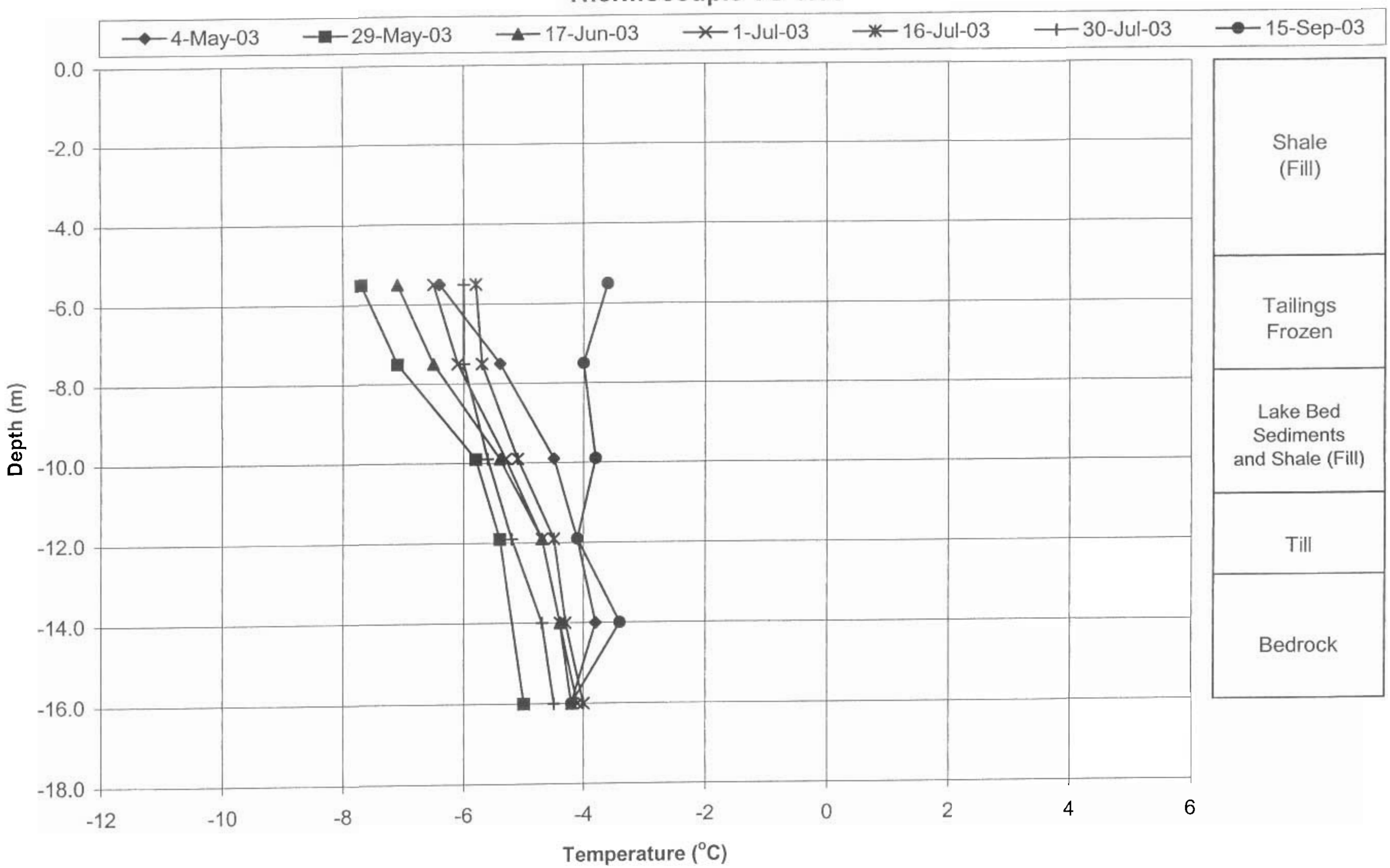
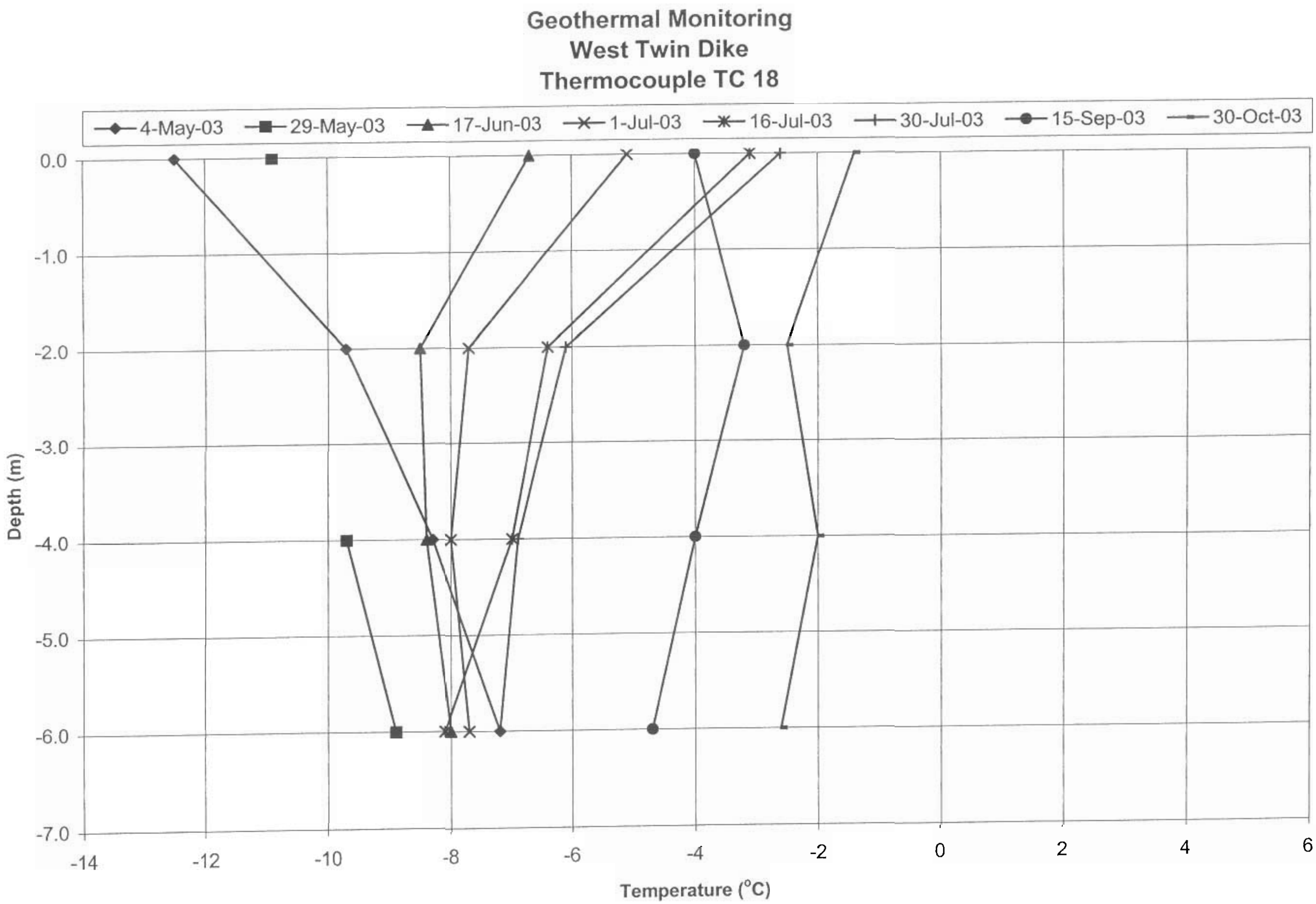
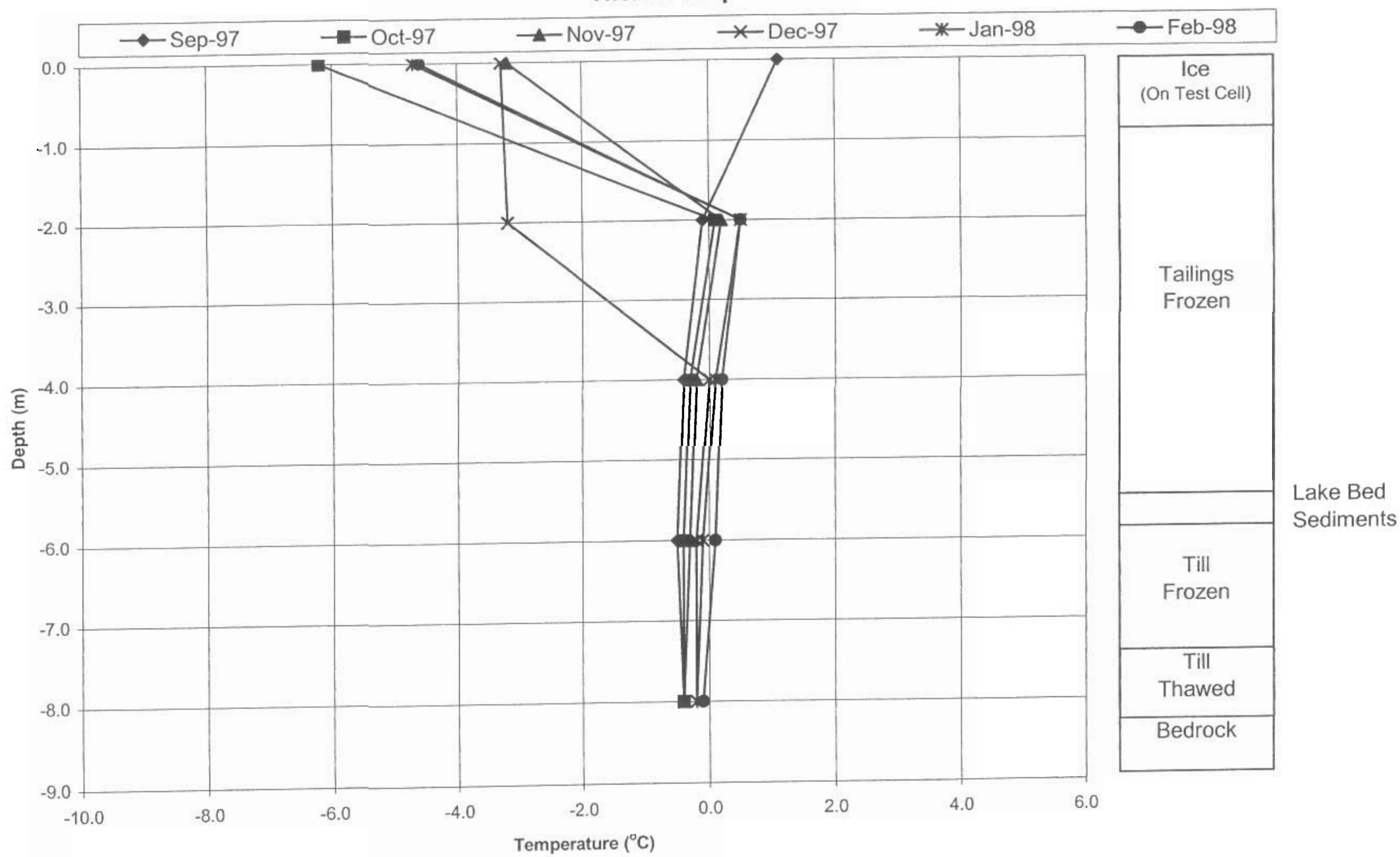

