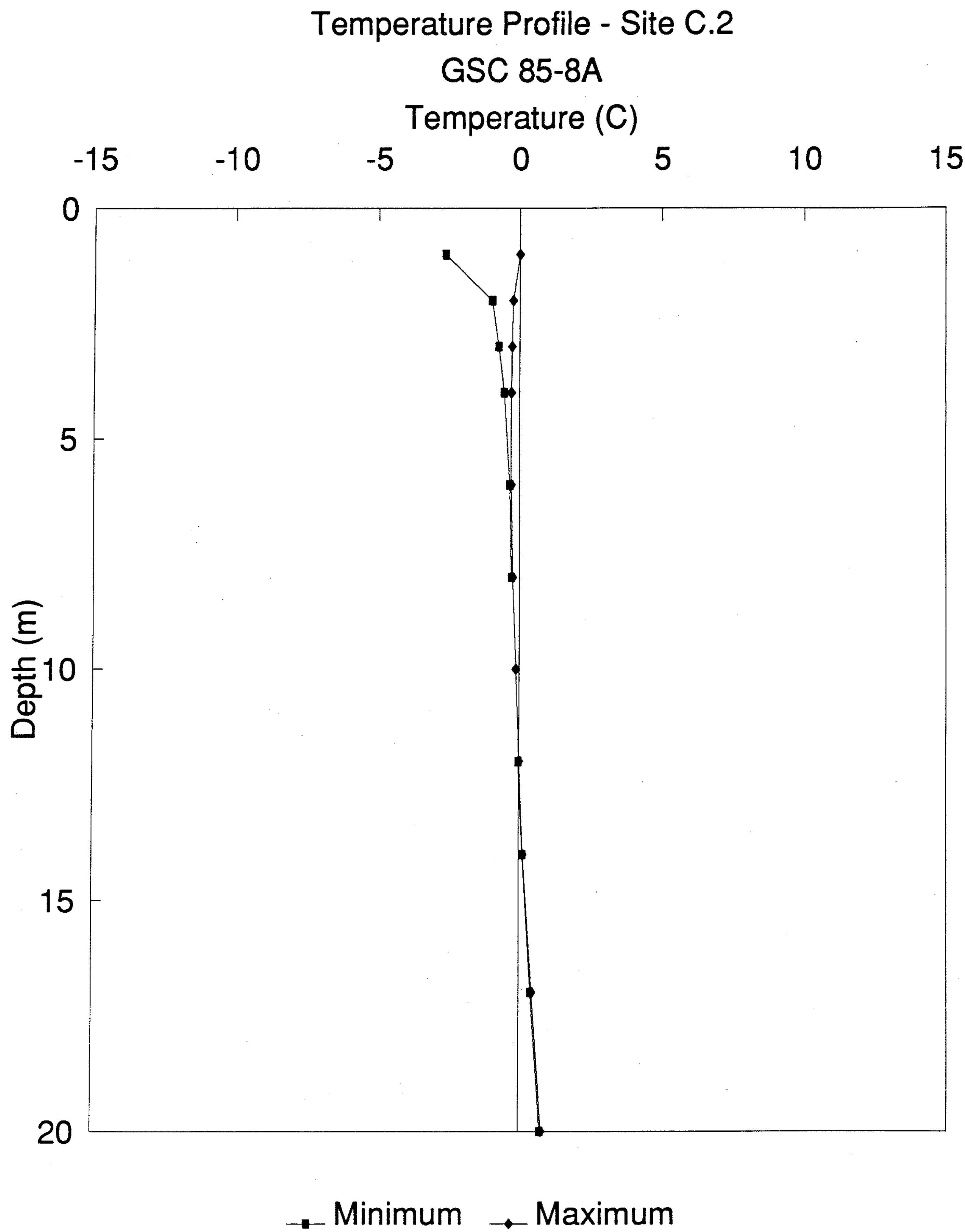

Temperature Profile - Site C.1
GSC 85-12B
Temperature (C)
-15
-10
-5
0
5
10
15
0
5
10
15
20
Depth (m)
Minimum
Maximum

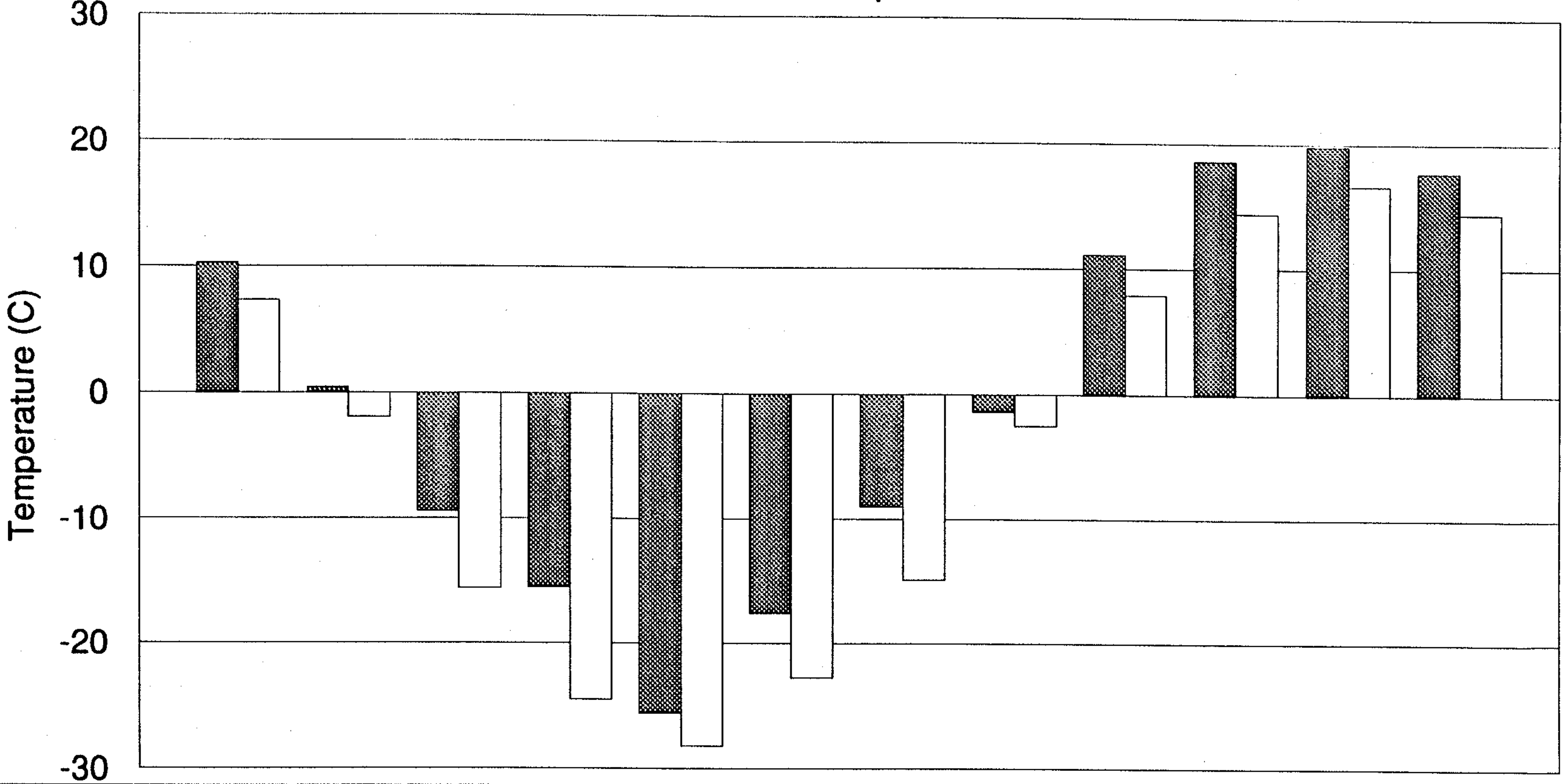
FIGURE 10



Temperature Profile - Site C.2
GSC 85-8A
Temperature (C)
-15
-10
-5
0
5
10
15
0
5
10
15
20
Depth (m)
Minimum
Maximum

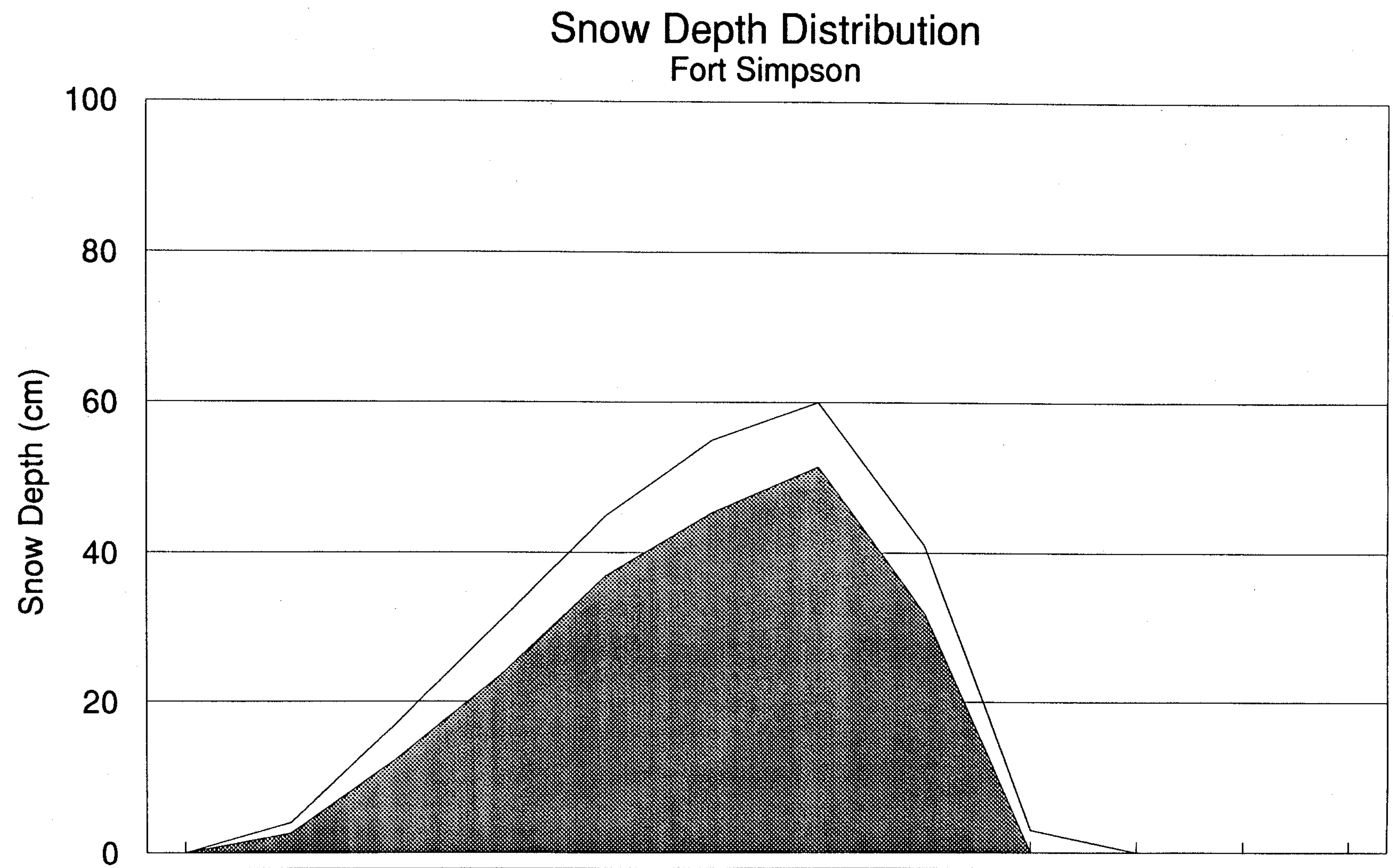
FIGURE 11

Mean-Monthly Air Temperatures
Fort Simpson



	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
2XCO2	10.3	0.4	-9.4	-15.5	-25.6	-17.6	-9.0	-1.4	11.1	18.6	19.8	17.7
1951-1980	7.3	-1.9	-15.6	-24.5	-28.2	-22.8	-14.9	-2.5	7.9	14.4	16.6	14.4

FIGURE 12



	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
2XCO2	0.0	2.6	12.3	23.6	37.0	45.4	51.5	31.9	0.0	0.0	0.0	0.0
1955-1980	0.0	4.0	17.0	31.0	45.0	55.0	60.0	41.0	3.0	0.0	0.0	0.0

FIGURE 13

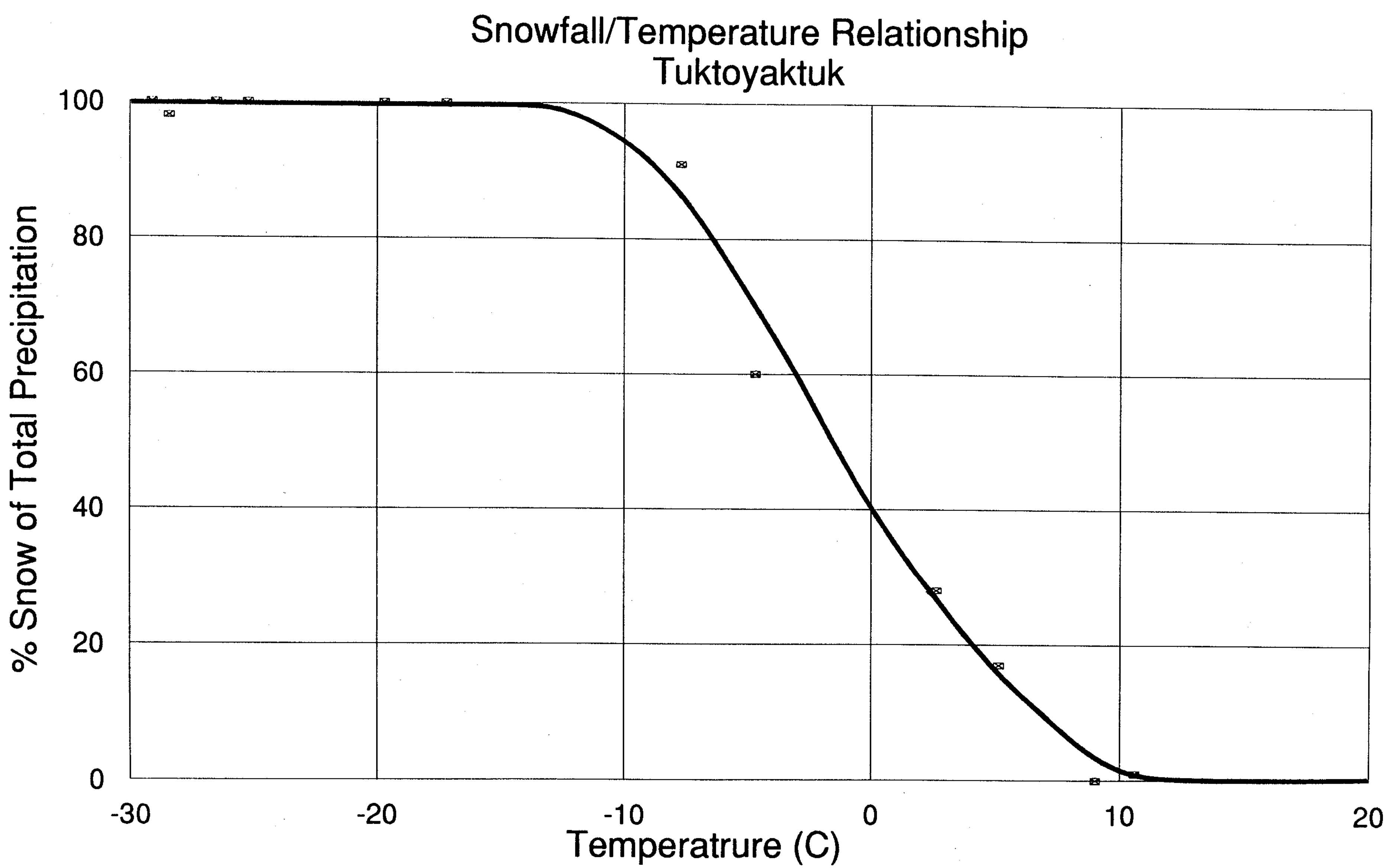
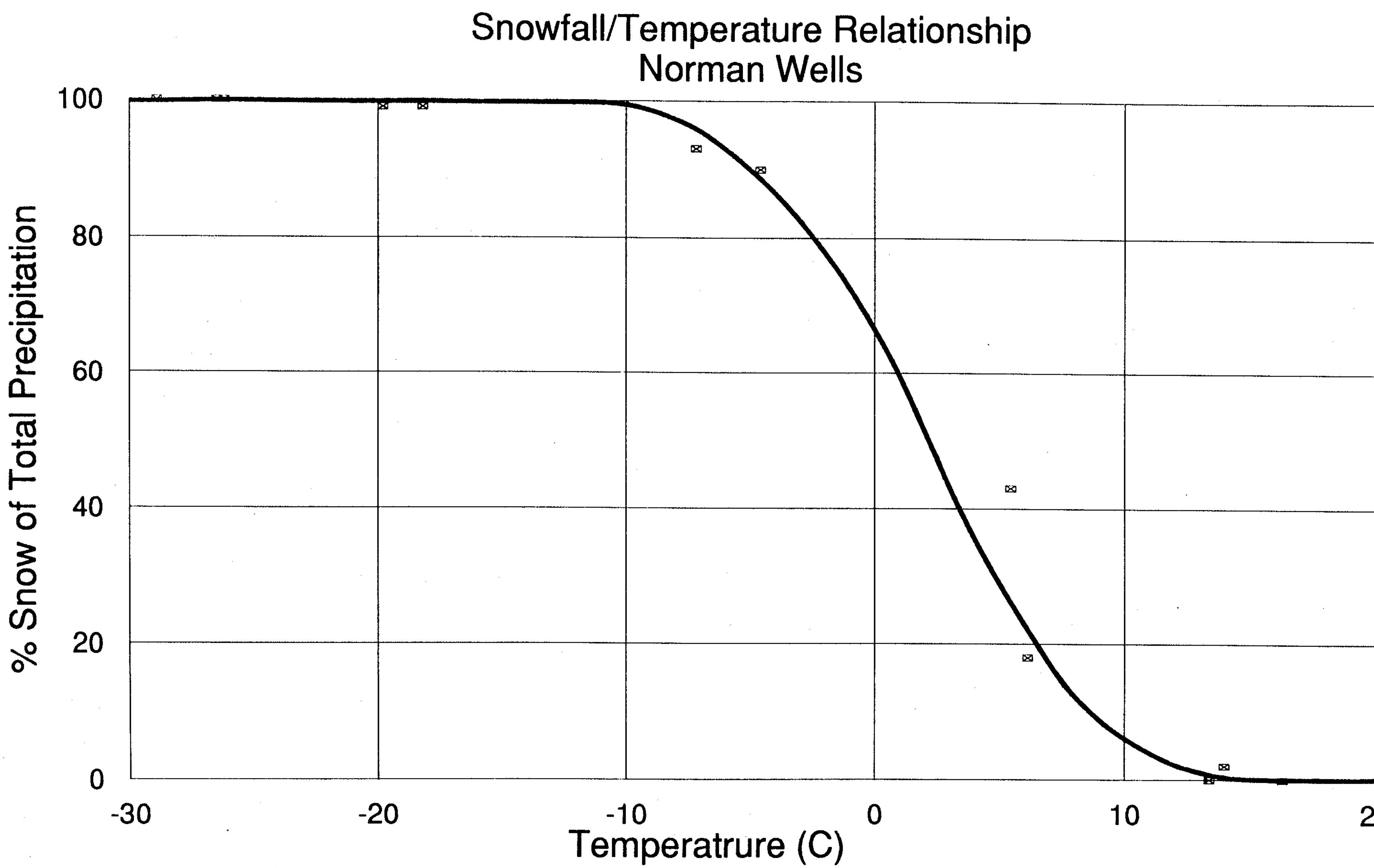

Snowfall/Temperature Relationship
Tuktoyaktuk
% Snow of Total Precipitation
100
80
60
40
20
0
-30
-20
-10
0
10
20
Temperatrure (C)

FIGURE 14



Snowfall/Temperature Relationship
Norman Wells
% Snow of Total Precipitation
100
80
60
40
20
0
-30
-20
-10
0
10
20
Temperatrure (C)

FIGURE 15

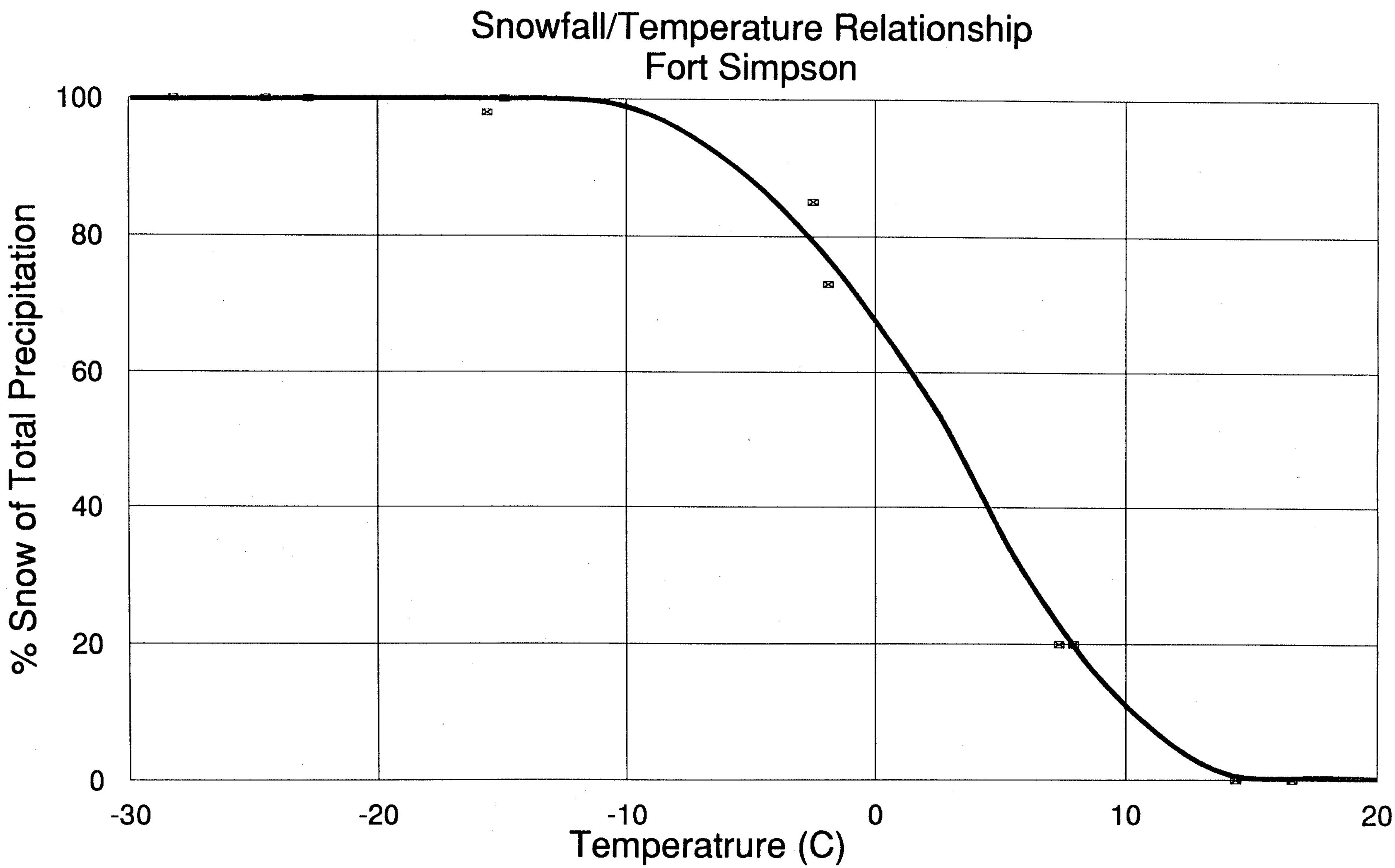
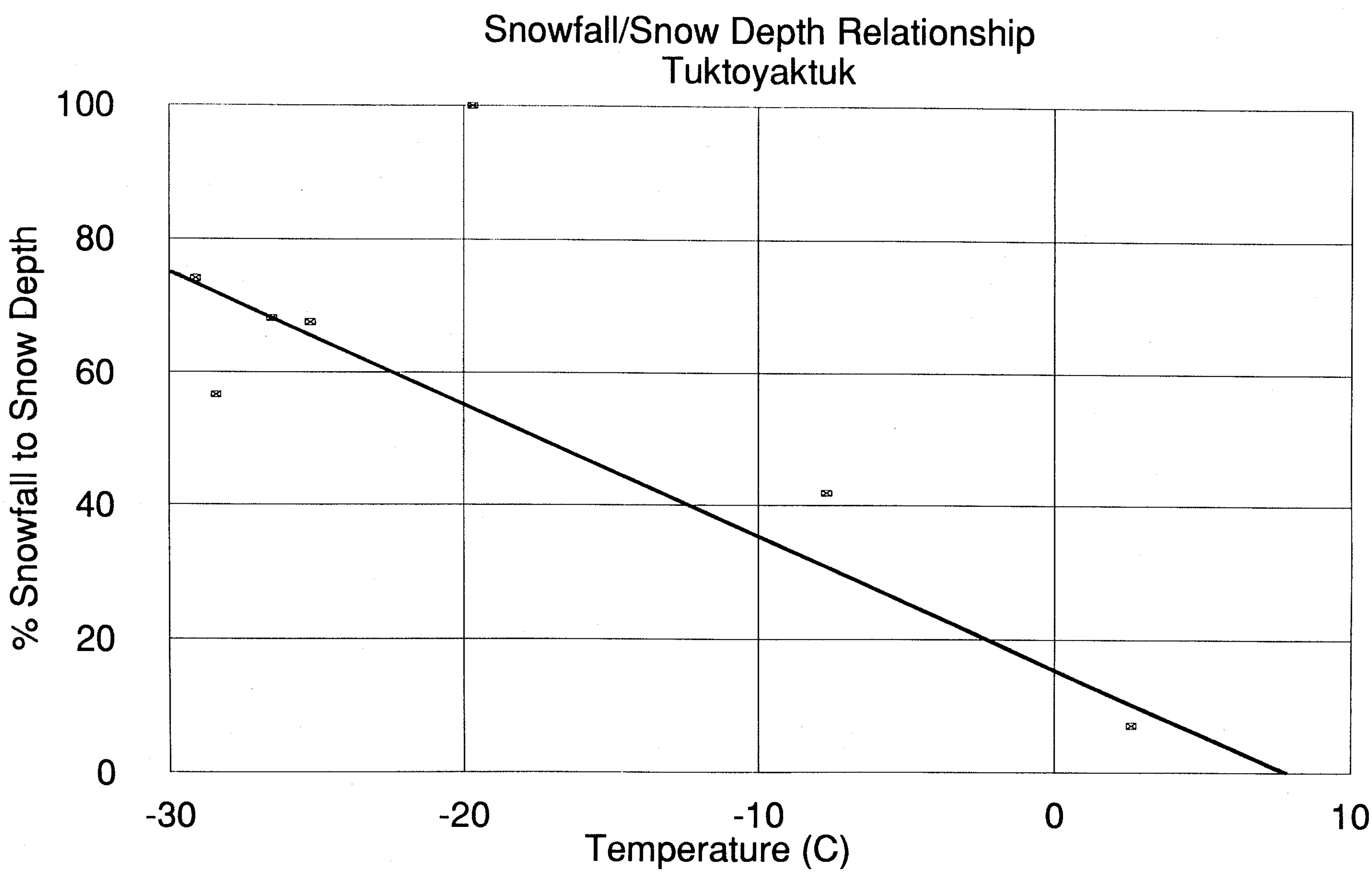

Snowfall/Temperature Relationship
Fort Simpson
% Snow of Total Precipitation
100
80
60
40
20
0
-30
-20
-10
0
10
20
Temperatrure (C)

FIGURE 16



Snowfall/Snow Depth Relationship
Tuktoyaktuk
% Snowfall to Snow Depth
100
80
60
40
20
0
-30
-20
-10
0
10
Temperature (C)

FIGURE 17

Snowfall/Snow Depth Relationship
Norman Wells

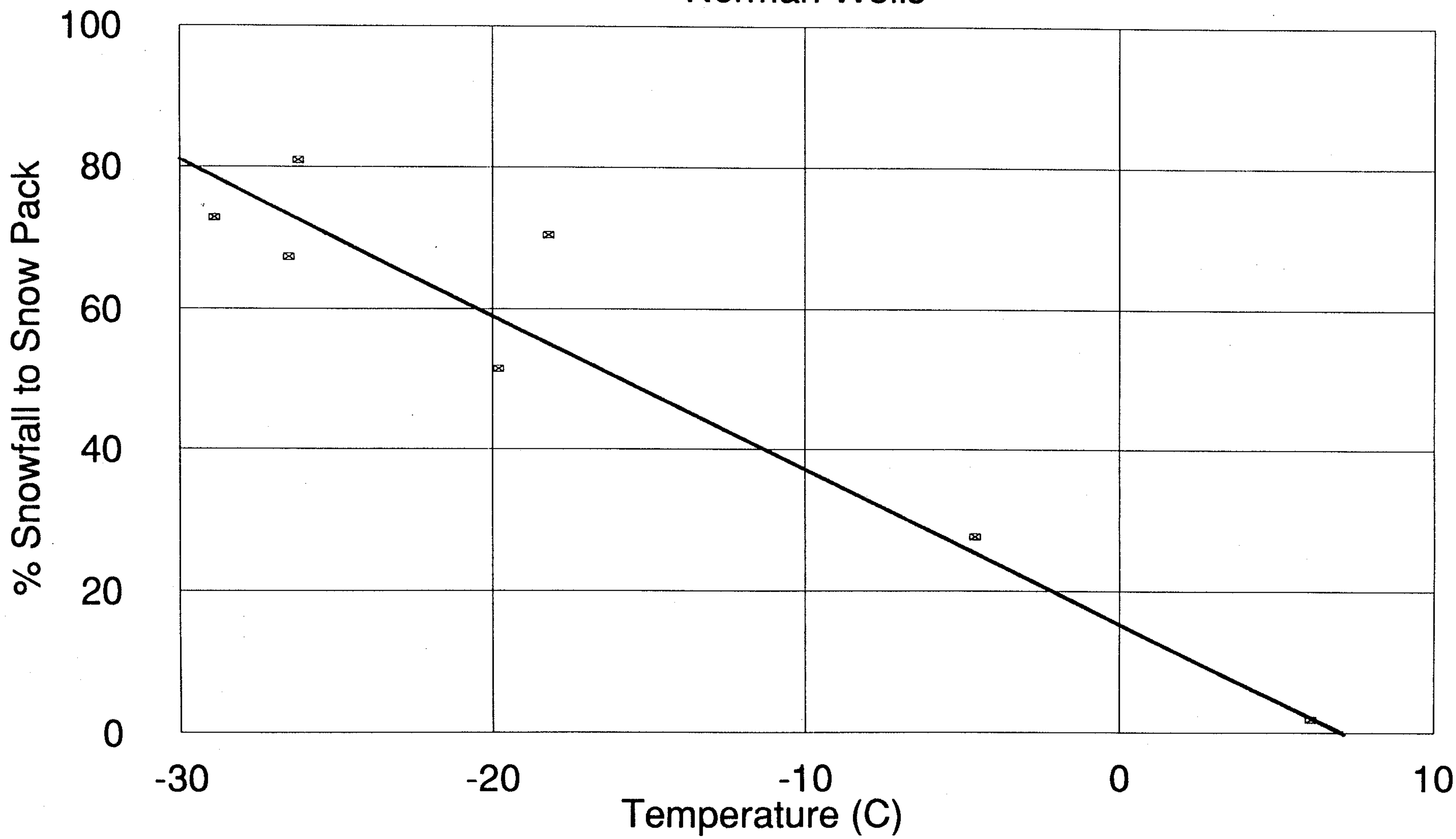
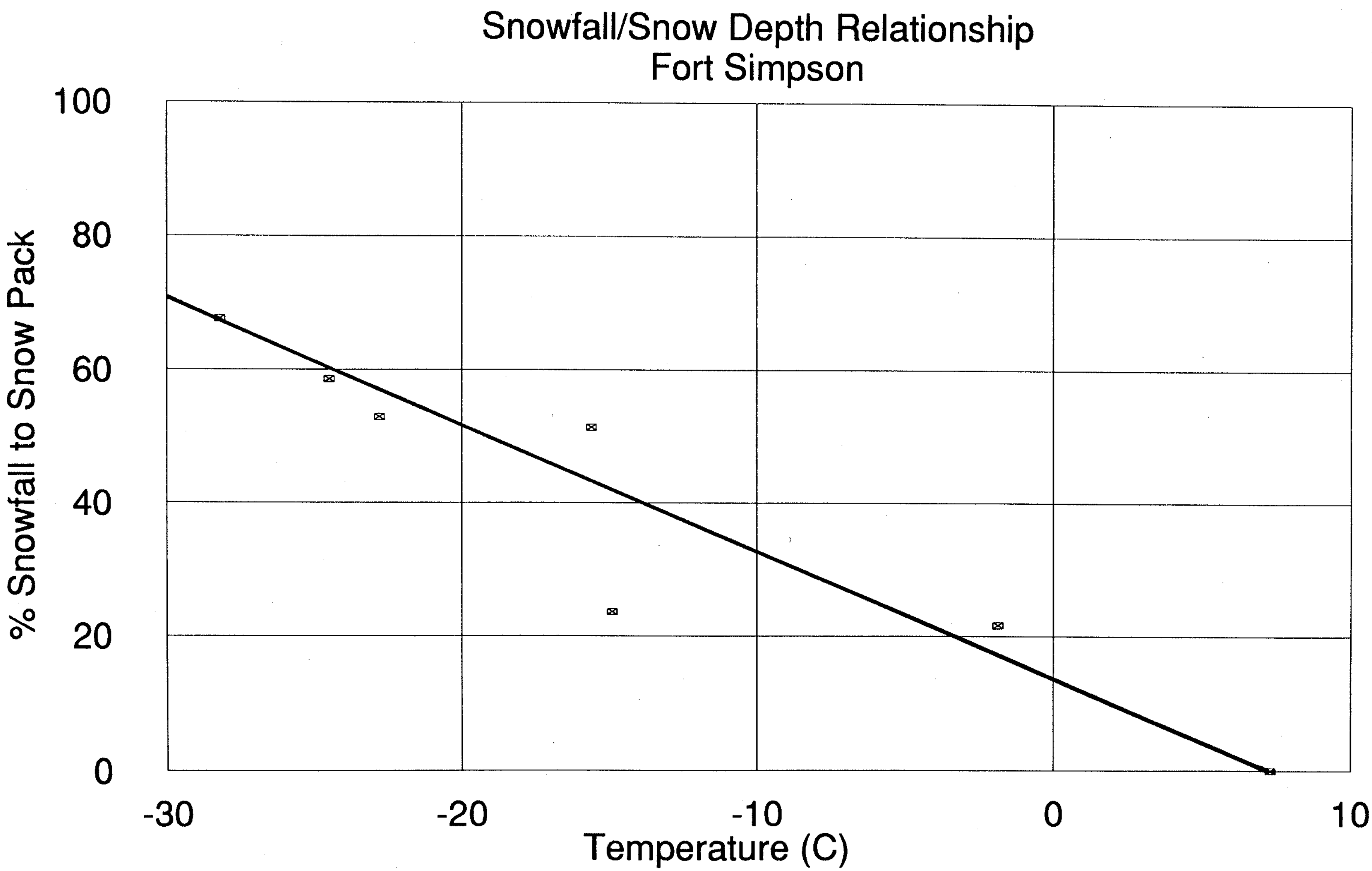


FIGURE 18



Snowfall/Snow Depth Relationship
Fort Simpson
100
80
60
40
20
0
% Snowfall to Snow Pack
-30
-20
-10
0
10
Temperature (C)

FIGURE 19

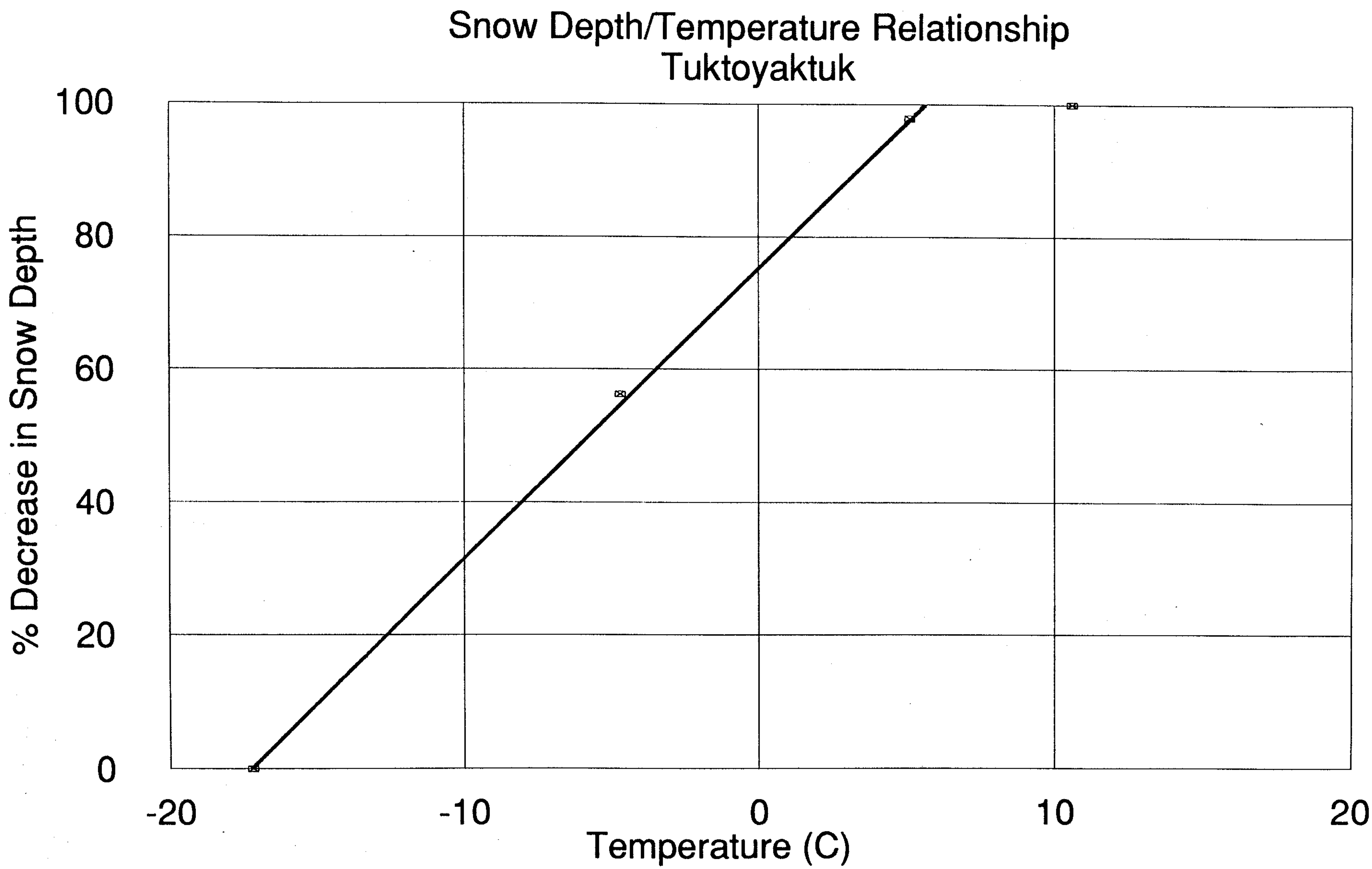

Snow Depth/Temperature Relationship
Tuktoyaktuk
% Decrease in Snow Depth
100
80
60
40
20
0
-20
-10
0
10
20
Temperature (C)

FIGURE 20

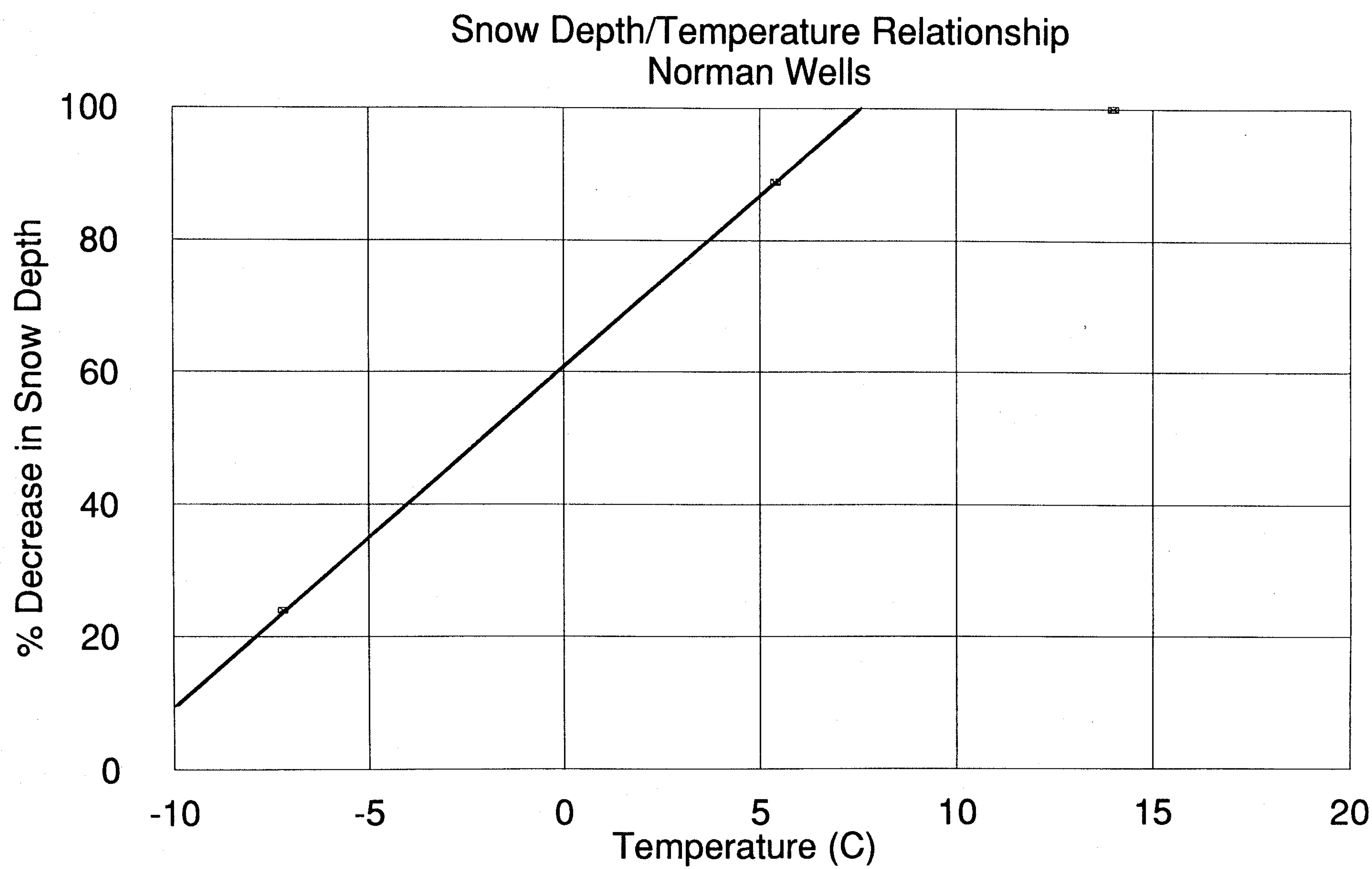
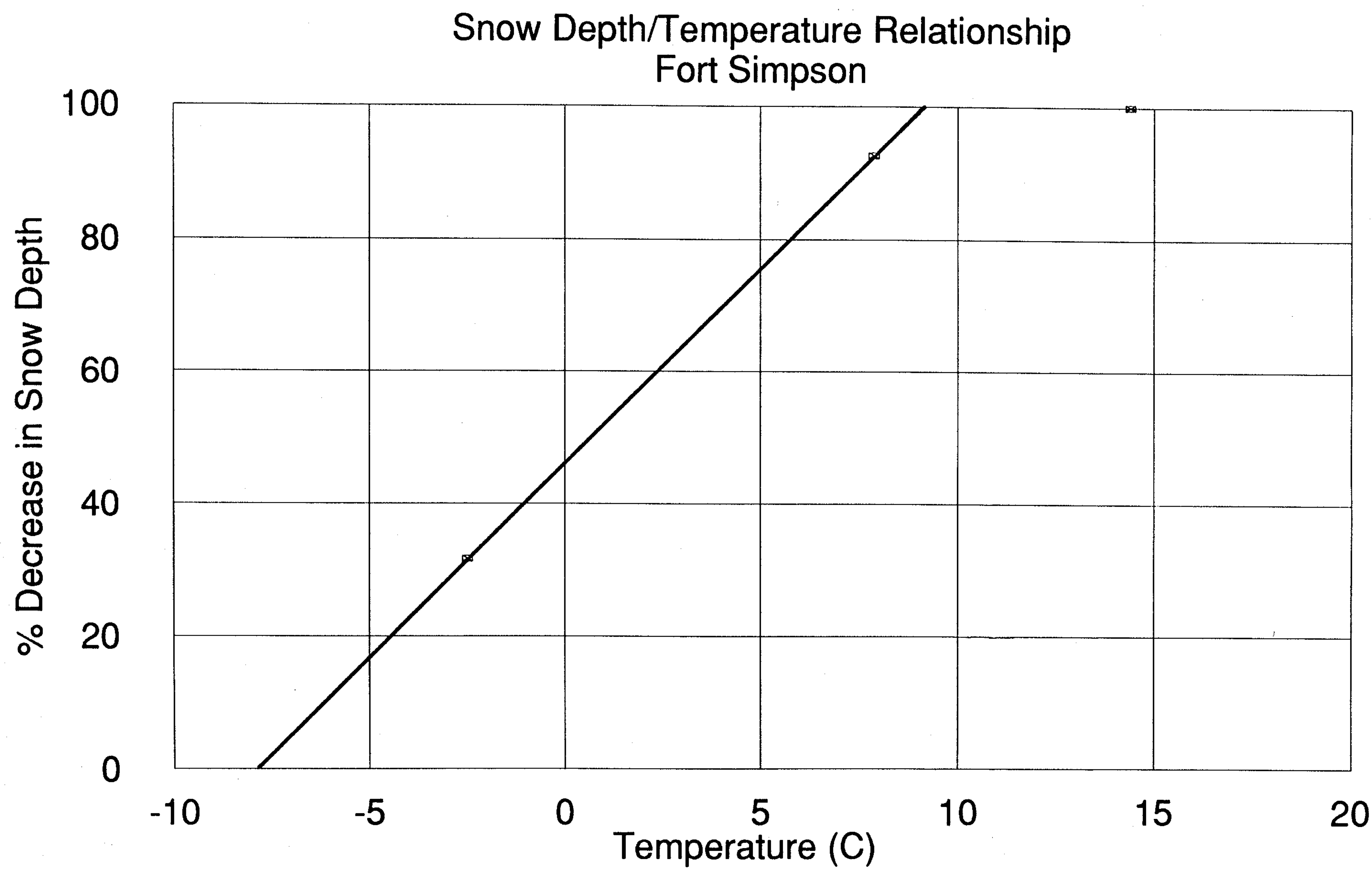
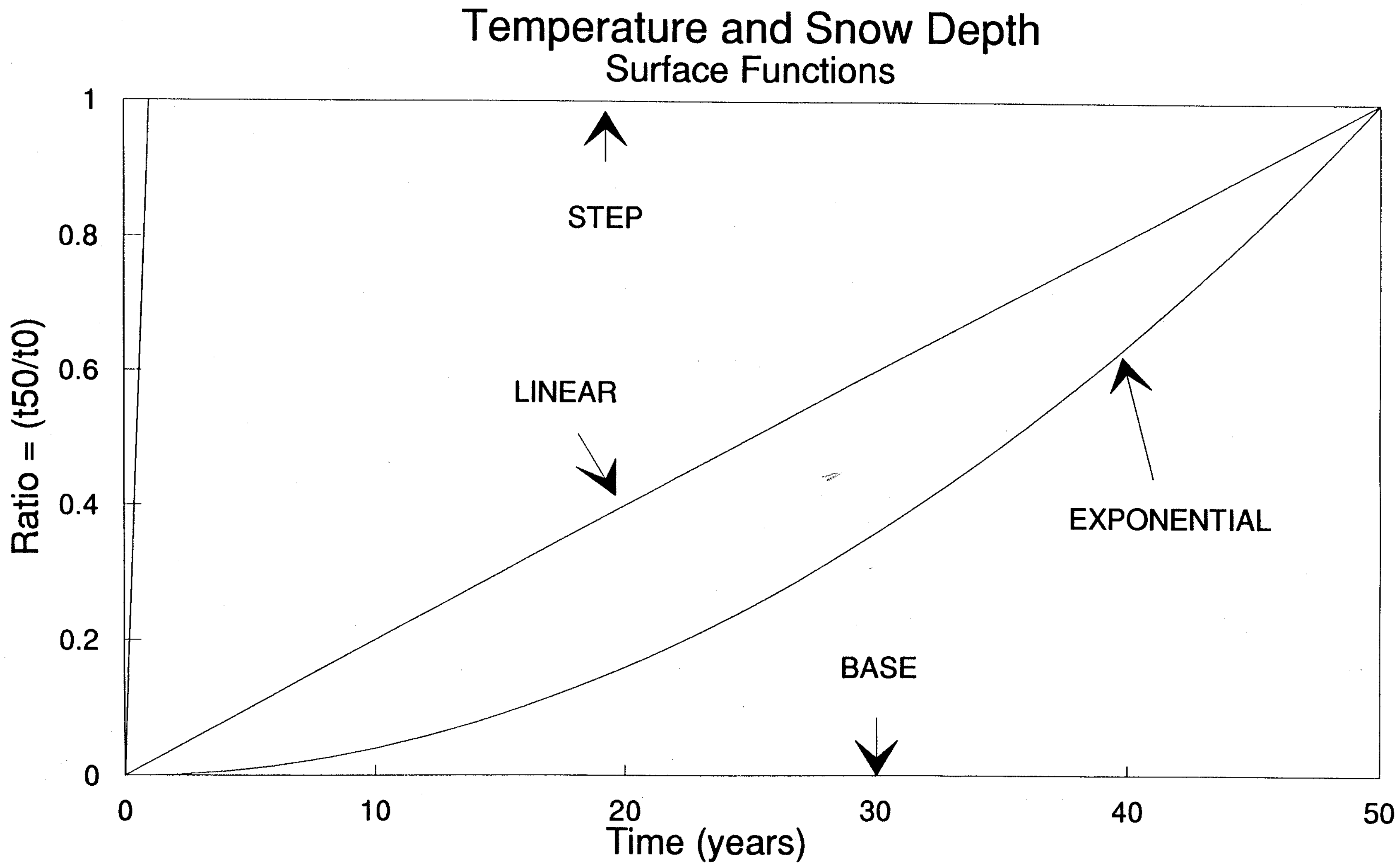

Snow Depth/Temperature Relationship
Norman Wells
% Decrease in Snow Depth
0
20
40
60
80
100
-10
-5
0
5
10
15
20
Temperature (C)

FIGURE 21



Snow Depth/Temperature Relationship
Fort Simpson
% Decrease in Snow Depth
100
80
60
40
20
0
-10
-5
0
5
10
15
20
Temperature (C)

FIGURE 22



Temperature and Snow Depth
Surface Functions
Ratio = (t50/t0)
1
0.8
0.6
0.4
0.2
0
STEP
LINEAR
EXPONENTIAL
BASE
0
10
20
30
40
50
Time (years)

FIGURE 23

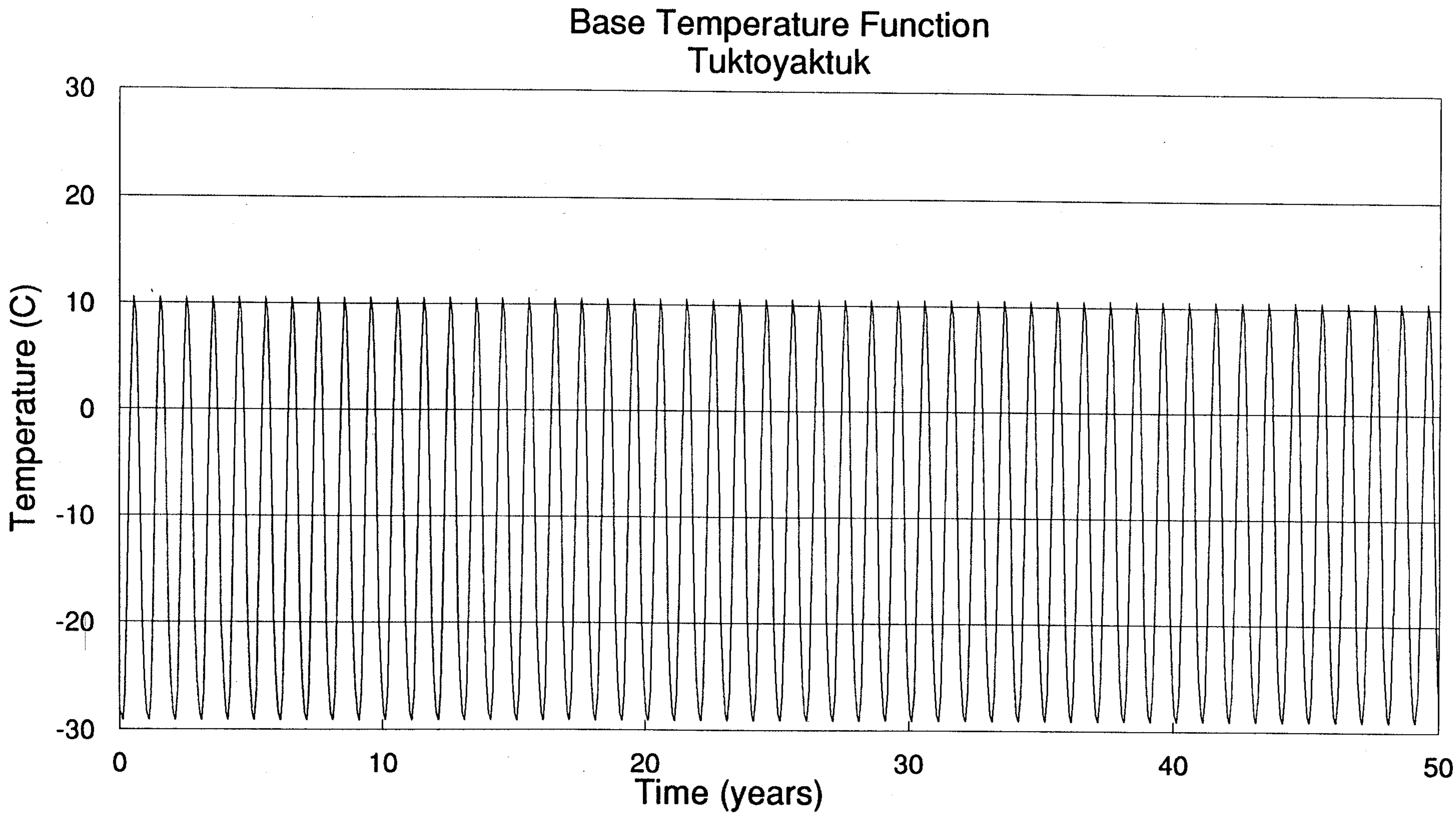
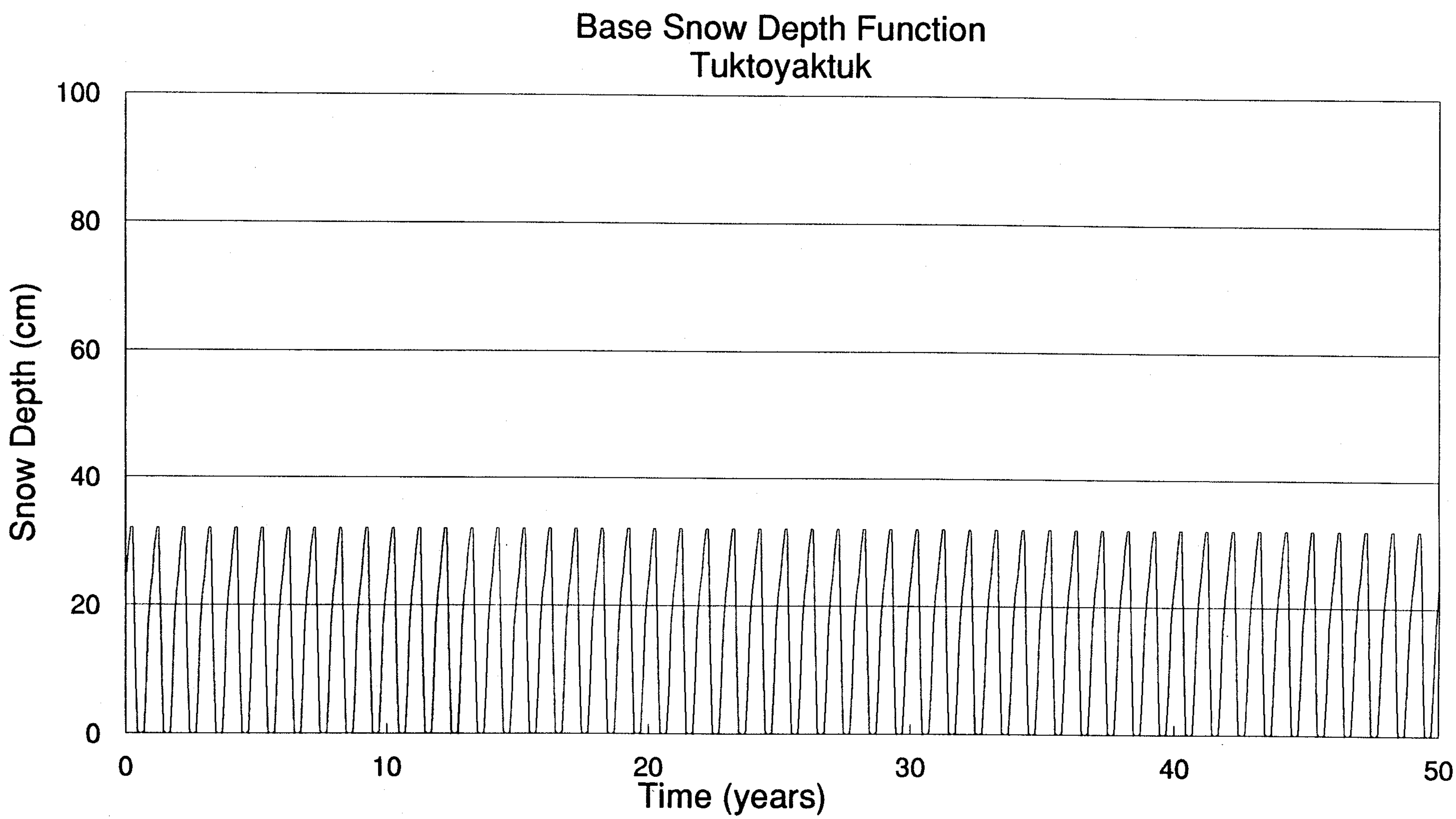

Base Temperature Function
Tuktoyaktuk
Temperature (C)
30
20
10
0
-10
-20
-30
0
10
20
30
40
50
Time (years)

FIGURE 24



Base Snow Depth Function
Tuktoyaktuk
Snow Depth (cm)
100
80
60
40
20
0
0
10
20
30
40
50
Time (years)

FIGURE 25

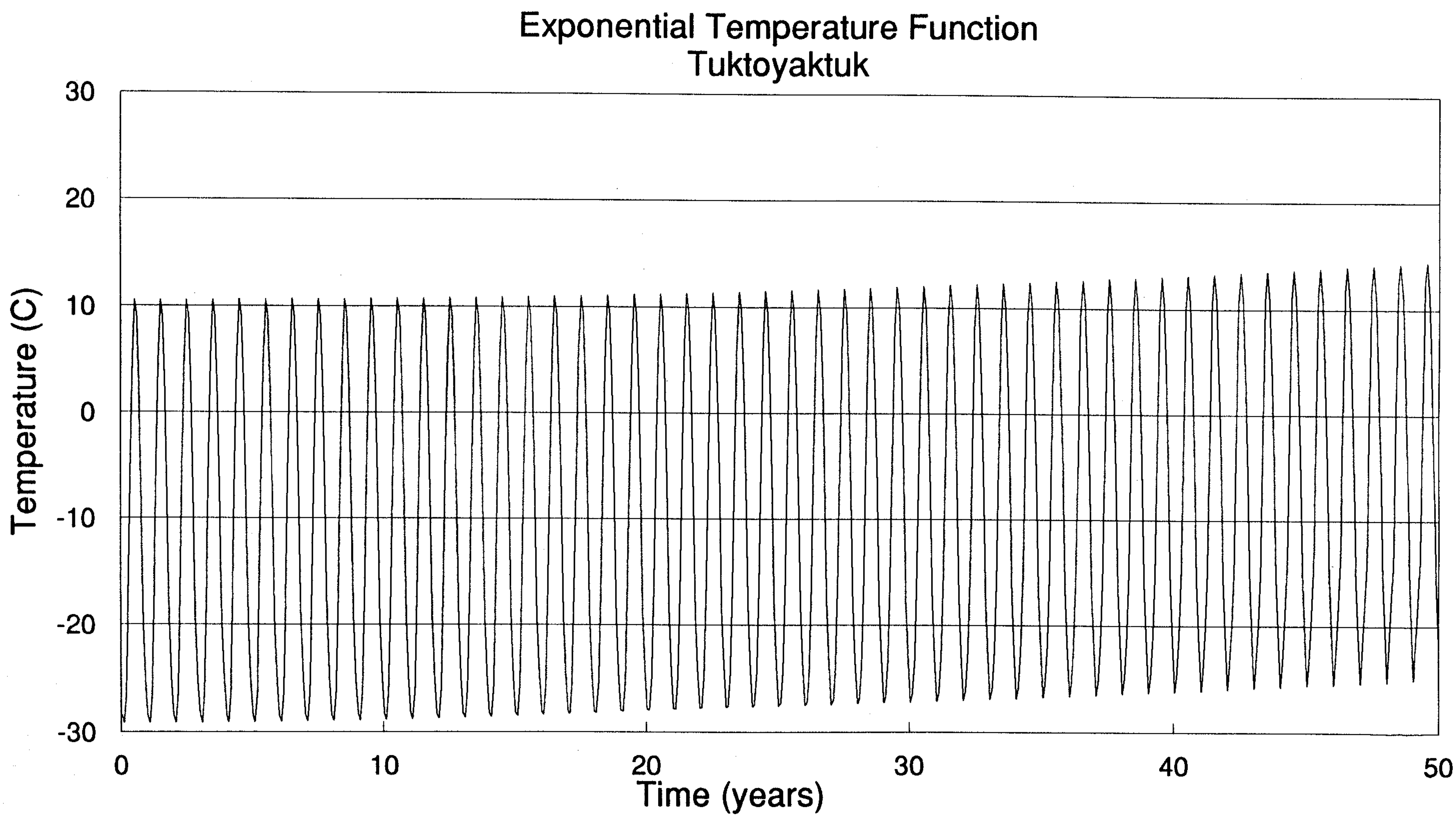

Exponential Temperature Function
Tuktoyaktuk
Temperature (C)
30
20
10
0
-10
-20
-30
0
10
20
30
40
50
Time (years)

FIGURE 26

Exponential Snow Depth Function
Tuktoyaktuk

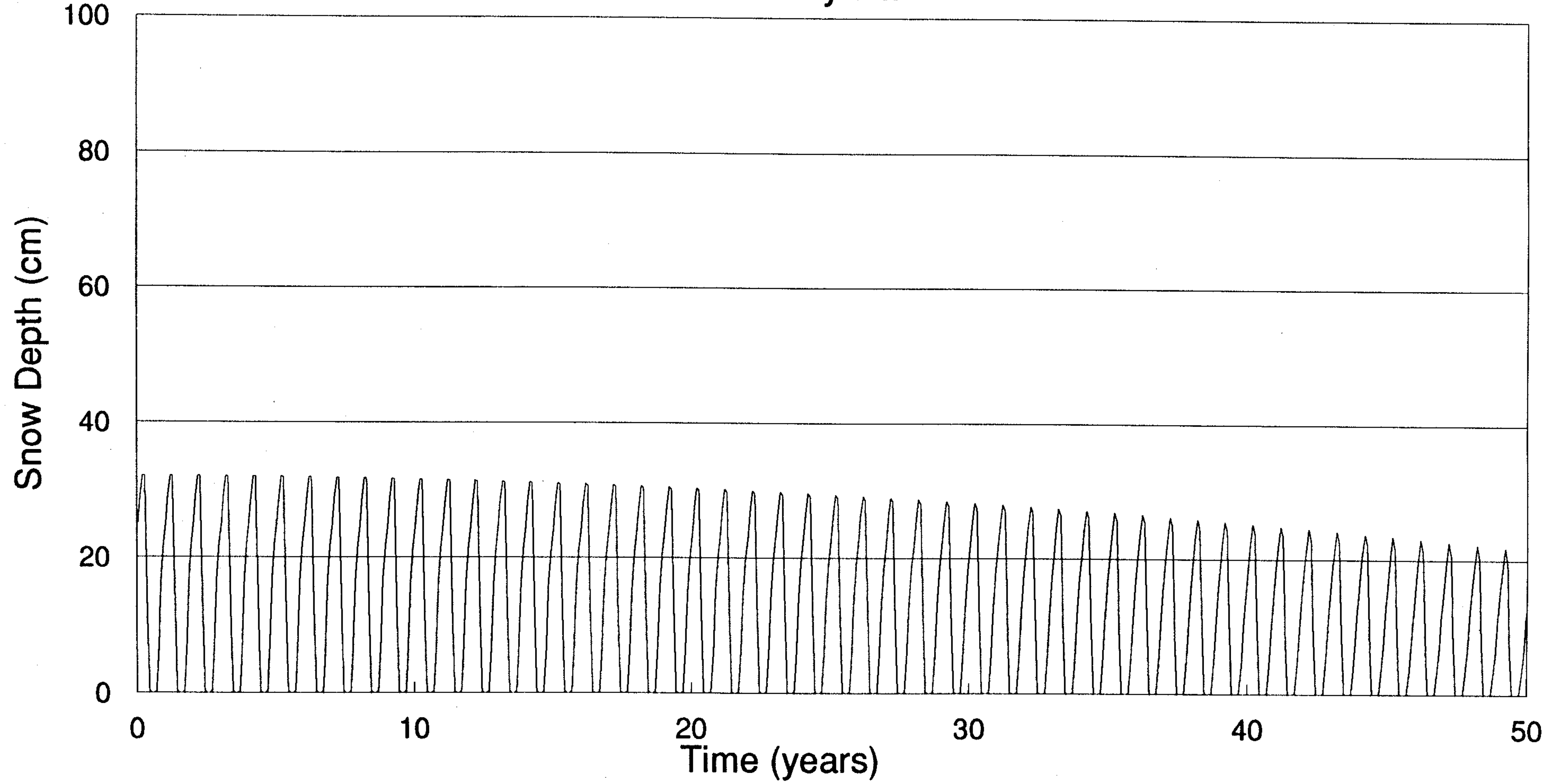


FIGURE 27

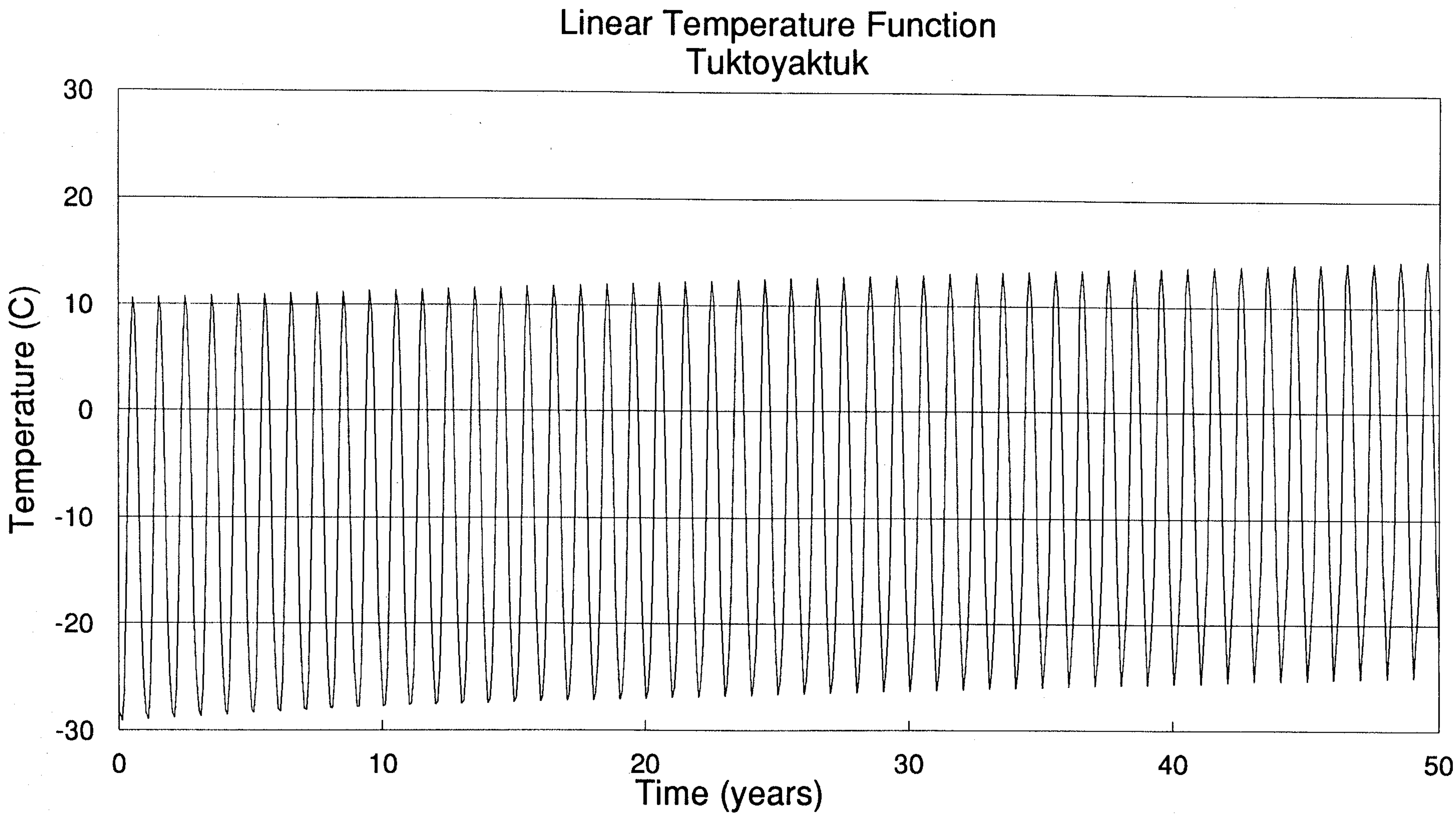
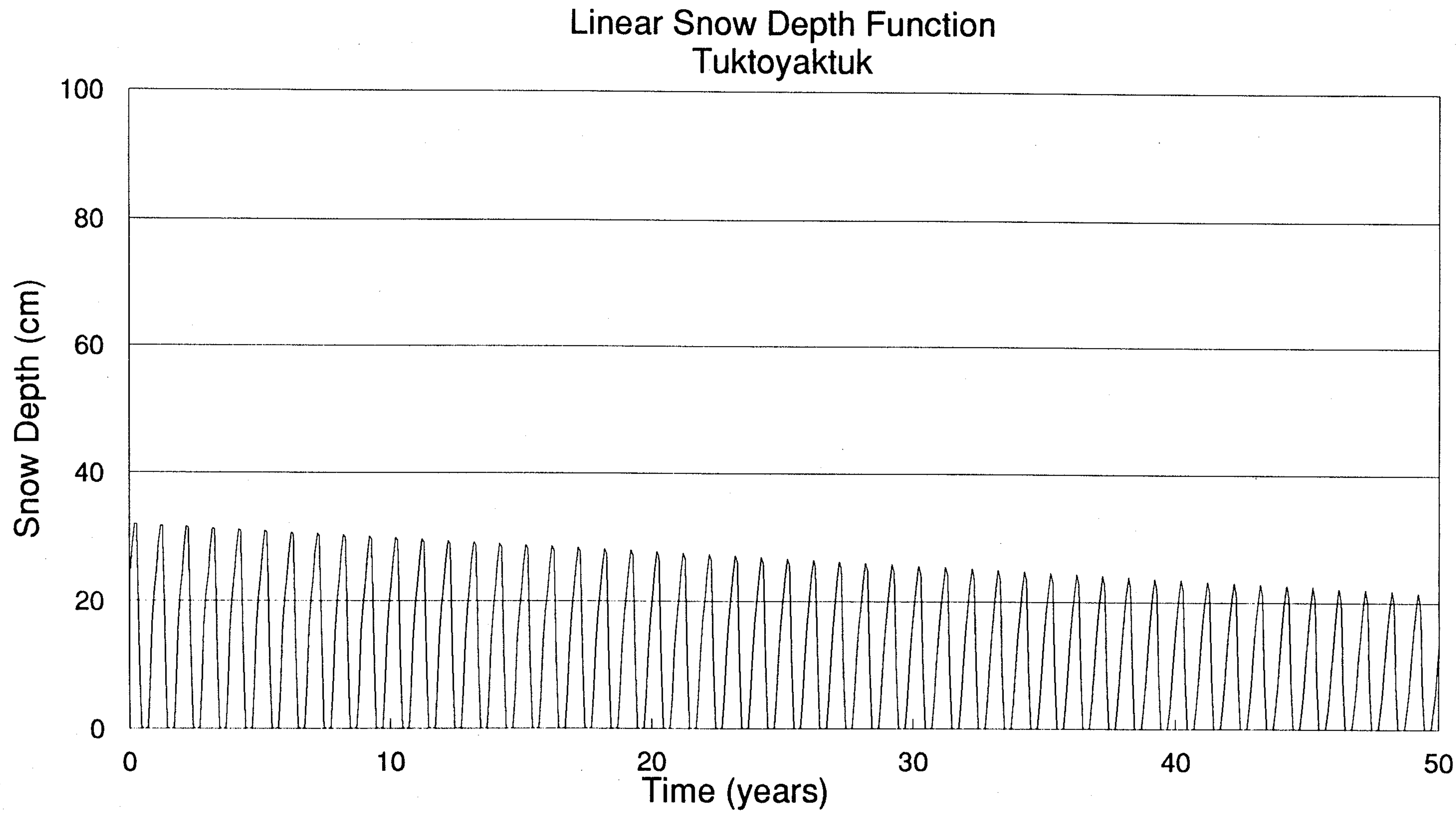

Linear Temperature Function
Tuktoyaktuk
Temperature (C)
30
20
10
0
-10
-20
-30
0
10
20
30
40
50
Time (years)

FIGURE 28



Linear Snow Depth Function
Tuktoyaktuk
Snow Depth (cm)
100
80
60
40
20
0
0
10
20
30
40
50
Time (years)

FIGURE 29

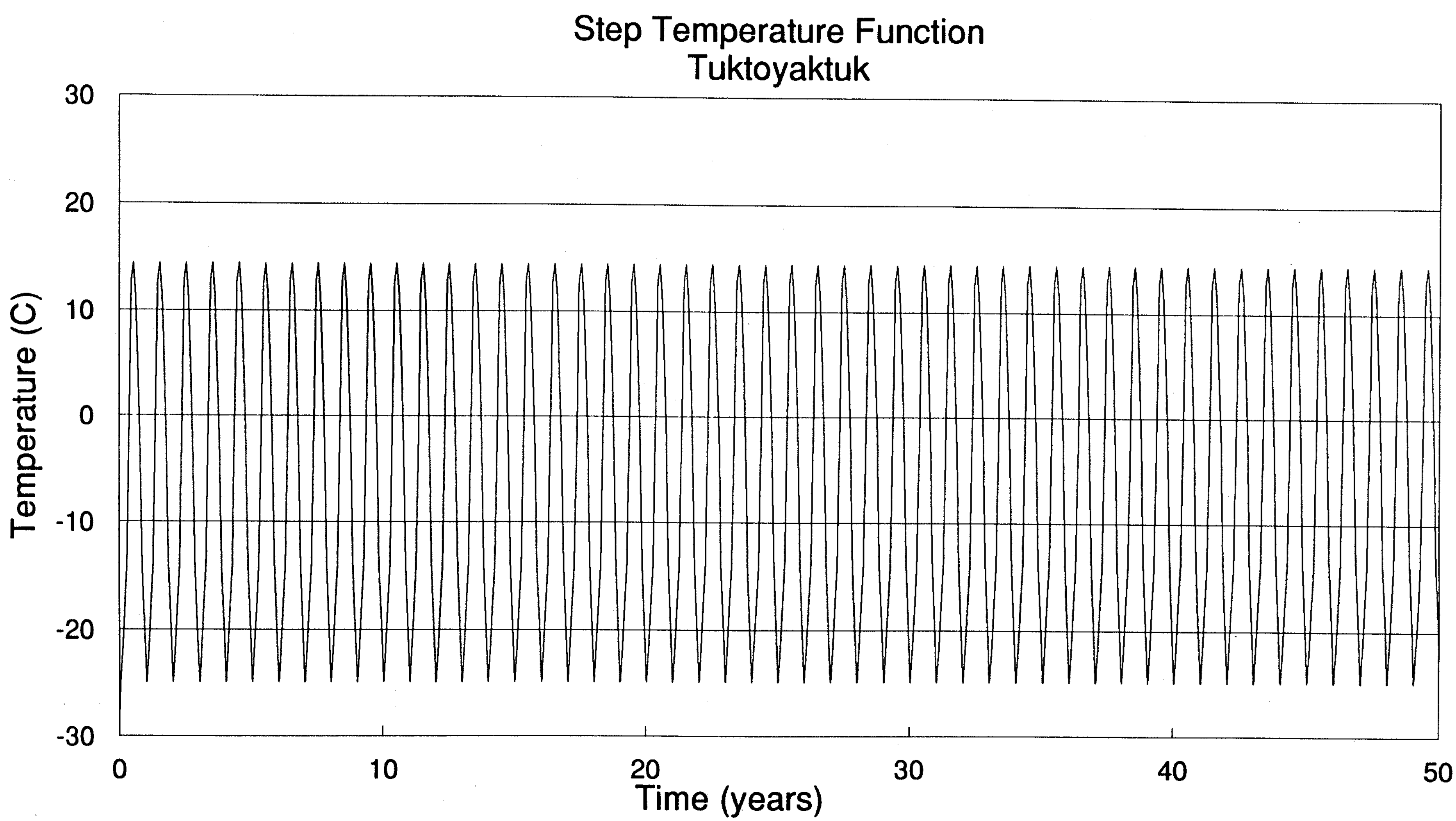

Step Temperature Function
Tuktoyaktuk
Temperature (C)
30
20
10
0
-10
-20
-30
0
10
20
30
40
50
Time (years)

