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GEOMAGNETIC REPORT

GEOMAGNETIC SURVEYS AT FOUR CANADIAN CRATERS

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Table of Contents

ABSTRACT

Magnetic and electrical surveys have been carried out at four circular structures which may be of meteoritic impact origin. These are located at Skeleton Lake, Ont., Lake St. Martin, Man., Lake Wanapitei, Ont. and Elbow, Sask. Data obtained by this multi-discipline approach have added to the available information and have provided some evidence in favour of meteoritic formation at the first three sites, but not at Elbow, Sask. Contour maps showing total magnetic intensity over the features exhibit low gradients of magnetic change typical of some meteorite craters. Analysis of the data has helped evaluate the several geophysical surveying techniques employed as to their usefulness and feasibility in the on-going investigations of these four, and other similar features. A study of the Skeleton Lake crater indicates it to be a typical example of a 'simple' meteorite crater.

RESUME

Des levés magnétiques et électriques ont été effectués à l'emplacement de quatre structures circulaires d'origine ancienne qui peuvent provenir de la chute de météorites. Ils sont Skeleton Lake, Ont., L. St. Martin, Man., L. Wanapitei, Ont. et Elbow, Sask. Les données obtenues grâce à cette approche pluridisciplinaire viennent s'ajouter aux renseignements déjà disponibles et apportent certaines preuves quant à la formation d'origine météorique de chaque structure, bien que Elbow, Sask. n'est pas preuvé. Cartes des contours du champ magnétique total ont demonstré les gradients basses; ils sont typiques pour certaines cratères météoriques. L'analyse des données a contribué à l'évaluation de plusieurs techniques de levés géophysiques employées, et ce du point de vue de leur utilité et de leur faisabilité dans le cadre des recherches actuelles sur ces quatre détails topographiques et sur d'autres éléments semblables. L'étude du cratère à Skeleton Lake est l'example qui peut provenir la modèle typique pour une cratere 'simple'.

I INTRODUCTION

Meteorite craters have certain characteristics which have been described by Beals (1957, 1960), Innes (1957) by Beals et al (1963), Halliday and Griffin (1963, 1966, 1967), by Dence (1964) and reviewed historically by Baldwin (1978). In Canada over 100 features have been identified as having some of these characteristics, such as circular or near-circular form, gravity and magnetic anomalies and crater-like depressions either surficially or sub-surface. In past years the Geomagnetism Division has conducted magnetic surveys at ten of these features to attempt to assess their origin and to add to the knowledge of their magnetic characteristics. This article reviews the progress of investigations at four locations, listed in Table I. The different survey techniques are explained and evaluated with a view to future use at other sites for evidence of causation. Recent observations and theory are reviewed by Dence et al. (1977) and Grieve and Robertson (1979), who have classified the Elbow and Skeleton Lake structures as possible impact sites and the other two craters (Table I) as probable impact craters.

Twenty-four of the many structures in Canada which have received consideration as meteoritic impact sites have been shown to contain definitive evidence of shock metamorphism to establish their impact origin. Six more exhibit some geologic and geophysical characteristics supportive of such an origin, but lack the definitive evidence of shock effects. Most of the remainder have not been investigated as yet, so that if magnetic and electrical characteristics can be outlined in detail at several of the confirmed sites this could prove useful as acceptable supportive evidence in favour of impact hypotheses where shock metamorphism features are not visible.

Table I

	Name	Location*	Crater Diam. (km)	Methods**
1)	Skeleton Lake, Ont.	$\phi = 45^o15'$N. $\lambda = 79^o27'$W.	3.3	T,E
2)	Lake St. Martin, Man. (Gypsumville)	$\phi = 51^o46'$N. $\lambda = 98^o31'$W.	22.7	T,R
3)	Lake Wanapitei, Ont.	$\phi = 46^o45'$N. $\lambda = 80^o44'$W.	9.5	T,E
4)	Elbow Structure, Sask.	$\phi = 50^o59'$N. $\lambda = 106^o43'$W.	4.9	T,R

* ϕ = Latitude, λ = Longitude, rounded to 1'

** T = Total Force magnetic survey
E = e.m., VLF (electromagnetic soundings, very low frequency waves)
R = electrical resistivity and conductivity systems

