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"STUDY OF EXISTING TEMPERATURE DATA FROM CANADIAN BASINS - PHASE IV"

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Earth Physics Branch Open File Number 85-6
Dossier public de la Direction de la Physique du Globe No. 85-6

Abstract

Over 8400 bottom-hole temperature (BHT) values from the Canadian part of the Williston Basin have been analysed and a temperature anomaly has been discovered in the Weyburn area of southeastern Saskatchewan. Regional heat flow variations are observed, and these are closely related to the hydrodynamics which is governed by the topography and geology. The blanketing effect of low conductivity shaly formations may cause a temperature anomaly in the south where the thickest Phanerozoic cover exists. However, the Weyburn anomaly can be only partly explained in this way. Hydrodynamics has also contributed to the formation of this temperature anomaly. Preliminary examination of data from the Northwest Territories has commenced.

Résumé

Plus de 8400 données de température de fond recueillies dans la partie canadienne du Bassin Williston ont été analysées. Une anomalie thermale a été découverte dans la région de Weyburn en Saskatchewan du sud-est. Les variations régionales du flux de chaleur qui sont observées, sont étroitement liées à l'hydrodynamique qui à son tour est fonction de la topographie et de la géologie. La couverture de formations schisteuses de basse conductivité thermique pourrait être à l'origine d'une anomalie thermale dans le sud, là où le couvert phanérozoique est le plus épais. L'anomalie de Weyburn n'est cependant qu'en partie expliquée par cet effet. L'hydrodynamique contribue également à sa formation. Une étude préliminaire de données des Territoires du nord-ouest a été mise en marche.

REPORT

"Study of Existing Temperature
Data from Canadian Basins -
Phase IV"

(DSS Contract OST84-00052)

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J.A. Majorowicz

March 31, 1985

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1. Introduction

During the tenure of this contract, a detailed study of the temperature regime of the sedimentary basin in Saskatchewan and Manitoba has been undertaken. This is an extension of the work carried out previously for Alberta [see the Report for DSS Contract UP-A-268 Phase II: "A Study of Existing Temperature Data from Canadian Sedimentary Basins by F.W. Jones, J.A. Majorowicz and H.-L. Lam, March 31, 1984]. As a result, the major part of the Prairies Basin in western Canada has been considered in detail.

The work has involved the determination of the temperature gradient and heat flow patterns and their variations with depth. The relationships between the hydrodynamics of the basin and the heat flow and gradient patterns have been considered, as well as the connection between hydrocarbon occurrences and the geothermics of the basin.

The work is based on existing bottom-hole temperature data from exploration and service company well logs and thermal conductivity estimates from the results of net rock analyses supplied by the Earth Physics Branch, EMR, Ottawa.

Initial work has begun on an extension of the project to the Northwest Territories. Data from the Northwest Territories have been collected from well logs, and preliminary analyses of these data have begun.

2. Saskatchewan and Manitoba results

Temperature data from 7,147 wells with 7,764 bottom-hole temperature (BHT) values from Saskatchewan and 663 BHT values from 631 wells in Manitoba have been used to study the temperature regime in the Prairies Basin areas of these provinces as well as the Canadian part of the Williston Basin.

Geothermal gradients, thermal conductivities and heat flow have been investigated for most of the Mesozoic + Cenozoic clastic units as well as the Upper Paleozoic carbonate-evaporite unit. Regional heat flow variations with depth occur, and these are closely related to the hydrodynamics which is governed by the topography and geology.

A temperature anomaly has been discovered in the Weyburn area of southeastern Sasktchewan which may be caused by the blanketing effect of low conductivity shaly formations where the thickest Phanerozoic cover exists. However, it is found that the Weyburn anomaly can be only partly explained in this way, and it is shown that hydrodynamics has also contributed to the formation of the temperature anomaly there.

The process of formation of the anomaly by the blanketing effect and hydrodynamics has also contributed to the process of oil deposition, and a correlation is found to exist between Mississippian oil occurrences in the southwestern part of the basin and the location of the Weyburn anomaly.

A detailed discussion of these findings is given in Appendix I.

3. Work in progress: The Northwest Territories

Bottom-hole temperature data (BHT) from 2658 wells in the continental area of the Northwest Territories were collected (Fig. 1, Appendix II). In addition, data from 39 wells in the Yukon were collected.

In 695 of the Northwest Territories wells (see Fig. 2, Appendix II for locations) there were at least two readings of BHT run at different times after circulation had stopped. For these data it was possible to apply a correction, usually called the Horner correction (Fertl and Wichmann, 1977)[1] to allow for the approach of well temperature to equilibrium. Temperature 'time' corrections applied to the NWT BHT data are large. For example, such corrections change the average Grad T for the studied area by about 15-20 mKm^{-1} (compare Fig. 5 with Figs. 6, 7 and 8 in Appendix II).

The locations of the wells with corrected and uncorrected BHT data for the NWT are shown in Figs. 1 and 2. The locations of the BHT data from the Yukon and the neighbouring Northwest Territories are shown in Figs. 3 and 4 (see Appendix II). The corrected and uncorrected BHT data were plotted against depth for two areas (60°-66°N Lat., 115°-127°W Long. and 65°-70°N Lat., 123°-137°W Long.). The average gradient value based on the corrected BHT data versus depth regression line is

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1 Fertl, W.M. and P.A. Wichmann, 1977. How to determine static BHT from well log data, World Oil, 1984, 105-106.

high for the southern area and equals 52.4 mKm^{-1} (see Fig. 6 in Appendix II). It is less for the Mackenzie Delta and neighboring areas and the average geothermal gradient based on corrected BHT data equals 35.6 mK/m there (Fig. 8, Appendix II). The standard error of estimate for the temperature versus depth regression line is high in both cases and equals 21.6 mKm^{-1} and 18.1 mKm^{-1} respectively.

The available temperatures are much higher for the southern region of the NWT in the northern part of the Prairies Basin. Table 1 shows the average temperatures at four depths for these two areas.

Table 1

Average temperature with depth in the NWT area

	Area 60°-66°N Lat. 115°-127°W Long.	Area 65°-70°N Lat.. 123°-137°W Long.
Depth(km)	Temperature °C	Temperature °C
-1 km	36	19
-2 km	88	53
-3 km	137	89
-4 km	~160	~125

The geothermal energy prospect is very good for the southern area as far as temperature is concerned.

Preliminary studies of geothermal gradients in the NWT area based on corrected BHT data show large regional variations and large variations with depth. The geothermal gradient values vary from 20 mKm^{-1} to 65 mKm^{-1}. The depth variations also appear to be large, and they are being studied. Effective conductivity and heat flow studies are underway.

APPENDIX I

Geothermics of the Williston Basin in Canada in Relation to Hydrodynamics and Hydrocarbon Occurrences

A paper being prepared for submission to Geophysics.

GEOTHERMICS OF THE WILLISTON BASIN IN CANADA IN RELATION TO HYDRODYNAMICS AND HYDROCARBON OCCURRENCES

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Abstract

Over 8400 bottom-hole temperature (BHT) values from the Canadian part of the Williston Basin have been analysed and a temperature anomaly has been discovered in the Weyburn area of southeastern Saskatchewan. Geothermal gradients, thermal conductivities and heat flow have been investigated for most of the Mesozoic + Cenozoic clastic unit as well as the Upper Paleozoic carbonate-evaporite unit. Regional heat flow variations with depth occur, and these are closely related to the hydrodynamics which is governed by the topography and geology. The blanketing effect of low conductivity shaly formations may cause a temperature anomaly in the south where the thickest Phanerozoic cover exists. However, the Weyburn anomaly can be only partly explained in this way. Hydrodynamics has also contributed to the formation of the temperature anomaly there. The process of formation of the anomaly by the blanketing effect and hydrodynamics has also contributed to the process of oil deposition. A correlation exists between Mississsippian oil occurrences in the southeastern part of the basin and the location of the Weyburn temperature anomaly.

Introduction

Sedimentary basin studies have shown that large scale redistribution of heat from the crystalline crust and upper mantle can be caused by gravity forced water motion in the sediments. As a result of this hydrodynamic effect, both regional and depth variations in heat flow occur. Examples of this have been found in the Alberta part of the Western Canadian Sedimentary Basin (Majorowicz and Jessop, 1981a,b; Majorowicz et al., 1984a,b; Hitchon, 1984) and in the North Sea Basin (Andrews-Speed et al., 1984).

The hydrodynamics also affects the basin heat flow history, and thus the temperature environments of hydrocarbon deposits and source rocks change with time and influence the generation and maturation of oil and gas in sedimentary strata. This is evident for the Alberta basin (Majorowicz and Jessop, 1981b, Majorowicz et al., 1985b, Hitchon, 1984, Beaumont et al., 1984).

The present paper examines the geothermal field of the Canadian part of the Williston Basin using petroleum bottom-hole temperature data (BHT) from 7,147 wells in Saskatchewan and 631 wells in Manitoba. The area of study and its geological setting are shown in Fig. 1.

The Williston Basin developed within the Western Canada Sedimentary Basin as an intracratonic basin. It is of circular shape with over 4 km of sediments which range in age from Cambrian to Tertiary. The maximum thickness of the sediments in Canada is about 3.5 km. Ahern and Mrkvicka (1984) considered a mechanical and thermal model of the evolution of the basin and suggested the cooling of a heat source to produce the basin structure.

The main aim of the present paper is to investigate the relationship between heat flow in the basin and the hydrodynamics on a general regional scale. In addition, the relationship between the heat flow and major hydrocarbon occurrences in the Canadian part of the basin is considered.

Overview of previous studies of the basin geothermics

The first geothermal gradient map of the Williston Basin was included as part of the Geothermal Gradient Map of North America prepared by the American Association of Petroleum Geologists in 1976. It was based on BHT data and annual mean surface temperatures. The BHT data were from a wide depth range and different geological formations with different heat conductivity values. For the Canadian part of the basin, the map showed an overall increase of geothermal gradient toward the shallower eastern part of the basin, with a maximum value in the Brandon region.

Majorowicz and Jessop (1981a) analysed temperature data from shut-in wells from Mississippian formations in the Saskatchewan part of the basin, and reported a high geothermal gradient anomaly in the Weyburn area.

Temperature logging of a borehole in Regina has been carried out by Jessop and Vigrass (1984) as part of a geothermal project there. Accurate temperature measurements from this 2 km deep hole have shown that a significant change of temperature gradient from about 36°C/km to 17°C/km occurs between the upper clastic unit from 0 to 1000 m and the Paleozoic carbonate-evaporite sequence from 1000 m to 2000 m. Jessop and Vigrasss (1984) attributed this change to the contrast in thermal conductivity between the clastic and carbonate-evaporitic units, but they also suggested that the difference is partly due to a hydrodynamic effect similar to that described by Majorowicz et al. (1984a) in Alberta.

Jones et al. (1982) collected BHT data from petroleum exploration well logs from Saskatchewan and Manitoba deposited with the Saskatchewan Department of Mineral Resources. Almost an order of magnitude more temperature values from this area were collected (7,764 BHT from 7,147 wells in Saskatchewan, and 663 BHT from 631 wells in Manitoba) than were used for the AAPG map). Only very preliminary analysis of these data was undertaken by Jones et al. (1982) in their report. These data have been used in the present study. Locations of the wells from which data were used are shown in Figs. 2 and 3.

Geothermal gradients

Construction of the AAPG Geothermal Gradient Map of North America (1976) was based on geothermal gradients calculated from the formula

$$\frac{\partial T}{\partial z} = (T_B - T_G)\frac{1}{D} \qquad (1)$$

where z is depth, T_B is the temperature recorded at the bottom of the hole at depth D, and T_G is the ground surface temperature. Uncertainties due to common measurement errors often occur when only single recordings of T_B are considered. Furthermore, in the interval between the ground surface and depth D where the value of T_G is recorded, major variations of heat conductivity often exist, and transport of heat by water motion may occur. Therefore, values of $\frac{\partial T}{\partial z}$ may be expected to tell us more about the conductivity variations and water movement than they do about variations in heat flow. For this reason, and because major changes in conductivity exist between the Mesozoic + Cenozoic formations and the Upper Paleozoic formations in the Williston Basin as will be shown later, the method of equation (1) was not used here. In the present work, the temperature gradient values were determined from the slopes of least squares fitted straight lines to temperature/depth plots from the BHT data for each 3x3 township/range area. (A township/range is defined by the Dominion Land Survey System and is approximately 9.6 x 9.6 km). Gradients for the two intervals, Mesozoic + Cenzozoic and Upper Paleozoic, were determined. Average gradient values of Grad T_1 for the upper interval were calculated from the BHT data in that interval and the average ground surface temperature of +5°C as given by Judge (1973) and Jessop and Vigrass (1984). The geothermal gradients below the Paleozoic surface (Grad T_2) were based on BHT values only, by using the least squares fit method.

For many wells in the southern part of the Western

Canadian Sedimentary Basin, several temperature readings at successive times are known, so that the correction described by Fertl and Wichmann (1977) can be applied to take into account the cooling of the well-bore by circulation fluids. By plotting and comparing uncorrected and corrected values versus depth where a sufficient number of data provided a good comparison, regional temperature corrections were determined on a statistical basis. The correction varies from 5% to 15% for the whole southern part of the Western Canadian Sedimentary Basin, and averages 6% for the study area. More detailed information on the correction procedure is given by Majorowicz et al. (1984b).

Maps of grad T for the upper part of the sedimentary section (grad T_1) and the lower part of the sedimentary section (grad T_2) are shown in Figs. 4 and 5 respectively. A contour interval of 5°C km^{-1} was chosen which is 20% of the average grad T for the study area. Only regional variations with changes greater that 5°C km^{-1} are interpreted in this paper.

Heat conductivity estimates

Jones et al. (1984) showed for an area of the western prairies in Alberta that heat conductivity estimates based on net rock analysis and heat conductivity values for different rock types can give more reliable results than conductivity estimates based on measured data from only the intervals from which core samples are available. In thick shale intervals core samples are rarely taken. The cores are mainly from formations of interest for oil and gas exploration, i.e. sandstones and high porosity carbonates, and so values based on measurements of these samples do not well represent the effective heat conductivity for the whole column.

Effective heat conductivity, K, is given by

$$K = \frac{\sum_{i=1}^{n} \ell_i}{\sum_{i=1}^{n} (\ell_i/K_i)} \qquad (2)$$

where the quantities $K_1, K_2, \ldots, K_n$ are estimated heat conductivities based on rock types for discrete layers of thicknesses $\ell_1, \ell_2, \ldots, \ell_n$. The details of this method of estimating effective heat conductivity are given in Majorowicz and Jessop (1981a) and Jones et al. (1984), and it is the technique used in the present work.

An example of the heat conductivity profile for the well Dillman Tuxford 1 in Saskatchewan based on the net rock method is shown in Fig. 6. With an assumed heat flow Q and by using the measured ground surface temperature T_G and effective heat conductivity from the net rock method, a temperature profile with depth can be predicted. Heat flow Q is given by

$$Q = K|\text{grad } T| \qquad (3)$$

where grad T is the temperature gradient and so the temperature profile is given by

$$T_z = T_G + Q \sum_i (\ell_i/K_i). \tag{4}$$

Different values of Q were assumed in order to obtain a match between the predicted temperature profile, T_z, and the measured profile of the Regina well where similar geological conditions occur. A heat flow of 70 mWm^{-2} gave a close match between the measured and predicted temperature profiles. The predicted temperature profile is shown in Fig. 6. A significant change in grad T with depth can be explained by the increase in conductivity from the upper clastic unit to the carbonate-evaporitic units. A sharp increase of grad T at the bottom of the profile is associated with a further decrease in conductivity in the basal clastic unit.

The increase of effective heat conductivity in the Paleozoic formations, as compared to the Mesozoic + Cenozoic formations above, is an overall regional feature which is apparent when maps of the effective heat conductivities for the study area (Figs. 7 and 8) are compared. This is further evident from the heat conductivity histograms for the two intervals given in Fig. 9. The mean heat conductivity for the Mesozoic + Cenozoic is 2.1 $Wm^{-1}K^{-1}$, whereas that for the Paleozoic formations is 3.7 $Wm^{-1}K^{-1}$.

Heat flow

In order to determine whether regional and depth variations of grad T as well as variations of grad T for different geological units are a result of effective heat conductivity variations, or whether they are related to heat generation variations or variations in the transport of heat by forced fluid convection, the heat flow distribution must be known.

Equation (3) was used to estimate heat flow (Q) for the two major intervals: (1) from the ground surface to the Paleozoic surface (the mostly clastic unit) and (2) below that surface (in the mainly carbonate-evaporitic unit). The upper interval heat flow is denoted by Q_1, and that for the lower interval as Q_2. Contour plots of these two quantities are shown in Figs. 10 and 11, and it is seen that the heat flow densities above and below the Paleozoic erosional surface differ both regionally and in detail. Histograms of the Q_1 and Q_2 values are shown in Fig. 12, and a difference in the average heat flow value as well as in the statistical distribution is apparent. The mean value of Q_2 is greater than that of Q_1 and the Q_2 values are more scattered. The heat flow Q_1 above the Paleozoic surface shows the trend of increase from low values in the southwest where $Q_1 < 60\ mWm^{-2}$ to highs in the northeast where $Q_1 > 100\ mWm^{-2}$ (Fig. 10). That situation is similar to the trend shown in the Grad T map (Fig. 4), because regional variations of heat conductivity in this interval (Fig. 7) are low. The heat flow below the Paleozoic surface, Q_2, is low in the northeast ($Q_2 < 40\ mWm^{-2}$) and high ($Q_2 > 100\ mWm^{-2}$) in the central part of the Canadian part of the Williston Basin (Fig. 11).

Heat flow differences between the Mesozoic + Cenozoic sediments and the Paleozoic sediments were calculated by the equation

$$\Delta Q_i = Q_{1_i} - Q_{2_i} \quad (5)$$

where ΔQ_i is the difference at a particular location and Q_{1_i} and Q_{2_i} are the heat flows above and below the Paleozoic surface where i=1,2,...,n represents the location. The results for Saskatchewan and Manitoba were combined with the results from similar calculations for Alberta (Majorowicz et al., 1985) and mapped for the whole Prairies Basin. The map of ΔQ is shown for the prairies in Fig. 13.

In an ideal steady-state conductive situation, heat flow should not vary with depth (i.e. ΔQ =0), and any change in the geothermal gradient across any particular depth interval should be associated with a change in K to maintain a constant product. The amount of heat entering the system from below should equal that leaving above. This does not happen in the Prairies Basin of western Canada.

The ΔQ pattern exhibits mainly positive values in the northeastern part of the Prairies and negative values to the south and southwest with a zone in which ΔQ=0 between them. This overall regional trend indicates the decrease in heat flow from the Mesozoic + Cenozoic unit to the Paleozoic unit in the shallower part of the basin but an increase for the deep part of the basin described by Majorowicz et al. (1985) for Alberta extends to the Canadian part of the Williston Basin as part of a large-scale Prairies-wide feature and related to the hydrodynamics.

A histogram of ΔQ_i for the Canadian part of the Williston Basin is given in Fig. 14 and shows a prevalence of negative ΔQ_i values. This reflects the fact that there are no heat flow data for the part of the very shallow basin where Q_2 is higher than Q_1. The shallow depth of bottom-hole temperature data did not allow good quality heat flow estimates to be made there.

The heat flow values above the Paleozoic surface (Q_1) and below that surface were plotted against elevation above sea level and the plots are shown in Fig. 15. There is a clear statistical relationship between the shallower interval heat flow values Q_1 and the elevation above sea level (Fig. 15a) whereas such a correlation is not evident for the deeper heat flow plot (Fig. 15b).

Heat generation

Heat generation for the Precambrian (mostly Churchill) basement rocks has been determined on the basis of uranium, thorium and potassium radioactive isotope data by Burwash and Cumming (1976) and by Burwash (1976). The formula

$$A = 10^{-5} \rho (9.52 \times CU + 3.48 \times CT + 2.56 \times CK) \quad (6)$$

was used, where CU, CT and CK are respectively uranium, thorium and potassium isotope contents for a given density ρ.

The distribution and magnitudes of A values are shown in Fig. 16 and a histogram of the values is given in Fig. 17. The values are scattered, but the highest values of $\bar{A} > 5\ \mu Wm^{-3}$ are found in the deeper southern part of the basin. A mean of A=2.6 μWm^{-3} from 33 observations is higher than that observed for the shield of the Churchill province by Drury (1984). This implies that a potentially higher basement heat flow exists in the study area than that in the Churchill province of the shield where the average heat flow is $45 \pm 9\ mWm^{-2}$ (Drury, 1984). The average heat flow for the Superior Province which underlies the eastern part of the basin is $\bar{Q} = 40 \pm 8\ mWm^{-2}$ according to Jessop and Lewis (1978). This is much lower than the average values of Q_1 and Q_2 for the Williston basin which are 64 mWm^{-2} and 78 mWm^{-2} respectively. However, individual Q_1 and Q_2 values for particular locations are often different because a steady-state conductive heat flow situation does not exist. The expected average heat flow for the Canadian part of the Williston Basin can be calculated from

$$Q = Q^* + Ah \qquad (7)$$

as long as

$$\int_0^\infty A(z)dz = hA(o) \qquad (8)$$

where h is a characteristic depth and Q* is the reduced heat flow.

Assuming h = 14 km and $Q^* = 28\text{-}37\ mWm^{-2}$, as reported for the shield by Drury (1984) and by Jessop and Lewis (1978), and taking the average value of $A = 2.6\ \mu Wm^{-3}$ for the Williston Basin, the average Q will vary from $64\ mWm^{-2}$ to $73\ mWm^{-2}$ depending on the value chosen for Q*. Since a difference can be expected between the h and Q* values of the crystalline crust of the shield and the crystalline crust of the basin beneath the sedimentary cover deposited since Cambrian times, the value of Q calculated in this way can give only an approximate idea of the heat flow.

Heat flow and hydrodynamics

The major hydrodynamic features of the Canadian part of the Williston Basin have been studied by Hitchon (1969). Fluid flow takes place toward the shallower part of the basin to the east toward Lake Winnipegosis. This is characterized by a gradual drop in the hydraulic head from the high elevation areas in the southwest (see Fig. 18) toward the low elevation areas in the east in every depth interval slice investigated by Hitchon (1969) and Hitchon et al. (1969)(see Fig. 19). It was also noted by Hitchon et al. (1969) that evaporites are present in most of Saskatchewan and Manitoba except in the southwestern part of the basin, and this plays a significant role in hydraulic head distribution and fluid flow pattern. Halite deposits form a barrier between the downward seepage of water from the surface and upward flows in the Paleozoic formations. An example of this is shown in the cross section (Fig. 19c).