FIGURE 30

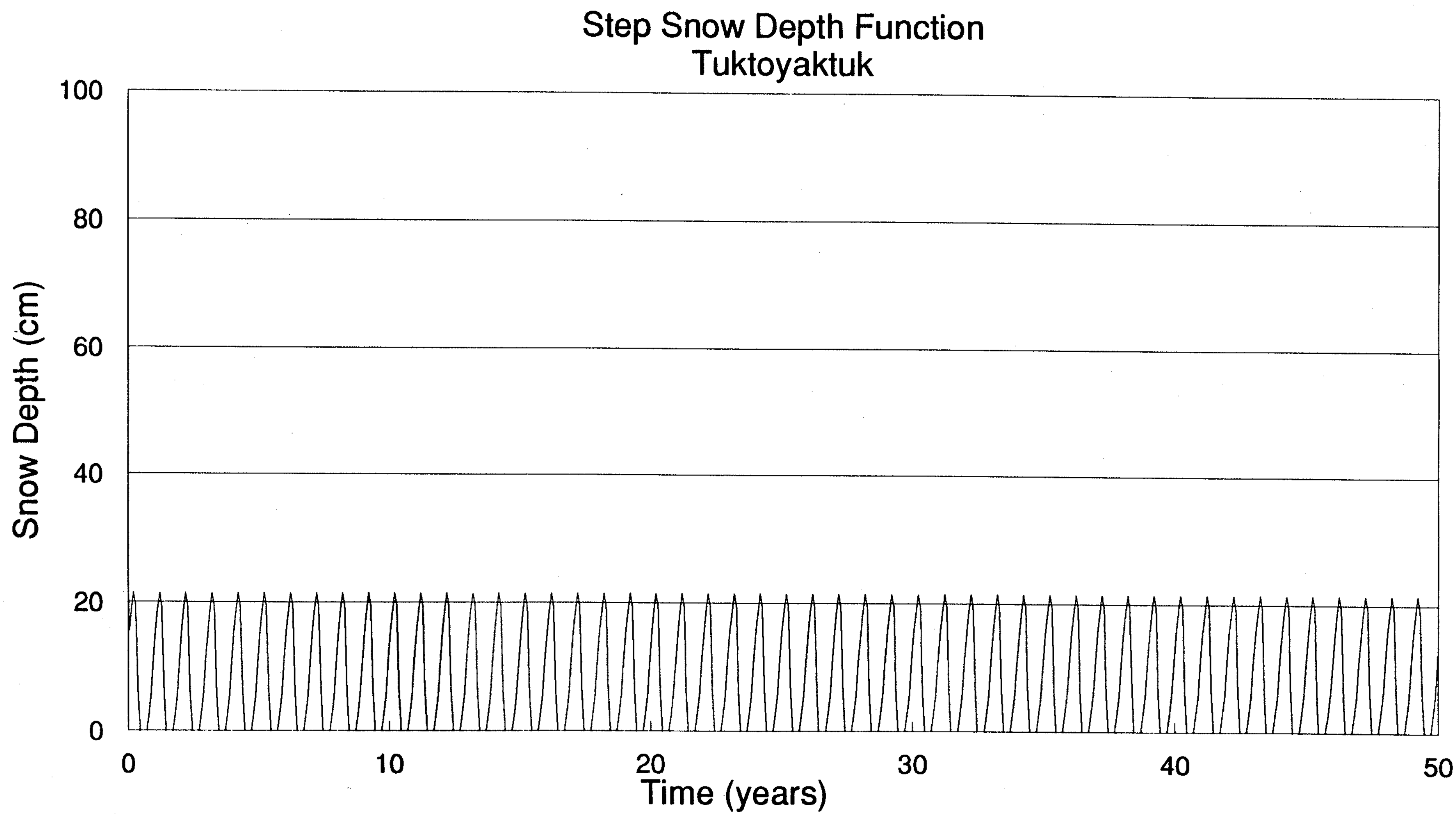

Step Snow Depth Function
Tuktoyaktuk
Snow Depth (cm)
100
80
60
40
20
0
0
10
20
30
40
50
Time (years)

FIGURE 31

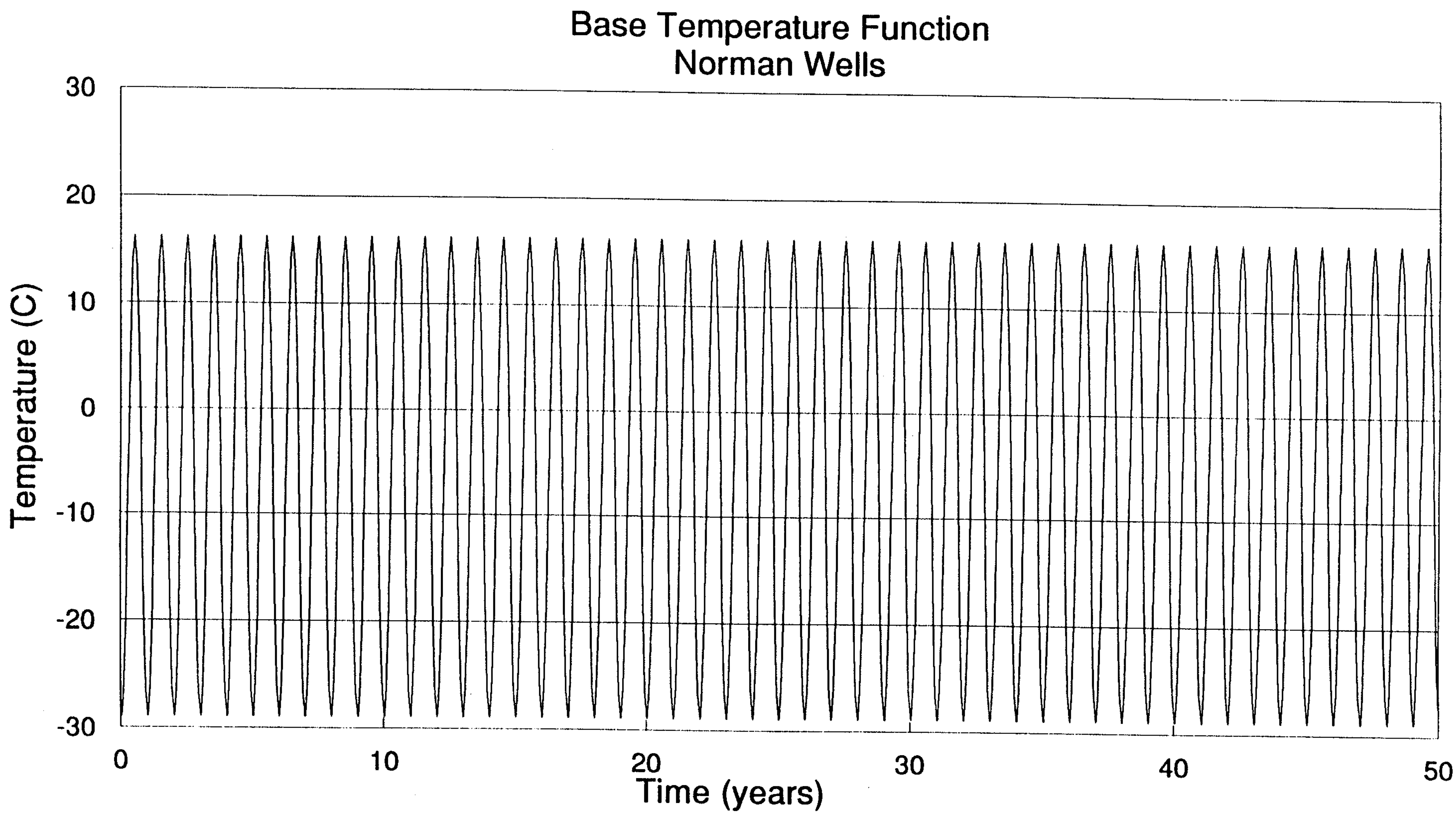

Base Temperature Function
Norman Wells
30
20
10
0
-10
-20
-30
Temperature (C)
0
10
20
30
40
50
Time (years)

FIGURE 32

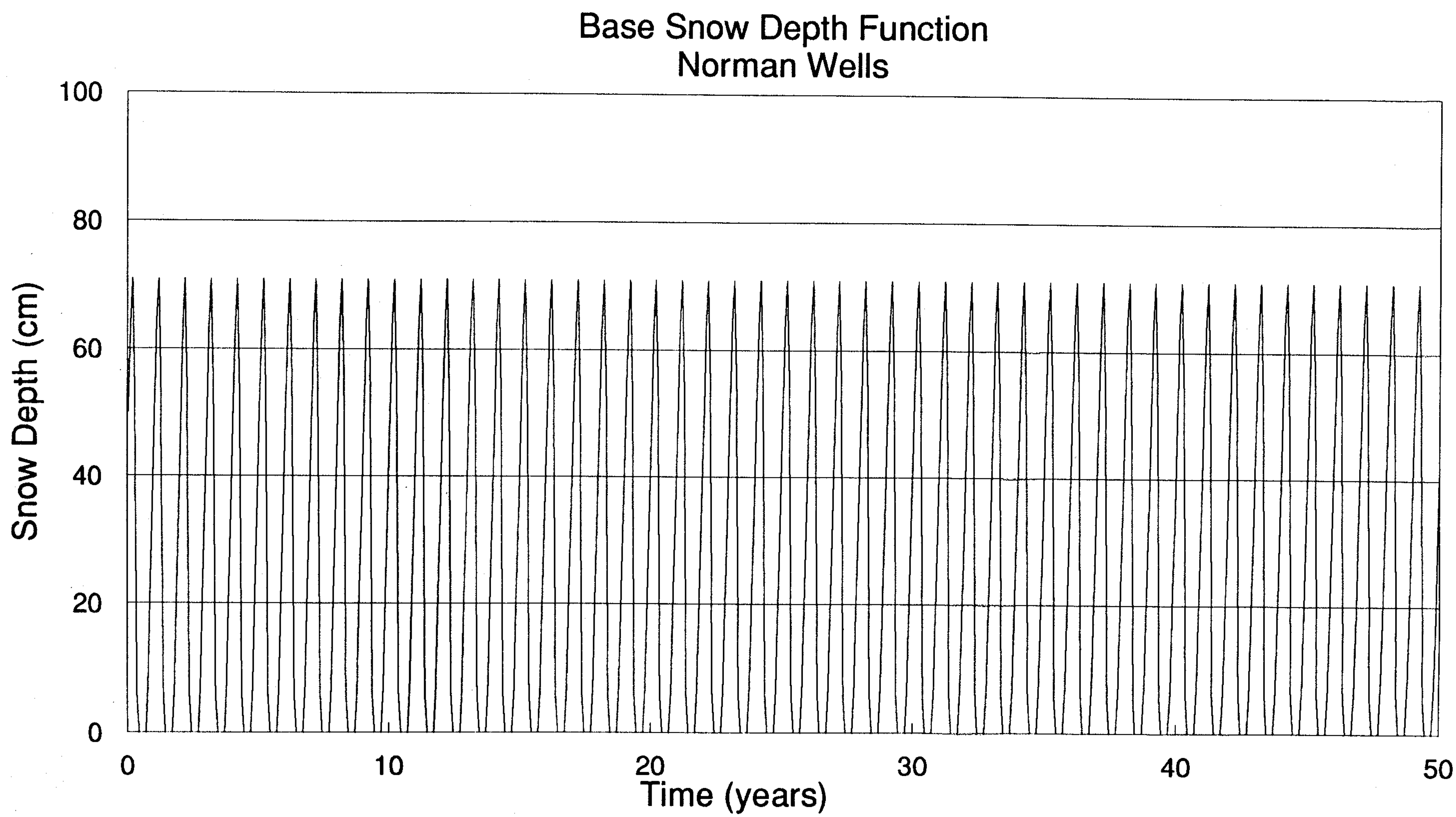

Base Snow Depth Function
Norman Wells
Snow Depth (cm)
100
80
60
40
20
0
0
10
20
30
40
50
Time (years)

FIGURE 33

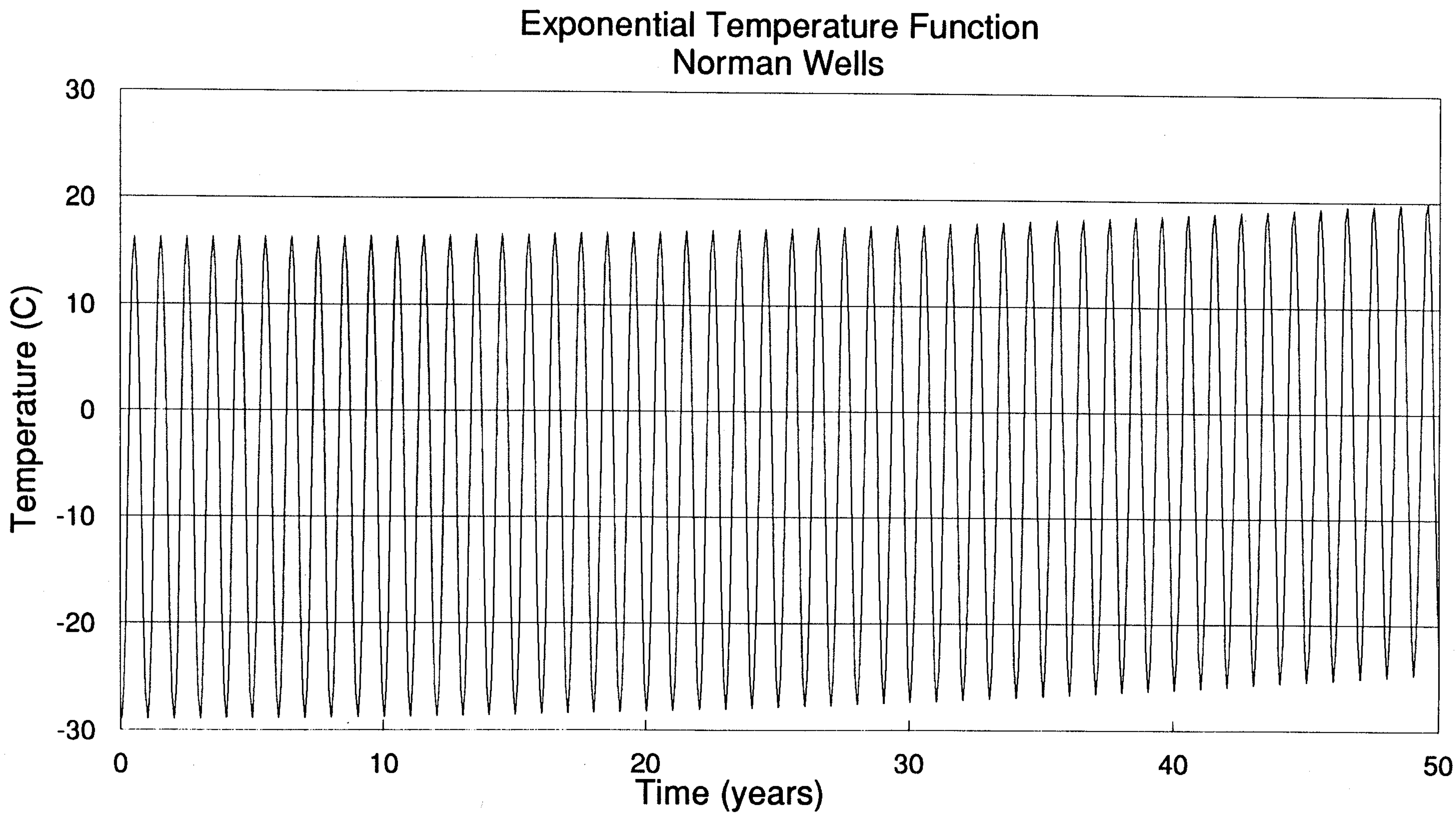
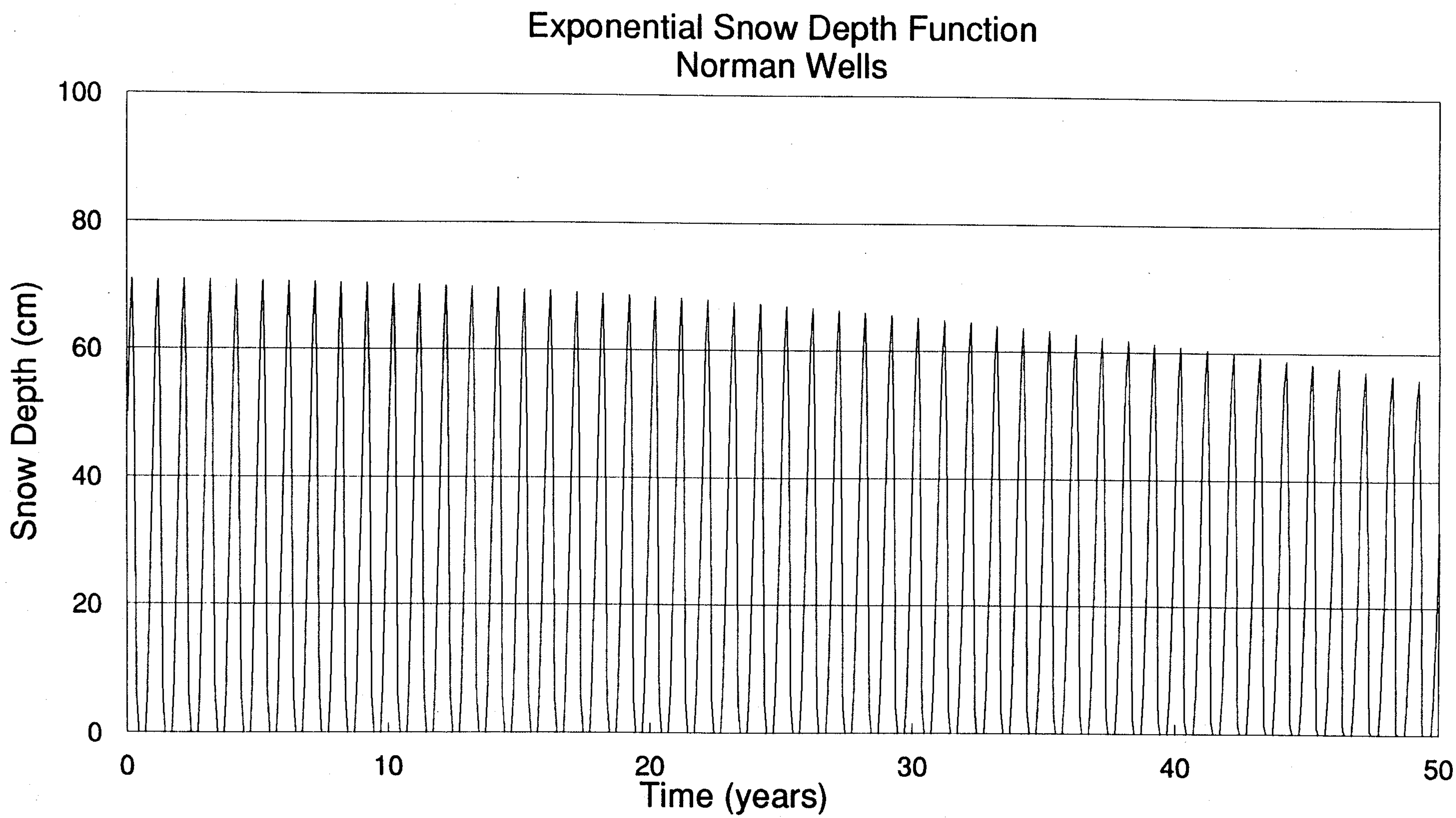

Exponential Temperature Function
Norman Wells
Temperature (C)
30
20
10
0
-10
-20
-30
0
10
20
30
40
50
Time (years)

FIGURE 34



Exponential Snow Depth Function
Norman Wells
Snow Depth (cm)
100
80
60
40
20
0
0
10
20
30
40
50
Time (years)

FIGURE 35

Linear Temperature Function
Norman Wells

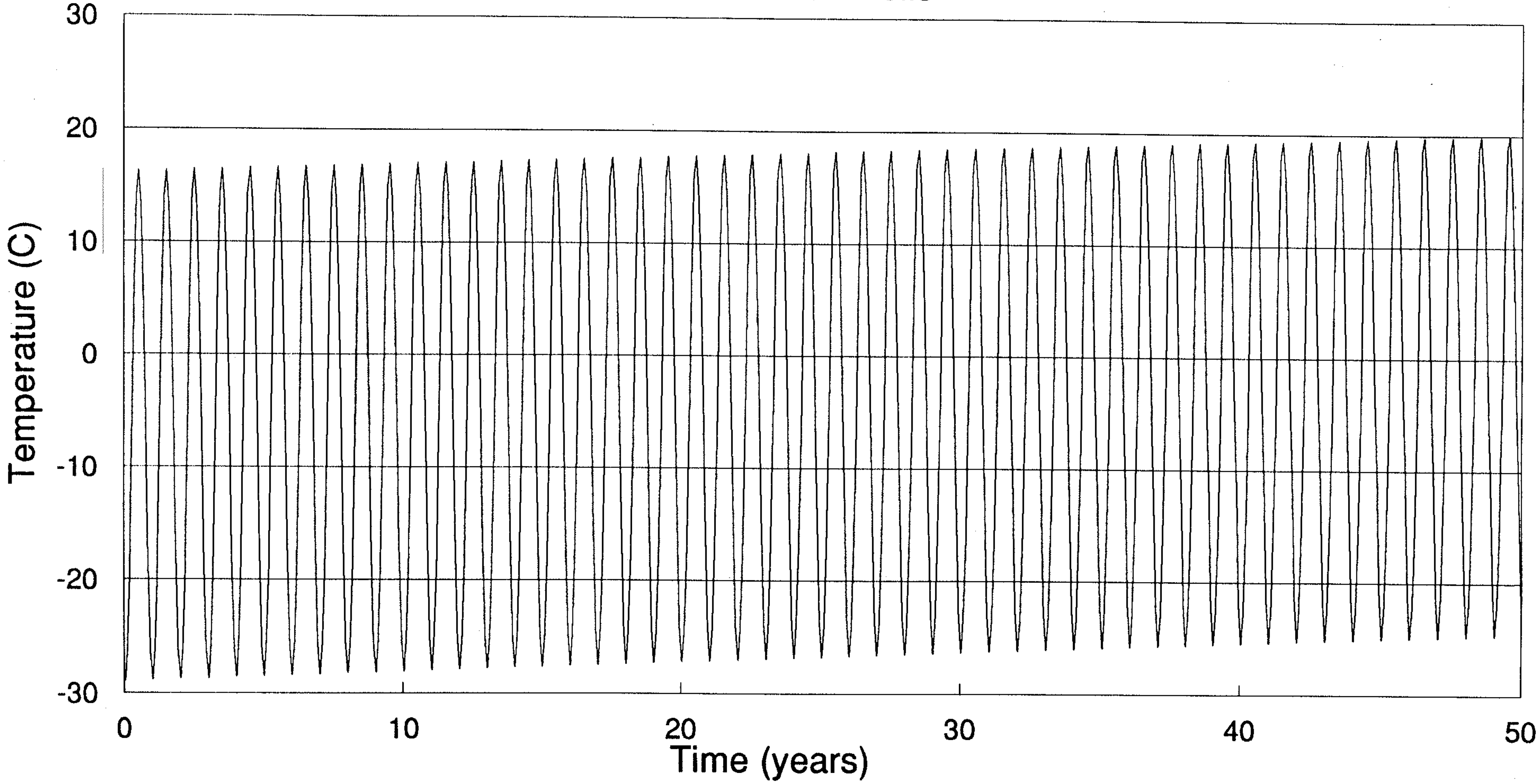


FIGURE 36

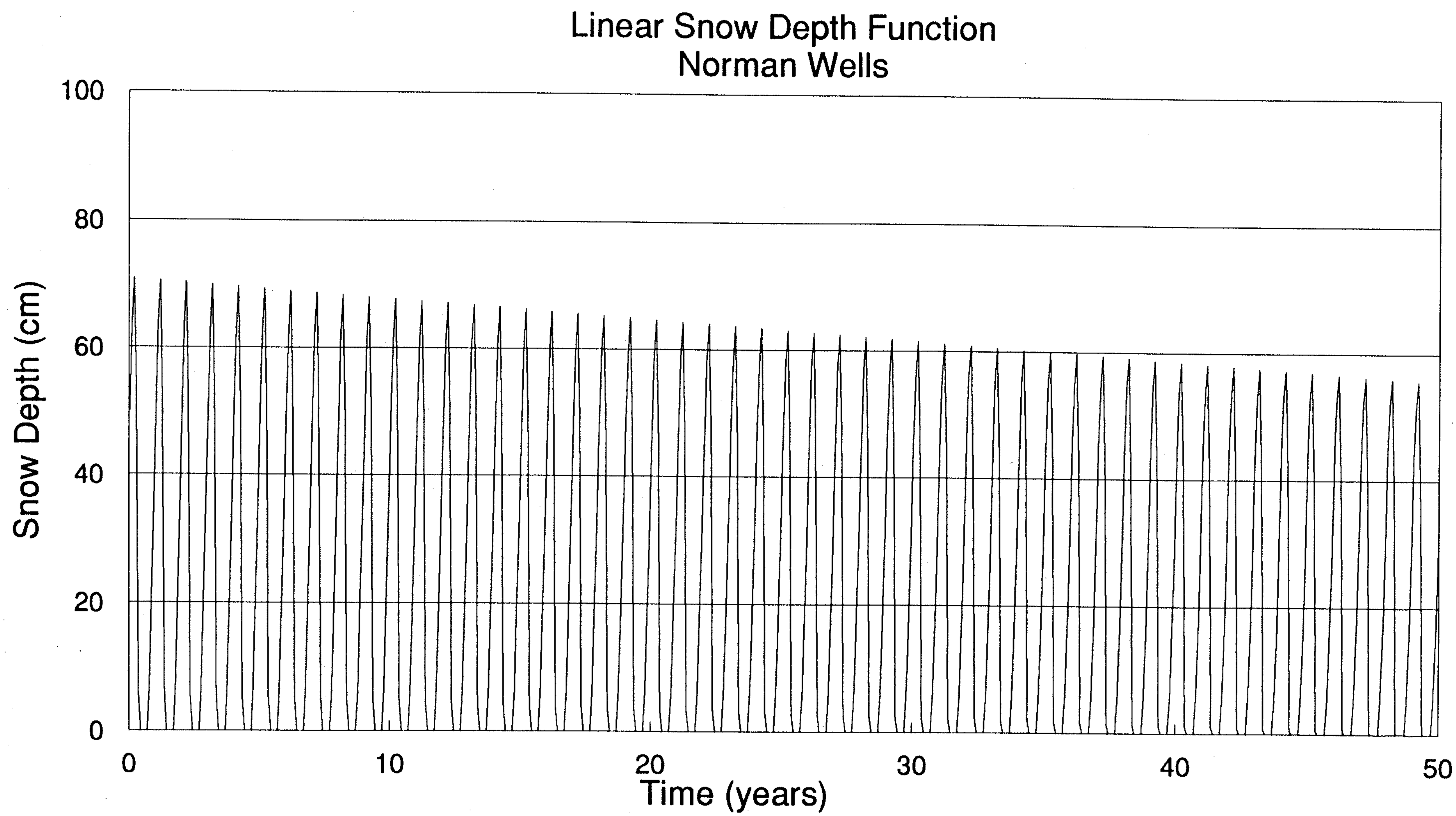
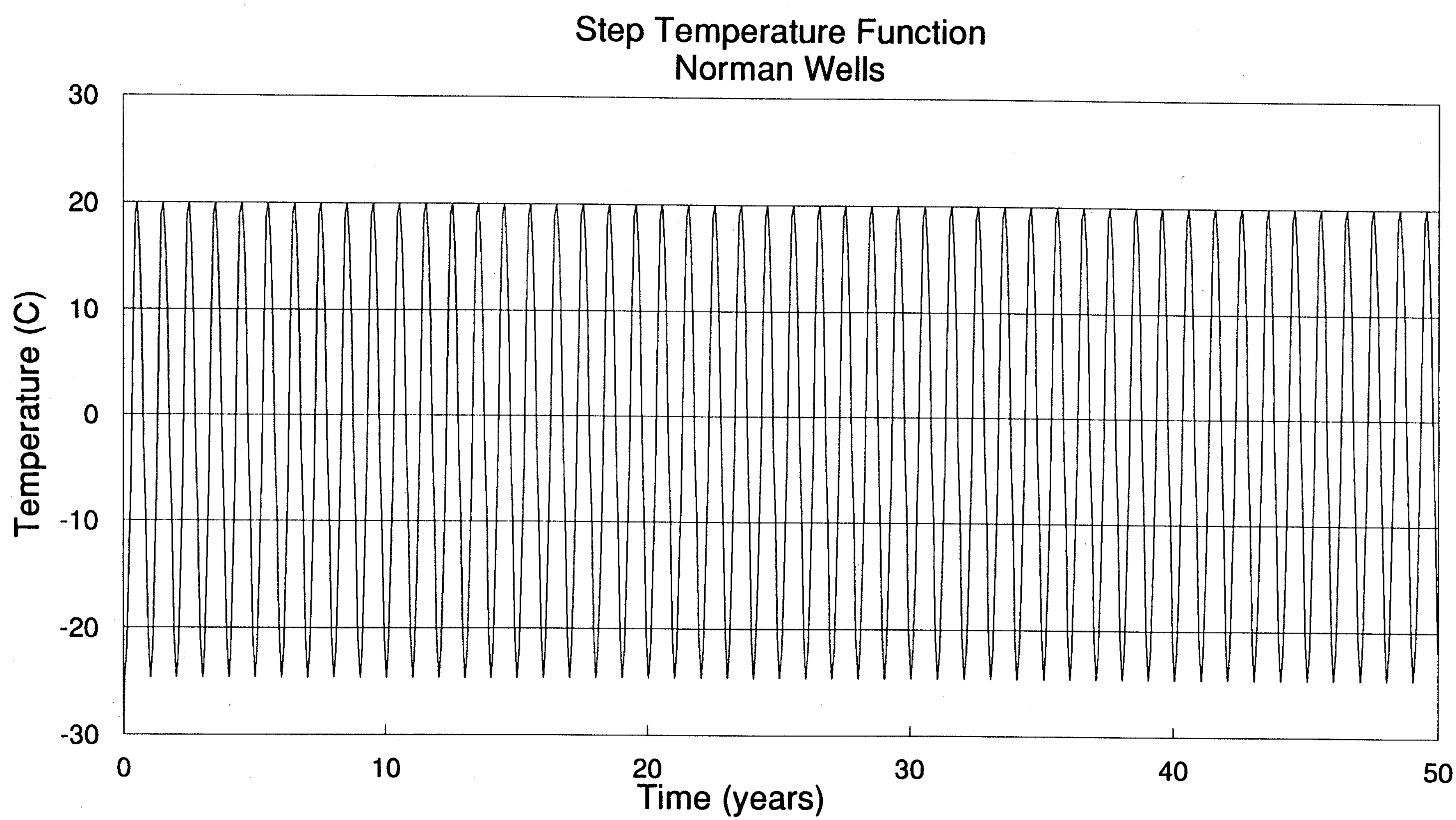

Linear Snow Depth Function
Norman Wells
100
80
60
40
20
0
Snow Depth (cm)
0
10
20
30
40
50
Time (years)

FIGURE 37



Step Temperature Function
Norman Wells
Temperature (C)
30
20
10
0
-10
-20
-30
0
10
20
30
40
50
Time (years)

FIGURE 38

Step Snow Depth Function
Norman Wells

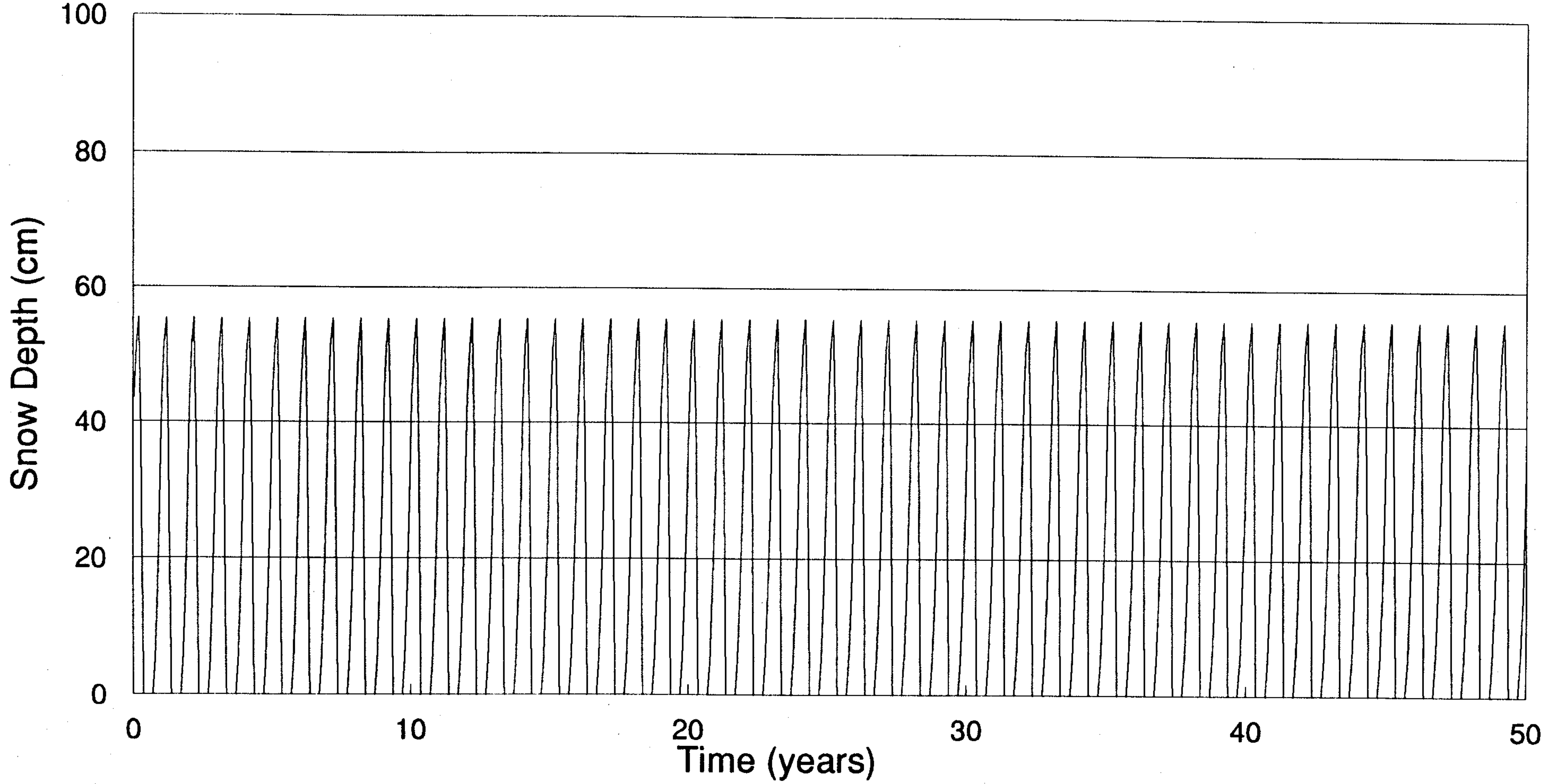
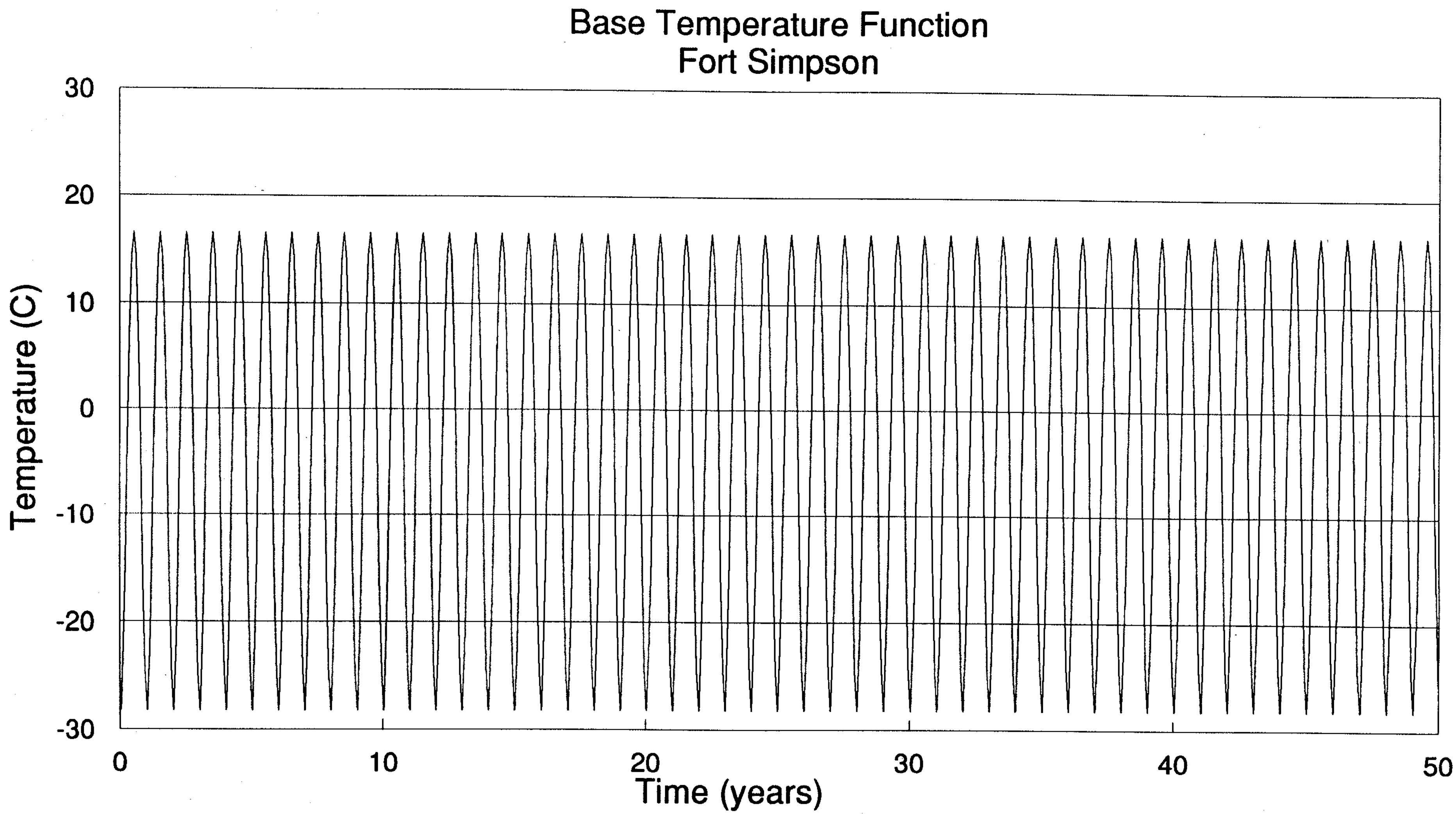
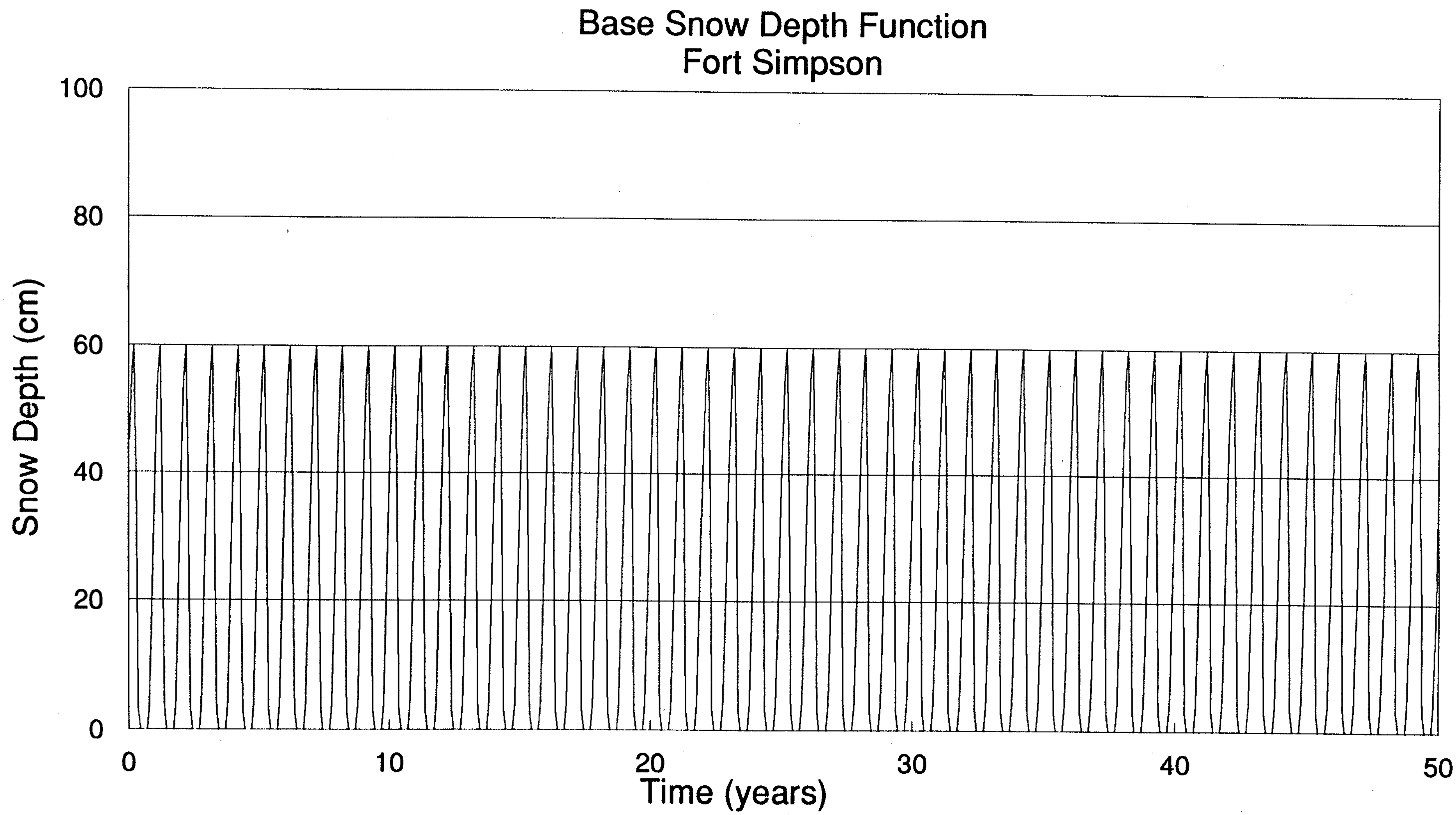


FIGURE 39



Base Temperature Function
Fort Simpson
Temperature (C)
30
20
10
0
-10
-20
-30
0
10
20
30
40
50
Time (years)

FIGURE 40



Base Snow Depth Function
Fort Simpson
Snow Depth (cm)
100
80
60
40
20
0
0
10
20
30
40
50
Time (years)

FIGURE 41

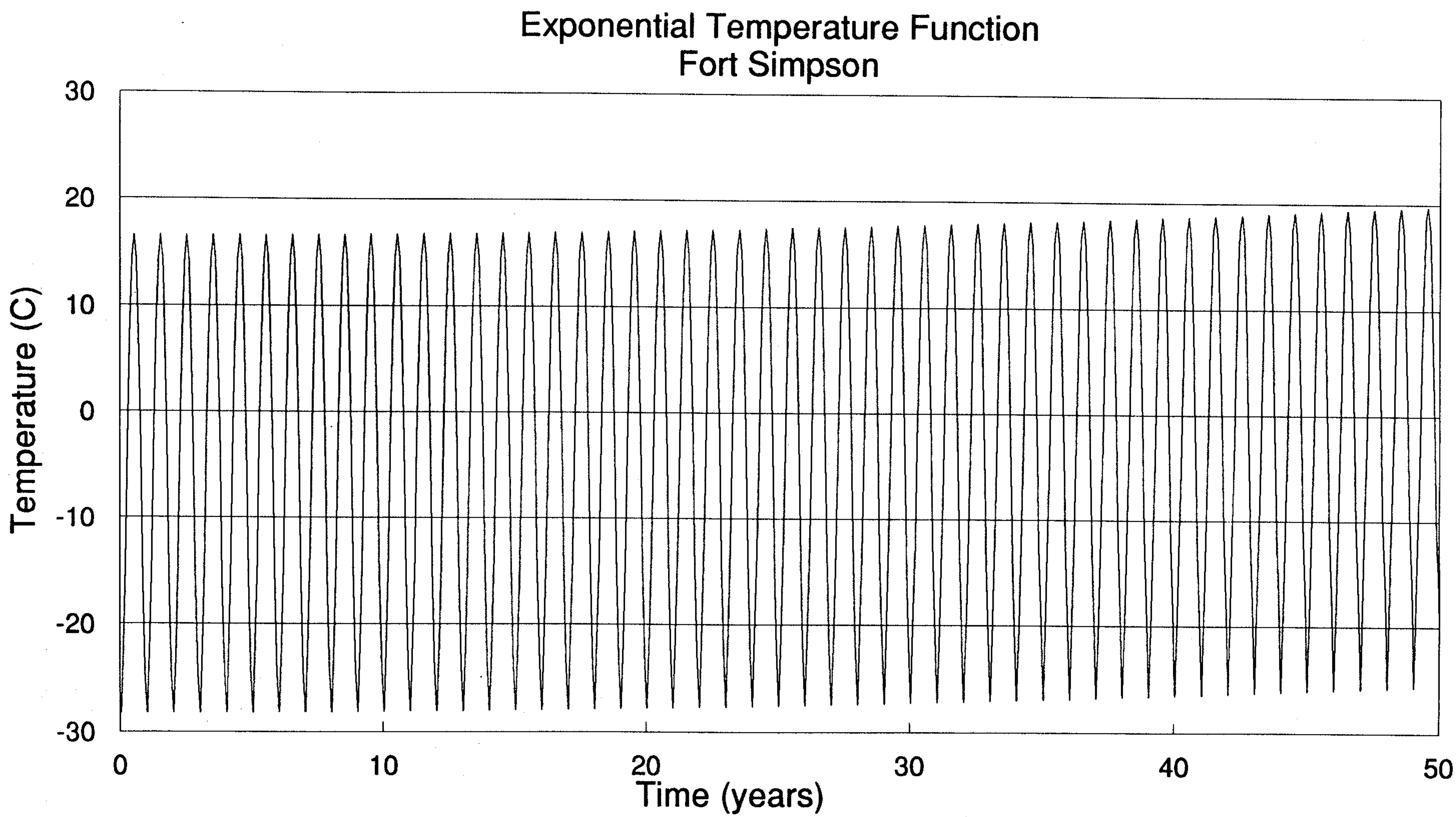
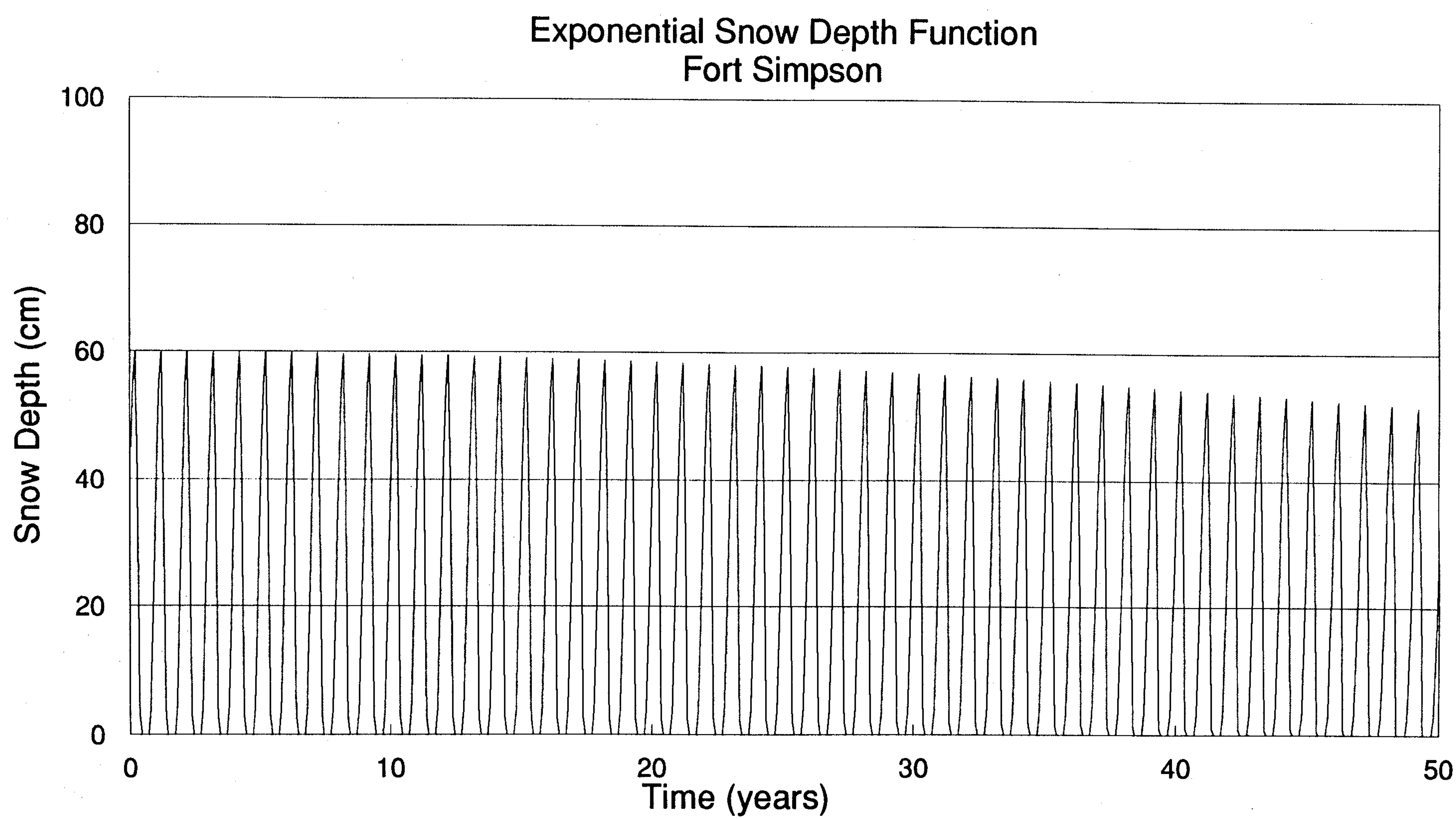

Exponential Temperature Function
Fort Simpson
Temperature (C)
30
20
10
0
-10
-20
-30
0
10
20
30
40
50
Time (years)

FIGURE 42



Exponential Snow Depth Function
Fort Simpson
100
80
60
40
20
0
Snow Depth (cm)
0
10
20
30
40
50
Time (years)

FIGURE 43

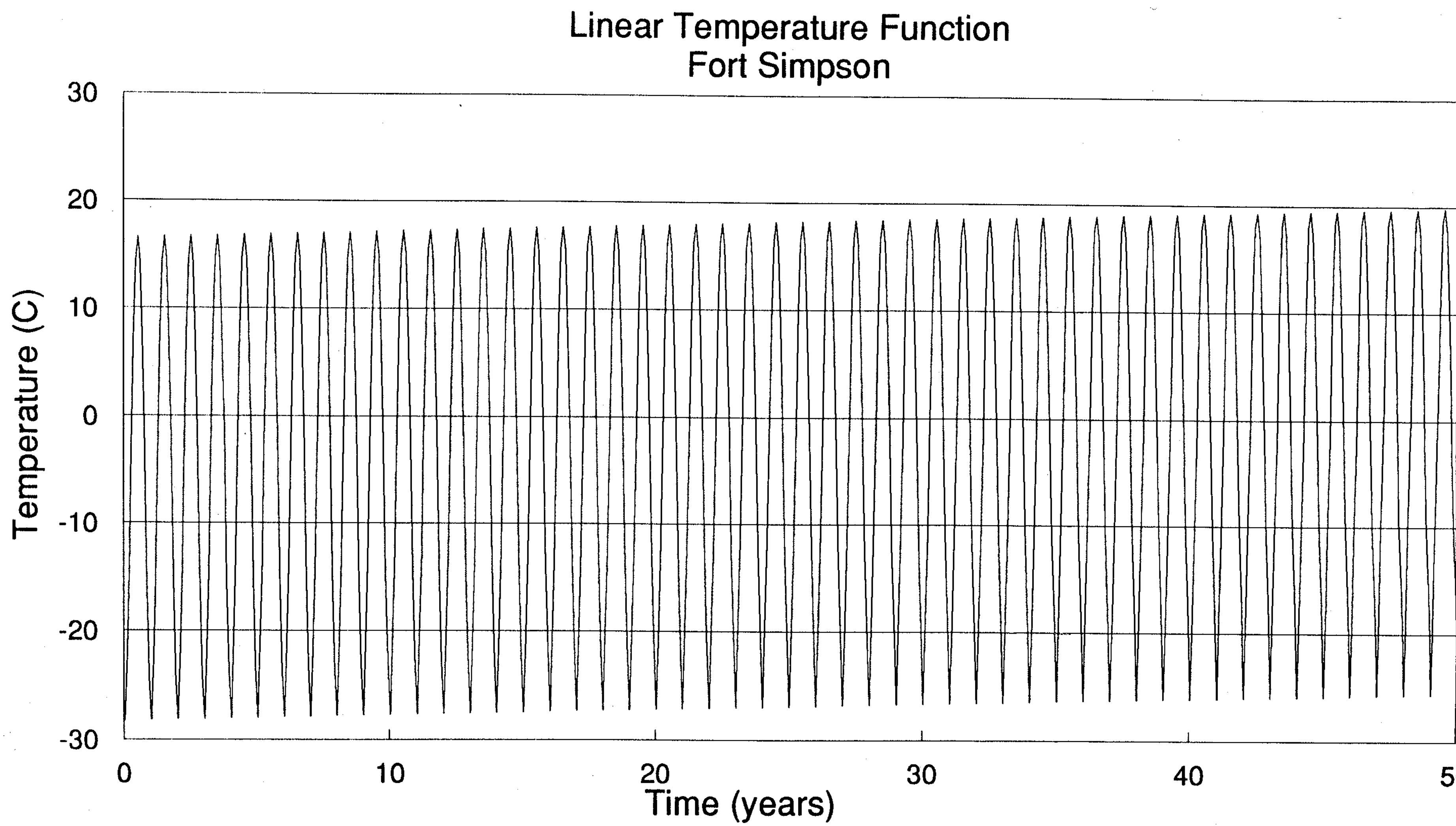

Linear Temperature Function
Fort Simpson
Temperature (C)
30
20
10
0
-10
-20
-30
0
10
20
30
40
50
Time (years)

FIGURE 44

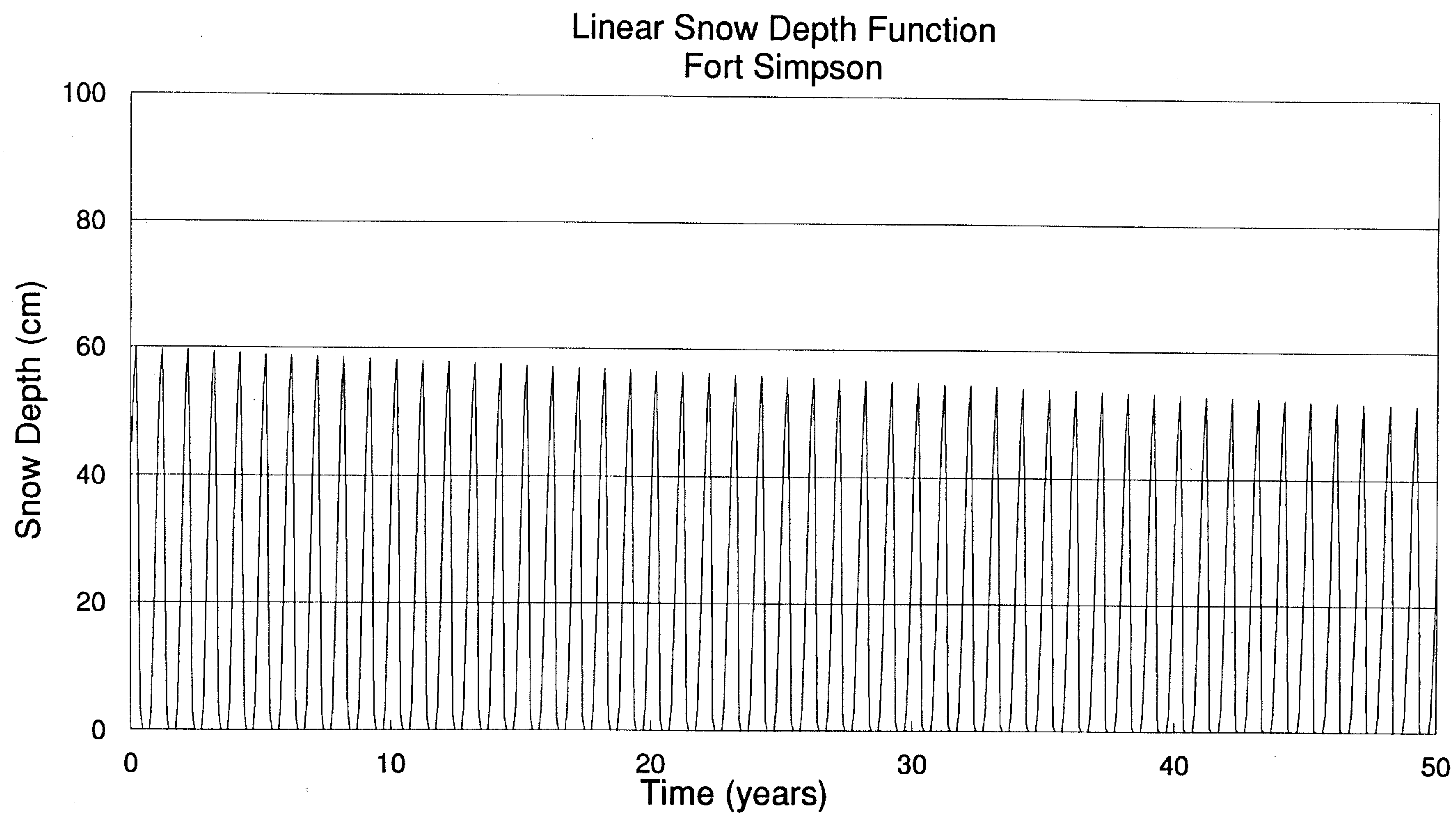

Linear Snow Depth Function
Fort Simpson
Snow Depth (cm)
100
80
60
40
20
0
0
10
20
30
40
50
Time (years)

FIGURE 45

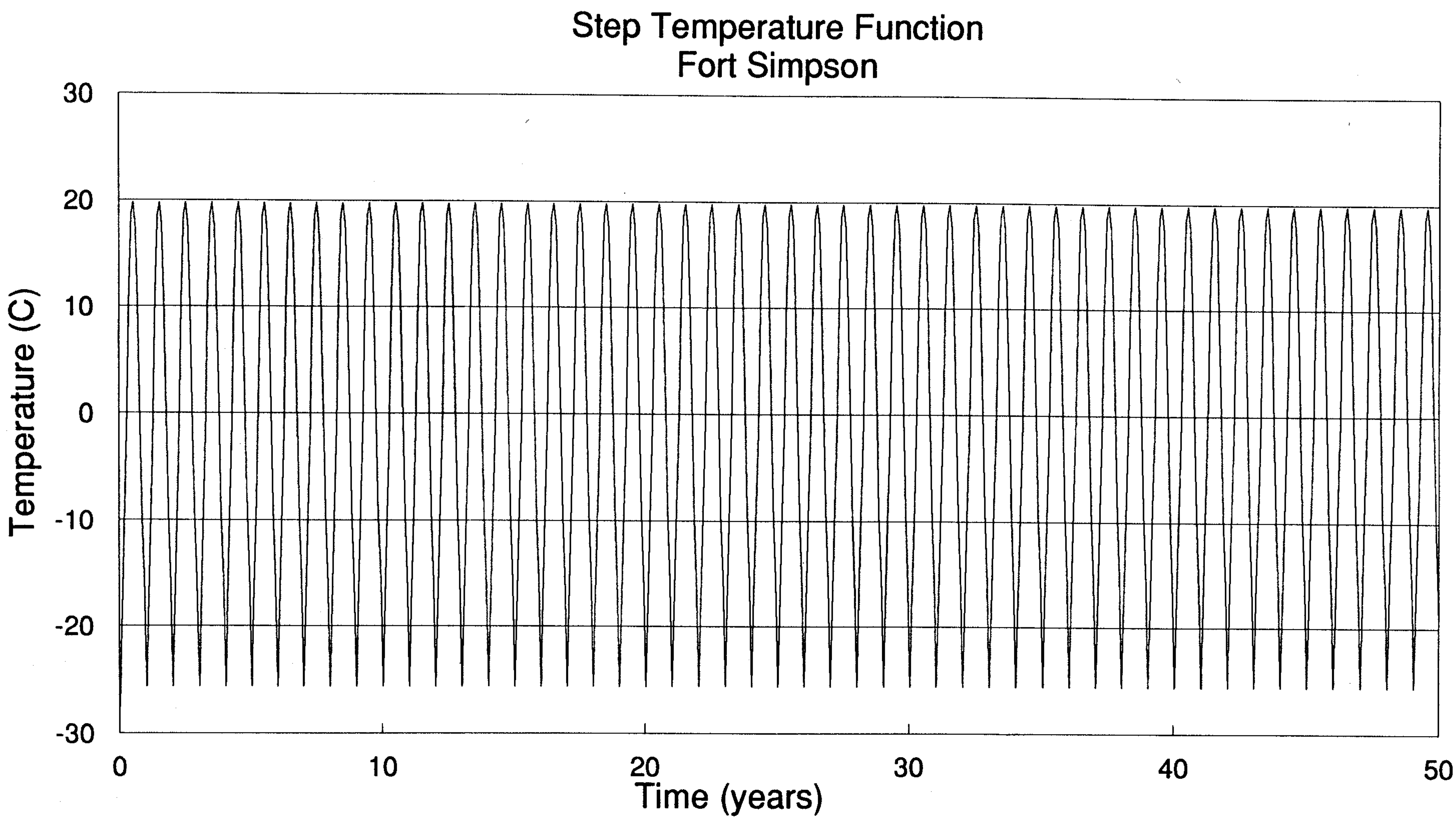
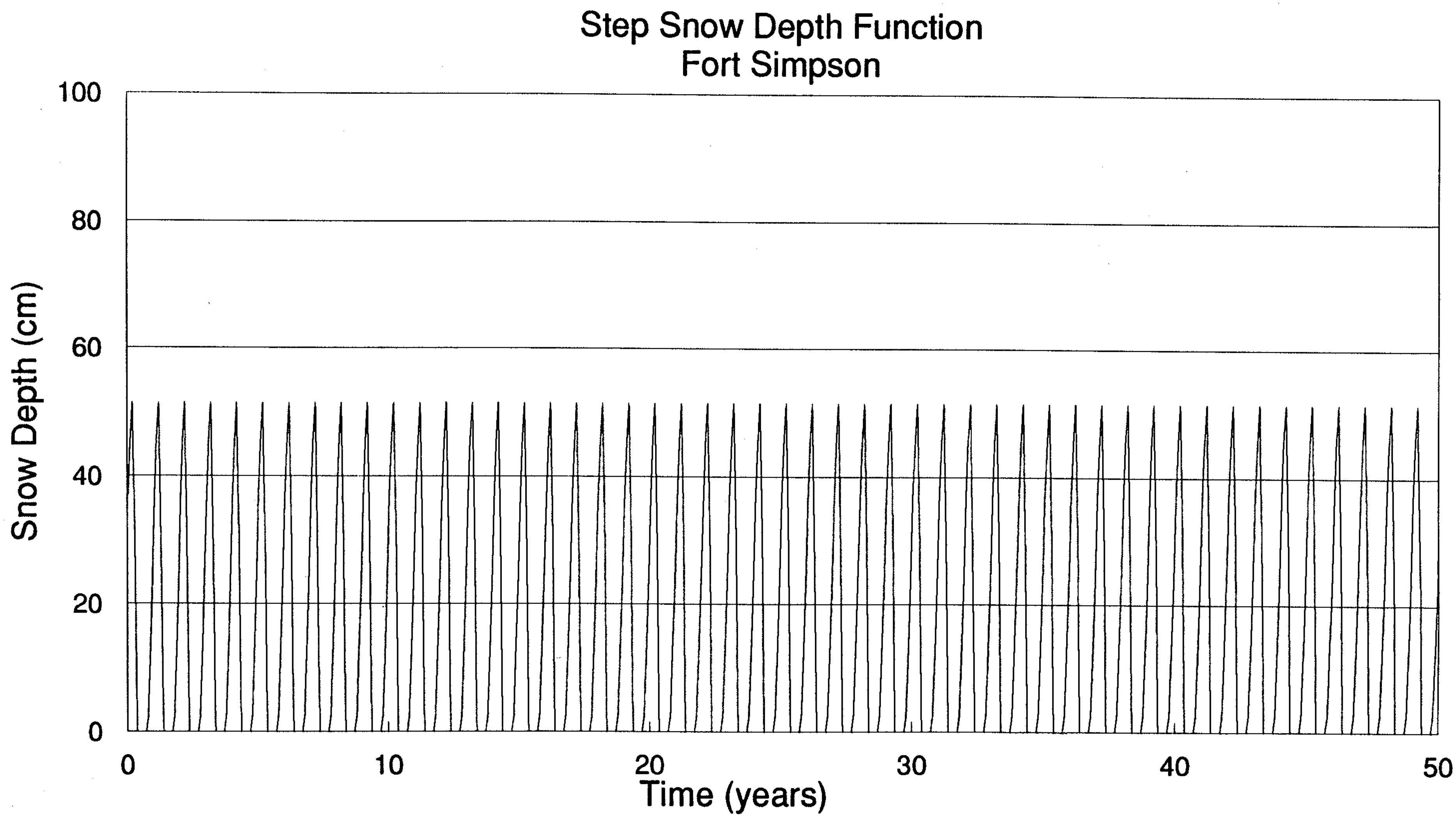
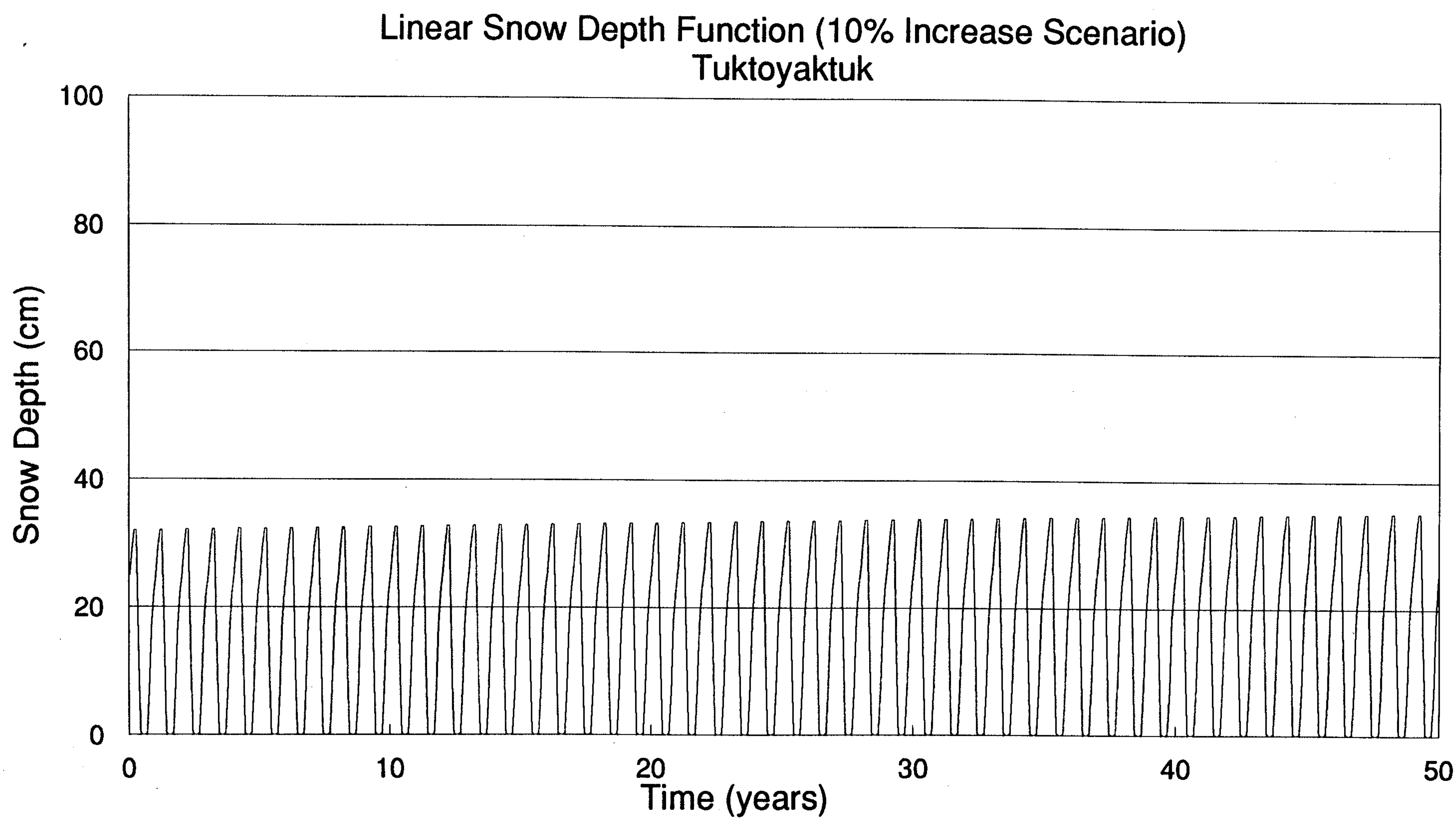

Step Temperature Function
Fort Simpson
30
20
10
0
-10
-20
-30
Temperature (C)
0
10
20
30
40
50
Time (years)

FIGURE 46



Step Snow Depth Function
Fort Simpson
100
80
60
40
20
0
Snow Depth (cm)
0
10
20
30
40
50
Time (years)

FIGURE 47



Linear Snow Depth Function (10% Increase Scenario)
Tuktoyaktuk
Snow Depth (cm)
100
80
60
40
20
0
0
10
20
30
40
50
Time (years)

FIGURE 48

Linear Snow Depth Function (10% Increase Scenario)
Norman Wells

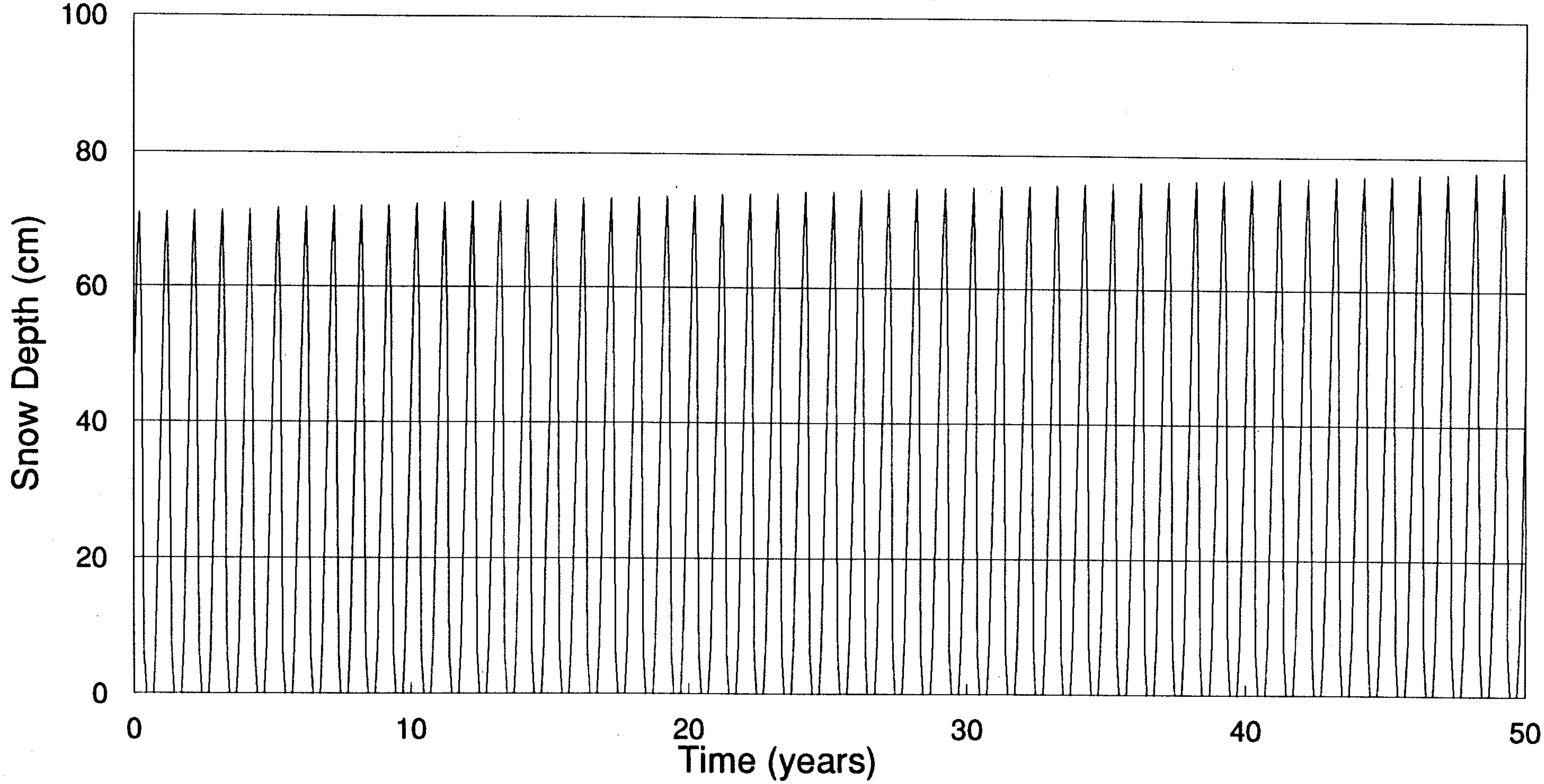


FIGURE 49

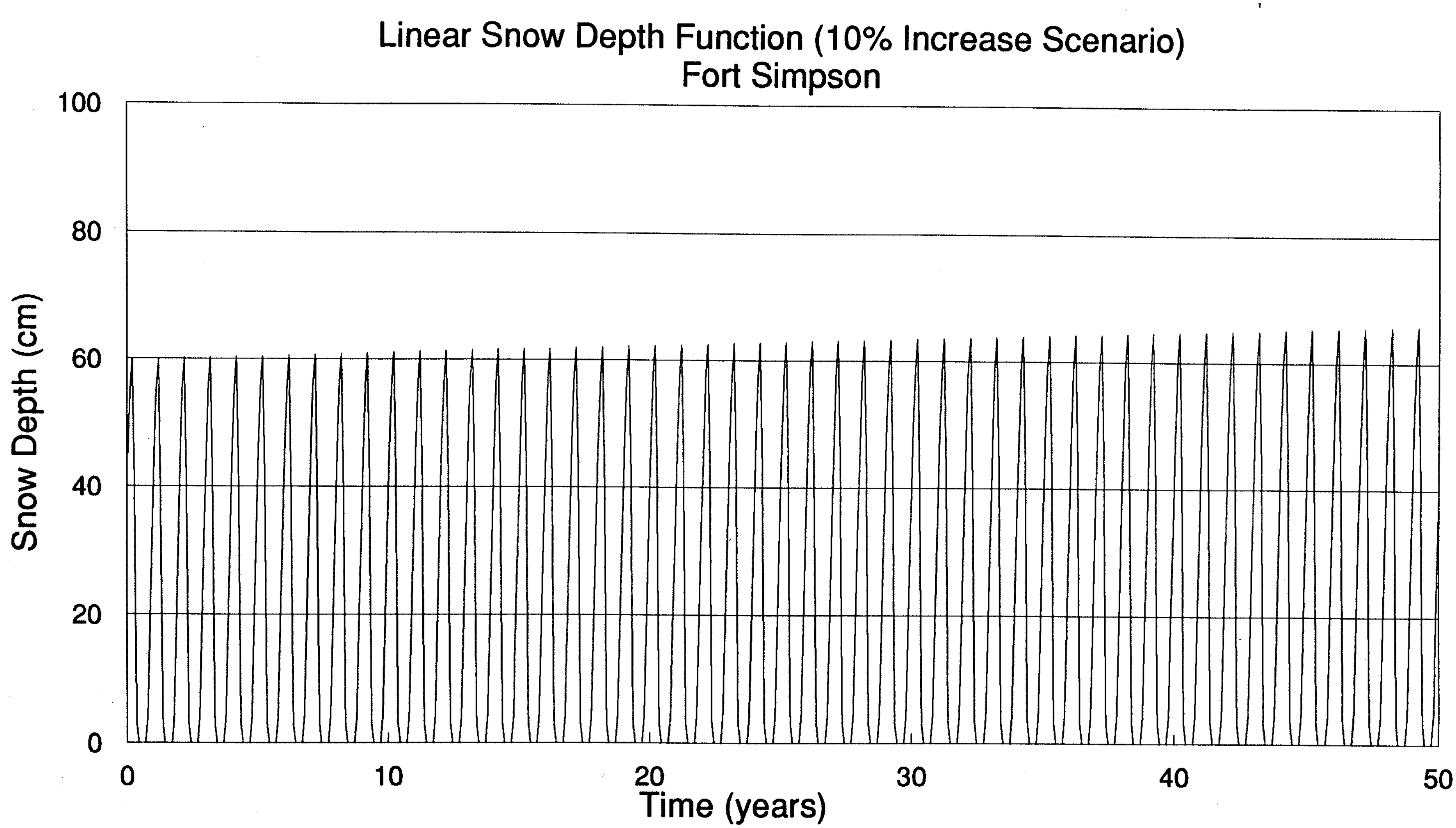
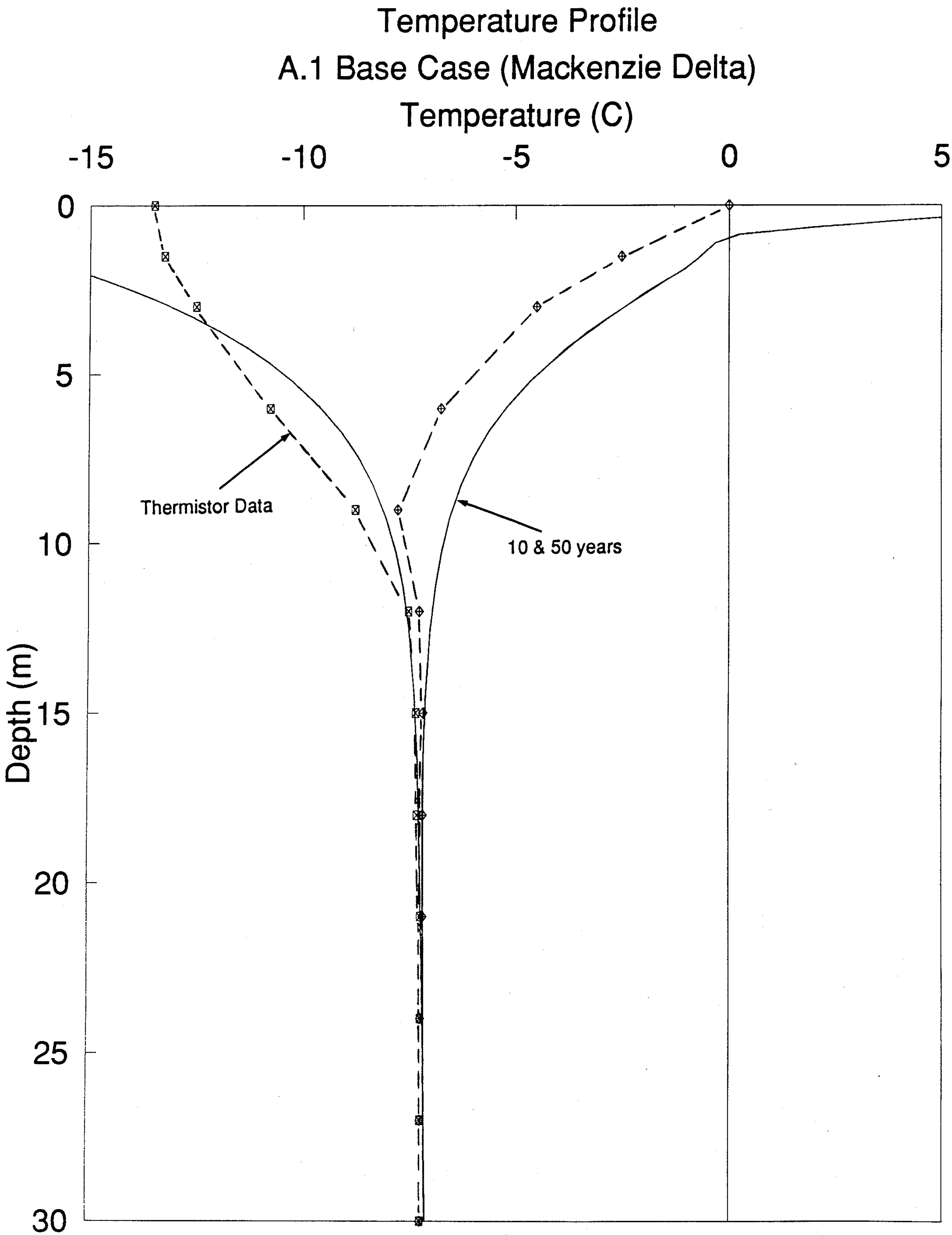