II GEOLOGY AND PHYSIOGRAPHY

1. Skeleton Lake

Bedrock formations are of Precambrian age, principally granitic and migmatic gneisses, amphibolite and basic intrusive types. A geological map compiled by Hewitt (1967) identifies veined, banded and homogeneous grey migmatitic gneiss produced by injection and granitization of various metamorphic types, (Fig. 1). The rocks are mainly upper amphibolite and granulite metamorphic facies, exposed on the cliffs of Skeleton Bay, and around the south shore of Skeleton Lake as outcrops. In the latter area one obtains absolute values of total magnetic intensity greater than normal, suggesting the presence of magnetite and perhaps pyrrhotite. The strong glaciation in Pleistocene times has left glacial till, moraines and deposits of sand and gravel, which are quarried in the area, for example at Nutt Lake, 1.5 km south of Skeleton Bay. Many Ordovician pebbles are found here in the gravel, implying a covered outlier of Ordovician limestone sediments which were originally extant over the Skeleton Lake depression and have been partially removed and re-deposited by the southerly moving Keewatin ice sheet.

There is a pronounced synclinal axis trending NW to SE, beginning north of the Lake and bending a little to the west south of the Lake, with the appearance there of highly folded gneissic structures. Briefly, the lake is entirely surrounded by crystalline rocks, mostly hornblende migmatites moderately to strongly granitized, with breccias in the shoreline outcrops similar to those at Brent (Robertson and Grieve, 1975).

One can observe a surface expression of the geological trend lines and outcropping on the aerial photos of the district, with at least one metasedimentary occurrence emerging about 1 km northwest of Tomelin Bluffs, see Fig. 6 for location, and extending a distance of 3 km to the NW (Fig. 1). A surficial ellipse 200 m wide is clearly visible. Strike of foliation is S.E. with dips ranging from 70° to 20° down, generally to the N.E. Skeleton Lake has a mean elevation of 280 m above m.s.l. and drains into Rosseau Lake, through the Muskoka lakes system and then into Georgian Bay, Lake Huron; it has only a few streams, unrelated to general drainage pattern.

The curved nature of the glacial grooves is noticeable on the topographic map of the area coinciding with the strike of foliation, see map reference, N.T.S., Dept. EMR, 1:250,000 Series, 31 E/SW Muskoka. The impact hypothesis for this structure is discussed by Waddington and Dence (1979), who point out its similarity to Lake Wanapitei.

2. Lake Saint Martin

An unusual geological feature is located near Lake St. Martin in Central Manitoba, near the town of Gypsumville. It is about 23 km in diameter, with the western perimeter passing west and north of Gypsumville; there is a gypsum quarry 1 km north of the townsite, and another one 3 km north.

The site is about 50 km west of the Precambrian Shield margin and there are thin deposits of Palaeozoic and Mesozoic, but not platform sediments, over the Archean basement rocks. There is a minor but noticeable surface expression of a circular depression with a rim-like cirque on the north side, severe erosion over the centre and submergence by the waters of L. St. Martin to the south (Fig. 2). Outcroppings of anorthosite and impure gypsum are found at several locations in the area. The central zone is nearly flat topographically, with marshy areas over most of its northern half. Favourable evidence for impact origin is given by McCabe and Bannatyne (1970). A more detailed magnetic survey has been carried out by Coles and Clark (1978, In Preparation).

3. Lake Wanapitei

The lake is situated about 40 km northeast of Sudbury, Ont., a deep, near-circular feature of age approximately 37 m.y. Hills in the vicinity rise 130 m above the water surface which is 267 m above m.s.l. Maximum water depth is about 125 m, increasing proportionally from shore to centre. The eastern salient of the Sudbury Basin is 2 km to the west (Fig. 3). The crater is centred near $\phi = 46^{o}45'N$, $\lambda = 80^{o}44'W$ and has an estimated diameter of 9.5 km. Glacial float appears on the southern shores with many boulders of breccia and melt rock. Proterozoic rocks of Aphebian age surround the western perimeter with younger Helikian formations on the easterly side. Granite, norite, and allied plutonic rocks outcrop at higher elevations on all sides. Thomson (1969) provides a further discussion of the area. See also Douglas (1969), Thurston et al (1970) for the bedrock geology, Dence and Popelar (1972) for evidence of impact formation and Popelar (1971) for gravity measurements in this area.