Geothermal Monitoring
West Twin Dike
Thermocouple TC 17
1-Jul-03
16-Jul-03
30-Jul-03
15-Sep-03
06-Nov-03
21-Nov-03
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
-9.0
Depth (m)
-12
-10
-8
-6
-4
-2
0
2
4
6
Temperature (°C)

Geothermal Monitoring West Twin Dike Thermocouple TC 17A




Geothermal Monitoring
West Twin Dike
Thermocouple TC 18
4-May-03
29-May-03
17-Jun-03
1-Jul-03
16-Jul-03
30-Jul-03
15-Sep-03
30-Oct-03
Depth (m)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
Temperature (°C)

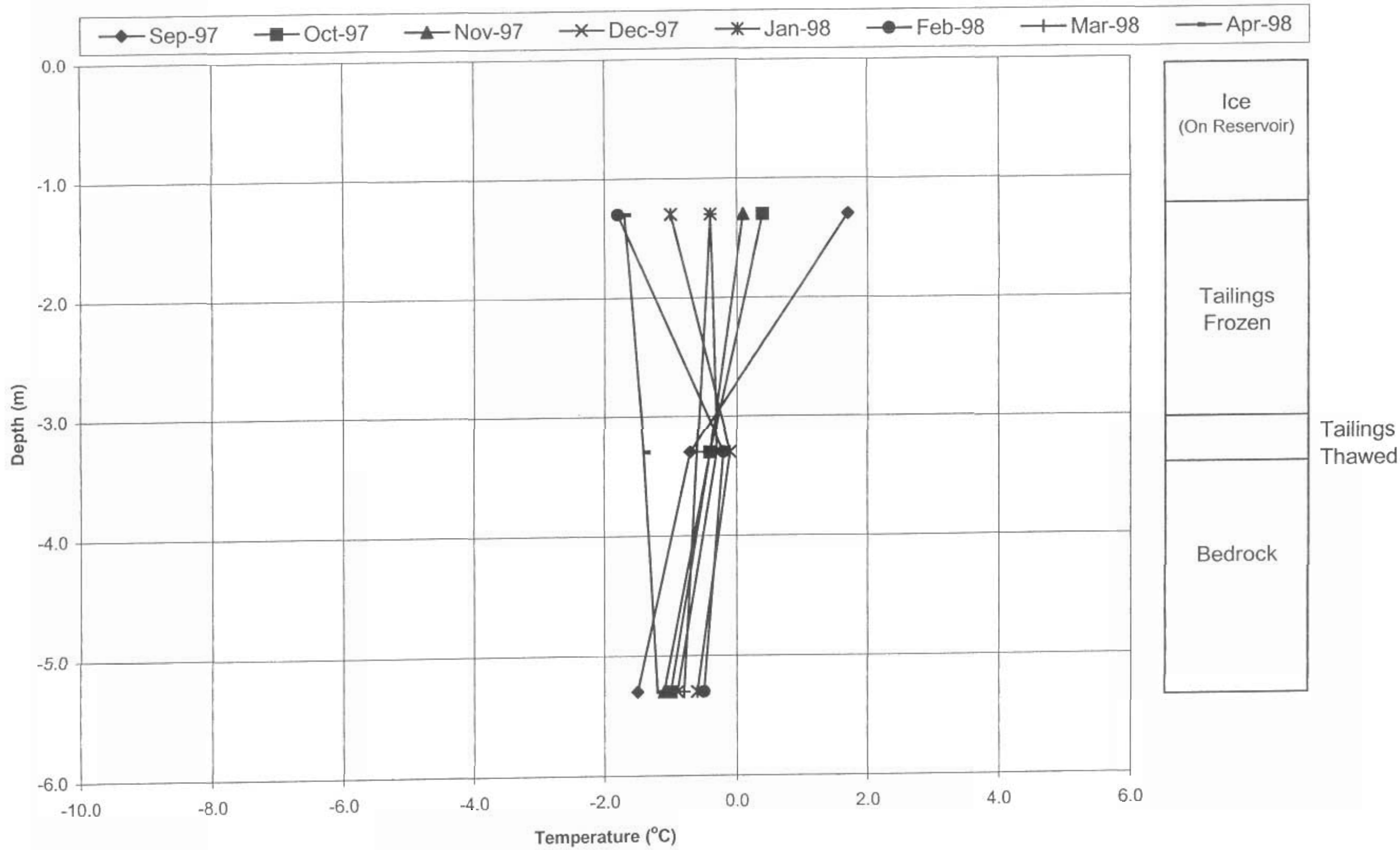
Geothermal Monitoring
Test Cell (15 m into Lake)
Station 04+50
Thermocouple TC 19



Note: Instrument is no longer operational.
Not Monitored.xls
TC 19 Trmp

BGC ENGINEERING INC.