Several observations can be made on the relationship between the observed heat flow pattern and the hydraulic head patterns:

1. A positive correlation exists between the elevation above sea level and heat flow Q_1 in the Mesozoic + Cenozoic formations (see Fig. 15 and compare Figs. 10 and 19).

2. Areas of low hydraulic head in the east are characterized by high Q_1 values but much lower Q_2 values in the Paleozoic (compare Fig. 9 with Fig. 10 and see also Fig. 19).

3. The areas of positive values of ΔQ are mainly in the east where low ground surface elevation and low hydraulic head exist. The high hydraulic head areas are mainly characterized by negative ΔQ values (refer to Figs. 13, 18 and 19).

4. In the area where the hydraulic head and ground surface above sea level are highest, the heat flow Q_1 for the Mesozoic + Cenozoic and heat flow Q_2 for the Paleozoic are low and are nearly equal (i.e. $Q_1 \sim Q_2 \approx 60$ mWm^{-2}). That area coincides with the region where there are no Elk Point evaporites to prevent water seepage to great depth into the deep Paleozoic.

The above is consistent with the findings by Majorowicz and Jessop (1981a) and Majorowicz et al. (1984b,1985) based on heat flow studies in relation to the hydrodynamics in the neighbouring Alberta Basin. G. van der Kamp (1984) has shown that the effects of forced convective groundwater flow can be approximately determined by means of the dimensionless Peclet number P which is a measure of the overall temperature disturbance within the flow system. The ratio of heat transfer by forced convection to heat transfer by conduction approximately equals

$$P = \frac{\rho_w C_w q_w}{K \; L/H}$$

where the flow system has length L between water recharge and discharge, H is depth, q_w is the total amount of water flow through the system per unit width, ρ_w is the density of water and C_w is the specific heat capacity of water. Taking an approximate length L = 600 km between water recharge areas in southwestern Saskatchewan and water discharge areas in western Manitoba and H=2 km as the average basin thickness and seepage water velocity $v = q_w/h$ to be of order 10^{-8} m/s, the ratio between the heat transfer by forced convection and heat transfer by conduction is of the order of tenths and so is significant. More detailed numerical studies of that effect are now underway.

Temperature

Observed temperatures

The general feature of the temperature field as determined from corrected BHT data is an increase in temperature at certain depths in the south and southeast toward the deeper part of the basin. This can be seen from temperature maps constructed for depths of 1 km and 2 km below ground surface (Figs. 20 and 21). The highest temperatures are observed in the Weyburn area in the southeastern part of Saskatchewan. These approximately coincide with high heat flow and Grad T values below the Paleozoic surface (Figs. 11 and 5).

The higher temperatures in the southeastern part of Saskatchewan in the Weyburn area are also evident if the temperatures at the top of the Precambrian basement are compared with isopachs of the Phanerozoic sediments (Figs. 22). For example, at a depth of 3 km, the temperature increases eastward from 70°C to 100°C toward the Weyburn geothermal anomaly area. The top of the Precambrian basement is hottest in the Weyburn region.

Blanketing effect

The southward increase in the thickness of the low conductivity shaly-clastic blanket can be one of the reasons for the observed southward increase in temperature (see Figs. 20, 21 and 22). The change in conductivity between the clastic blanket and the Paleozoic carbonates and evaporites is large (Fig. 9). For assumed basement heat flow values of 60 mWm^{-2} and 70 mWm^{-2} and a ground surface temperature of 5°C, temperature distributions for 1 km and 2 km depths were calculated from knowledge of the heat conductivity variations with depth in the basin. The results are presented in Fig. 23. The blanketing effect is significant and a southward increase in temperatures at 1 km and 2 km depths is observed for both assumed uniform heat flows of 60 mWm^{-2} and 70 mWm^{-2}. However, the Weyburn temperature anomaly is not explained in full by the blanketing effect. This is evident by comparing the observed temperature distributions with the predicted ones.

Temperature-depth cross sections from north to south and from west to east were investigated (Fig. 24). Only two of the four profiles are presented here, since the other two profiles confirm the results of those presented. The predicted temperature profiles are compared with those observed in Fig. 25 for the two depths. It is evident that the Weyburn temperature anomaly cannot be explained by the blanketing effect only, assuming uniform heat flow. In the western section of the west-east profile (Fig. 25a) the observed temperatures are lower than the predicted ones, and indicate a heat flow less than 60 mWm^{-2}. In the eastern part of the west-east profile the observed temperatures are higher than predicted and show that the heat flow is higher than 60 mWm^{-2} at the 1 km depth level and higher than 70 mWm^{-2} at 2 km depth. This is consistent with the heat flow estimates made earlier (Figs. 10 and 11). The increase in temperature from the north towards the south which was observed earlier corresponds to the predicted temperatures along the profiles BB and CC (Fig. 25b).

It is probable that the west-east increase of heat flow, especially at greater depths, is responsible for the Weyburn anomaly. This lateral heat flow variation is a result of the cooling of the deep sedimentary shales by downflowing water in the high hydraulic head and high elevation areas of southwestern Saskatchewan and Alberta. The deep water seepage may also be due to the absence of Upper Elk Point halite in that area so that no barrier for downward water circulation exists there as in the remainder of the area (Fig. 26).

There may also be a contribution to the Weyburn anomaly from a high temperature region in the crystalline crust. This is not evident from the heat generation map of Saskatchewan and Manitoba, but there are not much data. It is interesting to note, though, that the elevated heat flow for the Paleozoic in the Swift Current area may be in response to the elevated heat generation there.

Oil distribution and the temperature anomaly

A remarkable correlation exists between the occurrence of Mississippian oil pools in the Canadian part of the Williston Basin and the location of the Weyburn temperature anomaly. This can be seen in Fig. 27 which shows the pool locations with respect to two isotherms at different depths. The Earth's heat influences the maturation of organic matter and the process of hydrocarbon generation from source rock, as well as the oil and gas migration process. The principal agent for mass and heat transfer in sedimentary basins is water movement, so that correlations between hydrocarbon occurrences and temperature field patterns will occur, and these are related to the hydrodynamics. Roberts (1979) and Klemme (1975) have presented good evidence for this on a global scale, and Majorowicz and Jessop (1981b) and Hitchon (1984) have shown that both hydrodynamics and heat flow contribute to oil and gas generation and migration in Alberta.

The apparent relationship between the Weyburn anomaly and the Mississippian oil pools as shown in Fig. 27 is further evidence to support this conclusion. Two main factors may contribute to the correlation between oil locations and temperature anomalies:

1. The temperature increase associated with the blanketing effect as a result of deposition of thick sequences of low conductivity shales in the deep part of the basin will produce a thermal anomaly which can contribute to oil generation.

2. The temperature field can be modified by water motion and this same water motion will contribute to migration of the hydrocarbons.

Certain temperature conditions must be met for the onset of oil generation. A temperature of 60°C is usually considered to be the minimum necessary to start the process (Vassojewicz et al., 1969; Pusey, 1973). In the neighbouring Alberta basin, most of the Mississippian oils lie within the temperature window 70°-160°C (Majorowicz and Jessop, 1981b; Majorowicz et al., 1985b). It is interesting to note that most of the oil in the Mississippian and also in the Jurassic occurs in high temperature zones or in their immediate vicinities as a result of the blanketing effect (Fig. 28). Ahern and Mrkvicka (1984) have shown that the first subsidence pulse ended about 320 m.y. ago and the following increase in subsidence occurred approximately 150 m.y. ago in the Jurassic and continued until the Paleocene. During this later pulse, the Williston basin area became part of the foreland basin which was developing to the east of the Cordilleran orogenic belt. This second pulse after the Jurassic was the most important one to enable the oil source rock to achieve the 'onset temperature' needed for oil generation.

The second factor, the hydrodynamics, caused a modification of the temperature field associated with the blanketing effect and any heat sources. Deep downward water penetration in the southeastern part of Saskatchewan would be unfavourable for oil accumulation according to the theory of Toth (1980). The Jurassic oil deposits migrated northward away from the 'blanketing effect anomaly' which subsequently disappeared in southwestern Saskatchewan because of the cooling effect of the water. The hydrocarbons migrated toward the Swift Current temperature anomaly which is evident on the temperature map for depth 2 km. Mississippian oil pools occur much closer to the anomaly in the Weyburn region because of the blanketing effect and because of the upward motion in the Paleozoic strata (Hitchon, 1969; Hitchon et al., 1969) which is more conducive to accumulation of hydrocarbons (Toth, 1980). Some of the hydrocarbons accumulated in pools to the east and northeast from the center of the anomaly because of migration in these directions.

Conclusions

The crustal and upper mantle heat flowing into the Canadian part of the Williston Basin has been greatly disturbed by the hydrodynamics of the basin and significant redistribution of heat has taken place. As a consequence, heat flow in the high elevation and high hydraulic head areas of southwestern Saskatchewan has been greatly reduced. This reduction of heat flow is particularly large for areas outside the Elk Point halite deposits which otherwise act as an hydrodynamic barrier at depth.

Comparison of the heat flow patterns for the Mesozoic + Cenozoic and Paleozoic formations has shown that:

1. The heat flow through the Mesozoic + Cenozoic formations correlates with the ground surface elevation above sea level, but such a correlation does not exist for the Paleozoic formations.

2. Heat flow through the Mesozoic + Cenozoic formations is greater than that through the Paleozoic formations in low hydraulic head areas toward the east, i.e. toward the shield. In the high hydraulic head areas, the heat flow through the Paleozoic is generally greater than through the Mesozoic + Cenozoic.

From analysis of the observed temperature field, it is found that:

1. There is a temperature anomaly in the Weyburn area of southeastern Saskatchewan.

2. The Weyburn temperature anomaly can be only partly explained by the blanketing effect of the thick shaly units in southern Saskatchewan and Manitoba. The hydrodynamic effect must have contributed to its formation.

From comparison of the oil pool locations and the temperature field it may be concluded that:

1. A correlation exists between the occurrence of Mississippian oil in the southeastern part of the Williston Basin in Canada and the location of the Weyburn temperature anomaly.

2. Most of the Mississippian Jurassic oils are located in or near the high temperature zone in the south as a result of the 'blanketing temperature effect'.

The influence of hydrodynamics on the temperature regime and heat flow in the Williston Basin is further evidence to support that for similar effects found in other platform type basins such as the Alberta basin in Canada and the North Sea basin in Europe. The hydrodynamic effect can influence the regional heat flow pattern on a large scale over a wide area, and it is apparent that this may be the case in many sedimentary basin.

Acknowledgements

The authors wish to acknowledge assistance given by H.-L. Lam and M. Rahman in computer contouring of the maps and C. Nguyen for technical support. The help of R. Beach in the evaluation of heat generation in Saskatchewan and Manitoba is also acknowledged.

The work has been done during a leave of absence of one of the authors (J.A.M.) from the Geophysical Department of the Geological Institute in Warsaw, Poland. The work has been supported by the Department of Energy, Mines and Resources of the Government of Canada and by the Natural Sciences and Engineering Research Council of Canada.

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Figure captions

Fig. 1. The study area of the Williston Sedimentary Basin in western Canada. The contours show sediment thickness in km.

Fig. 2. Locations of wells in Saskatchewan from which BHT are used in this study (from Jones et al., 1982).

Fig. 3. Locations of the wells in Manitoba from which BHT are used in this study (from Jones et al., 1982).

Fig. 4. Geothermal gradients for the upper interval of Mesozoic + Cenozoic formations. Gradients are expressed in units of mKm^{-1} (°C/km).

Fig. 5. Geothermal gradients for the interval below the Paleozoic erosional surface (the Paleozoic formations). Gradients are expressed in mK/m^{-1} (°C/km).

Fig. 6. Predicted temperature versus depth profile (solid line) based on estimated heat conductivity variations from net rock data in the borehole Dillman Tuxford No. 1 in Saskatchewan (locations LSD 1, Sec. 3, Twp. 19N, Rge. 26W, Mer W2). The assumed heat flow is 70 mWm^{-2} with an assumed ground surface temperature of 5°C.

Fig. 7. Effective heat conductivity distribution in southern Saskatchewan and Manitoba for the Mesozoic + Cenozoic formations (in $Wm^{-1}K^{-1}$).

Fig. 8. Effective heat conductivity distribution in southern Saskatchewan and Manitoba for the Paleozoic formations (in $Wm^{-1}K^{-1}$).

Fig. 18. Elevation above sea level in the study area adapted from the Relief and Drainage Map, in Maps of the Prairie Provinces, Ed. J.R. Weir (1969).

Fig. 19. Hydraulic head distribution adapted from Hitchon (1969). (a) in the slice -1250 to -3250 feet, (b) in the slice below -3250 feet, and (c) in cross section through Saskatchewan and Manitoba (1 ft. = 0.3048 m).

Fig. 20. Temperature distribution at 1 km depth below ground surface in southern Saskatchewan and Manitoba based on corrected BHT data. Isotherms are in °C. The 'highs' in the temperature field are shaded.

Fig. 21. Temperature distribution at 2 km depth below ground surface in southern Sasktchewan and Manitoba based on corrected BHT data. Isotherms are in °C. The 'highs' in the temperature field are shaded.

Fig. 22. Temperature distribution on the Precambrian basement surface based on corrected BHT data [(1) isotherms in °C; (2) isopachs in km]. Zones where the isotherms are parallel to the Phanerozoic isopachs are shown (3), and the zone where the temperature is greater than 90°C is shown (4).

Fig. 23. Predicted temperature distribution in the Saskatchewan part of the Williston Basin (A) for 1 km below ground level assuming regional heat flow of 60 mWm^{-2}. (B) for 1 km depth assuming regional heat flow of 70 mWm^{-2}, (C) for 2 km depth assuming heat flow of 60 mWm^{-2},

(D) for 2 km depth assuming regional heat flow of 70 mWm^{-2}.

Fig. 24. Locations of the wells for which estimates of heat conductivity and temperature with depth were made. The analysed profiles are also marked.

Fig. 25. Comparison of observed and predicted temperature variations for two profiles (see Fig. 24):

(a) west-east profile DD,

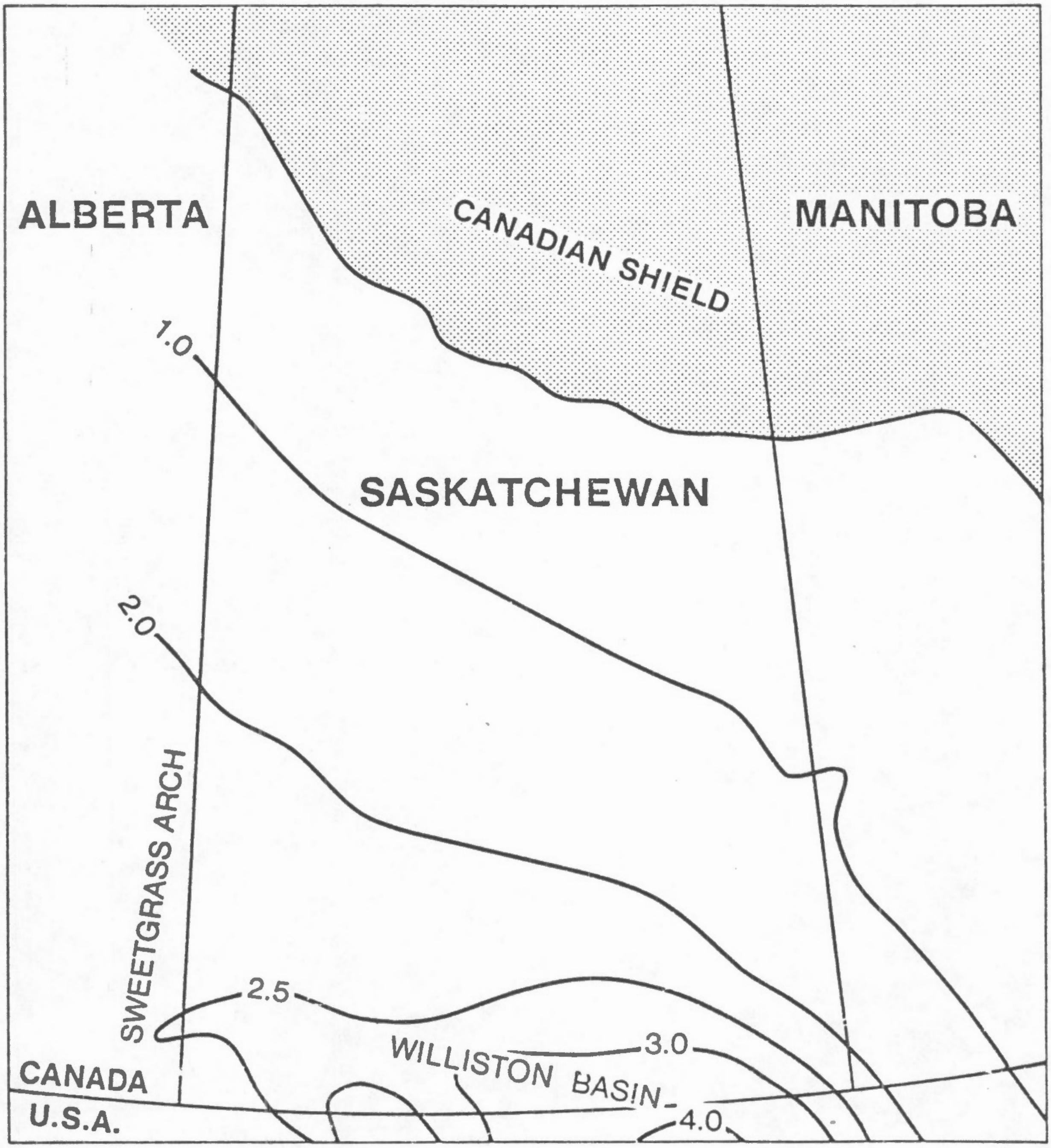
(b) north-south profile BB.

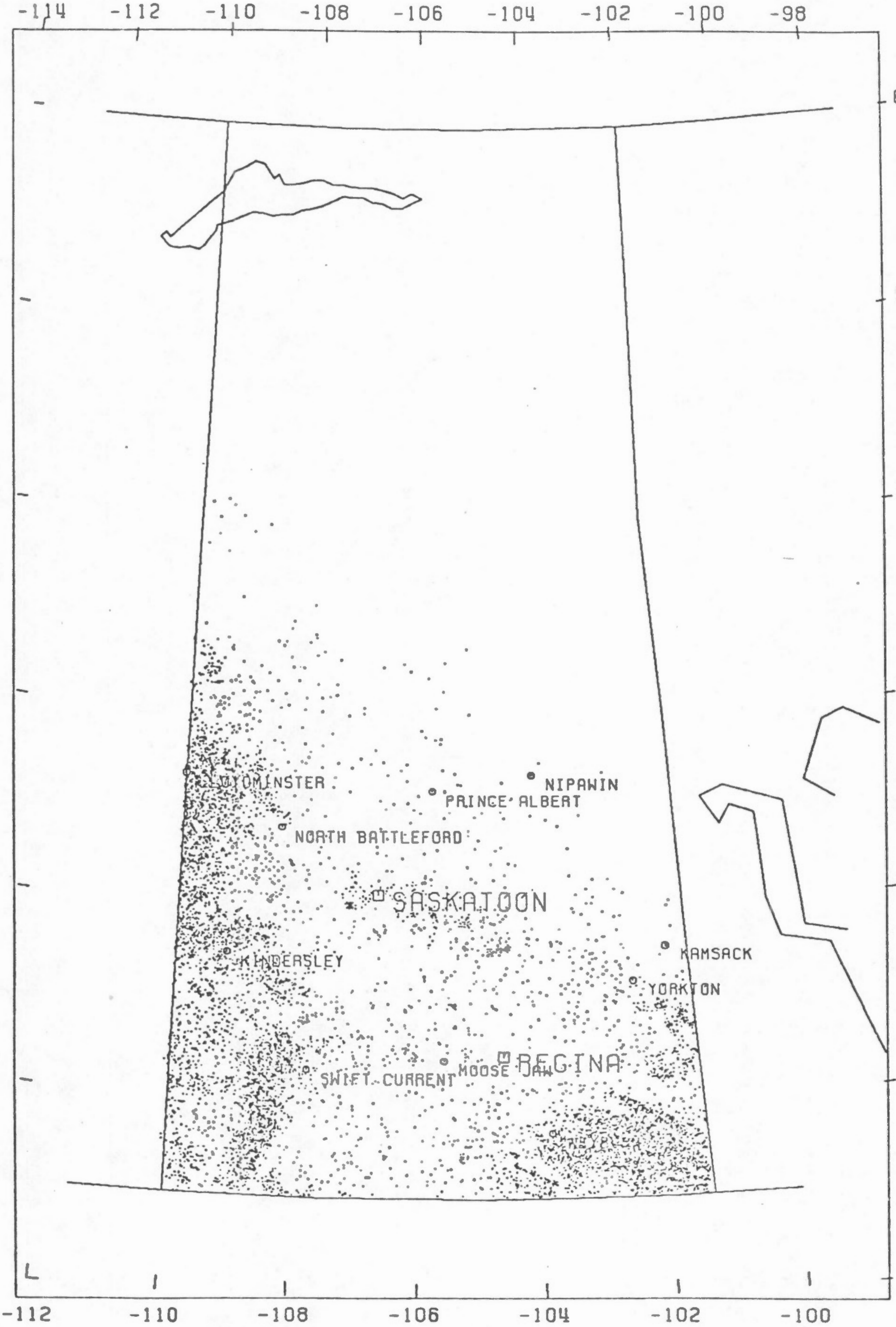
Fig. 26. Subgroup of the Upper Elk Point halite according to the Geological History of Western Canada (1969).