4. Elbow Structure

This unusual feature is found a few km from the great elbow of the South Saskatchewan River where the channel bends northward to join the North Branch, Fig. 4. The elbow structure resembles a buried dome of diameter 3 km extending 2-3 km in depth and exhibiting no surface expression. De Mille (1960) believed it to be a crypto-volcanic dome and has reported on the diamond-drilling results obtained there in a search for petroleum. It is covered by Cretaceous age sediments including the Beauport formation. Nearer the surface there are chiefly Bearpaw age formations of dark grey shales, greenish sands and fine-grained sandstones in part glauconitic; smooth chert pebbles, concretionary beds; strata of bentonite and volcanic ash with random conglomerates overlain by glacial debris, till and the surface overburden of clay loam, sandy soil and erratic boulders. The diamond drilling results neither confirm nor deny meteoritic impact origin, but have shown that the central portion of the feature is covered by 1.5 km of sediments. Location in more detail is shown in Fig. 5. A smaller, similar structure known as the Gilroy dome is located 5 km south of the Elbow site.

III DESCRIPTION OF GEOPHYSICAL METHODS

Total Magnetic force survey (F)

A Sanders MK II proton precession magnetometer and a Barringer magnetometer were used for the surveys. Both instruments have a resolution of $\pm$ 1 nT, (1 nT = 10^{-5} Gauss). Observations were made at equal distances along a profile line or in a grid pattern. Regional gradients were then removed and profiles plotted, or a contour map constructed. The pattern obtained enables one to model the feature in a general way. From the lateral gradients of change in F assumptions can be made of the depth to basement, or source of magnetic anomalies, as described by Heiland (1946). Comparisons made between surface and aeromagnetic surveys provide additional useful information, (Zietz and Henderson 1949). A modified form of this method has been utilized by Sander et al (1964) at the Deep Bay crater.

The total force observations were taken at Skeleton Lake along the tracks of an airborne survey projected downwards. The surface and aeromagnetic profiles are compared to one another, see Fig. 6 for positioning. The usual geophysical prospecting methods were followed at Elbow structure, and at Lake St. Martin (Fig. 7) by observing at numerous stations in the central area. At Wanapitei the magnetic observations were taken in a boat on the lake surface and around the edge on land, and correlated with aeromagnetic surveys.

E.M. methods (VLF)

An Apex double-dipole EM unit supplied by Apex Parametrics, Ltd., was used for reconnaissance traverses. A Geonics Ltd., EM-16 VLF unit was used for more detailed surveys at Skeleton Lake and Lake Wanapitei. At the latter site, A Scopas SE-80 VLF receiver (Scintrex Ltd.) was also utilized to investigate electrical conductivity.

The search for mineralized deposits containing base metals has led to the development of the surface and airborne electromagnetic systems beginning over a decade ago. Instruments operating in the VLF range have been manufactured and described by Geonics (1972) Apex (1973), and interpretation is discussed by Geonics (1972) Ronka (1972) Becker (1967, 1968, 1970) and Paterson (1970). For surface work, E.M. waves are generated by transmitters in the 15-25 kHz band and broadcast from stations throughout the world. A portable receiver is then used to monitor these signals and determine how they are affected by the ground beneath the observer. There is a secondary or induced field created which is directly proportional to the specific electrical conductivity, see Serson (1973). From variations in strength, amplitude and phase of signal on the receiver one may be able to infer a model of the body being surveyed, location of geological faults, contact zones and general level of electrical conductivity. The method is described by Paterson and Ronka (1971) Barringer and McNeill (1970) and Taylor (1973). Depth penetration of only about 100 m is attainable with this equipment at present.

Electrical Resistivity

A Sharpe SP5-R meter (Sharpe, 1960, Scintrex Ltd., 1972) has been utilized with some modifications. Supplemental measurements were made with a Radiohm EM-16R unit over the same baselines at Skeleton Lake and L. Wanapitei only.

For ground surveys the classical electrical prospecting system has been used here, as described by Heiland (1946) Vozoff (1958) and Berdichevskiy (1965). The basic principle consists of introducing an electrical current into the earth between 2 points, utilizing metallic electrodes or porous containers filled with electrolyte. By increasing the distance between points one obtains deeper penetration into the subsurface media. The resultant voltage distributions are measured on a modified ohmmeter which indicates apparent resistivity in ohm-meters. One can then plot profiles of apparent resistivity at different depths and construct equipotential lines. Configurations of electrodes are shown in Figure 9. The measured apparent resistivities are affected by porosity and the presence of ionized saline solutions (electrolyte) in the subsurface media. Assumptions must be made about these parameters, as discussed by Wetzel and McMurry (1951) and Kunetz (1966). Typical values of resistivity for different rock types are given by Jakosky (1957), see also Table II Appendix. Computational methods of processing data are reported by Mooney et al (1966) and Vacquier et al (1957). In crater study applications one assumes that brecciated and fractured rocks with their resultant greater porosity and permeability will have higher electrical conductivity than undisturbed sedimentary layers; this enables one to construct a model of the structure. Further details are given by Wyder (1967) and by Bhattacharya and Patra (1968).