Linear Snow Depth Function (10% Increase Scenario)
Fort Simpson
Snow Depth (cm)
100
80
60
40
20
0
0
10
20
30
40
50
Time (years)

FIGURE 50

APPENDIX B

RESULTS



Temperature Profile
A.1 Base Case (Mackenzie Delta)
Temperature (C)
-15
-10
-5
0
5
0
5
10
15
20
25
30
Depth (m)
Thermistor Data
10 & 50 years

PLATE B.1

Thaw Depth vs Time
A.1 Base Case (Mackenzie Delta)

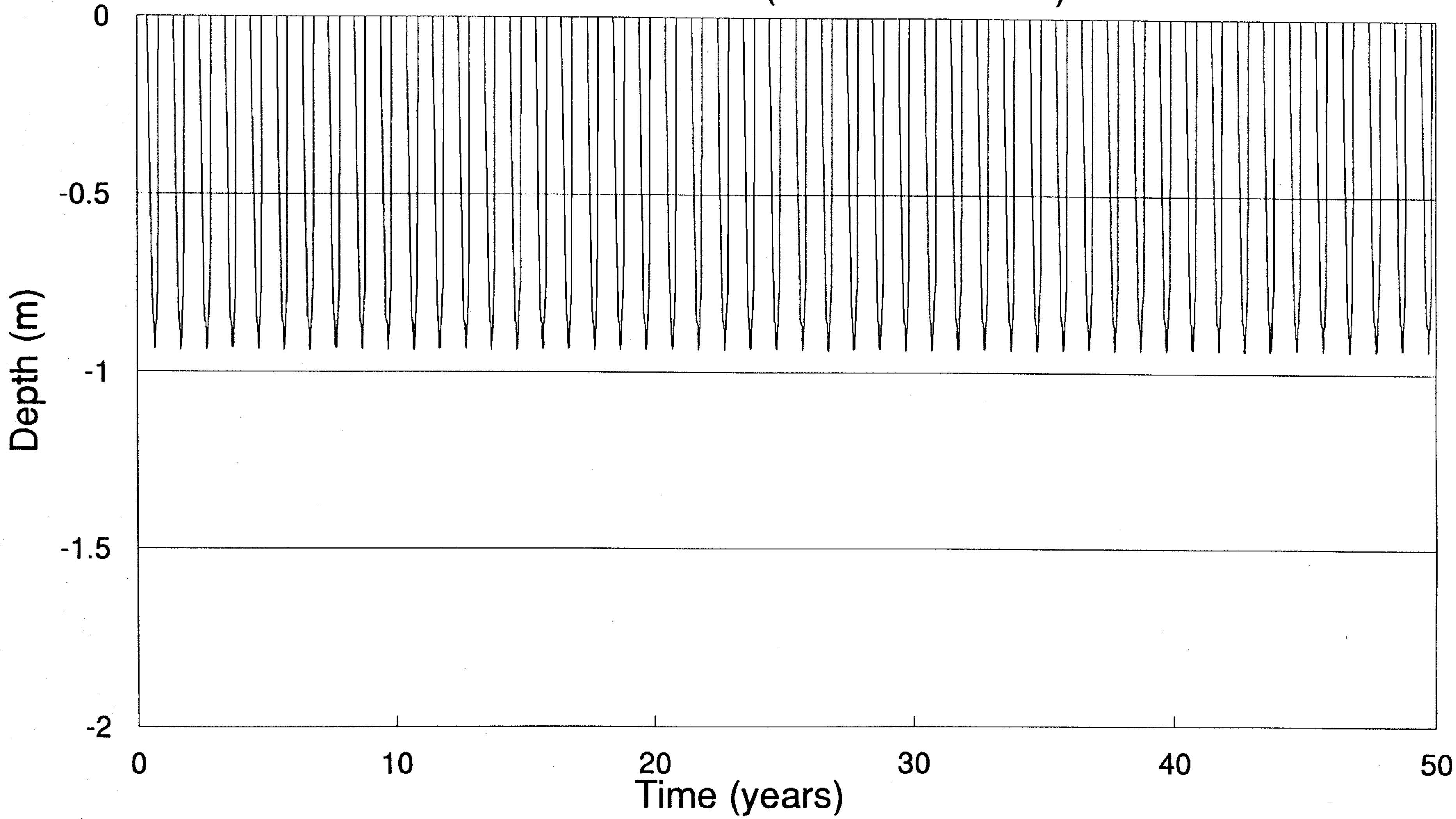


PLATE B.2

Surface Temperature vs Time
A.1 Base Case (Mackenzie Delta)

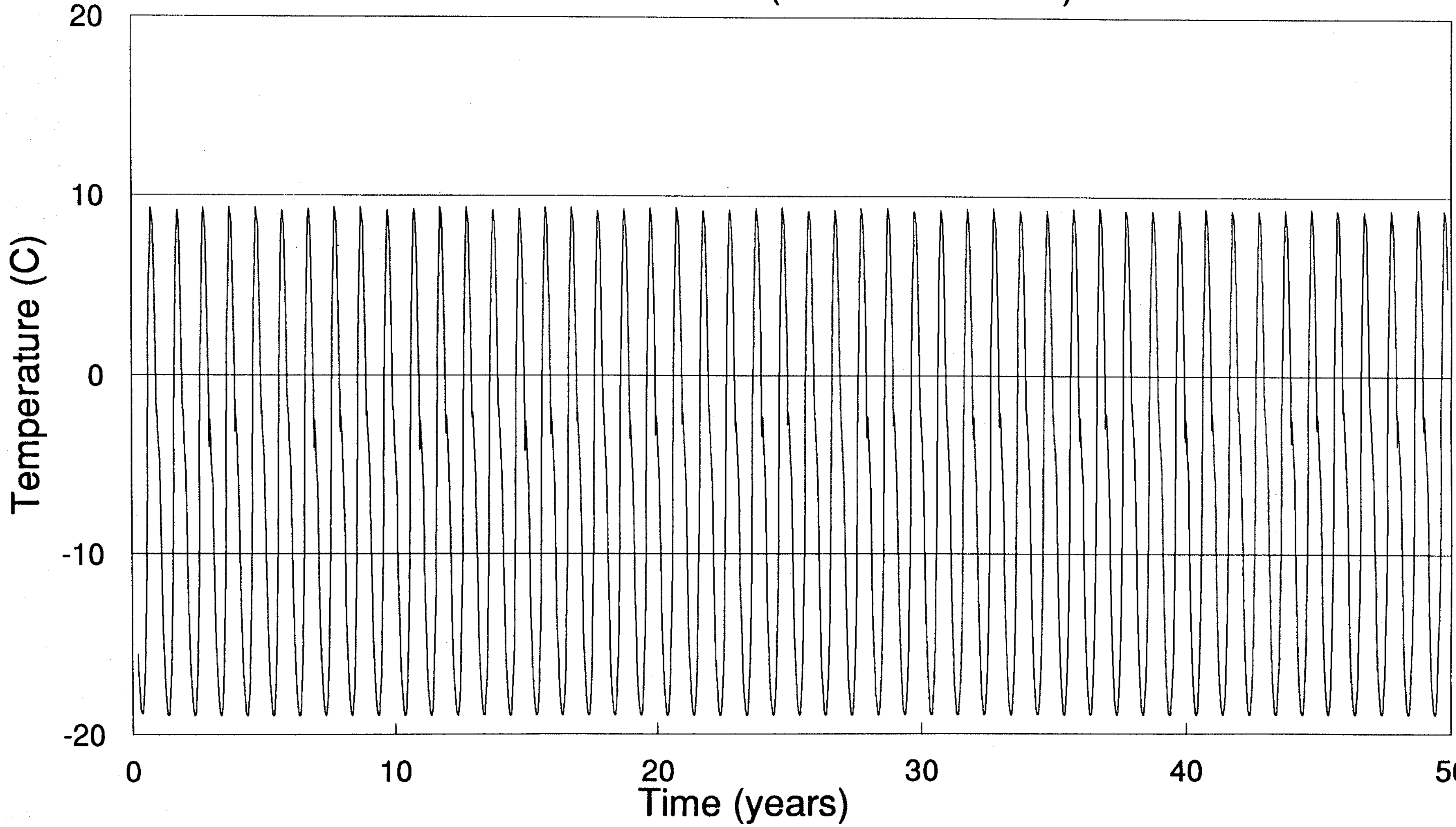


PLATE B.3

Ground Temperature vs Time
A.1 Base Case (Mackenzie Delta)

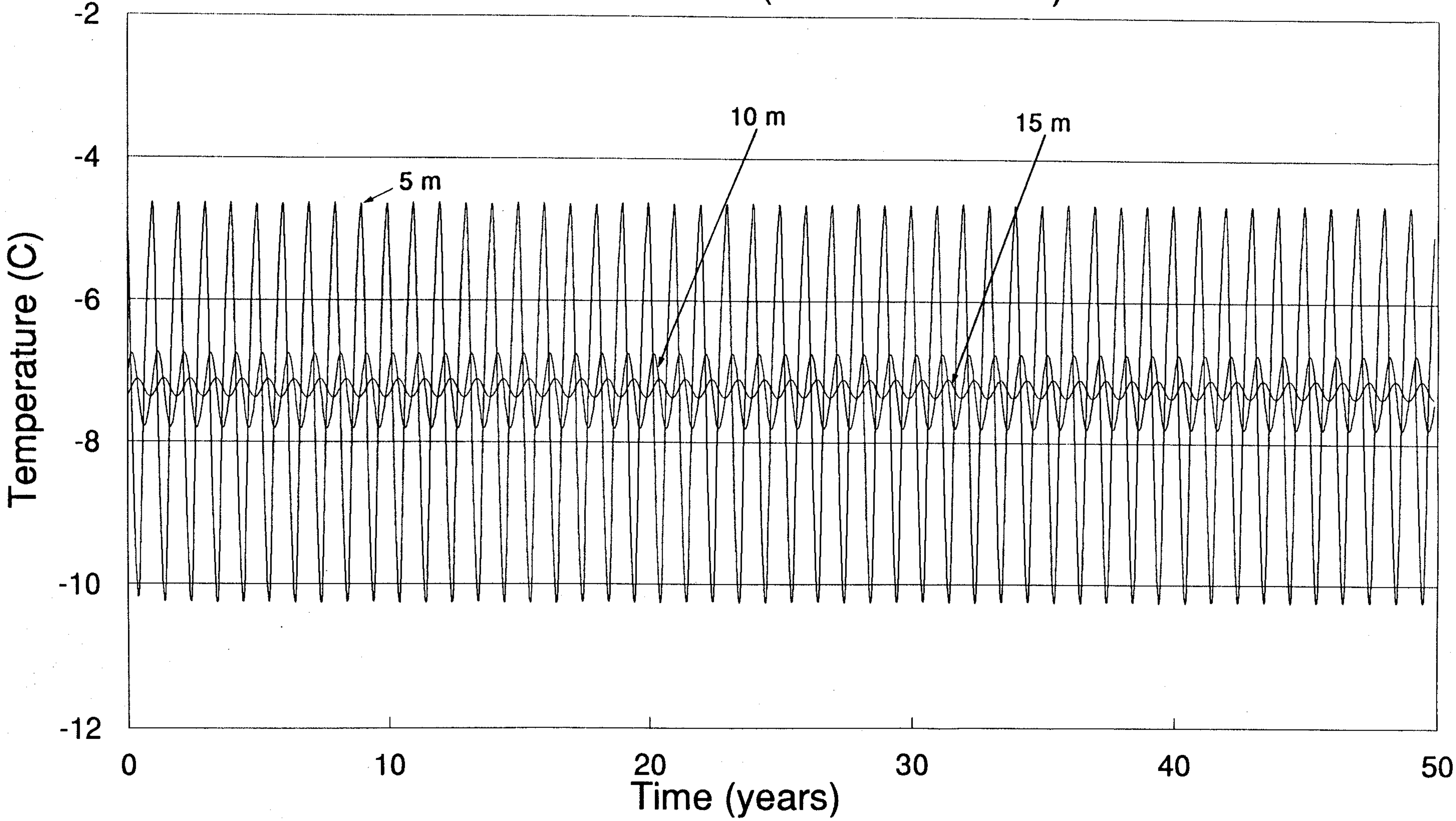


PLATE B.4

Temperature Profile
A.1 Exponential Case (Mackenzie Delta)

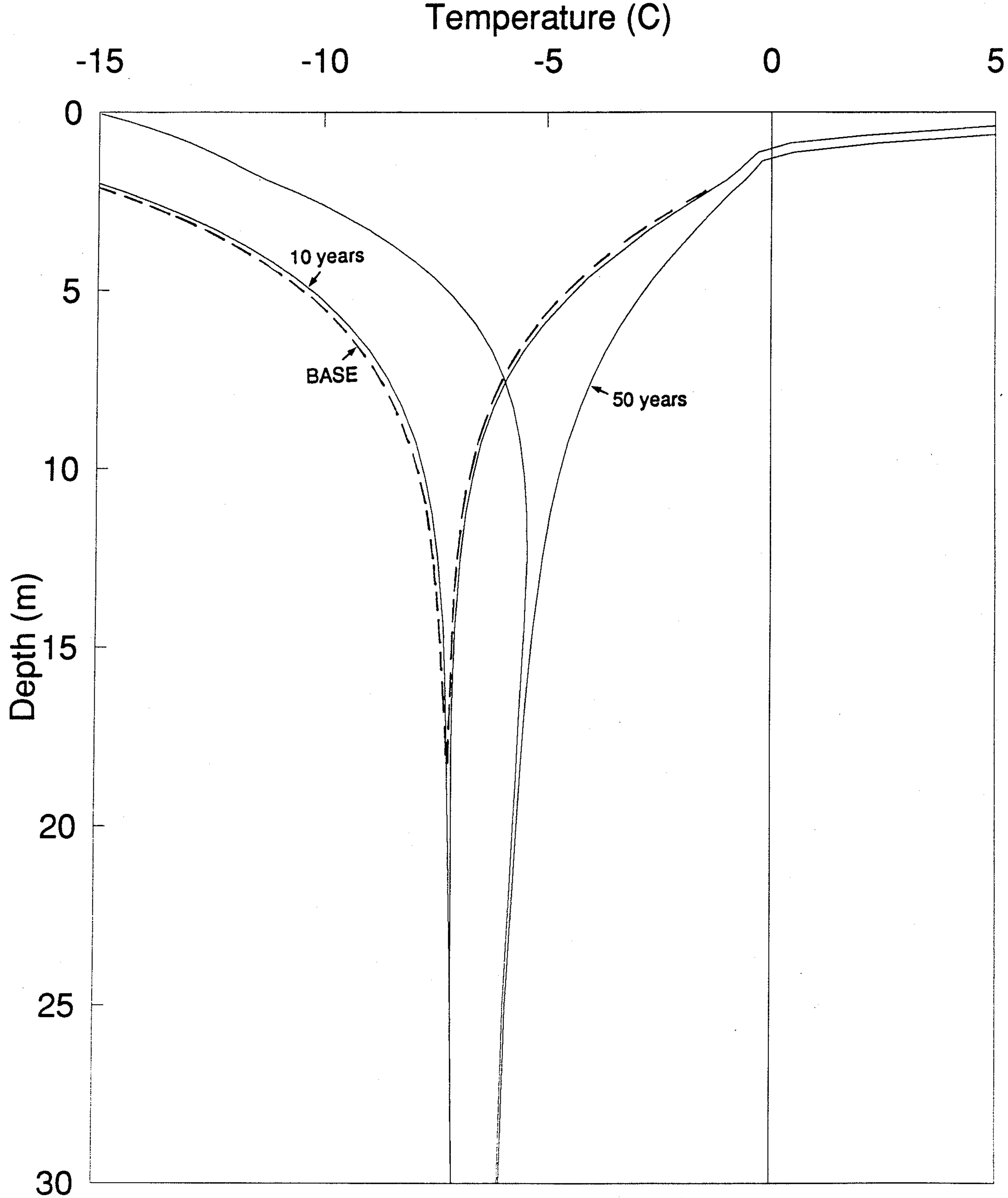


PLATE B.5

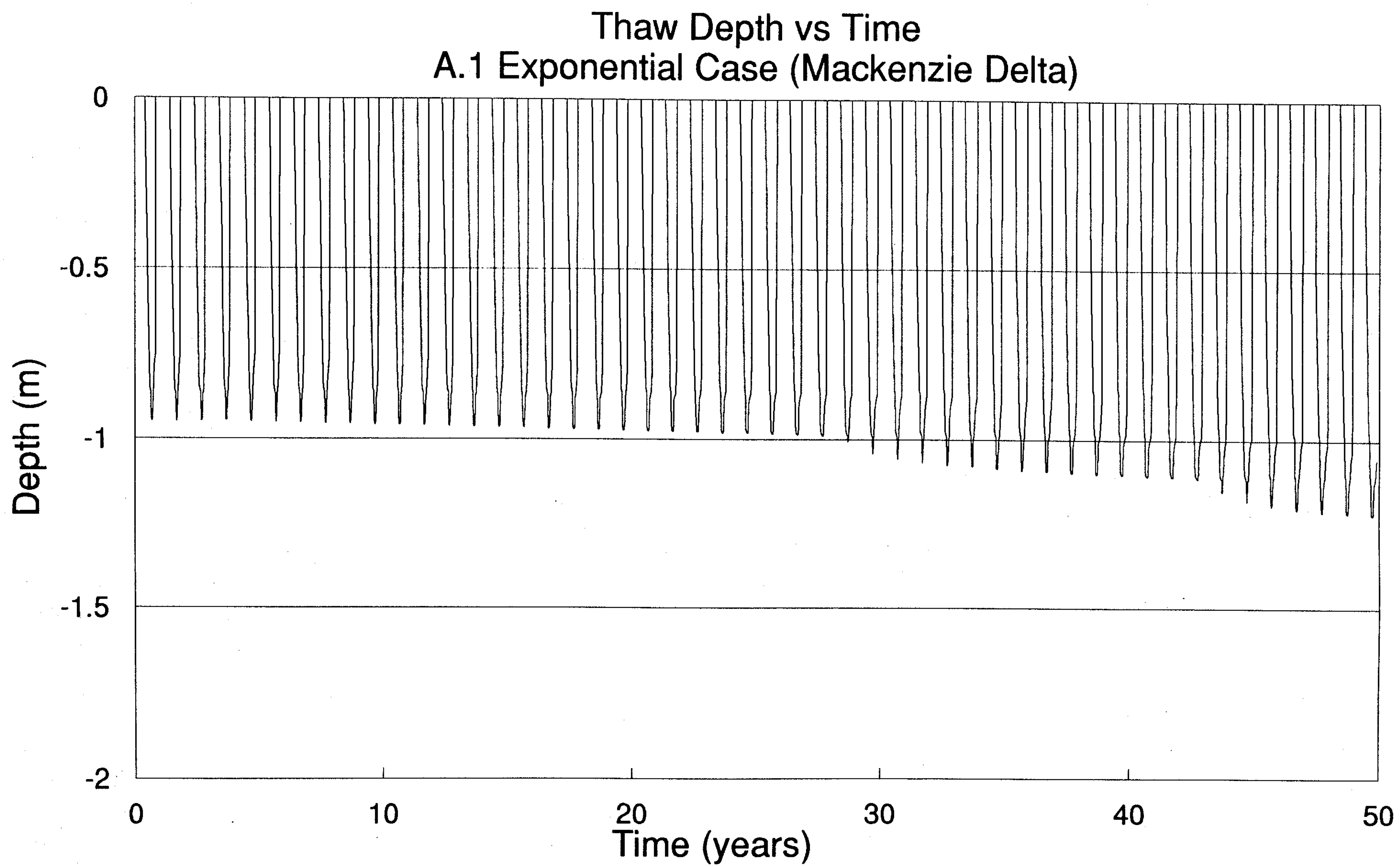

Thaw Depth vs Time
A.1 Exponential Case (Mackenzie Delta)
Depth (m)
0
-0.5
-1
-1.5
-2
Time (years)
0
10
20
30
40
50

PLATE B.6

Surface Temperature vs Time
A.1 Exponential Case (Mackenzie Delta)

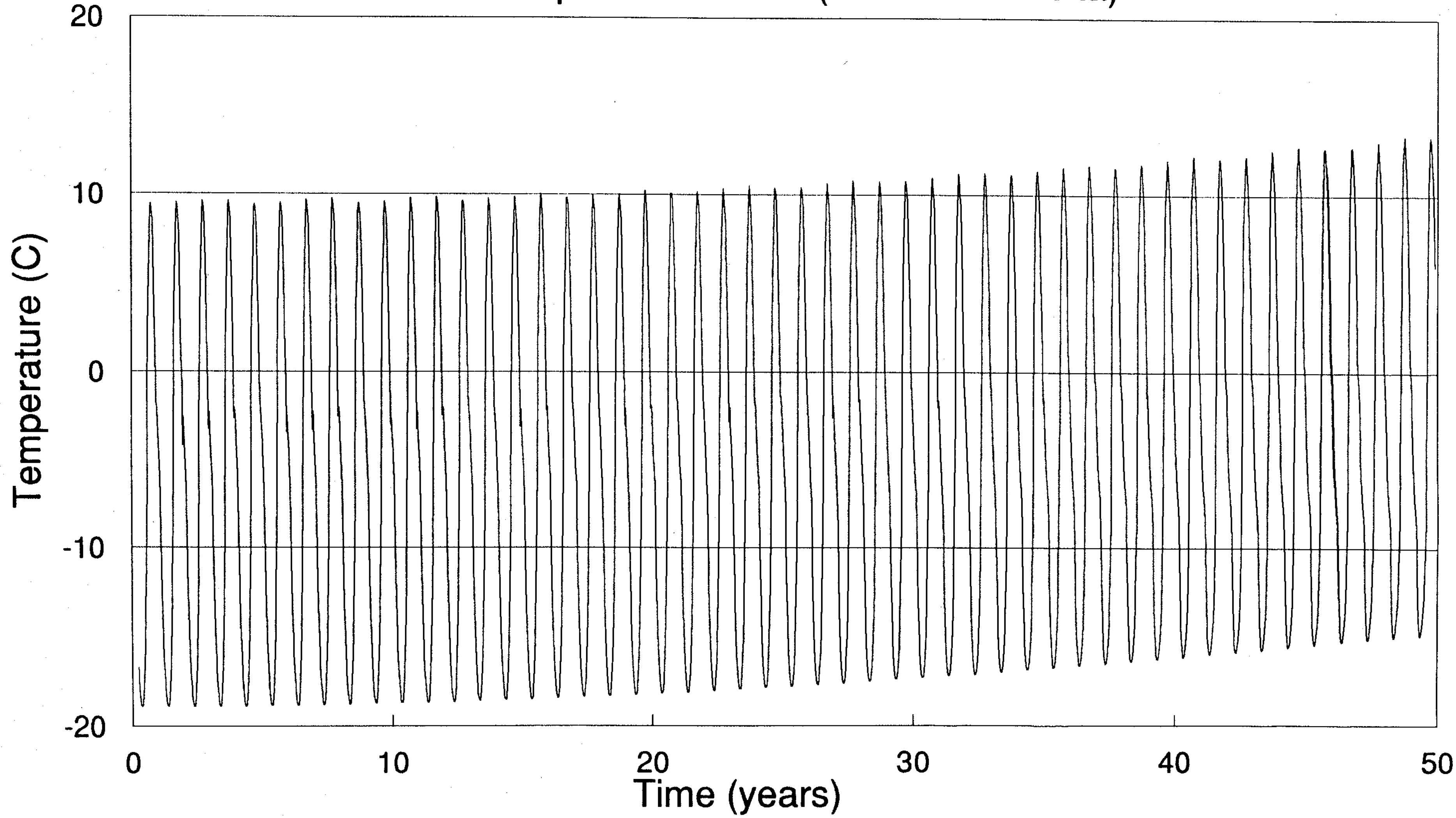


PLATE B.7

Ground Temperature vs Time
A.1 Exponential Case (Mackenzie Delta)

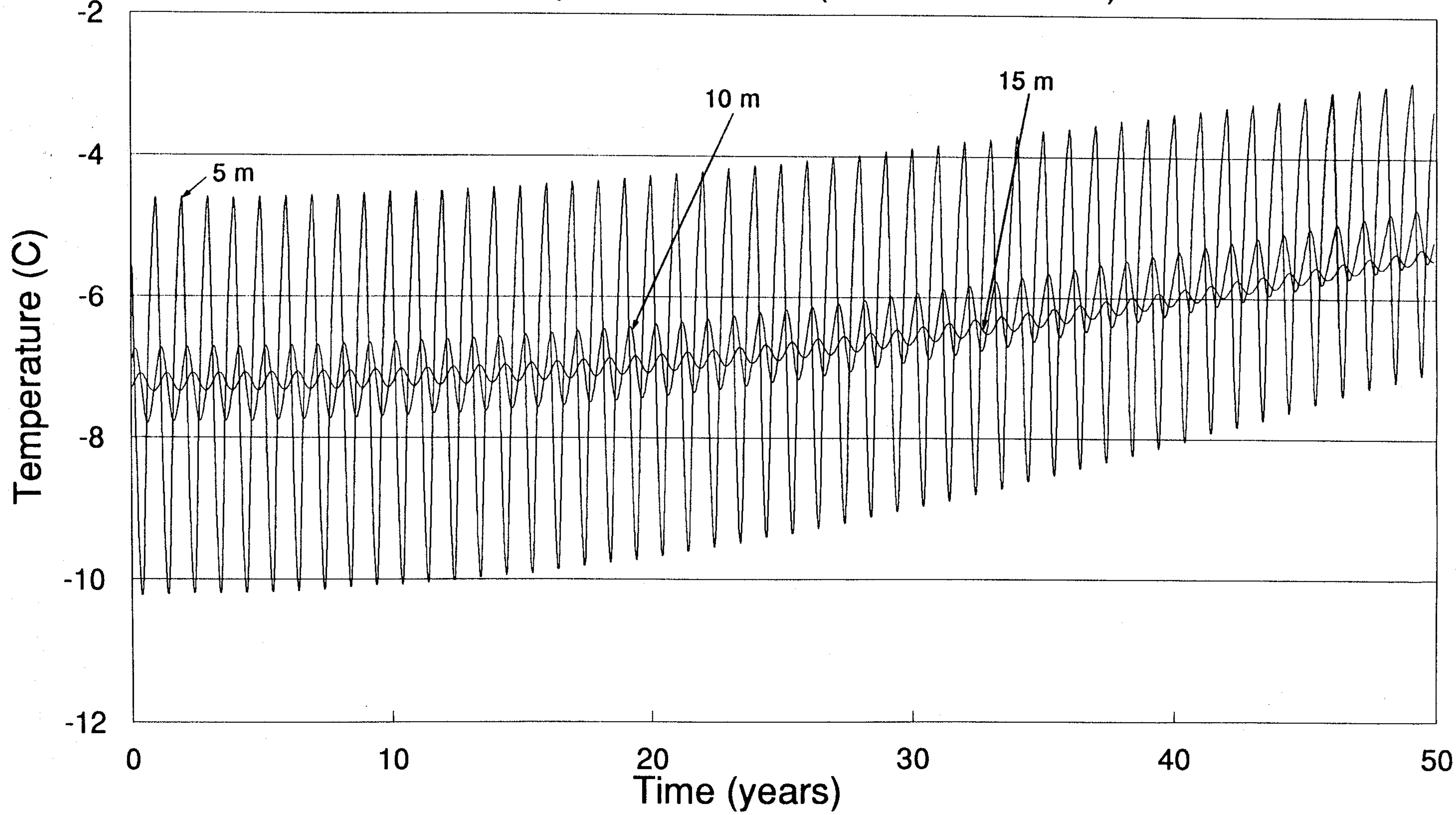


PLATE B.8

Temperature Profile
A.1 Linear Case (Mackenzie Delta)

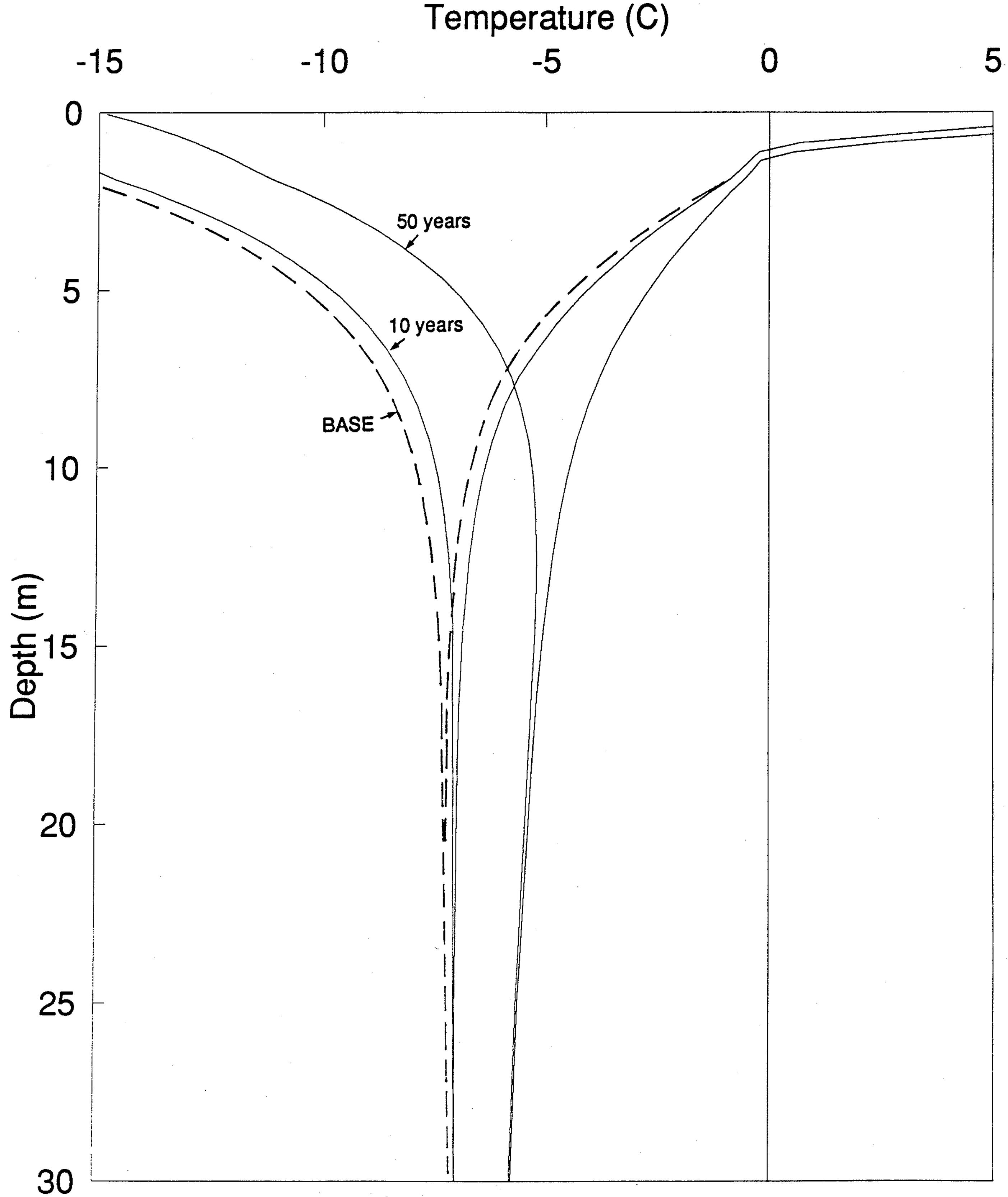


PLATE B.9

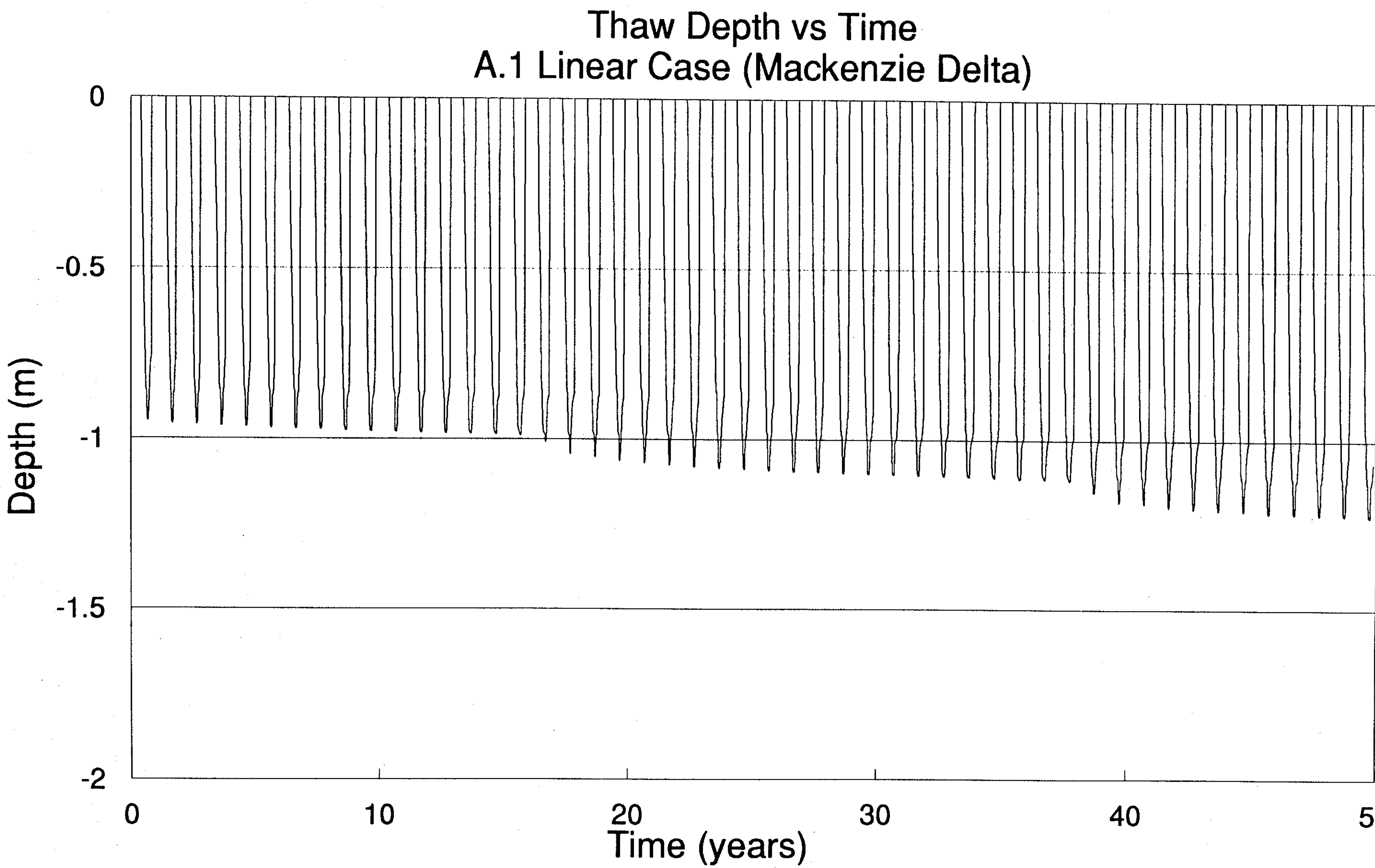

Thaw Depth vs Time
A.1 Linear Case (Mackenzie Delta)
0
-0.5
-1
-1.5
-2
Depth (m)
0
10
20
30
40
50
Time (years)

PLATE B.10

Surface Temperature vs Time
A.1 Linear Case (Mackenzie Delta)

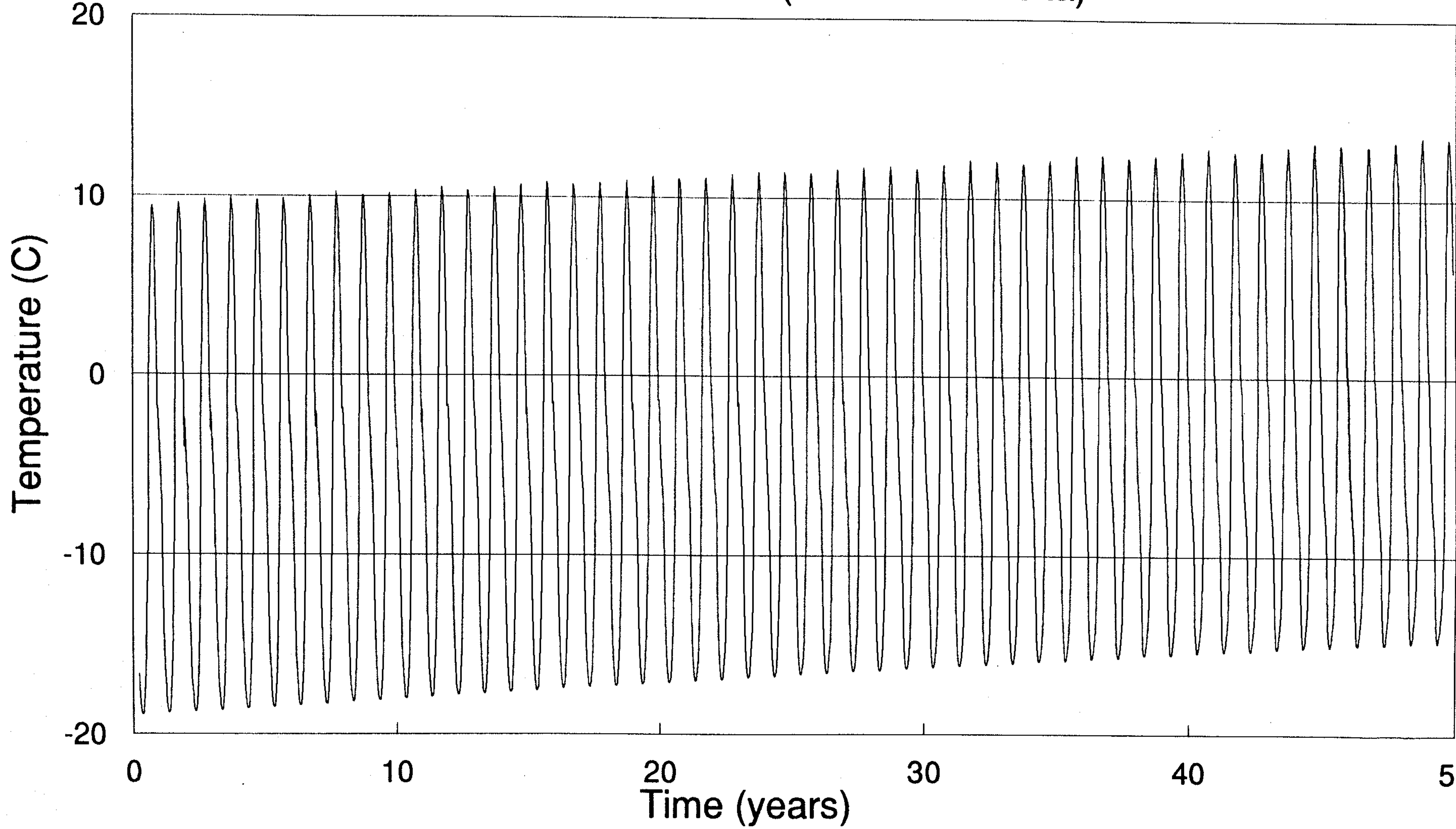


PLATE B.11

Ground Temperature vs Time
A.1 Linear Case (Mackenzie Delta)

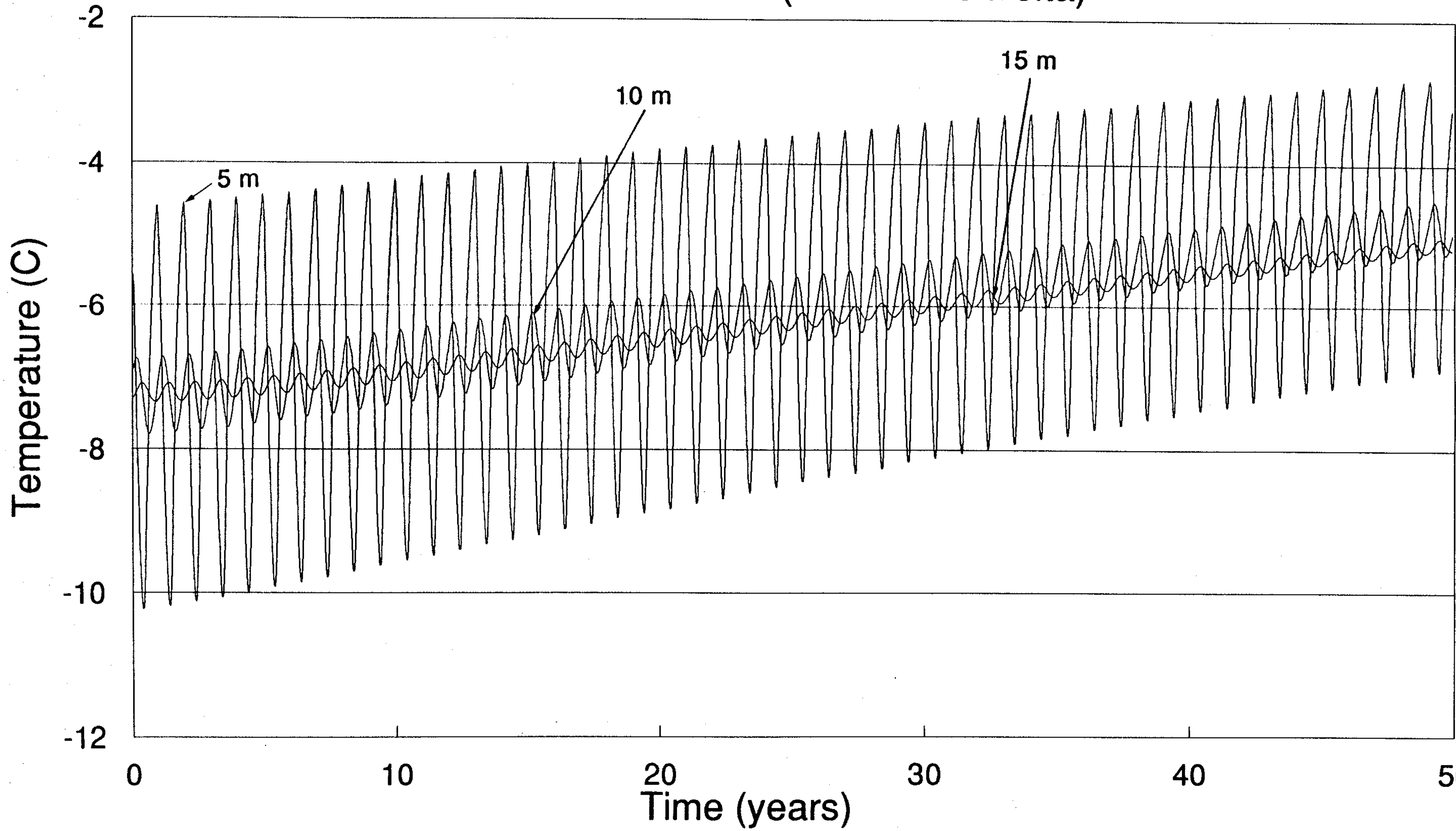
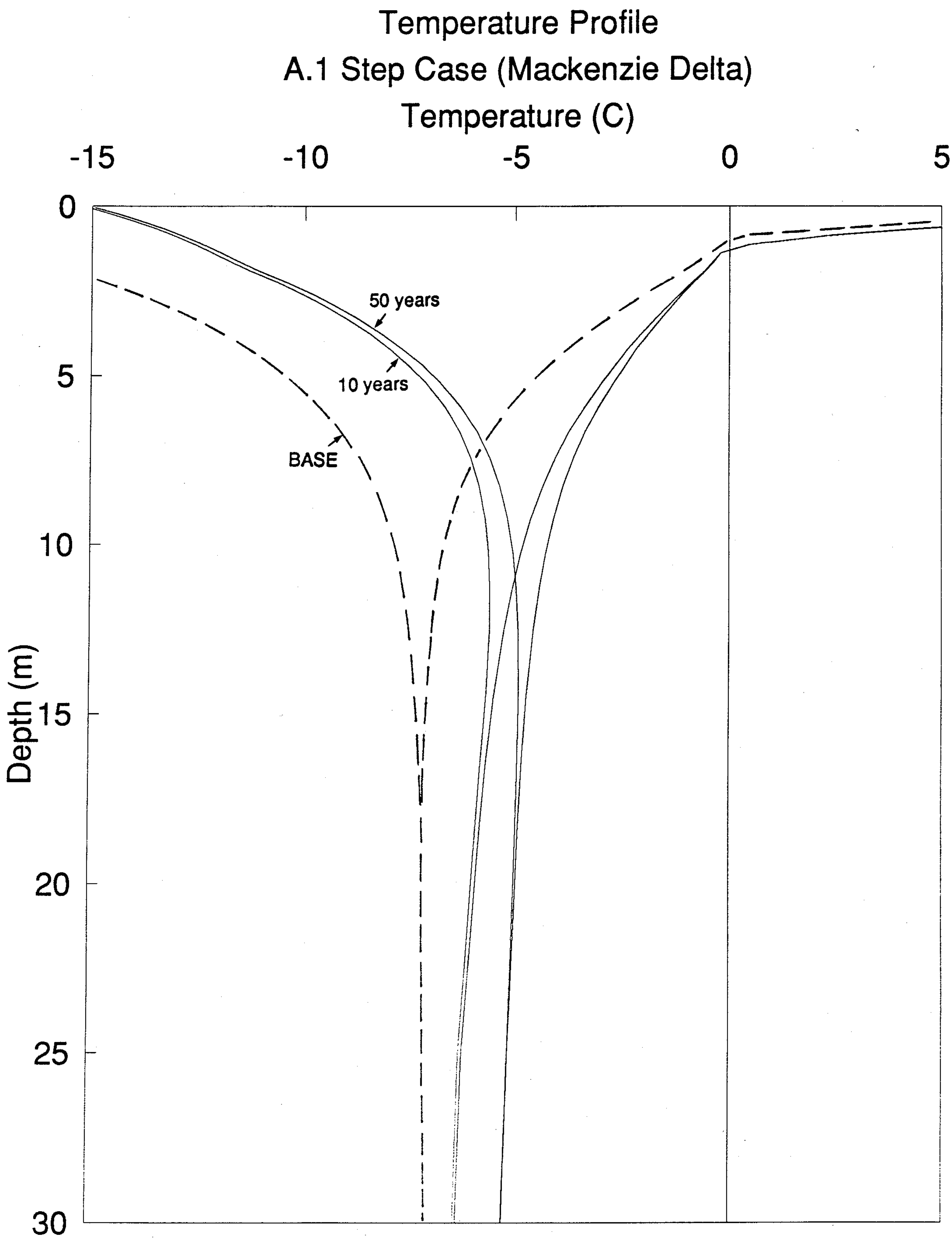


PLATE B.12



Temperature Profile
A.1 Step Case (Mackenzie Delta)
Temperature (C)
-15
-10
-5
0
5
0
5
10
15
20
25
30
Depth (m)
50 years
10 years
BASE

PLATE B.13

Thaw Depth vs Time
A.1 Step Case (Mackenzie Delta)

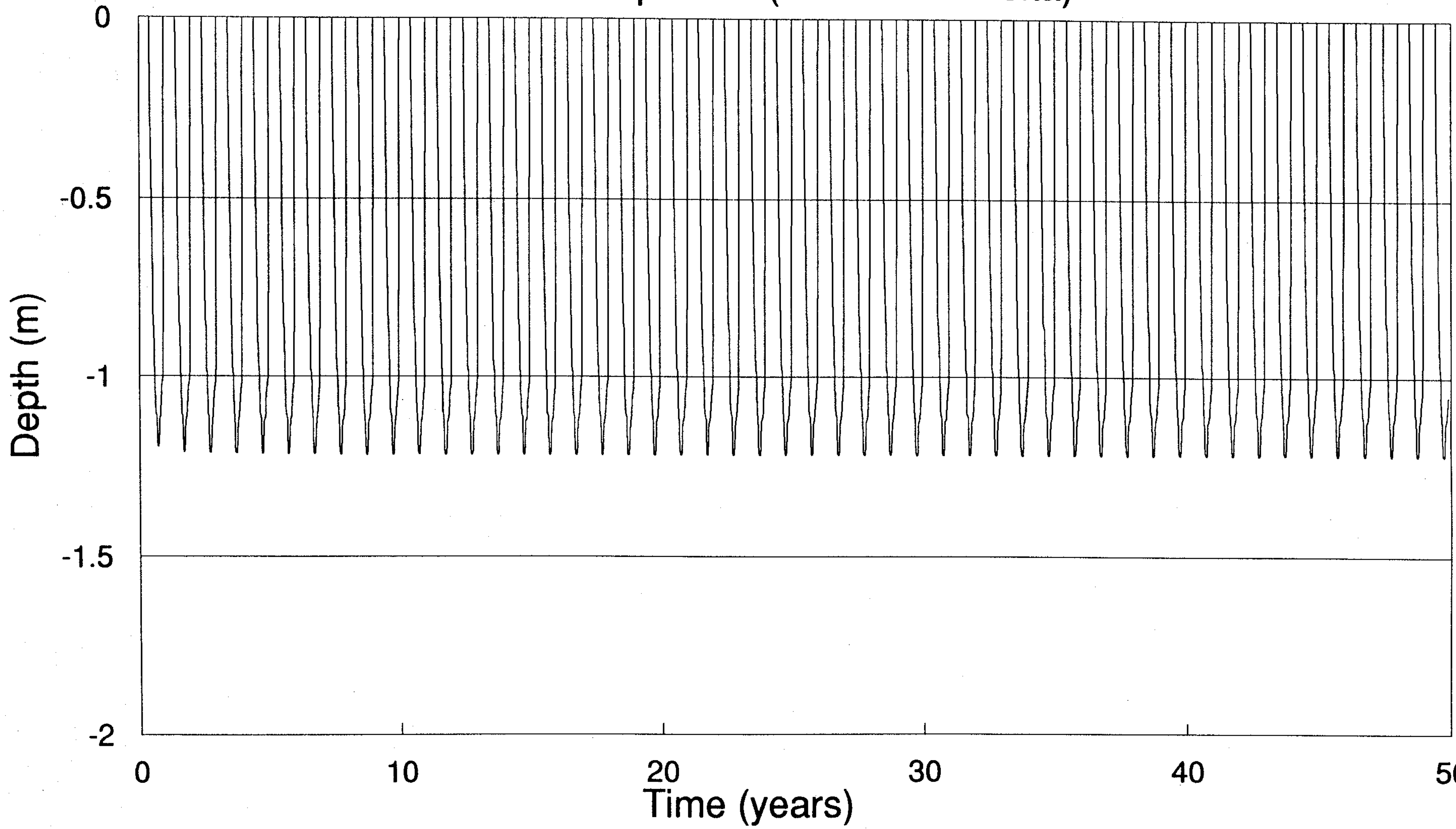


PLATE B.14

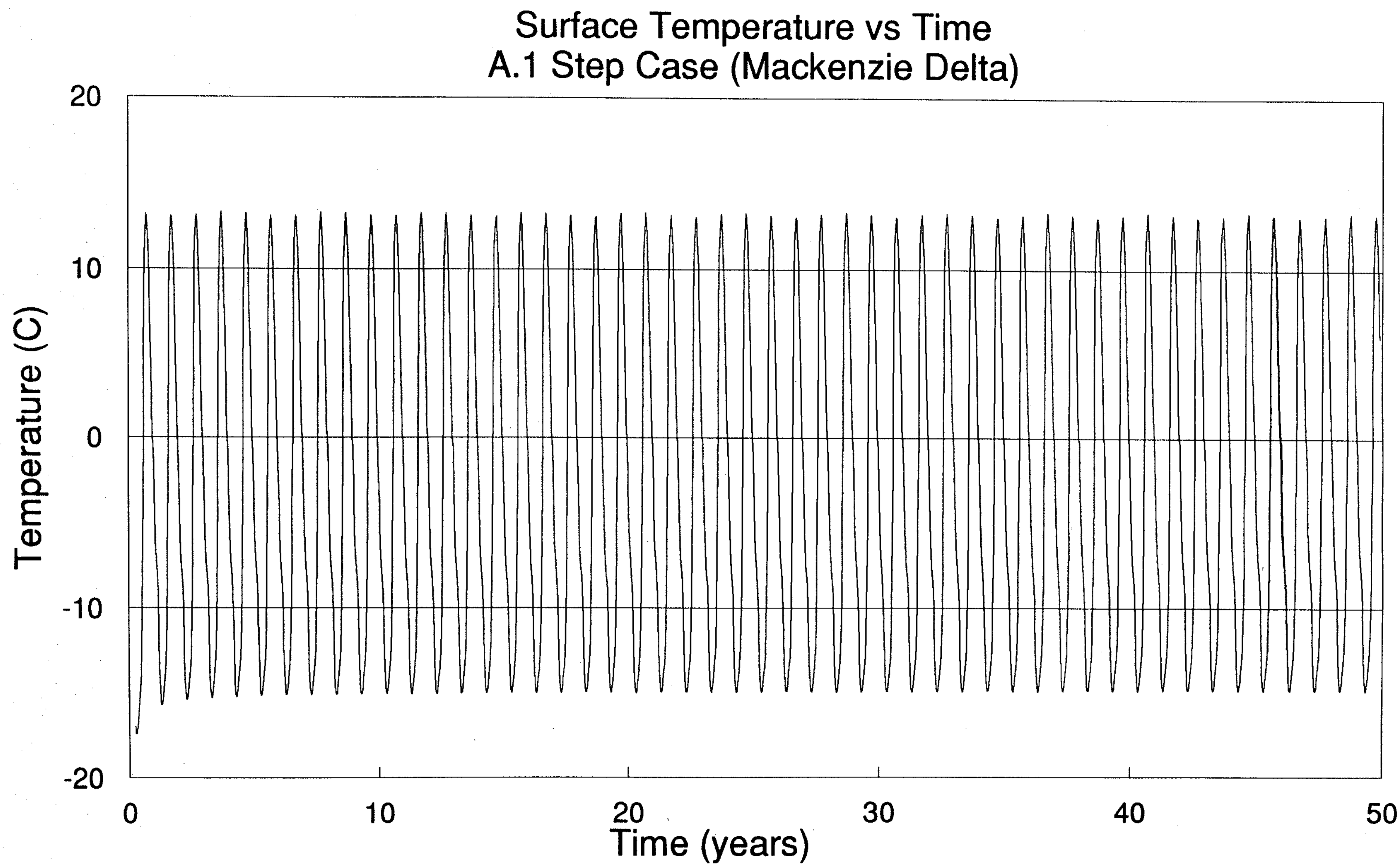

Surface Temperature vs Time
A.1 Step Case (Mackenzie Delta)
20
10
0
-10
-20
Temperature (C)
0
10
20
30
40
50
Time (years)

PLATE B.15

Ground Temperature vs Time
A.1 Step Case (Mackenzie Delta)

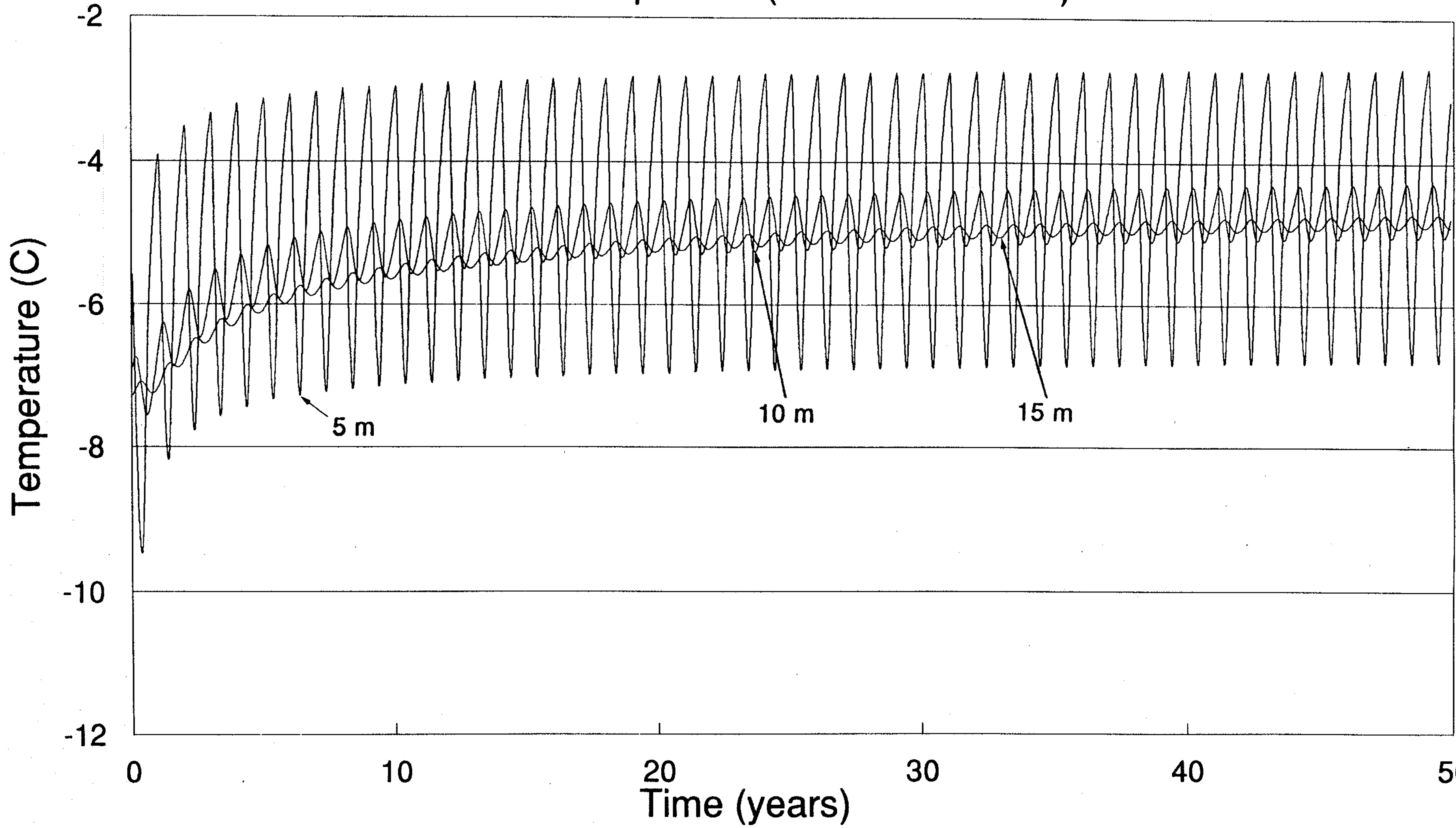


PLATE B.16

Temperature Profile

A.1 Linear Case with Increased Snow Pack (Mackenzie Delta)

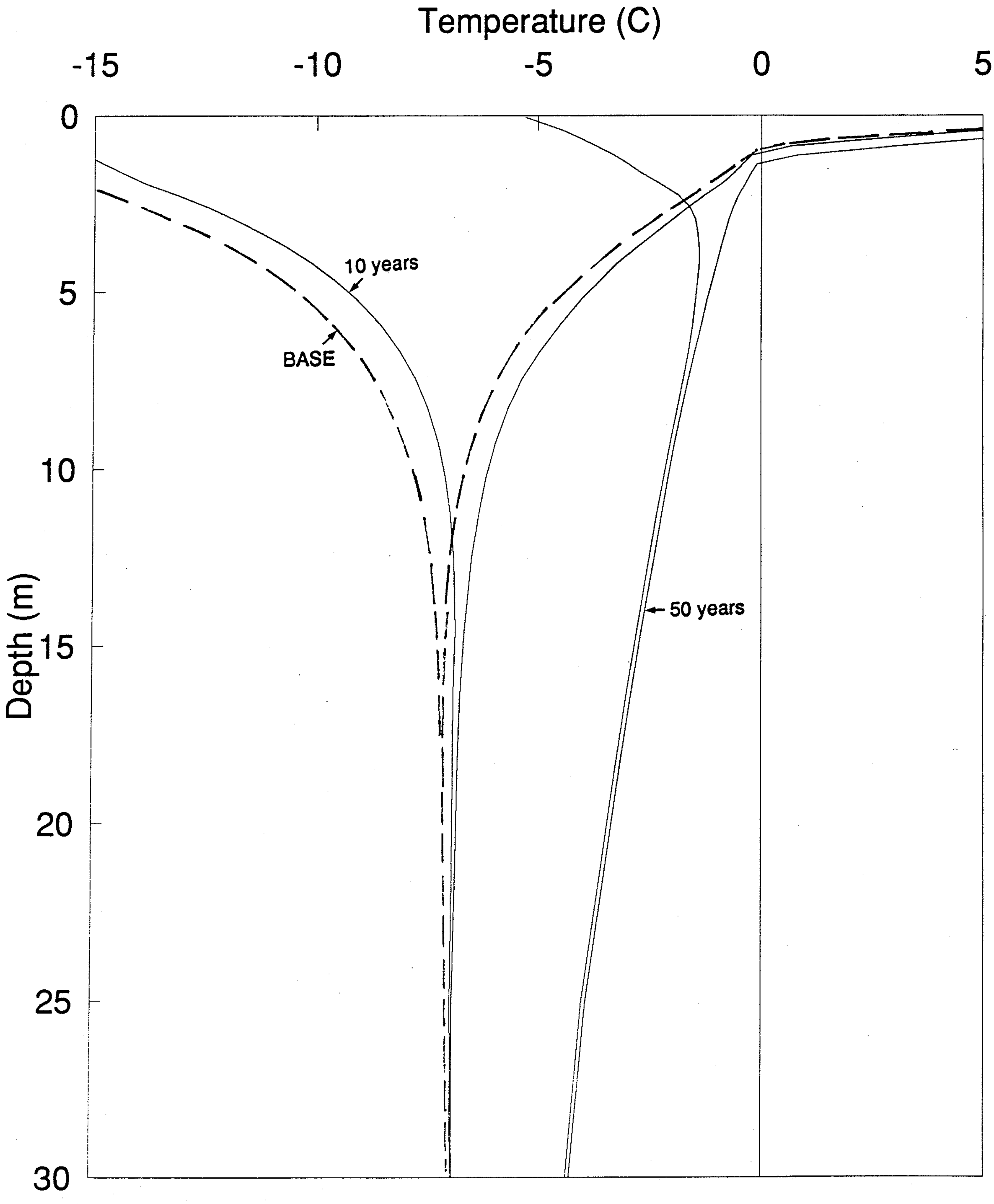


PLATE B.17

Thaw Depth vs Time
A.1 Linear Case with Increased Snow Pack (Mackenzie Delta)

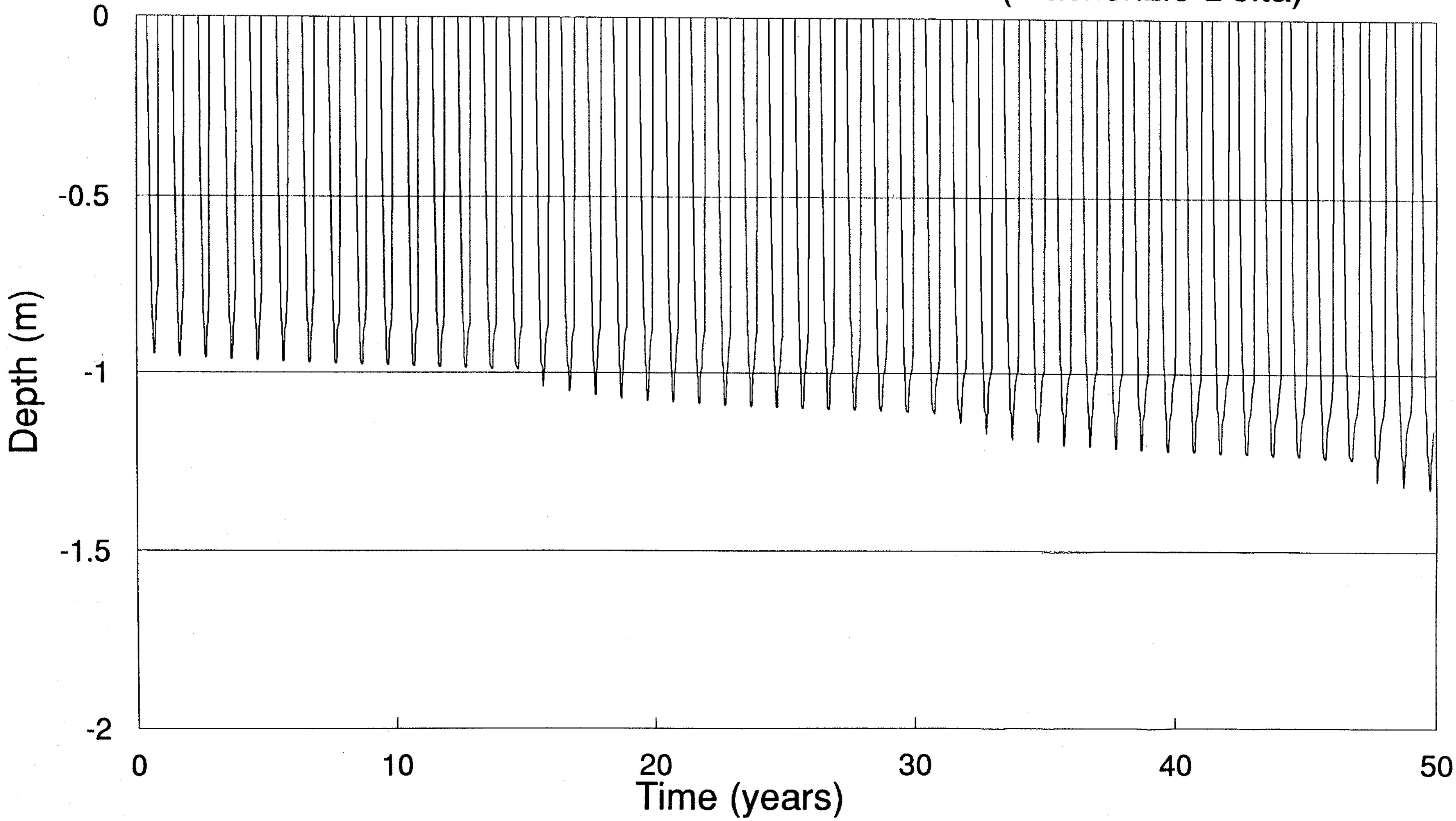


PLATE B.18

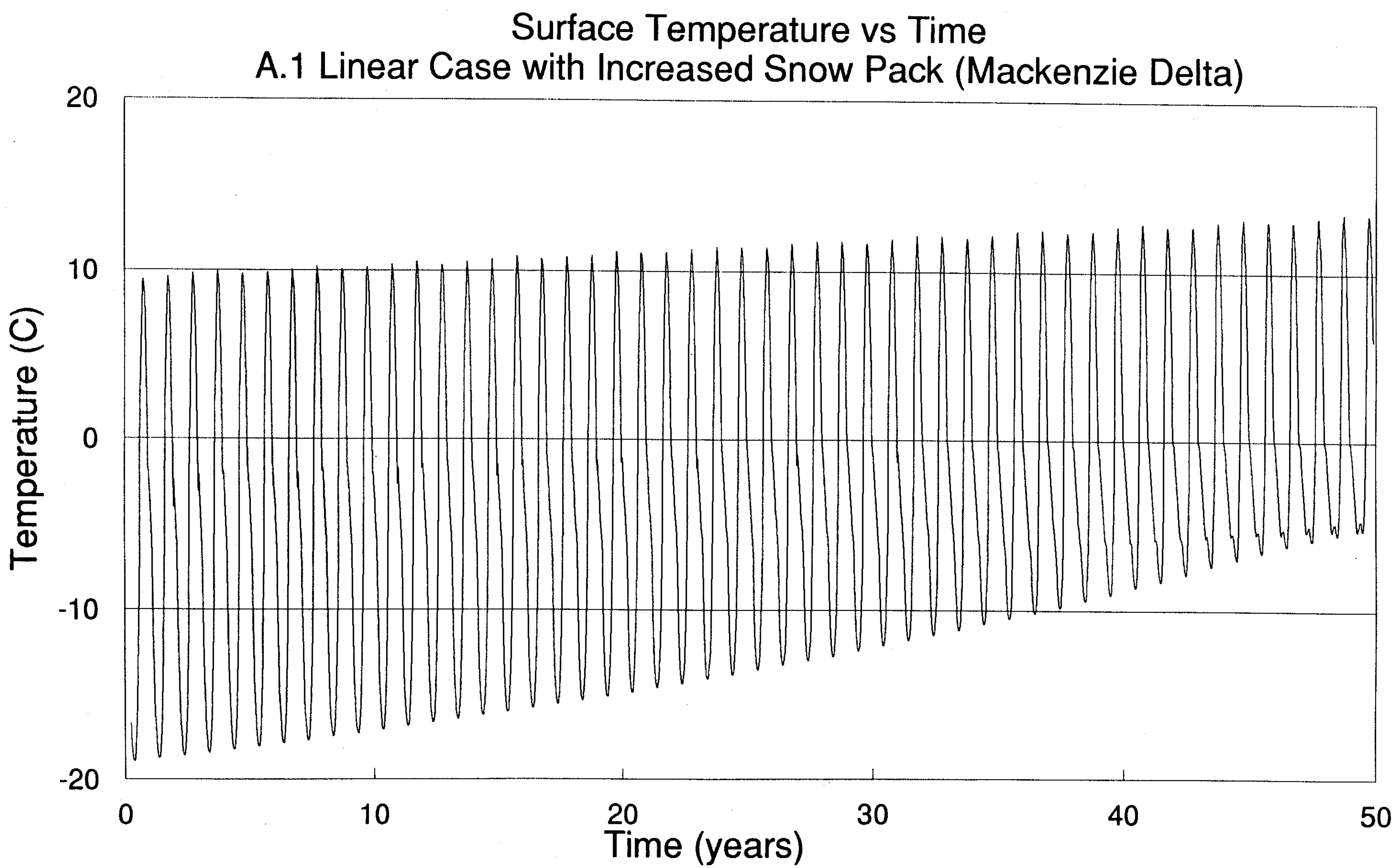

Surface Temperature vs Time
A.1 Linear Case with Increased Snow Pack (Mackenzie Delta)
20
10
0
-10
-20
Temperature (C)
0
10
20
30
40
50
Time (years)

PLATE B.19

Ground Temperature vs Time
A.1 Linear Case with Increased Snow Pack (Mackenzie Delta)

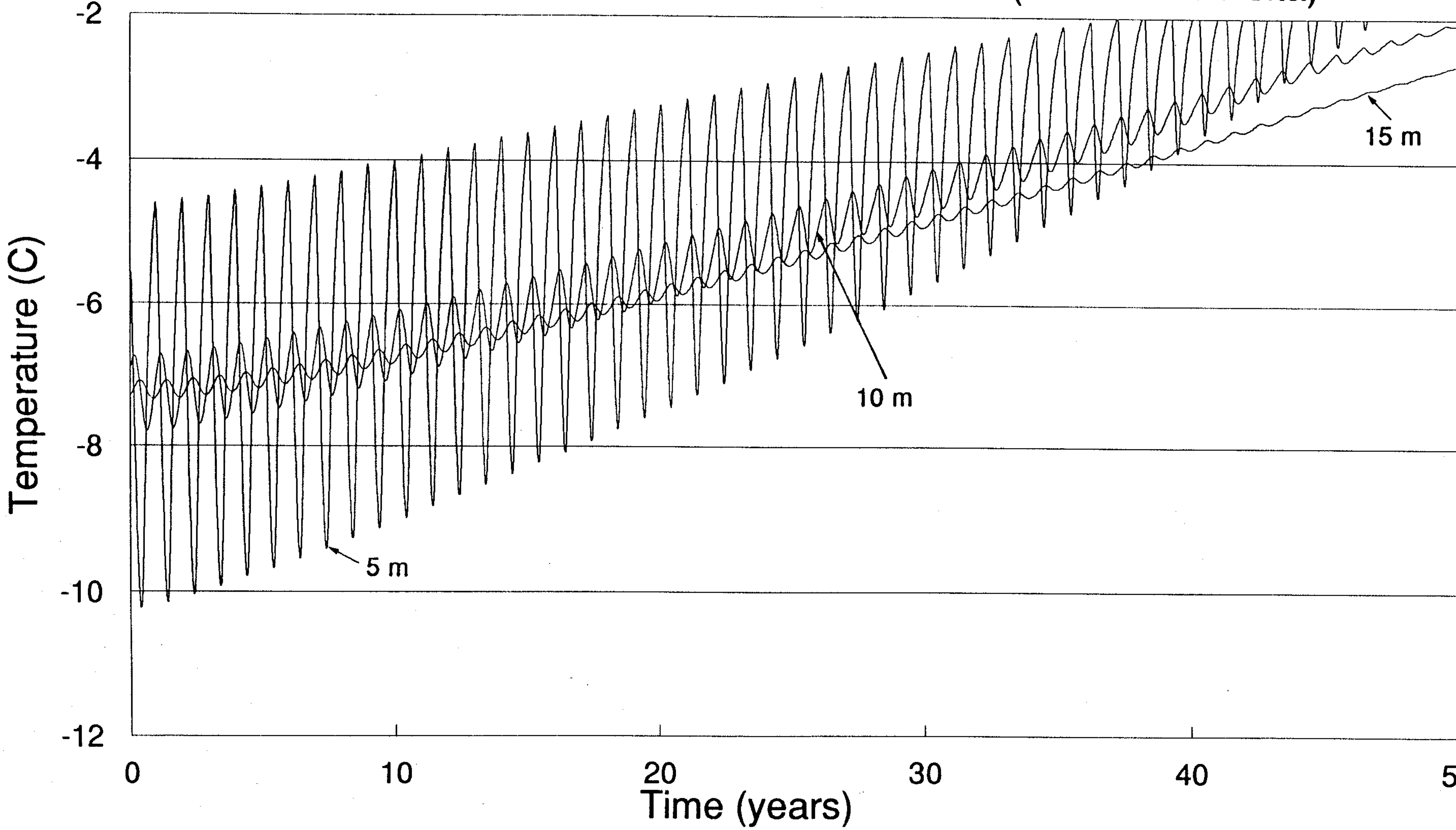
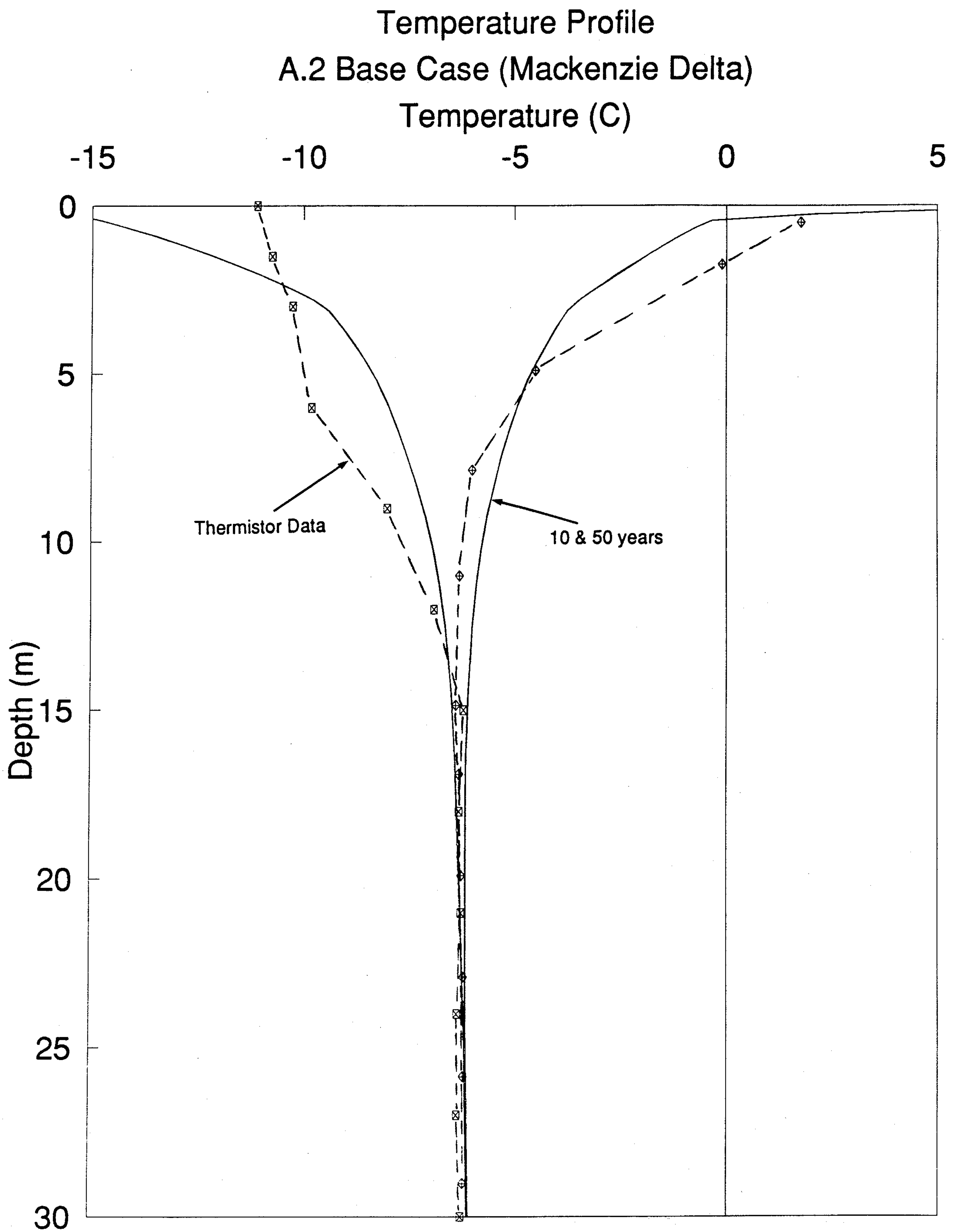