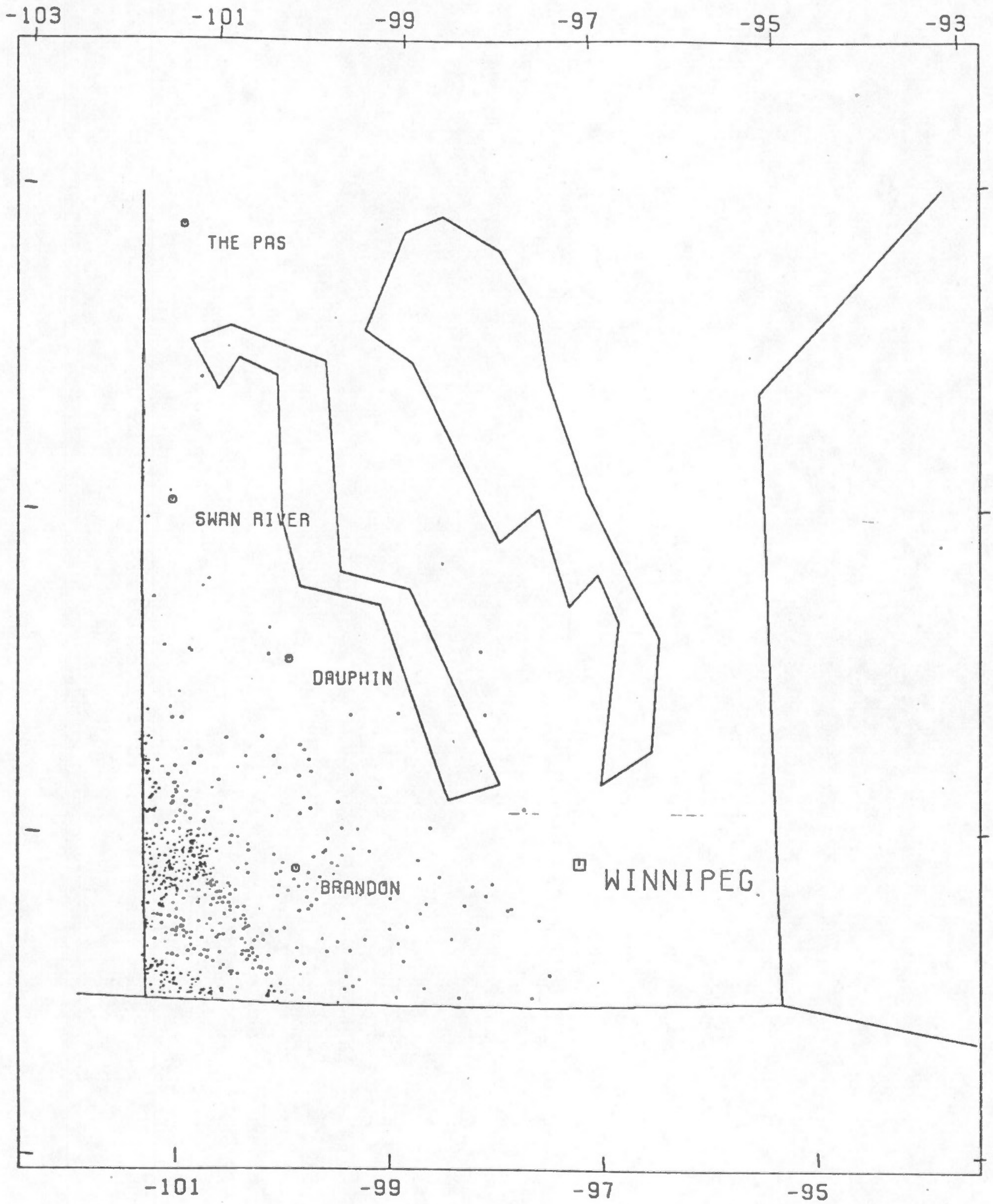
Fig. 27. Oil pool locations in the Canadian part of the Williston Basin and the observed temperatures.

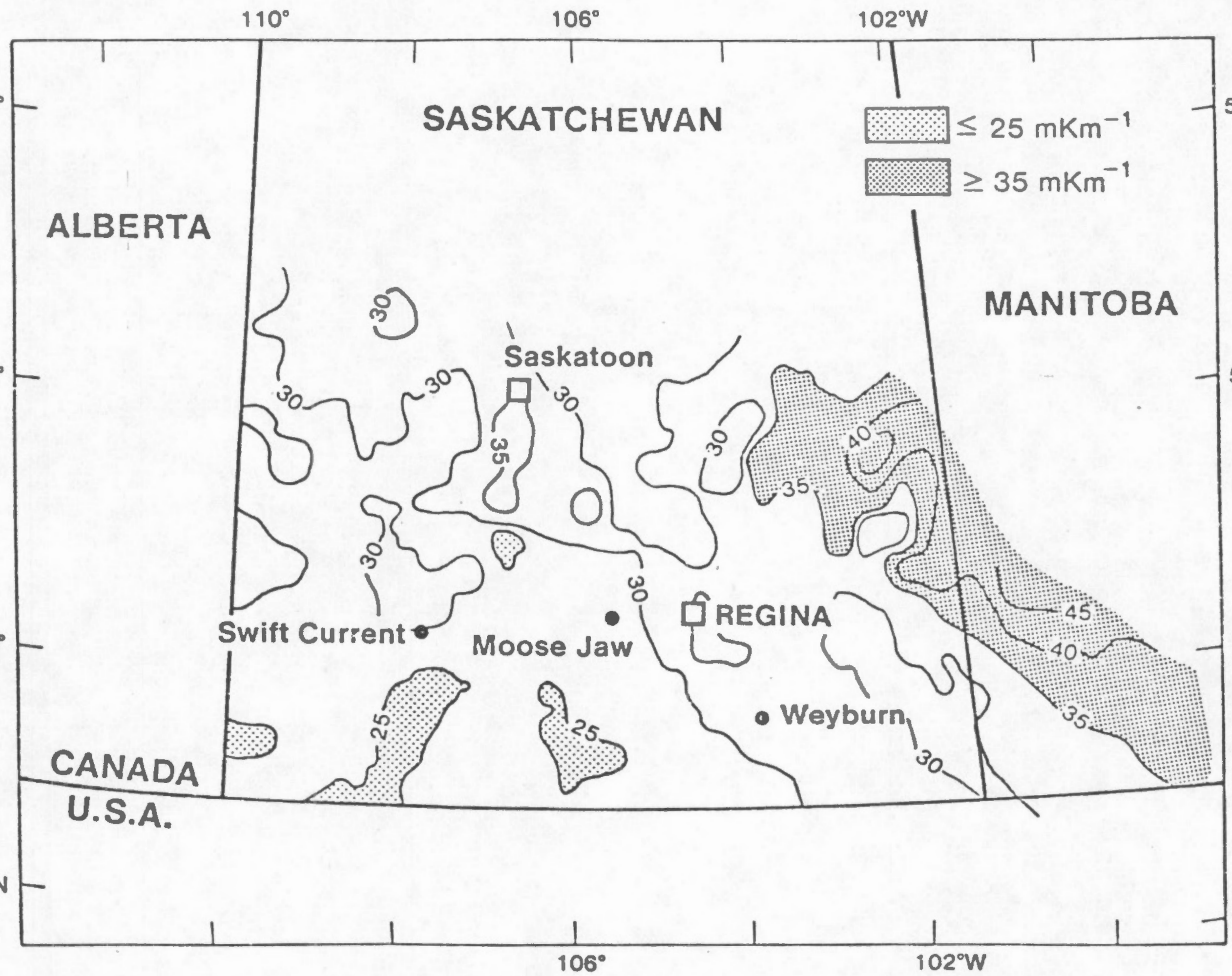
Fig. 28. Oil pool locations and the predicted temperature distribution at 2 km depth, assuming regional heat flow of 70 mWm^{-2}. Note that the oil and gas accumulations are outside the temperature field anomaly caused by the southward thickening of the low conductivity shaly clastic formations in the upper part of the sedimentary column.

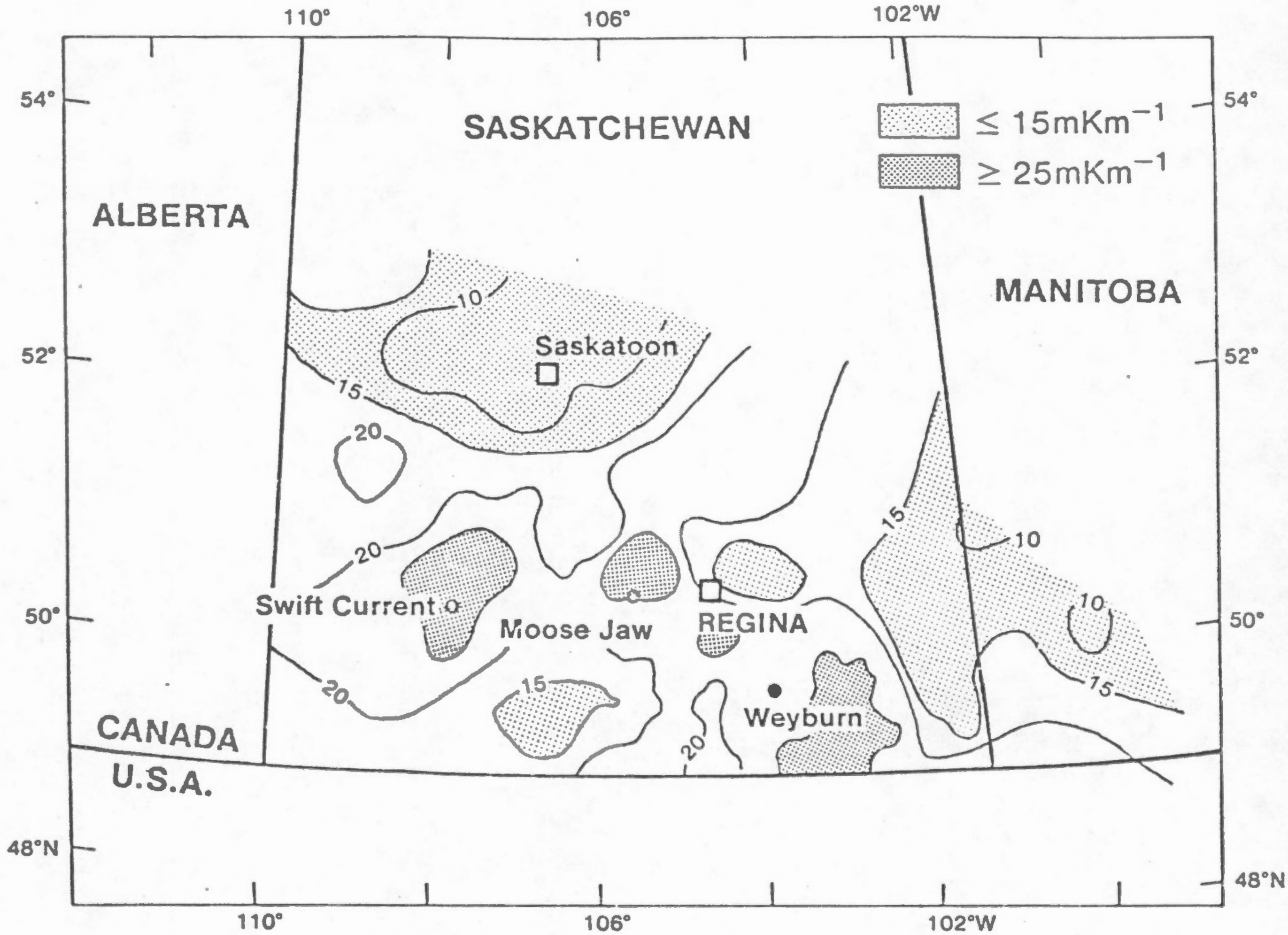
THICKNESS OF PHANEROZOIC

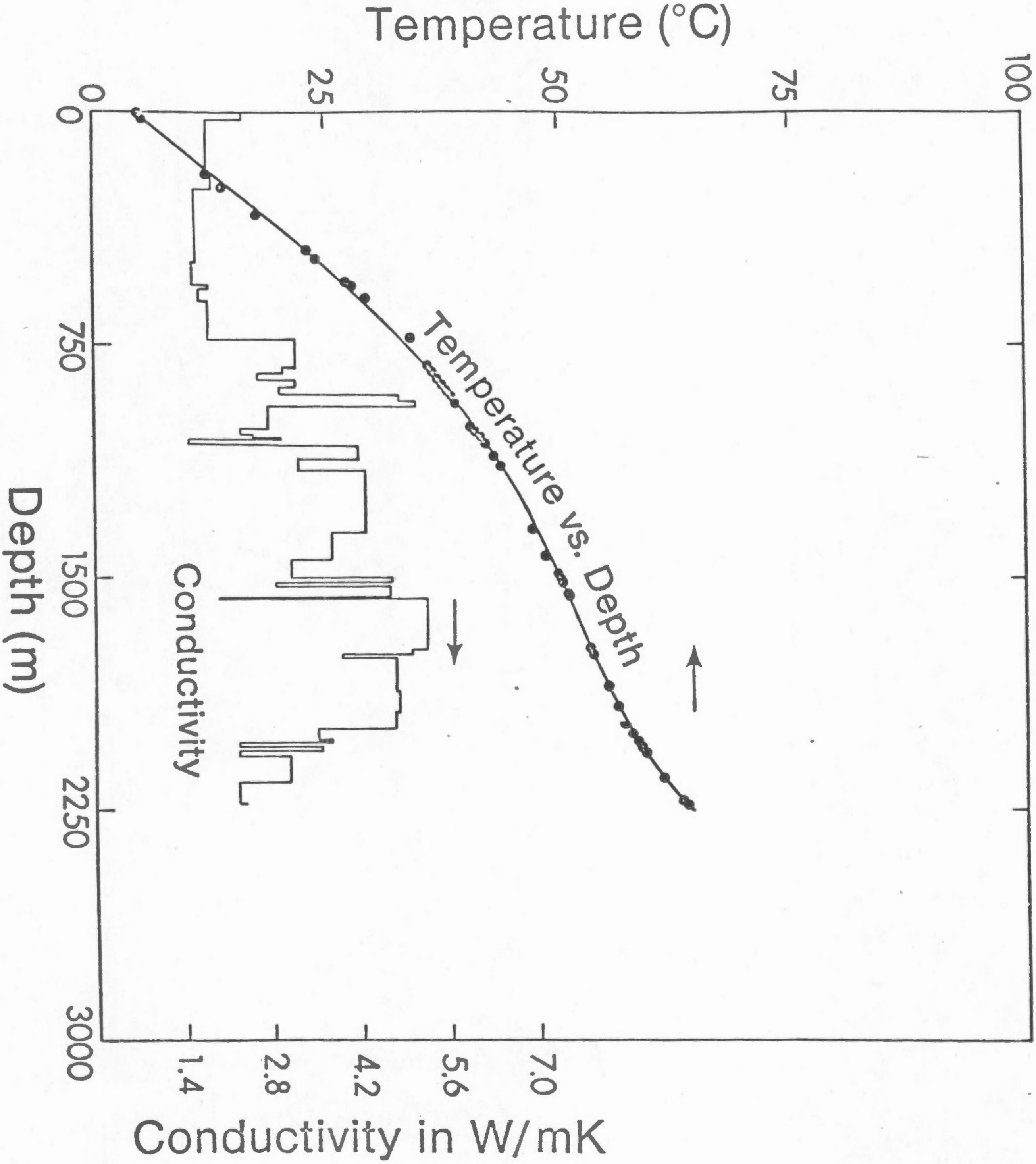


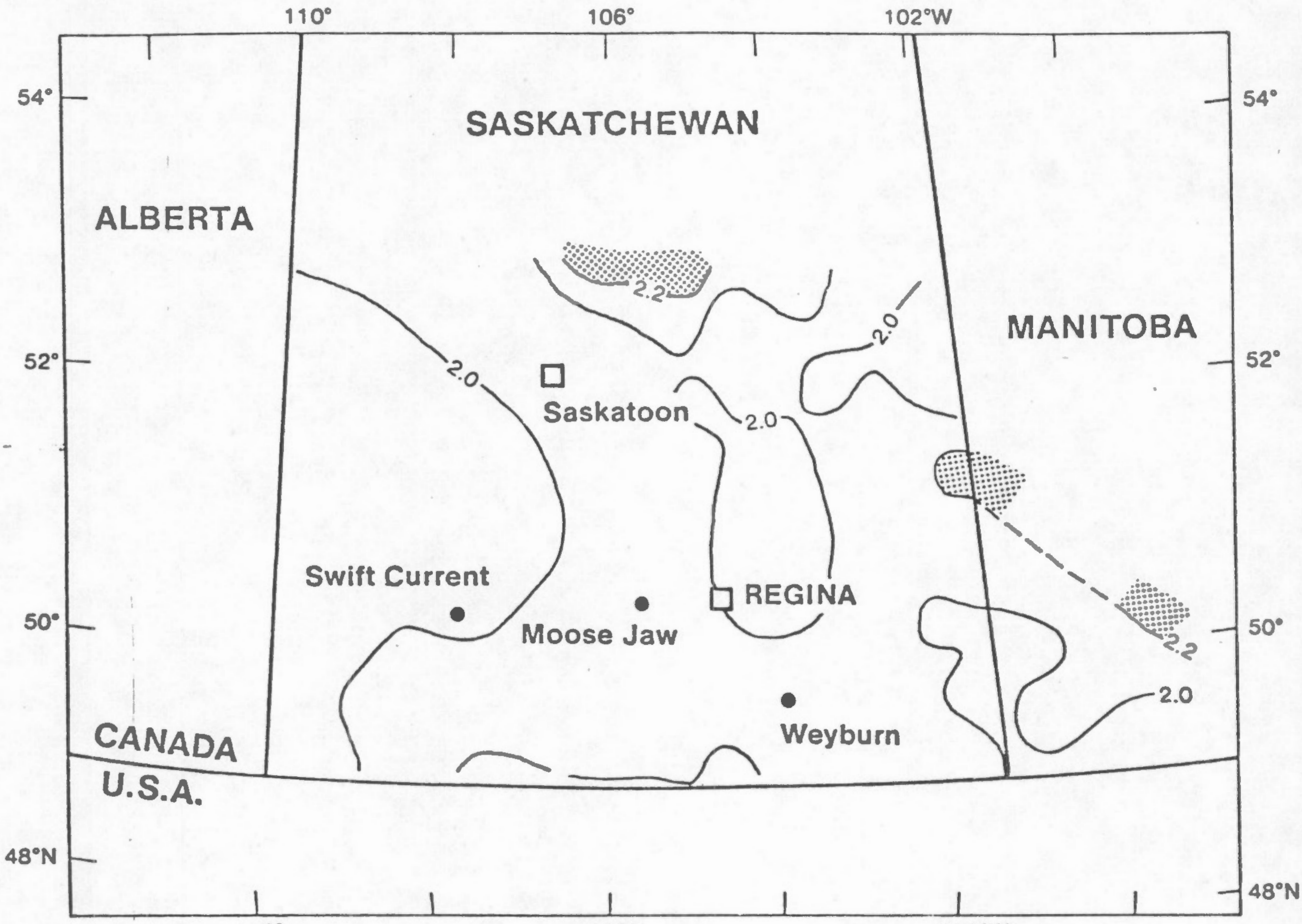

-114 -112 -110 -108 -106 -104 -102 -100 -98
60
58
56
54
52
50
48
LLOYDMINSTER
NIPAWIN
PRINCE ALBERT
NORTH BATTLEFORD
SASKATOON
KINDERSLEY
KAMSACK
YORKTON
SWIFT CURRENT
MOOSE JAW
REGINA
L
-112 -110 -108 -106 -104 -102 -100