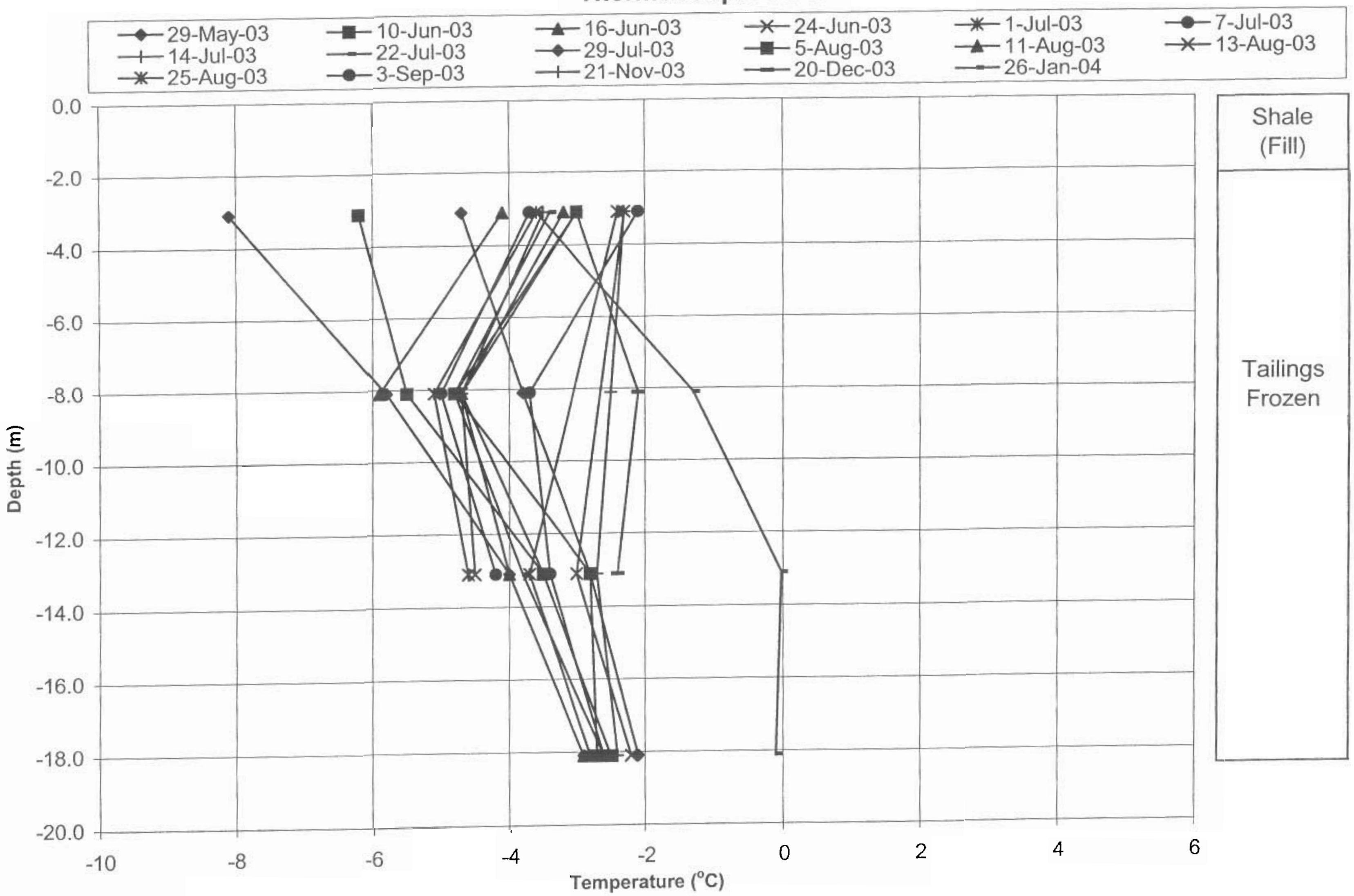
Geothermal Monitoring
Reservoir (15 m into Lake)
Station 01+50
Thermocouple TC 20



Note: Instrument is no longer operational.
Not Monitored.xls
TC 20 Trmp

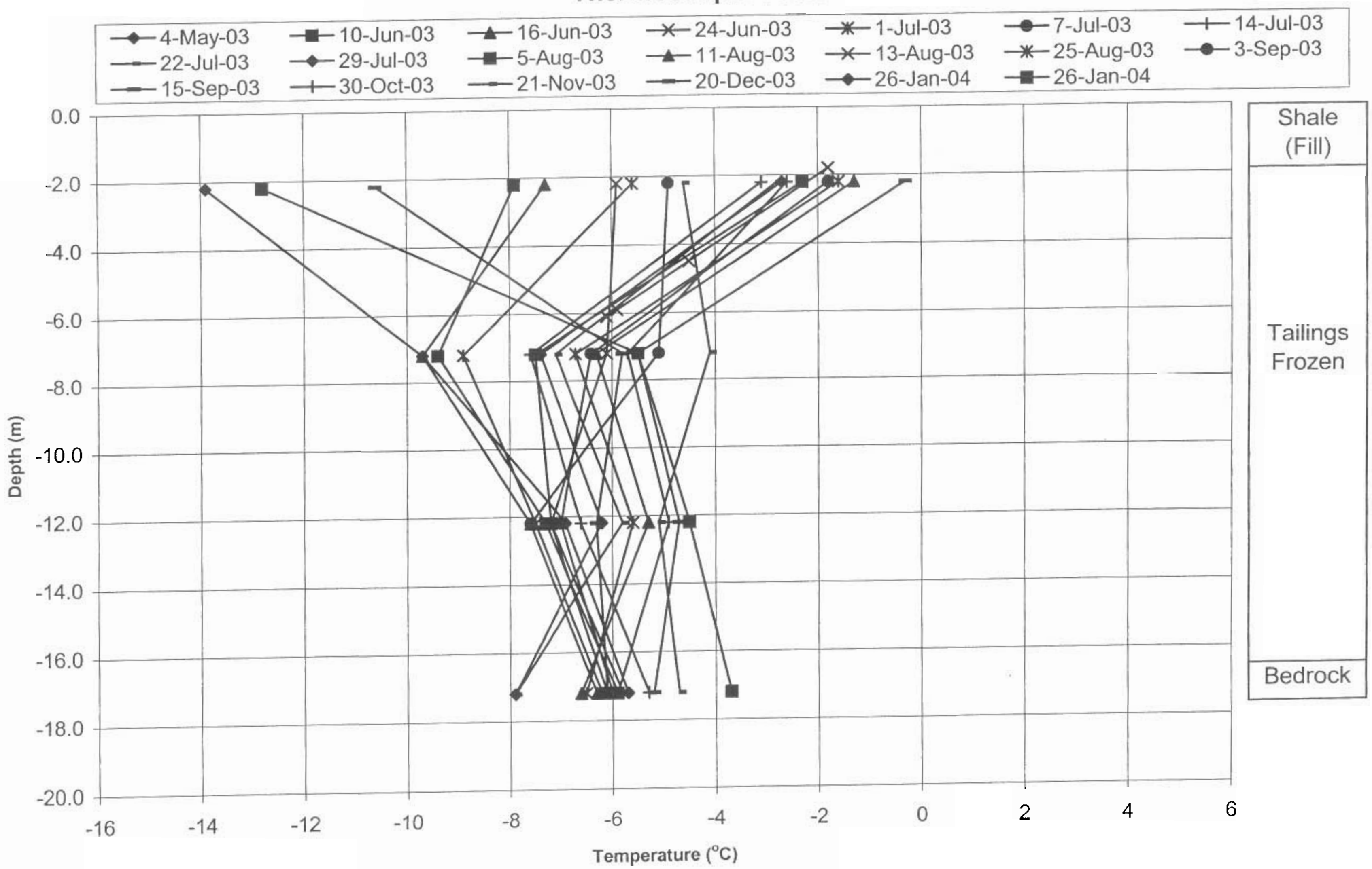
BGC ENGINEERING INC.