PLATE B.20

SITE A.2 - MACKENZIE DELTA

Low-Ice Content Glaciofluvial Deposit



Temperature Profile
A.2 Base Case (Mackenzie Delta)
Temperature (C)
-15
-10
-5
0
5
0
5
10
15
20
25
30
Depth (m)
Thermistor Data
10 & 50 years

PLATE B.21

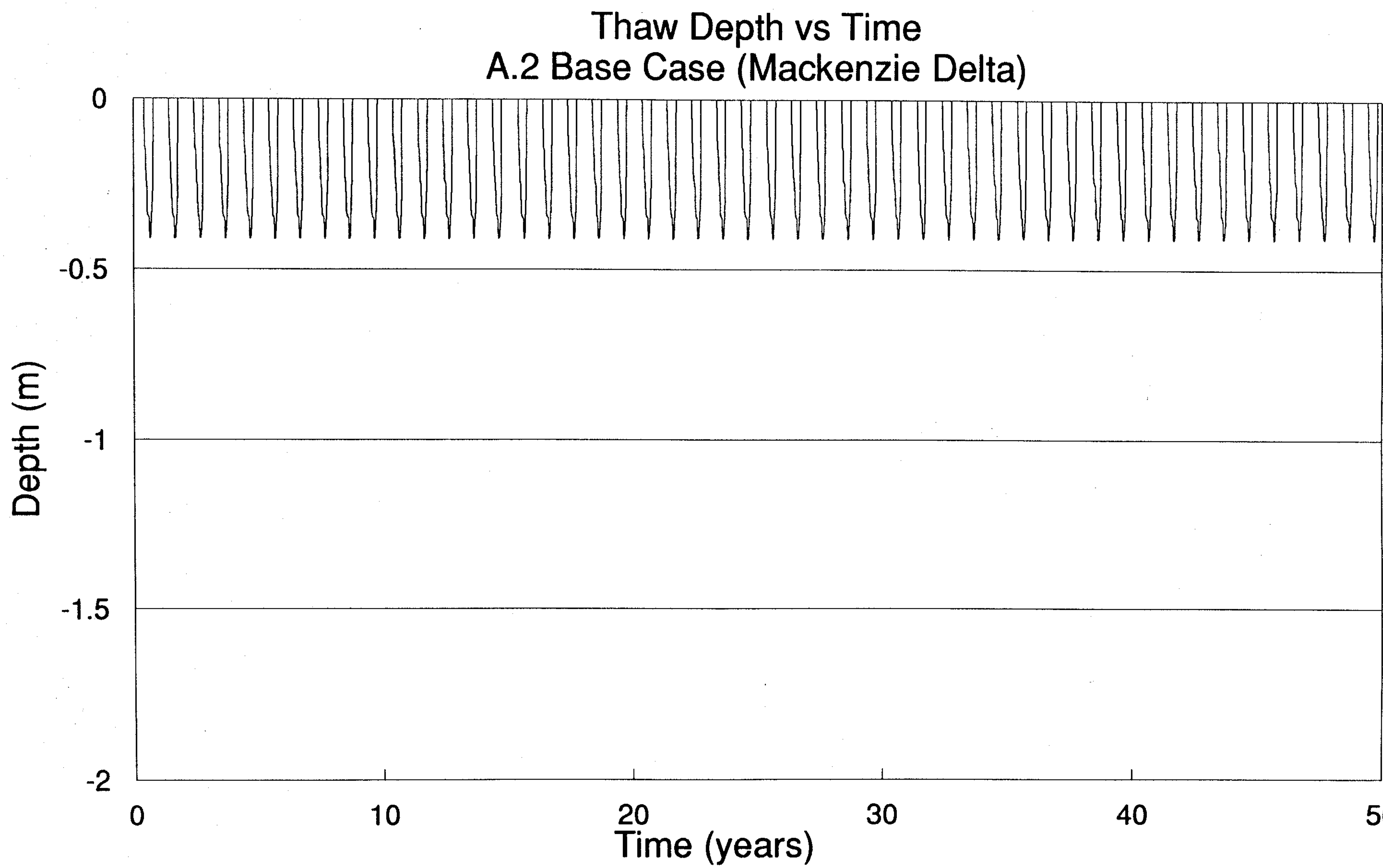

Thaw Depth vs Time
A.2 Base Case (Mackenzie Delta)
0
-0.5
-1
-1.5
-2
Depth (m)
0
10
20
30
40
50
Time (years)

PLATE B.22

Surface Temperature vs Time
A.2 Base Case (Mackenzie Delta)

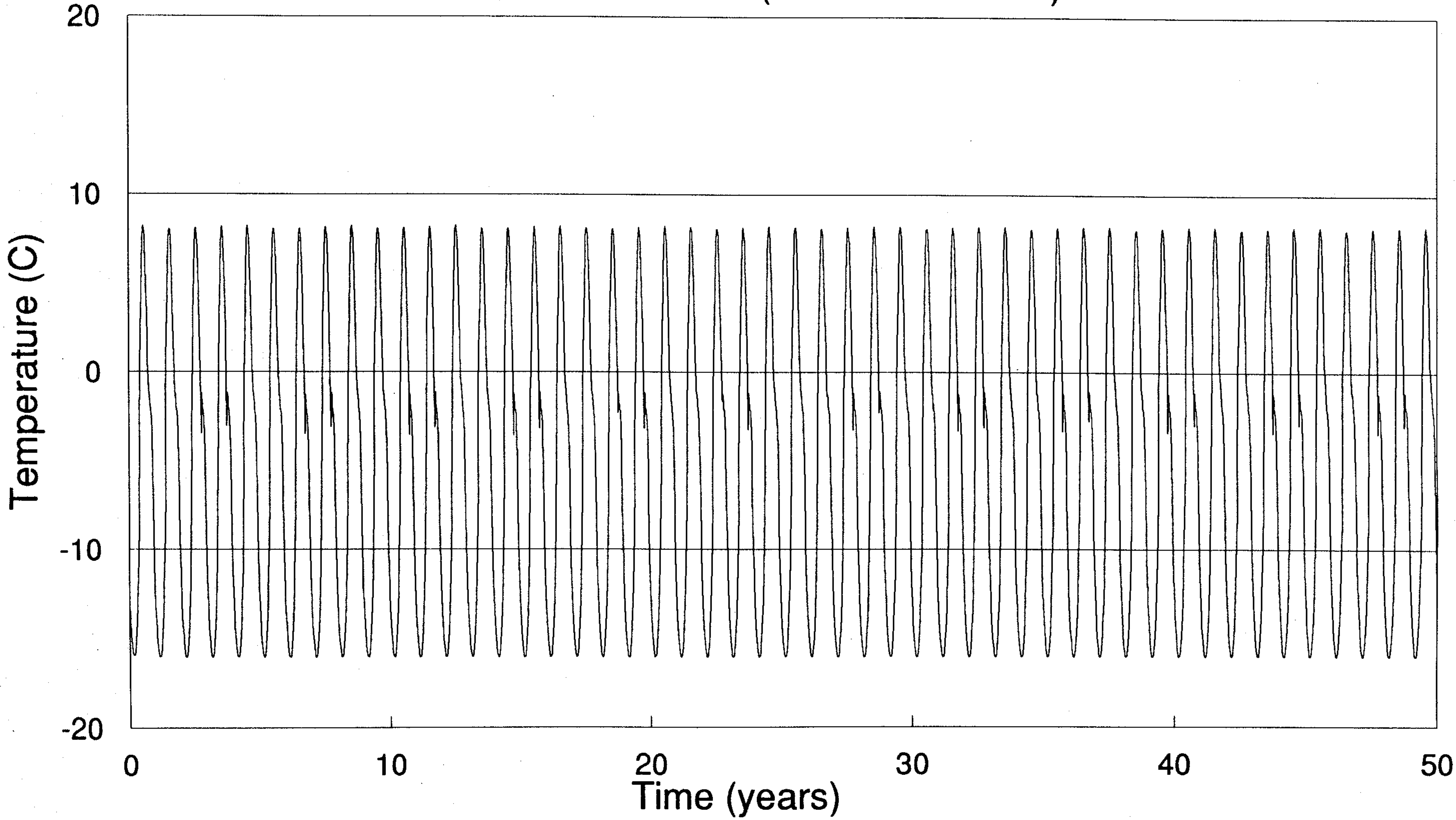


PLATE B.23

Ground Temperature vs Time
A.2 Base Case (Mackenzie Delta)

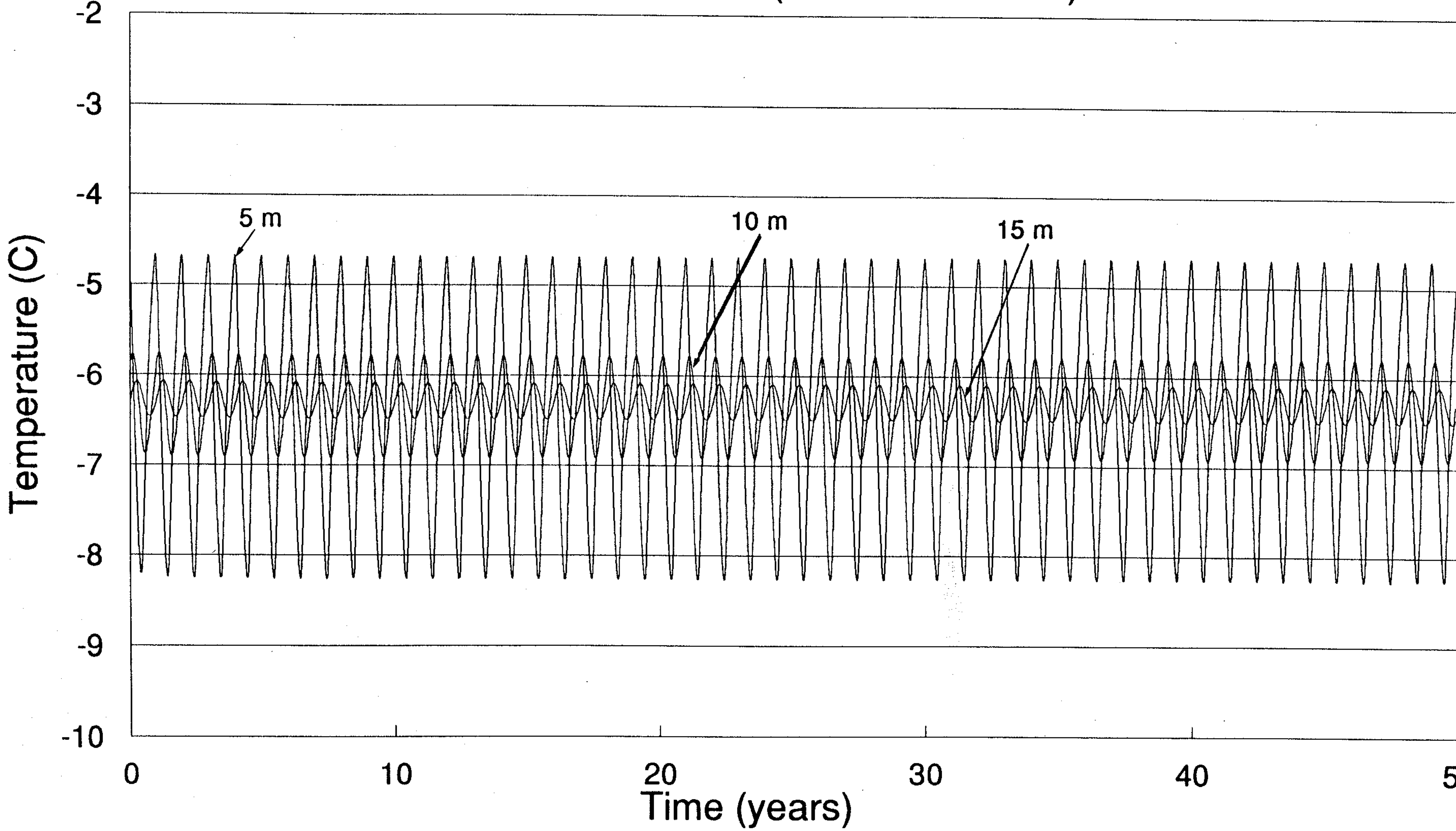


PLATE B.24

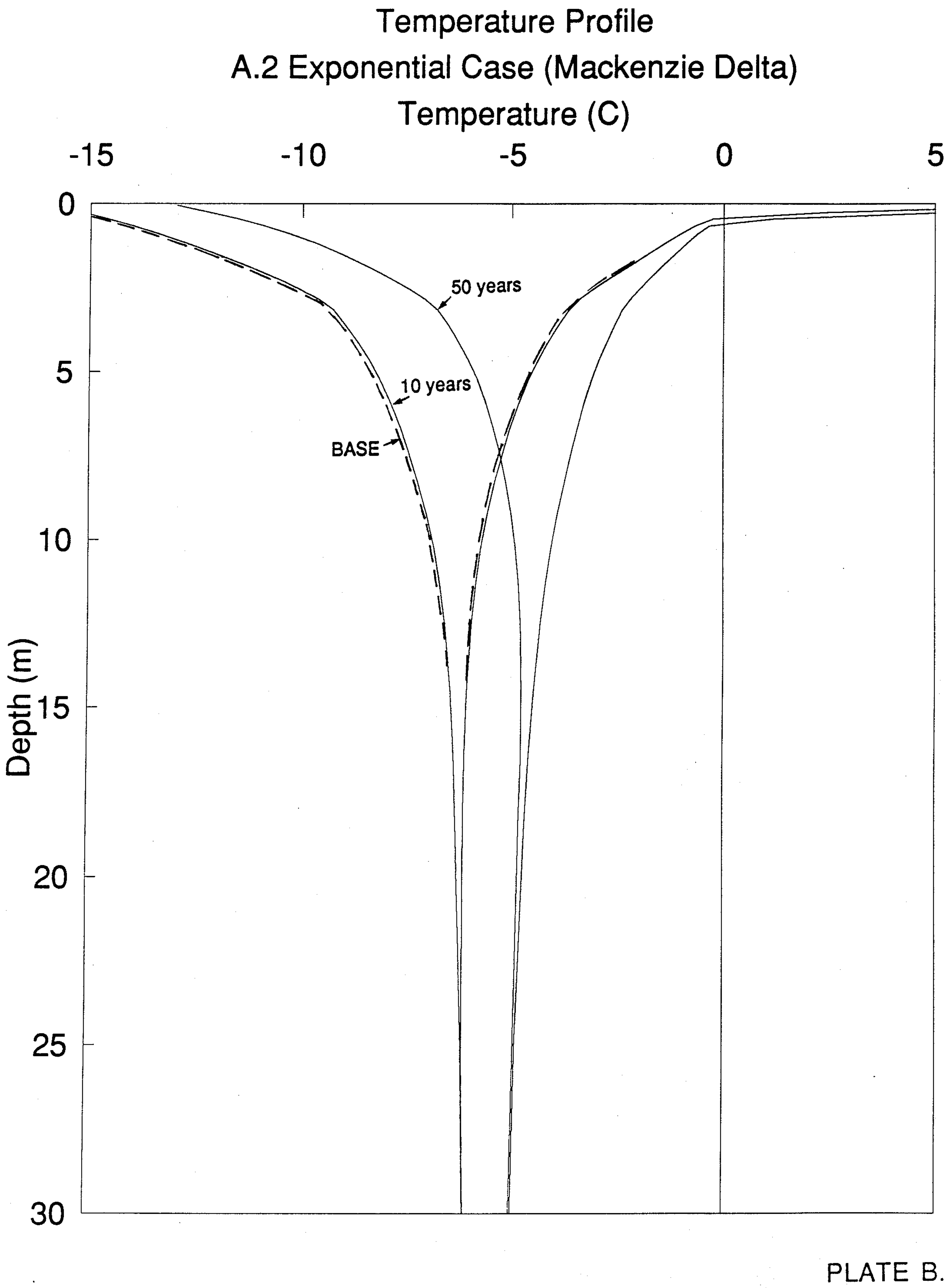
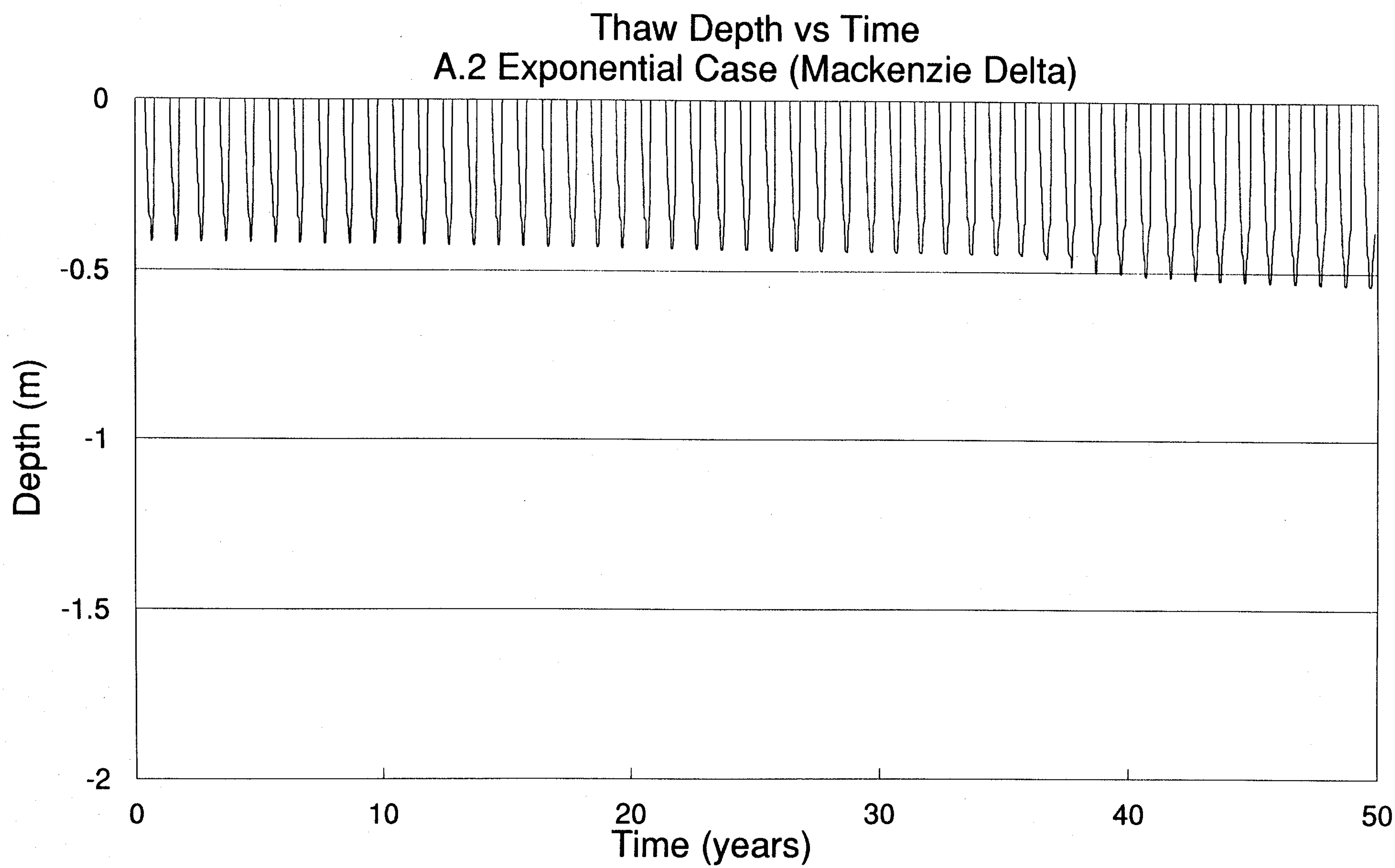

Temperature Profile
A.2 Exponential Case (Mackenzie Delta)
Temperature (C)
-15
-10
-5
0
5
0
5
10
15
20
25
30
Depth (m)
50 years
10 years
BASE

PLATE B.25



Thaw Depth vs Time
A.2 Exponential Case (Mackenzie Delta)
0
-0.5
-1
-1.5
-2
Depth (m)
0
10
20
30
40
50
Time (years)

PLATE B.26

Surface Temperature vs Time
A.2 Exponential Case (Mackenzie Delta)

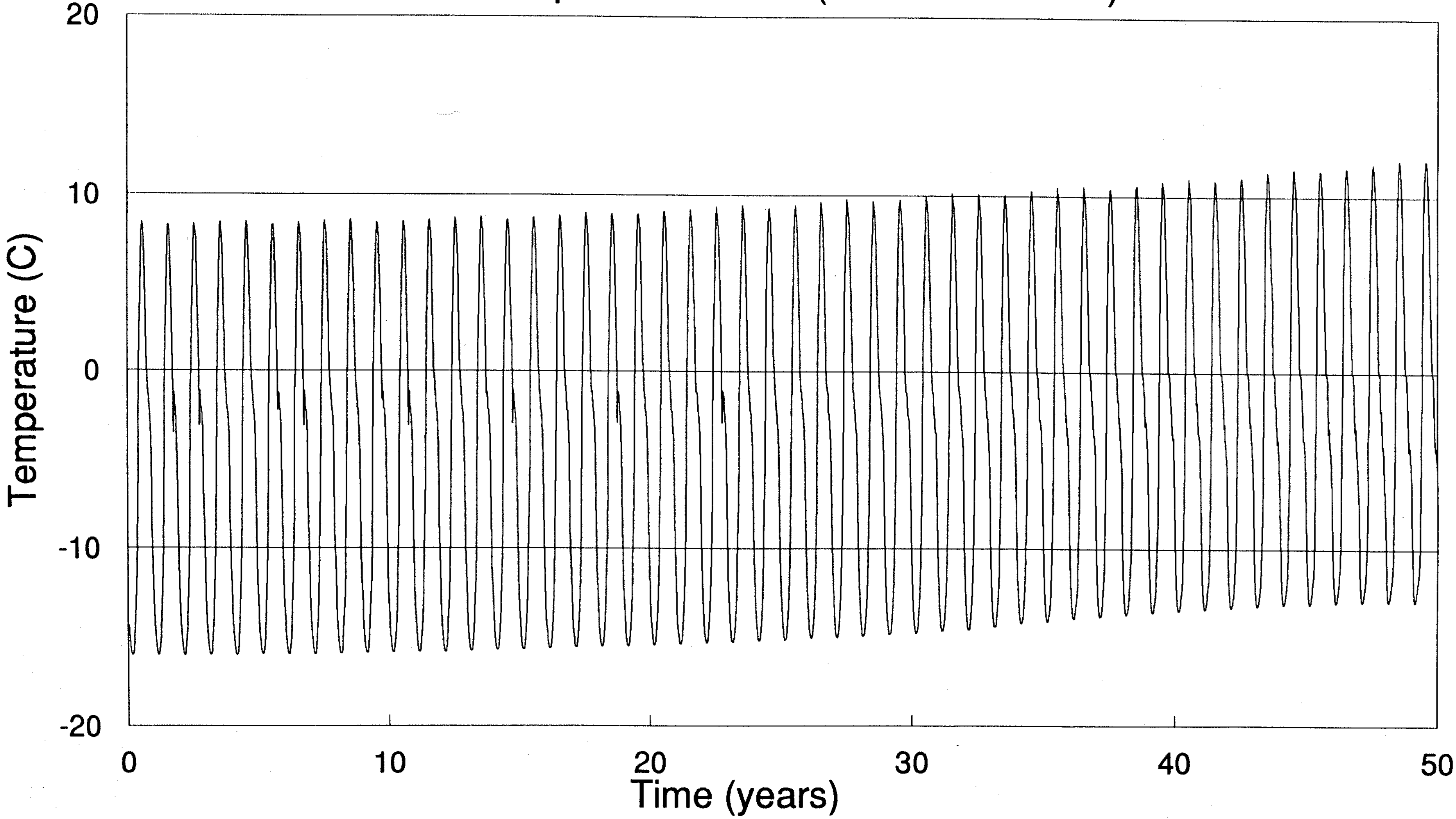


PLATE B.27

Ground Temperature vs Time
A.2 Exponential Case (Mackenzie Delta)

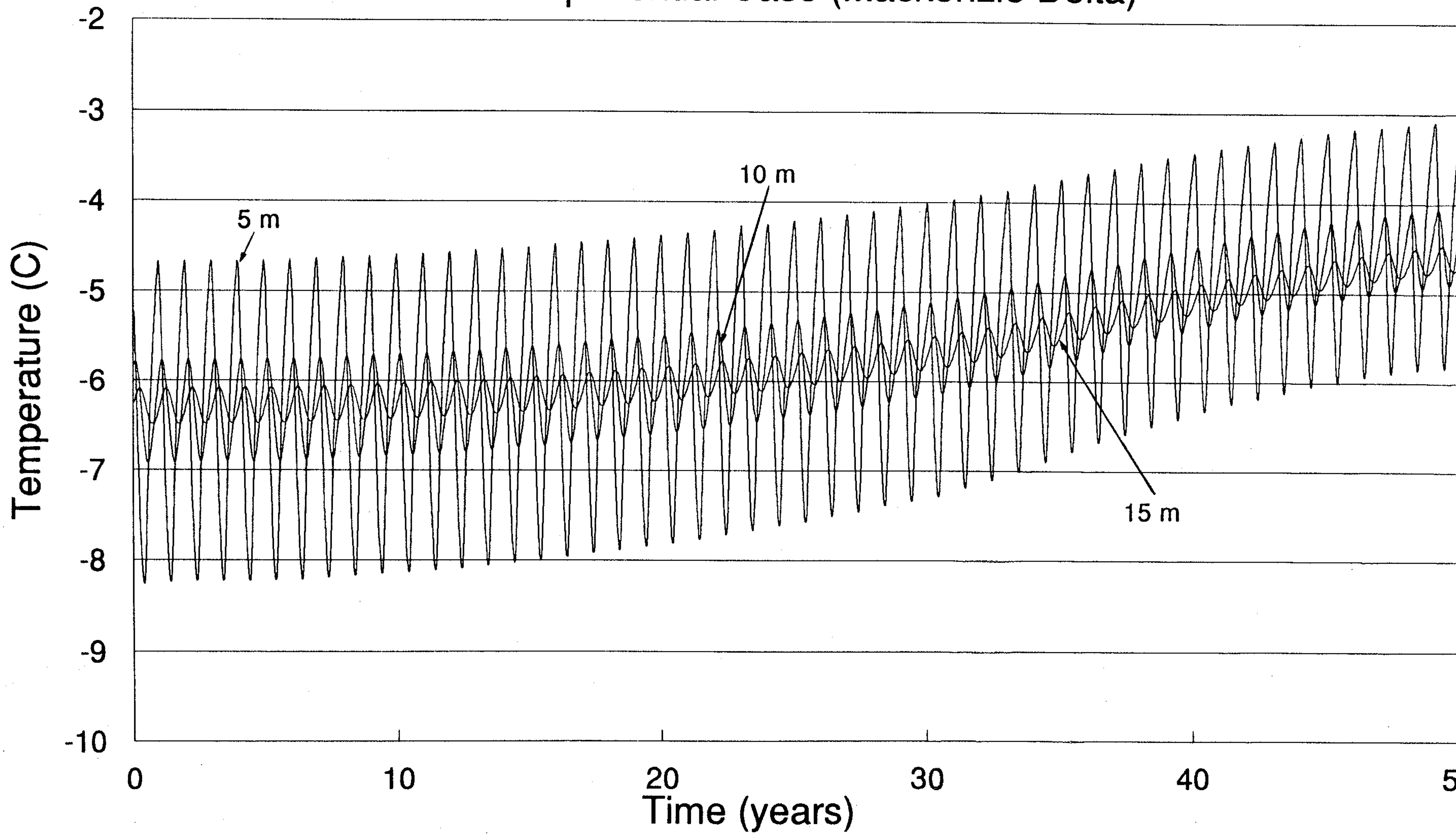


PLATE B.28

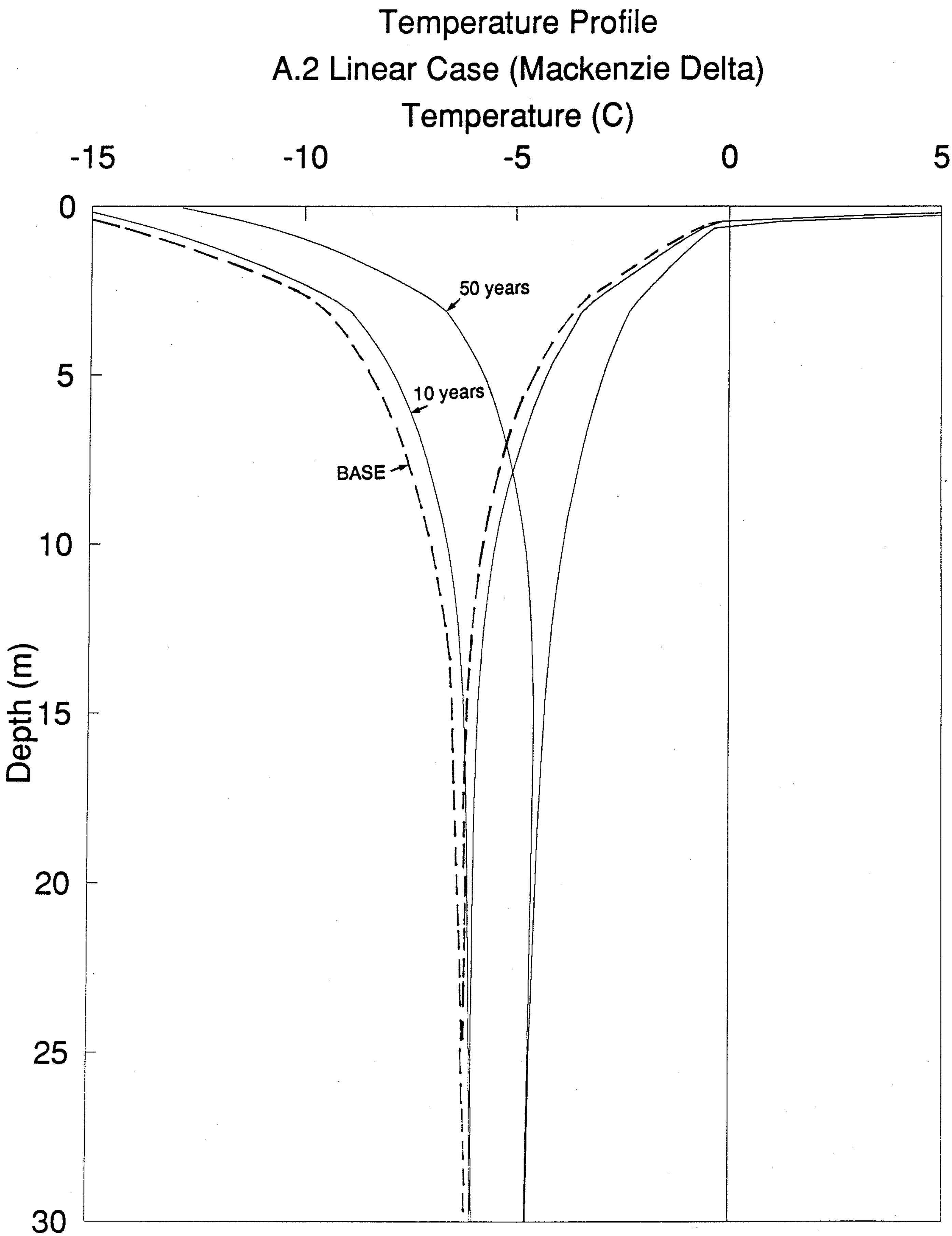

Temperature Profile
A.2 Linear Case (Mackenzie Delta)
Temperature (C)
-15
-10
-5
0
5
0
5
10
15
20
25
30
Depth (m)
50 years
10 years
BASE

PLATE B.29

Thaw Depth vs Time
A.2 Linear Case (Mackenzie Delta)

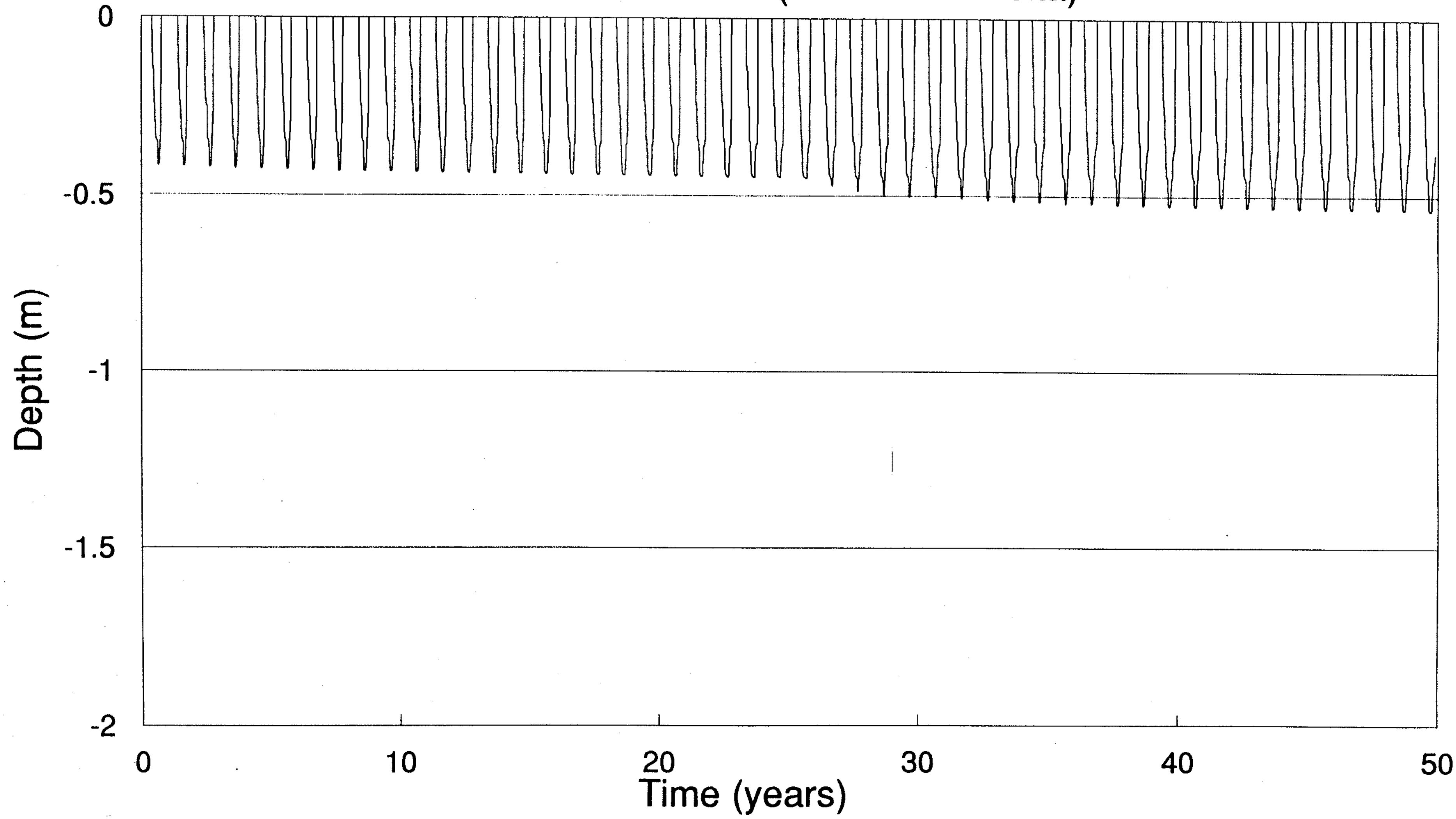


PLATE B.30

Surface Temperature vs Time
A.2 Linear Case (Mackenzie Delta)

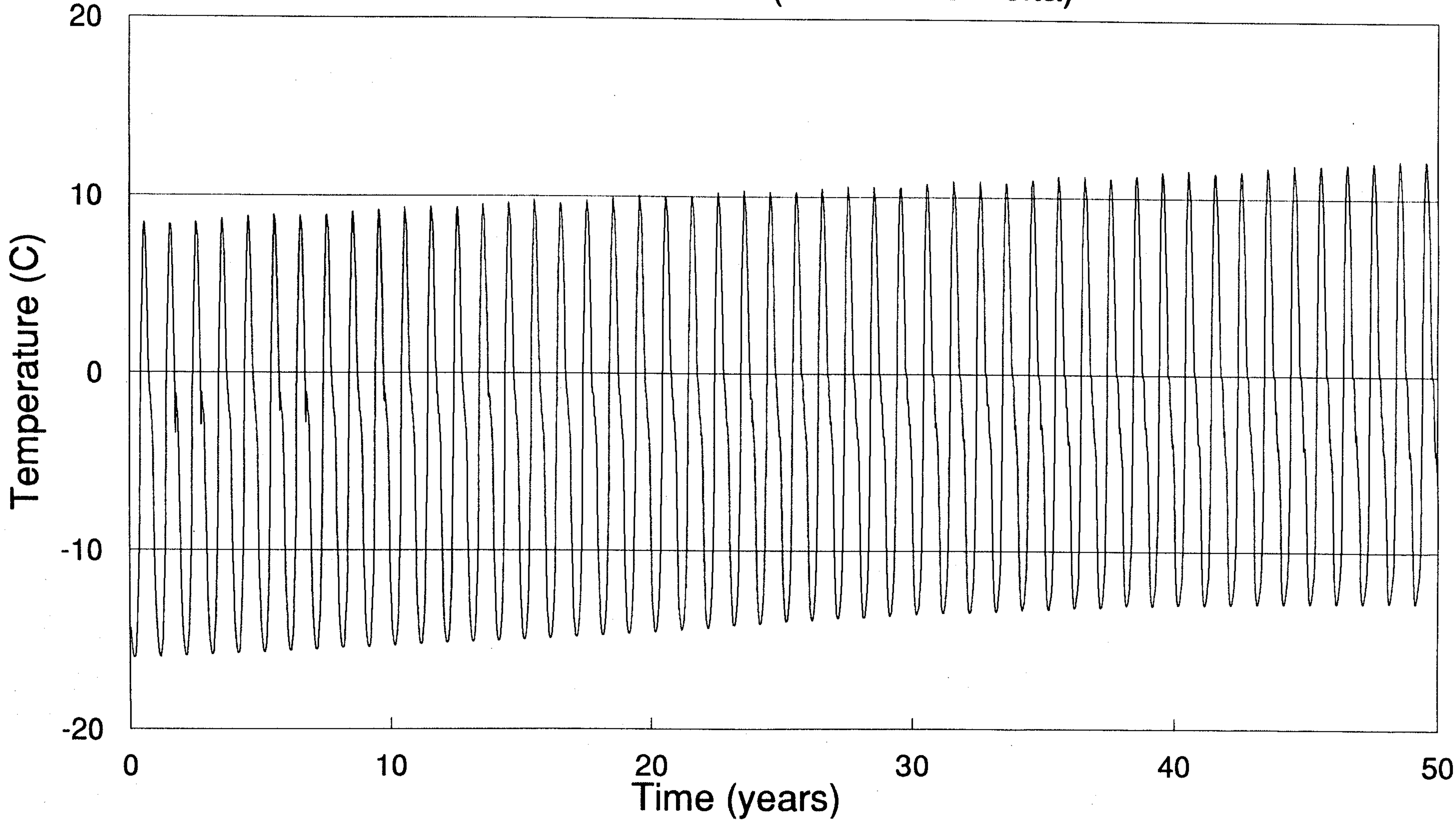


PLATE B.31

Ground Temperature vs Time
A.2 Linear Case (Mackenzie Delta)

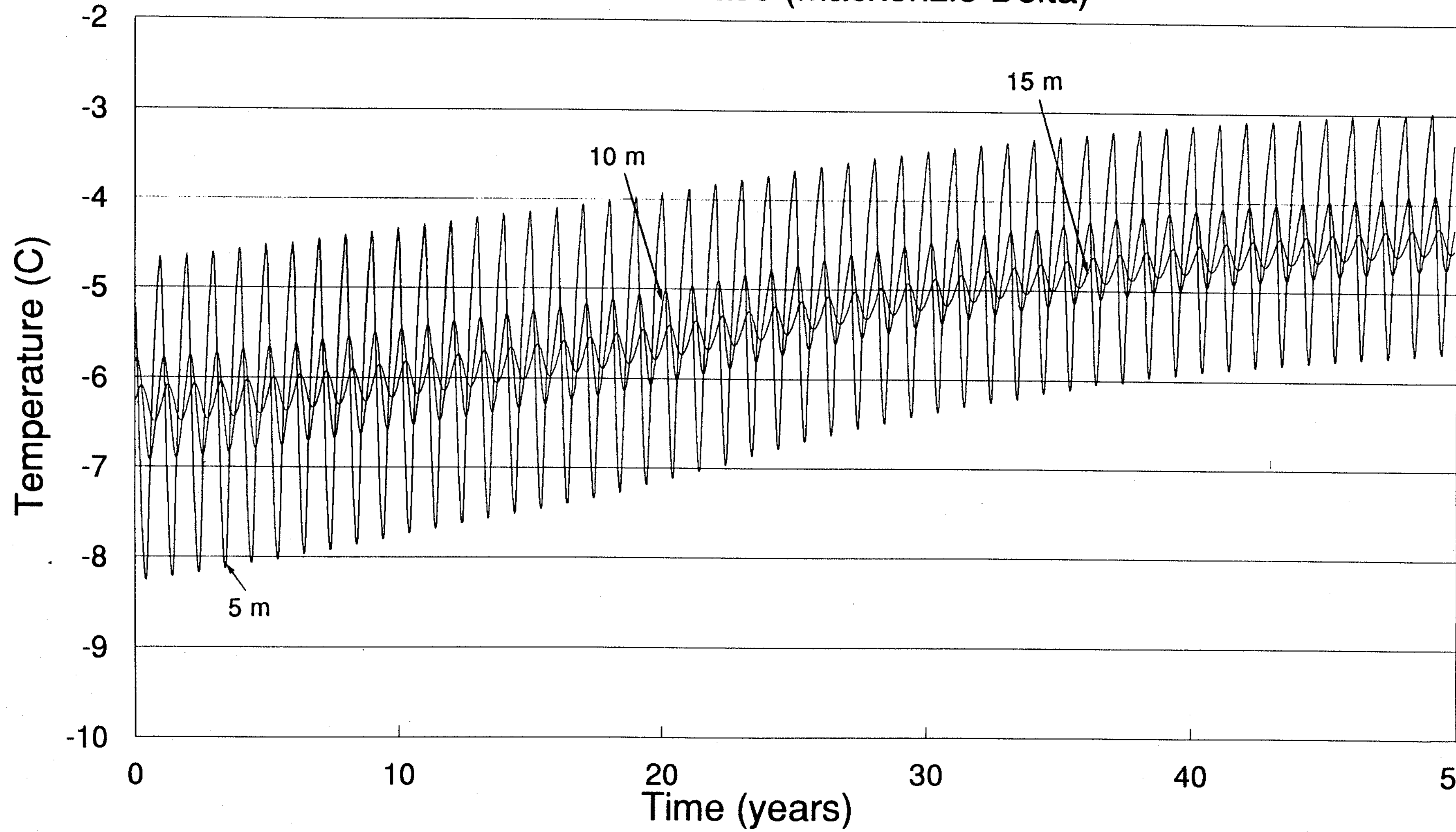


PLATE B.32

Temperature Profile
A.2 Step Case (Mackenzie Delta)

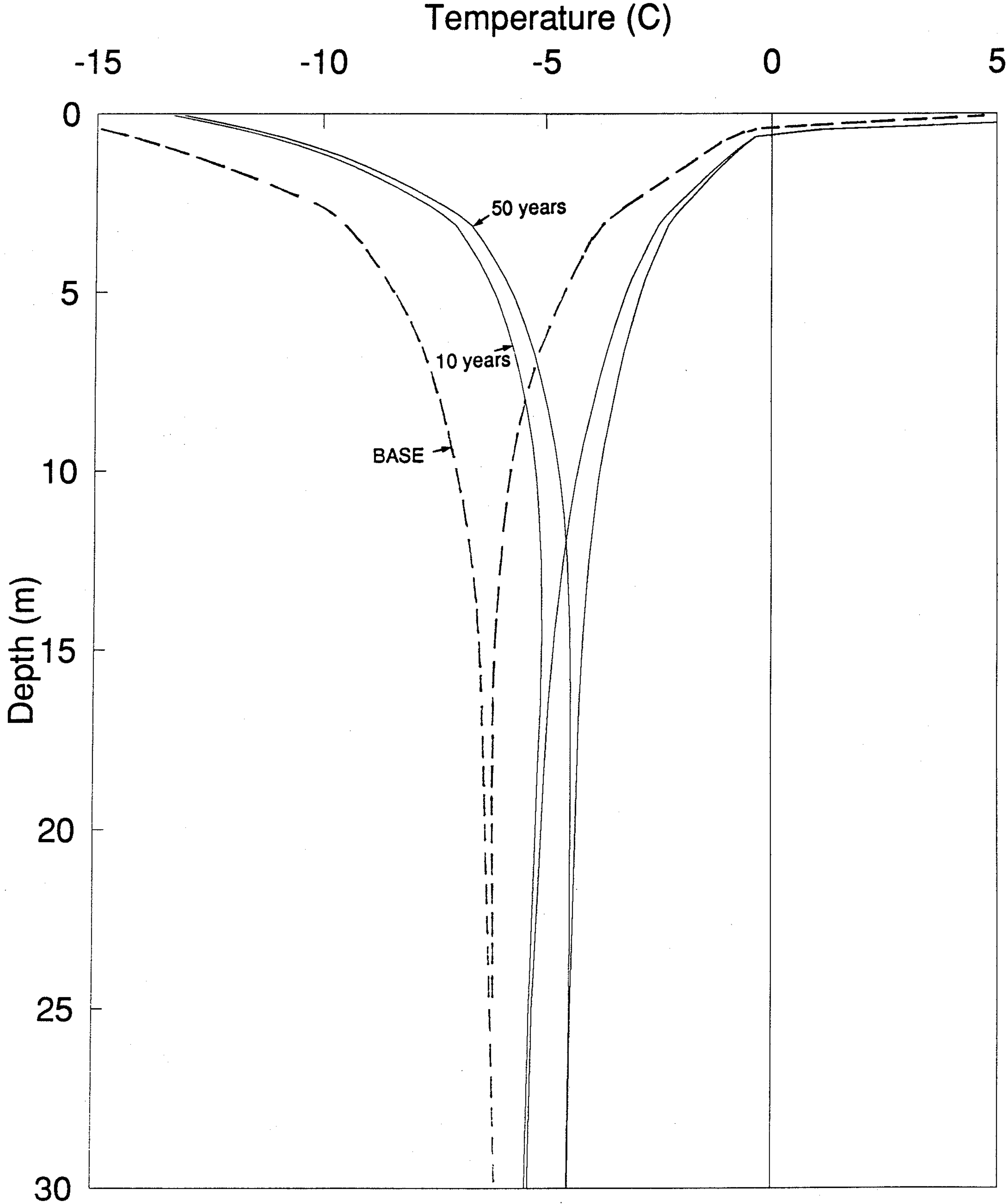


PLATE B.33

Thaw Depth vs Time
A.2 Step Case (Mackenzie Delta)

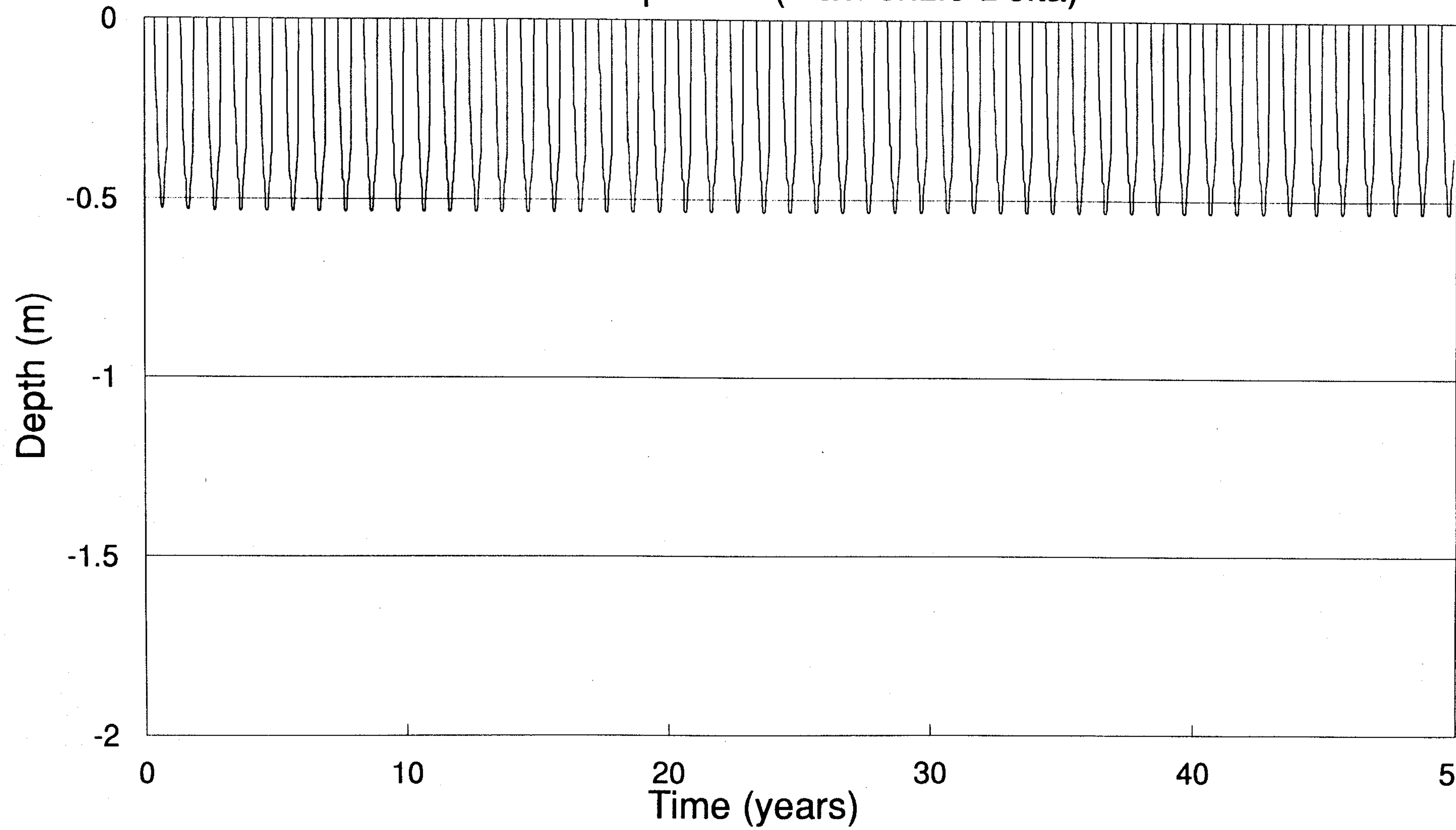


PLATE B.34

Surface Temperature vs Time
A.2 Step Case (Mackenzie Delta)

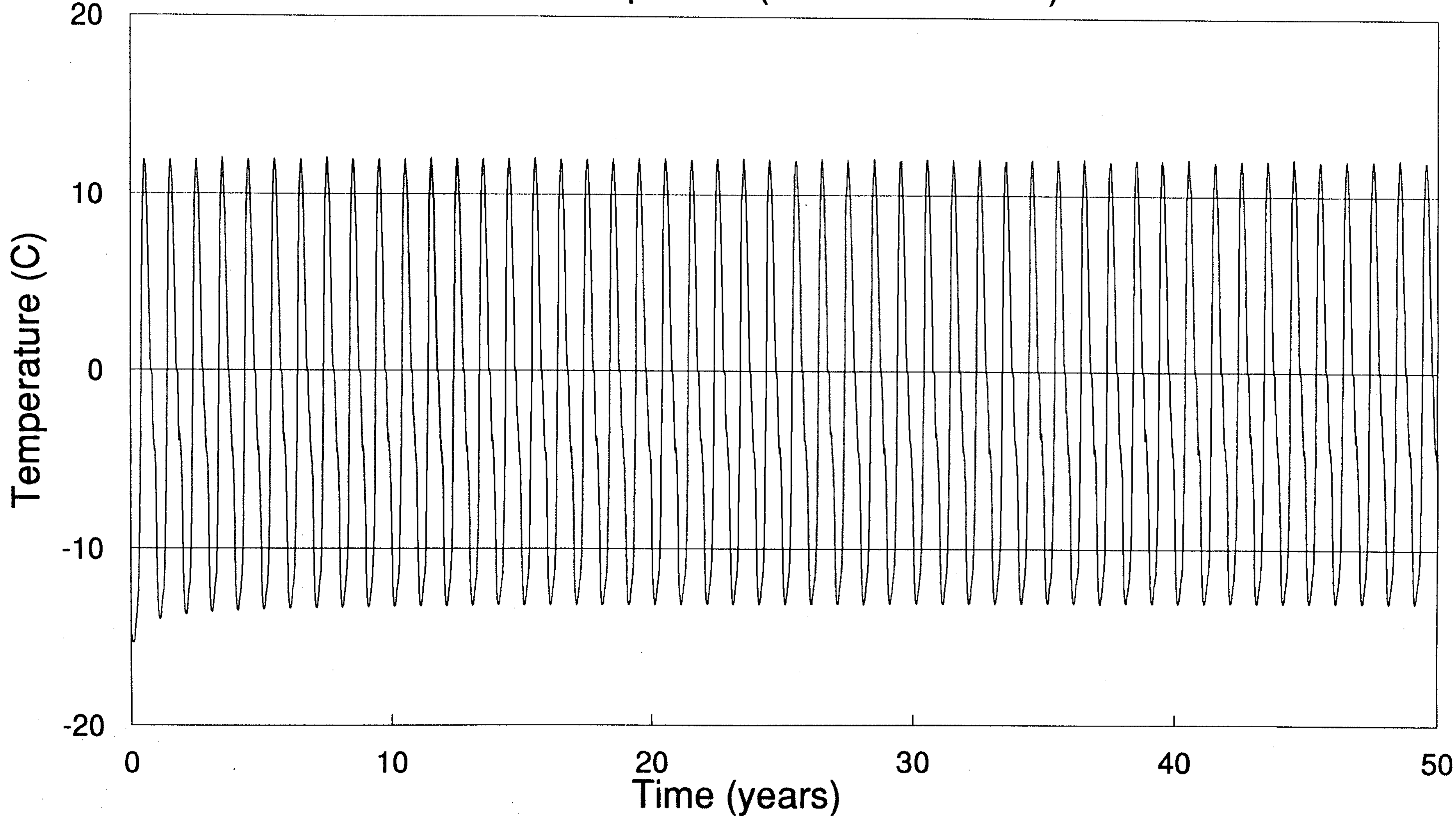


PLATE B.35

Ground Temperature vs Time
A.2 Step Case (Mackenzie Delta)

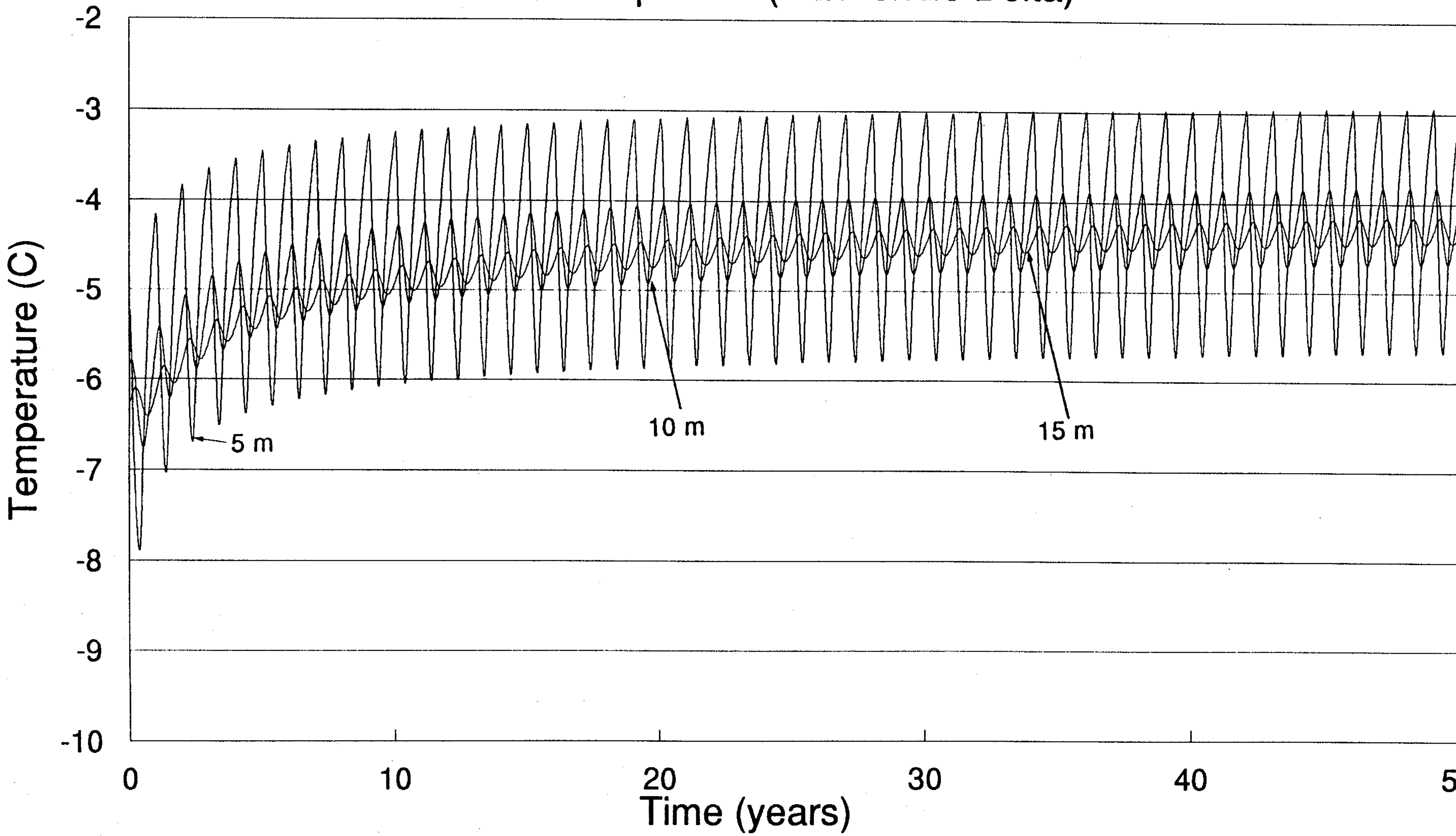


PLATE B.36

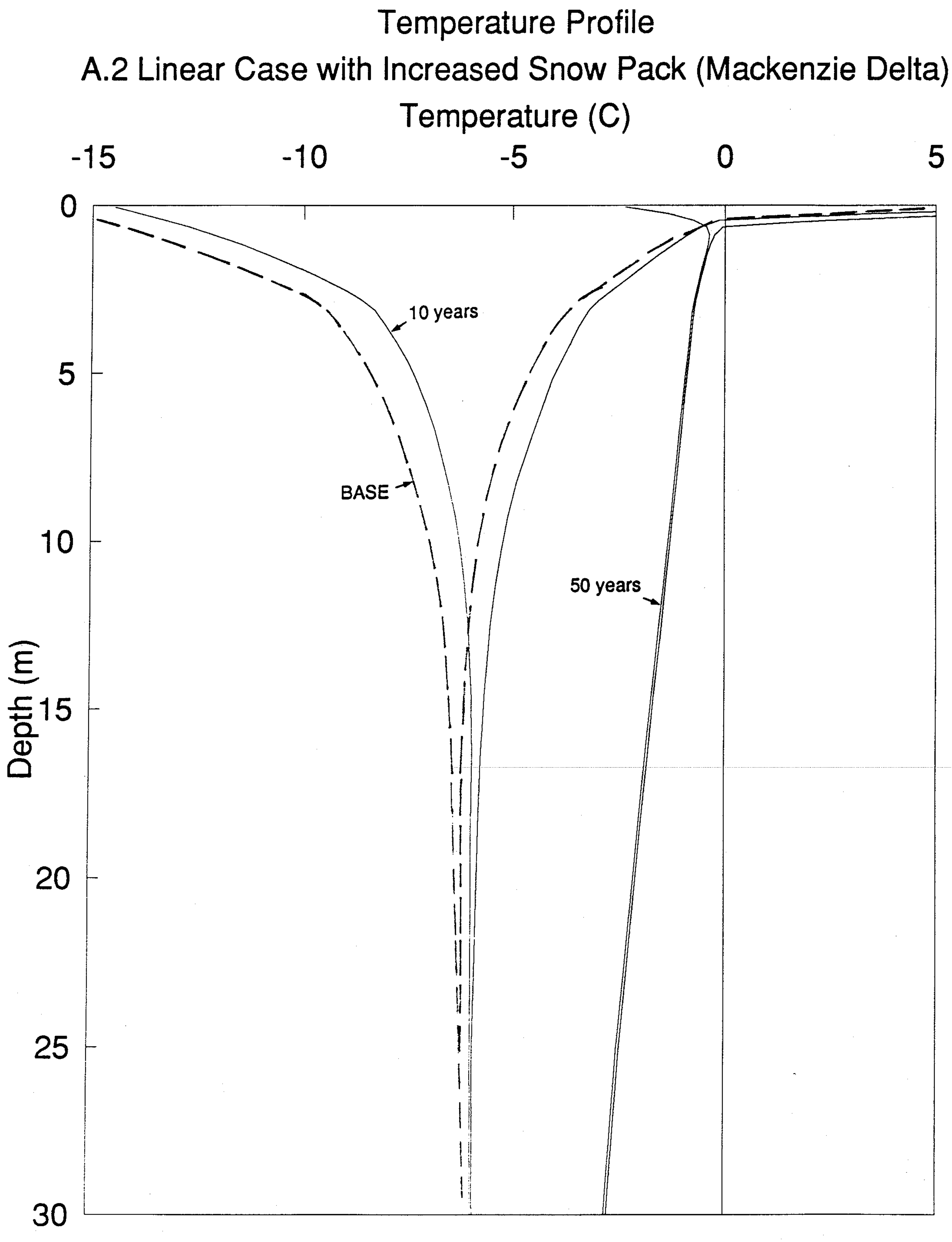
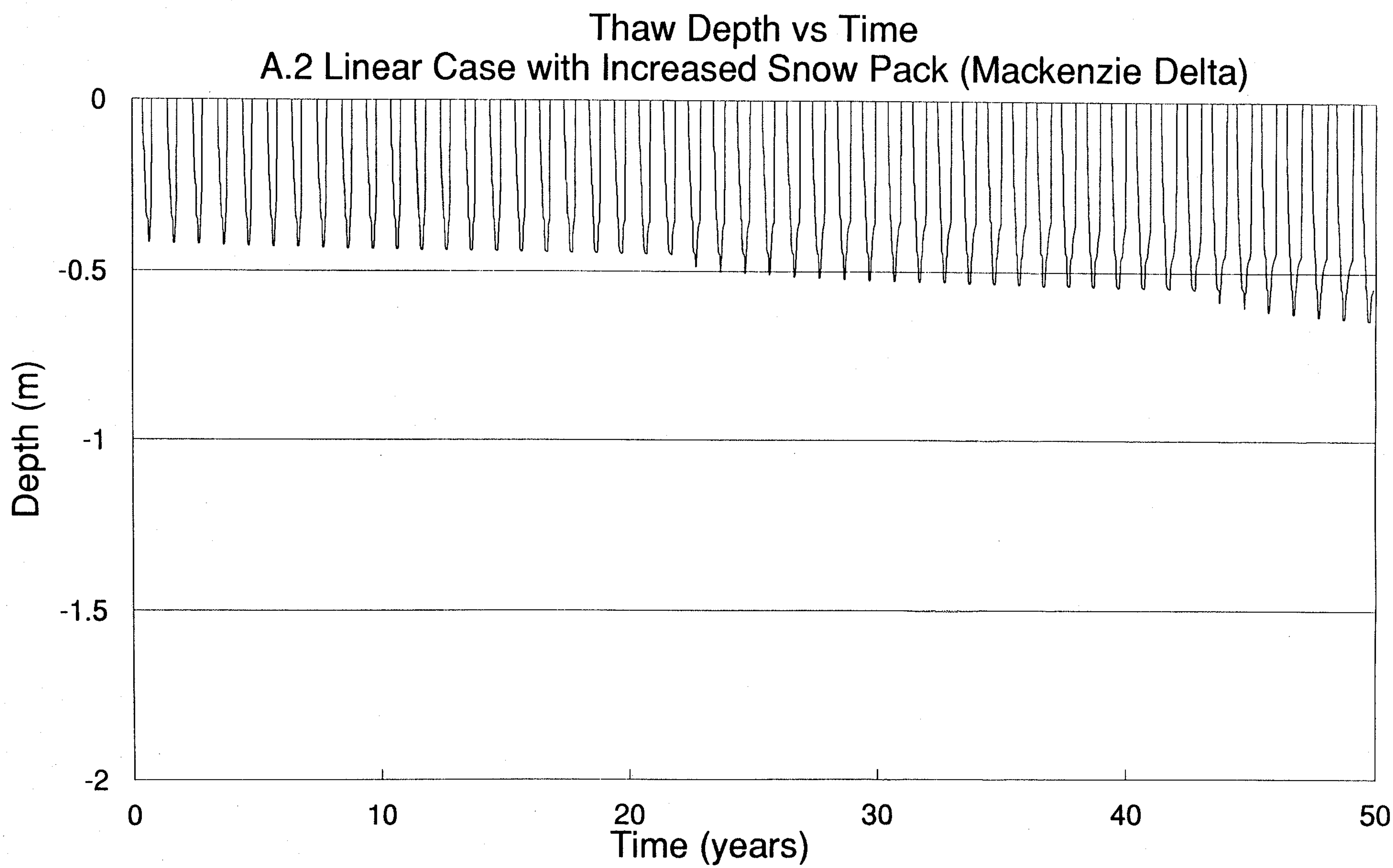

Temperature Profile
A.2 Linear Case with Increased Snow Pack (Mackenzie Delta)
Temperature (C)
-15
-10
-5
0
5
0
5
10
15
20
25
30
Depth (m)
10 years
BASE
50 years

PLATE B.37



Thaw Depth vs Time
A.2 Linear Case with Increased Snow Pack (Mackenzie Delta)
Depth (m)
0
-0.5
-1
-1.5
-2
0
10
20
30
40
50
Time (years)

PLATE B.38

Surface Temperature vs Time
A.2 Linear Case with Increased Snow Pack (Mackenzie Delta)

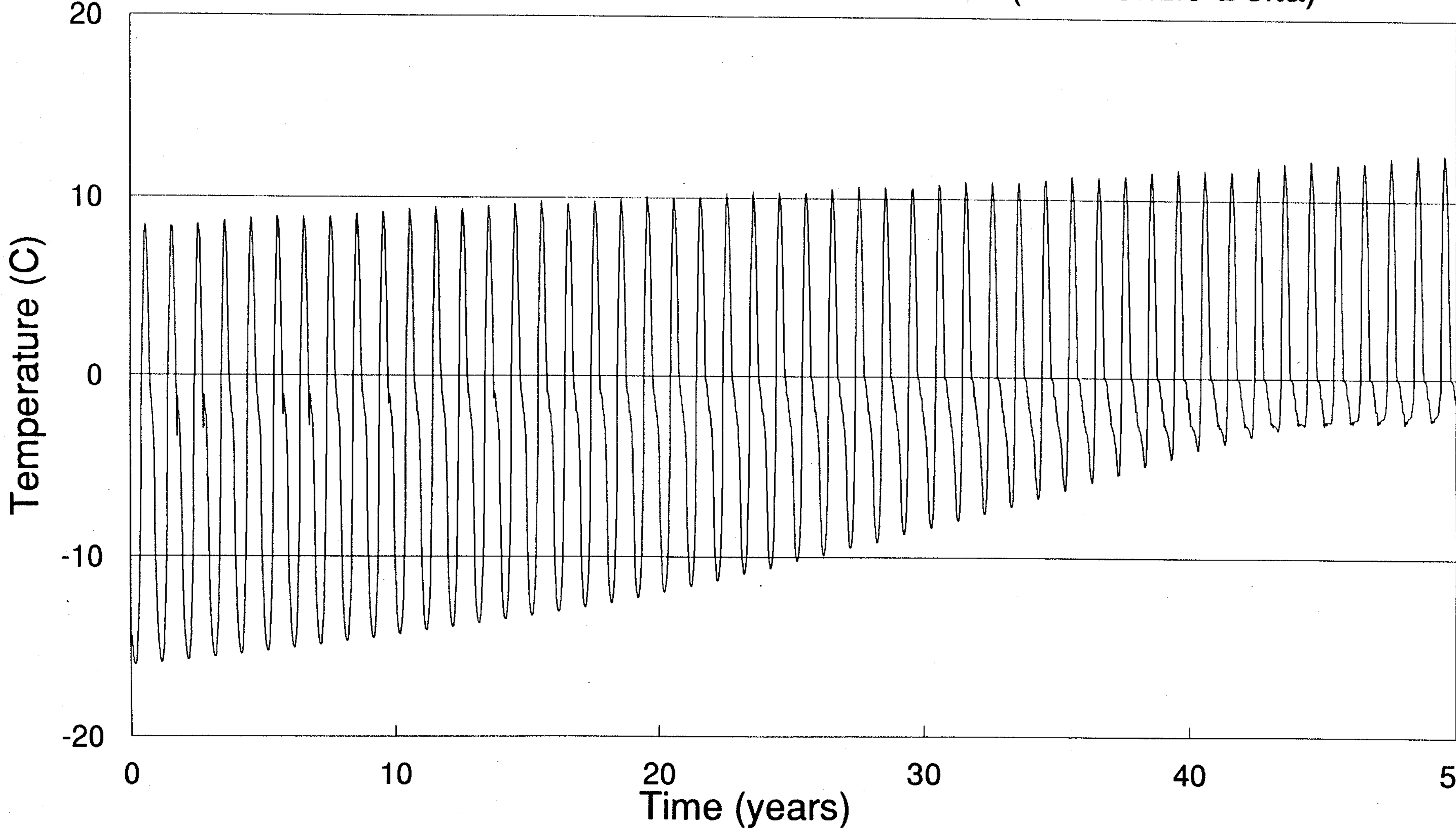


PLATE B.39

Ground Temperature vs Time
A.2 Linear Case with Increased Snow Pack (Mackenzie Delta)

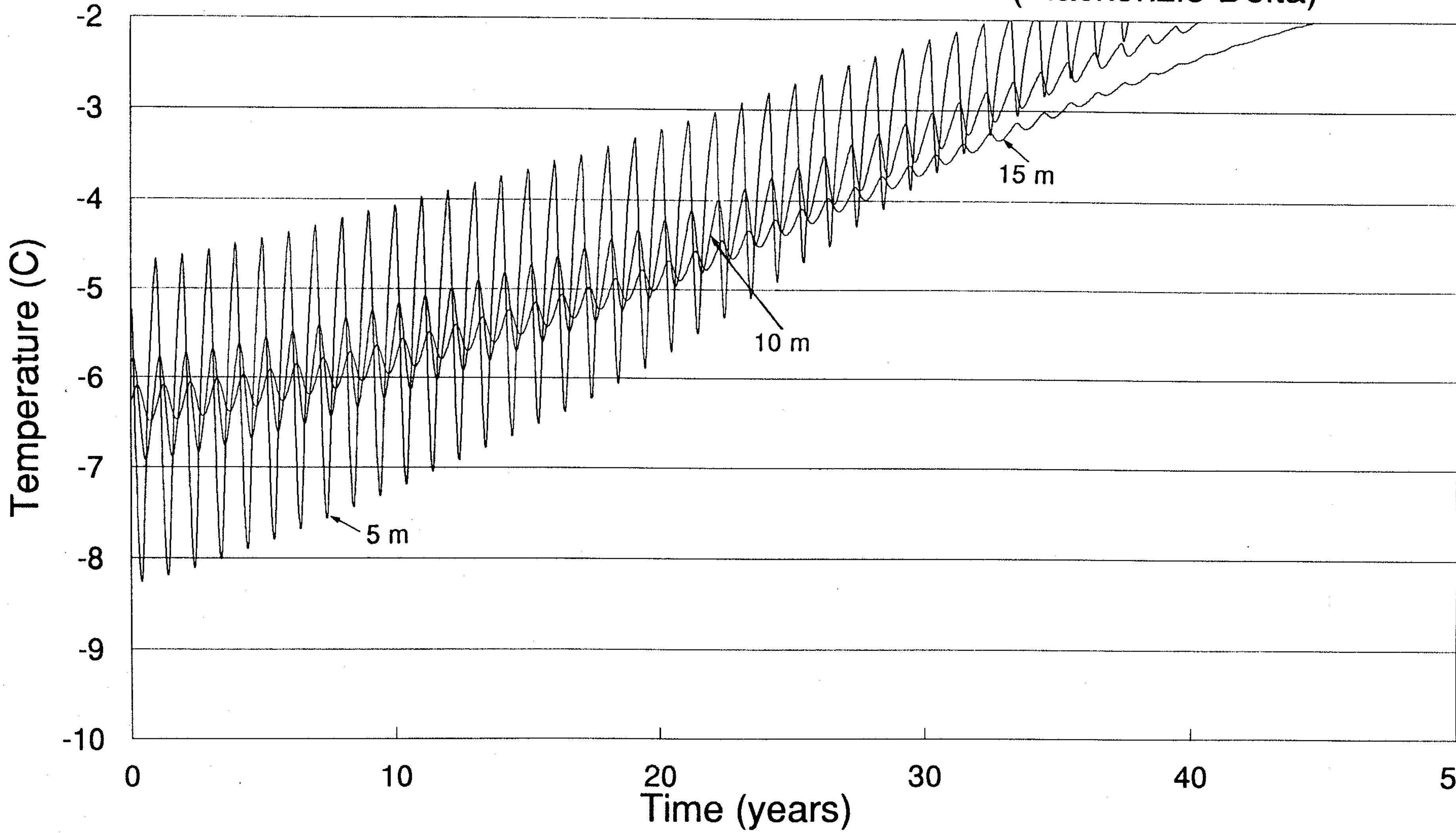
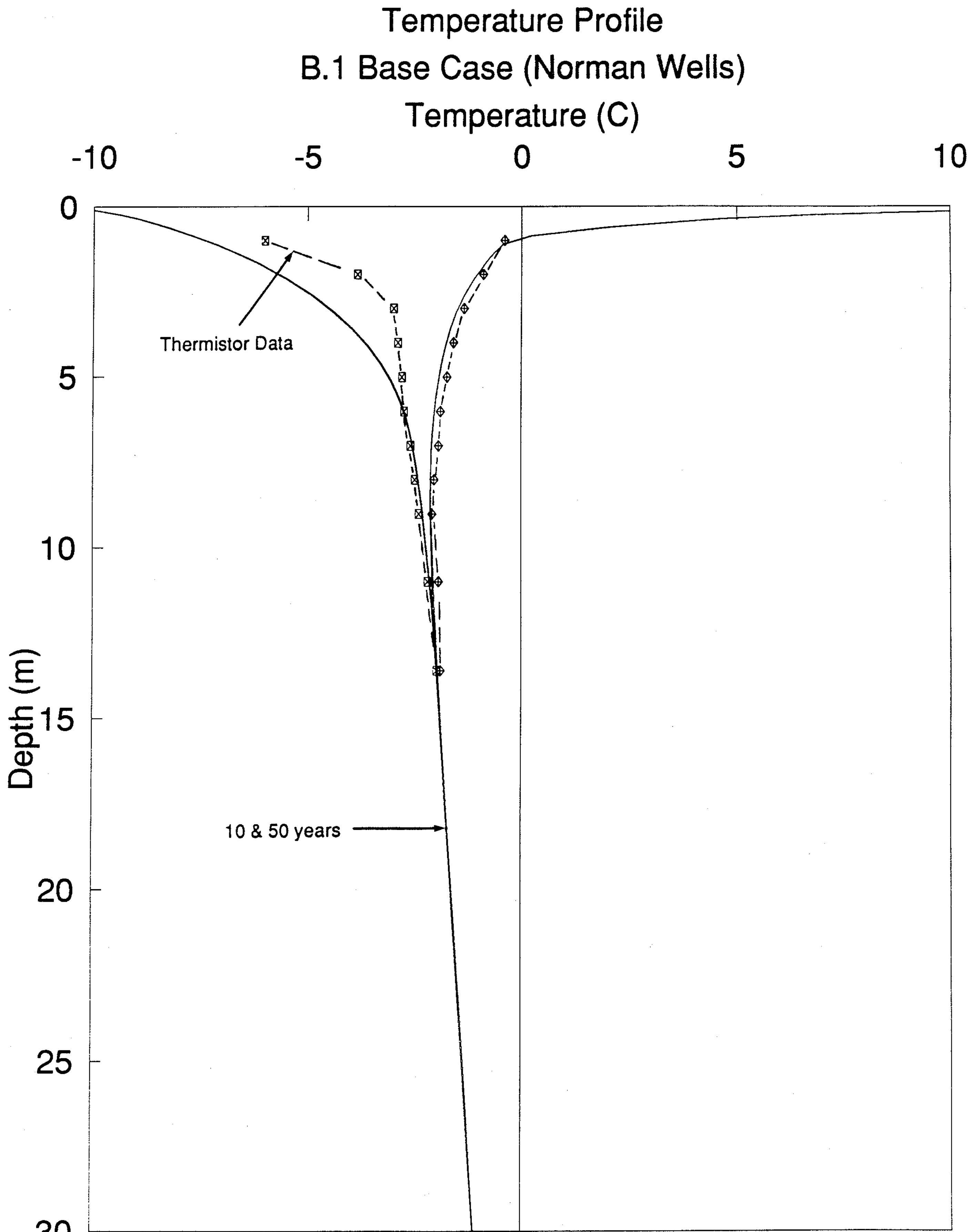


PLATE B.40

SITE B.1 - NORMAN WELLS

Ice-Rich Lacustrine Plain



Temperature Profile
B.1 Base Case (Norman Wells)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
Thermistor Data
10 & 50 years