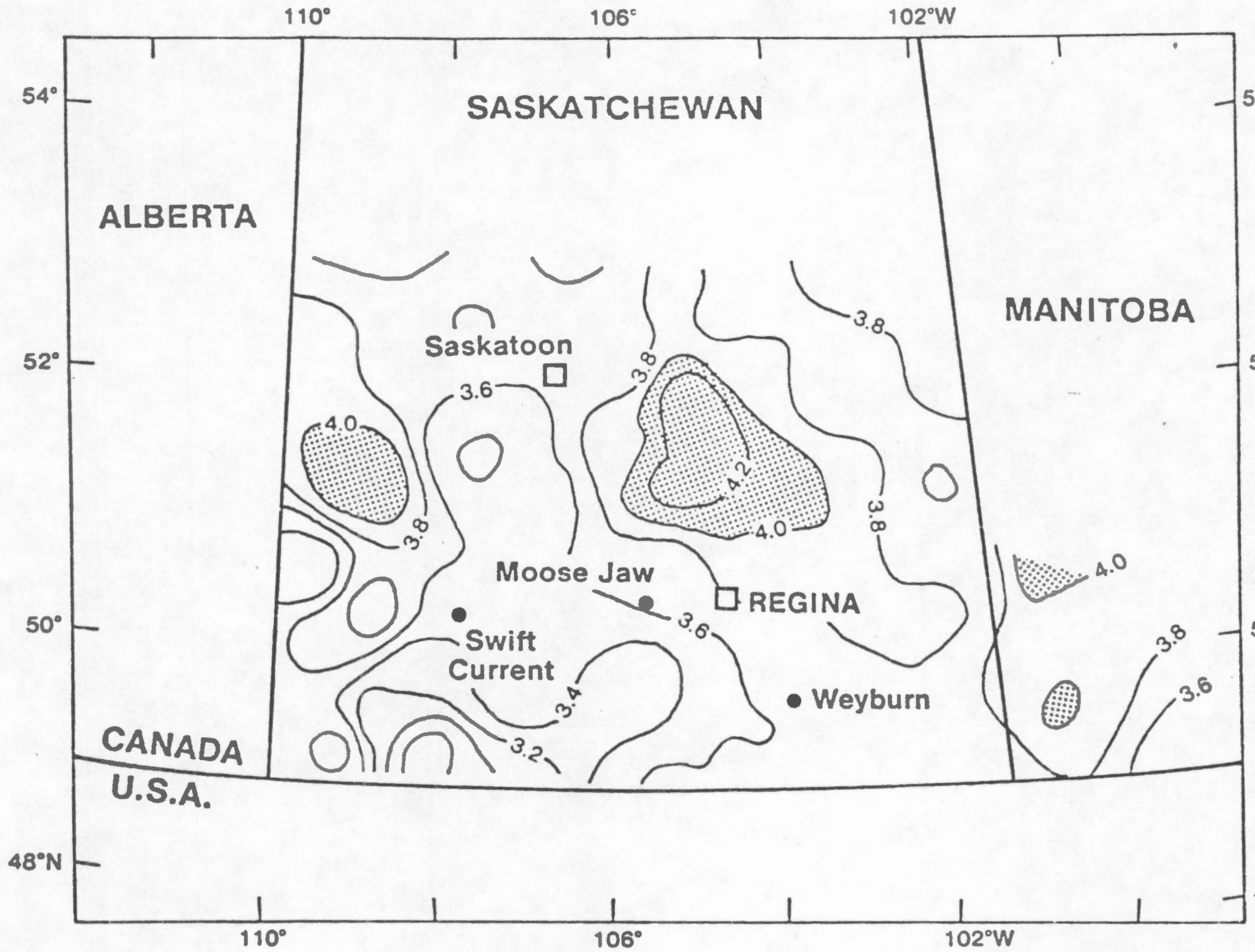

-103
-101
-99
-97
-95
-93
54
52
50
48
THE PAS
SWAN RIVER
DAUPHIN
BRANDON
WINNIPEG
-101
-99
-97
-95

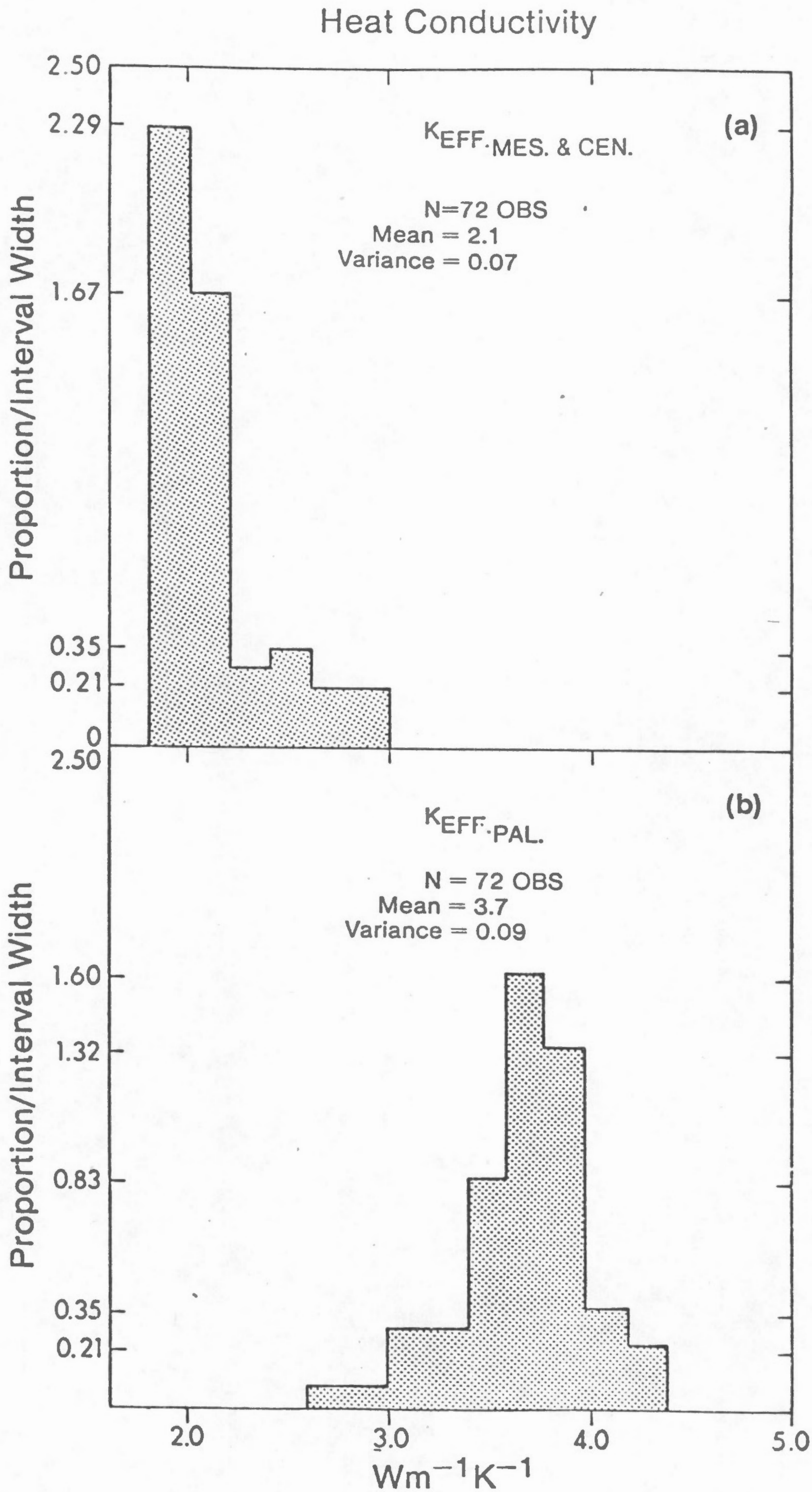

110°
106°
102°W
54°
52°
50°
48°N
SASKATCHEWAN
ALBERTA
MANITOBA
≤ 25 mKm⁻¹
≥ 35 mKm⁻¹
Saskatoon
REGINA
Swift Current
Moose Jaw
Weyburn
CANADA
U.S.A.
25
30
35
40
45

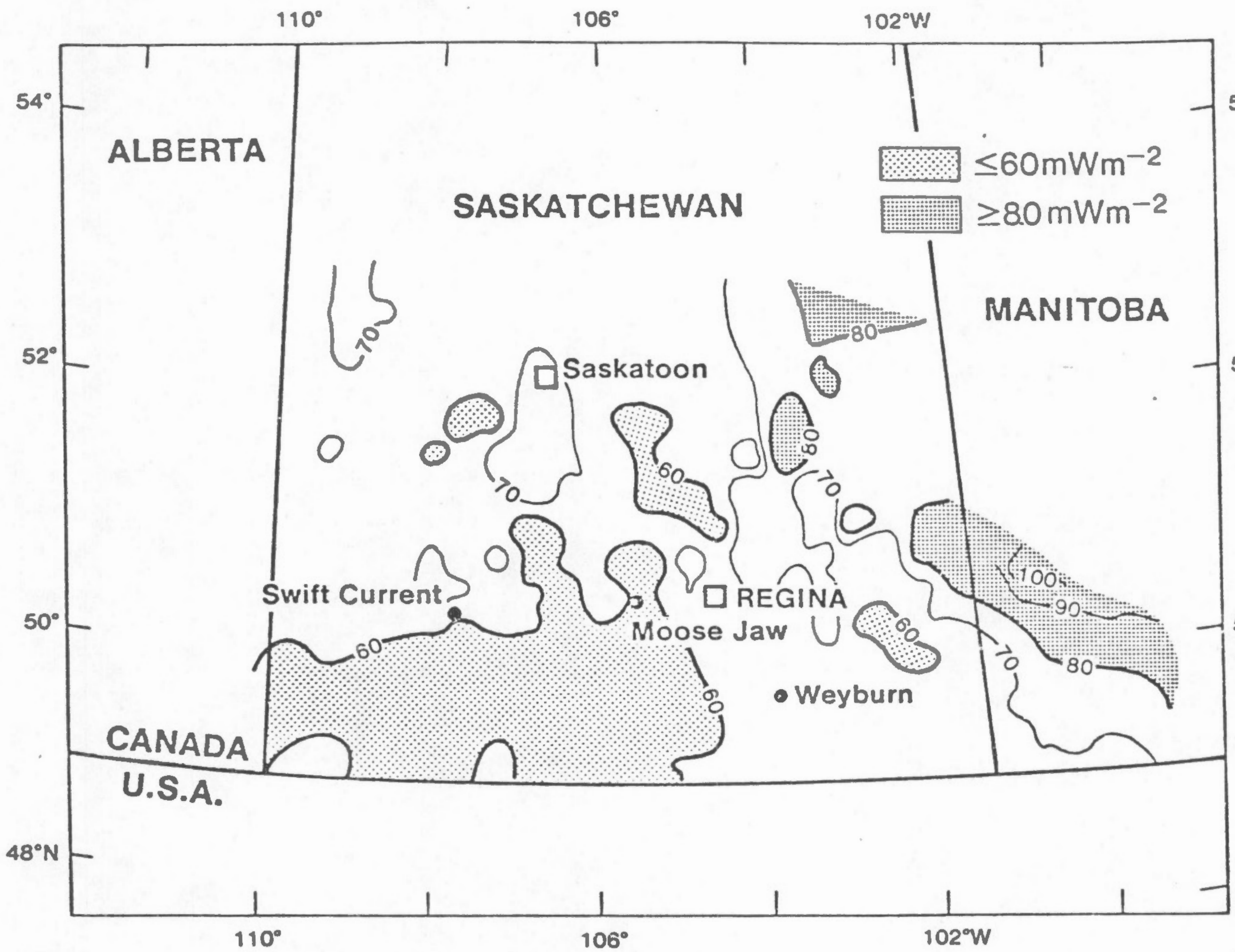

110°
106°
102°W
54°
52°
50°
48°N
SASKATCHEWAN
ALBERTA
MANITOBA
≤ 15mKm⁻¹
≥ 25mKm⁻¹
Saskatoon
Swift Current
Moose Jaw
REGINA
Weyburn
CANADA
U.S.A.
10
15
20

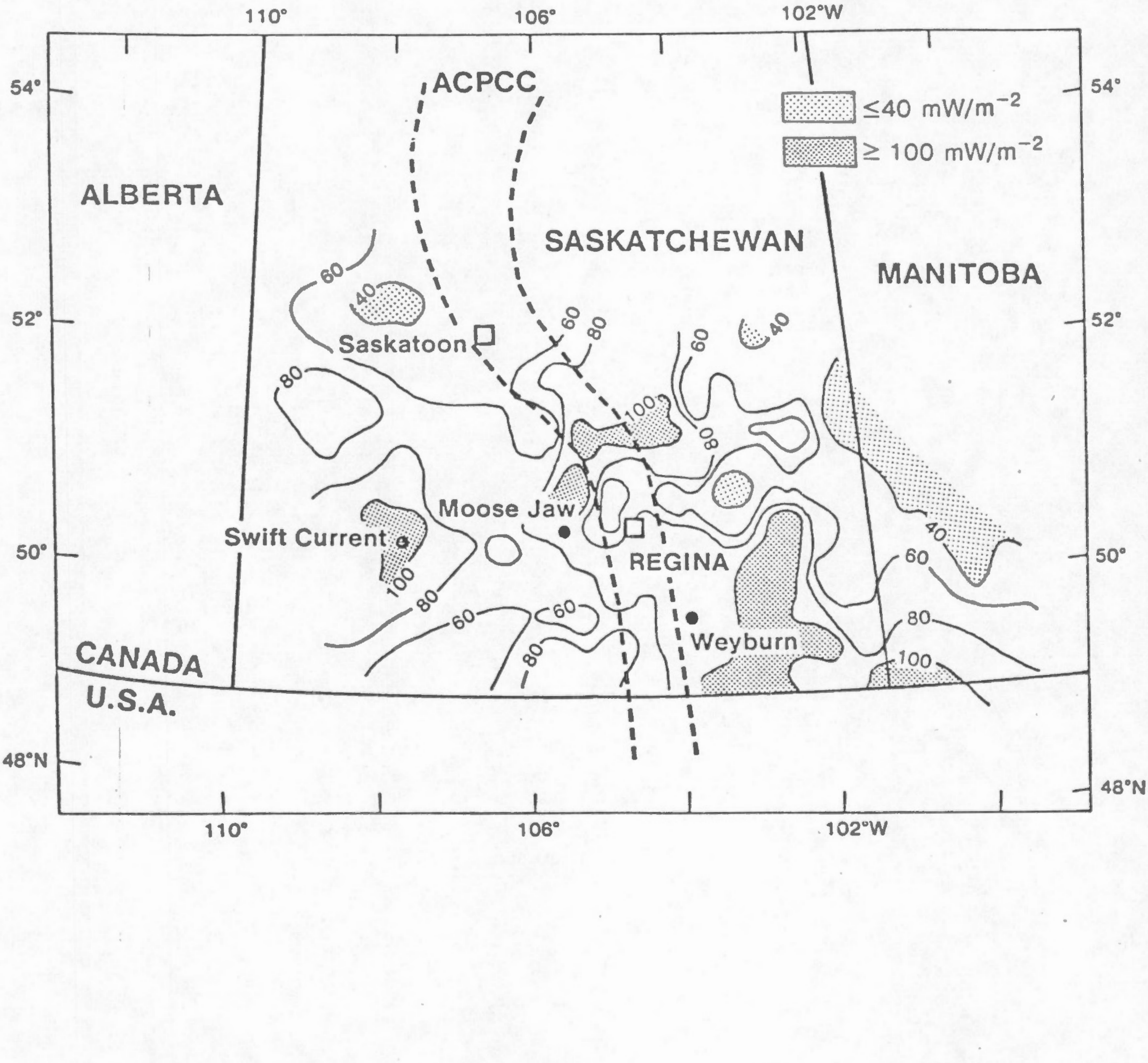

Temperature (°C)
0
25
50
75
100
Temperature vs. Depth
Conductivity
Depth (m)
0
750
1500
2250
3000
1.4
2.8
4.2
5.6
7.0
Conductivity in W/mK

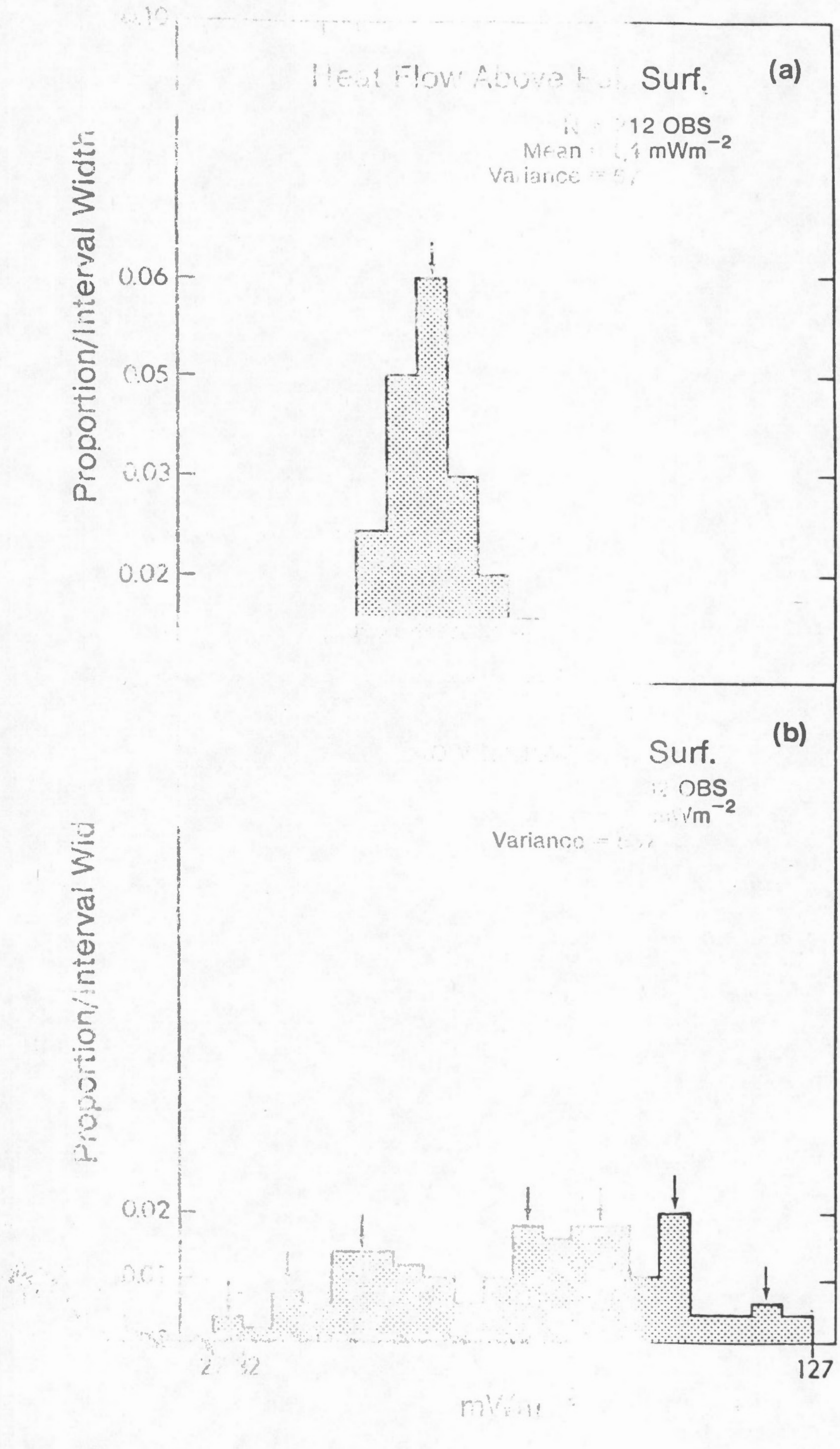

110°
106°
102°W
54°
52°
50°
48°N
SASKATCHEWAN
ALBERTA
MANITOBA
2.2
2.0
Saskatoon
2.0
2.0
Swift Current
Moose Jaw
REGINA
2.2
2.0
Weyburn
CANADA
U.S.A.
110°
106°
102°W
54°
52°
50°
48°N

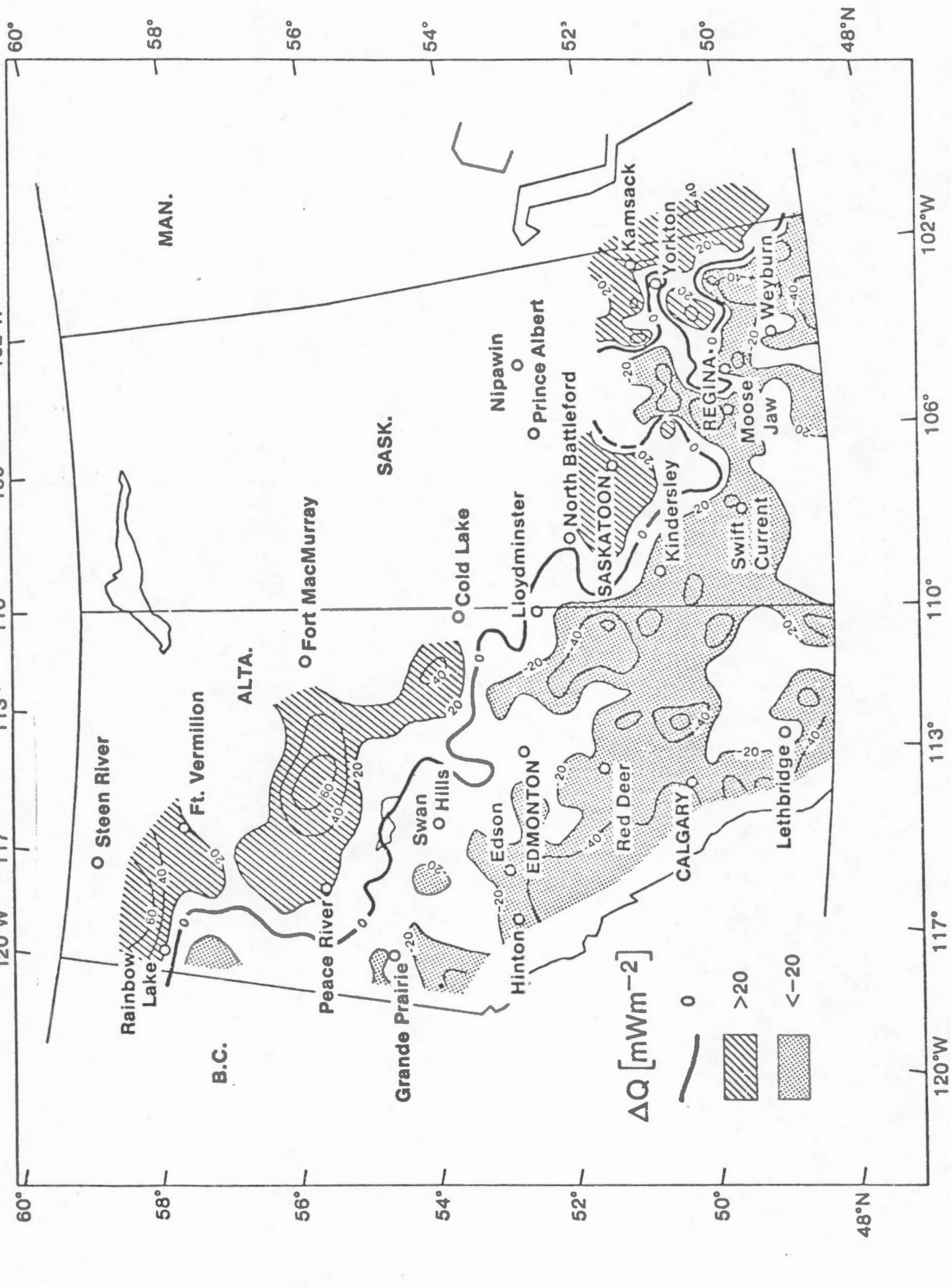

110°
106°
102°W
54°
52°
50°
48°N
SASKATCHEWAN
ALBERTA
MANITOBA
Saskatoon
Moose Jaw
REGINA
Swift
Current
Weyburn
CANADA
U.S.A.
3.2
3.4
3.6
3.8
4.0
4.2


Heat Conductivity
(a)
$K_{EFF.MES. \& CEN.}$
N=72 OBS
Mean = 2.1
Variance = 0.07
(b)
$K_{EFF.PAL.}$
N = 72 OBS
Mean = 3.7
Variance = 0.09
Proportion/Interval Width
Proportion/Interval Width
2.50
2.29
1.67
0.35
0.21
0
2.50
1.60
1.32
0.83
0.35
0.21
2.0
3.0
4.0
5.0
$Wm^{-1}K^{-1}$