Geothermal Monitoring
West Twin Dike
Thermocouple TC 28

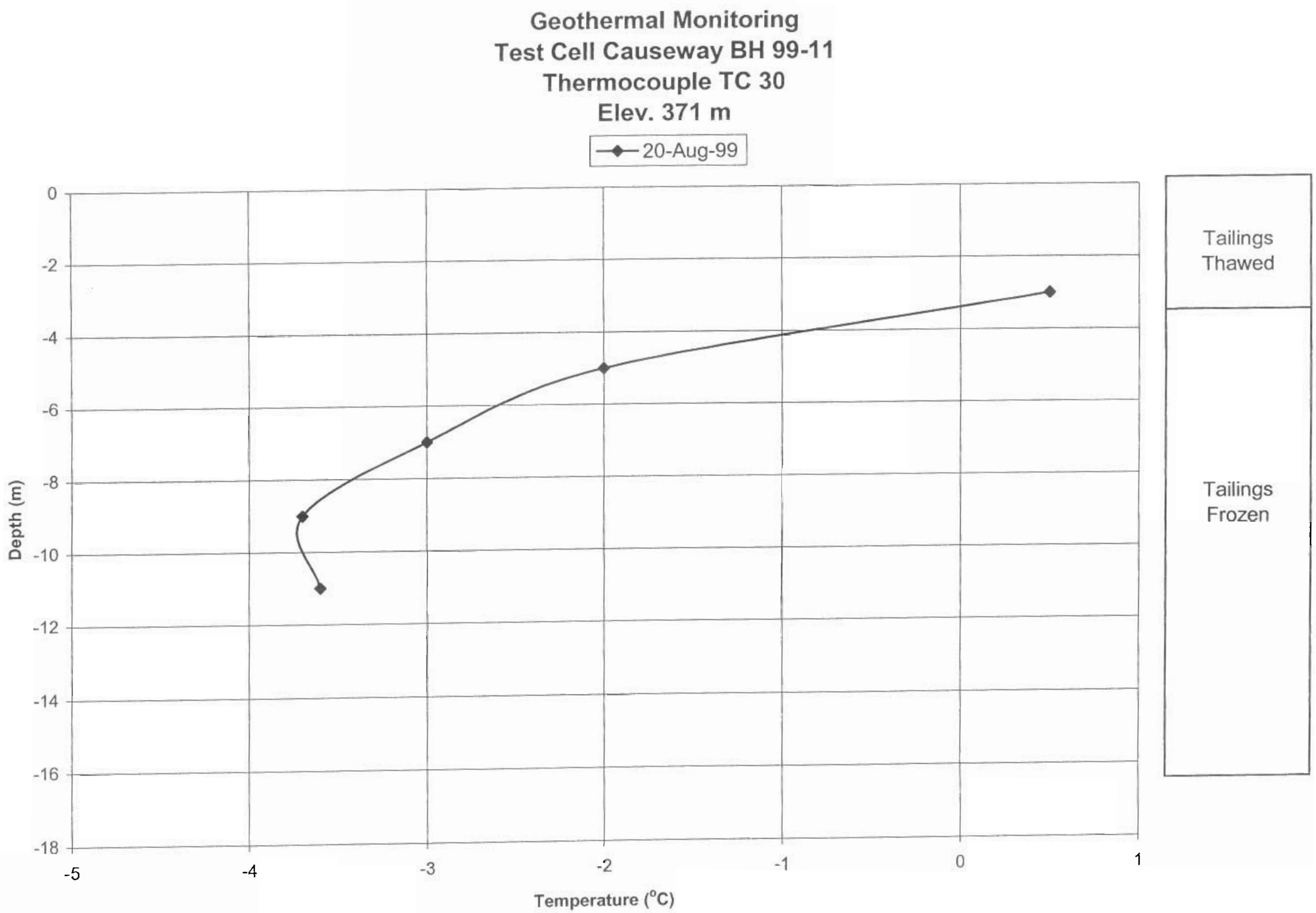


Note: Log derived from info. in Golder (98)

Geothermal Monitoring West Twin Dike Thermocouple TC 29

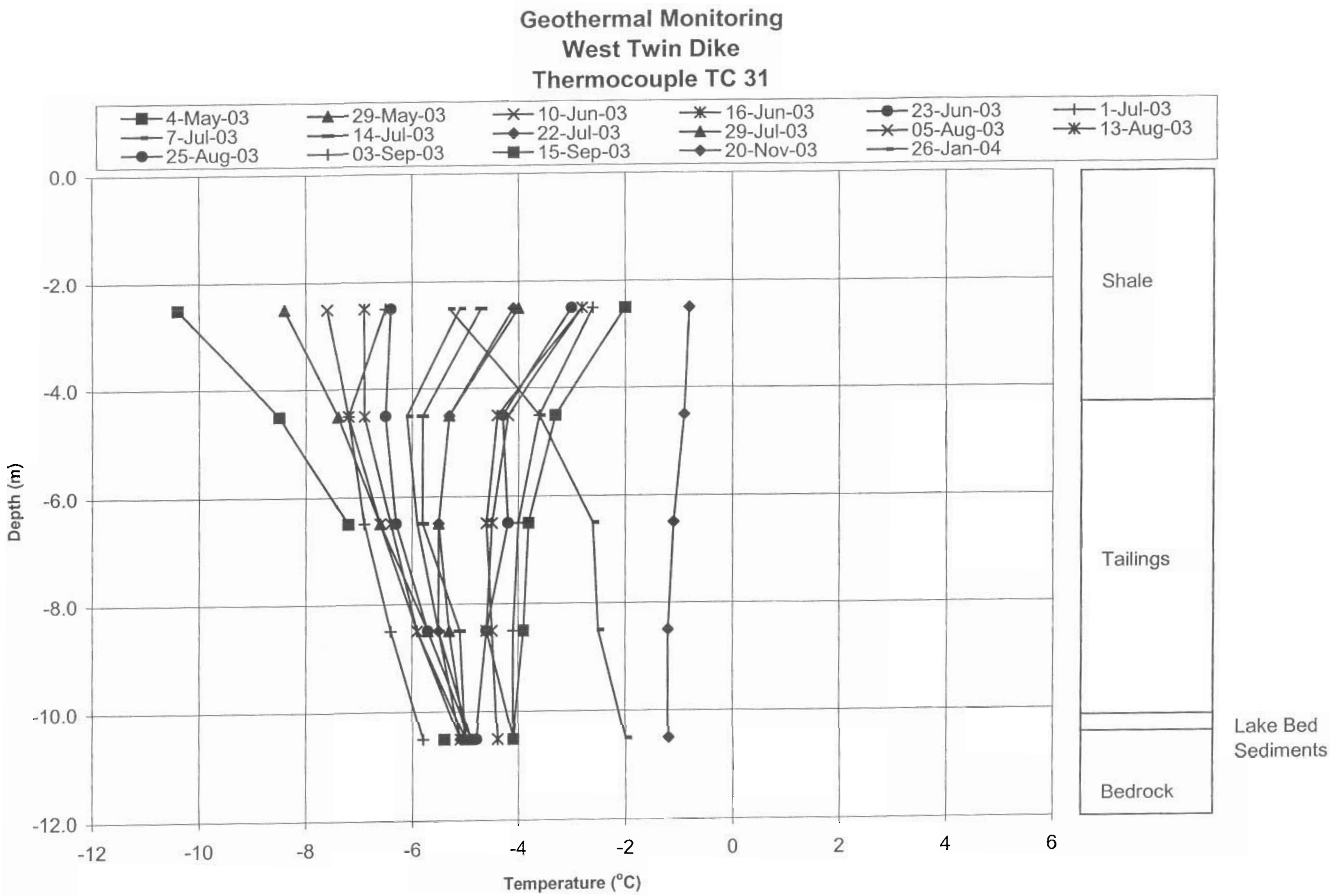


Note: Log derived from info. in Golder (98)