Recent advances in instrumental design have been made, substituting a portable transmitter and receiver (transceiver system) for the classical prospecting method. The Radiohm EM16-R (Geonics) can be used for both e.m. and resistivity measurements and eliminates much cumbersome field equipment and long reels of cable necessary for the Wenner and similar arrays. Serson (1973) has reviewed instruments for induction studies on land.

IV SURVEY PROCEDURES AND INTERPRETATION

1. Skeleton Lake

Observations of total magnetic intensity were made with a Sanders proton precession magnetometer with a specified resolution of ±1 nT. Diurnal variation measurements were made at a base station and corrections applied for time of observations. Reference was also made to Agincourt magnetic observatory and to the Ottawa magnetic observatory magnetograms for magnetic disturbance corrections.

Observations (about 50) in 1968 were mainly for reconnaissance and establishment of a reference station. Updated to 1970.0 the base datum of a station on land near Skeleton Bay is F = 58,711 nT. Diurnal variation was found to be very low, owing to the fairly low magnetic latitude; 20 nT for quiet days and about 40 nT on disturbed days. The records of F at Ottawa Observatory (Blackburn), geographical co-ordinates $\phi = 45^{o}24'$, $\lambda = 75^{o}33'$, showed no great disturbances during times of observations in July 1969 although sunspots were near a cyclical maximum. Magnetic declination at Skeleton lake is $8^{o}36'$ W. During the 1969 field season 200 observations were taken at 200 metre intervals along the tracks of the airborne magnetometer survey, published by the Geological Survey of Canada, see Map references. A magnetic field contour map has been derived from the original GSC maps (Fig. 8), showing the central low and higher gradients beyond this low.

A 14 foot non-magnetic Peterborough boat was employed to obtain measurements on the lake with the instruments placed as far away as possible from the small magnetic influence of a 5 H.P. outboard motor. The profiles obtained are shown in Figs. 11-16 compared to the aeromagnetic data which was updated from the 1953 survey to epoch 1970.0. Profiles start and end near lakeshore, see Fig. 6. The original GSC maps (not the smoothed contour map, Fig. 8) were used to obtain the 'air' profiles.

After reduction of data the surface magnetic profiles were plotted along the tracks of each of six flight lines projected on the surface. Considering the various sources of errors, surface values are believed accurate to ±15 nT. Navigation and distances were by dead reckoning, making reference to topographic maps. Electromagnetic measurements were taken along the same tracks as the total force readings, and are plotted, Fig. 6, with these tracks as baselines. Surface e.m. data only were available; an airborne e.m. survey would be desirable.

To interpret these data one first considers the impact hypothesis. The impact of an 'iron' or 'stone' meteorite on the earth's surface creates a hemispherical cavity with a large volume of crushed and metamorphosed rock, including some melt-rock directly beneath the area of impact. The original magnetization may be partially nullified. One expects the integrated effect to be a reduction of the absolute strength of the total magnetic field with the space above the zone having shallower gradients of magnetic change both horizontally and vertically than previously extant. When this is found to be true it is evidence in a qualitative way favourable to an impact creation hypothesis, although it does not rule out other mechanisms (Innes, 1964). The filling in of the basin by sedimentary rocks would change the magnetic pattern over the area only slightly, but it would change the apparent gravitational anomaly appreciably. An analysis of the magnetic data over Skeleton Lake does in fact show a negative magnetic anomaly of 200 nT as compared with the surrounding region. The gradients of change in the magnetic field are lower over the central portion of the Lake than they are around much of the environs, Fig. 8. Appropriate corrections obtained by looping to base stations were applied to the surface observations to eliminate disturbance and diurnal variation error. An arbitrary baseline was maintained, viz., the average F for each profile. The attenuation of the magnetic profiles is shown by a comparison of observations of total force at the altitude of the aircraft, with observations at the surface, and the resultant ratios are listed in Table IV (Appendix). Intercomparisons of surface and air magnetic profiles are plotted in Figs. 11-16. The three most central profiles (3-5) show a typical magnetic signature for a sediment-filled cavity. The weighted mean of Surface-Air ratios of anomaly is 1.4:1 for these profiles. Absolute values on these profiles have been adjusted for secular change in the magnetic field, and have been updated to epoch 1970.0, using information from the Magnetic Charts of Canada for this epoch.