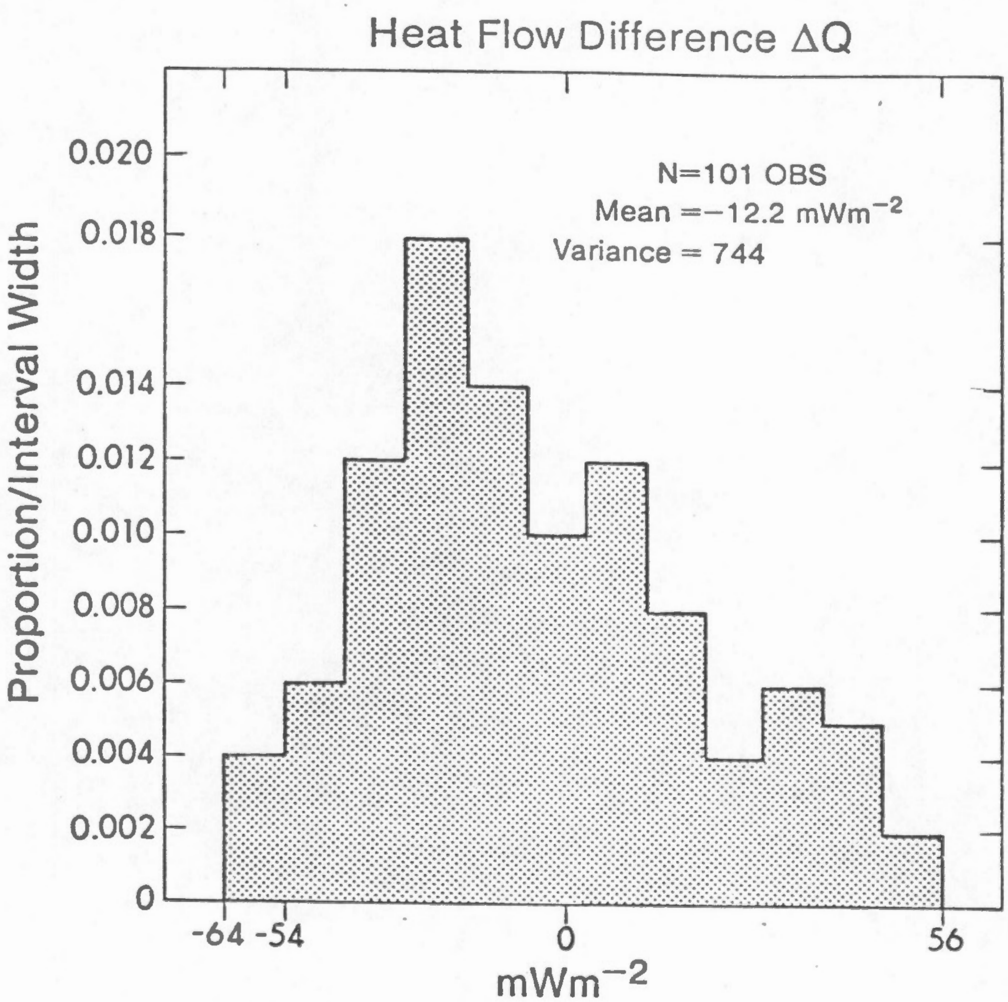

110°
106°
102°W
54°
ALBERTA
SASKATCHEWAN
MANITOBA
≤60mWm−2
≥80 mWm−2
52°
Saskatoon
Swift Current
REGINA
Moose Jaw
Weyburn
50°
CANADA
U.S.A.
48°N
70
60
80
90
100


110°
106°
102°W
54°
54°
ACPCC
≤40 mW/m^{-2}
≥ 100 mW/m^{-2}
ALBERTA
SASKATCHEWAN
MANITOBA
52°
52°
Saskatoon
Moose Jaw
Swift Current
REGINA
Weyburn
50°
50°
CANADA
U.S.A.
48°N
48°N
110°
106°
102°W

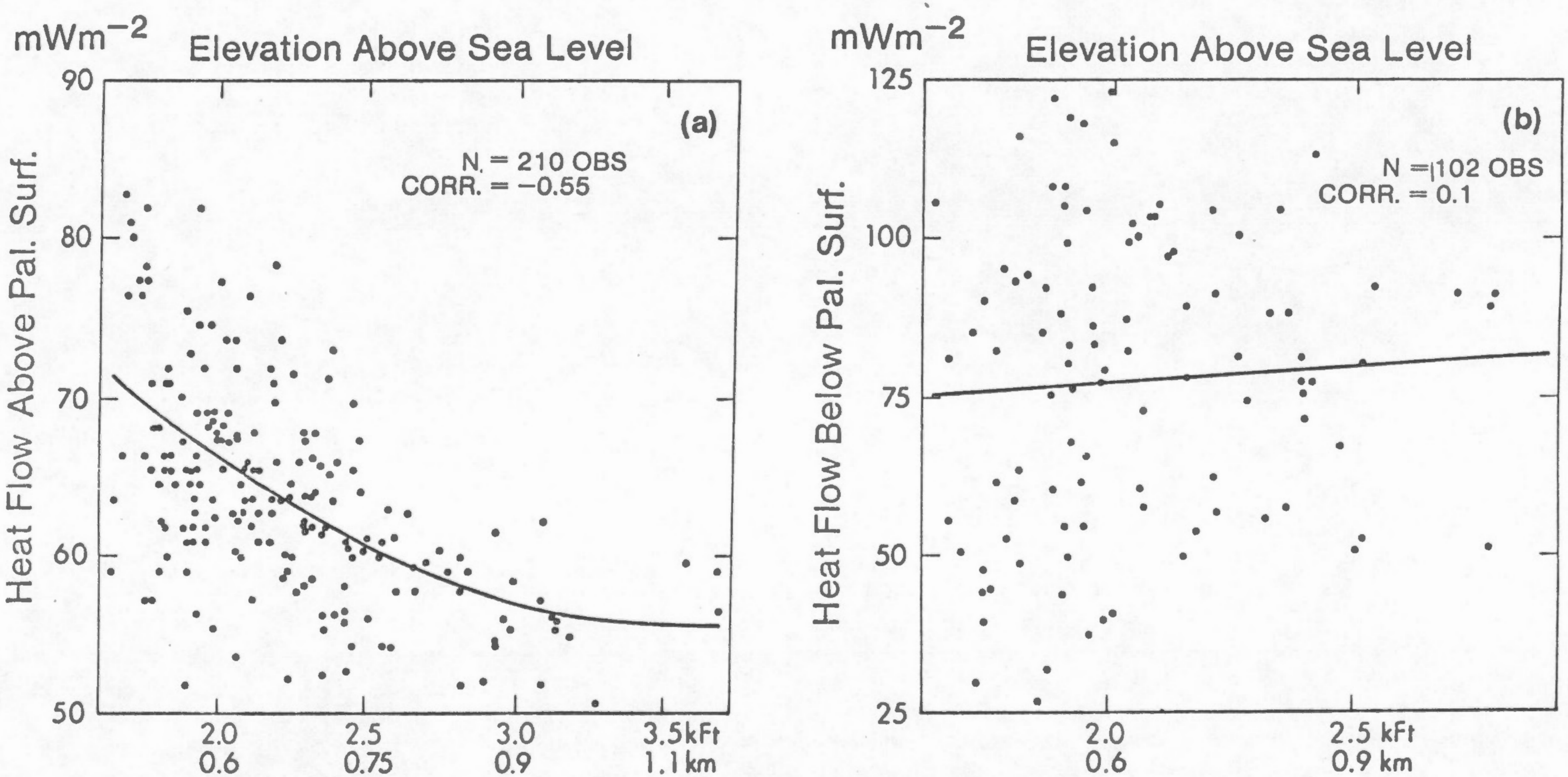

Surf.
(a)
12 OBS
mWm^{-2}
Proportion/Interval Width
0.06
0.05
0.03
0.02
(b)
Surf.
OBS
Variance
0.02
0.01
27
32
127



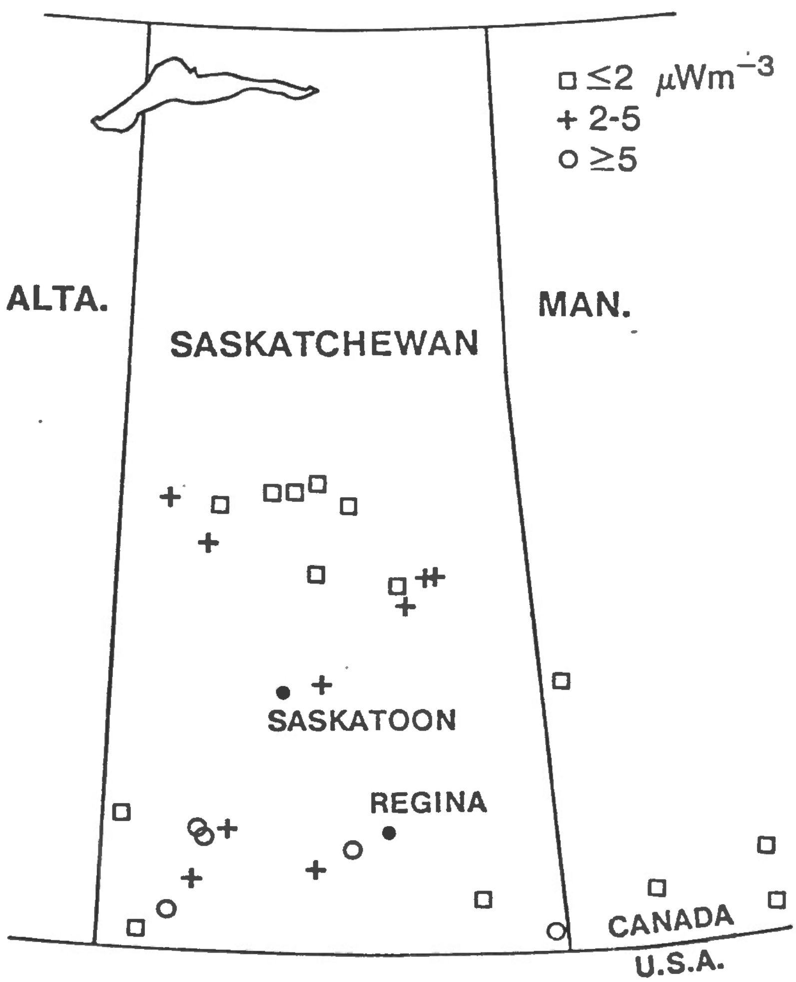
60°
58°
56°
54°
52°
50°
48°N
120°W
117°
113°
110°
106°
102°W
MAN.
SASK.
ALTA.
B.C.
Steen River
Ft. Vermillion
Rainbow Lake
Peace River
Grande Prairie
Fort MacMurray
Cold Lake
Swan Hills
Edson
Hinton
EDMONTON
Red Deer
CALGARY
Lethbridge
Lloydminster
North Battleford
Prince Albert
Nipawin
SASKATOON
Kindersley
Swift Current
Moose Jaw
REGINA
Weyburn
Yorkton
Kamsack
ΔQ [mWm⁻²]
0
>20
<−20

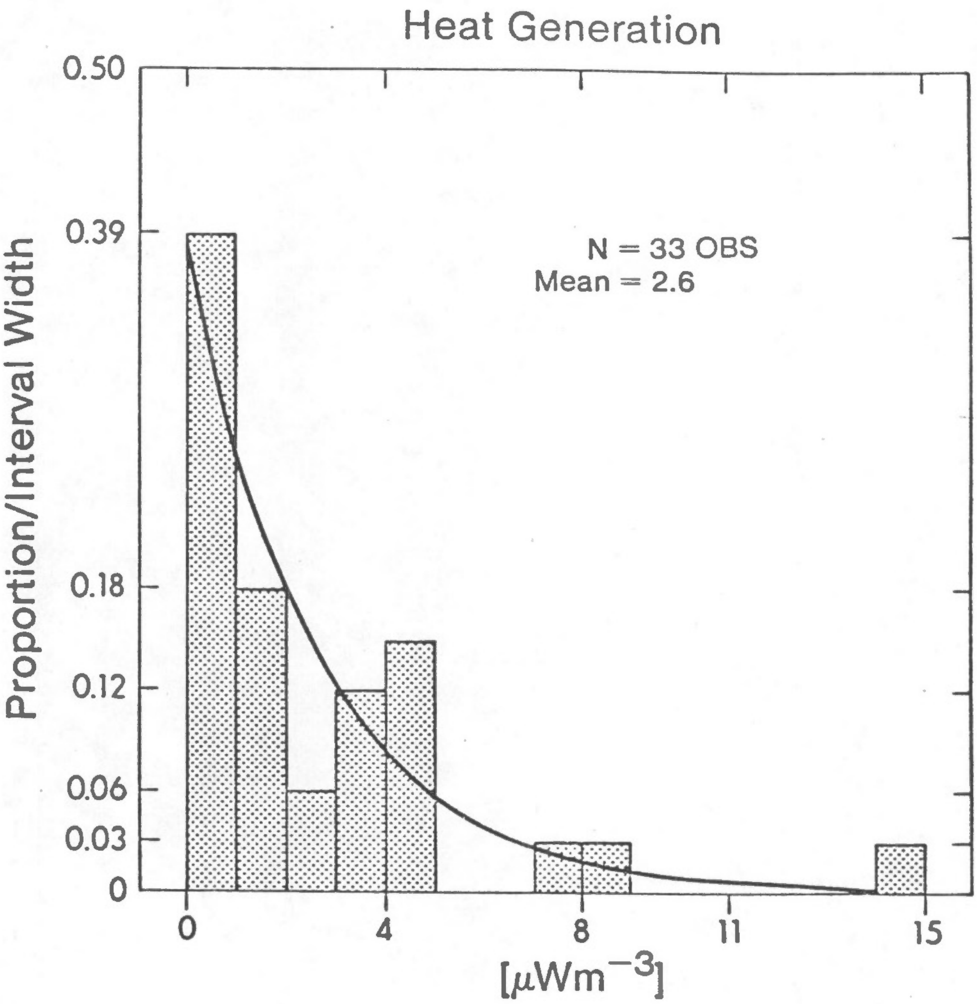


Heat Flow Difference ΔQ
N=101 OBS
Mean =−12.2 mWm−2
Variance = 744
Proportion/Interval Width
0.020
0.018
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0
-64 -54
0
56
mWm−2

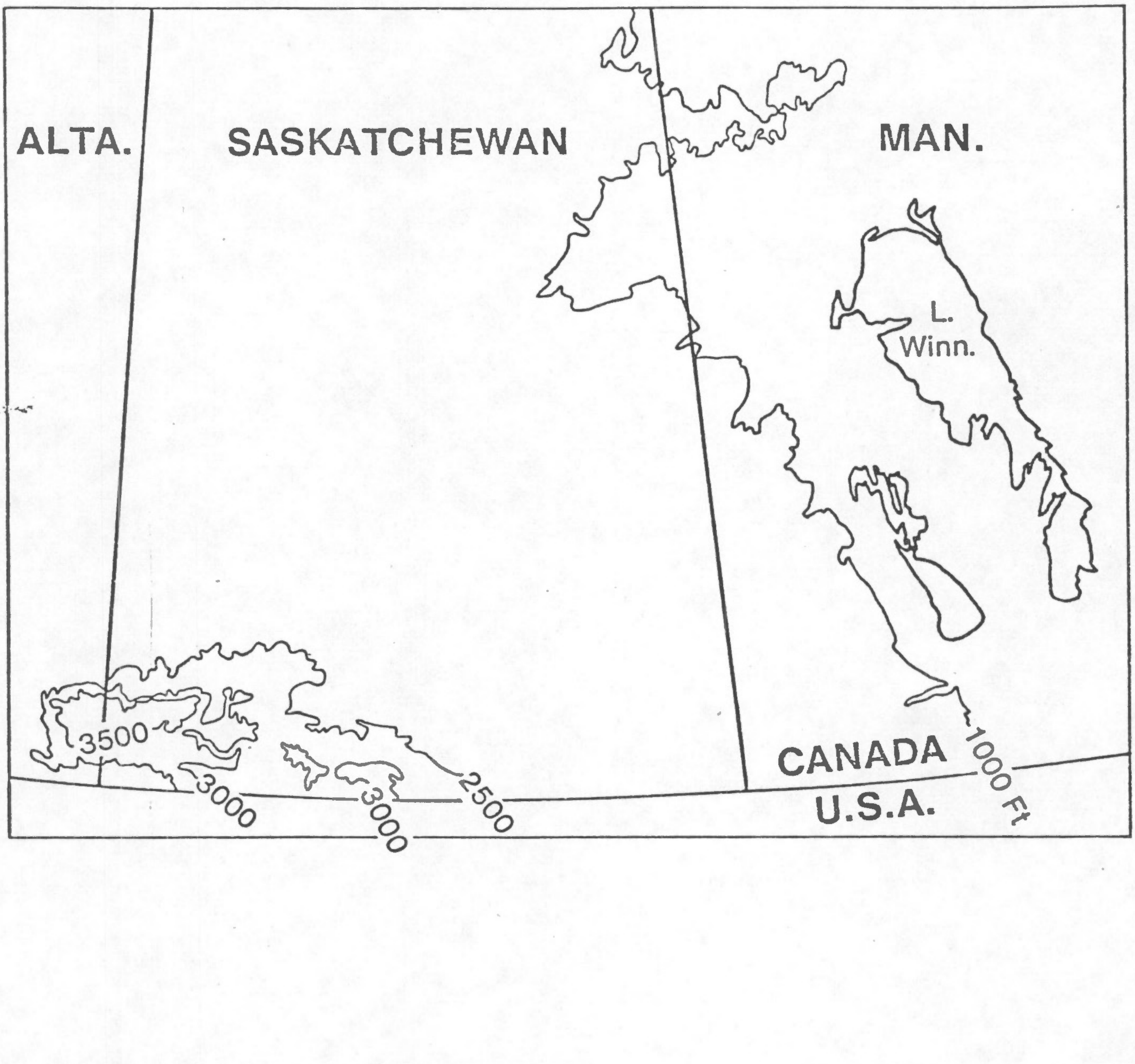

mWm^-2
Elevation Above Sea Level
Heat Flow Above Pal. Surf.
(a)
N = 210 OBS
CORR. = −0.55
90
80
70
60
50
2.0
0.6
2.5
0.75
3.0
0.9
3.5kFt
1.1km
mWm^-2
Elevation Above Sea Level
Heat Flow Below Pal. Surf.
(b)
N = 102 OBS
CORR. = 0.1
125
100
75
50
25
2.0
0.6
2.5 kFt
0.9 km

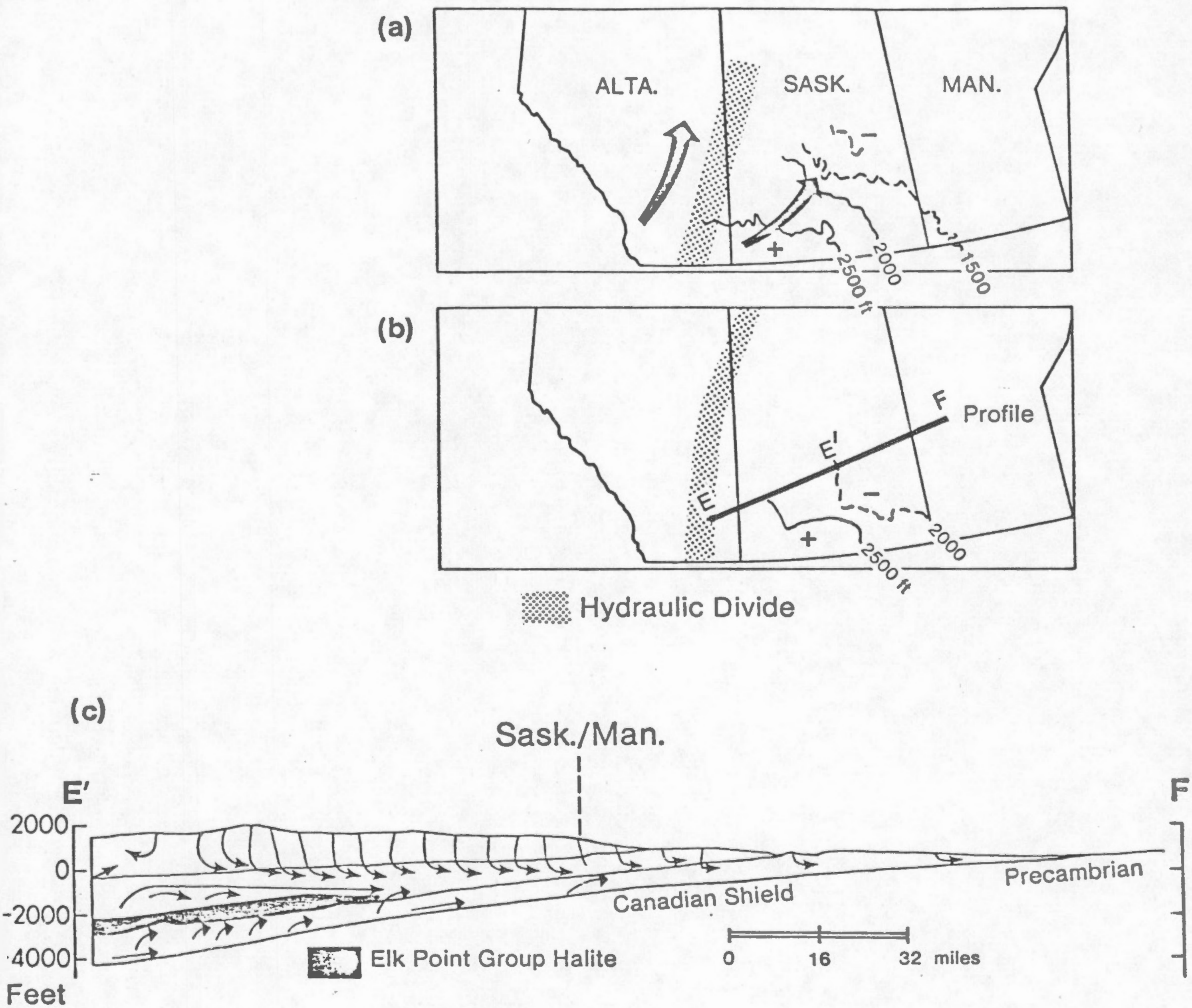
15

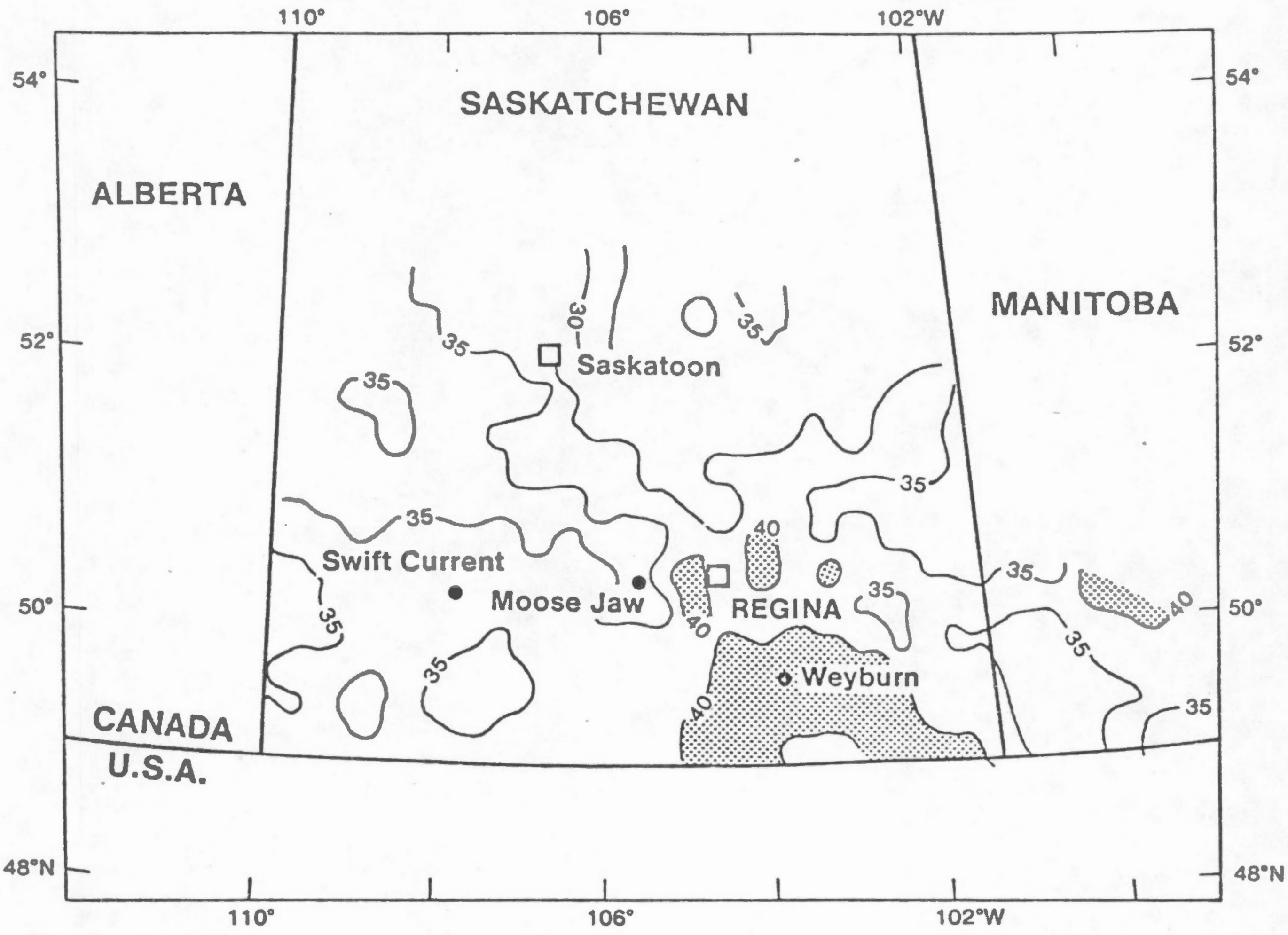

□ ≤2 µWm⁻³
+ 2-5
○ ≥5
ALTA.
MAN.
SASKATCHEWAN
SASKATOON
REGINA
CANADA
U.S.A.