PLATE B.41

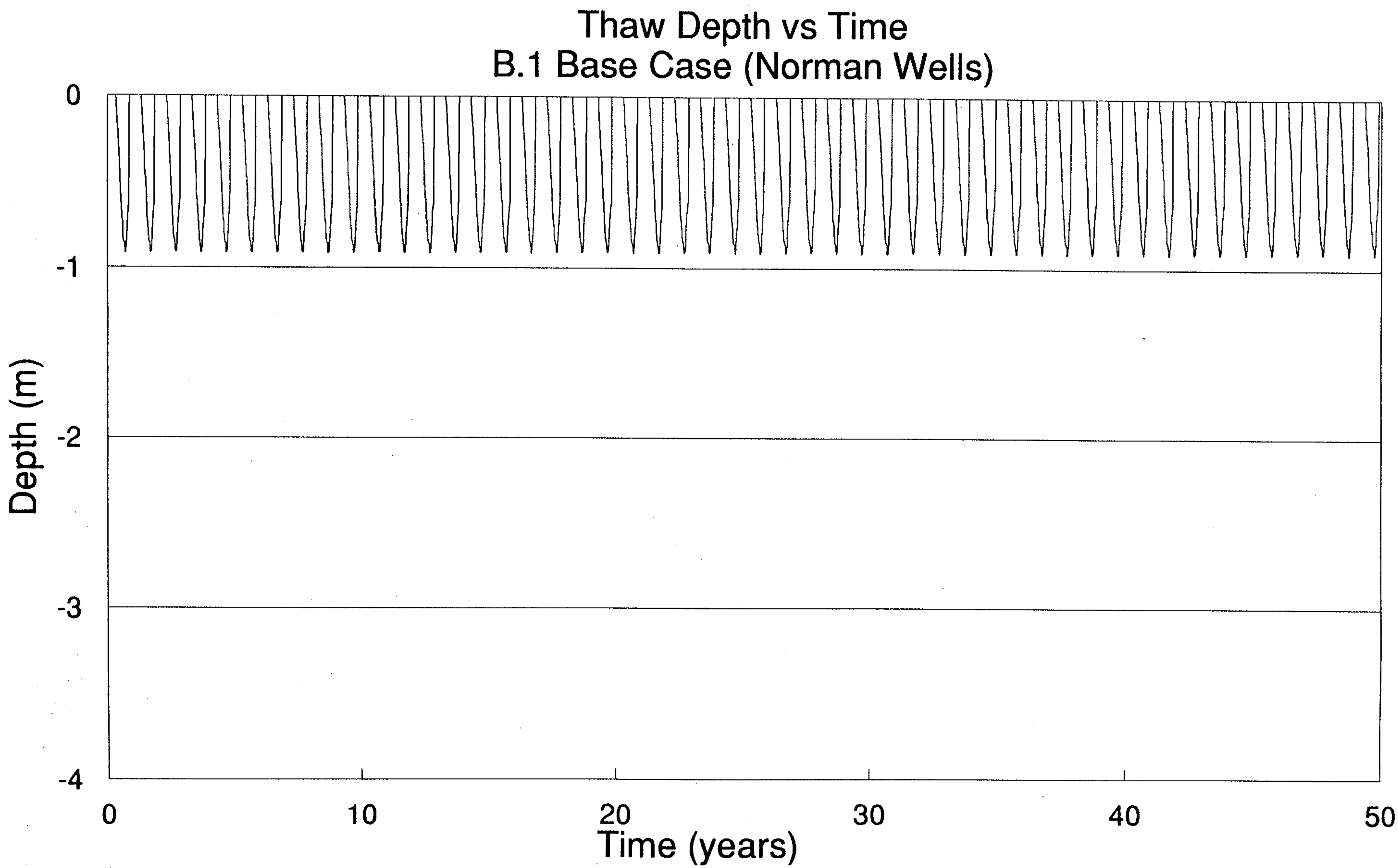

Thaw Depth vs Time
B.1 Base Case (Norman Wells)
Depth (m)
0
-1
-2
-3
-4
0
10
20
30
40
50
Time (years)

PLATE B.42

Surface Temperature vs Time
B.1 Base Case (Norman Wells)

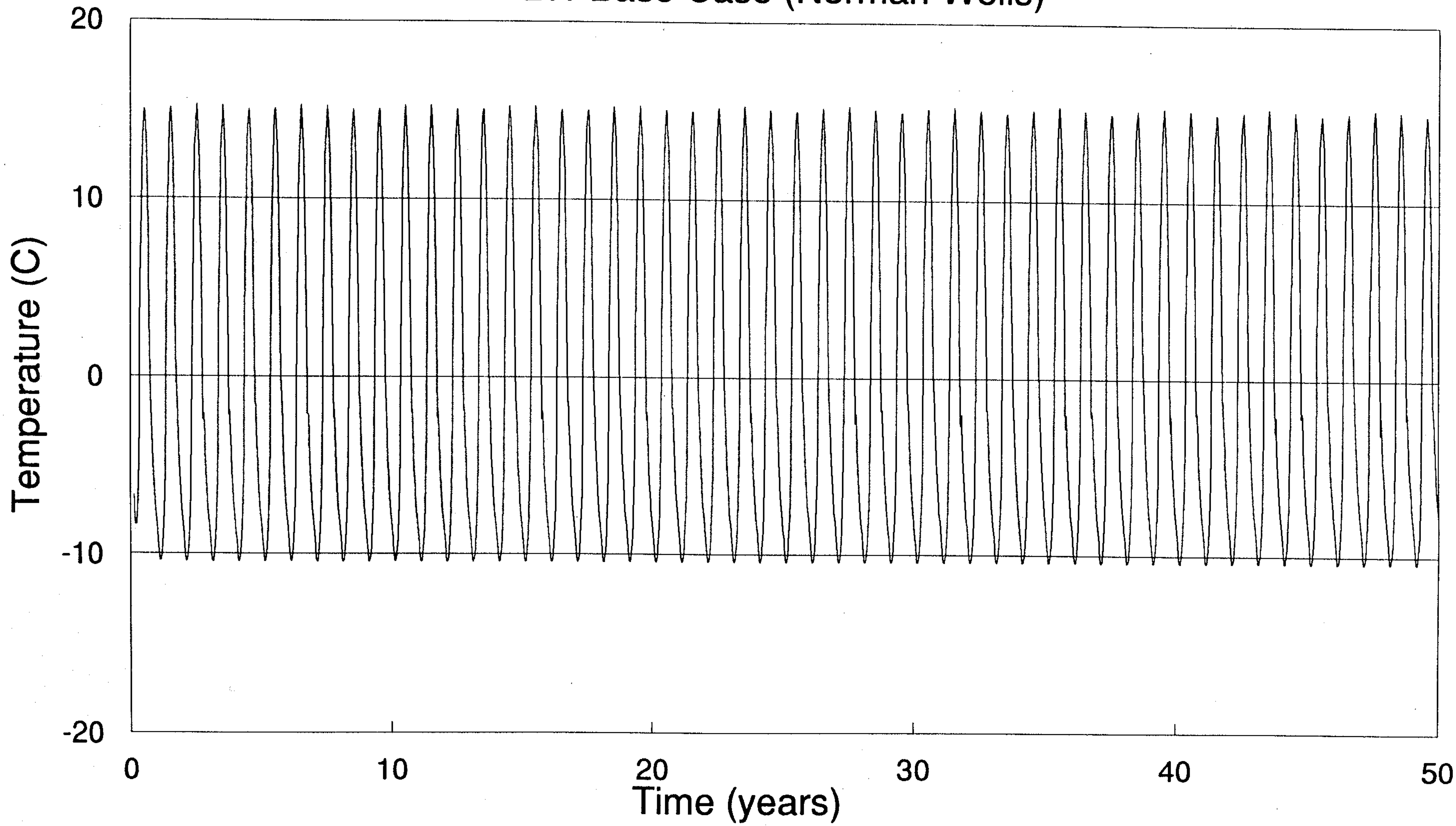


PLATE B.43

Ground Temperature vs Time
B.1 Base Case (Norman Wells)

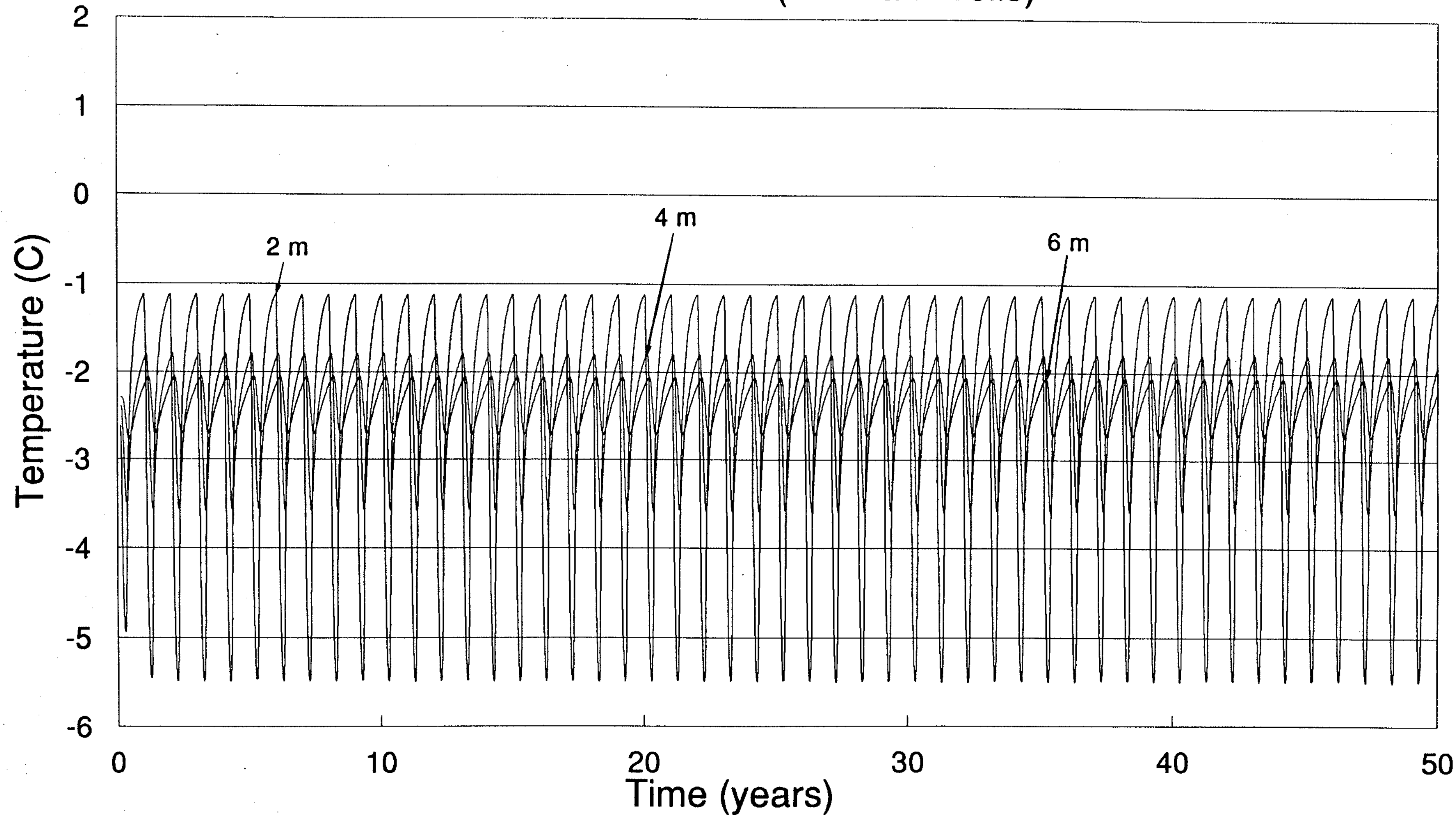


PLATE B.44

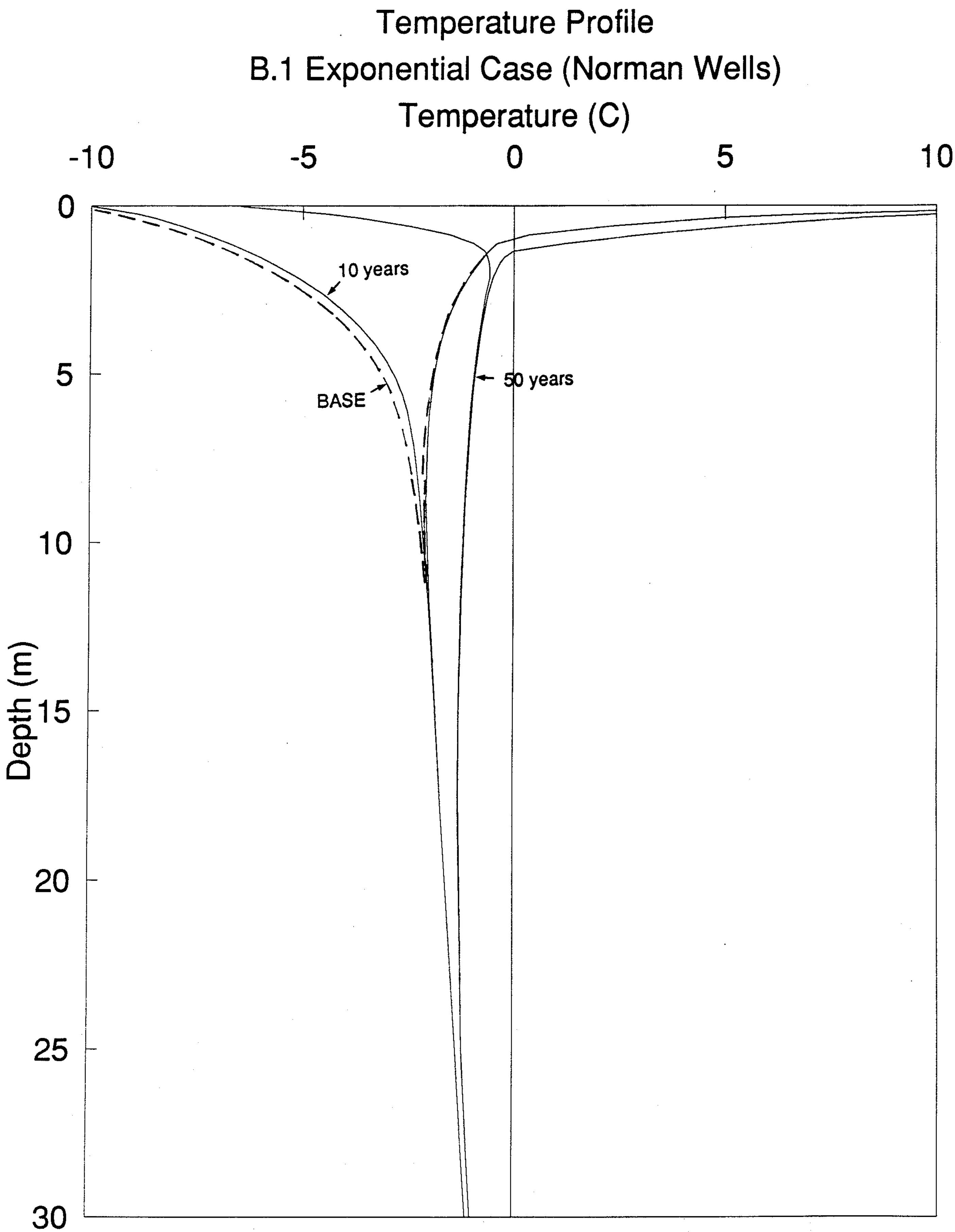

Temperature Profile
B.1 Exponential Case (Norman Wells)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
10 years
BASE
50 years

PLATE B.45

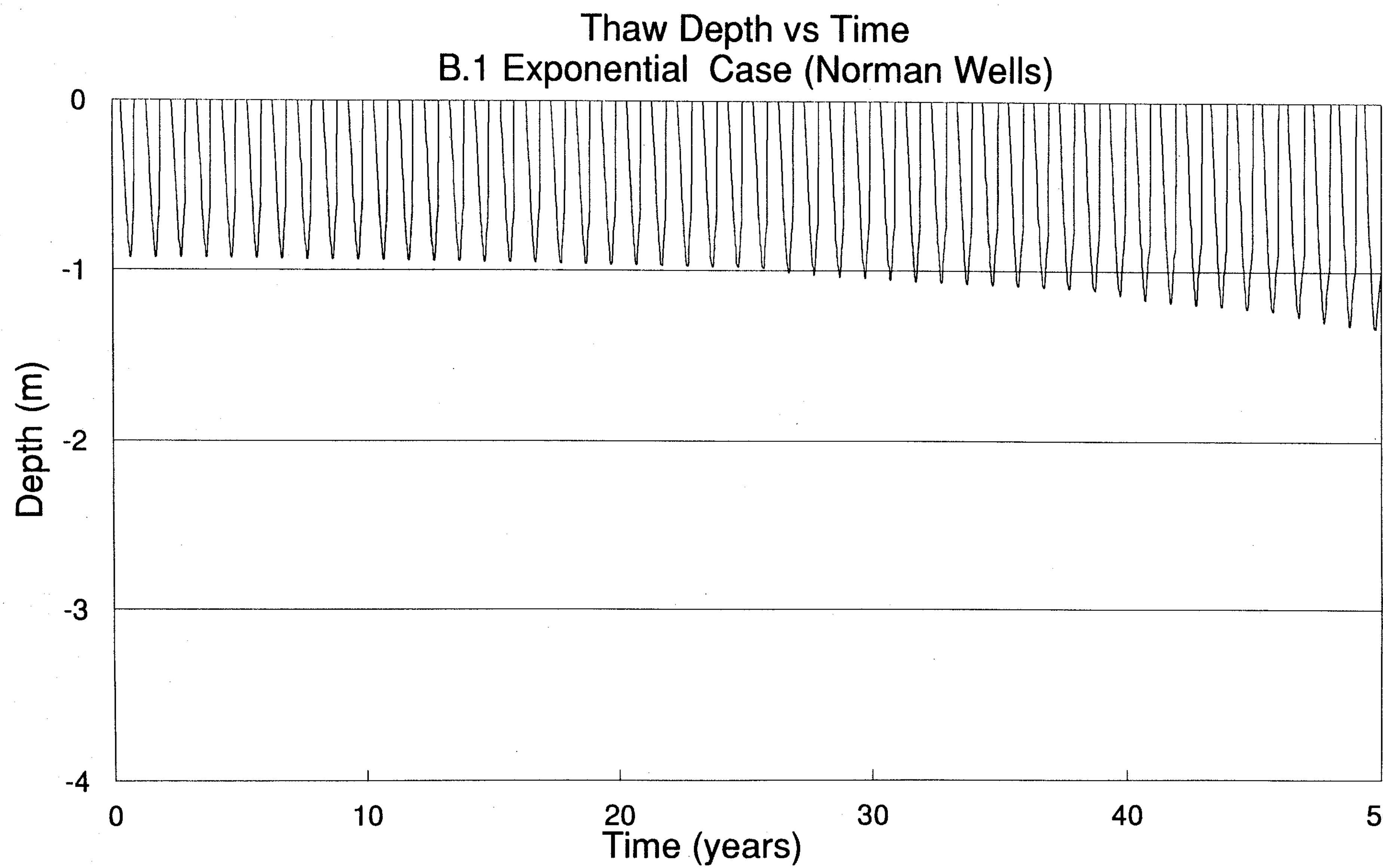
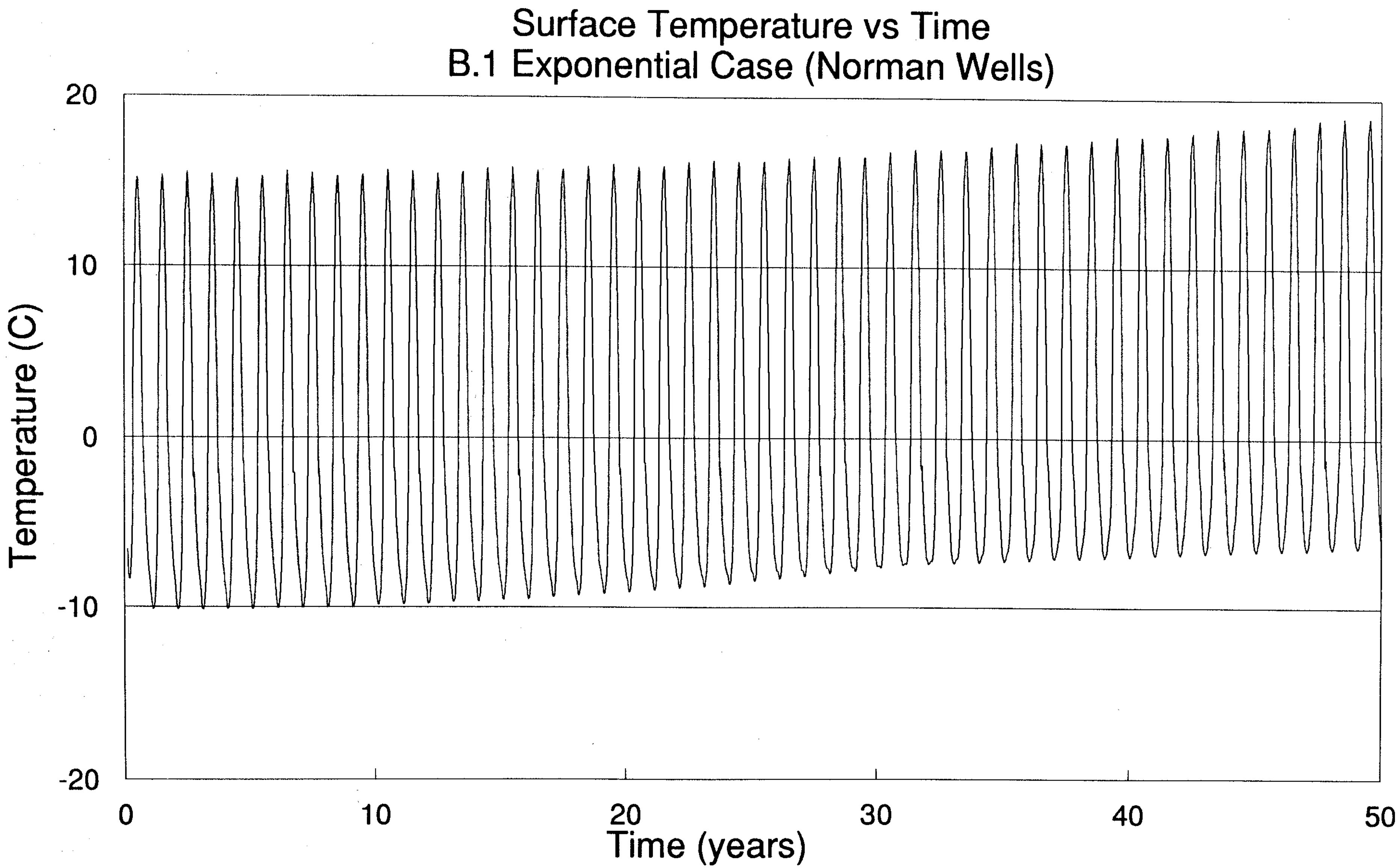

Thaw Depth vs Time
B.1 Exponential Case (Norman Wells)
0
-1
-2
-3
-4
Depth (m)
0
10
20
30
40
50
Time (years)

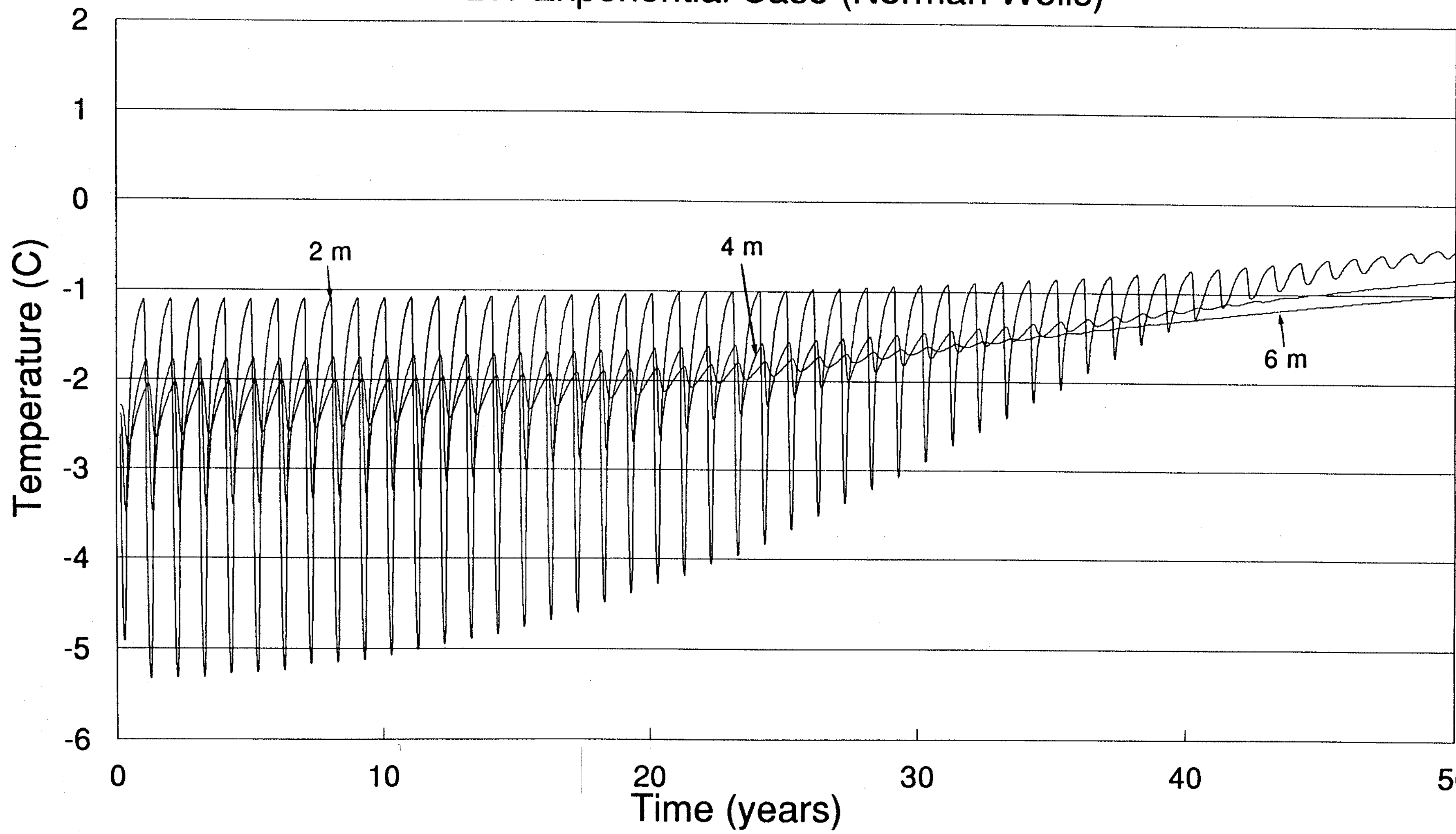
PLATE B.46

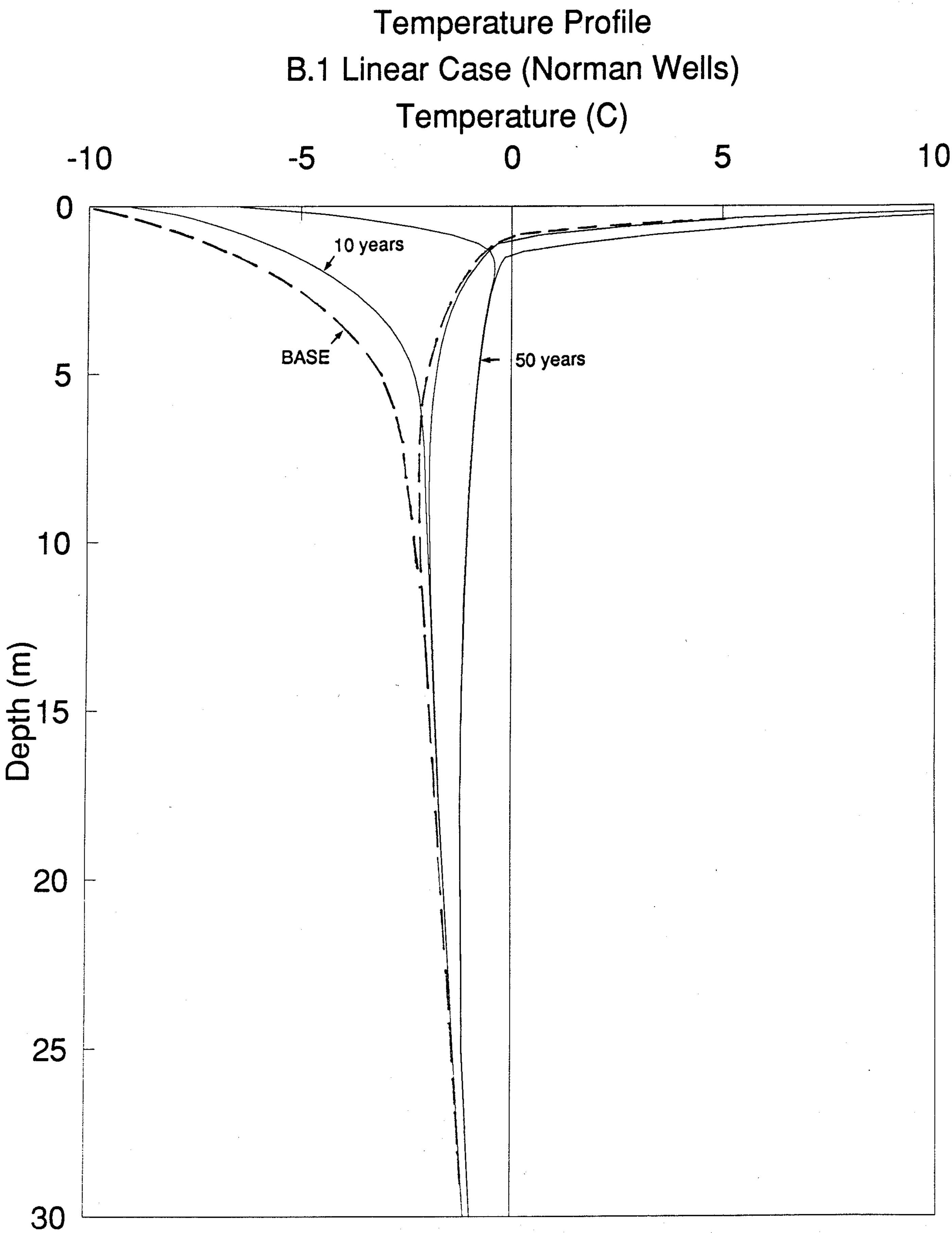


Surface Temperature vs Time
B.1 Exponential Case (Norman Wells)
Temperature (C)
20
10
0
-10
-20
0
10
20
30
40
50
Time (years)

PLATE B.47

Ground Temperature vs Time
B.1 Exponential Case (Norman Wells)





Temperature Profile
B.1 Linear Case (Norman Wells)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
10 years
BASE
50 years

PLATE B.49

Thaw Depth vs Time
B.1 Linear Case (Norman Wells)

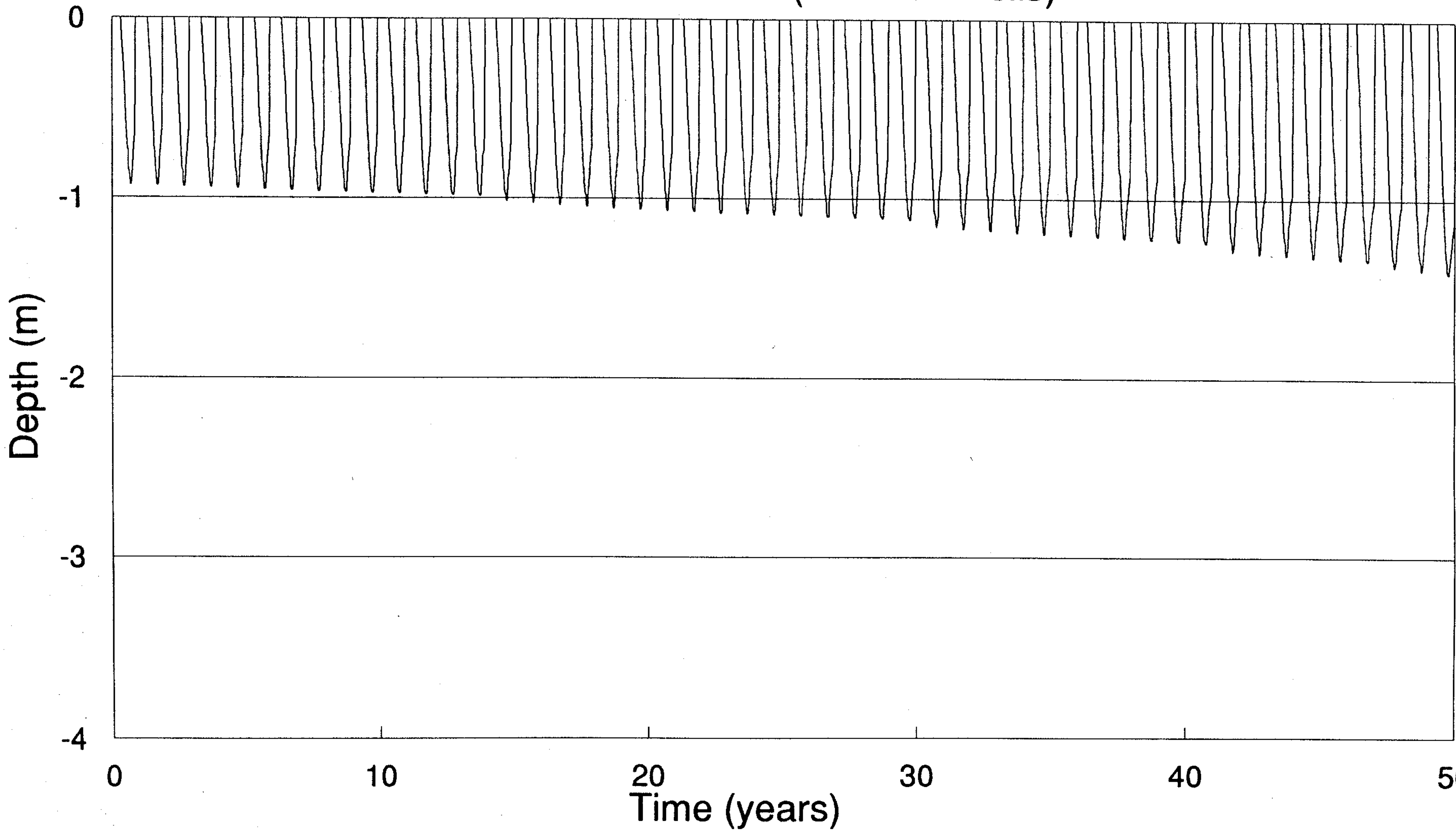


PLATE B.50

Surface Temperature vs Time
B.1 Linear Case (Norman Wells)

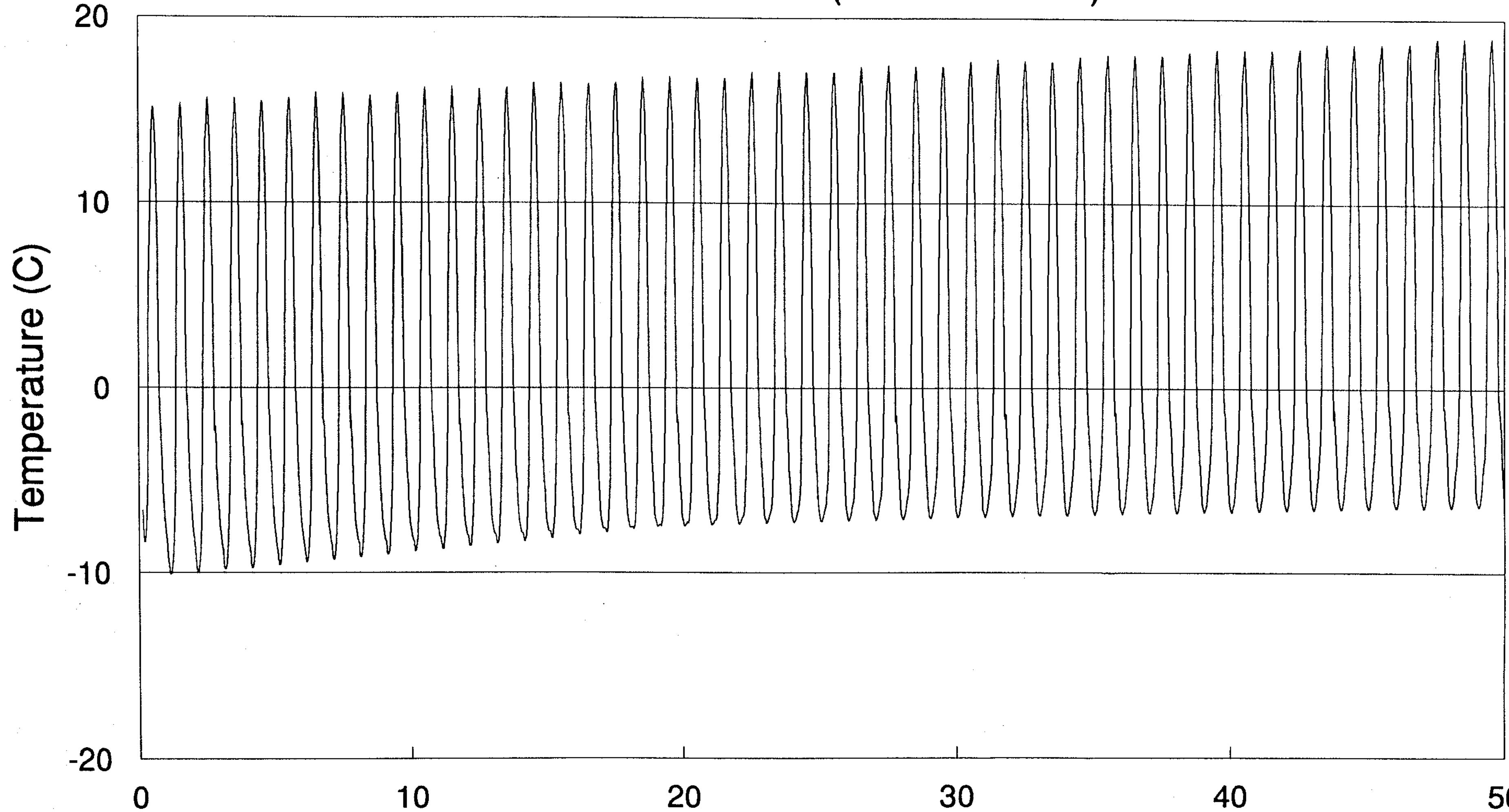


PLATE B.51

Ground Temperature vs Time
B.1 Linear Case (Norman Wells)

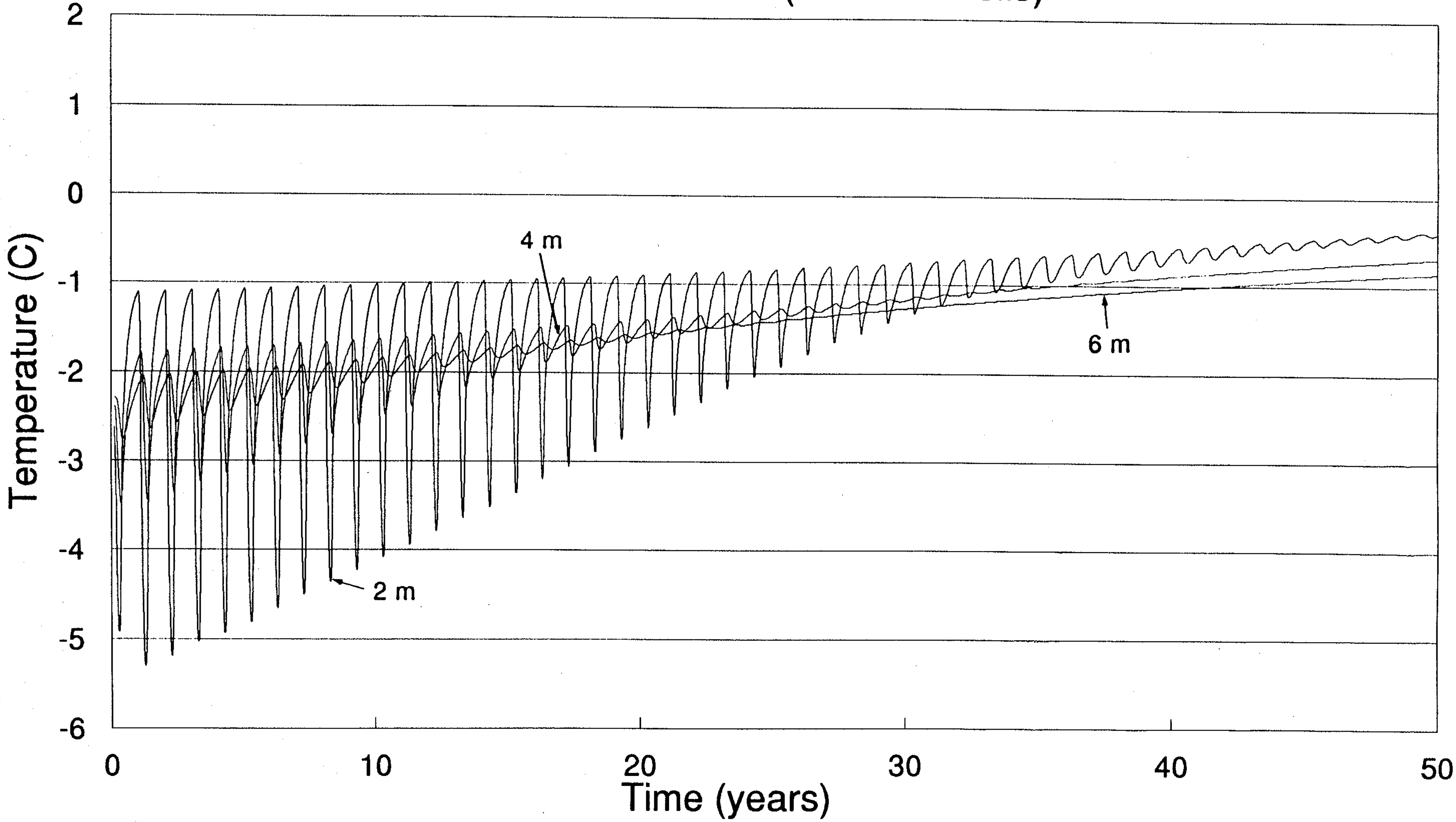
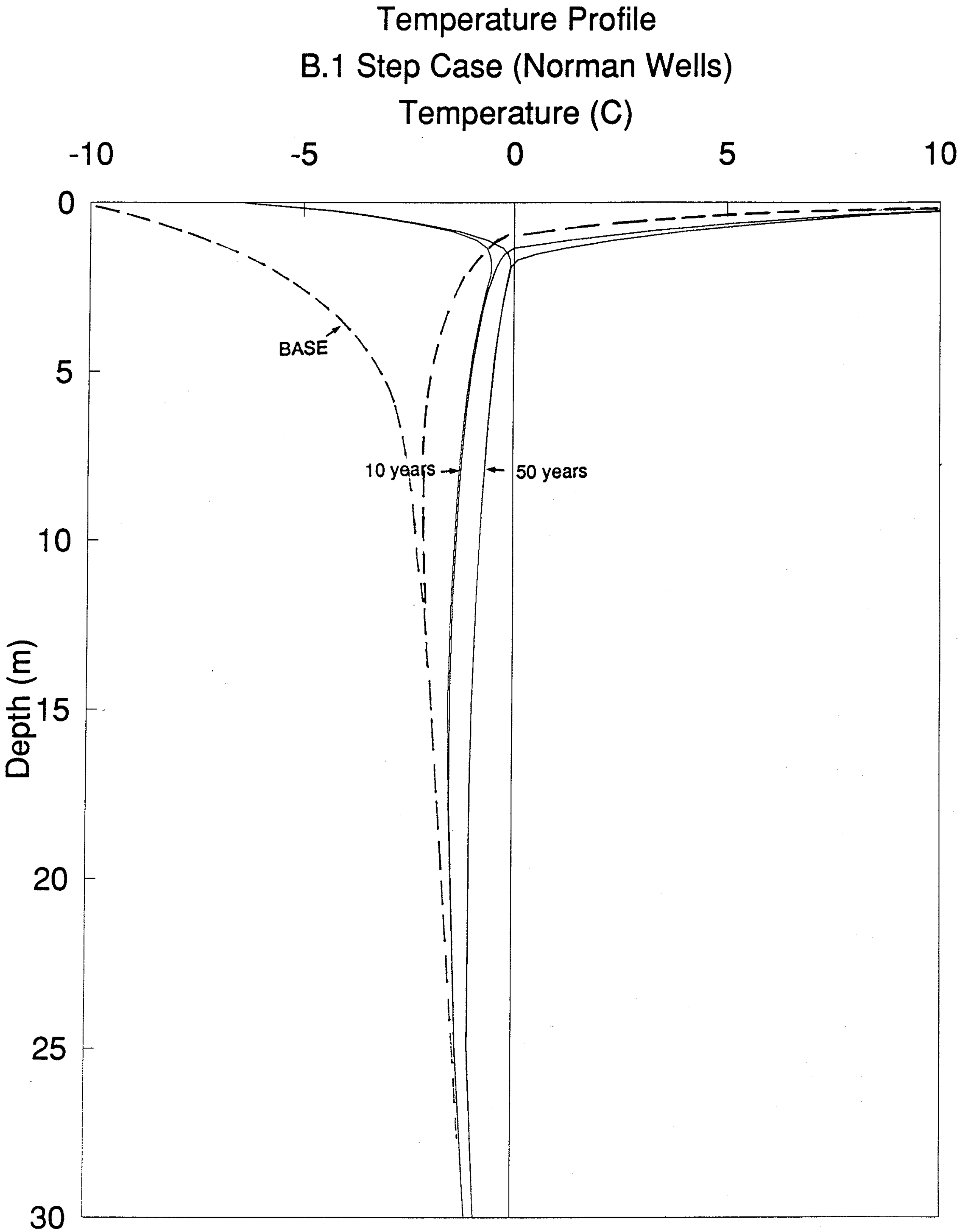
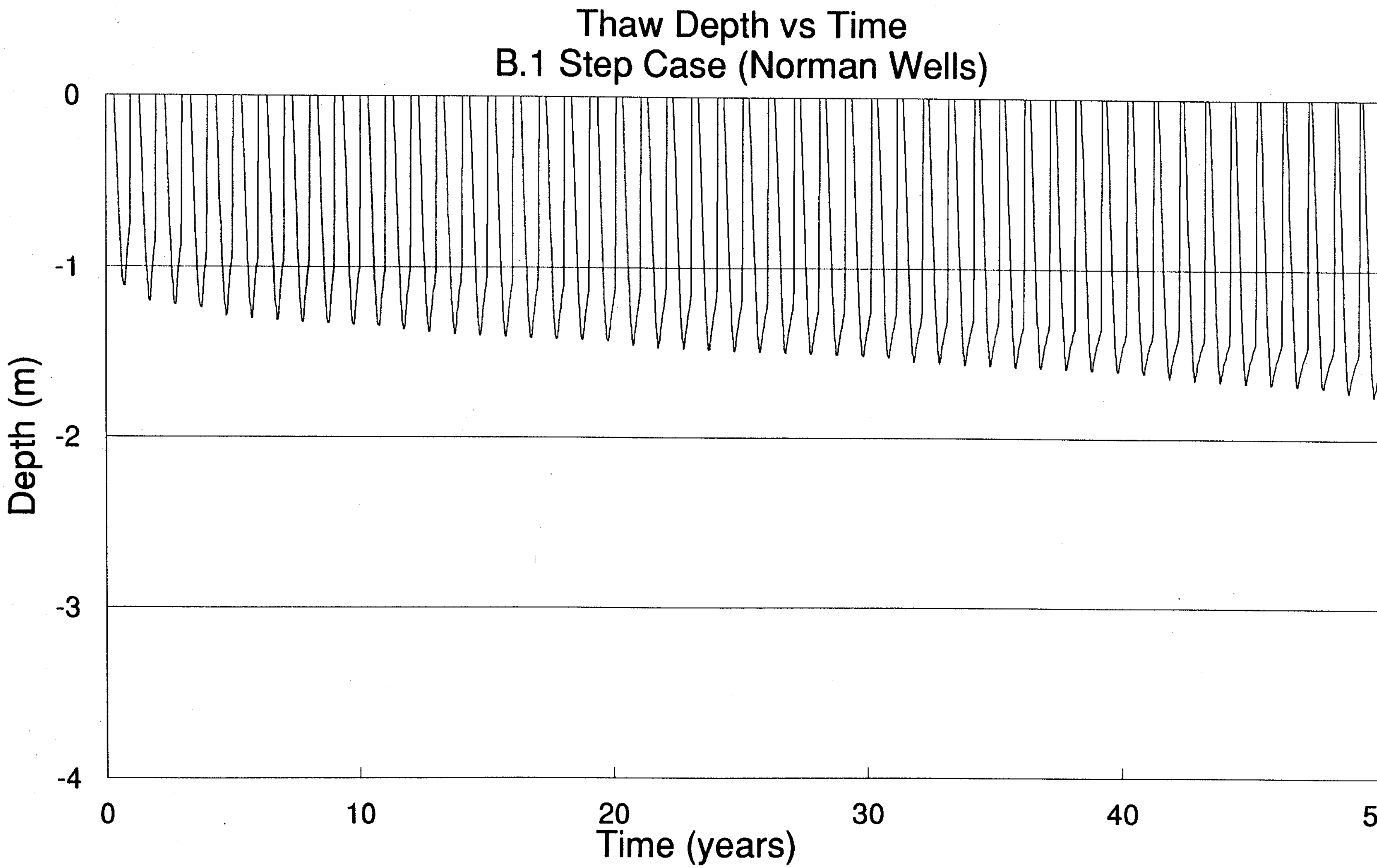


PLATE B.52



Temperature Profile
B.1 Step Case (Norman Wells)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
BASE
10 years
50 years

PLATE B.53



Thaw Depth vs Time
B.1 Step Case (Norman Wells)
0
-1
-2
-3
-4
Depth (m)
0
10
20
30
40
50
Time (years)

PLATE B.54

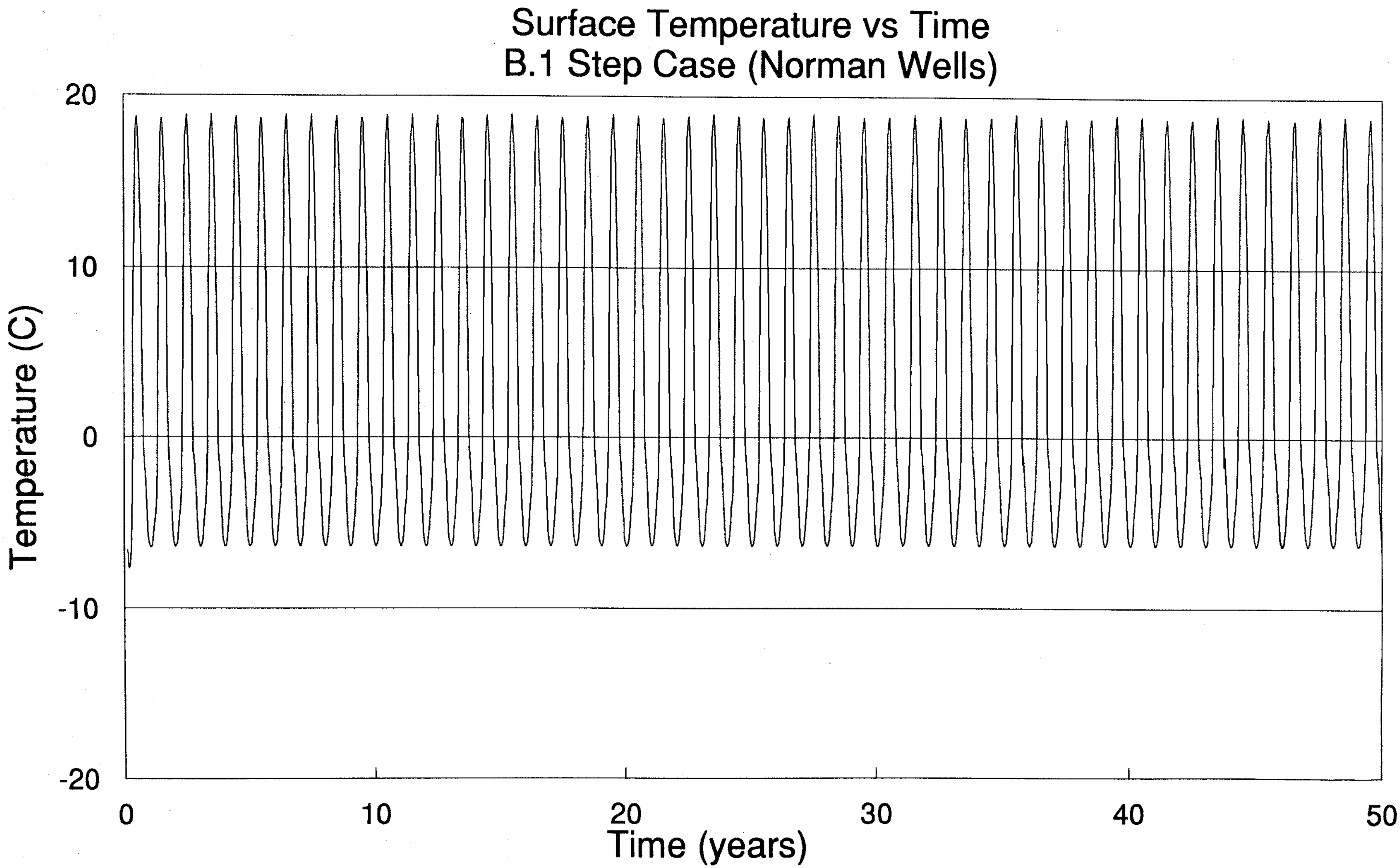

Surface Temperature vs Time
B.1 Step Case (Norman Wells)
20
10
0
-10
-20
Temperature (C)
0
10
20
30
40
50
Time (years)

PLATE B.55

Ground Temperature vs Time
B.1 Step Case (Norman Wells)

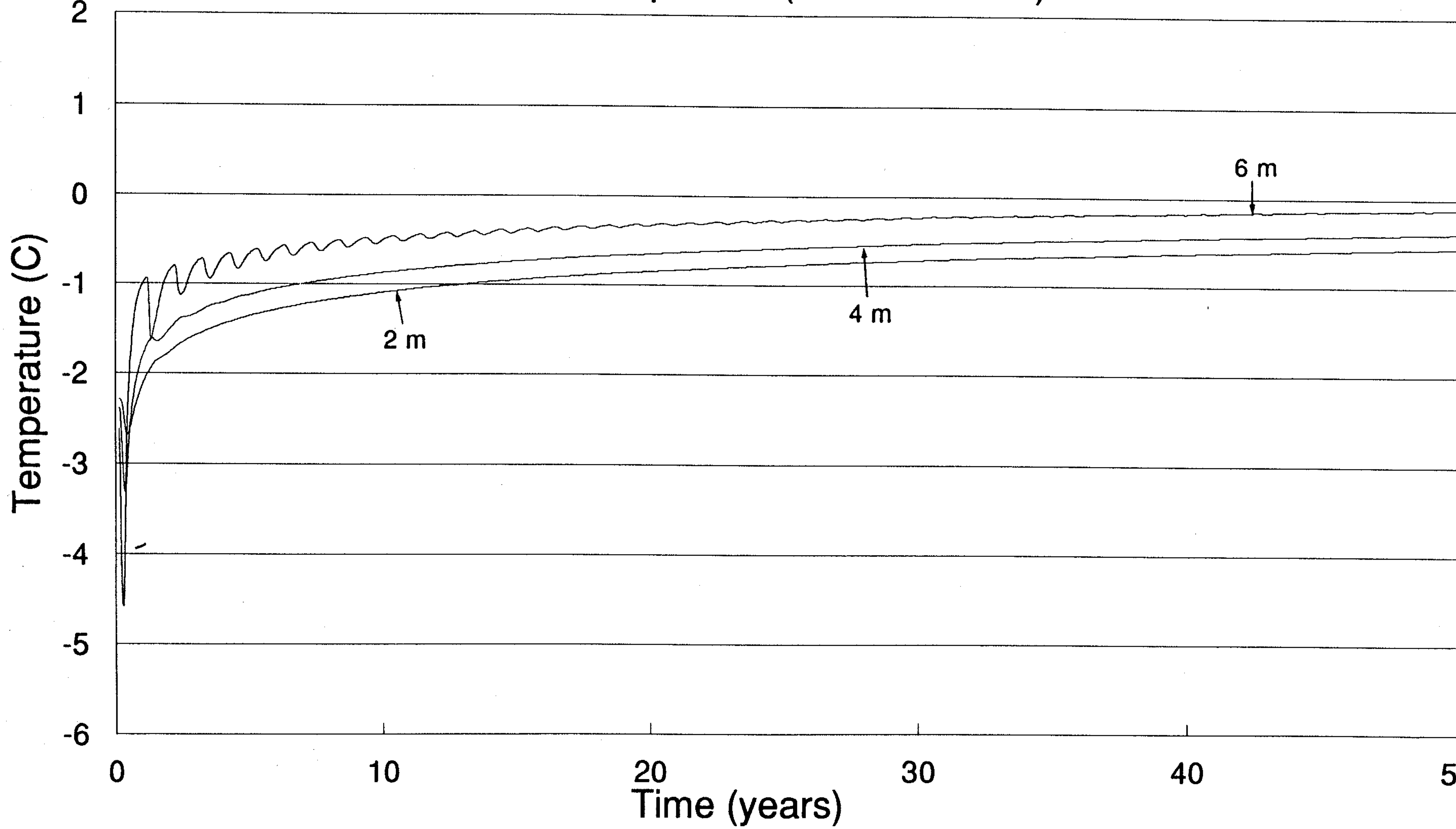


PLATE B.56

Temperature Profile

B.1 Linear Case with Increased Snow Pack (Norman Wells)

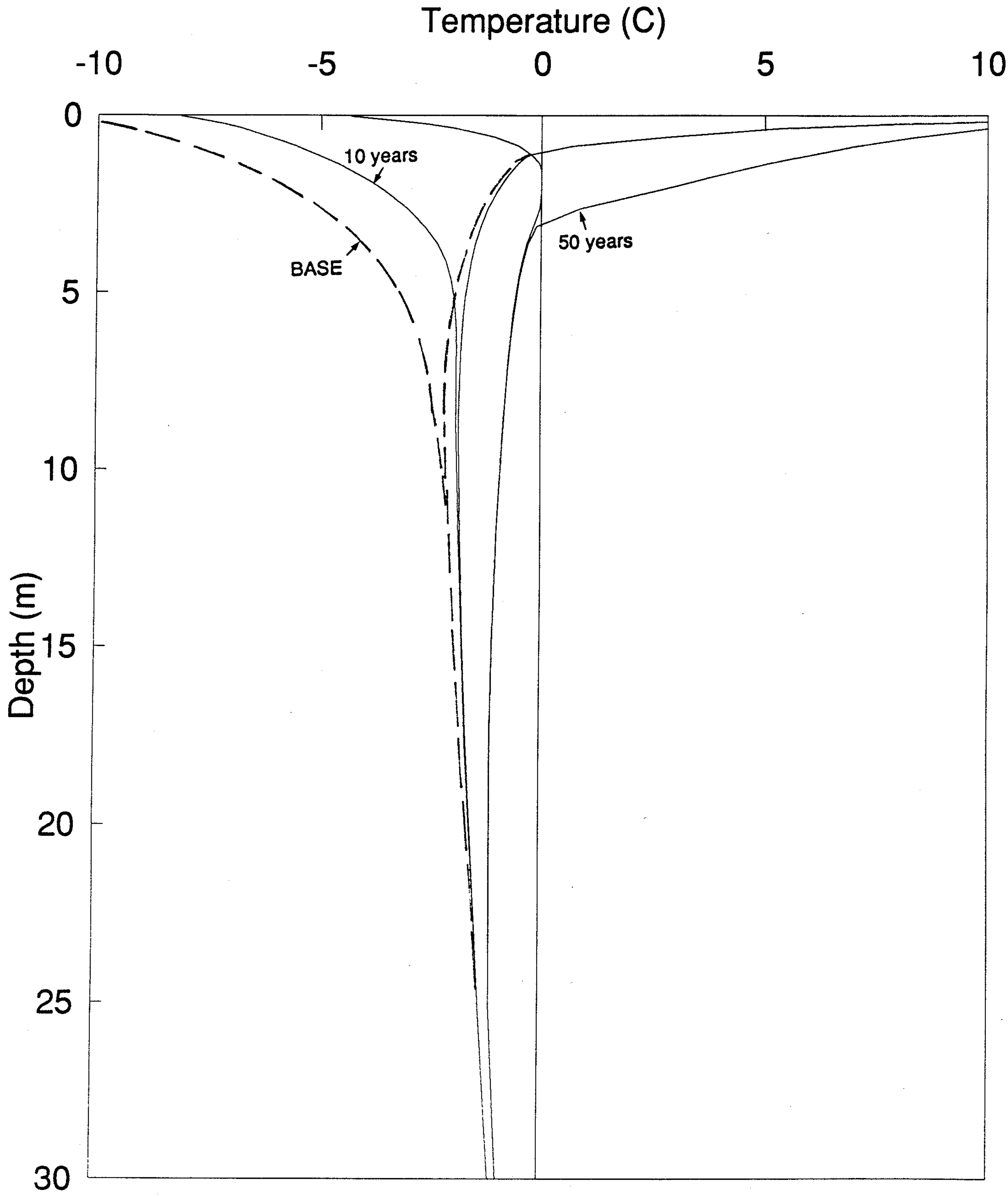


PLATE B.57

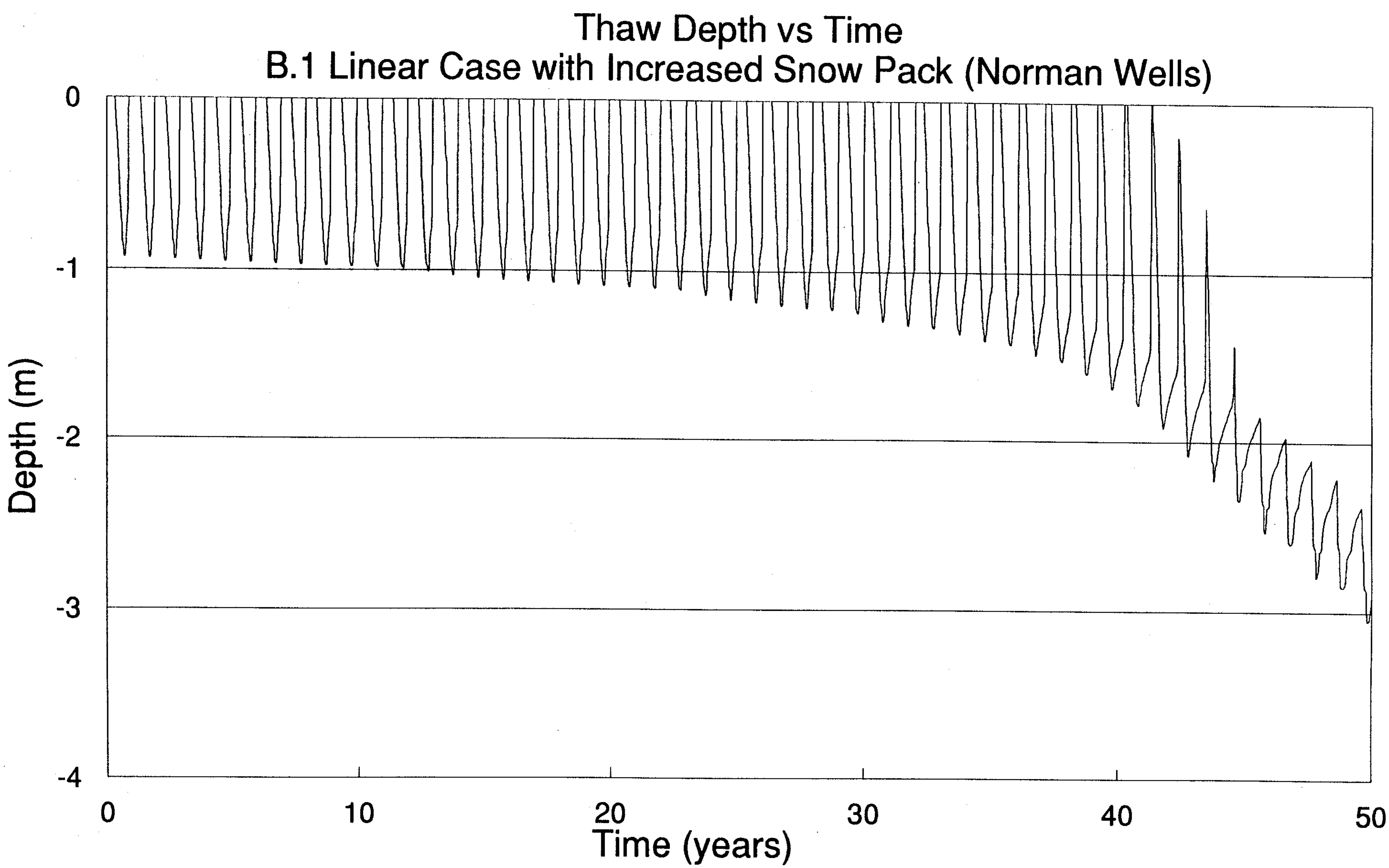

Thaw Depth vs Time
B.1 Linear Case with Increased Snow Pack (Norman Wells)
Depth (m)
0
-1
-2
-3
-4
0
10
20
30
40
50
Time (years)

PLATE B.58

Surface Temperature vs Time
B.1 Linear Case with Increased Snow Pack (Norman Wells)

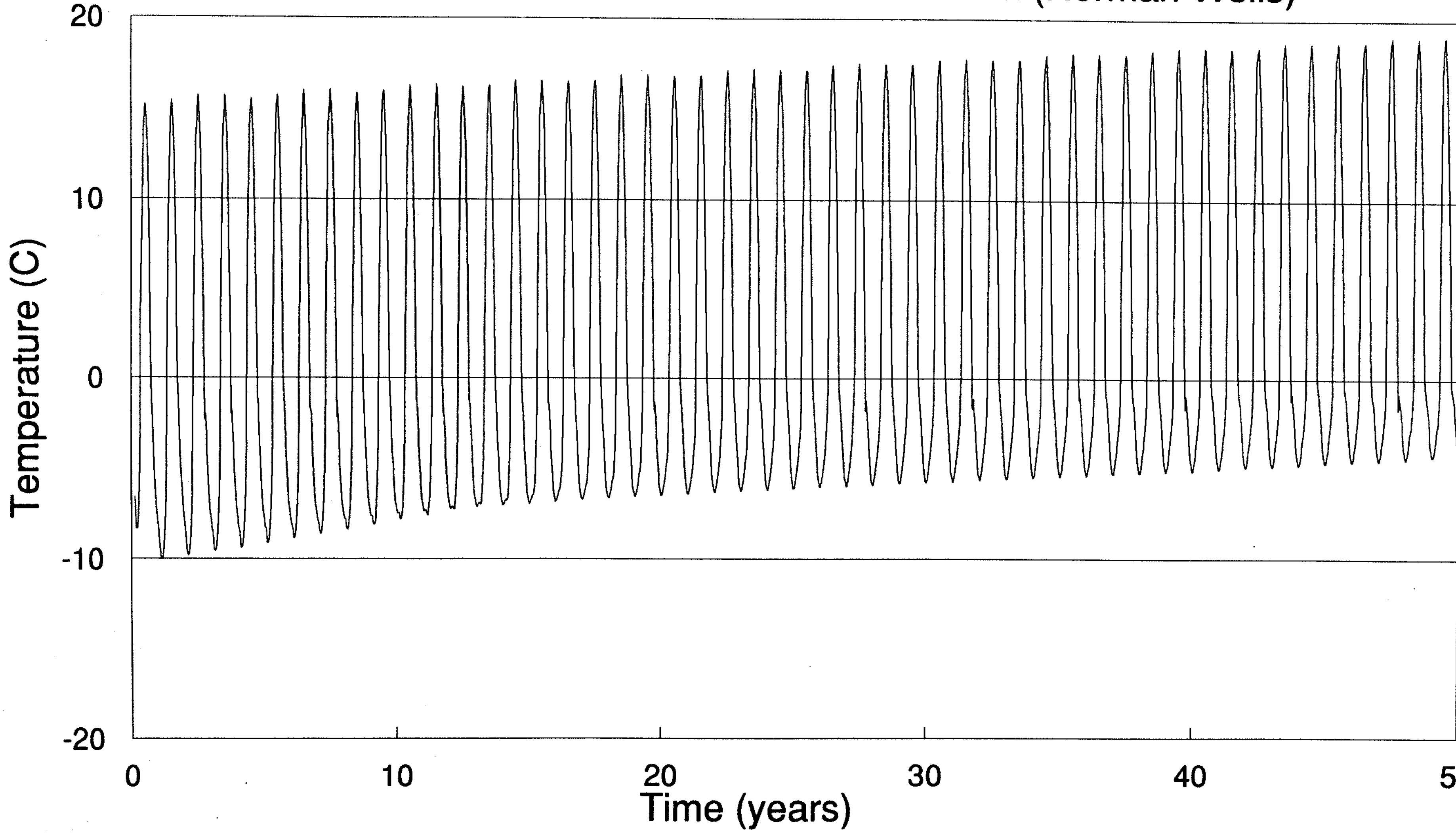


PLATE B.59

Ground Temperature vs Time
B.1 Linear Case with Increased Snow Pack (Norman Wells)

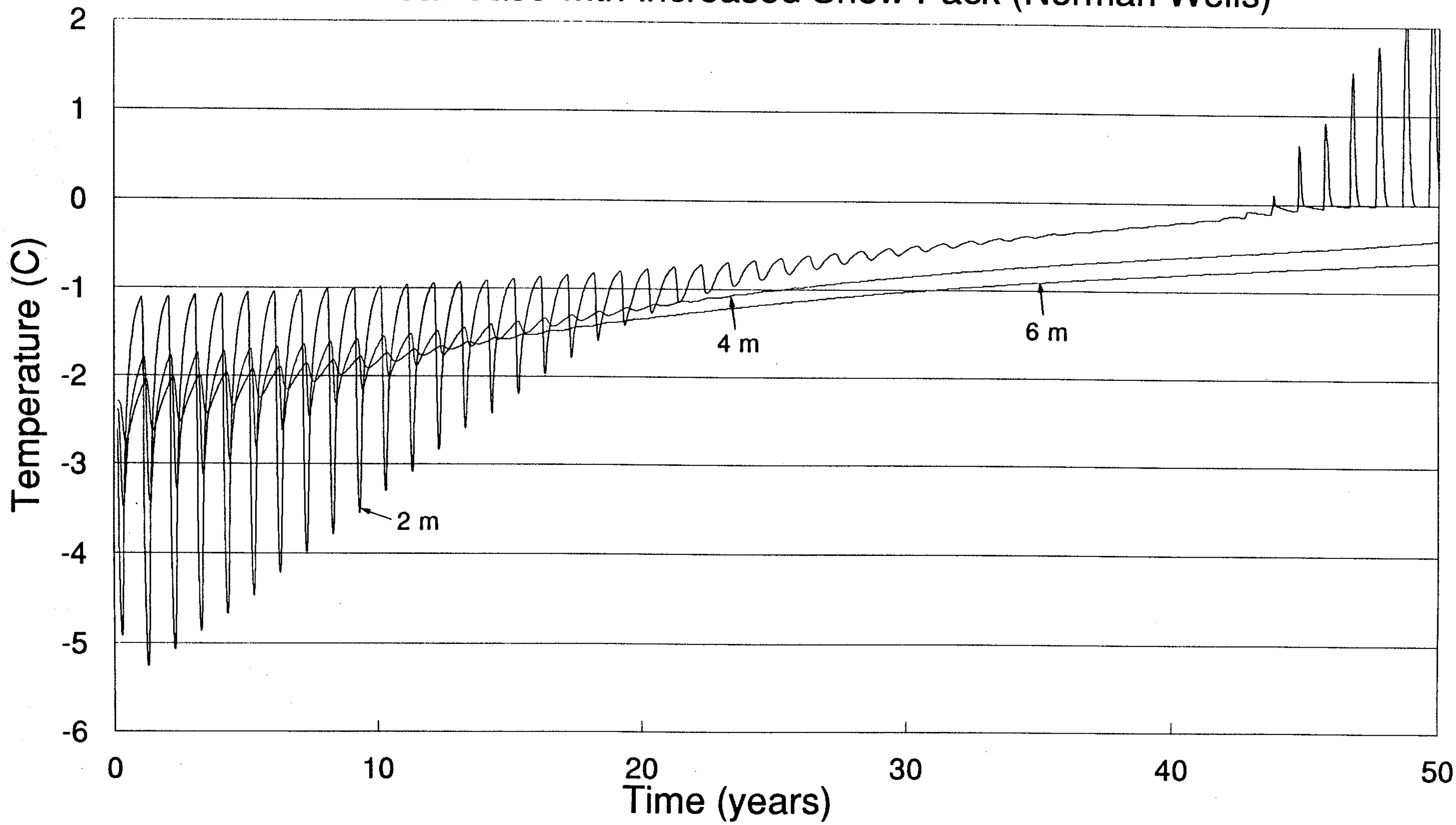
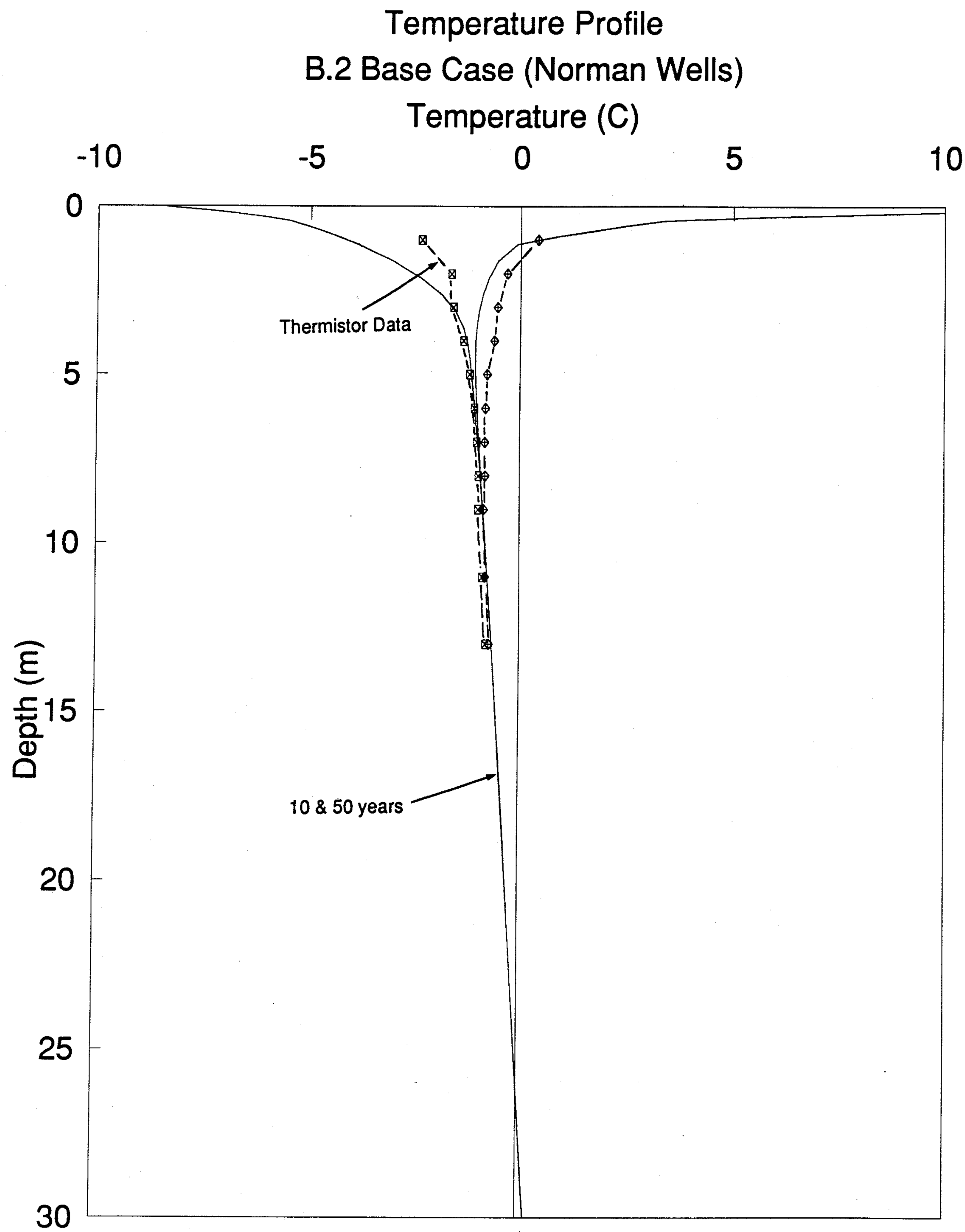


PLATE B.60

SITE B.2 - NORMAN WELLS

Low-Ice Content Glacial Till Deposit



Temperature Profile
B.2 Base Case (Norman Wells)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
Thermistor Data
10 & 50 years

PLATE B.61

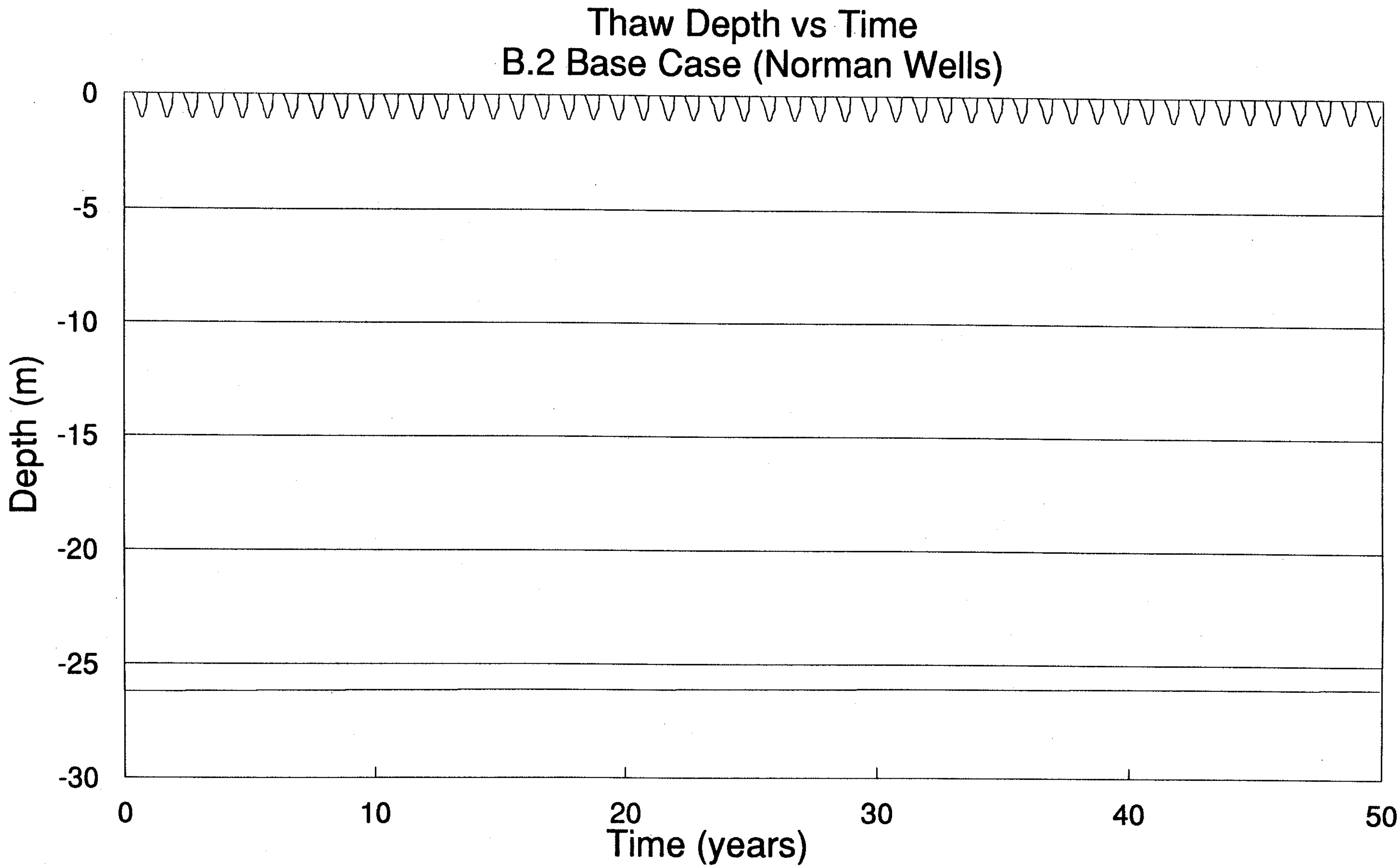

Thaw Depth vs Time
B.2 Base Case (Norman Wells)
0
-5
-10
-15
-20
-25
-30
Depth (m)
0
10
20
30
40
50
Time (years)