These data are similar to results obtained at other simple meteorite craters such as Brent and Holleford and the way in which a model is deduced from intercomparisons of magnetic data is shown by Andrieux and Clark (1969) for Holleford crater. No drill-hole data are available at Skeleton Lake yet.

Steenland and Gibbons (1964) have discussed the upward continuation of an aeromagnetic anomaly. From their graph and other similar ones by Vacquier et al. (1963) it is known that an observed anomaly of 100 nT at flight elevation 300 m above terrain would correspond to one of about 150 nT at the surface (a ratio of 1.5:1) when one assumes that there is a source of anomalous magnetization at a depth roughly equal to the elevation above the surface (in this case 300 m). The mean ratio of airborne to surface range of values over Skeleton Lake crater is 1.4:1. This is nearly equal to 1.5:1 which suggests a source of higher than normal magnetization 300 m or more below the surface of the central area. The source may coincide with crystalline, undisturbed bedrock at this depth. An intense source could be deeper than this and cause the same effect.

The electrical properties at Skeleton Lake are shown in Fig. 6 as vertical phase measurements. The e.m. profiles are uniformly low over the centre, rising to higher values at the rim where one is closer to altered rock. The surface drainage pattern supports a hypothesis of a highly conductive ionized solution entering the fracture zone and percolating outwards to the limit of the zone. This would affect the electrical conductivity outside the central crater basin beyond the rim, and the results are compatible with this hypothesis.

2. Lake St. Martin

Several hundred total force magnetic surface observations were taken, mainly over the southern half of the feature. Reference station B was established 1 km east of Gypsumville magnetic repeat station A, and a diurnal variation curve obtained for corrections of total force readings taken throughout the day. These corrections have been applied along with the appropriate regional trend increments. Survey lines and station locations appear on Fig. 7; the usual distance between stations is 200 m. Reference station (B) has a mean F value of 60814 nT. The magnetic repeat station 'A' values are in the Appendix (Table V). The magnetic contour map shown in Fig. 19 is based on surface observations.

GSC aeromagnetic maps are available for the region and the contour map, Fig. 20, was obtained from these maps, selecting a contour interval of 100 nT and updating the magnetic field to epoch 1970.5, using secular change data. Lower values of F occur in the central portion of the feature with the deepest low near the centre. Observations beyond the rim show fairly high gradients of change of F, and higher magnetic intensity (about 500 nT higher than the average field within the rim). Topographically the feature shows little surface expression of a typical crater, having been filled in by sediments and glacial debris and greatly eroded since formation.

Davies et al. (1962) describe the mineral deposits in the area; the age of the crater is Triassic (225 $\pm$ 40 my.). It lends itself to analysis by combining gravimetric and magnetic surveys (Innes, 1949). The physical size is about the same as a complex crater such as Clearwater Lake East, modelled by Dence (1964), and one could assume that central uplift is feasible. Shocked metamorphic rock types, as found in the interior of the crater at Manicouagan (Coles and Clark, 1978) occur at L. St. Martin to a lesser extent. The structure is well described by McCabe and Bannatyne (1970) who have proved from their diamond-drilling results that the Precambrian rocks are uplifted centrally. Methods of calculating crater parameters are discussed by Hall (1968) and Clark (1969); Reford (1964) has shown relevant examples of magnetic profiles over sediments, which are compatible with the data here.

The apparent electrical resistivity reconnaissance survey was made using a Sharpe SP-5R unit. A Schlumberger array was set up at the base station B, extending east for several kms, with current electrode spacings expanded in increments of 20 to 160 m, relative to fixed potential electrodes.

For a summary of resistivity results at Lake St. Martin, see Appendix, Table VII. The fairly uniform resistivity values are consistent with those normally obtained over considerable depths of sediments. There is some variation in electrical conductivity, probably caused by percolation of ground waters and local deposits of mineral salts.