Heat Generation
Proportion/Interval Width
0.50
0.39
0.18
0.12
0.06
0.03
0
N = 33 OBS
Mean = 2.6
0
4
8
11
15
[μWm⁻³]

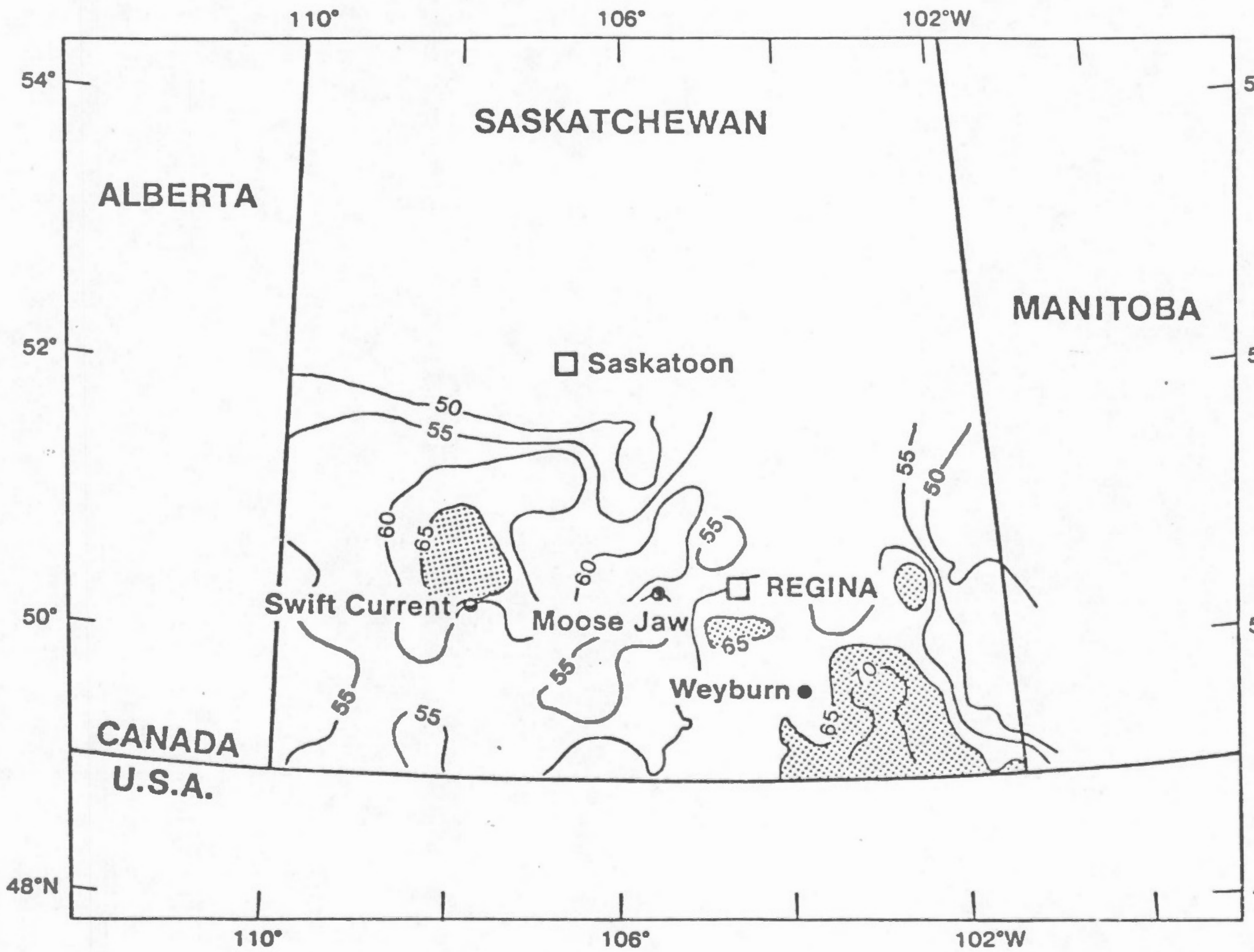
Topography


ALTA.
SASKATCHEWAN
MAN.
L. Winn.
3500
3000
3000
2500
1000 Ft
CANADA
U.S.A.

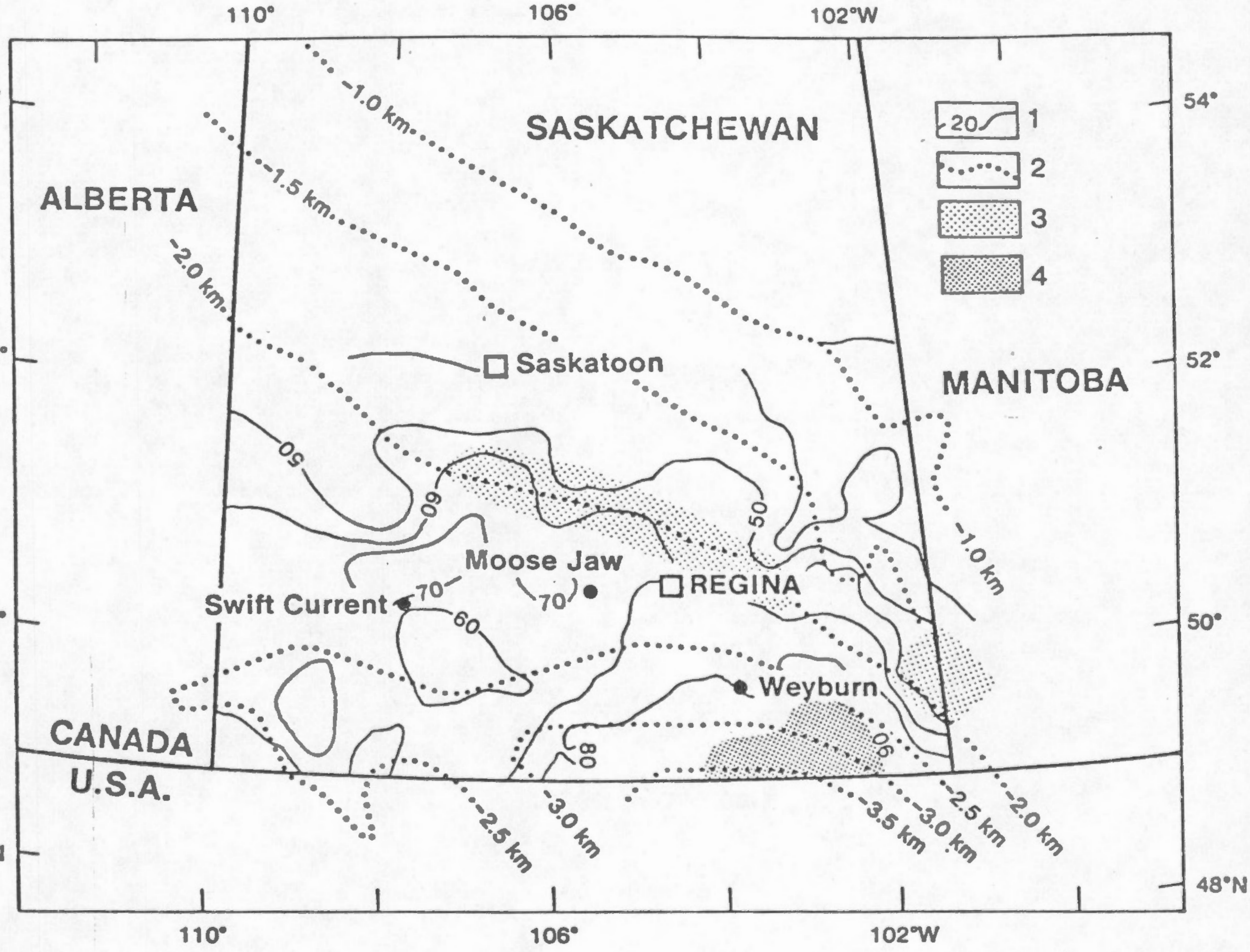

(a)
ALTA.
SASK.
MAN.
+
−
2500 ft
2000
1500
(b)
F
Profile
E′
E
+
−
2500 ft
2000
Hydraulic Divide
(c)
Sask./Man.
E′
F
2000
0
-2000
-4000
Feet
Canadian Shield
Precambrian
Elk Point Group Halite
0
16
32 miles

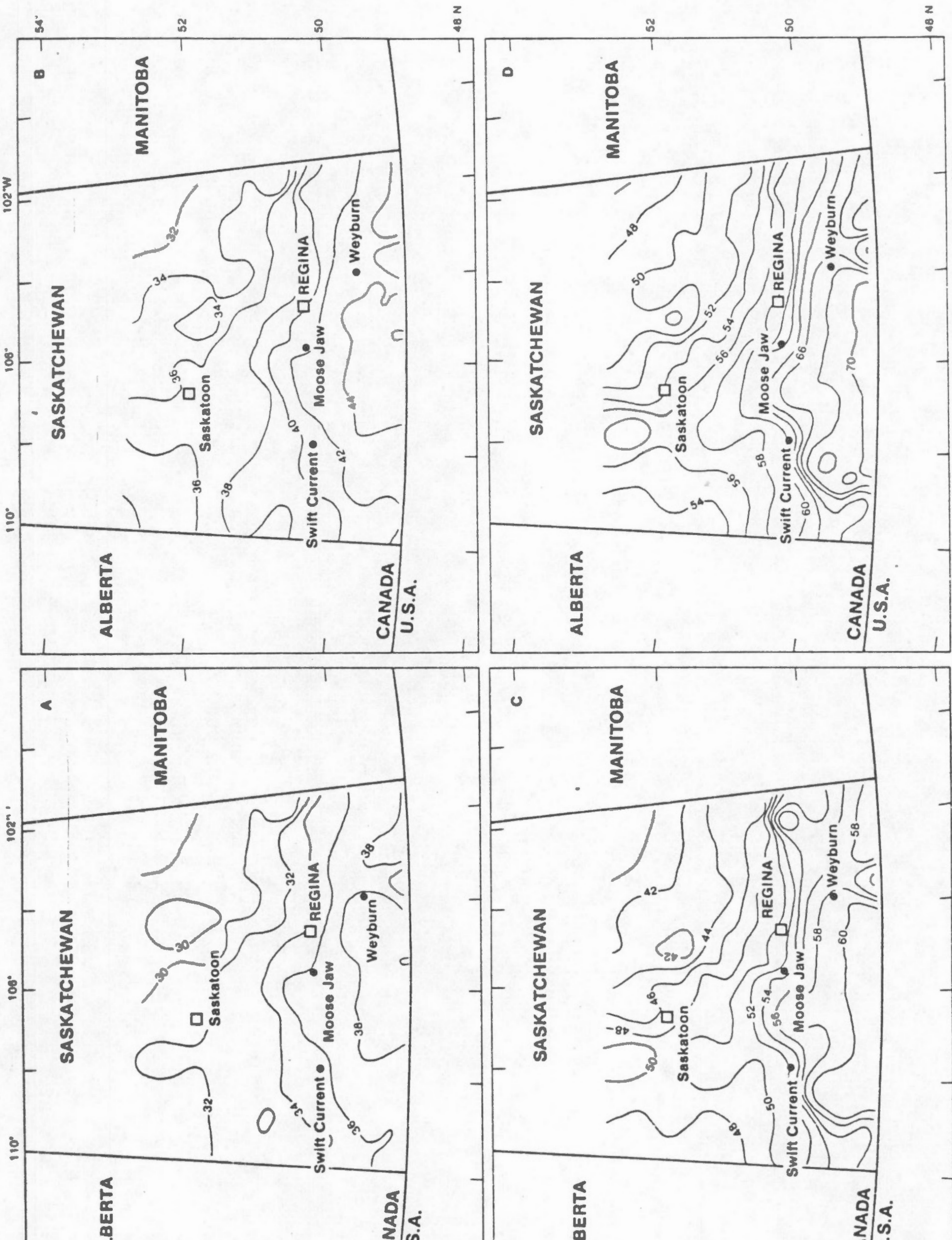

110°
106°
102°W
54°
52°
50°
48°N
SASKATCHEWAN
ALBERTA
MANITOBA
30
35
40
Saskatoon
Swift Current
Moose Jaw
REGINA
Weyburn
CANADA
U.S.A.

20



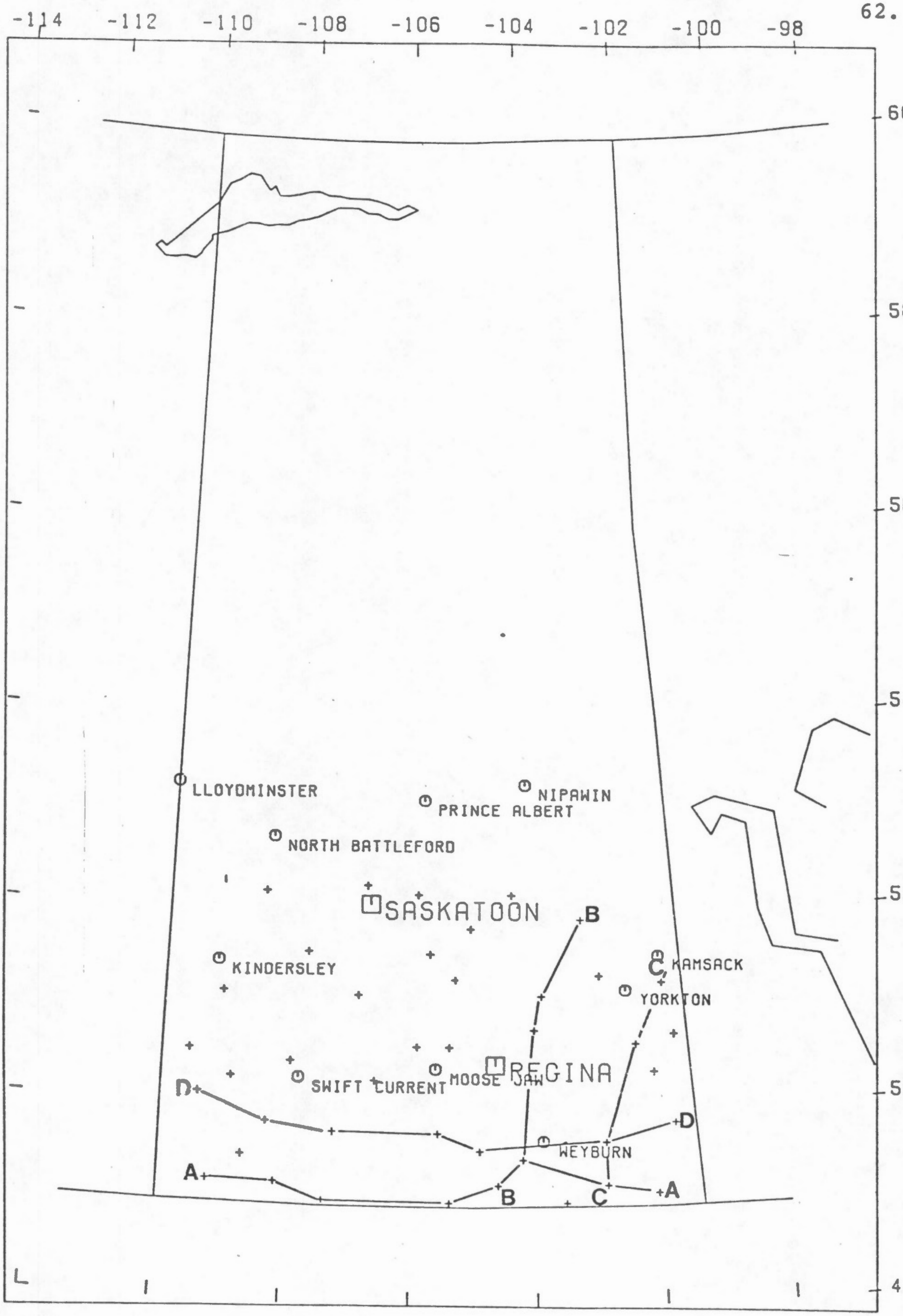
110°
106°
102°W
54°
SASKATCHEWAN
ALBERTA
MANITOBA
52°
Saskatoon
50
55
60
65
Swift Current
Moose Jaw
REGINA
Weyburn
70
50°
CANADA
U.S.A.
48°N

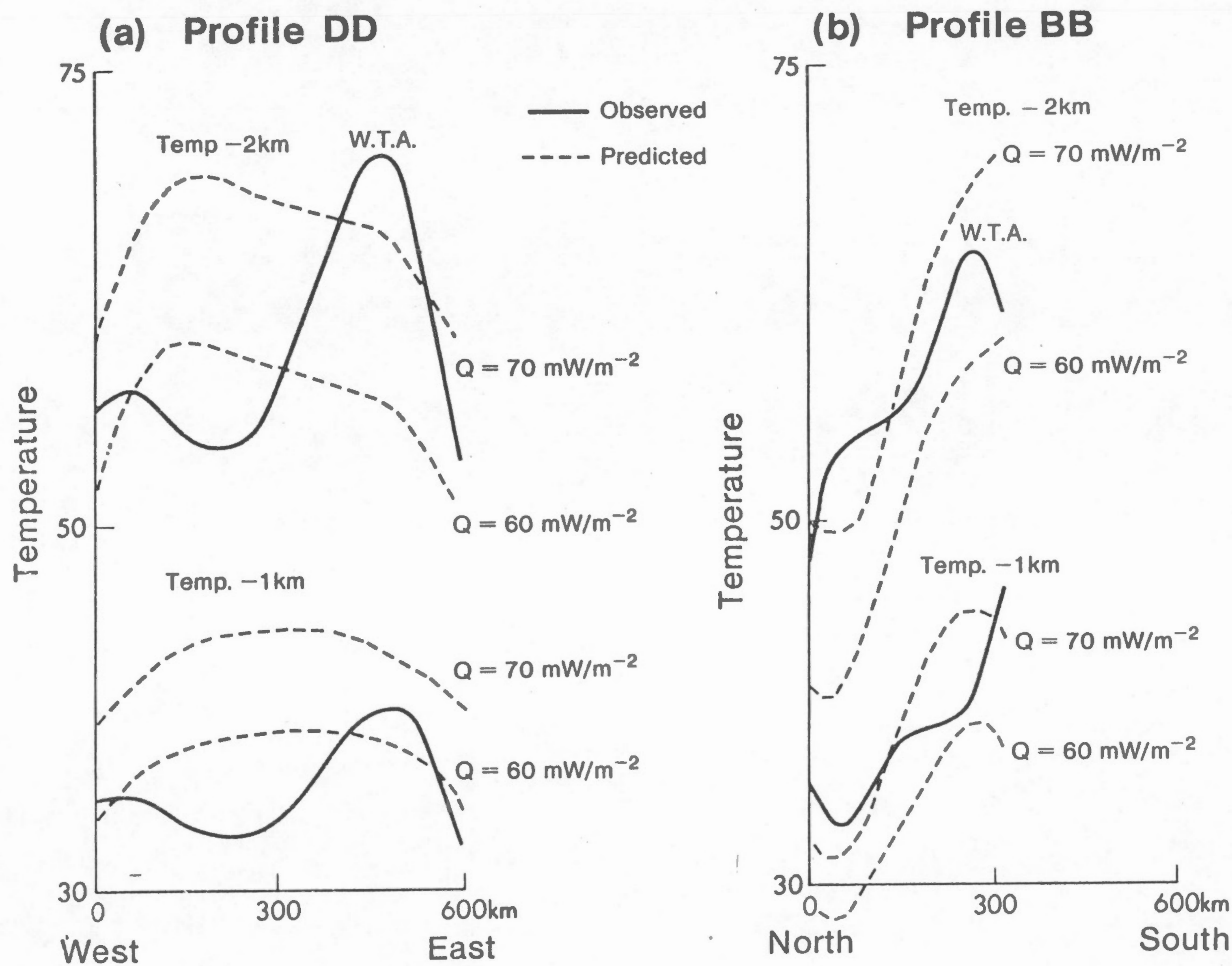

110°
106°
102°W
54°
52°
50°
48°N
SASKATCHEWAN
ALBERTA
MANITOBA
CANADA
U.S.A.
Saskatoon
REGINA
Moose Jaw
Swift Current
Weyburn
-1.0 km
-1.5 km
-2.0 km
-2.5 km
-3.0 km
-3.5 km
50
60
70
80
90
20
1
2
3
4