PLATE B.62

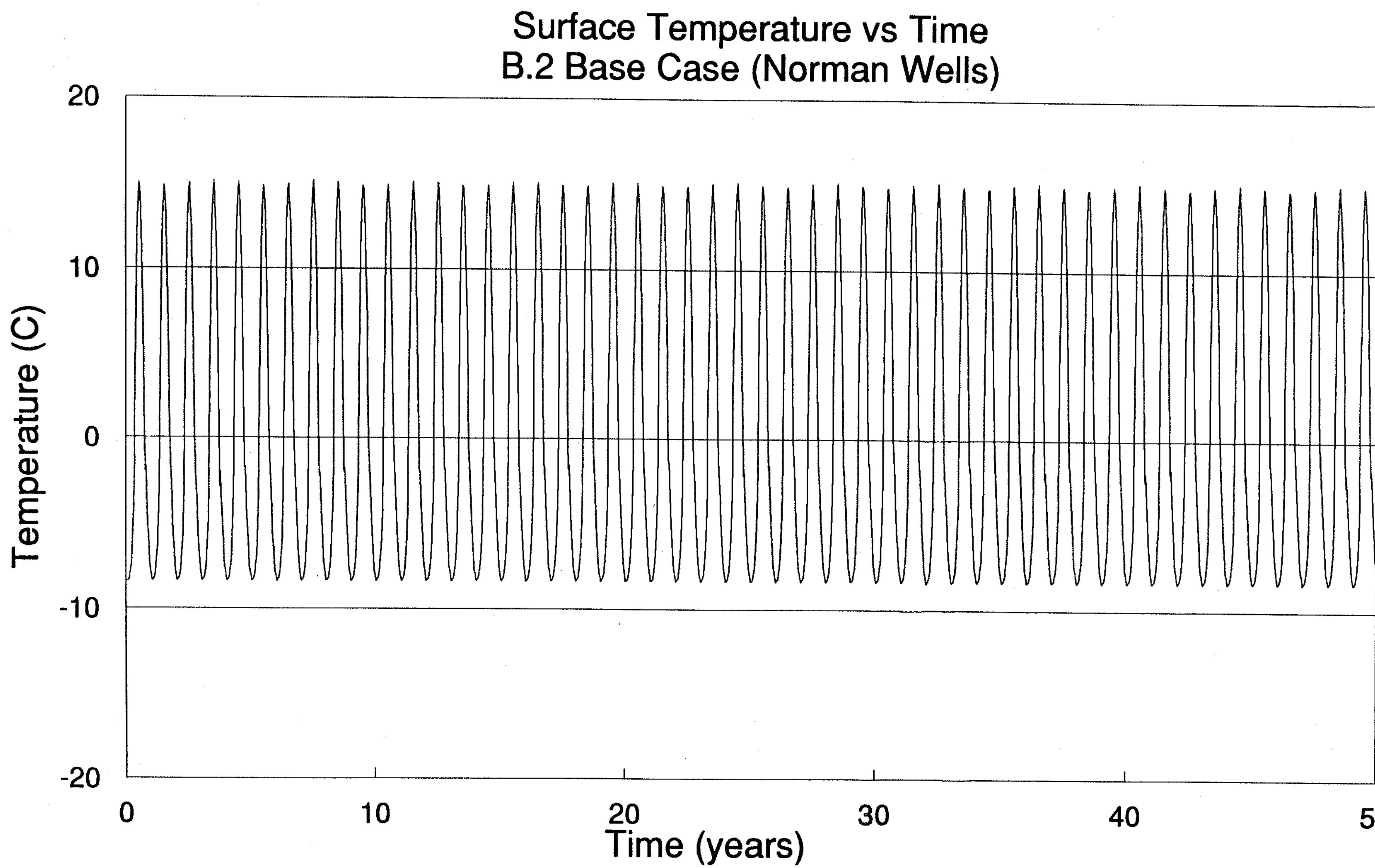

Surface Temperature vs Time
B.2 Base Case (Norman Wells)
Temperature (C)
20
10
0
-10
-20
0
10
20
30
40
50
Time (years)

PLATE B.63

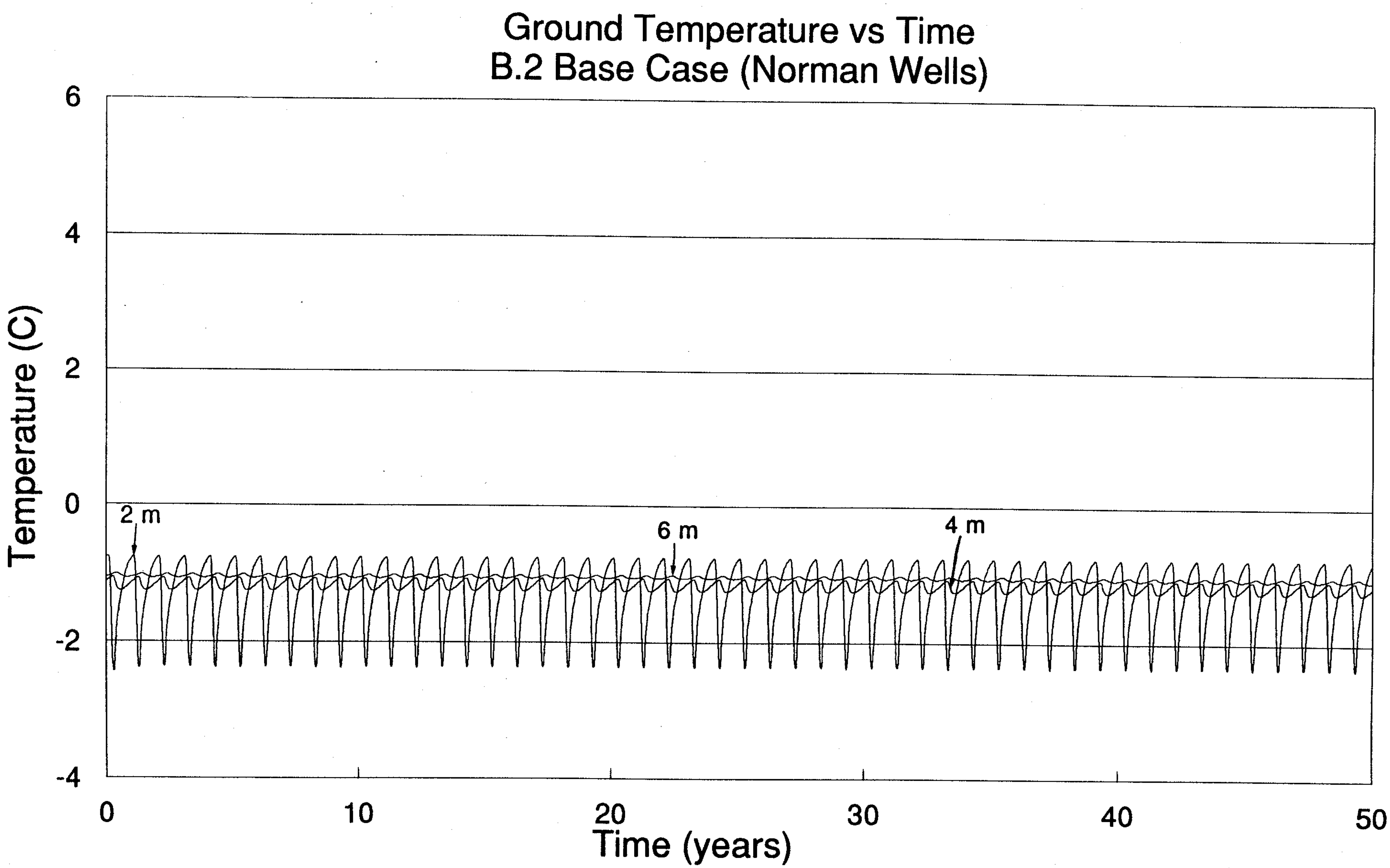

Ground Temperature vs Time
B.2 Base Case (Norman Wells)
Temperature (C)
6
4
2
0
-2
-4
2 m
6 m
4 m
0
10
20
30
40
50
Time (years)

PLATE B.64

Temperature Profile
B.2 Exponential Case (Norman Wells)

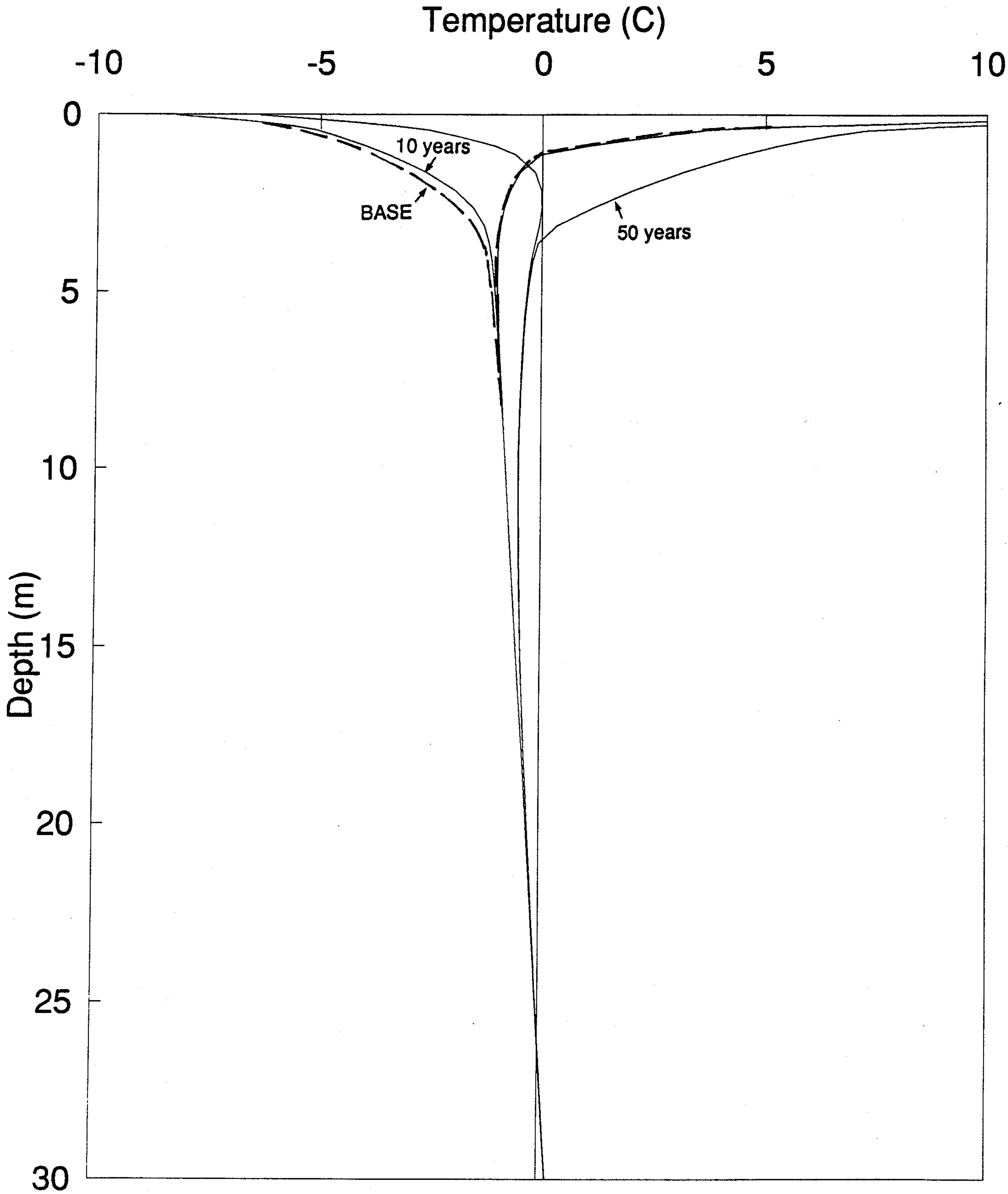


PLATE B.65

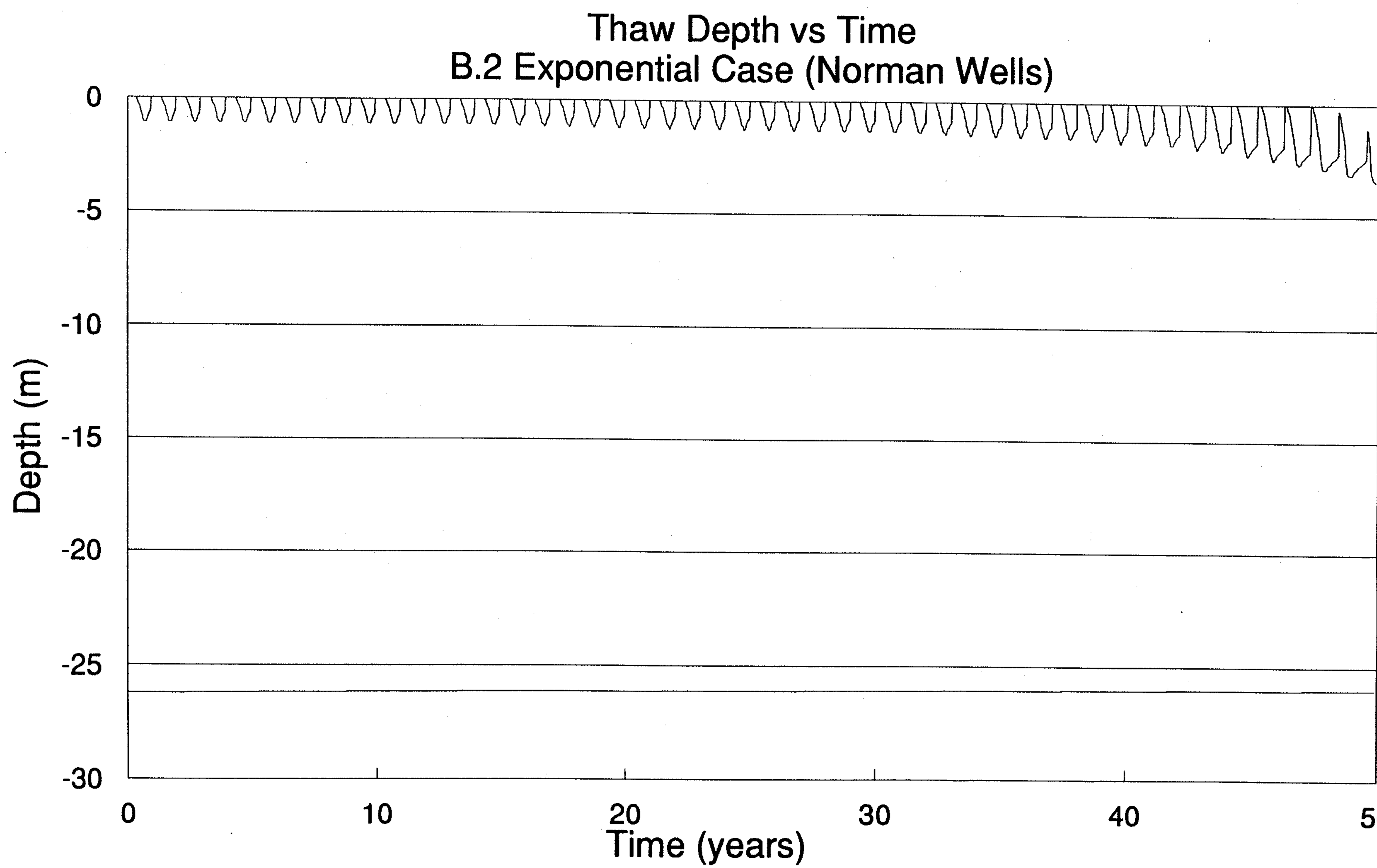

Thaw Depth vs Time
B.2 Exponential Case (Norman Wells)
Depth (m)
0
-5
-10
-15
-20
-25
-30
0
10
20
30
40
50
Time (years)

PLATE B.66

Surface Temperature vs Time
B.2 Exponential Case (Norman Wells)

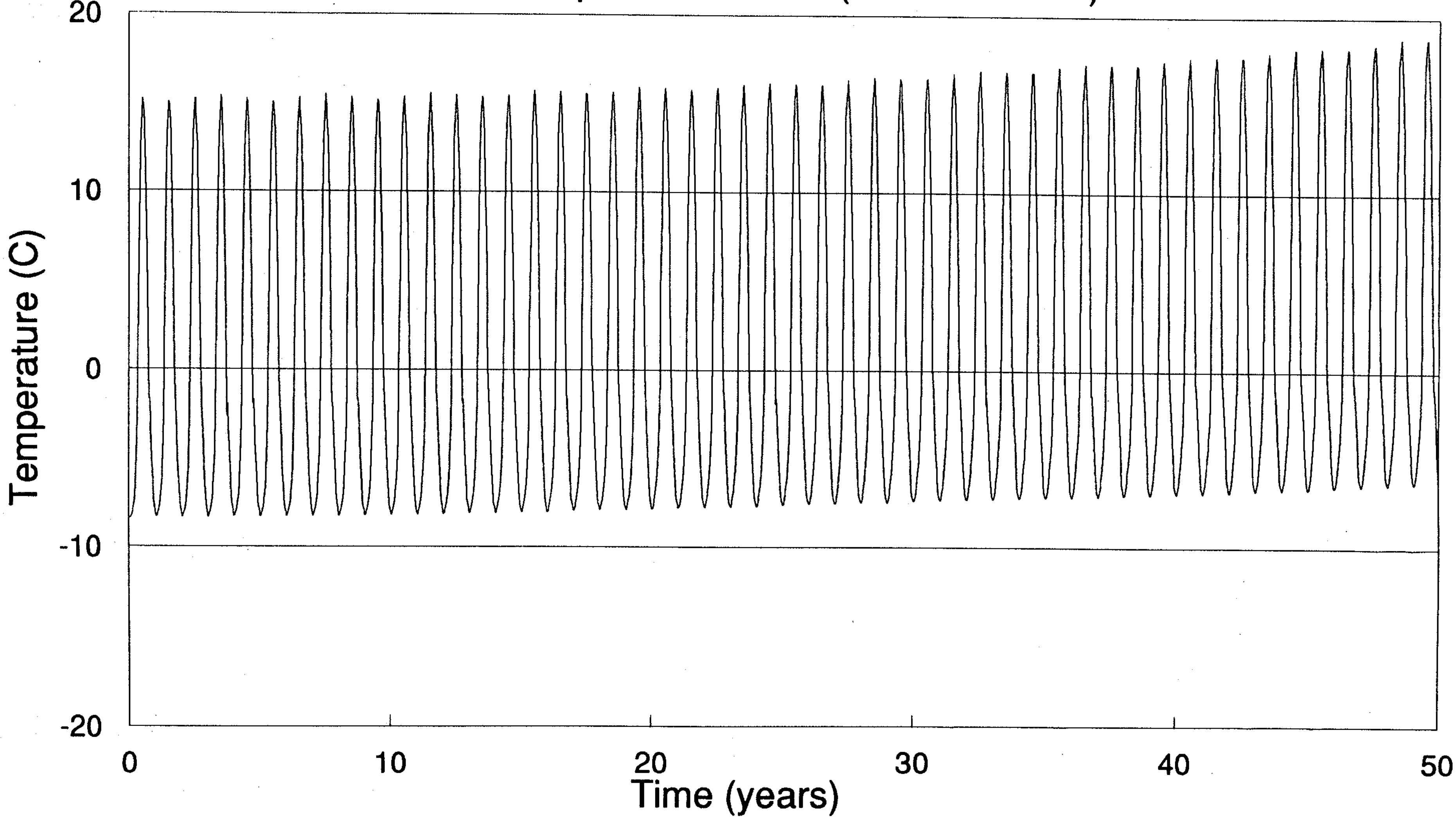


PLATE B.67

Ground Temperature vs Time
B.2 Exponential Case (Norman Wells)

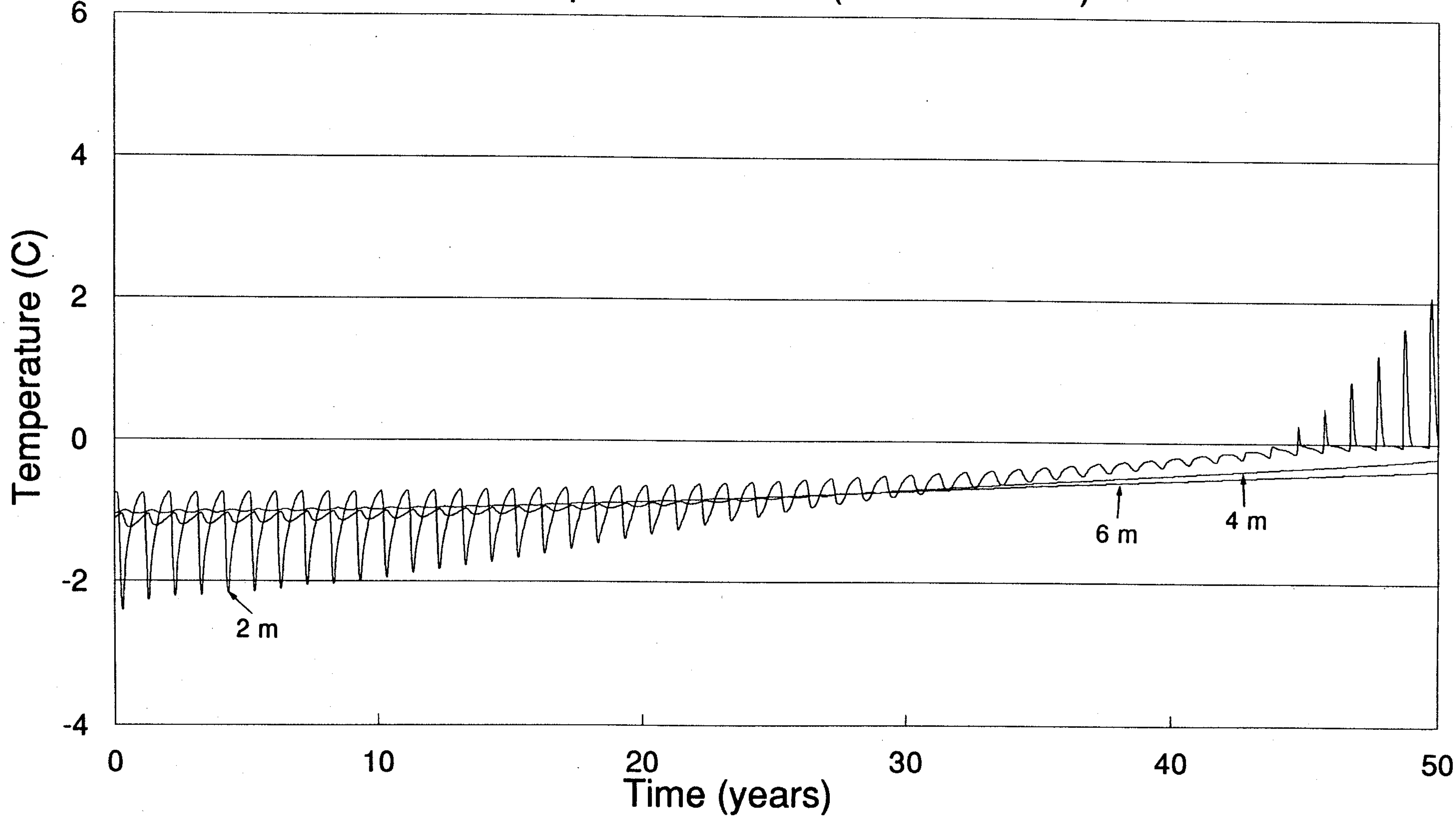
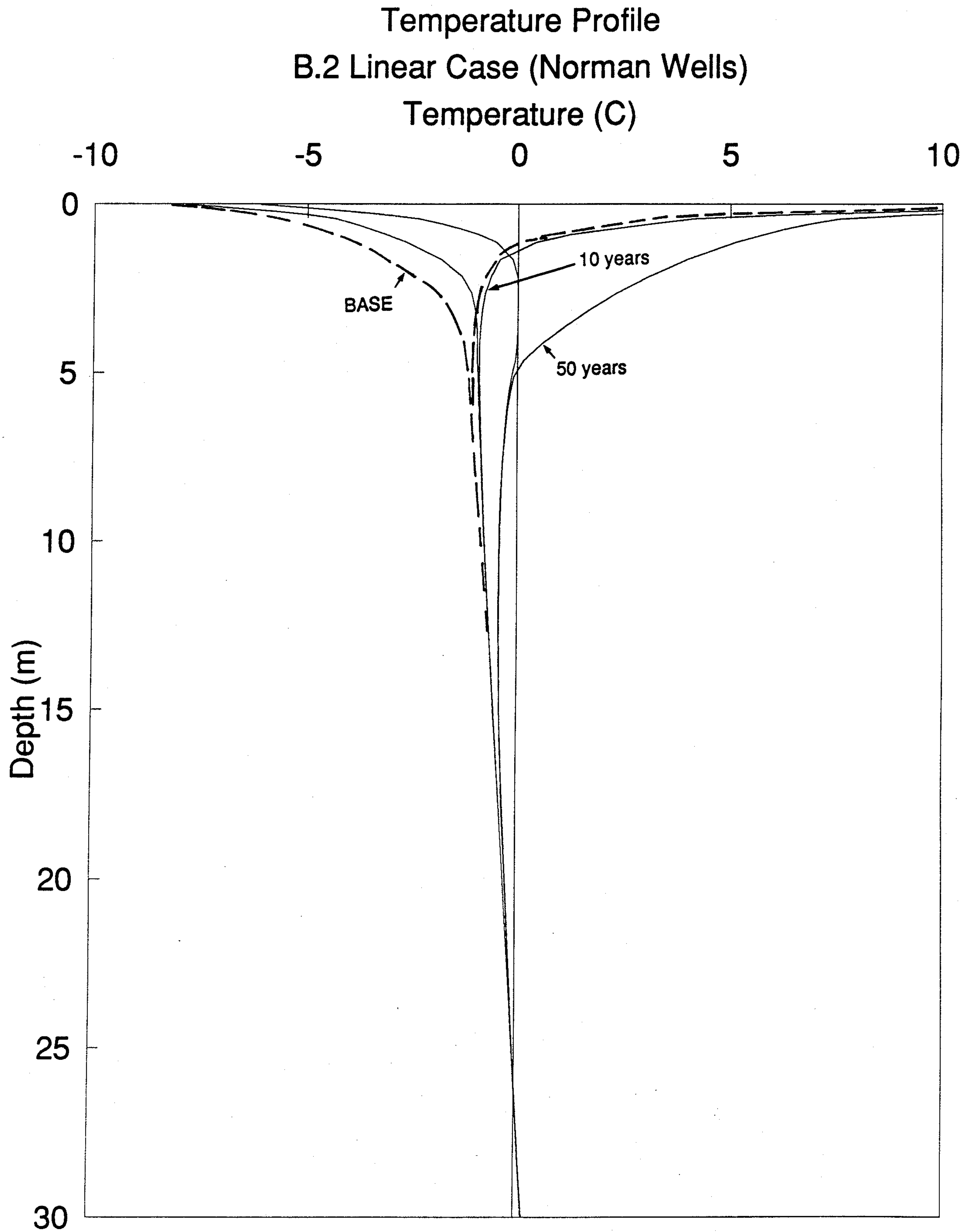


PLATE B.68



Temperature Profile
B.2 Linear Case (Norman Wells)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
10 years
BASE
50 years

PLATE B.69

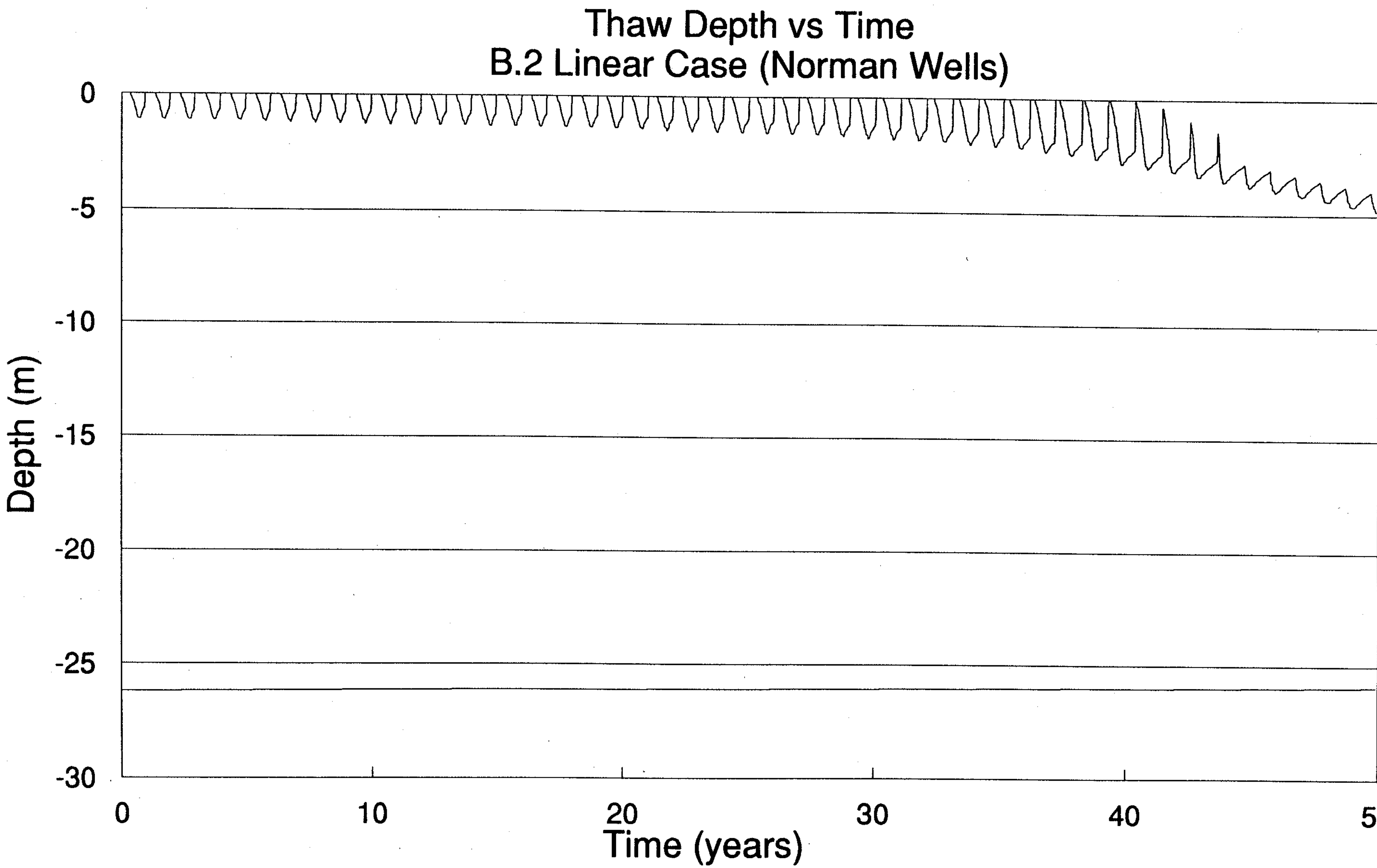

Thaw Depth vs Time
B.2 Linear Case (Norman Wells)
Depth (m)
0
-5
-10
-15
-20
-25
-30
Time (years)
0
10
20
30
40
50

PLATE B.70

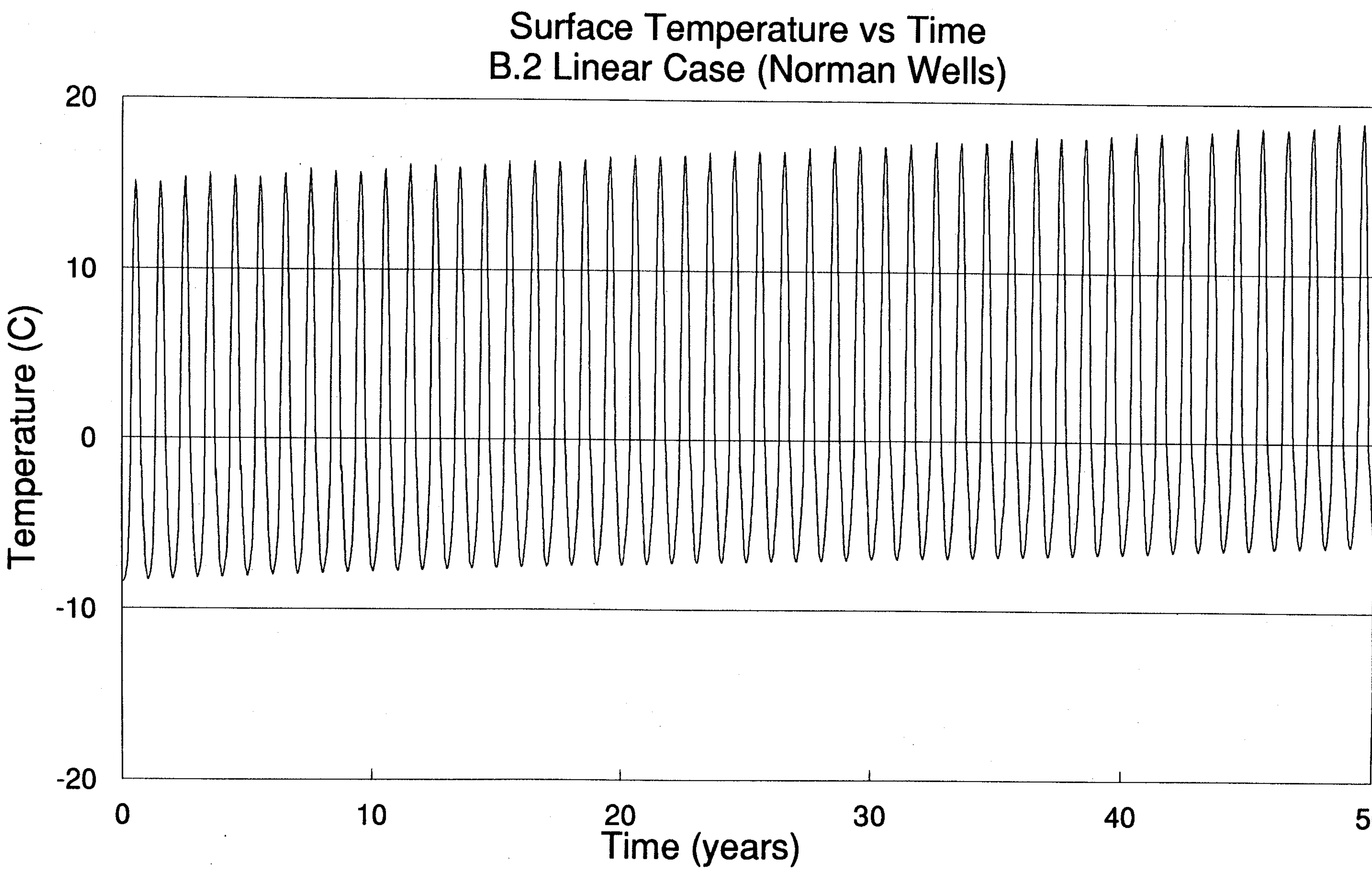

Surface Temperature vs Time
B.2 Linear Case (Norman Wells)
Temperature (C)
20
10
0
-10
-20
0
10
20
30
40
50
Time (years)

PLATE B.71

Ground Temperature vs Time
B.2 Linear Case (Norman Wells)

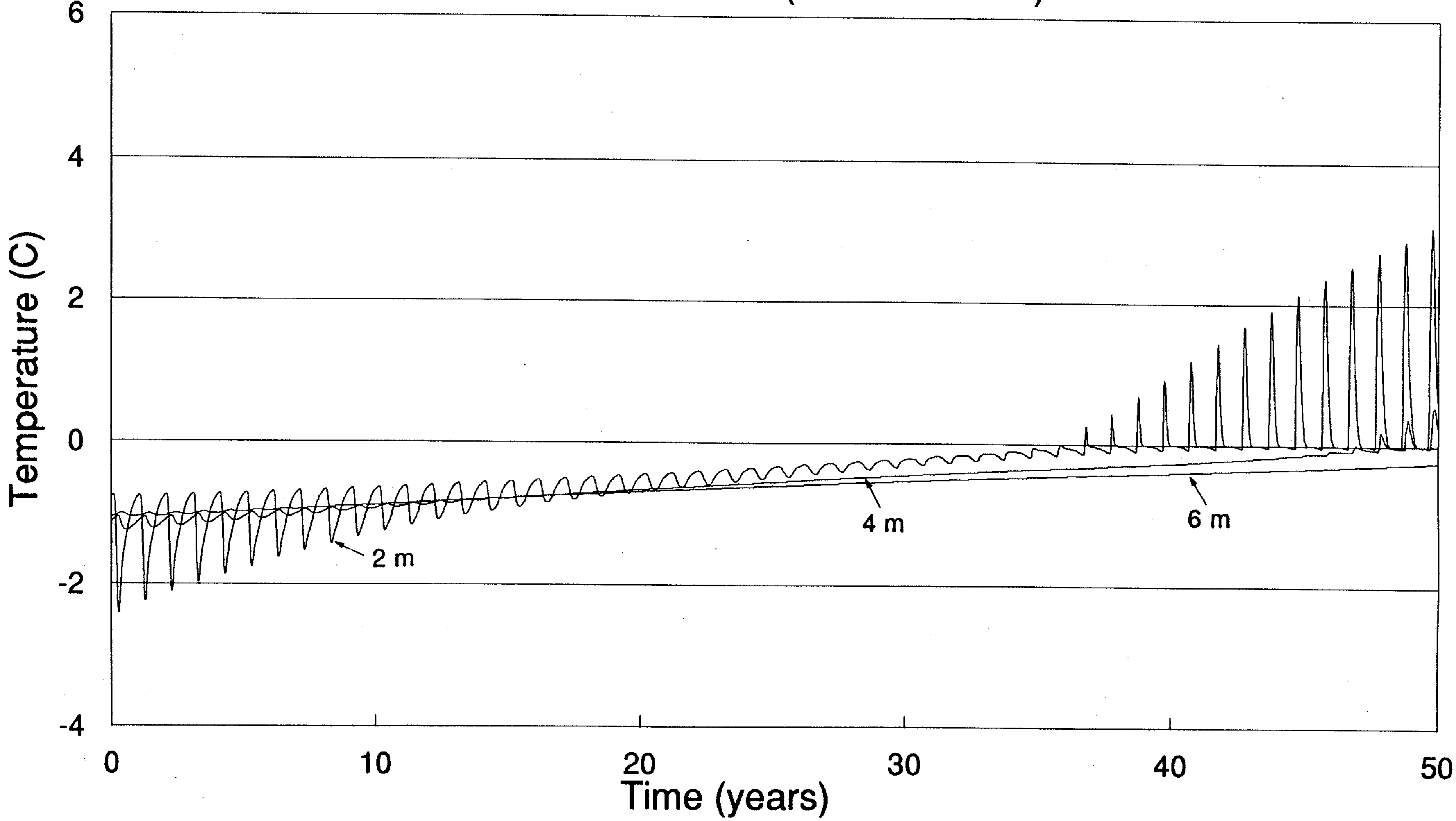
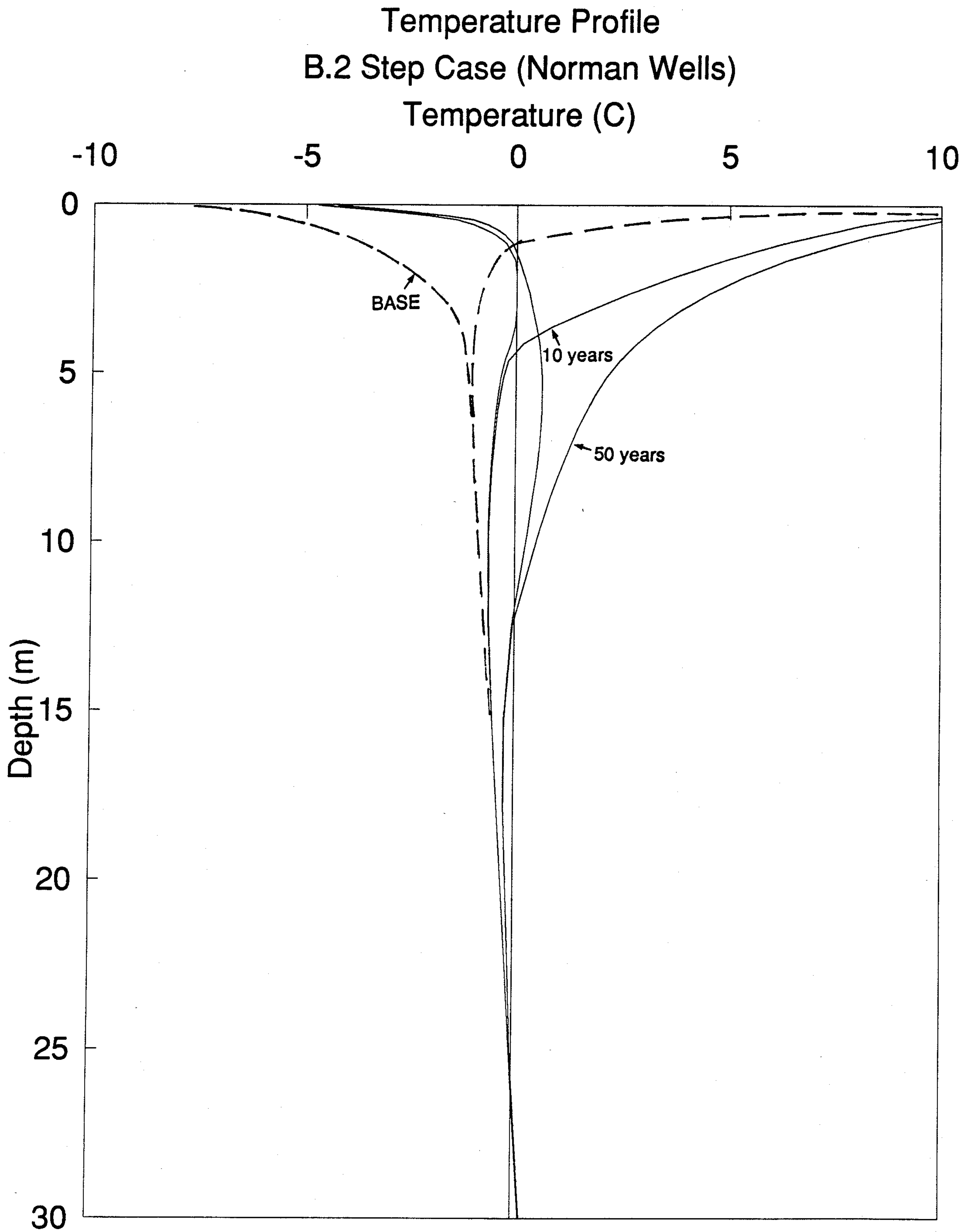


PLATE B.72



Temperature Profile
B.2 Step Case (Norman Wells)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
BASE
10 years
50 years

PLATE B.73

Thaw Depth vs Time
B.2 Step Case (Norman Wells)

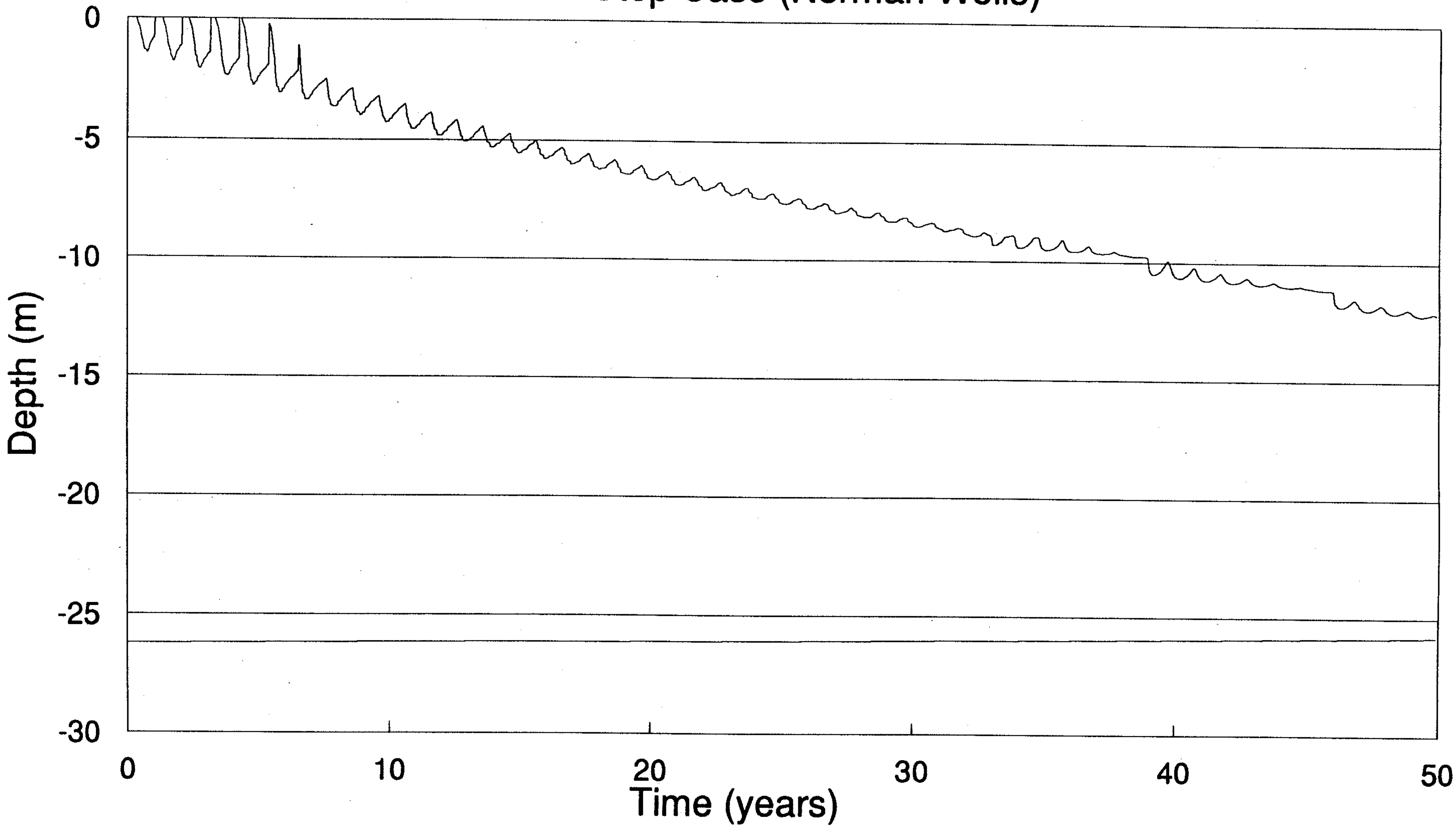


PLATE B.74

Surface Temperature vs Time
B.2 Step Case (Norman Wells)

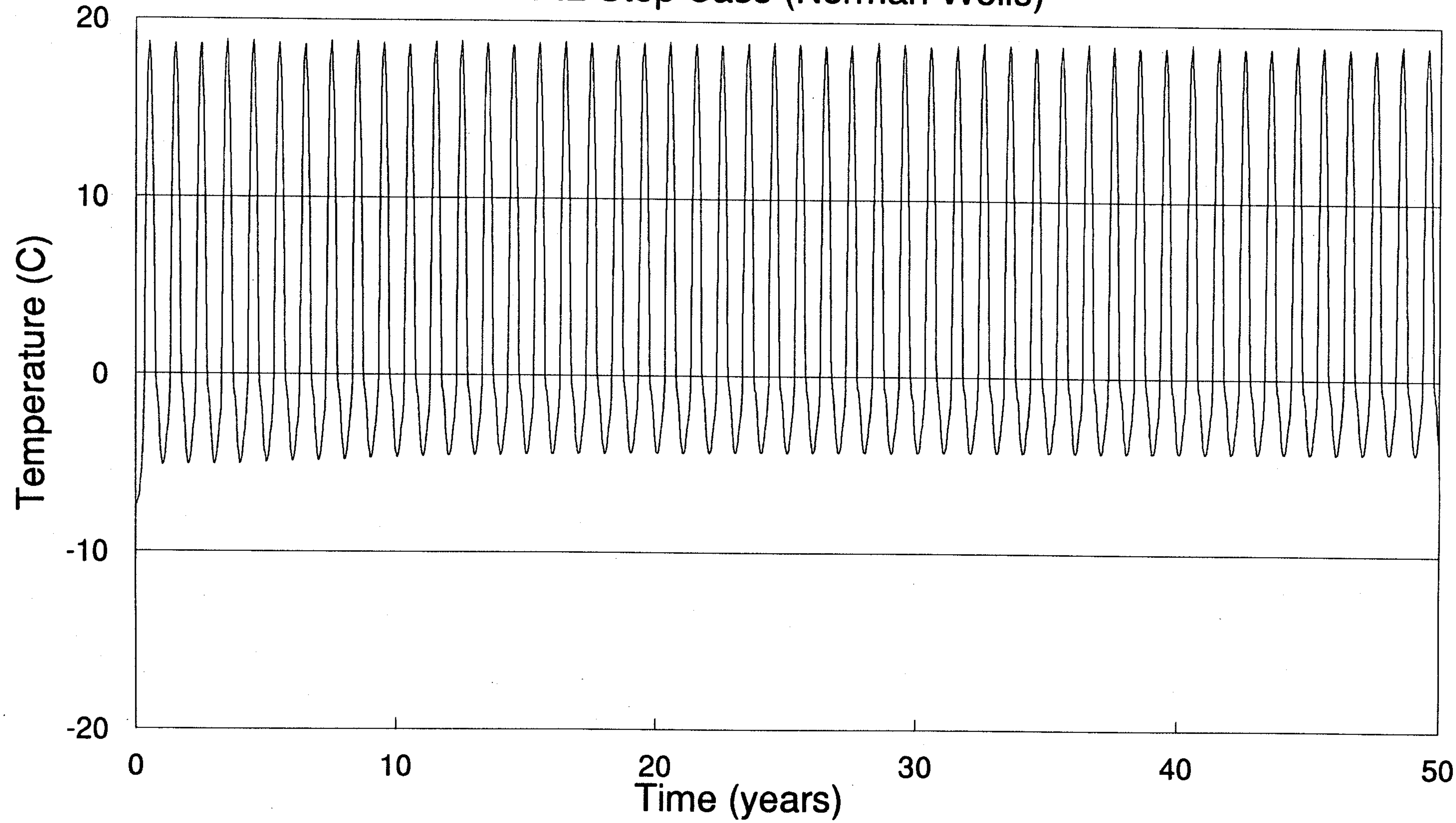


PLATE B.75

Ground Temperature vs Time
B.2 Step Case (Norman Wells)

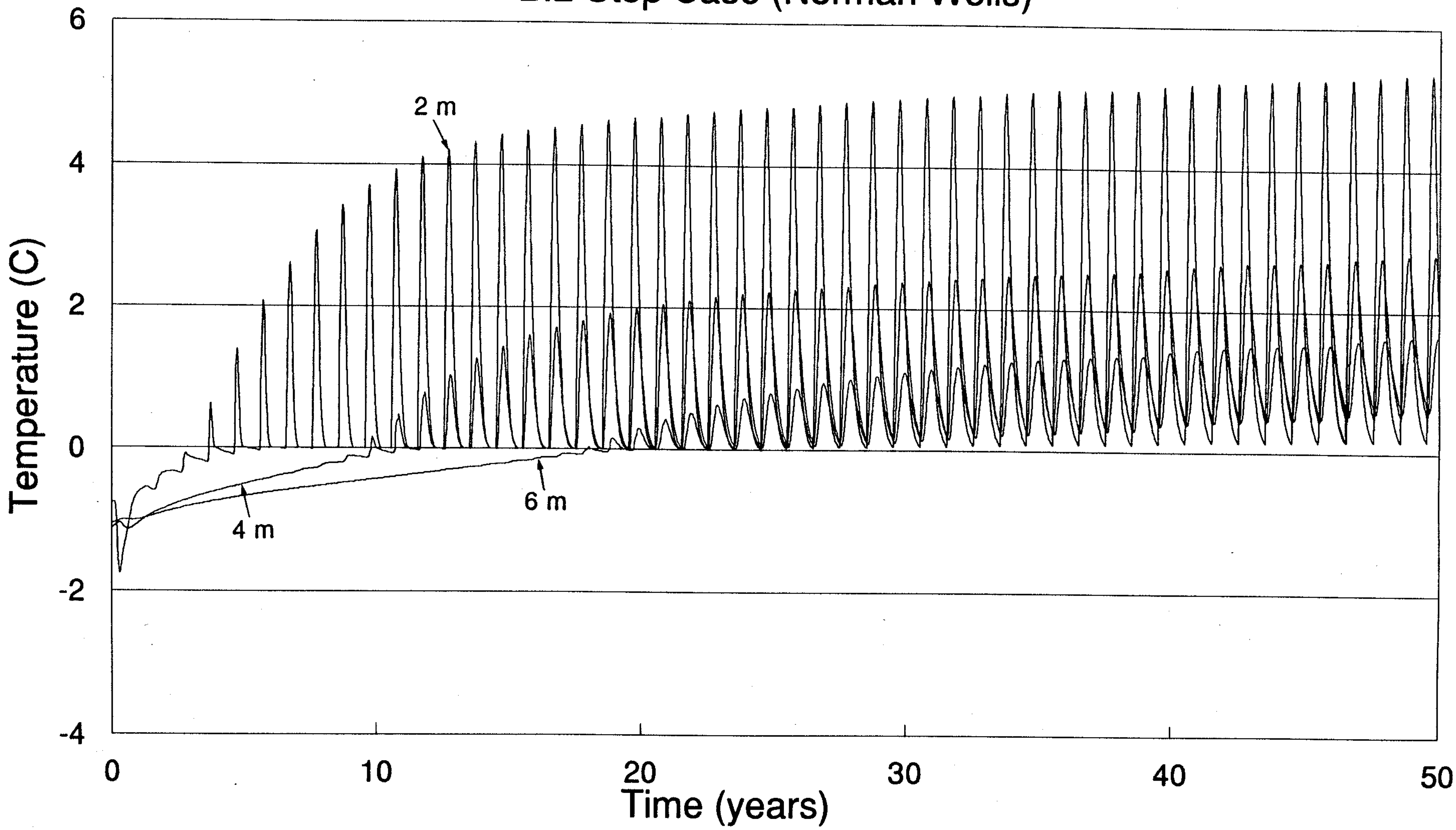
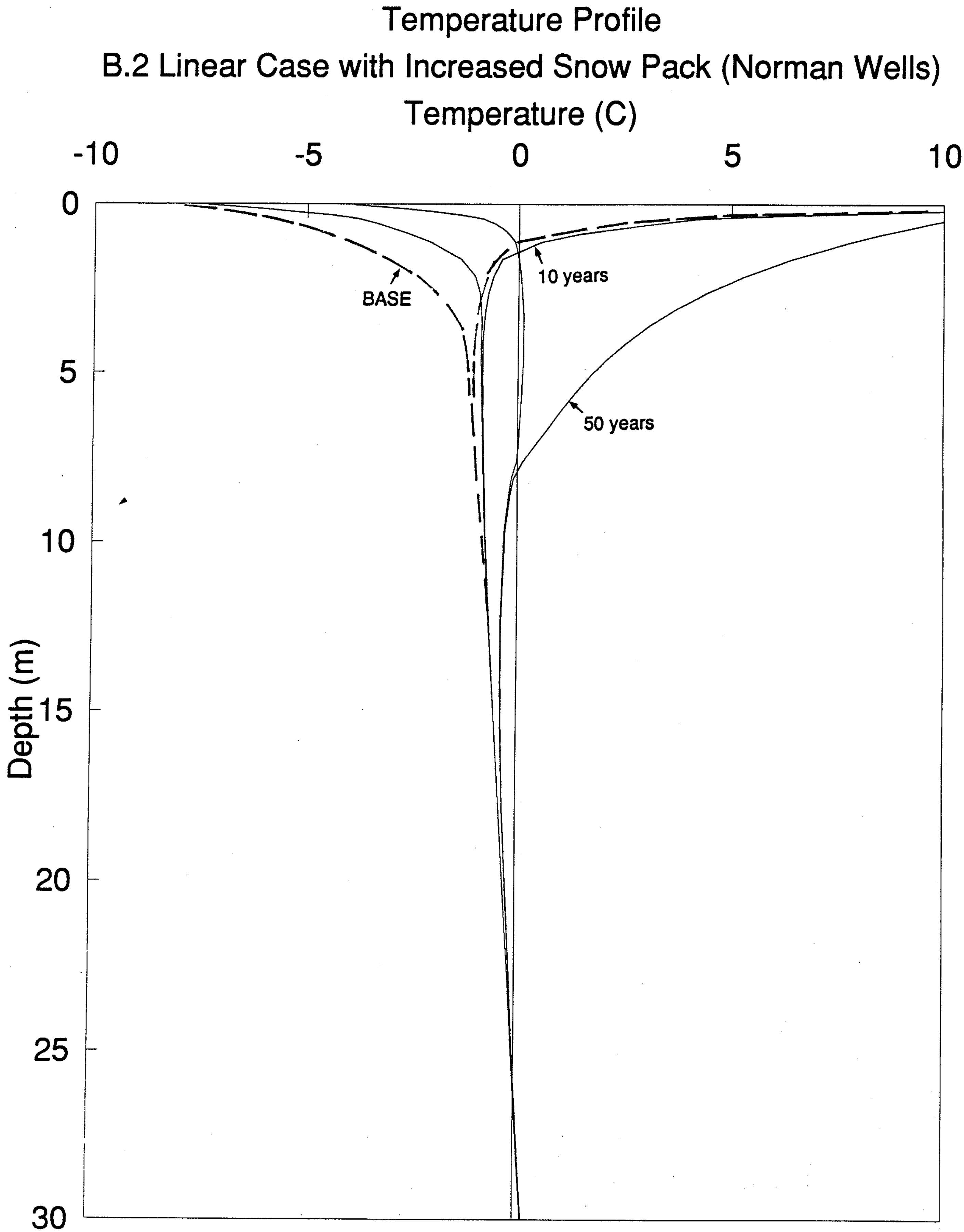


PLATE B.76



Temperature Profile
B.2 Linear Case with Increased Snow Pack (Norman Wells)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
BASE
10 years
50 years

PLATE B.77

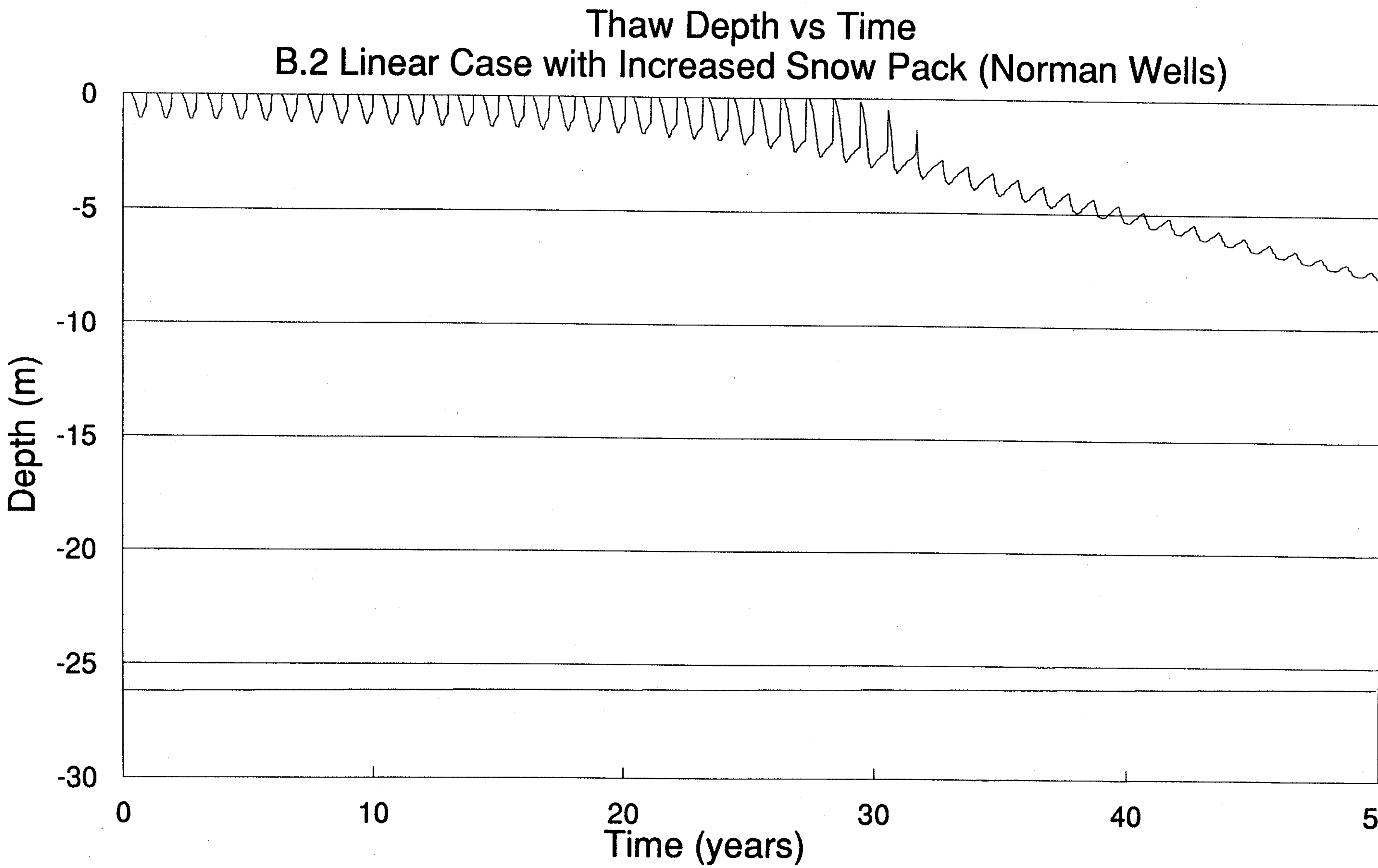
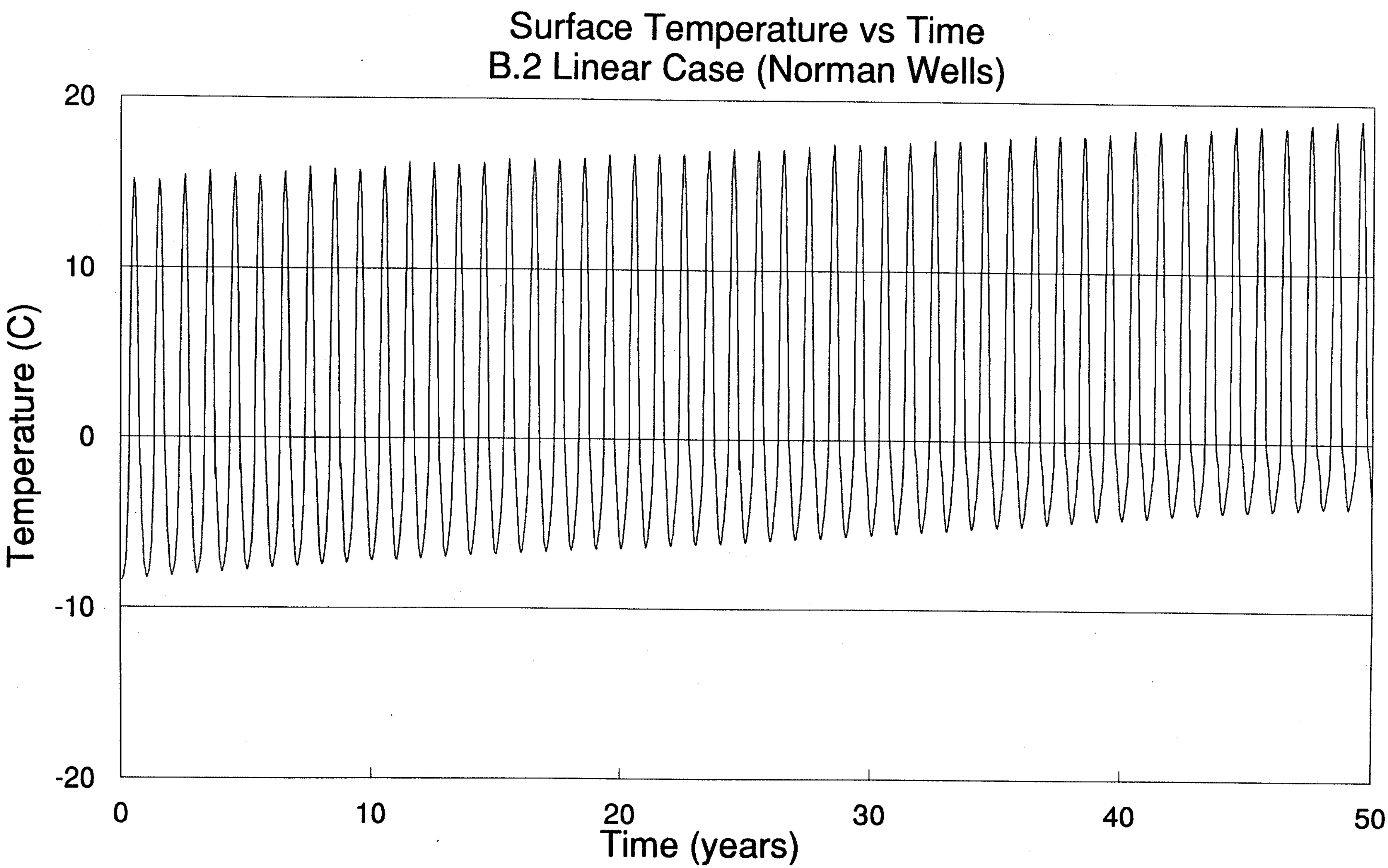

Thaw Depth vs Time
B.2 Linear Case with Increased Snow Pack (Norman Wells)
0
-5
-10
-15
-20
-25
-30
Depth (m)
0
10
20
30
40
50
Time (years)

PLATE B.78



Surface Temperature vs Time
B.2 Linear Case (Norman Wells)
20
10
0
-10
-20
Temperature (C)
0
10
20
30
40
50
Time (years)

PLATE B.79

Ground Temperature vs Time
B.2 Linear Case with Increased Snow Pack (Norman Wells)

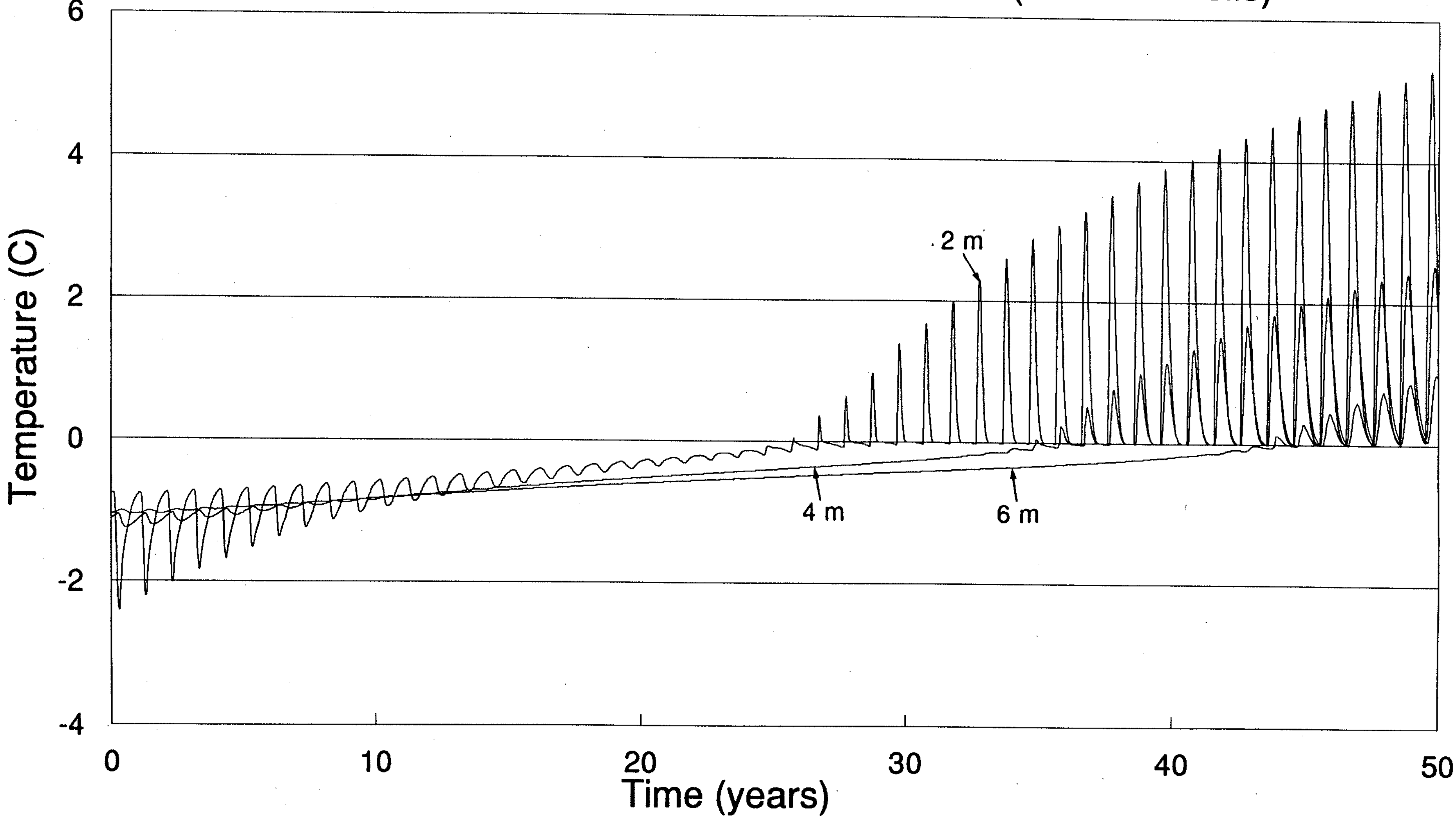
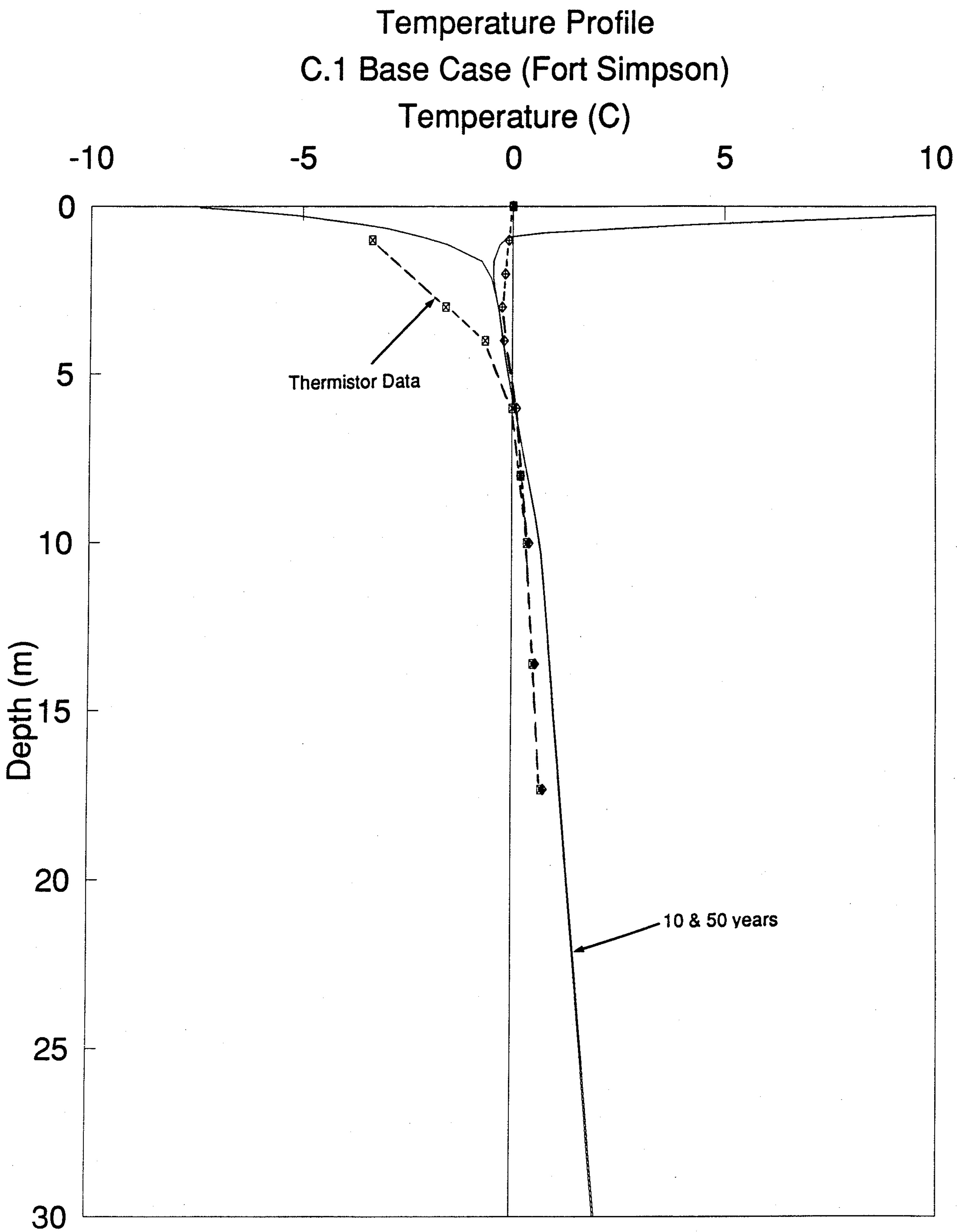


PLATE B.80

SITE C.1 - FORT SIMPSON

Ice-Rich Thick Organics - Peat Plateau



Temperature Profile
C.1 Base Case (Fort Simpson)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
Thermistor Data
10 & 50 years

PLATE B.81

Thaw Depth vs Time
C.1 Base Case (Fort Simpson)