3. Lake Wanapitei

Similar procedures were followed here as for other features. A non-magnetic boat was used for the magnetometer readings over the lake and points on the islands. Insufficient data were obtained to plot a detailed surface contour map, but intercomparisons with airborne results are in good agreement. The e.m. and resistivity data were obtained along lines A, B, C (Fig. 3) using an EM-16R unit and also the SCOPAS (Single Coil, Phase, Amplitude and Strike) receiver which employs as a source of energy VLF transmission in the 15-25 kHz band (i.e. the Cutler, Maine, U.S.A. Naval station (NAA) broadcasting on a frequency of 17.8 kHz, power 1000 watts). The e.m. waves generated by the transmission induce a secondary field; its direction and strength are functions of the electrical parameters of the subsurface media. Observations were made near the rim to determine from measurements of azimuths and dip, the attenuation of the field and hence deduce properties of the subsurface media and the extent of any anomaly. An attempt was made to correlate the data with shock metamorphism effects, which extend beyond the rim. Preliminary analysis of about 100 readings, mainly around the western edge of the feature, indicate low dip angles associated with higher vertical components of the electrical field. There is an area between western lakeshore and the eastern salient of the Sudbury Basin, where high electrical conductivity prevails (C. line, stations 2-9, fig. 17). At the easterly geological boundary of the Basin much more complex and highly variable results are obtained. Dence and Guy-Bray have modelled a cross-section of the Lake Wanapitei crater (1972). One can only infer from the e.m. survey that the electrical conductivities are very high at the surface and at shallow depths outside the crater's rim. The vertical readings are shown as vectors (Fig. 17) along the lines; the low numbers indicate zones of high electrical conductivity. Thomson (1969) has discussed the geology of the area. A gravity survey has been summarized by Popelar (1972), indicating a substantial negative Bouguer gravity anomaly over the whole feature. An examination of the aeromagnetic survey (Fig. 21) reveals a localized high near the northern boundary of the Wanipitei Indian Reserve, point C-9, Fig. 3. Over the lake the gradients of change of total magnetic intensity are more uniform than over surrounding country rock, averaging about 50 nT per km, increasing as one proceeds north, which is the accepted regional trend. The removal of this regional trend has been carried out and the resultant contour map is shown in Fig. 22. In general there is little correlation between the magnetic contours and electrical conductivity, except where the rocks causing the magnetic anomalies around the Lake have attenuated the e.m. signals and affected the azimuths. However the gradient-free map indicates a uniform magnetic field over the crater which is compatible with a hemispheroidal cavity filled with sediments and brecciated material. It also correlates well with the gravity survey. The Wanipitei feature has been described as a simple meteorite crater of age 37 $\pm$ 2 my., much younger than the Irruptive Sudbury Basin which is adjacent to it, and to have been caused by hypervelocity impact (Dence and Popelar, 1972). Because of the complex geology in this area the e.m and magnetic surveys are not able to distinguish between anomalies caused by shock metamorphism processes and those resulting from geological events.

4. Elbow Structure

A temporary magnetic base station was established to enable diurnal corrections to be made and the survey was conducted in the summer of 1970. Procedure was to traverse the central portion of the feature over an area of about 14 sq. kms, taking periodic F readings and correcting these. Corrected values are plotted in the form of contours in Fig. 10. Local magnetic element values are shown in Table III (Appendix) as observed at the base station. Several hundred total force observations were taken, distributed fairly uniformly over the feature.

Measurements of the apparent resistivity were made along the same tracks as the total force survey, using a Sharpe SP-5R unit and Wenner-Lee array.

From the resistivity values (Table VI) the structure appears to be uniform and isotropic, with no evidence of highly conductive media. The median value of ρ_a is 514 ohm-m. There is very little deviation from the median, either with increasing depth of penetration, to a maximum of 1.2 km, or laterally from the base station on the western perimeter to a point near the centre. This is consistent with weakly magnetized layers of sedimentary material which in this case are of age about 80 m.y. Drill-hole data, along with gravimetric and seismic results, have ruled out the presence of a stratigraphic trap containing petroleum and have suggested the feature is an anticline type of structural dome. The surface magnetic evidence does confirm the typical low gradients of change obtained considerable depths of sediments, but does not confirm or deny an impact hypothesis of origin. No further magnetic surveys are required at this site.

V DISCUSSION

Detailed total magnetic force surveys are desirable at all possible craters as the first stage of an investigation followed by the electrical methods where feasible. The magnetic surveys may give information on the shape and dimensions of the feature and whether the structure is uniform or not. In the general case of a circular or near-circular structure, geophysical prospecting methods give a clue as to lithology and, for simple craters, depth estimates to a crystalline basement. Combining suitable methods one is able to establish some constraints on the structure and morphology of a feature which may help in planning future investigations. Magnetic anomaly patterns consistent with meteoritic formation are visible at Skeleton Lake and L. St. Martin, but at the other two features are not very definitive. E.M. methods were useful at Skeleton Lake but of minor value elsewhere.