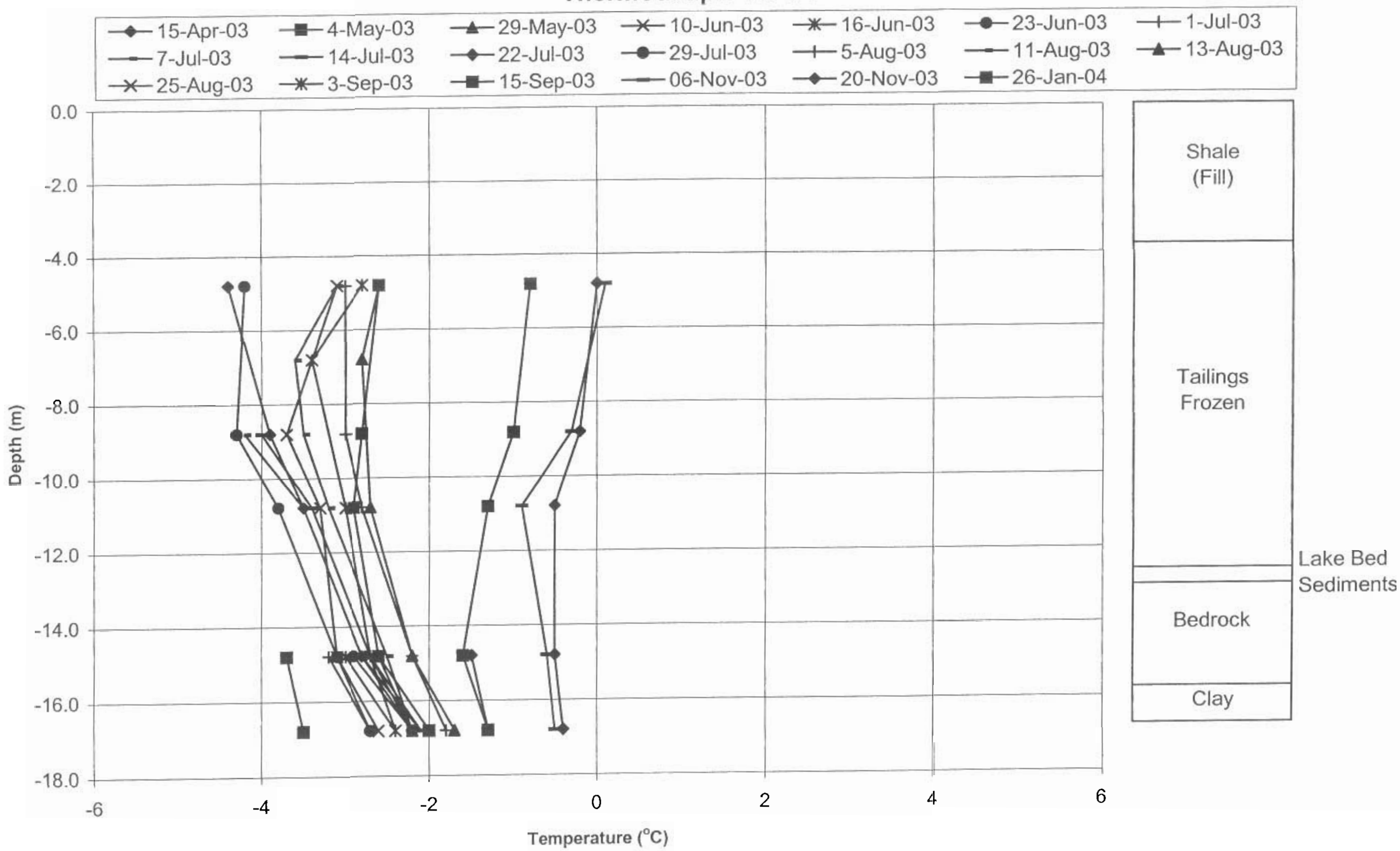
Note: This instrument is no longer operational.
Not Monitored.xls
BH 99-11 (TC30)

BGC ENGINEERING INC.

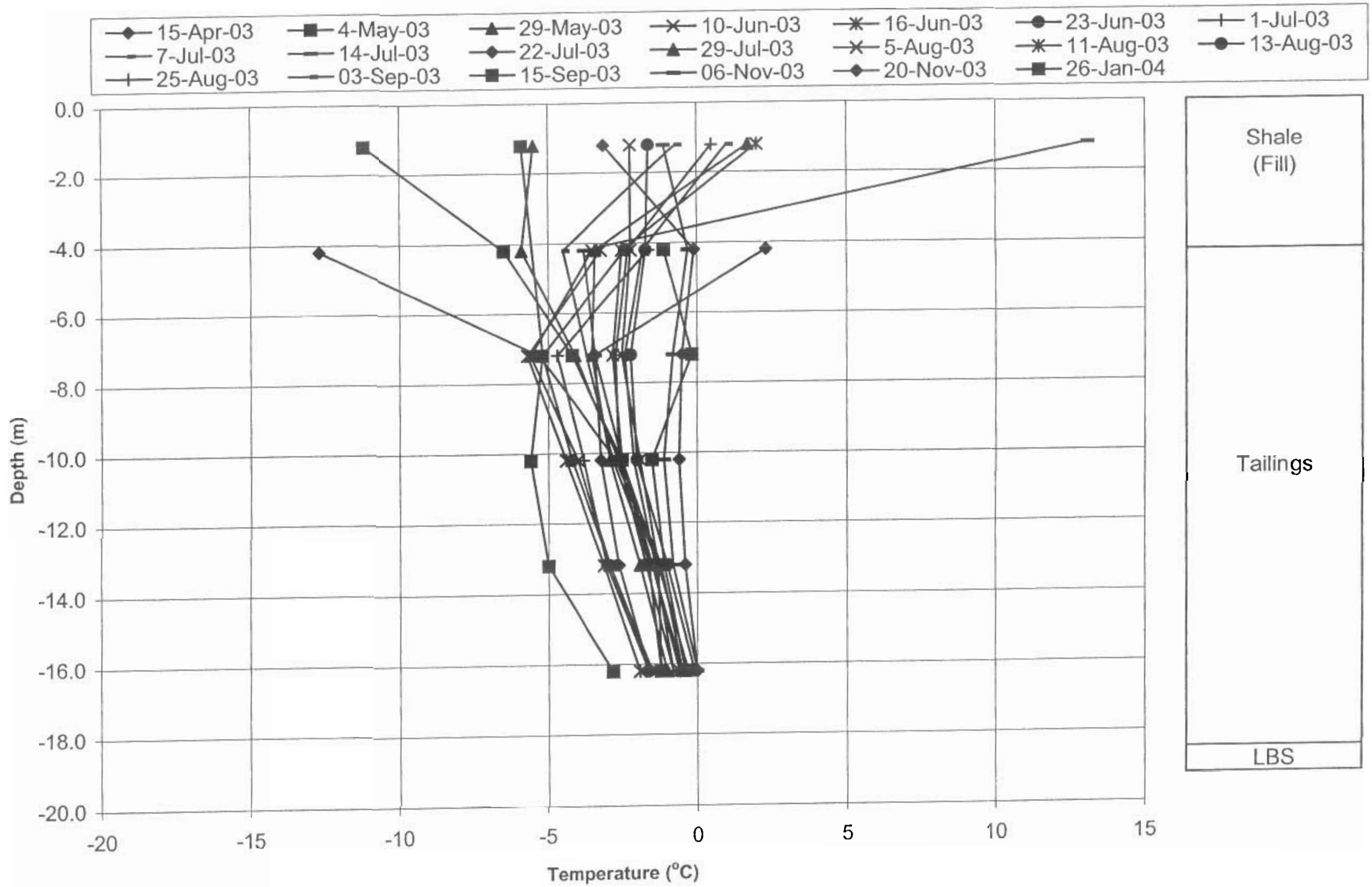


Note: Log derived from info. in Golder (99)