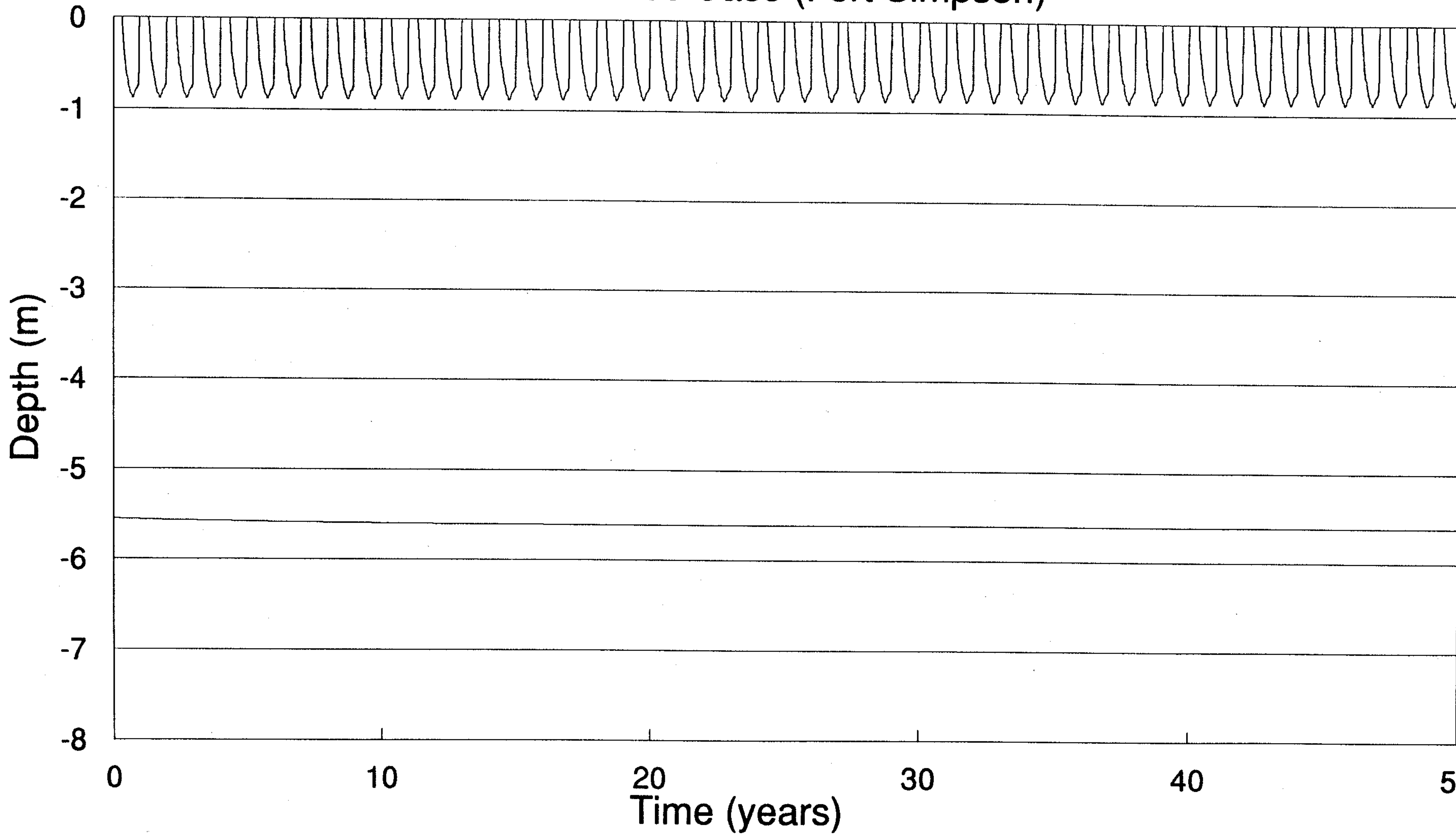


PLATE B.82

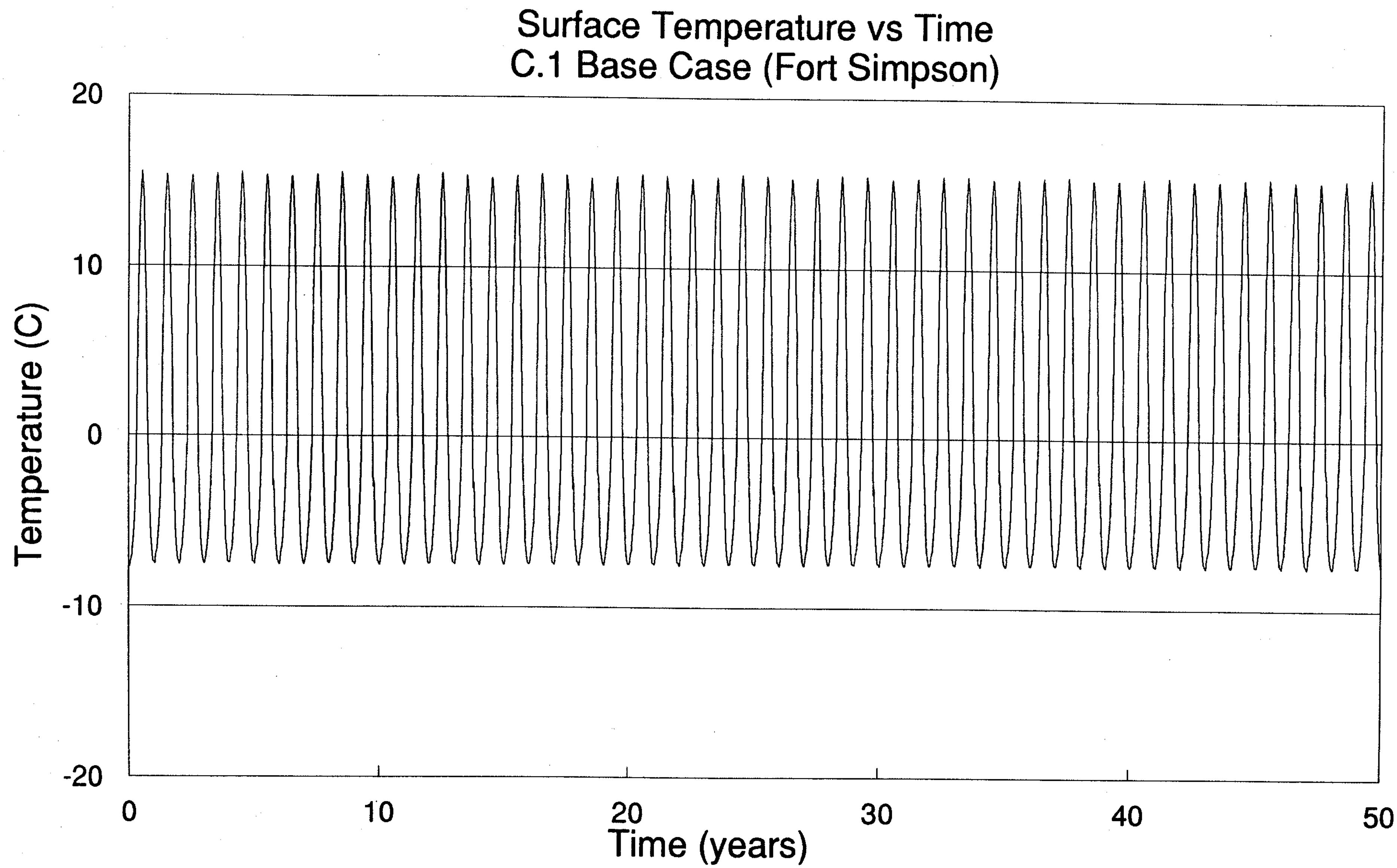
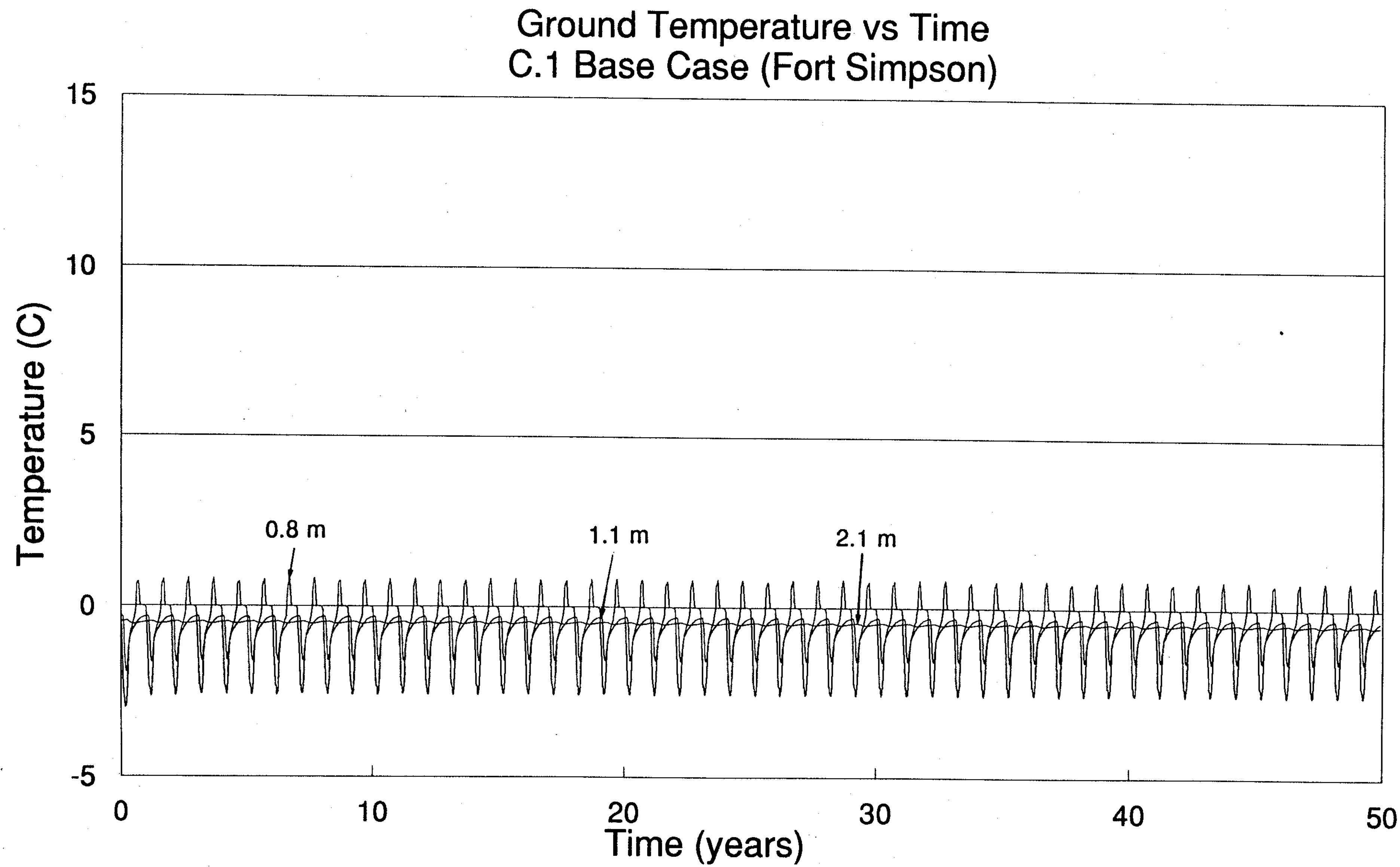
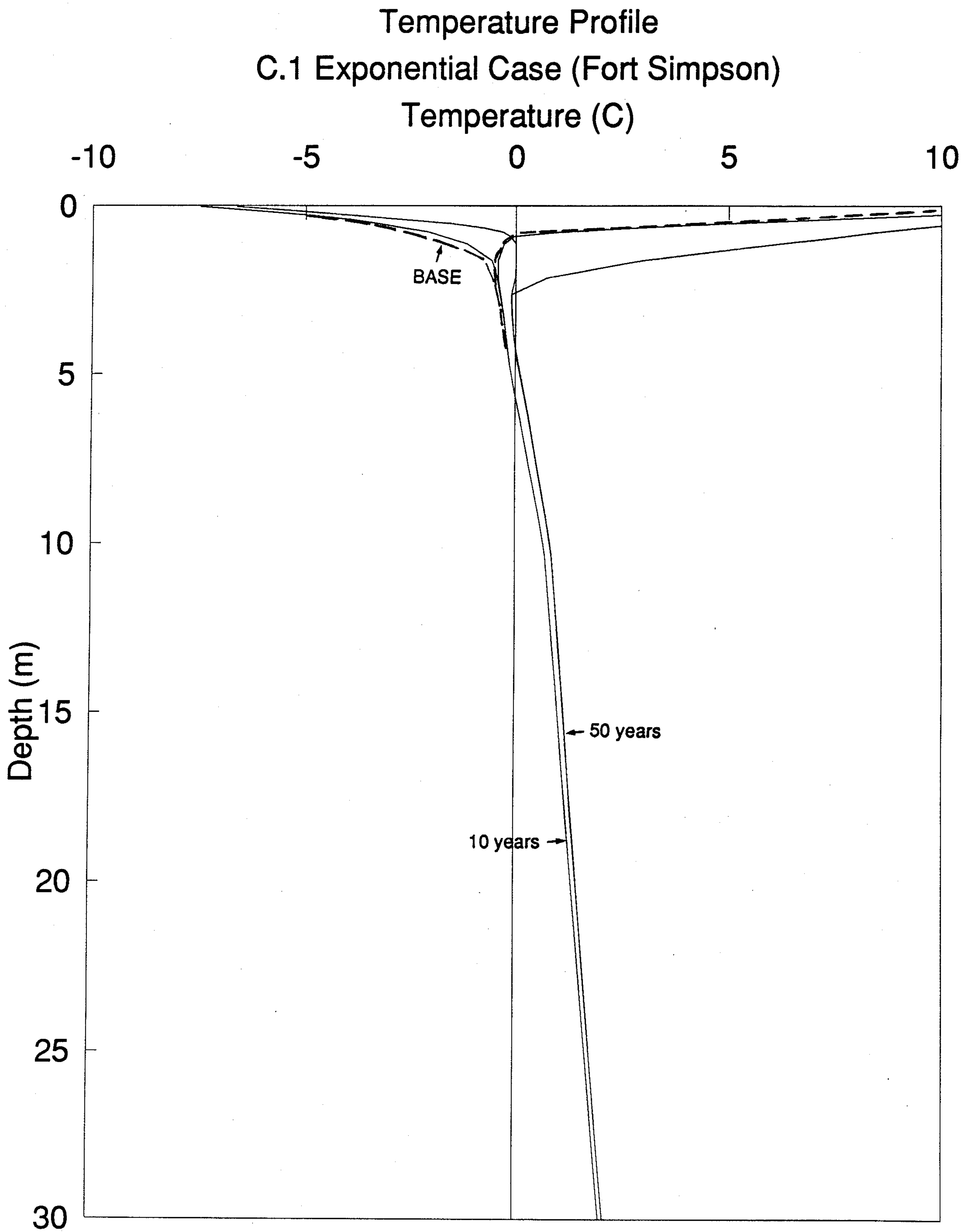

Surface Temperature vs Time
C.1 Base Case (Fort Simpson)
20
10
0
-10
-20
Temperature (C)
0
10
20
30
40
50
Time (years)

PLATE B.83



Ground Temperature vs Time
C.1 Base Case (Fort Simpson)
Temperature (C)
15
10
5
0
-5
0.8 m
1.1 m
2.1 m
0
10
20
30
40
50
Time (years)

PLATE B.84



Temperature Profile
C.1 Exponential Case (Fort Simpson)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
BASE
50 years
10 years

PLATE B.85

Thaw Depth vs Time
C.1 Exponential Case (Fort Simpson)

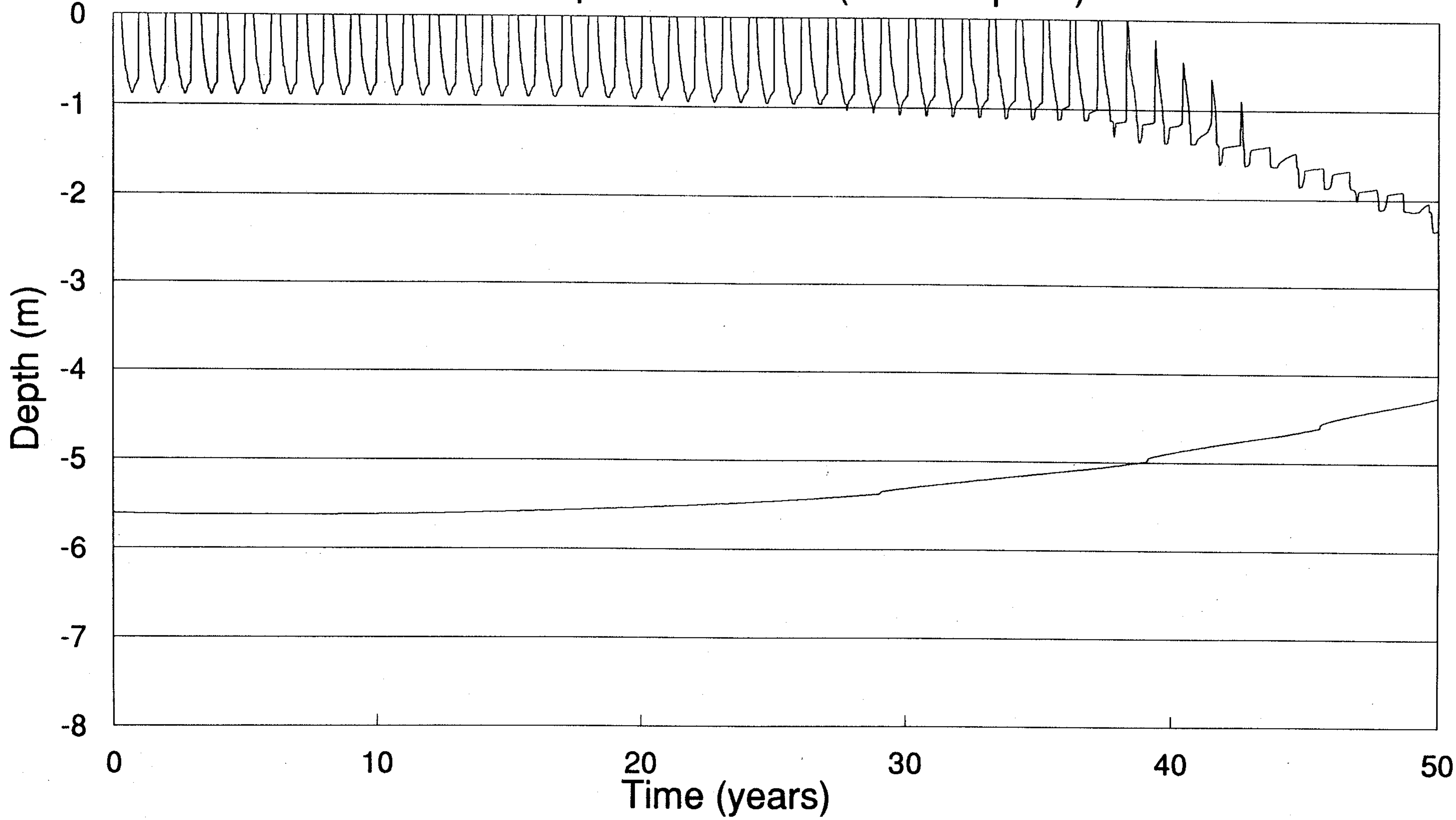


PLATE B.86

Surface Temperature vs Time
C.1 Exponential Case (Fort Simpson)

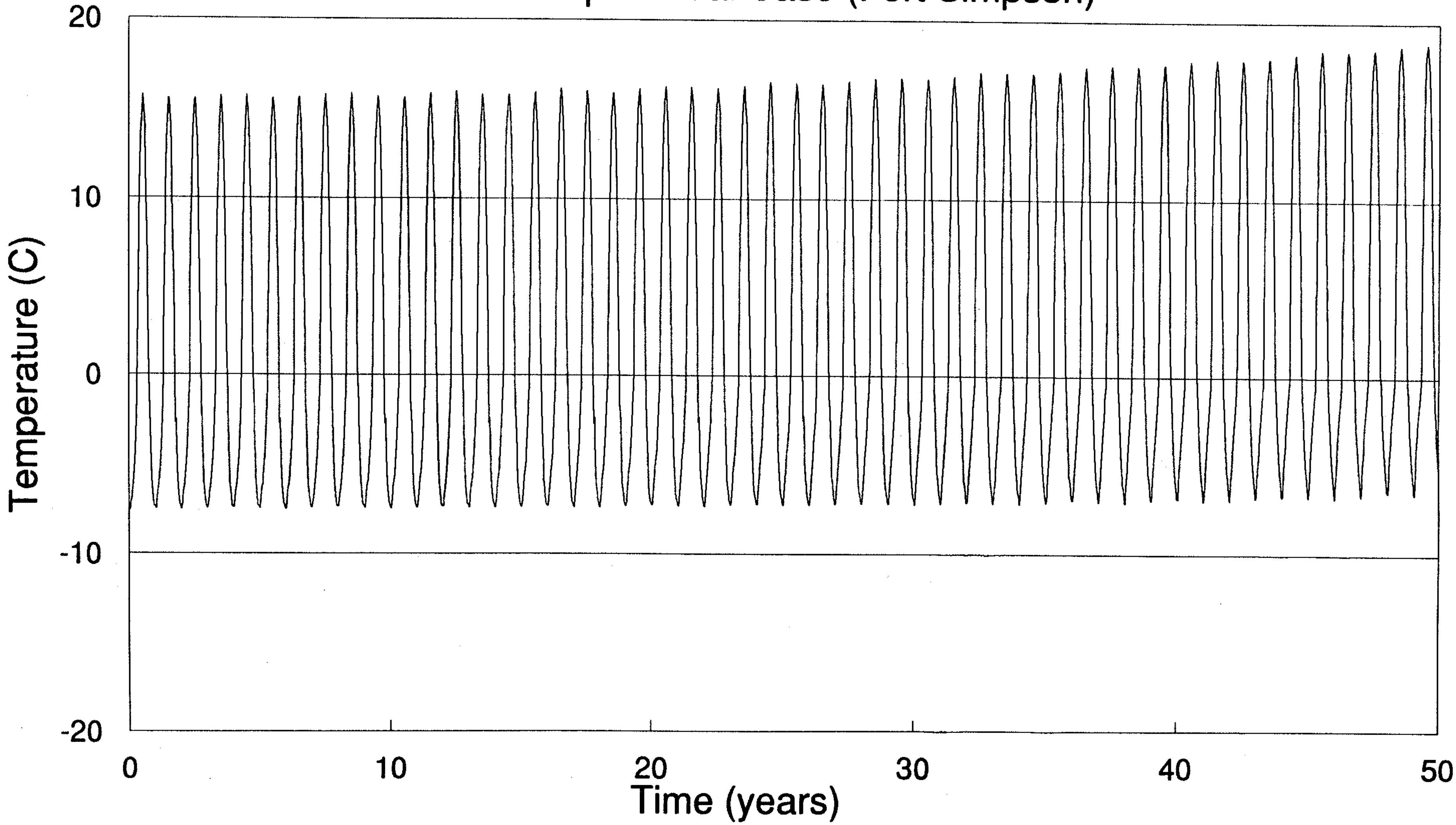


PLATE B.87

Ground Temperature vs Time
C.1 Exponential Case (Fort Simpson)

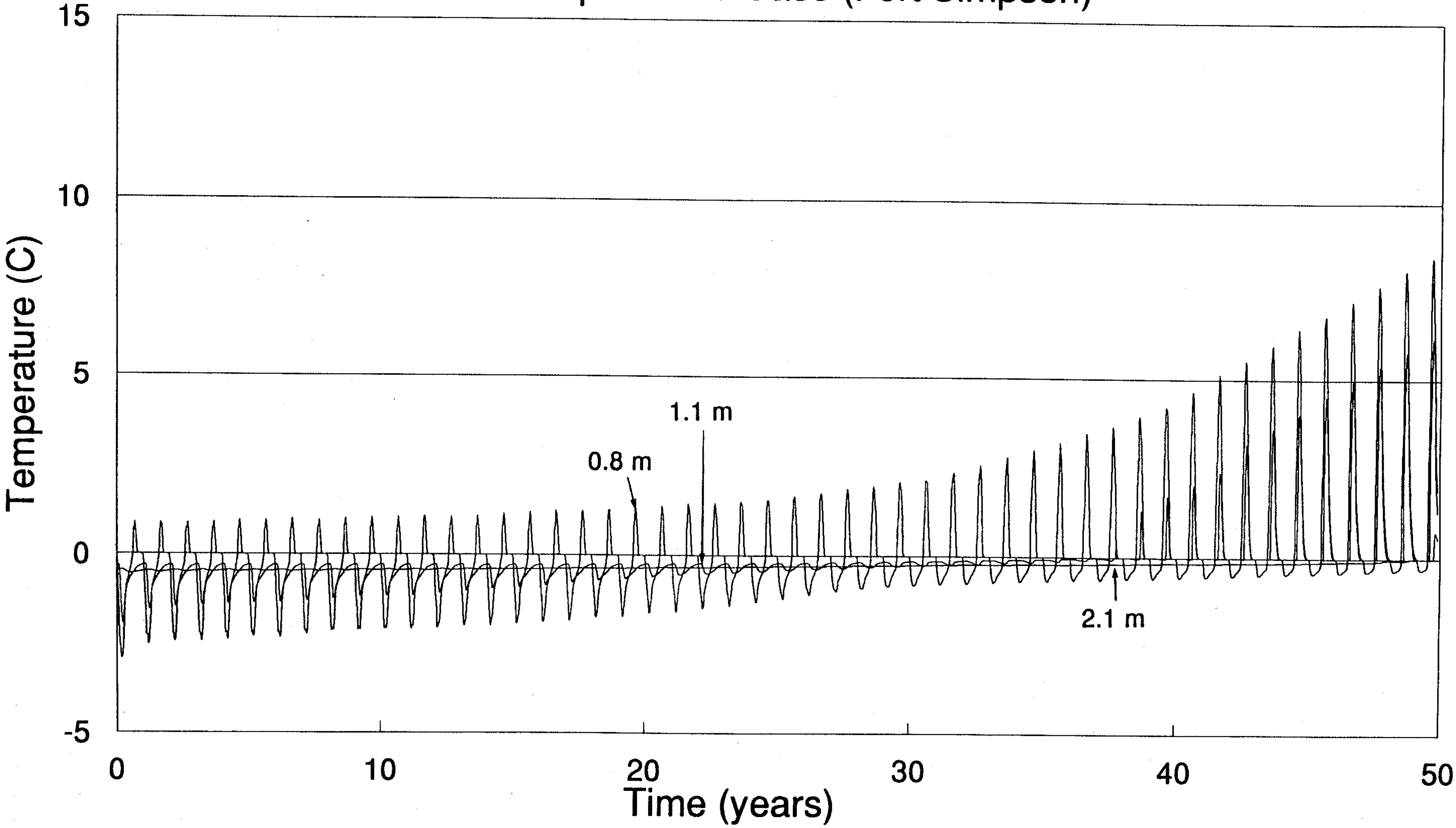


PLATE B.88

Temperature Profile
C.1 Linear Case (Fort Simpson)

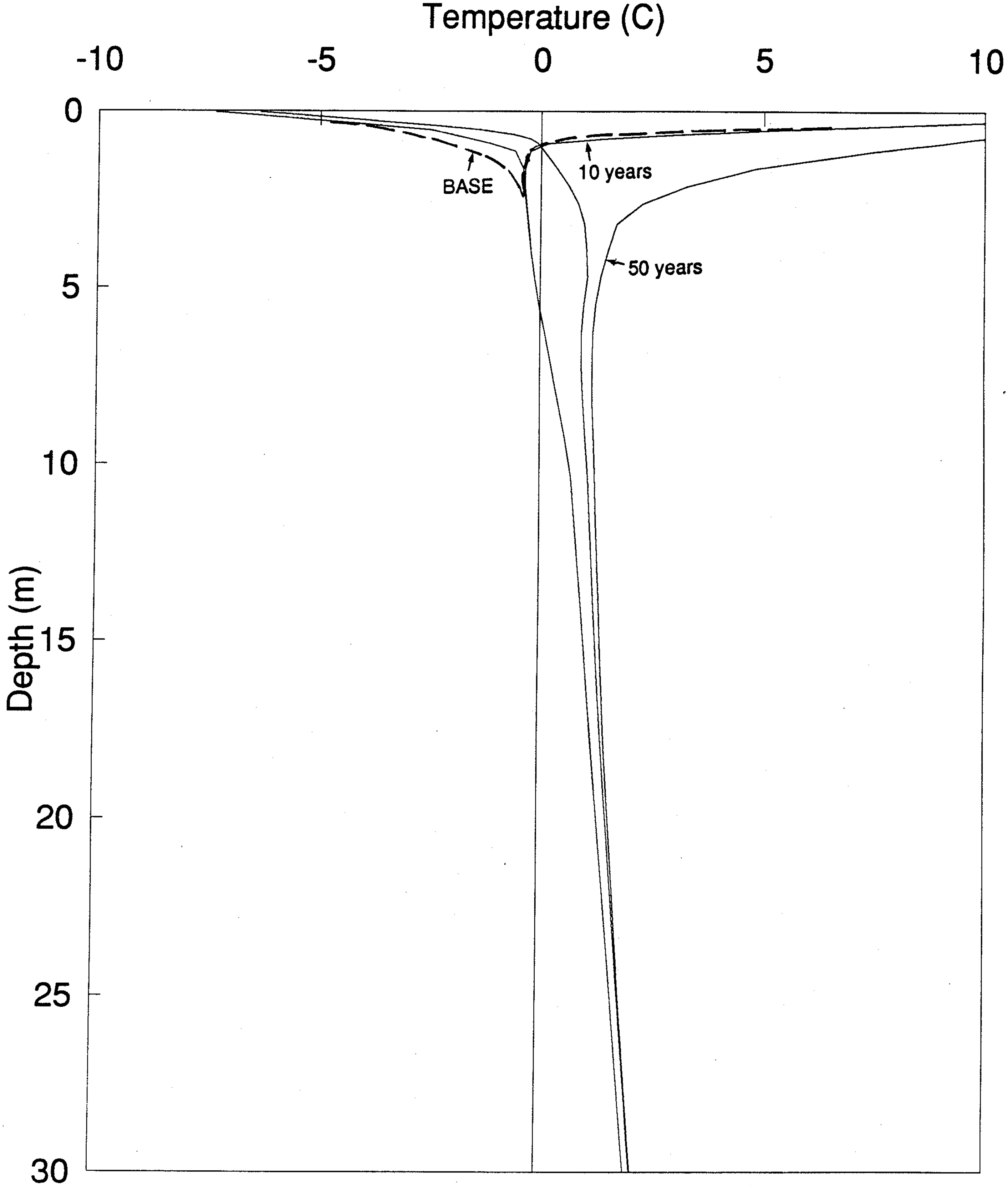


PLATE B.89

Thaw Depth vs Time
C.1 Linear Case (Fort Simpson)

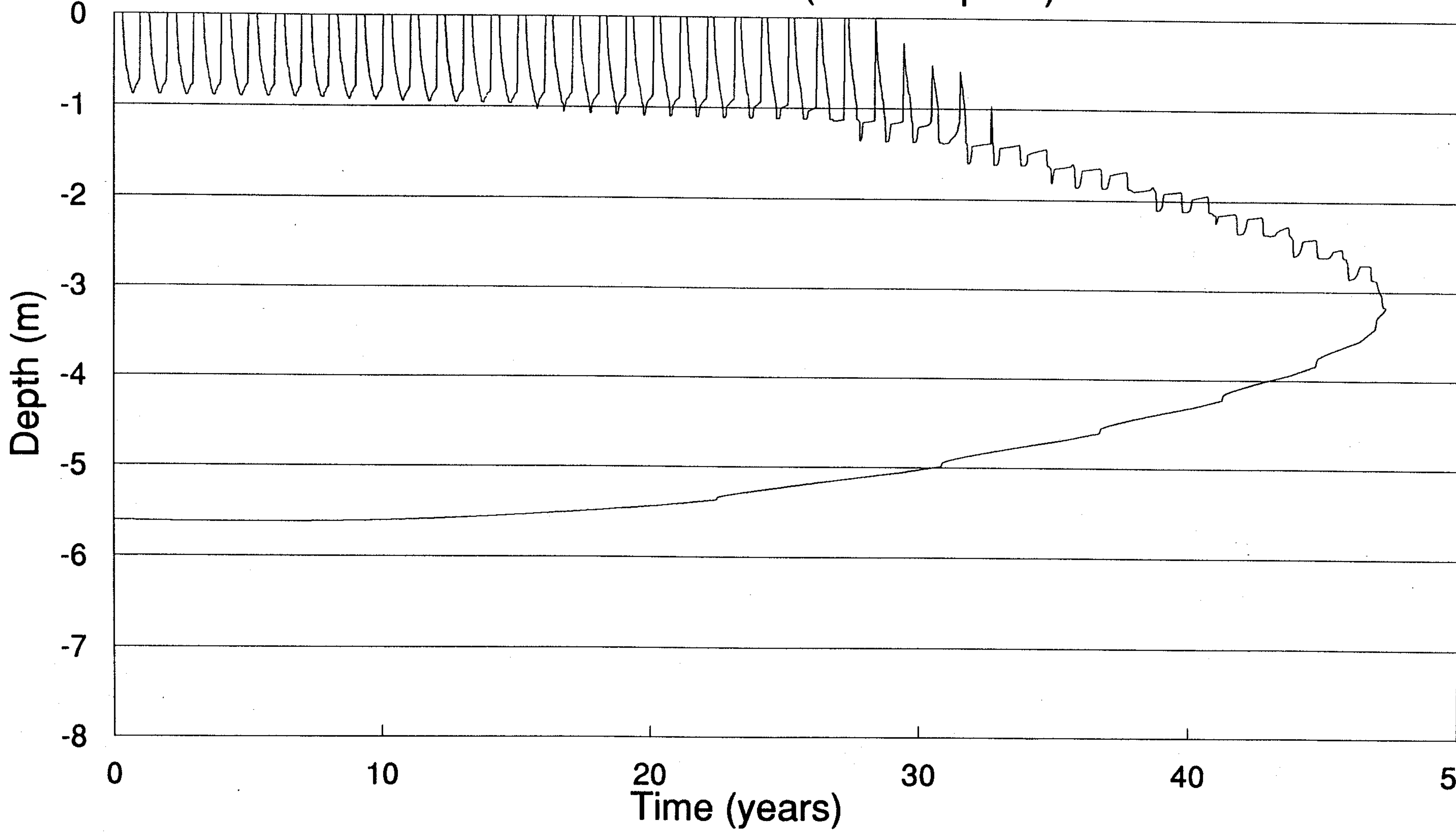
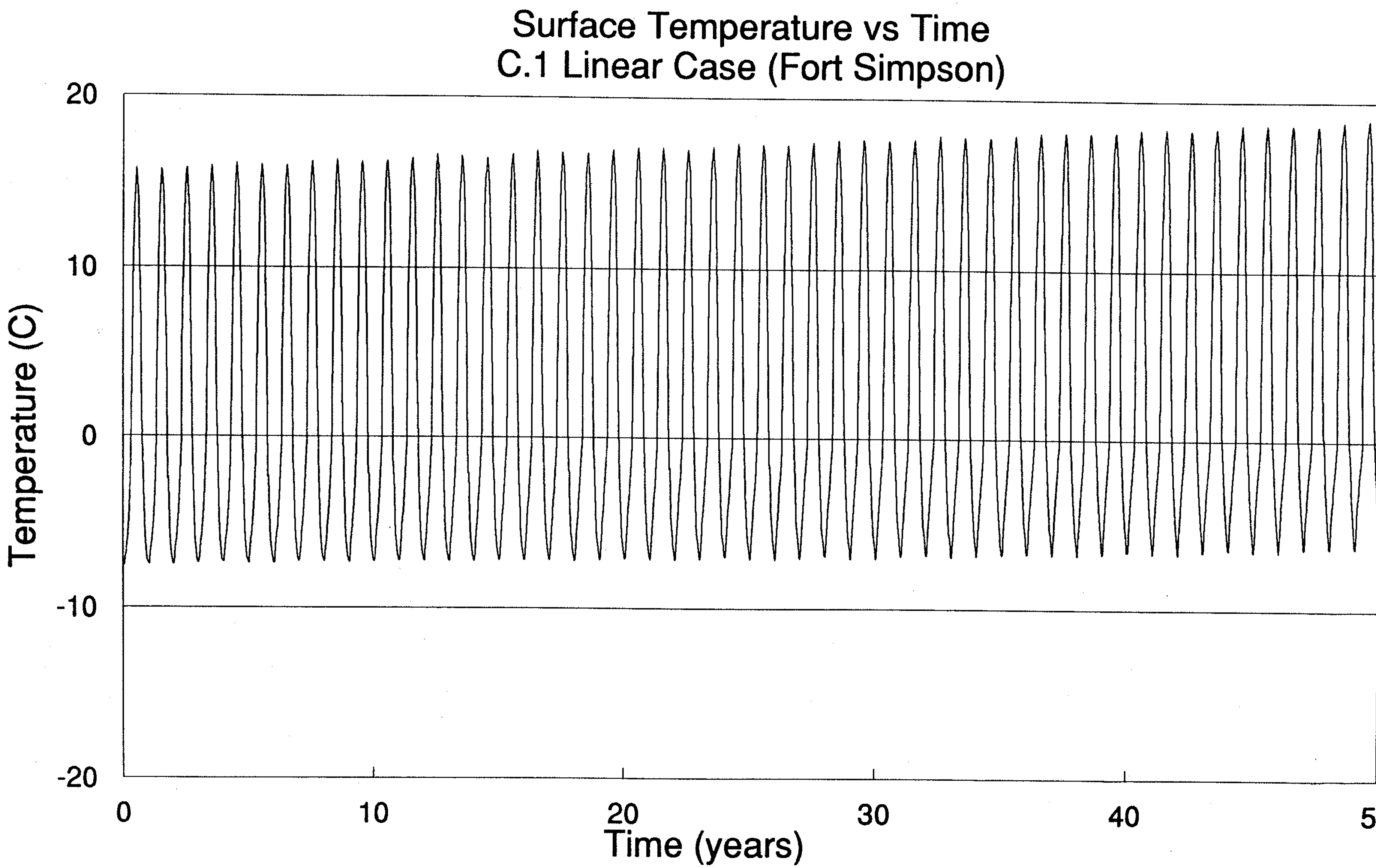


PLATE B.90



Surface Temperature vs Time
C.1 Linear Case (Fort Simpson)
Temperature (C)
20
10
0
-10
-20
0
10
20
30
40
50
Time (years)

PLATE B.91

Ground Temperature vs Time
C.1 Linear Case (Fort Simpson)

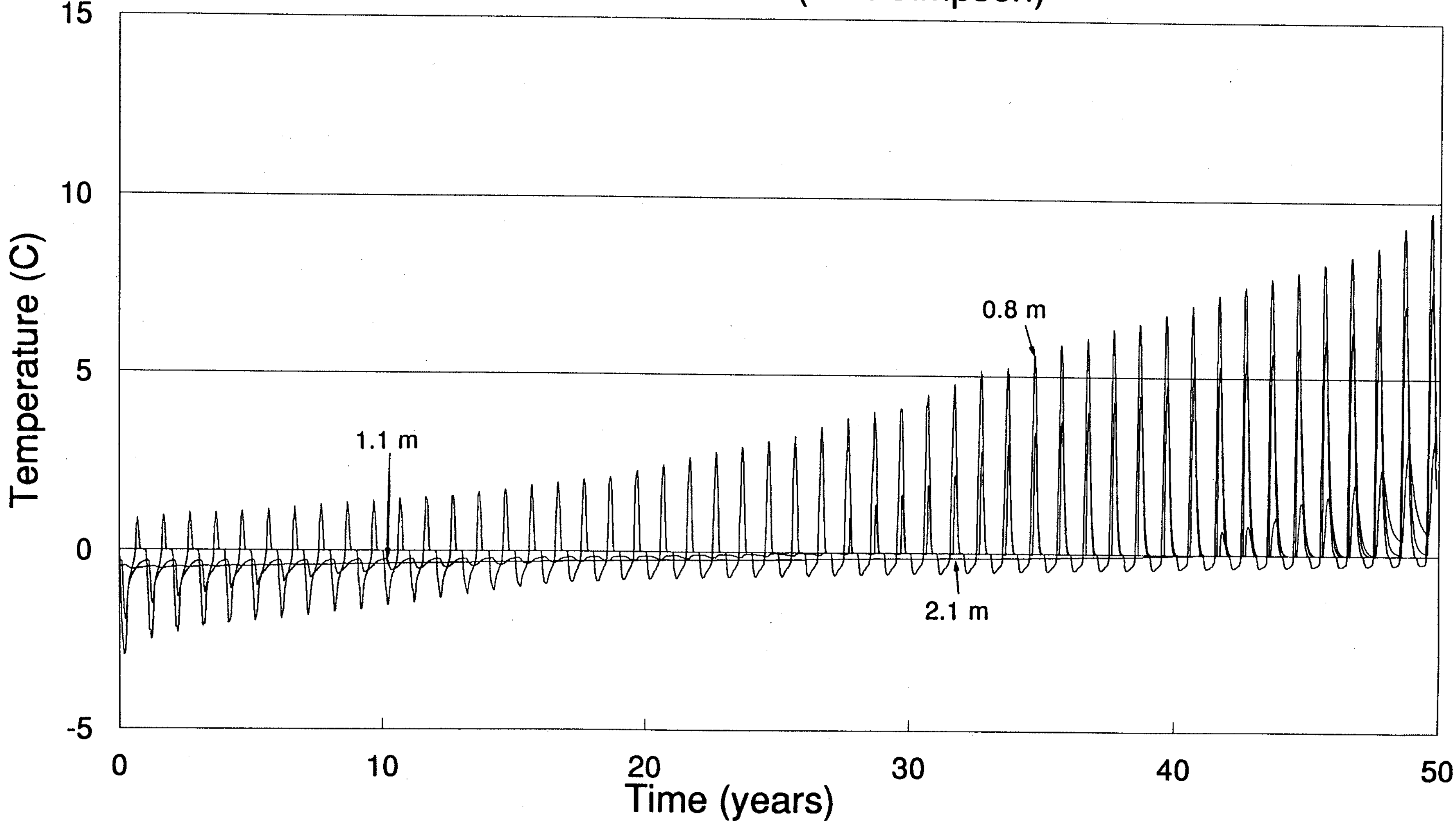


PLATE B.92

Temperature Profile
C.1 Step Case (Fort Simpson)

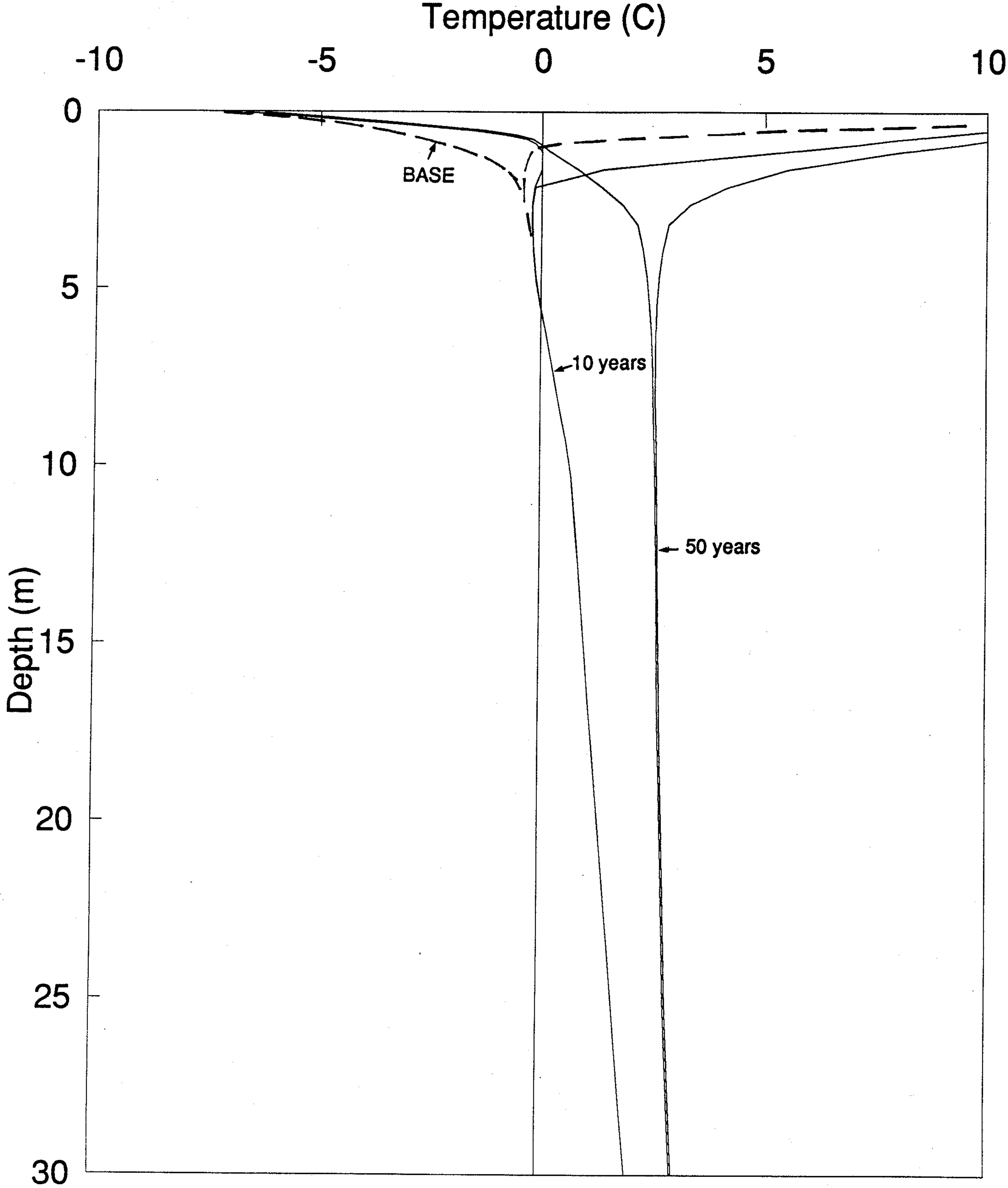


PLATE B.93

Thaw Depth vs Time
C.1 Step Case (Fort Simpson)

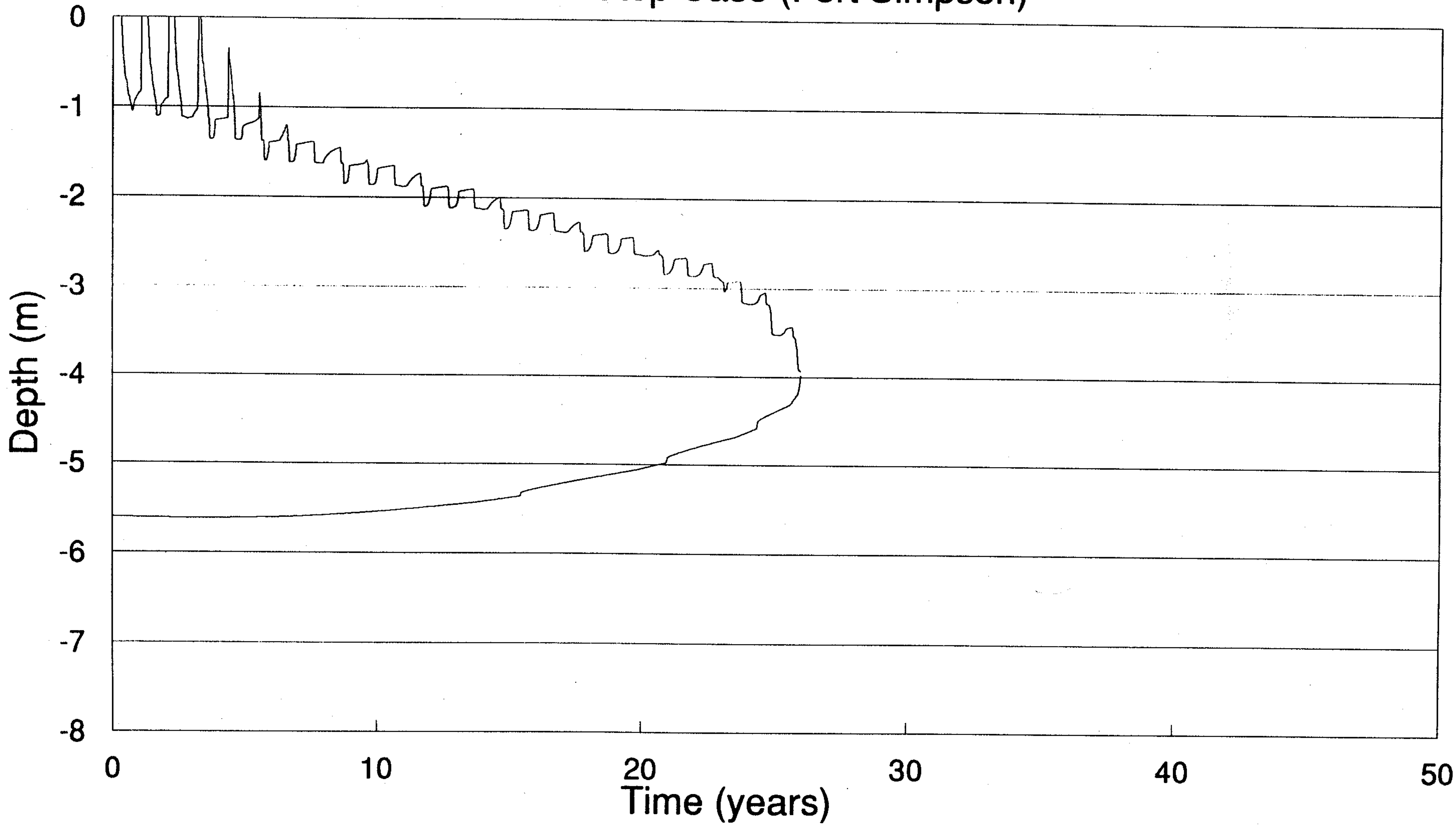


PLATE B.94

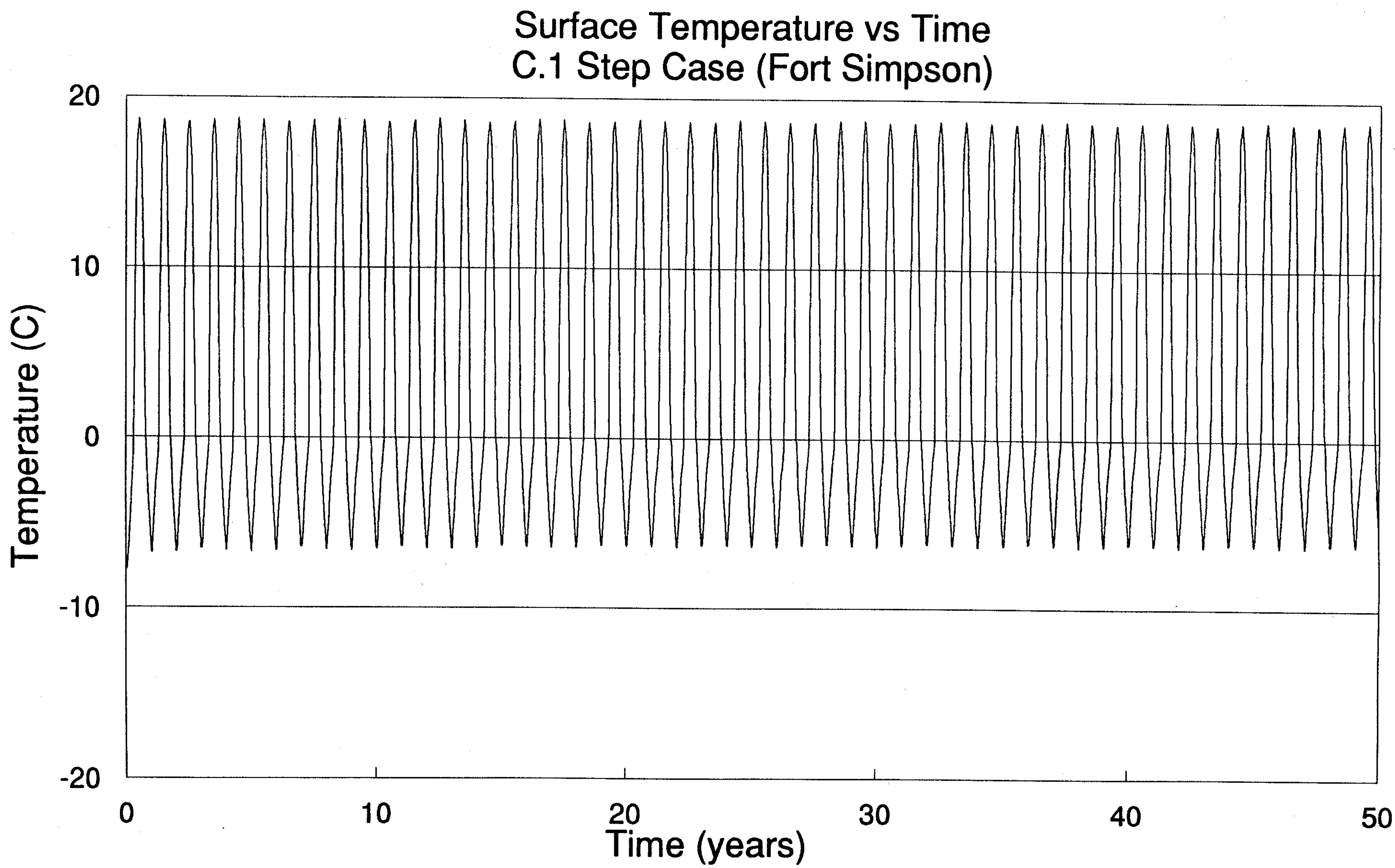
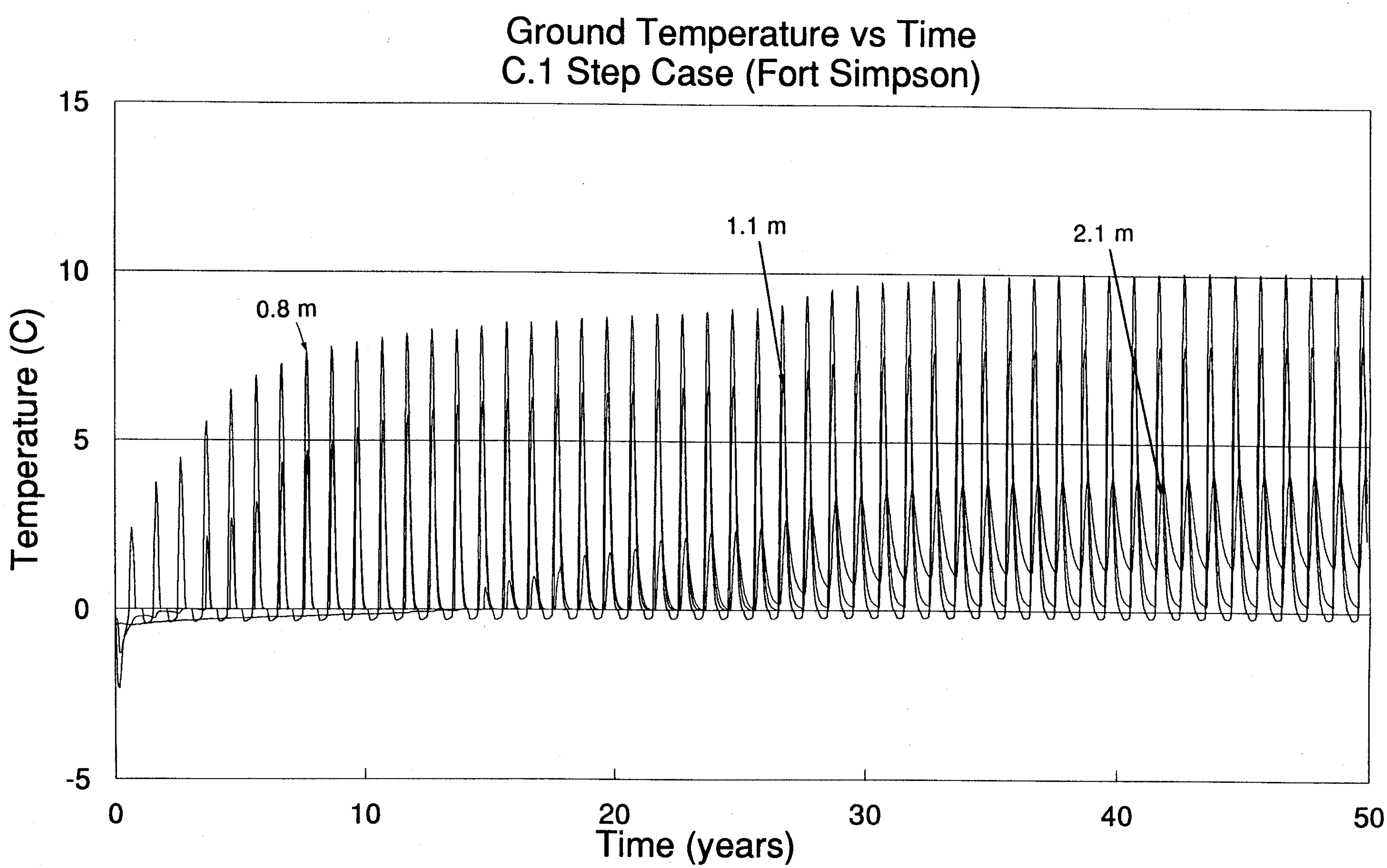

Surface Temperature vs Time
C.1 Step Case (Fort Simpson)
Temperature (C)
20
10
0
-10
-20
0
10
20
30
40
50
Time (years)

PLATE B.95



Ground Temperature vs Time
C.1 Step Case (Fort Simpson)
Temperature (C)
15
10
5
0
-5
Time (years)
0
10
20
30
40
50
0.8 m
1.1 m
2.1 m

PLATE B.96

Temperature Profile

C.1 Linear Case with Increased Snow Pack (Fort Simpson)

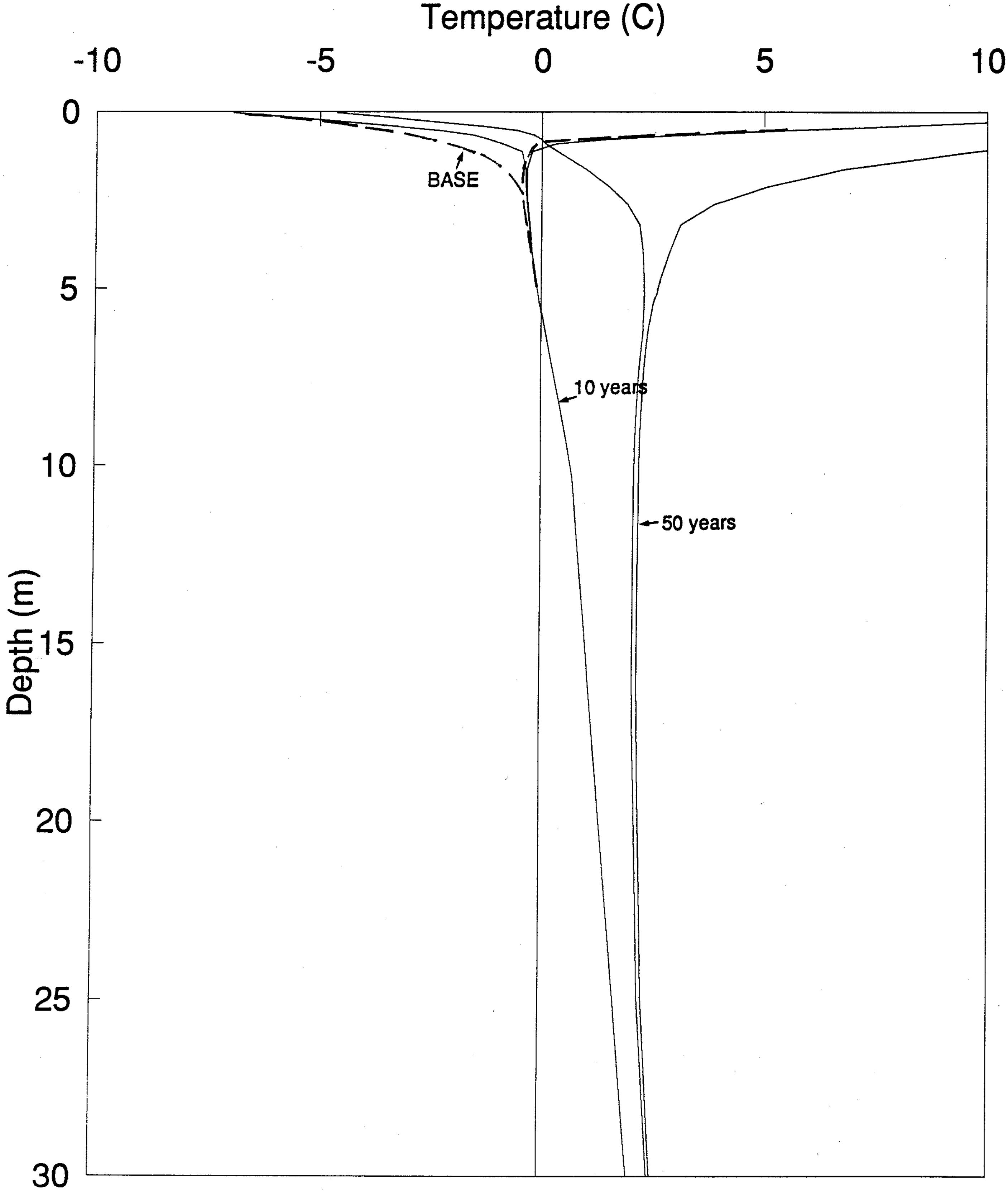


PLATE B.97

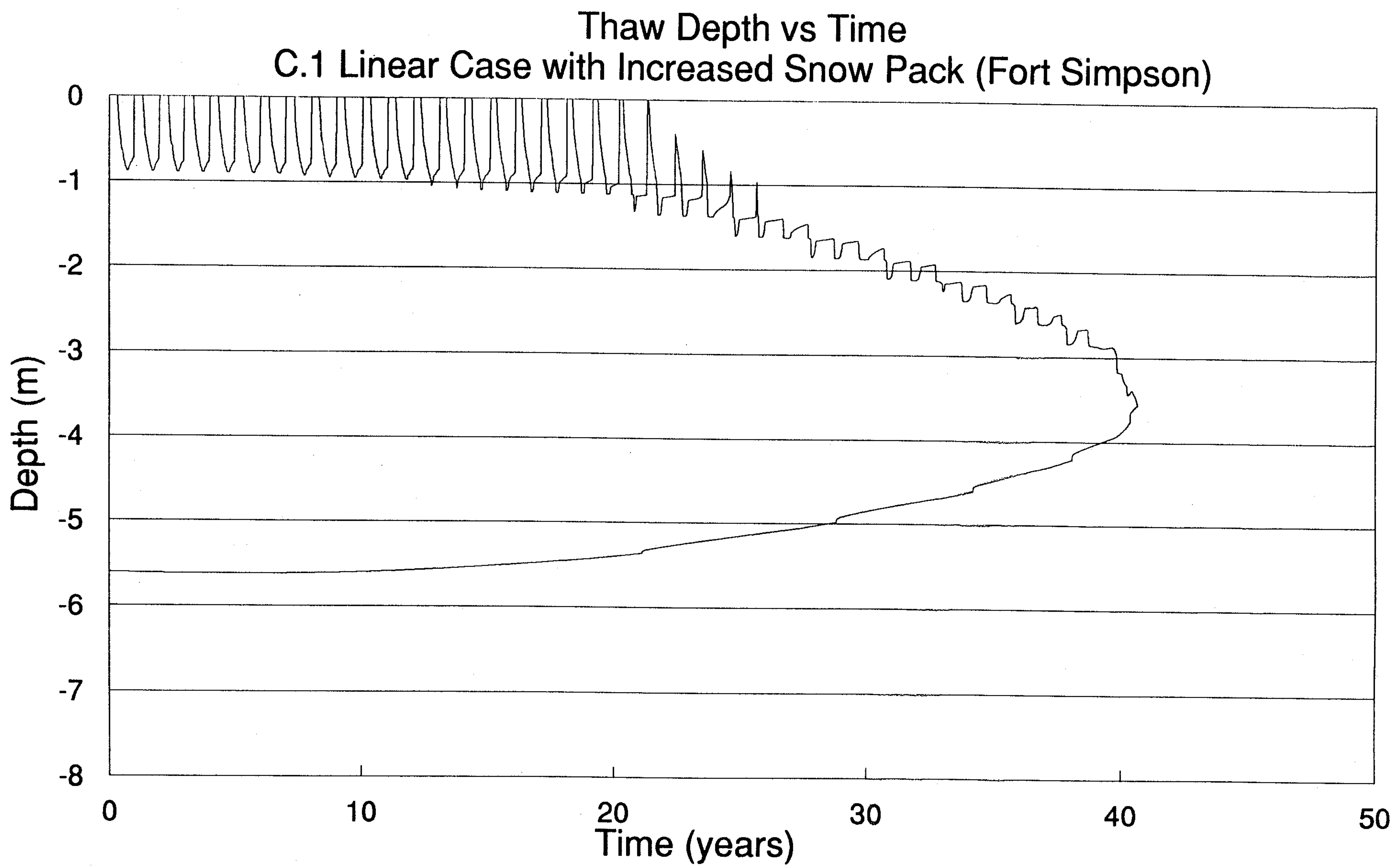

Thaw Depth vs Time
C.1 Linear Case with Increased Snow Pack (Fort Simpson)
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
Time (years)
0
10
20
30
40
50

PLATE B.98

Surface Temperature vs Time
C.1 Linear Case with Increased Snow Pack (Fort Simpson)

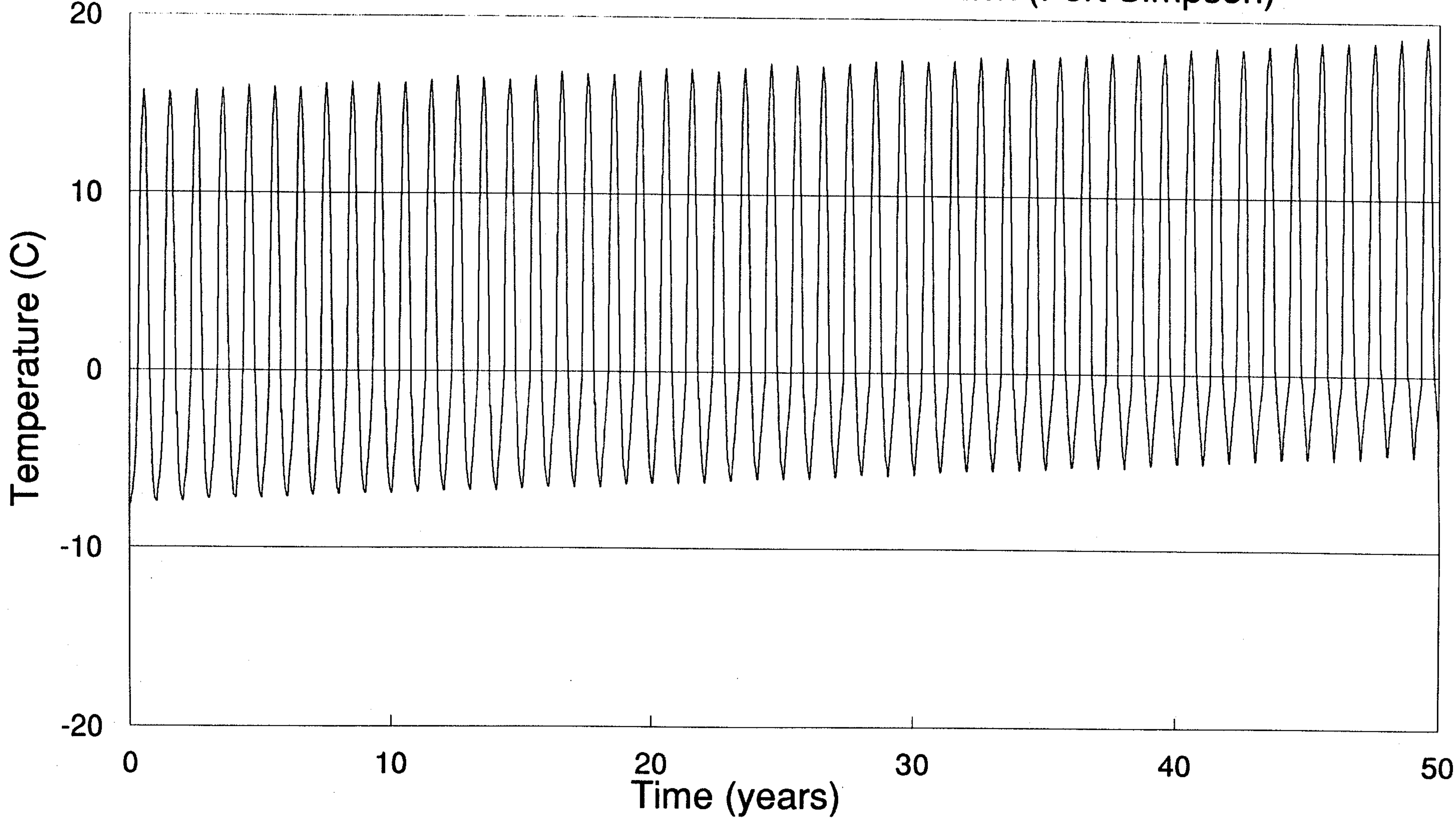


PLATE B.99

Ground Temperature vs Time
C.1 Linear Case with Increased Snow Pack (Fort Simpson)

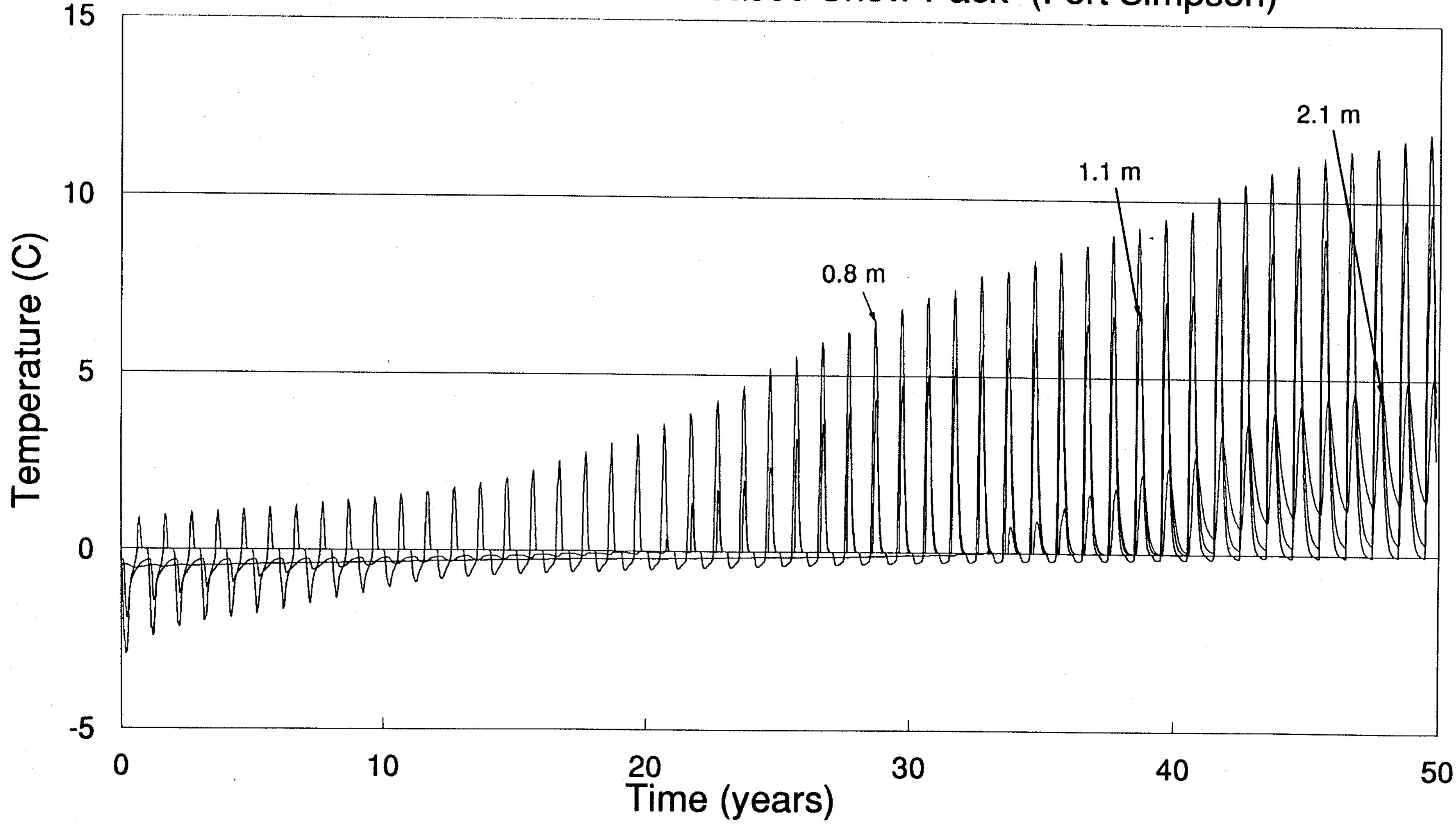
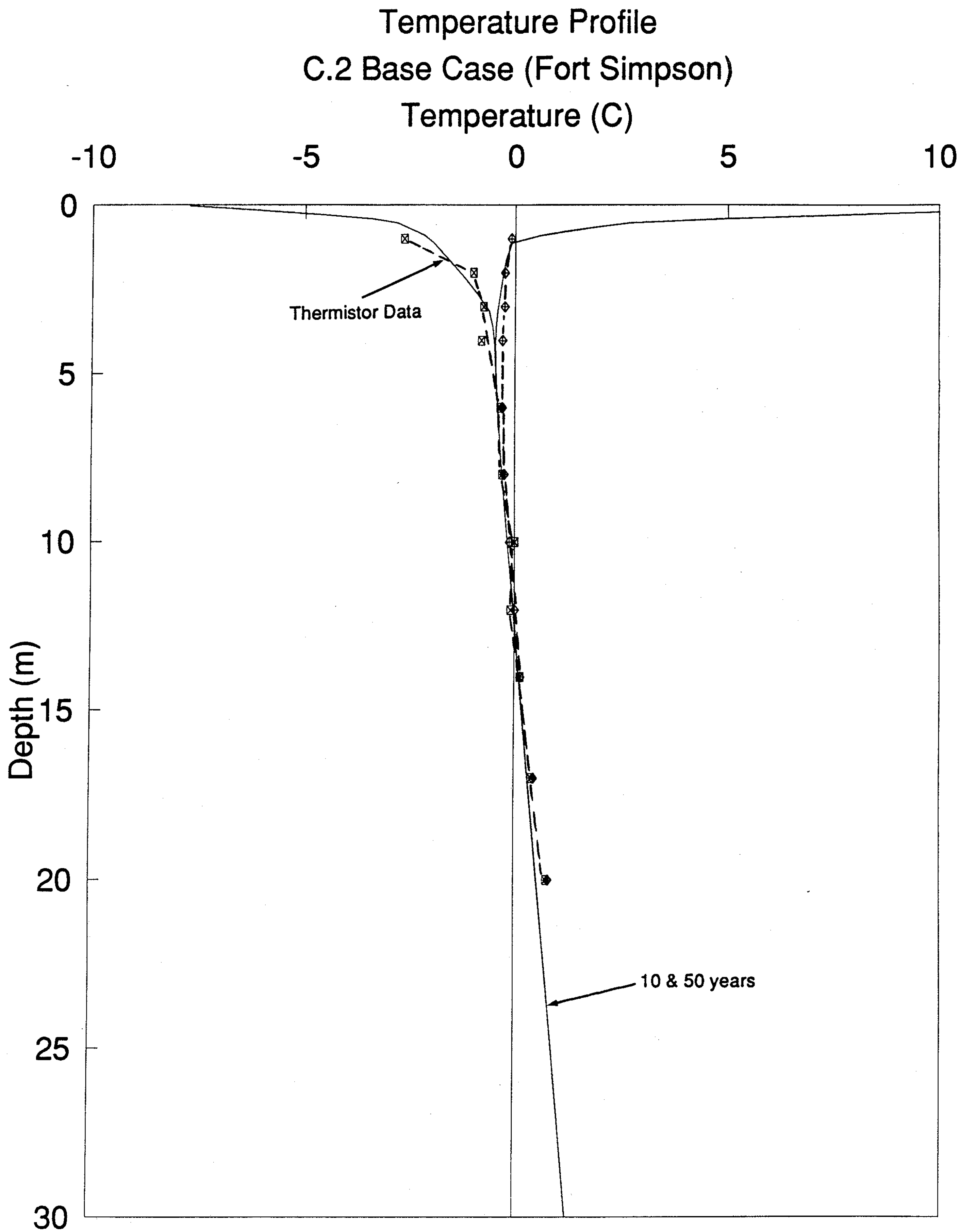


PLATE B.100

SITE C.2 - FORT SIMPSON

Ice-Poor in the Top 5 m; Ice-Rich Below 5 m



Temperature Profile
C.2 Base Case (Fort Simpson)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
Thermistor Data
10 & 50 years

PLATE B.101

Thaw Depth vs Time
C.2 Base Case (Fort Simpson)

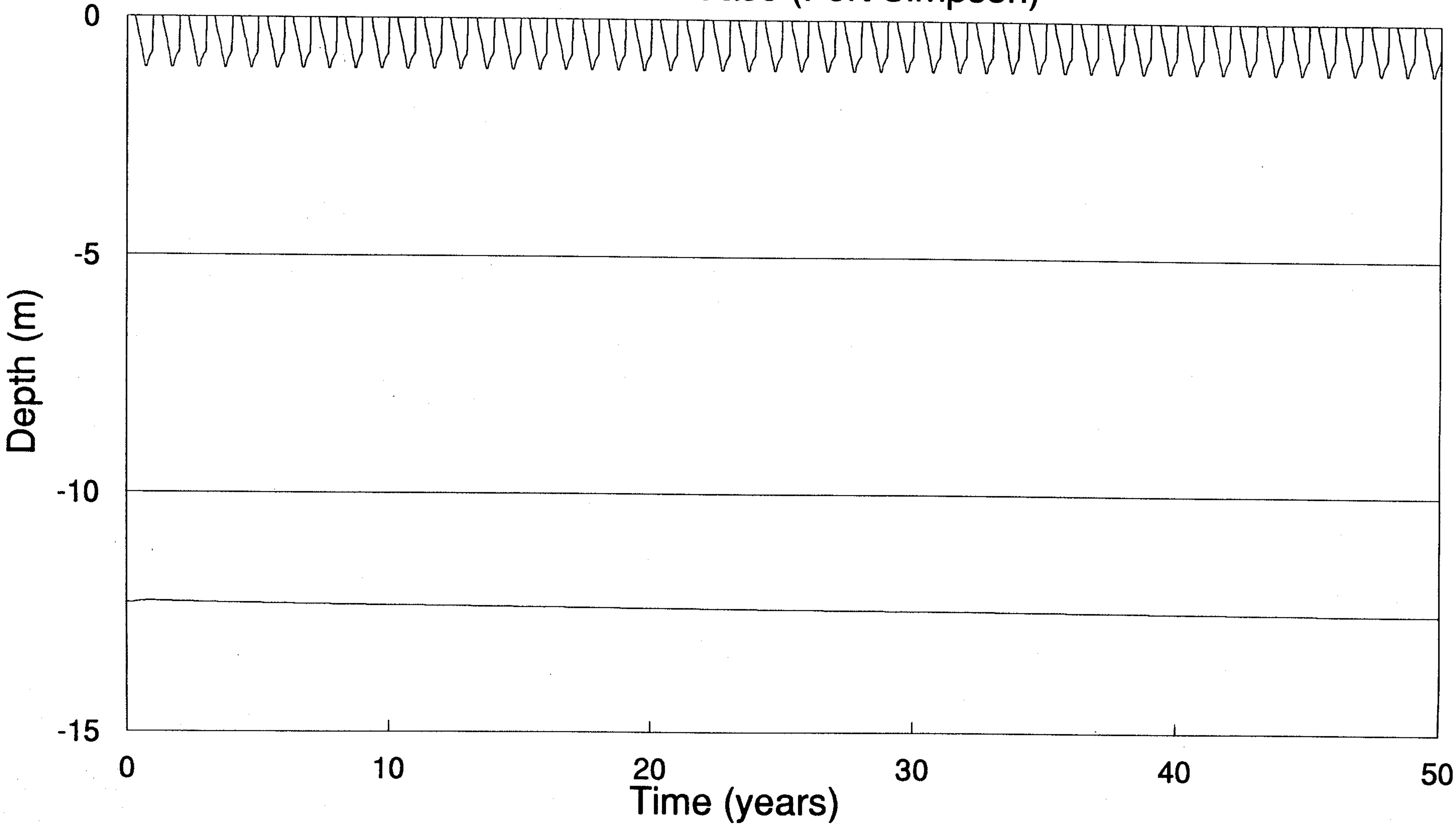


PLATE B.102

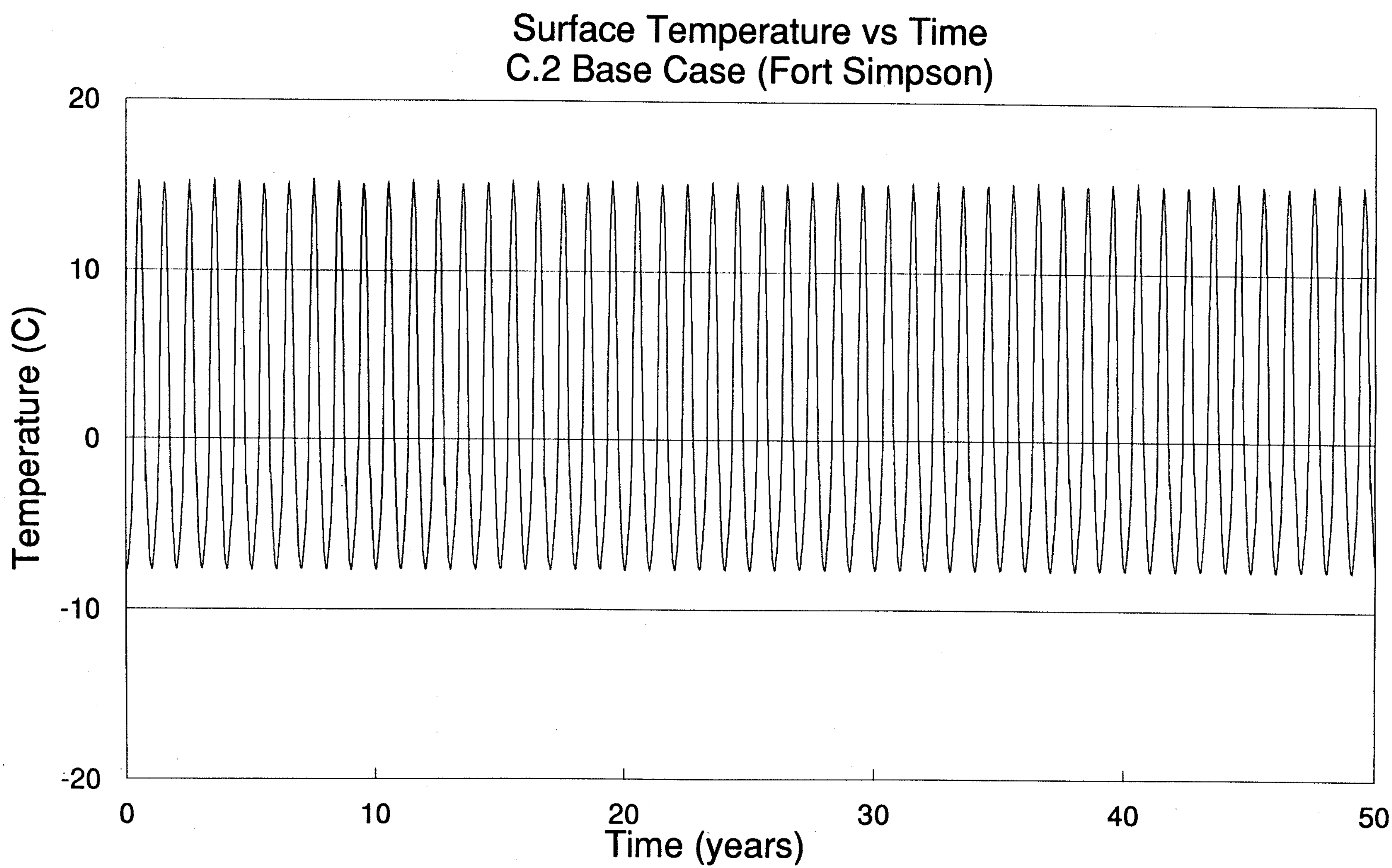

Surface Temperature vs Time
C.2 Base Case (Fort Simpson)
20
10
0
-10
-20
Temperature (C)
0
10
20
30
40
50
Time (years)