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VII Appendix

TABLE II

Apparent resistivity values

Media	Content	Value ρ_a (ohm-m)
Limestone	H_2O	2500
Sandstone	Salt, H_2O	300
Breccia	Ca CO_3	30
Marble	....	1000
Soil, Till	Moisture	50
Quartz	....	7000

These are considered typical values for use in computations.

TABLE III

Elbow Structure

Magnetic Element	Epoch 1970.0
D	17°15'E
I	77°38'N
H	13,040nT
Z	59,440nT
F	60,850nT

TABLE IV

Range of Variation in F. (nT)* Skeleton Lake

Track No.	Surface	Airborne	Ratio S/A:I**
1	350	250	1.40
2	450	350	1.31
3	520	370	1.40
4	400	300	1.33
5	225	150	1.50
6	300	250	1.20

*Rounded of to ±5 nT.
**Mean = $(\overline{1.41:1})$ (Attenuation Factor) Weighted for track lengths.

Figure Captions

Fig. 1 Geological Sketch of Skeleton Lake area, after Hewitt (1967).

Fig. 2 Geographical location, L. St. Martin feature. Theoretical rim is shown to indicate size of crater. B is base station, the Gypsumville magnetic repeat station A (Table V) is 1 km west of 'B'.

Fig. 3 Lake Wanipitei and environs, showing e.m. survey points on lines A, B, C.

Fig. 4 Geographical location map, Elbow Structure.

Fig. 5 Detailed location of Elbow Structure; squares are land sections, Dominion Land survey system. Centre is in Section 25, Range 6, Tp. 23, W. of 3rd Meridian.

Fig. 6 Position of tracks of flight lines and surface surveys at Skeleton Lake; circle is hypothetical rim of crater; e.m. profiles plotted with tracks as baselines. Bars on tracks show length of profiles plotted in Figs. 11-16.

Fig. 7 Lake St. Martin, location of survey lines and main stations, total magnetic intensity. Small dots represent one station, large dots two stations. Squares are towns.

Fig. 8 Aeromagnetic field over Skeleton Lake and its environs, derived from maps published by the Geological Survey of Canada.

Fig. 9 Electrical resistivity arrays. A, B denote current electrodes, M, N, potential electrodes. O is centre of array. Current (I), voltage (V) and power source symbols on (a) are assumed on (b) and (c).

Fig. 10 Surface magnetic survey (F) contours, Elbow structure, for epoch 1970.0. Base station datum = 60,000 nT, contour interval 20 nT. Resistivity traverse is from base station to Diamond-drill hole 2, (D.D.H. 2).

Fig. 11 Aeromagnetic and surface profiles of F along track 1, fig. 6. Gammas = nT. Epoch 1970.0, Skeleton Lake.

Fig. 12 Aeromagnetic and surface profiles of F, track 2 fig. 6.

Fig. 13 Aeromagnetic and surface profiles of F, track 3.

Fig. 14 Aeromagnetic and surface profiles of F, track 4, for gammas read nT.

Fig. 15 Aeromagnetic and surface profiles of F, track 5.

Fig. 16 Aeromagnetic and surface profiles of F, track 6.

TABLE V

Gypsumville "A"

Lat: 51°46.5'N
Long: 98°36.5'W

Magnetic Elements for Epoch 1970.5

D	10°15.0'E
I	77°48.1'N
F	61,174 nT
H	12,925 nT
Z	59,793 nT

Table VI

Apparent Resistivity, Elbow Structure

Depth (m)*	Observed ρ_a (ohm-m)
20	628
40	708
80	312
160	381
320	588
640	329
1280	320±50(?)**

*Depth of penetration = a (electrode separation) Wenner array.
Line extends from centre of feature (see fig. 5) to D.D.H. 2 (fig. 10).
**Value at greatest depth is at limit of instrument capability.

Table VII

Apparent Resistivity, L. St. Martin

Depth (m)*	Observed ρ_a (ohm-m)
50	1257
100	785
200	528
400	942
800	2850(?)

*Depth is distance of penetration in meters.
Line extends from base station easterly, Schlumberger array.