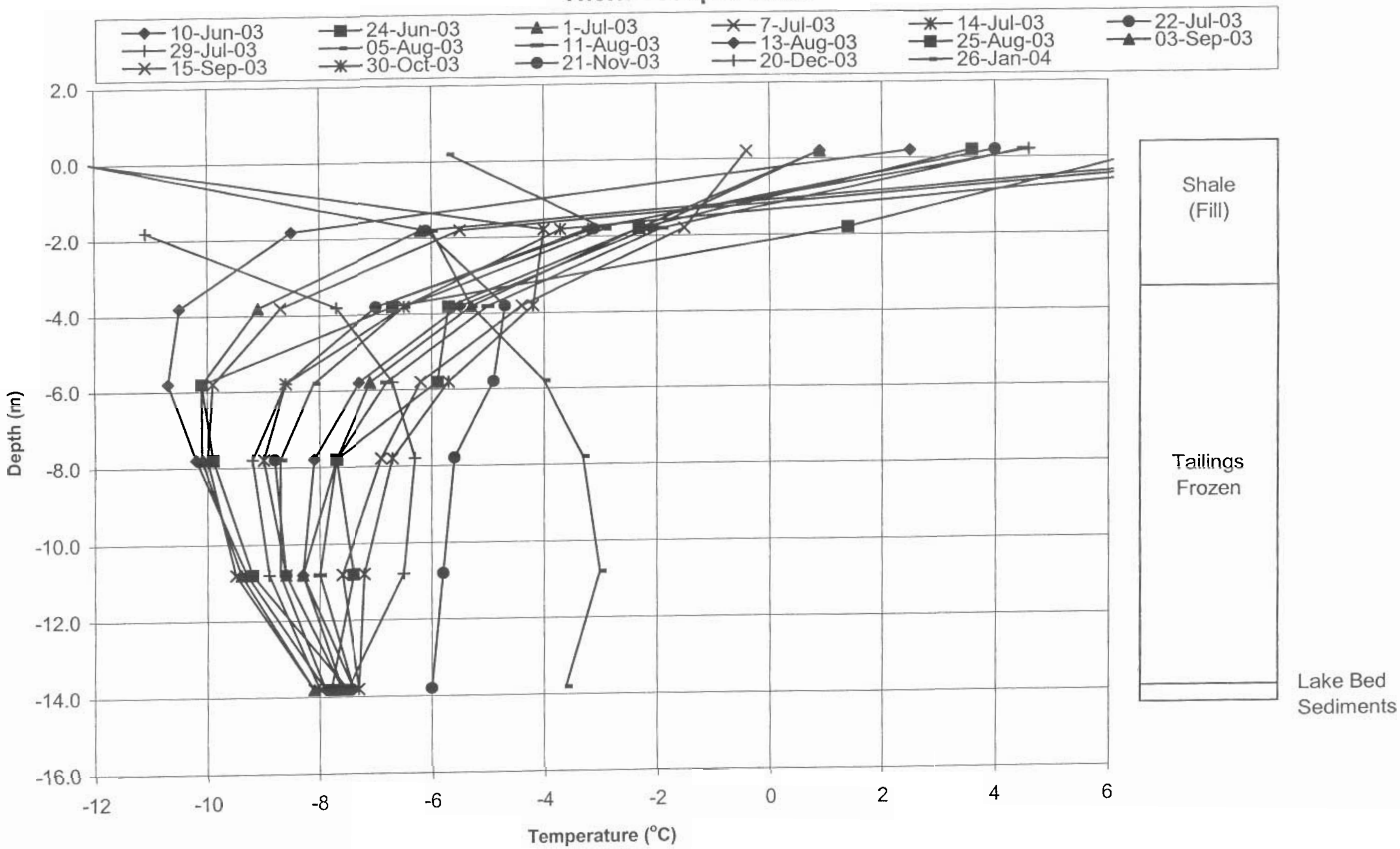
Geothermal Monitoring
West Twin Dike
Thermocouple TC 32



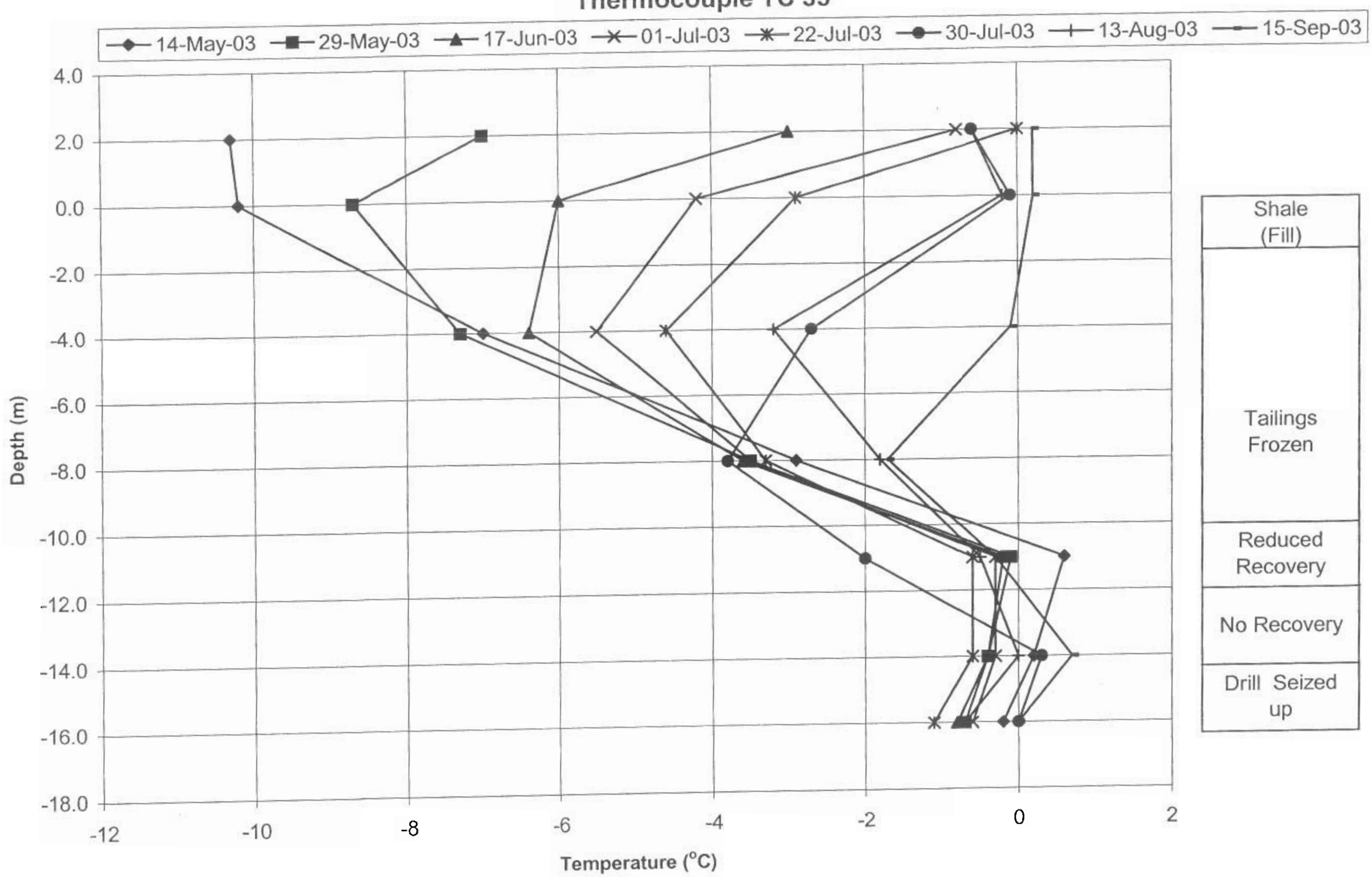
Geothermal Monitoring
West Twin Dike
Thermocouple TC 33