A
B
C
D
ALBERTA
SASKATCHEWAN
MANITOBA
Saskatoon
REGINA
Moose Jaw
Swift Current
Weyburn
CANADA
U.S.A.
110°
106°
102°W
54°
52°
50°
48°N

23

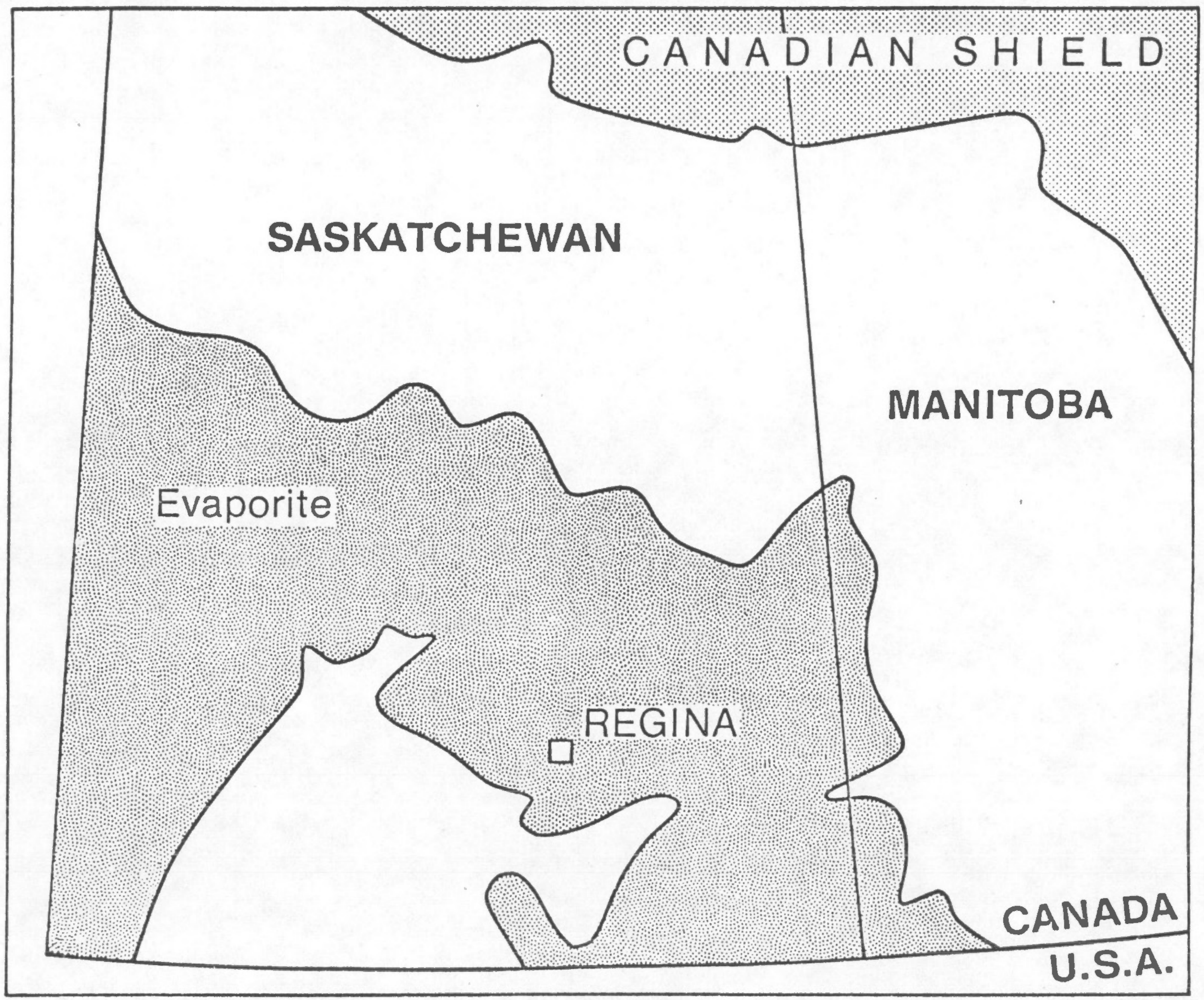
PREDICTED TEMPERATURE AT 1 KM BASED ON Q=70

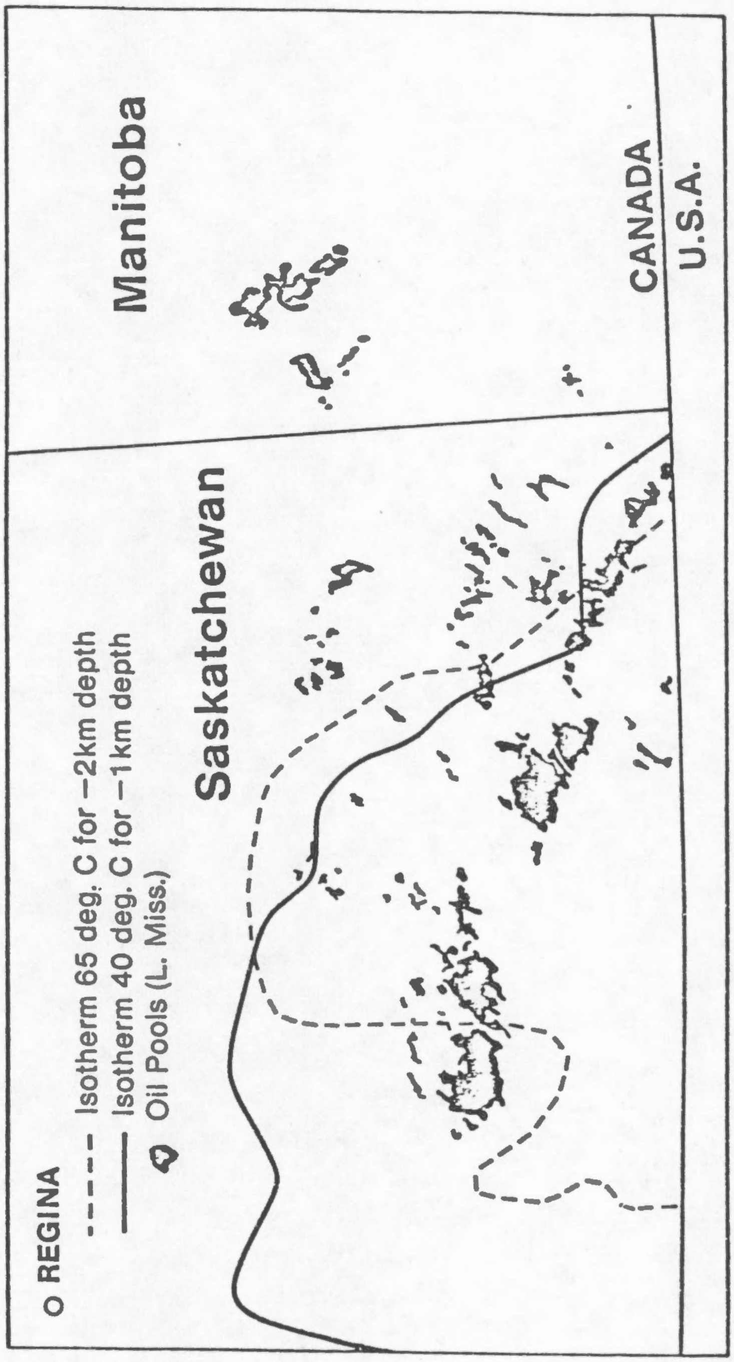


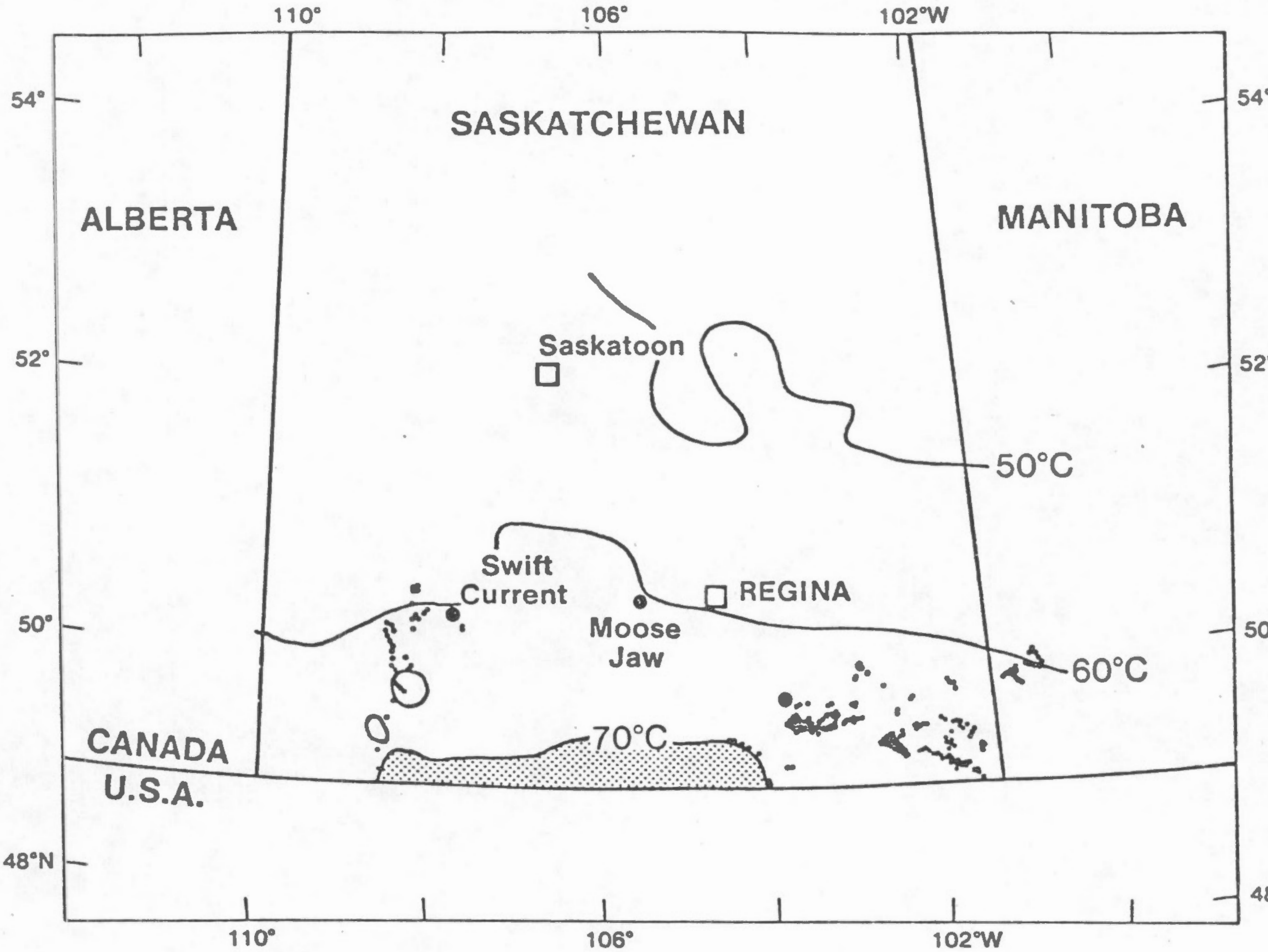

(a) Profile DD
Observed
Predicted
Temp −2km
W.T.A.
Q = 70 mW/m−2
Q = 60 mW/m−2
Temp. −1km
Q = 70 mW/m−2
Q = 60 mW/m−2
Temperature
75
50
30
0
300
600km
West
East
(b) Profile BB
Temp. − 2km
Q = 70 mW/m−2
W.T.A.
Q = 60 mW/m−2
Temp. −1km
Q = 70 mW/m−2
Q = 60 mW/m−2
Temperature
75
50
30
0
300
600km
North
South

98

Upper Elk Point Sub Group




O REGINA
Isotherm 65 deg. C for ~2km depth
Isotherm 40 deg. C for ~1km depth
Oil Pools (L. Miss.)
Saskatchewan
Manitoba
CANADA
U.S.A.


110°
106°
102°W
54°
52°
50°
48°N
SASKATCHEWAN
ALBERTA
MANITOBA
Saskatoon
50°C
Swift
Current
REGINA
Moose
Jaw
60°C
70°C
CANADA
U.S.A.

APPENDIX II

Preliminary results on Northwest Territories BHT data

Figure Captions

Fig. 1. Locations of the wells from which uncorrected BHT data were obtained in the area 60°-70°N, 115°-137°W.

Fig. 2. Locations of the wells for the corrected BHT data in the same area as Fig. 1.

Fig. 3. Locations of the wells from which uncorrected BHT data were obtained in the area 60°-70°N, 124.5°-141°W.

Fig. 4. Locations of the wells for the corrected BHT data in the same area as Fig. 3.

Fig. 5. Uncorrected BHT data versus depth plot for the area 60°-66°N, 115°-127°W.

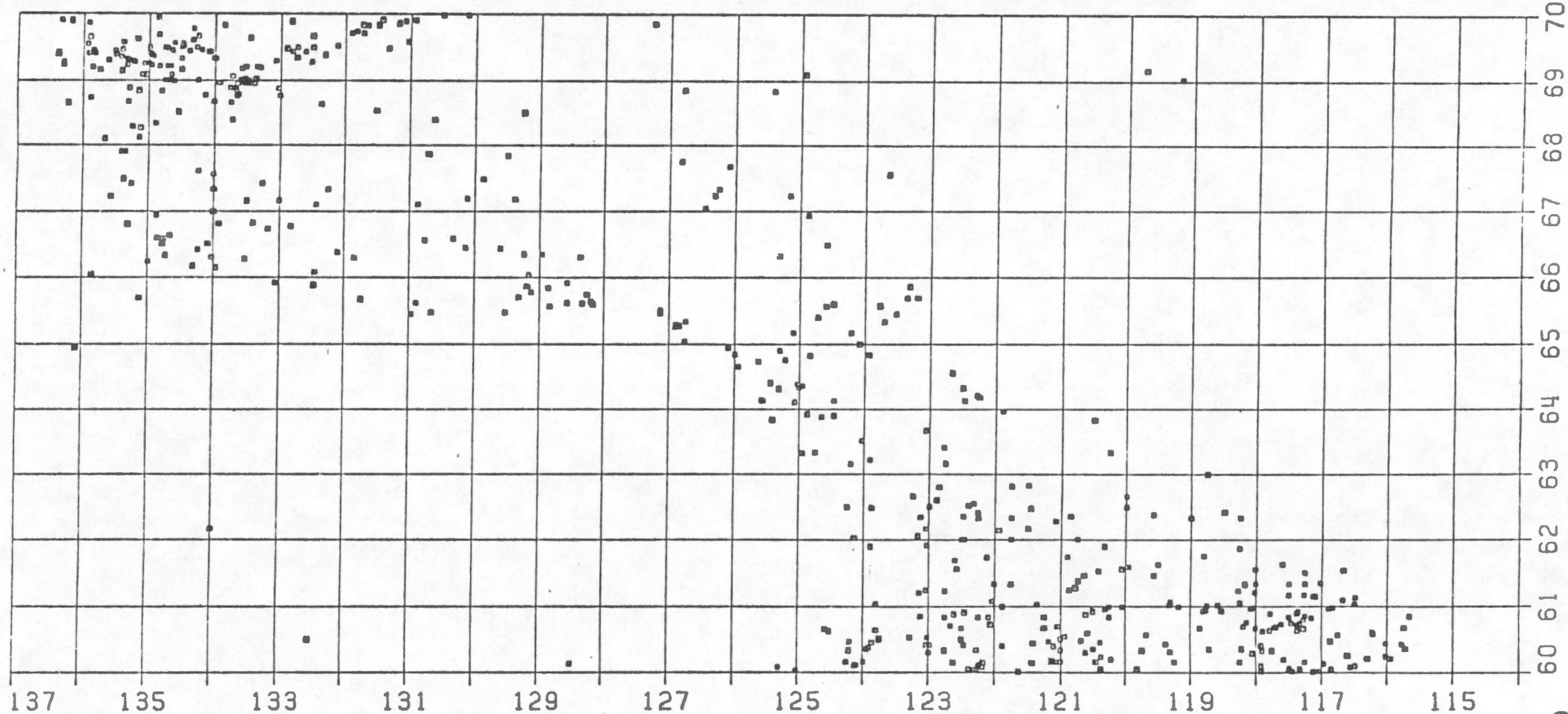
Fig. 6. Corrected BHT data plot for the same area as Fig. 5.

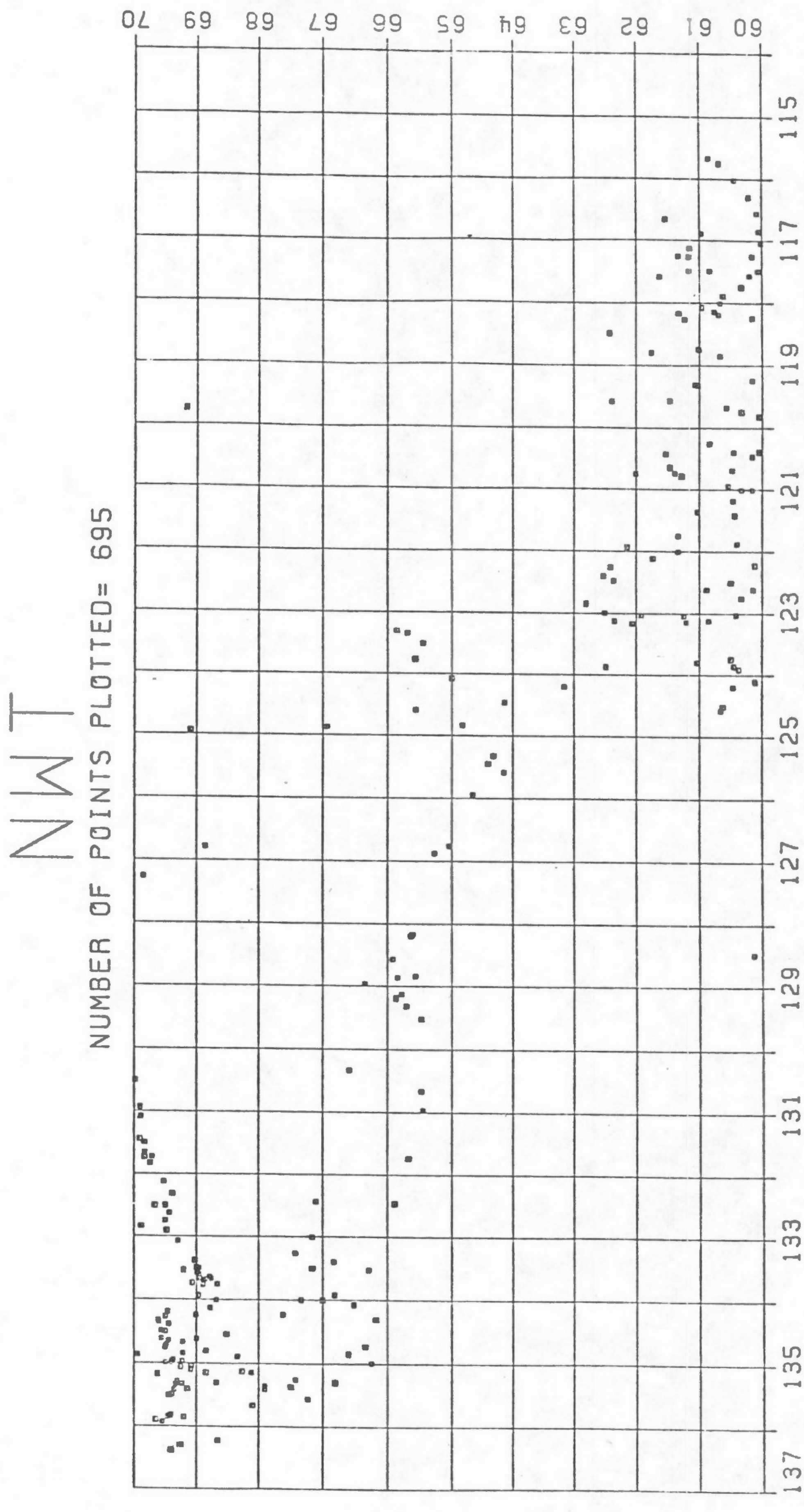
Fig. 7. Uncorrected BHT data versus depth plot for the area 65°-70°N, 123°-137°W.

Fig. 8. Corrected BHT data versus depth plot for the same area as Fig. 7.