PLATE B.103

Ground Temperature vs Time
C.2 Base Case (Fort Simpson)

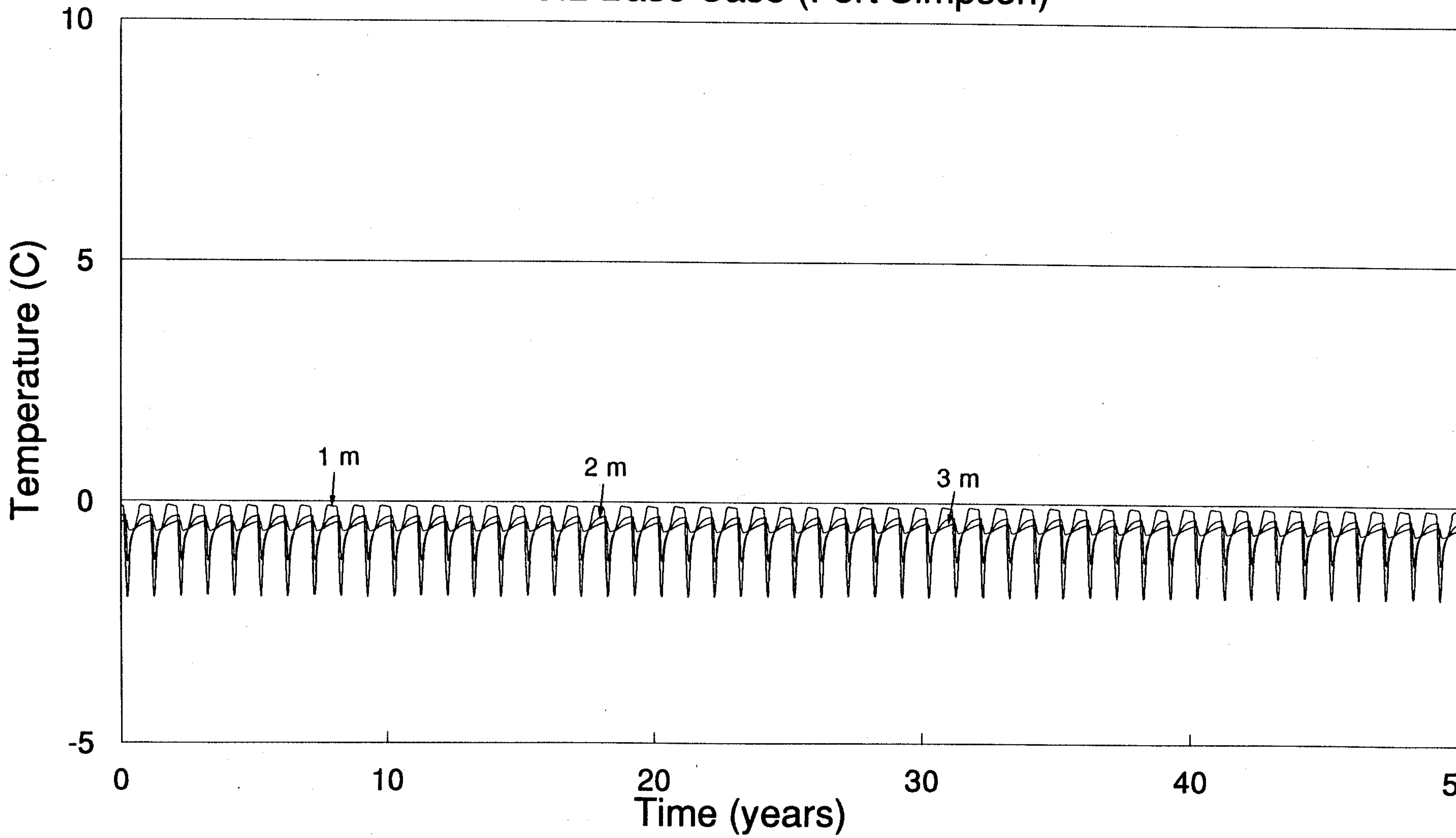
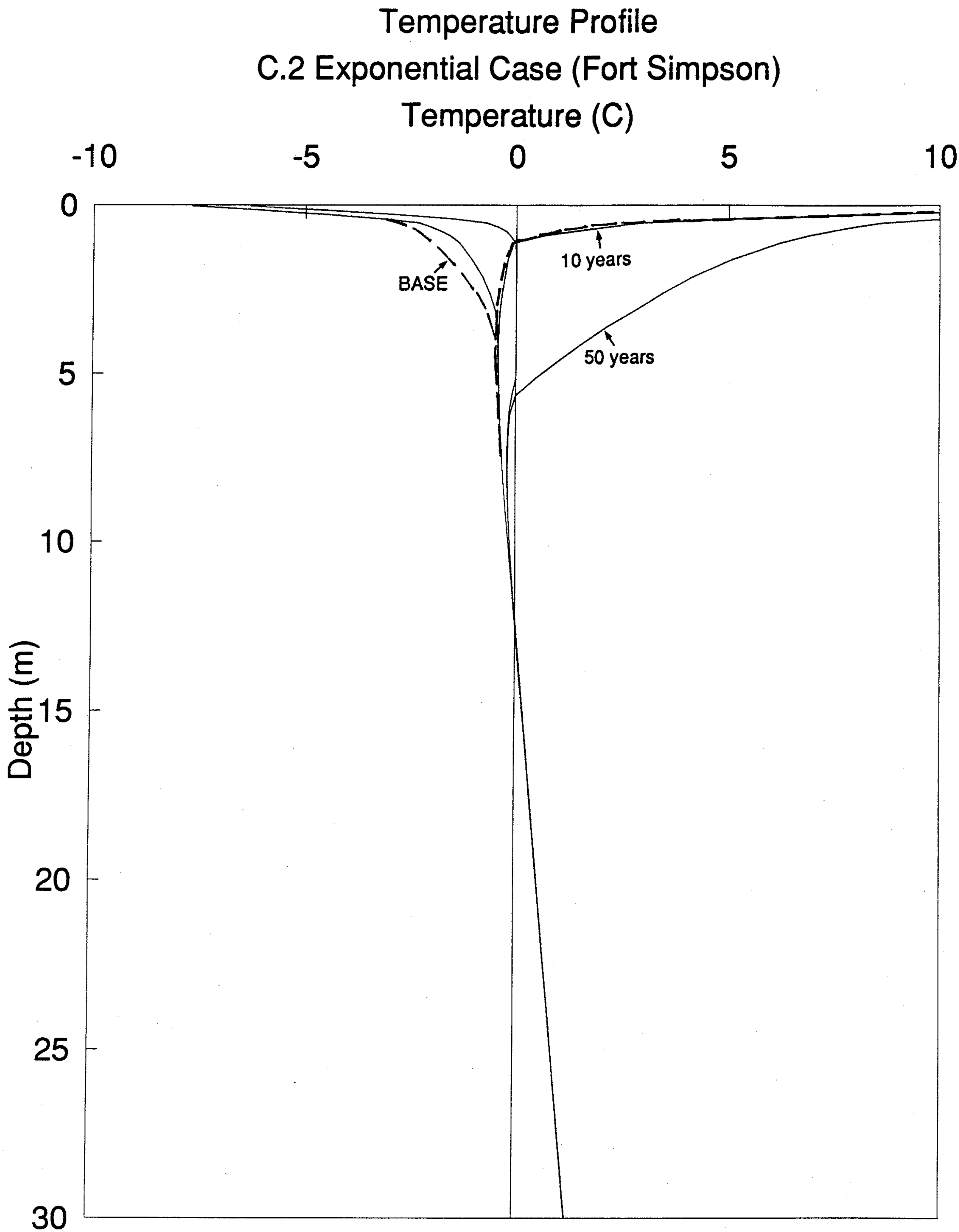


PLATE B.104



Temperature Profile
C.2 Exponential Case (Fort Simpson)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
BASE
10 years
50 years

PLATE B.105

Thaw Depth vs Time
C.2 Exponential Case (Fort Simpson)

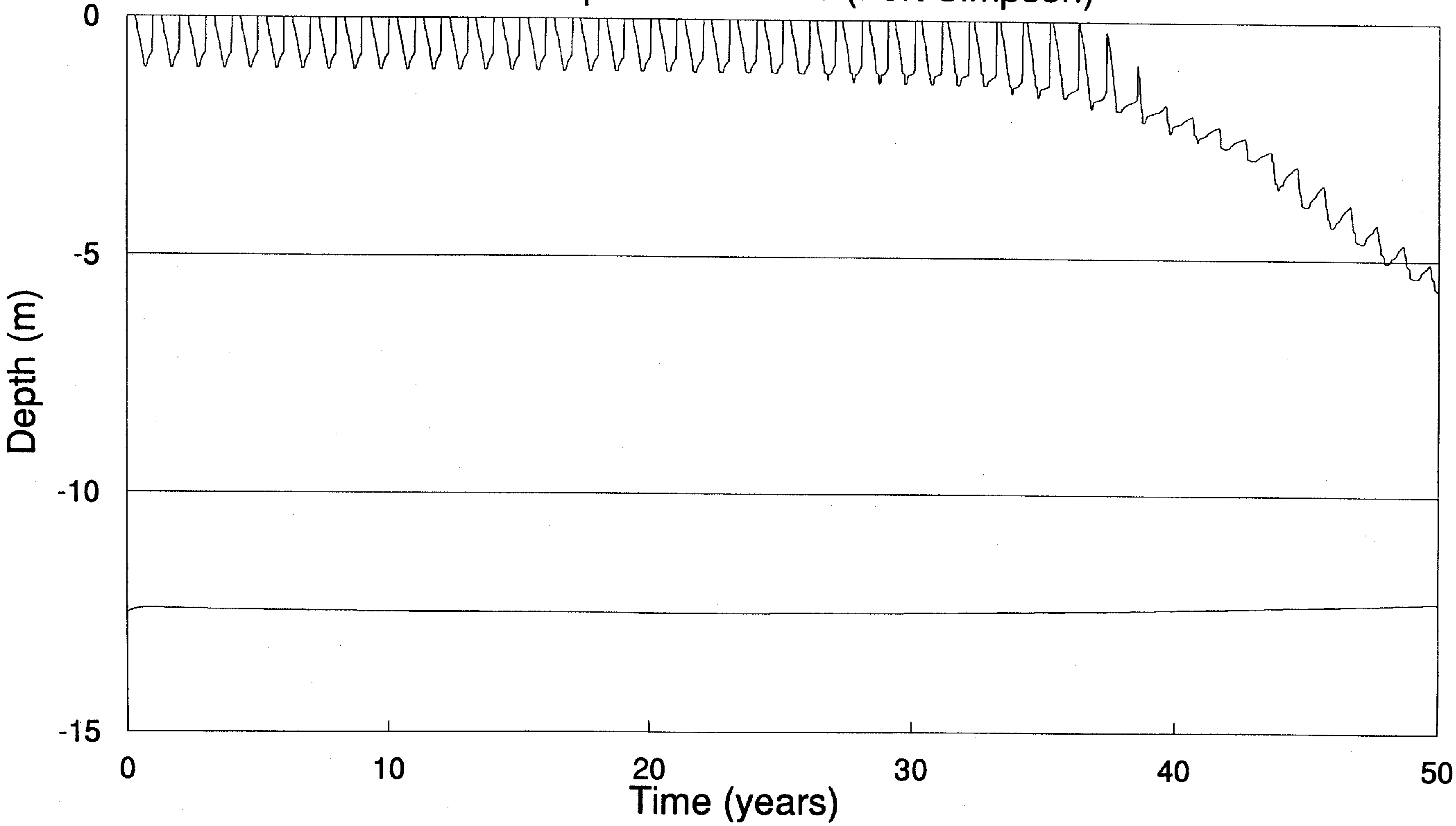


PLATE B.106

Surface Temperature vs Time
C.2 Exponential Case (Fort Simpson)

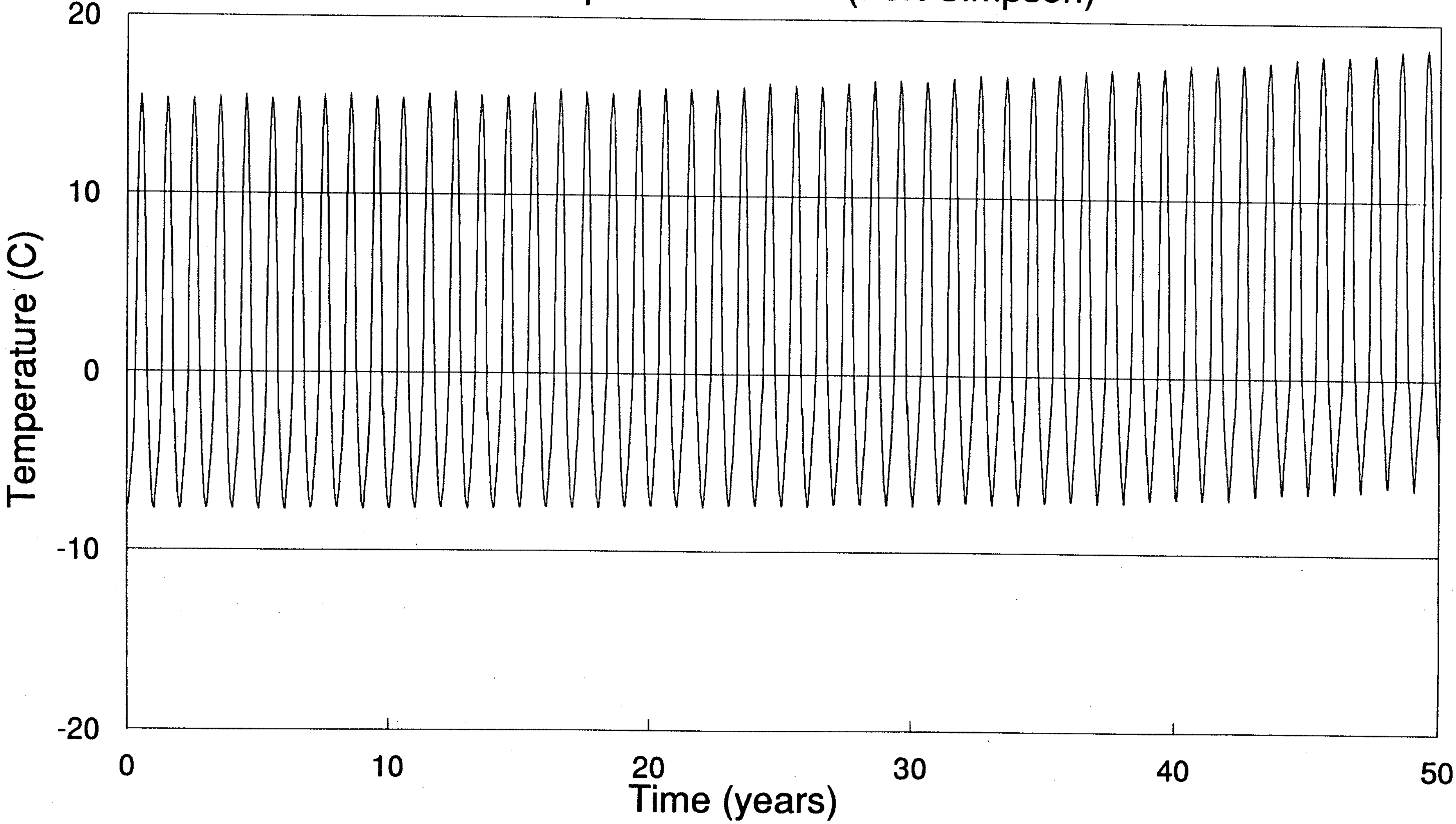


PLATE B.107

Ground Temperature vs Time
C.2 Exponential Case (Fort Simpson)

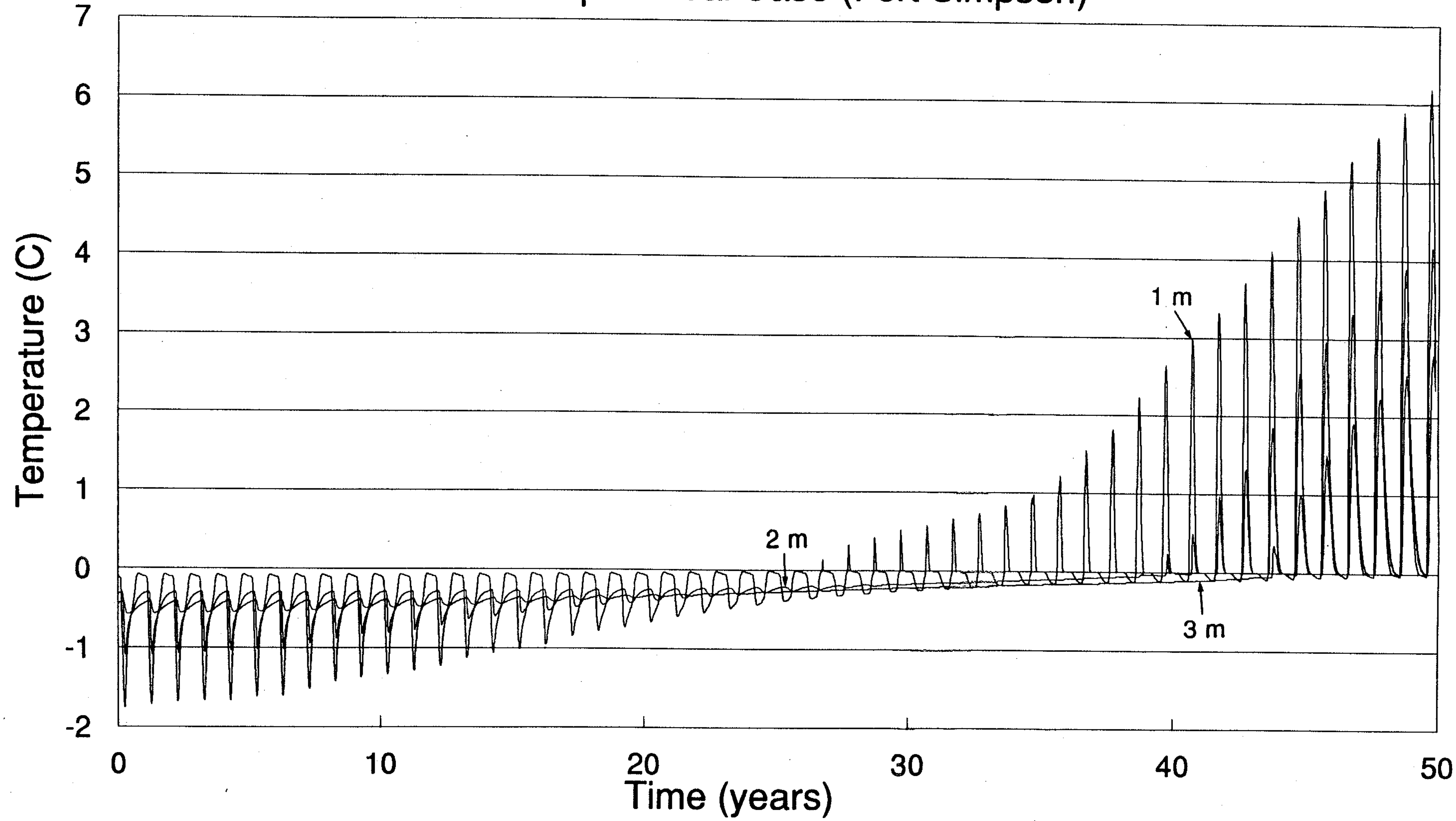
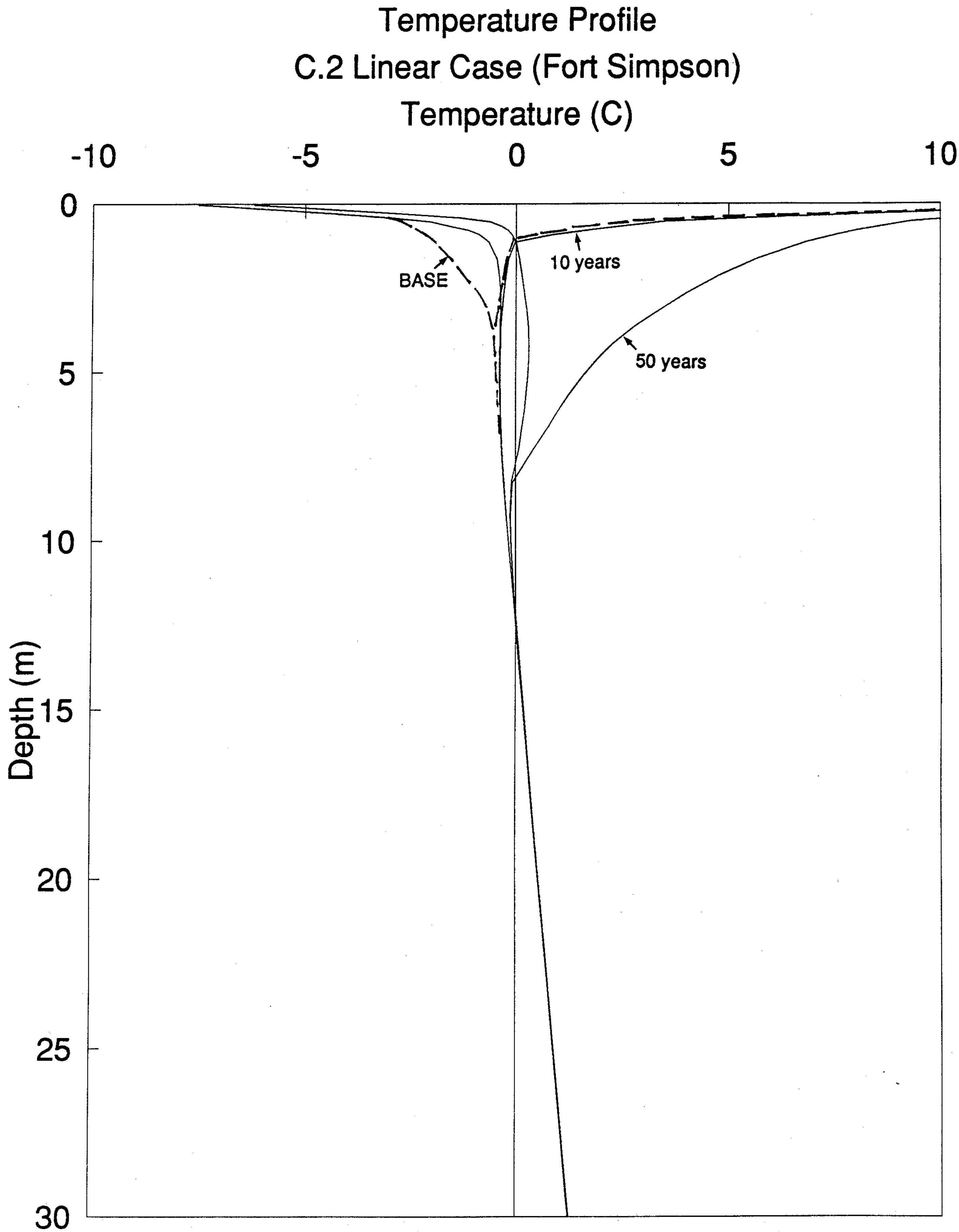


PLATE B.108



Temperature Profile
C.2 Linear Case (Fort Simpson)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
BASE
10 years
50 years

PLATE B.109

Thaw Depth vs Time
C.2 Linear Case (Fort Simpson)

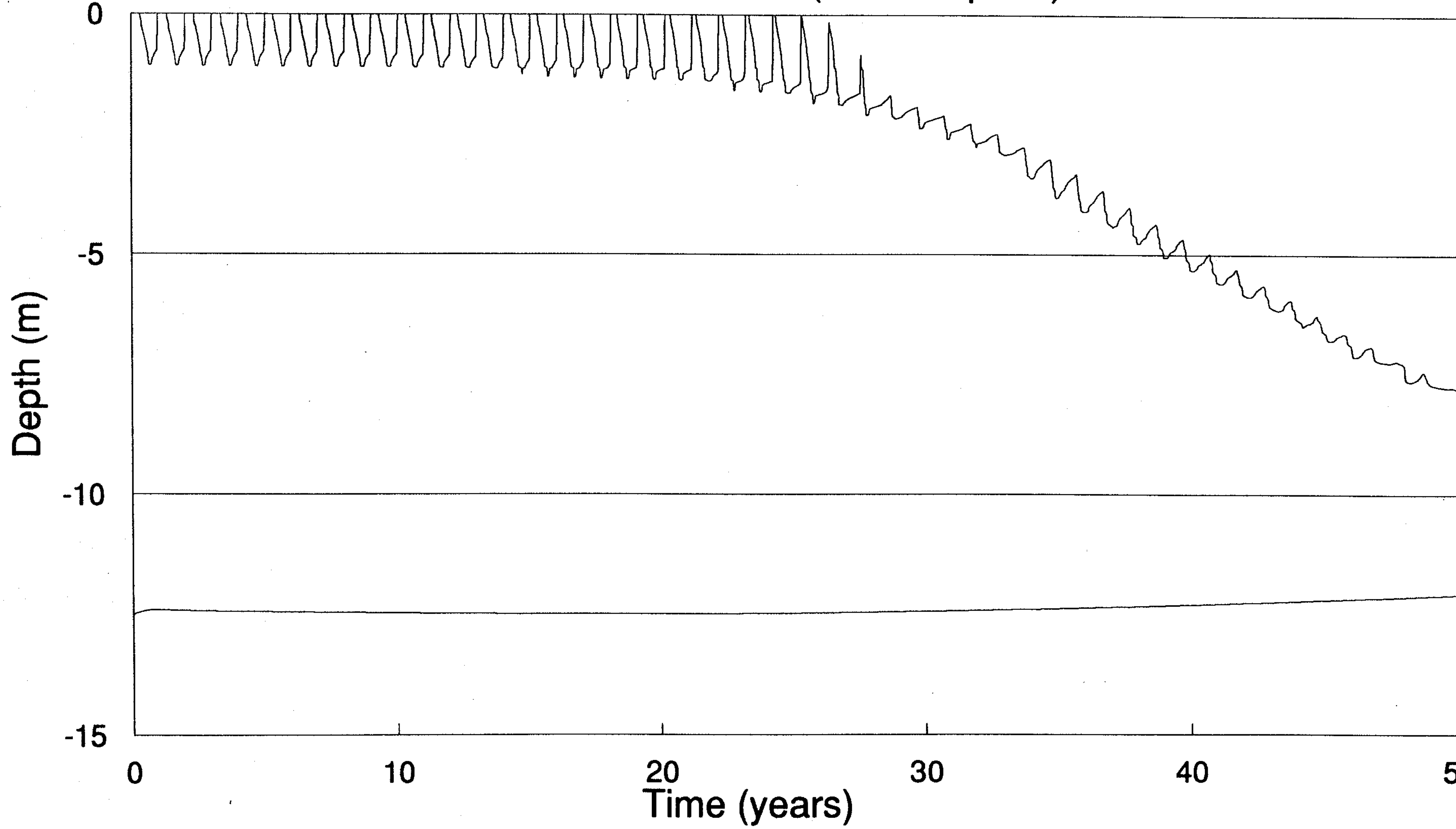


PLATE B.110

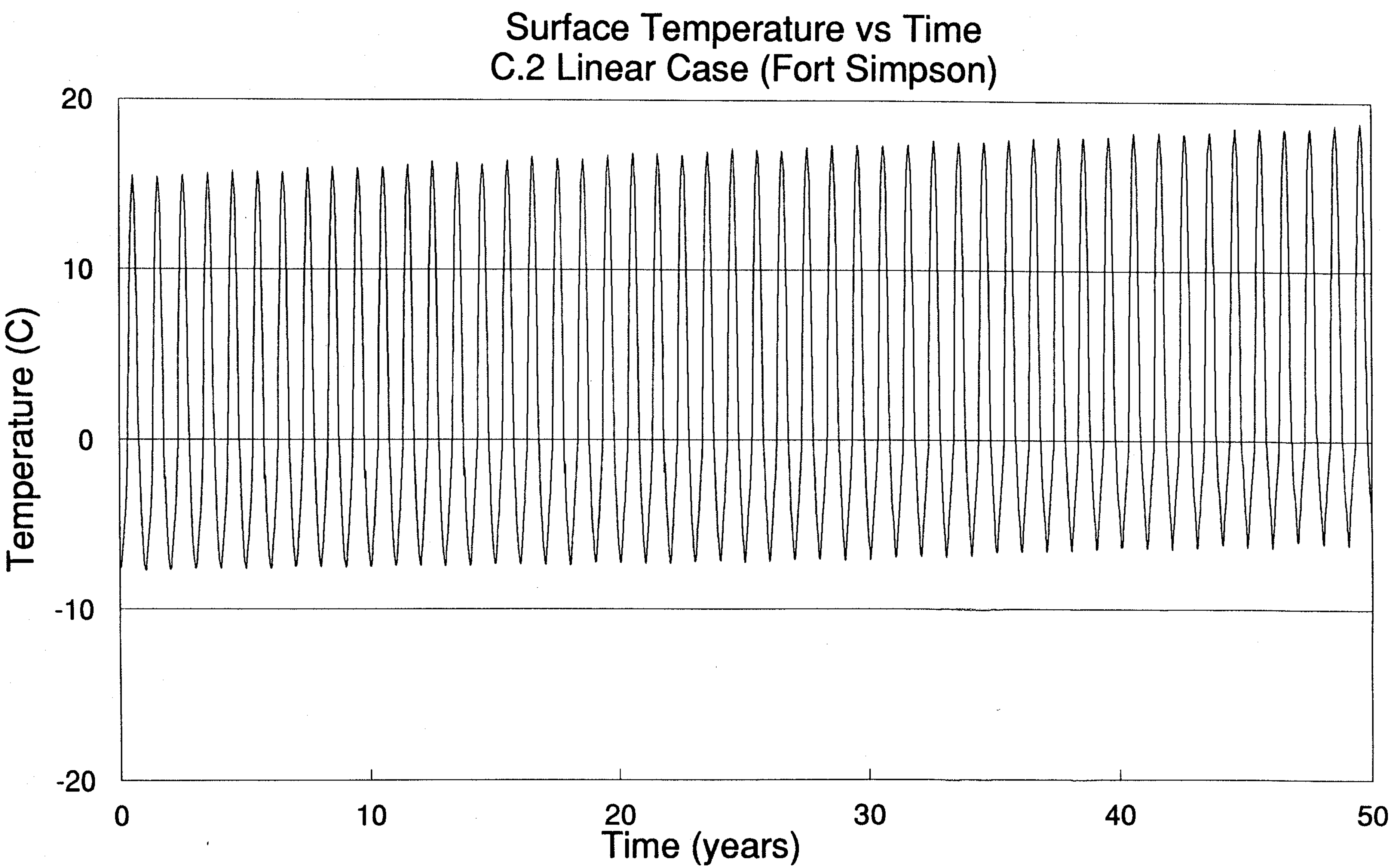

Surface Temperature vs Time
C.2 Linear Case (Fort Simpson)
Temperature (C)
20
10
0
-10
-20
0
10
20
30
40
50
Time (years)

PLATE B.111

Ground Temperature vs Time
C.2 Linear Case (Fort Simpson)

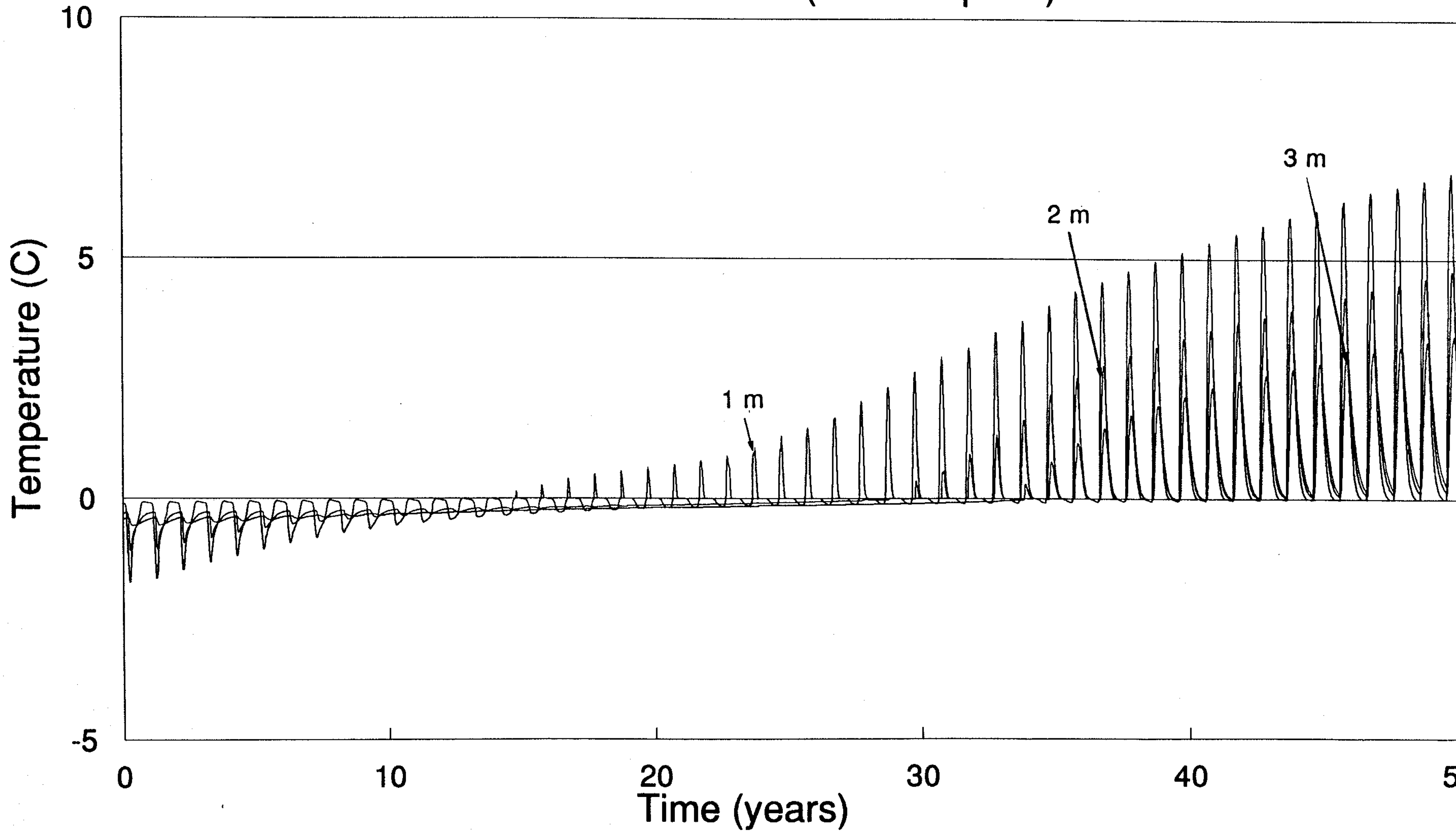
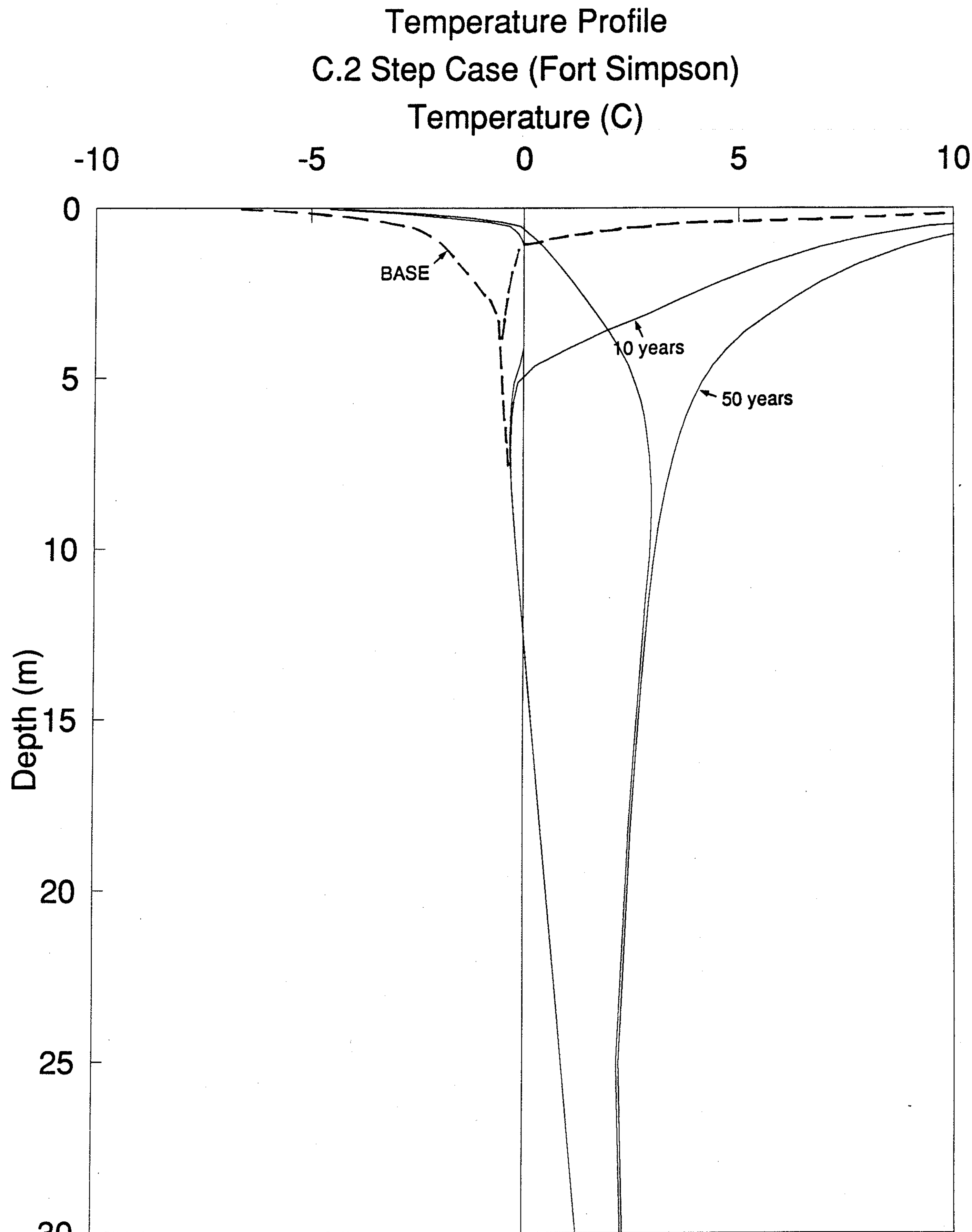


PLATE B.112



Temperature Profile
C.2 Step Case (Fort Simpson)
Temperature (C)
-10
-5
0
5
10
0
5
10
15
20
25
30
Depth (m)
BASE
10 years
50 years

PLATE B.113

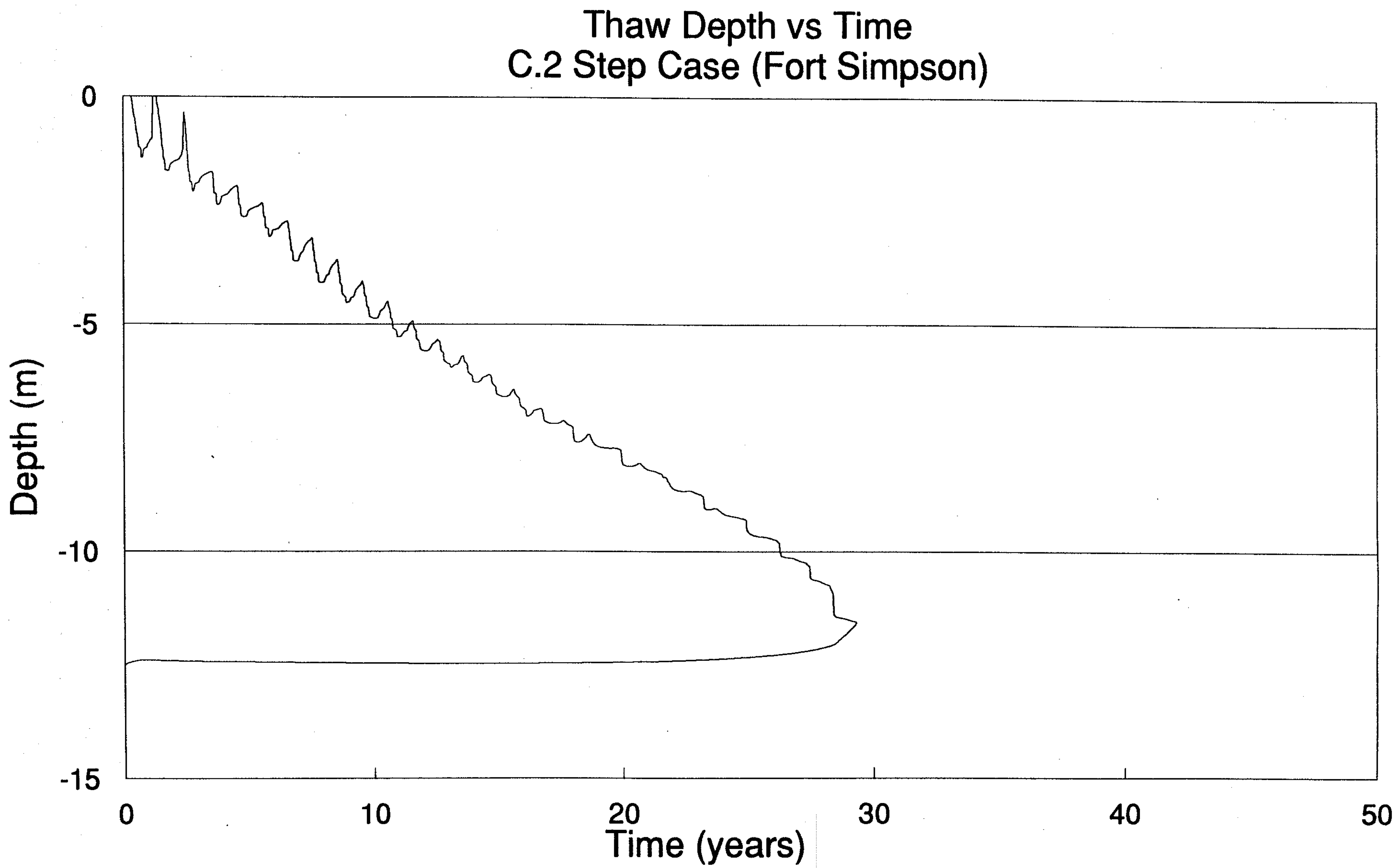

Thaw Depth vs Time
C.2 Step Case (Fort Simpson)
Depth (m)
0
-5
-10
-15
0
10
20
30
40
50
Time (years)

PLATE B.114

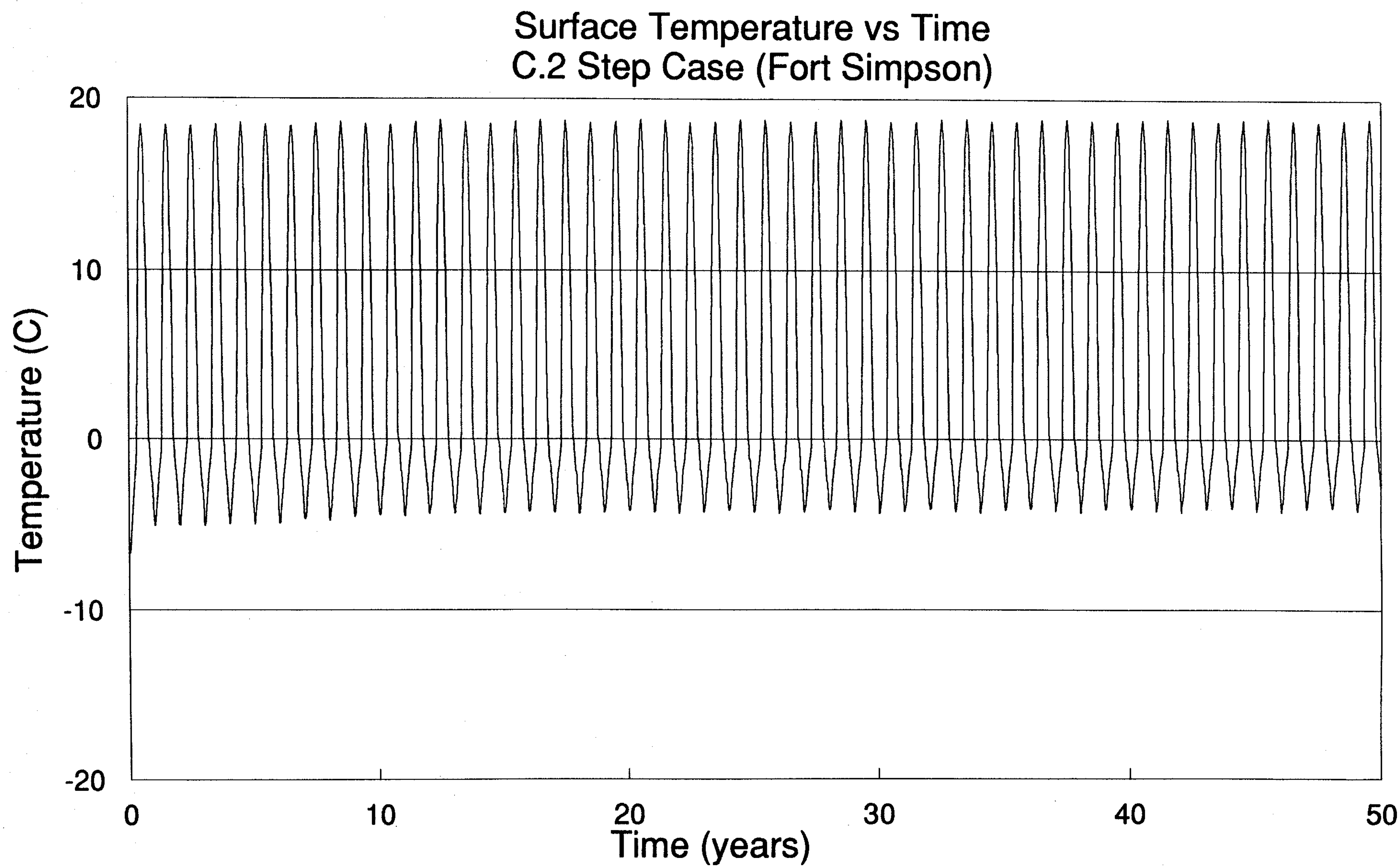
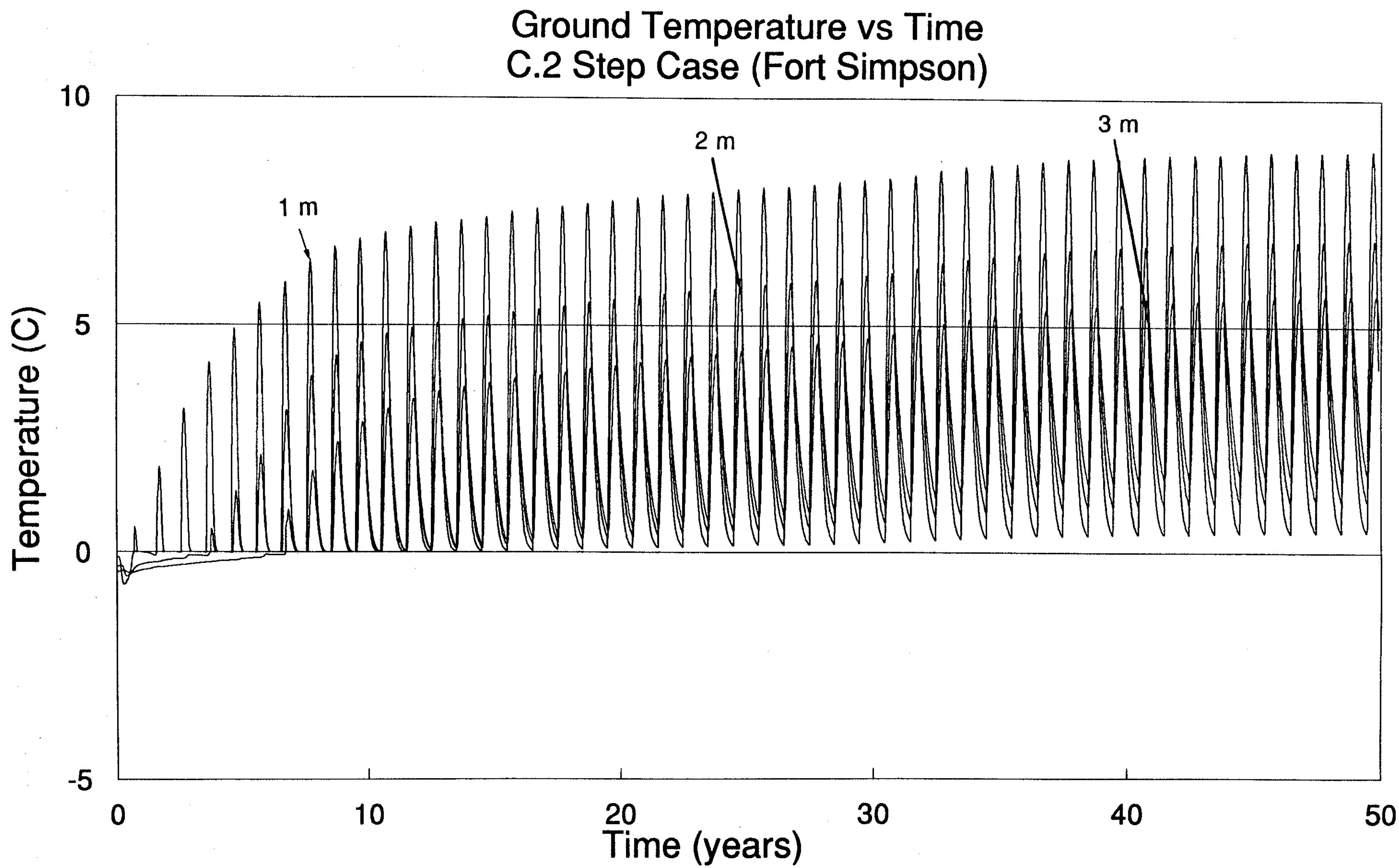

Surface Temperature vs Time
C.2 Step Case (Fort Simpson)
20
10
0
-10
-20
Temperature (C)
0
10
20
30
40
50
Time (years)

PLATE B.115



Ground Temperature vs Time
C.2 Step Case (Fort Simpson)
10
5
0
-5
Temperature (C)
0
10
20
30
40
50
Time (years)
1 m
2 m
3 m

PLATE B.116

Temperature Profile
C.2 Linear Case with Increased Snow Pack (Fort Simpson)

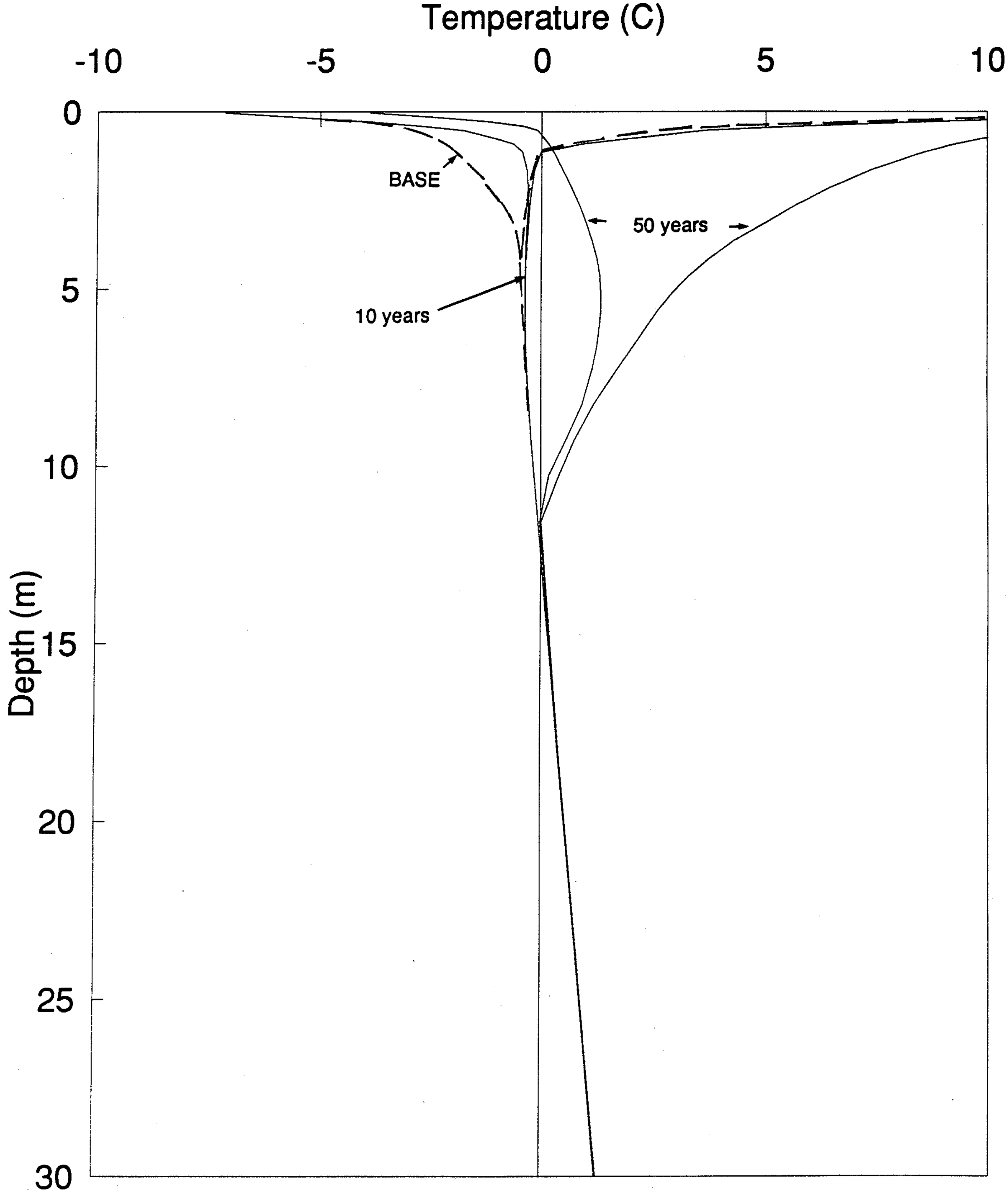


PLATE B.117

Thaw Depth vs Time
C.2 Linear Case with Increased Snow Pack (Fort Simpson)

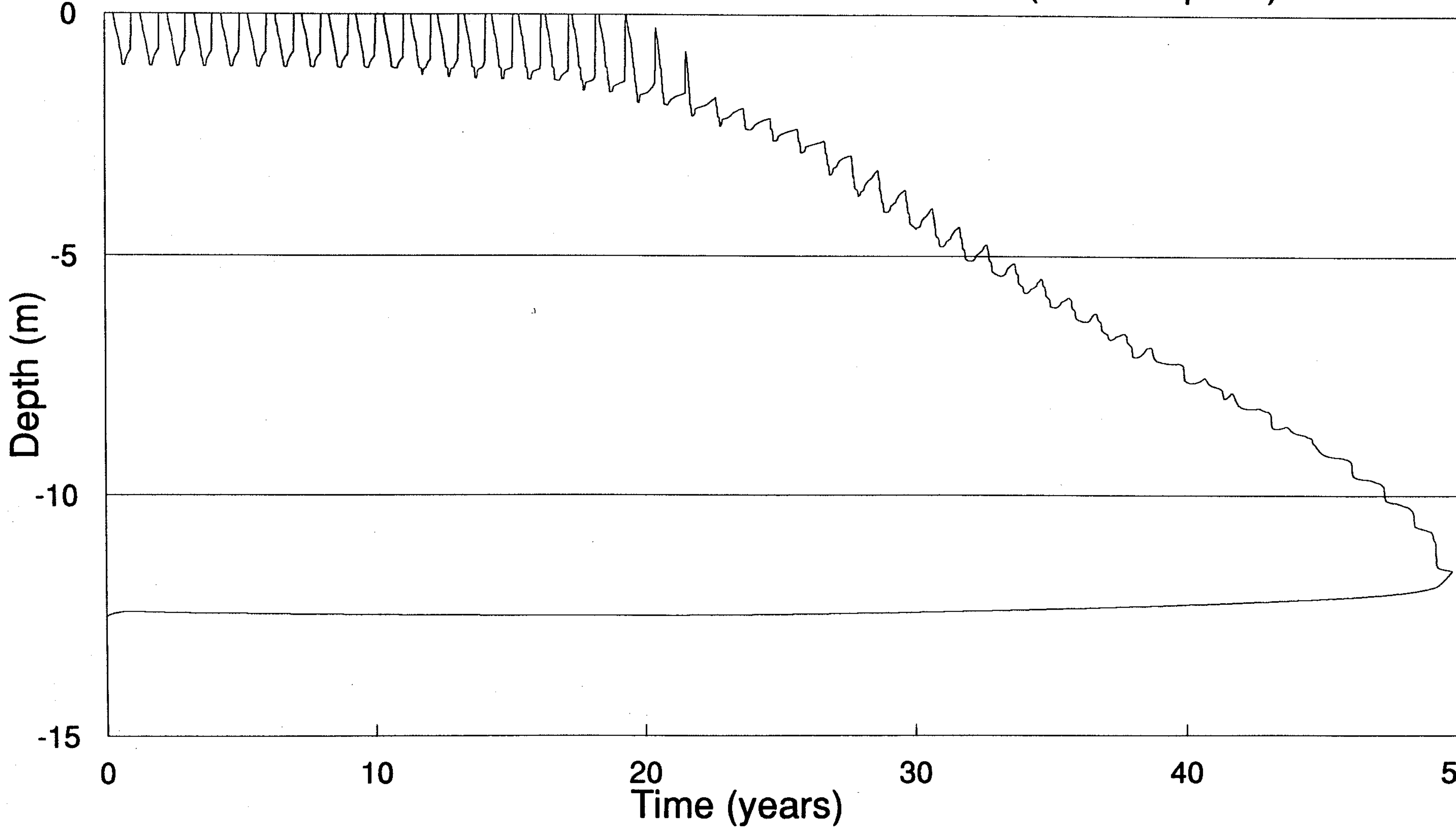


PLATE B.118

Surface Temperature vs Time
C.2 Linear Case with Increased Snow Pack (Fort Simpson)

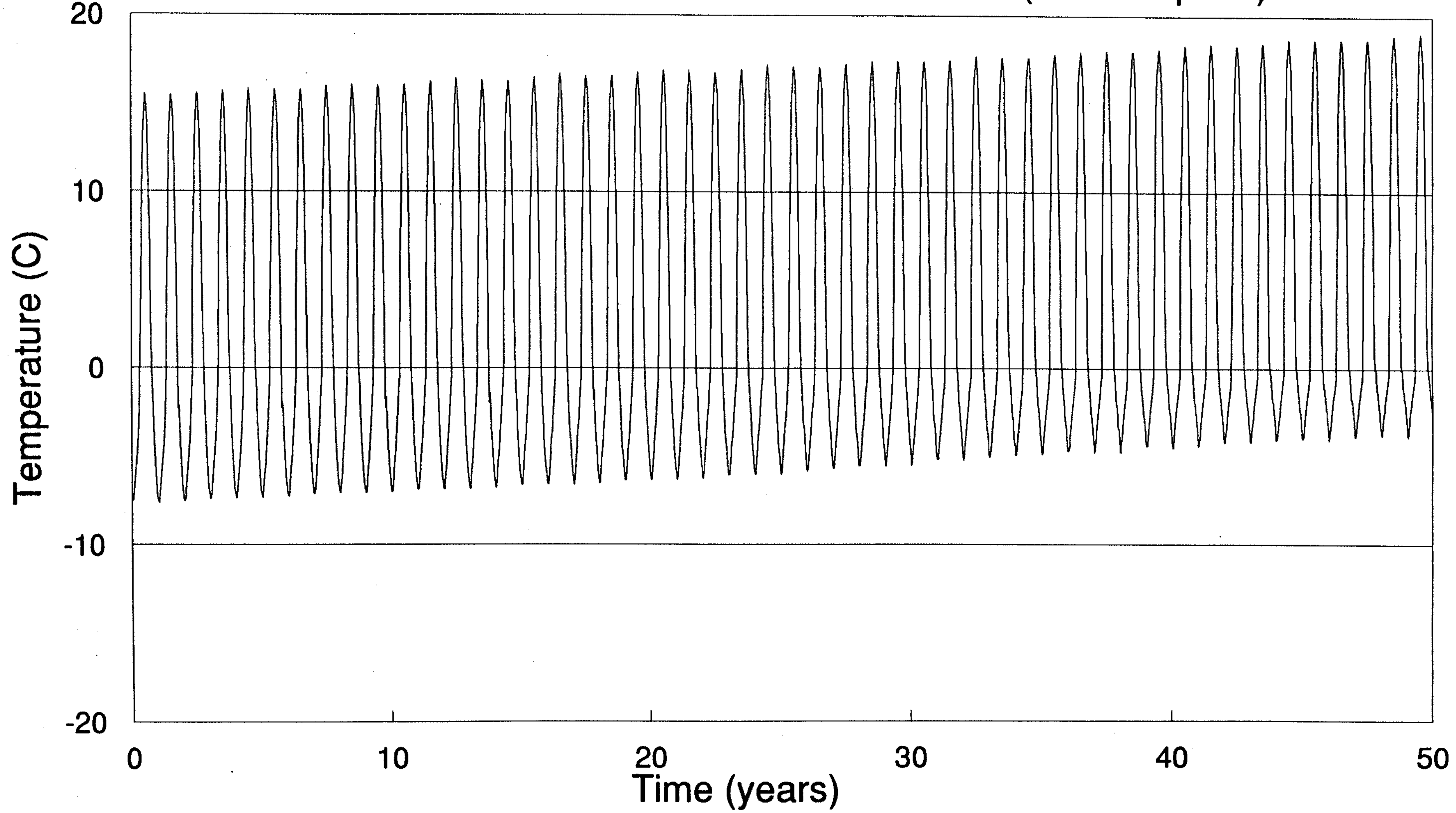


PLATE B.119

Ground Temperature vs Time
C.2 Linear Case with Increased Snow Pack (Fort Simpson)

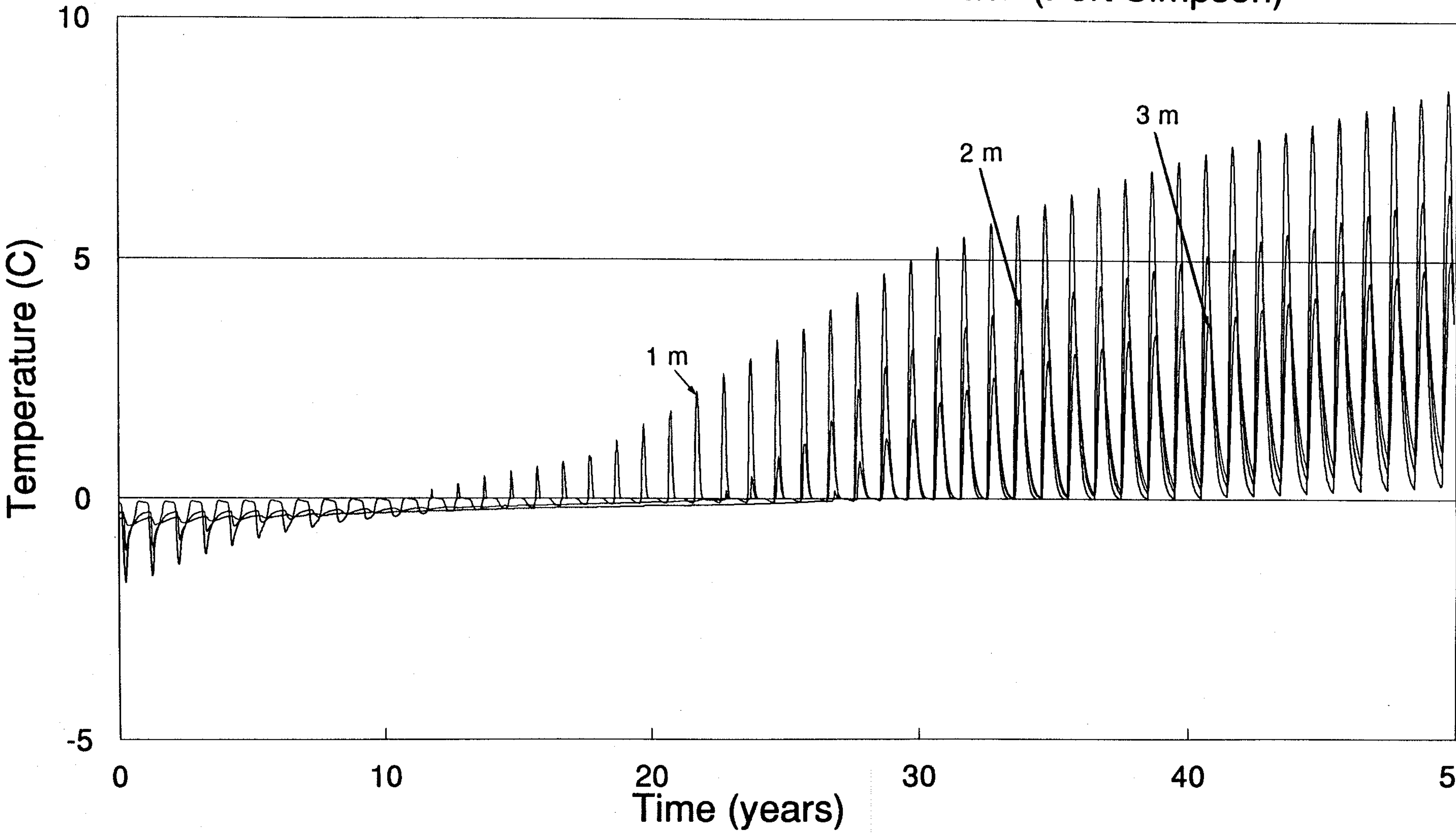


PLATE B.120

APPENDIX C

GCM PREDICTIONS

Energy, Mines and Resources Canada
Geological Survey of Canada Sector

Énergie, Mines et Ressources Canada
Secteur de la Commission géologique du Canada

TERRAIN SCIENCES DIVISION
Sedimentary & Cordilleran Geoscience Branch
601 Booth Street, Ottawa, Ontario K1A 0E8

DIVISION DE LA SCIENCE DES TERRAINS
Direction de la Géologie sédimentaire et de la Cordillère
601 rue booth, Ottawa, Ontario K1A 0E8

FAX MESSAGE FAX

TO/A Bob Saunders (Name/Nom) **FAX** ____________

FROM/DE Margo Burgess (Name/Nom) **FAX** (613) 992-2468

DATE Feb. 17/92 6 pages follow.

MESSAGE 2 x CO2 Climate Scenarios from AES

Let me know if transmission by fax is poor quality and we could send by mail/courier

Government of Canada | Gouvernement du Canada

MEMORANDUM | NOTE DE SERVICE

TO / A: Margo Burgess
GSC

FROM / DE: Jamie Smith
AES/CCC

SECURITY - CLASSIFICATION - DE SÉCURITÉ

OUR FILE — N / RÉFÉRENCE

YOUR FILE — V / RÉFÉRENCE

DATE: February 12, 1992

SUBJECT / OBJET

Re: Climate Scenarios for the Mackenzie Valley

Included are the climate data that you requested in December, 1991. The snow depth (cover) estimates were provided by the GNWT and are snow water equivalents in mm. These estimates were derived using remote sensing techniques, and should be referenced according to the attached memo.

The climate scenarios were derived from the Canadian Climate Centre's GCM, and the closest grid point of the GCM was used as the source of information. I will be producing a full set of interpolated values for the CCC GCM and the GFDL GCM models, as well as other scenarios, very shortly. I will forward these to you when they are available.

Jamie

Jamie Smith

Government of Canada Gouvernement du Canada

MEMORANDUM NOTE DE SERVICE

SECURITY - CLASSIFICATION - DE SÉCURITÉ

OUR FILE — N / RÉFÉRENCE

YOUR FILE — V / RÉFÉRENCE

DATE November 27, 1991

TO / A: Jamie Smith, CCAD

FROM / DE: Anne Walker, CCRD

SUBJECT / OBJET: Average Snow Water Equivalent for NWT, 1979-1990 (excluding 1987) Derived from Passive Microwave Satellite Data

The attached diskette contains an ASCII file of average snow water equivalent values for the North West Territories as derived from passive microwave satellite data. The file is the result of a cooperative study that was funded by Indian and Northern Affairs Canada (contact: Brian Latham, Water Resources Branch, Yellowknife) and performed by Ph.D. Associates Inc. (Toronto) with B. Goodison (CCRD) acting as Scientific Authority. Snow water equivalent values were extracted from passive microwave data from Nimbus-7 SMMR (1978-1986) and DMSP SSM/I (1988-1990) for the time of maximum snow cover (March) using one of the CCC algorithms and regridded onto a 38 km x 38 km grid. Corrections were applied to each SWE value to account for the amount of water cover and forest cover within each grid square. At each grid point an average SWE value was calculated to represent the average maximum snow cover conditions for the study area during the 1979 to 1990 time period (excluding 1987). At the time of the study, passive microwave data were not available for 1987. Brian Latham has informed us that he intends to acquire the 1987 data in order to complete the time period which was studied. A new set of "average SWE values" will be generated after the 1987 data have been analysed.

Brian Latham has given us permission to provide you with this dataset for use in the Mackenzie Basin Impact Study under the condition that you will acknowledge its source as appropriate. If you have any questions please feel free to contact me.

Anne Walker

Anne Walker
Special Projects Division, CCRD

c.c. Brian Latham, INAC (Yellowknife)

Tuktoyaktuk	Latitude	Longitude													
	69.3	133													
			January	February	March	April	May	June	July	August	September	October	November	December	Annual
		Temperature	-28.4	-29.1	-26.5	-17.2	-4.7	5.1	10.6	9	2.6	-7.7	-19.7	-25.2	-10.9
		Precipitation	5.4	5.4	4.4	7.1	5.9	12.9	19.9	27.8	14.9	17.6	8.9	7.4	137.6
		Snowfall (cm)	5.3	5.4	4.4	7.1	3.5	2.2	0.2	0.6	4.2	16	8.9	7.4	65.2
		Max. Snow Cover			37.8										
		[GNWT, 1979-90]													

CCC GCM	Latitude	Longitude													
	68.7	131.3													
[Change from 1XCO2 to 2XCO2]			January	February	March	April	May	June	July	August	September	October	November	December	Annual
	[Difference]	Temperature	3.5	7.3	8.9	3.2	3.5	7.7	3.9	2.5	2.6	5.2	5.8	5.8	5.0
	[Ratio]	Precipitation	1.33	0.96	1.32	1.09	1.38	1.02	0.92	1.39	0.86	1.35	0.78	1.29	1.1
	[Ratio]	Snowfall													
		Max. Snow Cover	0.86	0.94	0.99	0.99	0.76	0.15	1	1	0.01	0.22	0.45	0.72	0.8
		[GNWT, 1979-90]													

CCC GCM	Latitude	Longitude													
	69.3	133													
[Resulting Scenario]															
			January	February	March	April	May	June	July	August	September	October	November	December	Annual
		Temperature	-24.9	-21.8	-17.6	-14	-1.2	12.8	14.5	11.5	5.2	-2.5	-13.9	-19.4	-5.9
		Precipitation	7.2	5.2	5.8	7.7	8.1	13.2	18.3	38.6	12.8	23.8	6.9	9.5	157.0
		Max. Snow Cover			37.4										
		[GNWT, 1979-90]													

Inuvik A	Latitude	Longitude
	68.2	133.5

	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Temperature	-29.6	-28.9	-25	-14.3	-0.8	10.1	13.6	10.7	3.1	-8.1	-20.7	-27.2	-9.8
Precipitation	17.9	10.5	12	14.8	17.6	23.5	33.6	43.6	23.9	33.4	17.9	17.4	266.1
Snowfall (cm)	20.4	12.6	15	17	13	2.2	0.5	3.3	12	37.2	22.6	20.8	176.6
Max. Snow Cover [GNWT, 1979-90]			113.7										

CCC GCM [Change from 1XCO2 to 2XCO2]	Latitude	Longitude
	68.2	135

		January	February	March	April	May	June	July	August	September	October	November	December	Annual
[Difference]	Temperature	3	6.4	9.2	3.3	4.8	6.7	4.2	2.6	2.1	4.5	6.4	4.9	4.8
[Ratio]	Precipitation	1.22	1	1.3	0.96	1.38	1.08	0.9	1.37	0.83	1.33	0.8	1.05	1.1
[Ratio]	Snowfall													
	Max. Snow Cover [GNWT, 1979-90]	0.82	0.87	0.94	0.89	0.29	1	1	1	0.03	0.19	0.44	0.7	0.8

CCC GCM [Resulting Scenario]	Latitude	Longitude
	68.2	133.5

	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Temperature	-26.6	-22.5	-15.8	-11	4	16.8	17.8	13.3	5.2	-3.6	-14.3	-22.3	-4.9
Precipitation	21.8	10.5	15.6	14.2	24.3	25.4	30.2	59.7	19.8	44.4	14.3	18.3	293.2
Max. Snow Cover [GNWT, 1979-90]			106.9										

Norman Well A	Latitude	Longitude													
	65.4	126.8													
			January	February	March	April	May	June	July	August	September	October	November	December	Annual
		Temperature	-28.9	-26.2	-19.8	-7.2	5.4	14	16.3	13.4	6.1	-4.6	-18.2	-26.5	-6.4
		Precipitation	19.5	16.1	12.9	15.4	17	37	56.1	58.6	29.3	26.8	20.9	18.8	328.4
		Snowfall (cm)	20.6	17.3	13.6	15.3	8.4	0.6	0.1	T	5.3	25	21.3	19.3	146.8
		Max. Snow Cover [GNWT, 1979-90]			72.2										

CCC GCM	Latitude	Longitude													
	64.9	127.5													
[Change from 1XCO2 to 2XCO2]			January	February	March	April	May	June	July	August	September	October	November	December	Annual
	[Difference]	Temperature	4.3	4.2	5.3	1.2	3.7	4.9	3.7	3	3.1	1.5	8.8	5.8	4.1
	[Ratio]	Precipitation	1.23	0.75	0.68	1.16	1.14	1.2	0.81	1.23	1.35	1.1	1.24	1.1	1.1
	[Ratio]	Snowfall													
		Max. Snow Cover [GNWT, 1979-90]	0.8	0.84	0.94	0.32	0	1	1	1	1	0.49	0.47	0.69	0.7

CCC GCM	Latitude	Longitude													
	65.4	126.8													
[Resulting Scenario]															
			January	February	March	April	May	June	July	August	September	October	November	December	Annual
		Temperature	-24.6	-22	-14.5	-6	9.1	18.9	20	16.4	9.2	-3.1	-9.4	-20.7	-2.2
		Precipitation	24.0	12.1	8.8	17.9	19.4	44.4	45.4	72.1	39.6	29.5	25.9	20.7	355.5
		Max. Snow Cover [GNWT, 1979-90]			67.9										

	Latitude	Longitude													
Fort Simpson A	61.8	121.4													
			January	February	March	April	May	June	July	August	September	October	November	December	Annual
		Temperature	-28.2	-22.8	-14.9	-2.5	7.9	14.4	16.6	14.4	7.3	-1.9	-15.6	-24.5	-4.2
		Precipitation	19.9	19	21.7	14.6	31.1	38.7	59.3	44.8	31.3	24	27.2	23.5	355.1
		Snowfall (cm)	20.7	18.9	21.2	11.7	5.1	0	0	0	5.7	18.5	25.3	23.9	151.0
		Max. Snow Cover [GNWT, 1979-90]			100.7										

	Latitude	Longitude													
CCC GCM	61.2	120													
[Change from 1XCO2 to 2XCO2]			January	February	March	April	May	June	July	August	September	October	November	December	Annual
	[Difference]	Temperature	2.6	5.2	5.9	1.1	3.2	4.2	3.2	3.3	3	2.3	6.2	9	4.1
	[Ratio]	Precipitation	1.08	0.94	0.93	1.4	1.02	1.04	1.53	1.26	1.25	1.23	1.1	1.12	1.2
	[Ratio]	Snowfall													
		Max. Snow Cover [GNWT, 1979-90]	0.58	0.61	0.29	0.02	1	1	1	1	1	0.04	0.06	0.25	0.4

	Latitude	Longitude													
CCC GCM	61.8	121.4													
[Resulting Scenario]															
			January	February	March	April	May	June	July	August	September	October	November	December	Annual
		Temperature	-25.6	-17.6	-9	-1.4	11.1	18.6	19.8	17.7	10.3	0.4	-9.4	-15.5	-0.0
		Precipitation	21.5	17.9	20.2	20.4	31.7	40.2	90.7	56.4	39.1	29.5	29.9	26.3	411.3
		Max. Snow Cover [GNWT, 1979-90]			29.2										