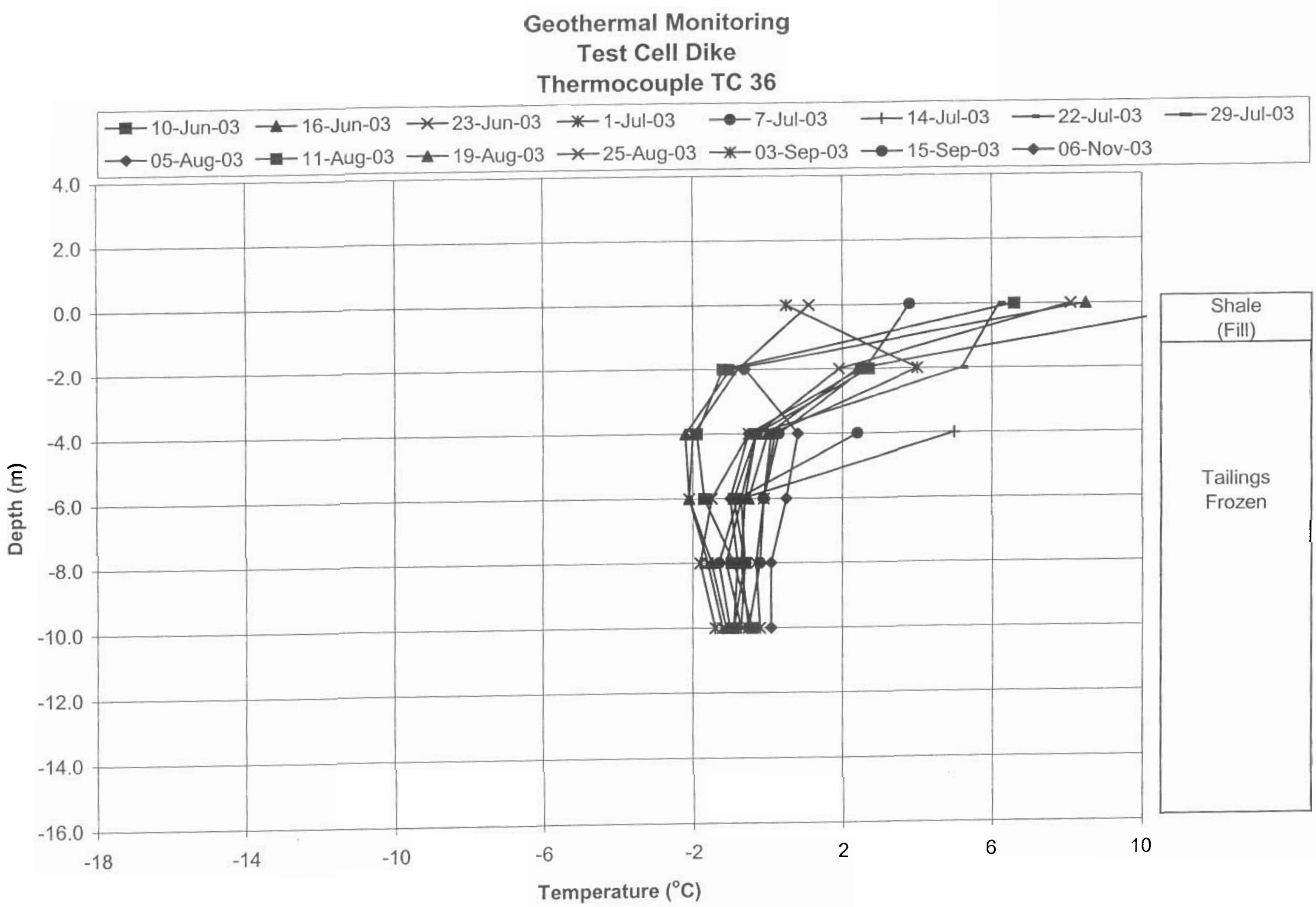


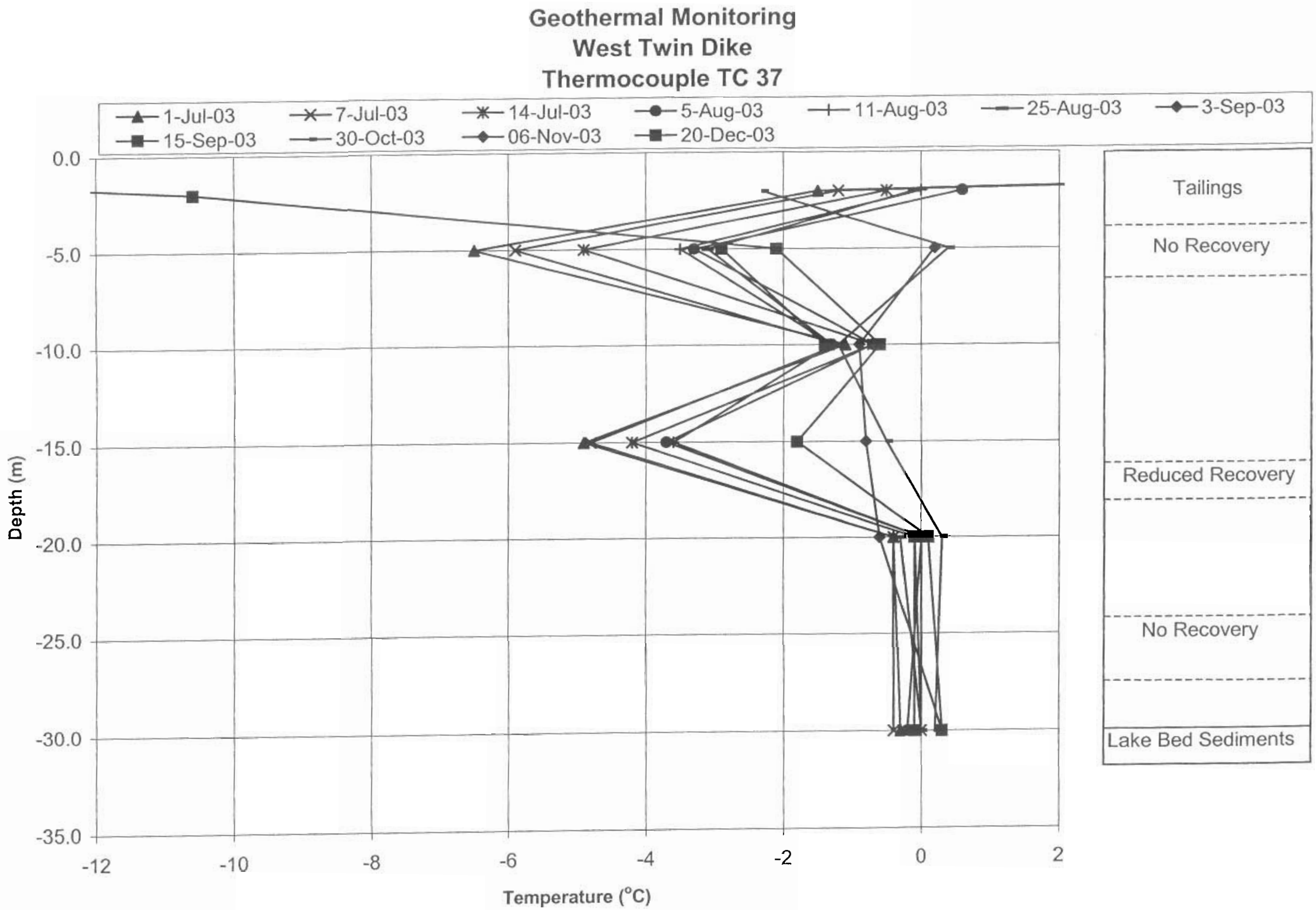
Geothermal Monitoring
West Twin Dike
Thermocouple TC 34



Geothermal Monitoring
West Twin Dike
Thermocouple TC 35




Geothermal Monitoring
Test Cell Dike
Thermocouple TC 36
10-Jun-03
16-Jun-03
23-Jun-03
1-Jul-03
7-Jul-03
14-Jul-03
22-Jul-03
29-Jul-03
05-Aug-03
11-Aug-03
19-Aug-03
25-Aug-03
03-Sep-03
15-Sep-03
06-Nov-03
Depth (m)
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
-16.0
-18
-14
-10
-6
-2
2
6
10
Temperature (°C)
Shale (Fill)
Tailings Frozen


Geothermal Monitoring
West Twin Dike
Thermocouple TC 37
1-Jul-03
7-Jul-03
14-Jul-03
5-Aug-03
11-Aug-03
25-Aug-03
3-Sep-03
15-Sep-03
30-Oct-03
06-Nov-03
20-Dec-03
Depth (m)
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
-30.0
-35.0
-12
-10
-8
-6
-4
-2
0
2
Temperature (°C)
Tailings
No Recovery
Reduced Recovery
No Recovery
Lake Bed Sediments

APPENDIX IX - GEOTHERMAL MODELLING RESULTS

Appendix IX - Geothermal Modelling Results

1. Objective of Thermal Modelling

The objective of the thermal modelling exercise was to estimate the time required for the complete freezeback of the Surface Cell talik.