NWT

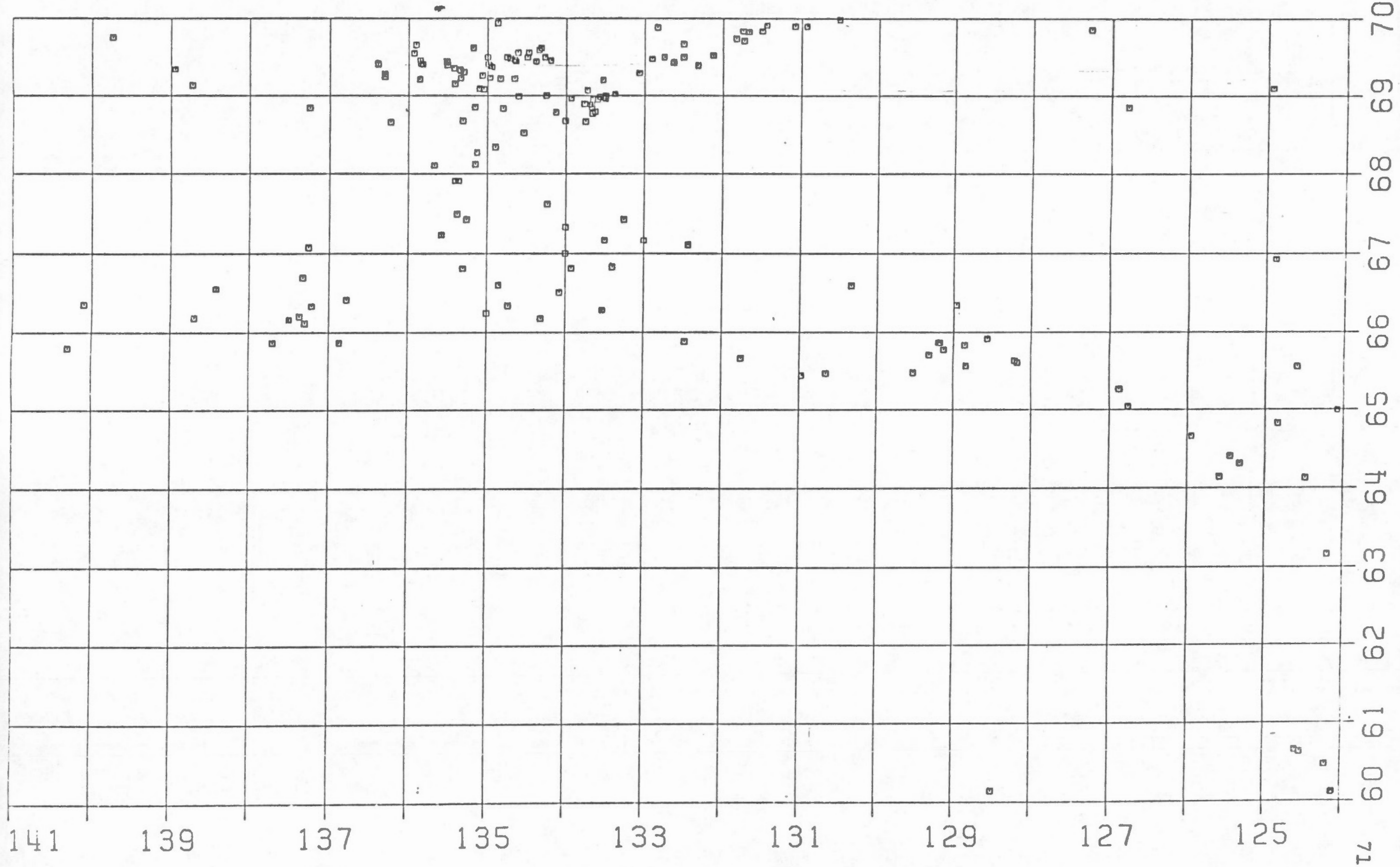
NUMBER OF POINTS PLOTTED=2658




NWT
NUMBER OF POINTS PLOTTED= 695
60 61 62 63 64 65 66 67 68 69 70
115 117 119 121 123 125 127 129 131 133 135 137

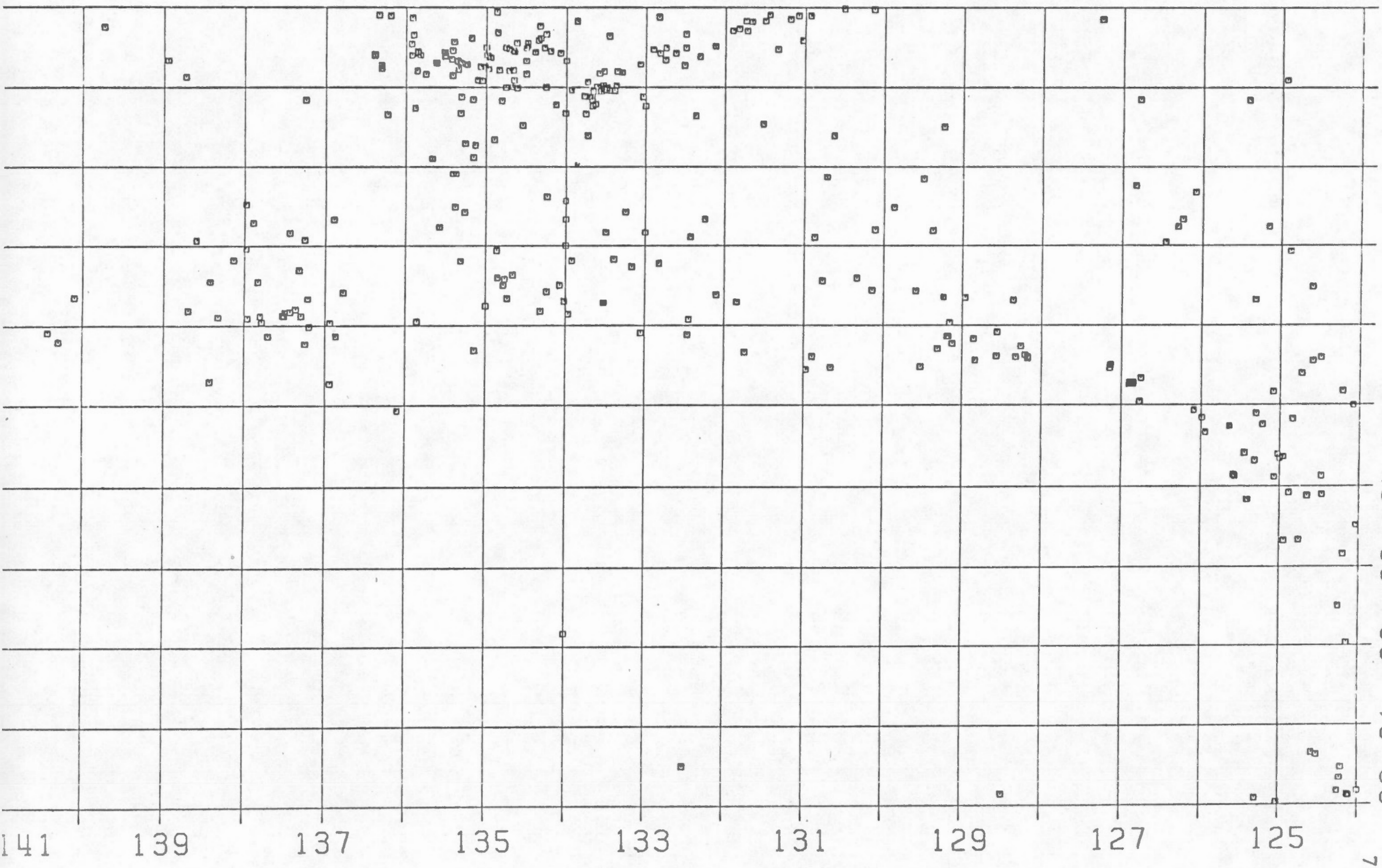
YUKØN

NUMBER ØF PØINTS PLØTTED= 561

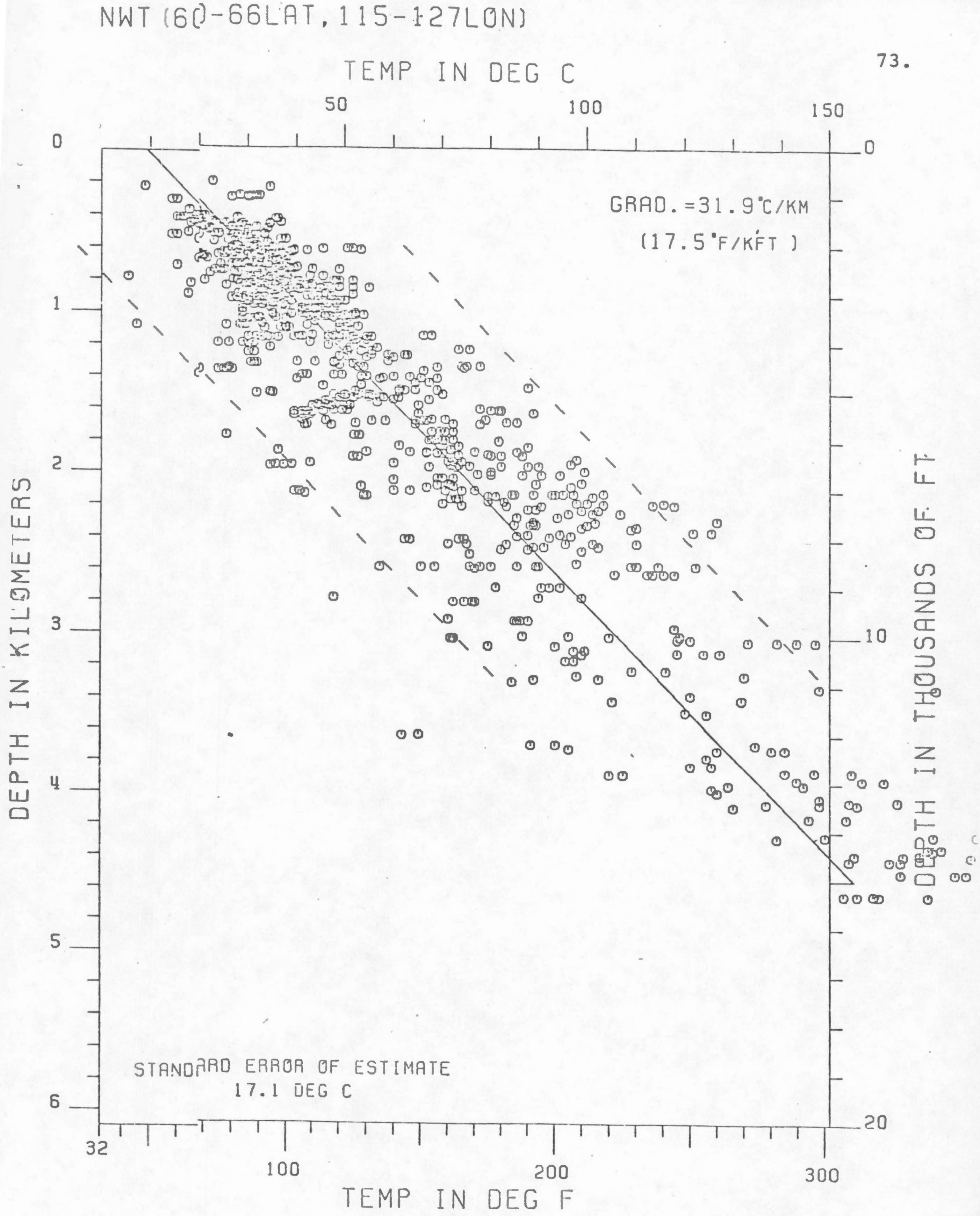


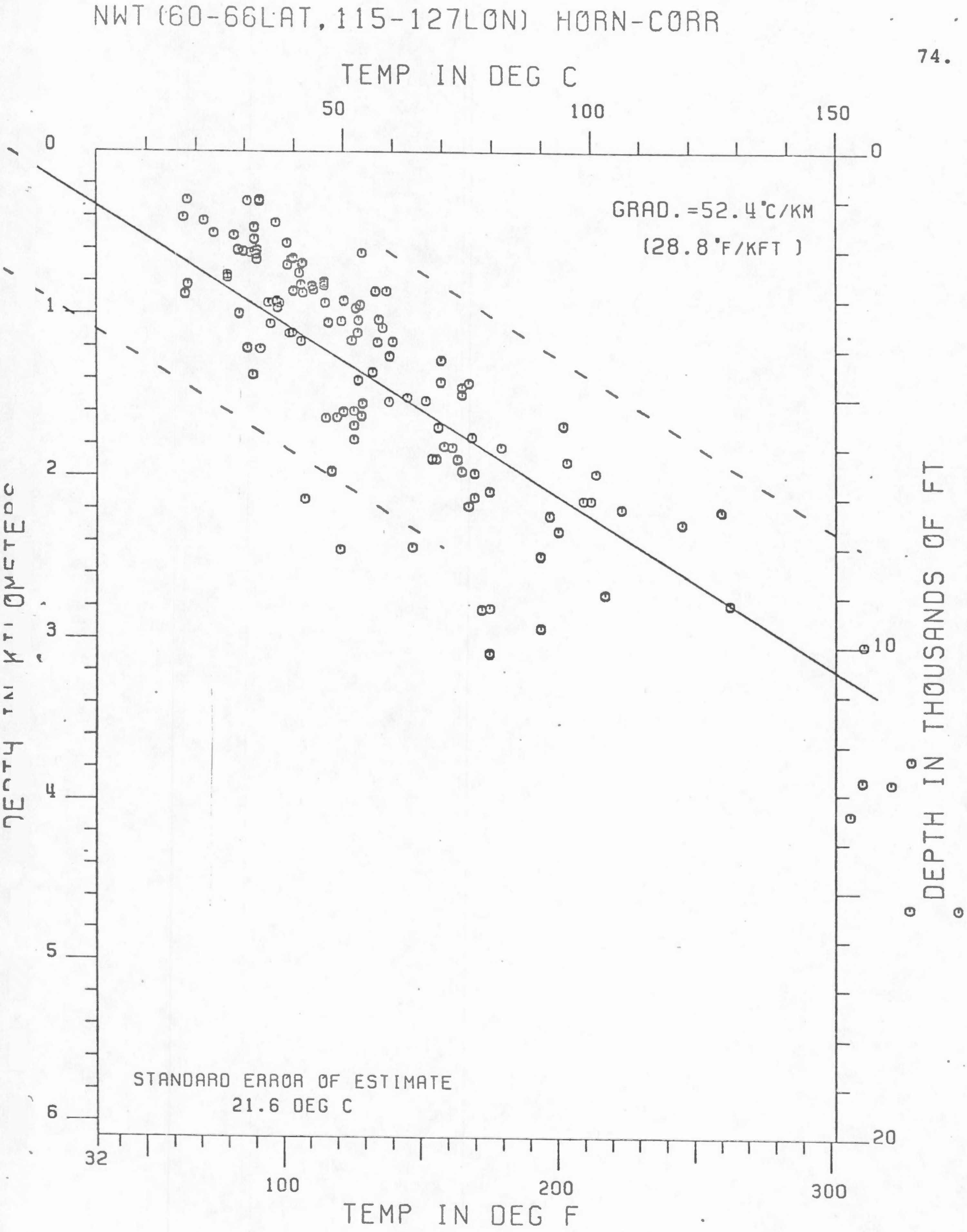
YUKON

NUMBER ØF PØINTS PLØTTED=2141

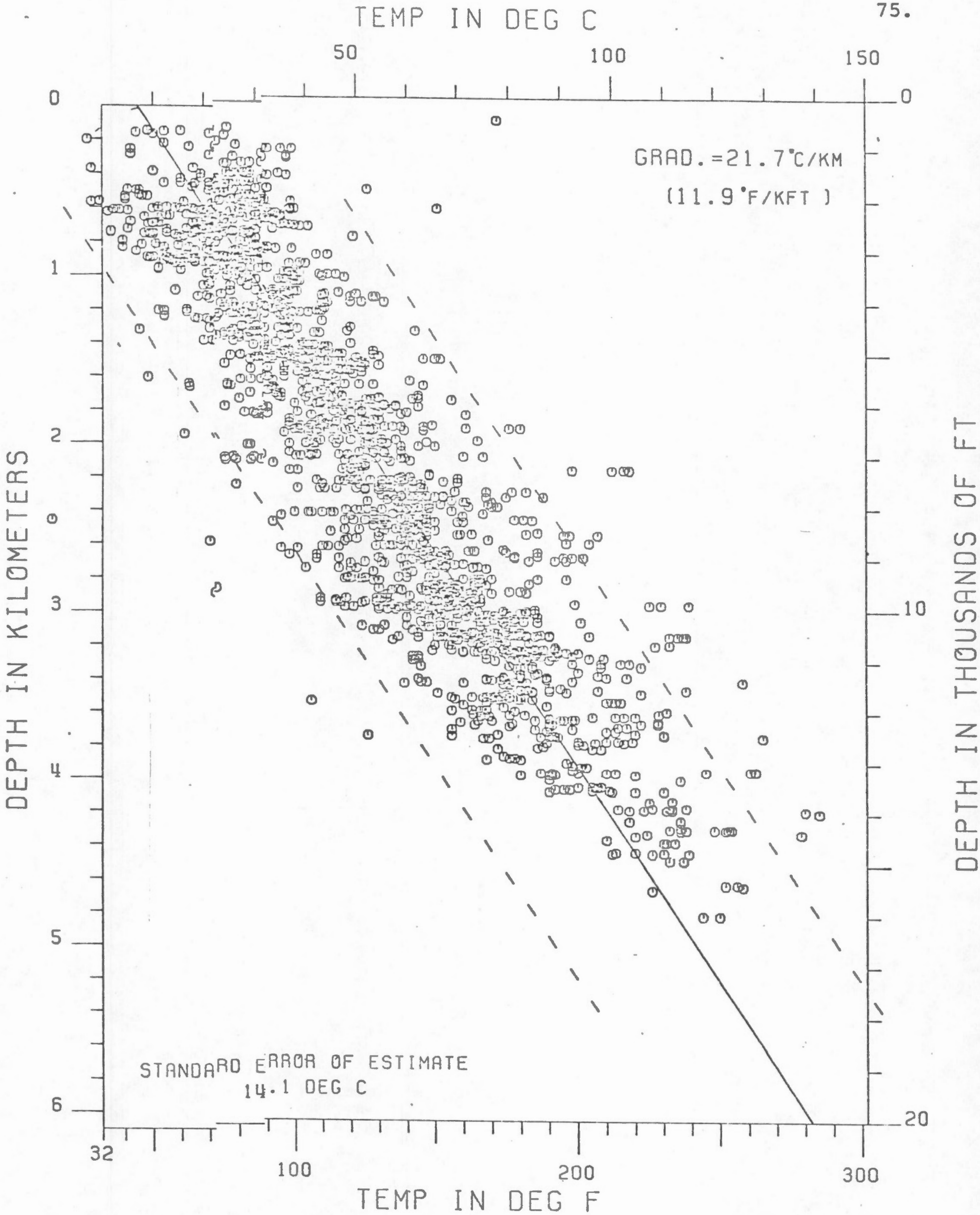


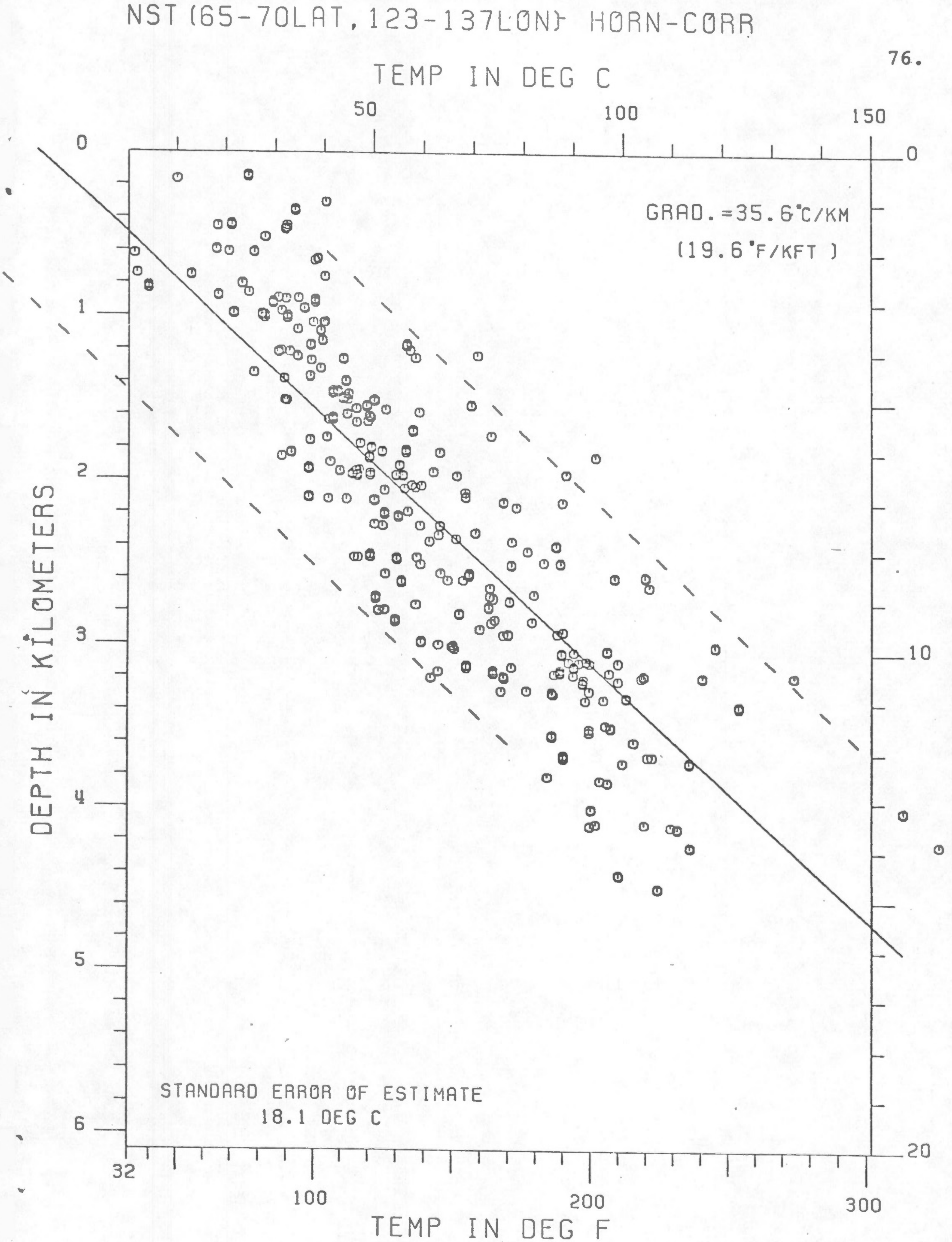
72.


NWT (60-66LAT, 115-127LON)
TEMP IN DEG C
50
100
150
0
1
2
3
4
5
6
0
10
20
GRAD. =31.9°C/KM
(17.5°F/KFT)
DEPTH IN KILOMETERS
DEPTH IN THOUSANDS OF FT
STANDARD ERROR OF ESTIMATE
17.1 DEG C
32
100
200
300
TEMP IN DEG F


NWT (60-66LAT, 115-127LON) HORN-CORR
TEMP IN DEG C
50
100
150
0
GRAD. =52.4°C/KM
(28.8°F/KFT)
1
2
3
4
5
6
DEPTH IN KILOMETERS
0
10
20
DEPTH IN THOUSANDS OF FT
STANDARD ERROR OF ESTIMATE
21.6 DEG C
32
100
200
300
TEMP IN DEG F

NWT (65-70 LAT, 123-137 LON)




NST (65-70LAT, 123-137LON) HORN-CORR
TEMP IN DEG C
50
100
150
0
1
2
3
4
5
6
0
10
20
GRAD. =35.6°C/KM
(19.6°F/KFT)
DEPTH IN KILOMETERS
DEPTH IN THOUSANDS OF FT
STANDARD ERROR OF ESTIMATE
18.1 DEG C
32
100
200
300
TEMP IN DEG F