Geothermal analyses were undertaken using the commercially available, finite element program, TEMP/W Ver. 5.17 by GEO-SLOPE International Ltd. TEMP/W is a finite element software product that can be used to model the thermal changes in the ground due to environmental changes or due to the construction of facilities such as buildings or pipelines (TEMP/W User's Guide, 2001). TEMP/W conducts thermal analyses of a user defined model that is created by developing a finite element mesh, defining the material properties, and specifying the boundary conditions. The climatic data and geotechnical material properties used as input for the analyses are described in detail below.

2. Input Parameters

Climatic Properties

In order to estimate a ground surface temperature, TEMP/W requires the input of several climate data parameters. These parameters include the following:

- Location,
- Daily climatic inputs,
- Snow (precipitation phase change temperature), and
- Dates.

The location is expressed as latitude and longitude and is used to calculate the global position of the site relative to the sun. This enables the program to compute solar radiation and day length for every day of the simulation. The coordinates used in the simulation for the Nanisivik mine are 73°02"N latitude and 84°31"W longitude.

The daily climatic inputs include maximum and minimum temperature, maximum and minimum relative humidity values, wind speed and precipitation. All of the these daily inputs were taken from Environment Canada data for the Nanisivik weather station from 1976 to 2003, except for the average wind speed values. The average wind speed values were taken from the Resolute Airport AES station since they were not available from the Nanisivik weather station. Since no minimum and maximum values were available for the relative humidity values, an average value was used for both. Table IX-1 summarises the daily values used in the simulations for each month.

A precipitation phase change temperature is used in TEMP/W in order to enable the simulation to determine if precipitation occurs as rain or snow. This is established with a maximum snowfall temperature and a minimum rainfall temperature input. While TEMP/W does not consider infiltration of water into the soil, it does consider that snow cover will affect the ground surface albedo and hence the net radiation received at the surface (TEMP/W User's Guide, 2001). For the thermal modeling at Nanisivik, a nominal phase change boundary temperature of -0.05^0C was used for both the maximum snowfall temperature and a minimum rainfall temperature.

Dates are also a required input for the TEMP/W thermal analysis. A nominal start date of July 1 was chosen since it allowed for the most gradual impact from outside air temperatures. The end date is dependent upon the user defined duration of the simulation. The majority of the test simulations were run over a period of 25 to 35 years or longer to better simulate long-term effects.

TEMP/W utilizes all of the above mentioned climatic data when applying boundary conditions to the model. Boundary conditions are discussed further in a following section.

Material Properties

In addition to the climatic inputs required by TEMP/W, material properties of the soil must also be established and defined. The geotechnical properties required for each soil type in the simulation include the following:

- Thermal conductivity.
- Unfrozen water content.
- Volumetric heat capacity.
- Volumetric water content.

Relationships between the thermal conductivity of a soil and its porosity and degree of saturation are reported by Kersten (1949) and others, mainly on the basis of experimental data. The thermal conductivity of ice is much higher than that of water; hence the thermal conductivity of a frozen soil generally exceeds its unfrozen equivalent. As soil porosity approaches 100%, frozen and unfrozen thermal conductivity values in a saturated system approach those of ice and water, respectively. Conversely, as the porosity of a soil approaches zero, frozen and unfrozen thermal conductivities converge on average values related to mineral constitutes.

For the purpose of the thermal analyses, laboratory tests were conducted on samples of the tailings deposits from Nanisivik. These tests were conducted to determine the following parameters:

- Thermal conductivity in both frozen and unfrozen states;
- Unfrozen water content versus freezing temperature; and
- Index tests to measure the frozen bulk density, water content, particle size distribution, and specific gravity.

Additional reference sources were consulted for the material properties of the bedrock and the shale cover materials. It should be noted that one dimensional analyses were previously undertaken on the shale cover layer and these thermal parameters were calibrated to actual site measurements. Soil thermal conductivities and other soil properties for the soil layers used in the geothermal analyses are listed in Table IX-2.

Soils that are below 0°C still contain some portion of unfrozen water within their pore space. The unfrozen moisture content values are expressed in TEMP/W as a curved function. An unfrozen water content versus freezing temperature plot for the tailings was obtained from the EBA lab test results. The power law relation below was used for determining the unfrozen water content curves for the soil materials other than the tailings.

$$w_u = A(-T)^B / w_{tot}$$

where:

w_u = unfrozen water content (fraction of total water content);
A = gravimetric unfrozen water content at -1°C;
B = exponent in power law function;
T = temperature in °C (negative); and,
w_{tot} = total water content.

Values of the A and B parameter used in the geothermal analyses, as shown in Table IX-2, come from Nixon, 1992.

In addition, a nominal freezing point depression of –0.2°C was assumed as the phase change boundary for the analyses noted herein. Any change in freezing point depression due to cryoconcentration effects was not accounted for in these analyses.

3. Geothermal Flux at Base of Model

At the base of the model, a geothermal flux boundary was used to account for thermal warming from the earth's core temperatures. The value of the unit heat flux boundary used in the model is 6.77 kJ/day.m^2. This value is obtained by multiplying the thermal conductivity of bedrock (Table IX-2) by the geothermal gradient, 0.0396 °C/m, as reported by Brown (1966).

4. 1D Model Calibration

A 1D model was set up in TEMP/W as a calibration test to compare historical readings from thermistors and thermocouples to predicted freezeback results. The model calibration was compared to field instrumentation that was installed within freshly deposited tailings. The instrumentation used in the comparison was Thermistor 02-03 and Thermocouple 03-36. Figure IX-1 shows the locations of these instruments. These two instruments were selected because they were installed in tailings recently deposited so initial thermal data was available. As a result, it provided the opportunity to see if the thermal model was able to accurately represent site observations, based on the use of laboratory measured parameters for the tailings.

The boundary conditions included the geothermal flux at the base, initial temperature conditions from the instruments and input climate data. The depth of tailings and initial temperature conditions were determined from the existing instrumentation. The depth of tailings was modelled as 16 m. A plot is included in Figure IX-2 showing the initial temperatures used in the 1D model, as well as thermistor and thermocouple values from October 1, 2002. The time period of the calibration model was from October 1, 2002 to November 20, 2003 in accordance with monitoring dates from the instrumentation.

The climate data used in the model calibration was based on mean annual values from Environment Canada over the time period from 1976 to 2003. Table IX-3 summarises the mean annual climatic values used and the actual recorded values for the period between October 1, 2002 and November 20, 2003. The table indicates that the period between October 2002 and November 2003 had higher actual monthly temperature values than the mean monthly air temperatures used in the model. The snow depth at the end of month values were also higher on average than assumed in the model. Therefore, the actual results were expected to be warmer than the model results.

The results of the model calibration test can be seen in Figure IX-2, which shows that, to a depth of 4 m below the surface, the model predicts colder results than observed data. Between the depths of 4 and 12 m below surface, the model predicts slightly warmer than actual results, which would be considered conservative in terms of predicting freezeback rates.

The reason for the discrepancies between the model results and the actual observed data in the upper 4 m of the tailings is likely a result of the warmer weather in 2002-2003 combined with the proximity to surficial water ponds. The warming effects of surface water ponds near the tailings is not accounted for in the thermal model, but is reflected in the actual field results. The four metre depth corresponds well with the tailings height above the proximal pond levels. The proximity to the surface water sources would also result in convection warming due to subsurface groundwater flow paths. This convection heat transfer cannot be accounted for in current thermal models.