Fig. 17. Lake Wanapitei e.m. readings;profiles of intensity of vertical phase.Low vector ordinals imply high electrical conductivity values.Station 7-B[plotted on A-line to extend it] is located 2 km south of station A-9.

Fig. 18 Gravity anomaly contour map, Elbow Structure.

Fig. 19 L. St. Martin, Total magnetic survey F, at surface.

Fig. 20 L. St. Martin aeromagnetic map, contour interval 100 nT. Values added to base datum 60,184 nT give total force, 1970.5.

Fig. 21 Aeromagnetic survey L. Wanapitei, total force in absolute units (nT), from maps published by the Geological Survey of Canada.

Fig. 22. Magnetic residuals map of Lake Wanapitei with regional trend largely removed. Some effect of regional structure is evident in the northerly sector where gradients exceed 50nT/km. The contour interval is 100 nT.

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IX EPILOGUE

Wanapatei is an Indian name, sometimes spelled Wahnapatei or Whanapatie, meaning lair of the Great Manitou. According to folklore, the Manitou was disturbed one day, and in a fit of rage plucked a huge stone from the landscape and hurled it far into space. It became a fiery comet which later returned to earth as a cosmic fireball, crashing to the surface to gouge out the large crater in the Lake. Legend whispers that his Spirit dwells there even today.

ADDENDUM

SKELETON LAKE, ONTARIO

ESTIMATE OF DEPTH TO BASEMENT

The half-slope method of Peters (1949) is used to estimate depth to source of magnetic anomaly - in this case the Precambrian rocks underlying the sediments and the column of water in the Lake at that point. See Figures 11-16 inclusive.

The aeromagnetic map F contours tend to follow the synclinal axis trend lines but are interrupted in this pattern over Skeleton Lake. One assumes this is due to displacement of ferromagnetic material with a new interface at the boundary of shattered basement breccias and subsequent metasedimentary material. A strong contrast in magnetic susceptibilities at the interface allows one to compute the residual total field anomaly. The general equation has the form

$$\Delta F = F.'K.' \ (\chi_1 - \chi_2) \ \ D^0 \ . \ I^0.$$

F being the residual F anomaly caused by contrast of two rock formations R_1R_2 with corresponding susceptibilities $\chi_1\chi_2$: D^0, I^0 are declination and inclination of the ambient magnetic field (known). D^0 is converted to azimuth of the magnetic meridian, i.e. the angular difference of the meridian from direction of the flight lines. Steenland & Gibbons (1964) have discussed the upward continuation of an aeromagnetic anomaly. From their graph and other similar ones by Vacquier et al. (1951), one can infer that an observed anomaly of 100γ at elevation 1000 ft above terrain would increase to approximately 150γ at the surface when one assumes an intrabasement source. Therefore when the observed residual anomalv in F over the crater is 300γ (negative), one would expect to obtain -200γ at aircraft altitude, accepting the same conditions, i.e. a ratio of 1.5:1.

The mean ratio of airborne to surface range of values is 1.36/1; however, the tracks are of different lengths. Allowing for this difference one obtains a ratio of $\sqrt{2}:1$. This is for the total length of the flight lines 1-6 over the water surface:- the actual ratio for selected anomaly sections is somewhat higher but in good agreement with the usual attenuation characteristics. The methods used by Peters (1949) and Nettleton (1950), in computing basement depths, have also been utilized here.

Assuming first a model of a thin layer of magnetic poles one obtains depth to source of $d = 1500$ ft. A thin layer of magnetic dipoles leads to a depth $d = 2250$ ft, as does a thick layer of dipoles extending from surface. The mean depth to basement is around 2000 ft for these three assumptions, i.e. approximately 600 m.

In Nettleton's method the residual anomalies are derived from a second derivative calculation which gives greater weight to the local anomalies and reduces the large anomalies of the wavelengths corresponding to intrabasement magnetic sources. An estimate from this method gives a depth of 2200 ft below plain level. Thus the structure has many of the characteristics of known craters, see Beals and Halliday (1967).

INTERPRETATION

The granitic gneiss outcrops produce highly variable magnetic fields due to siderite ($Fe.CO_3$) or magnetite (Fe_3O_4) crystals concentrated in contact zones and along bedding planes. The earth's magnetic field extent during orogeny impressed itself on these rocks after cooling below 570°C, i.e. paleomagnetic remanent fields cause the steep gradients to change here. Contours of equal magnetic intensity tend to follow and outline the trend of major structural features in the crust.

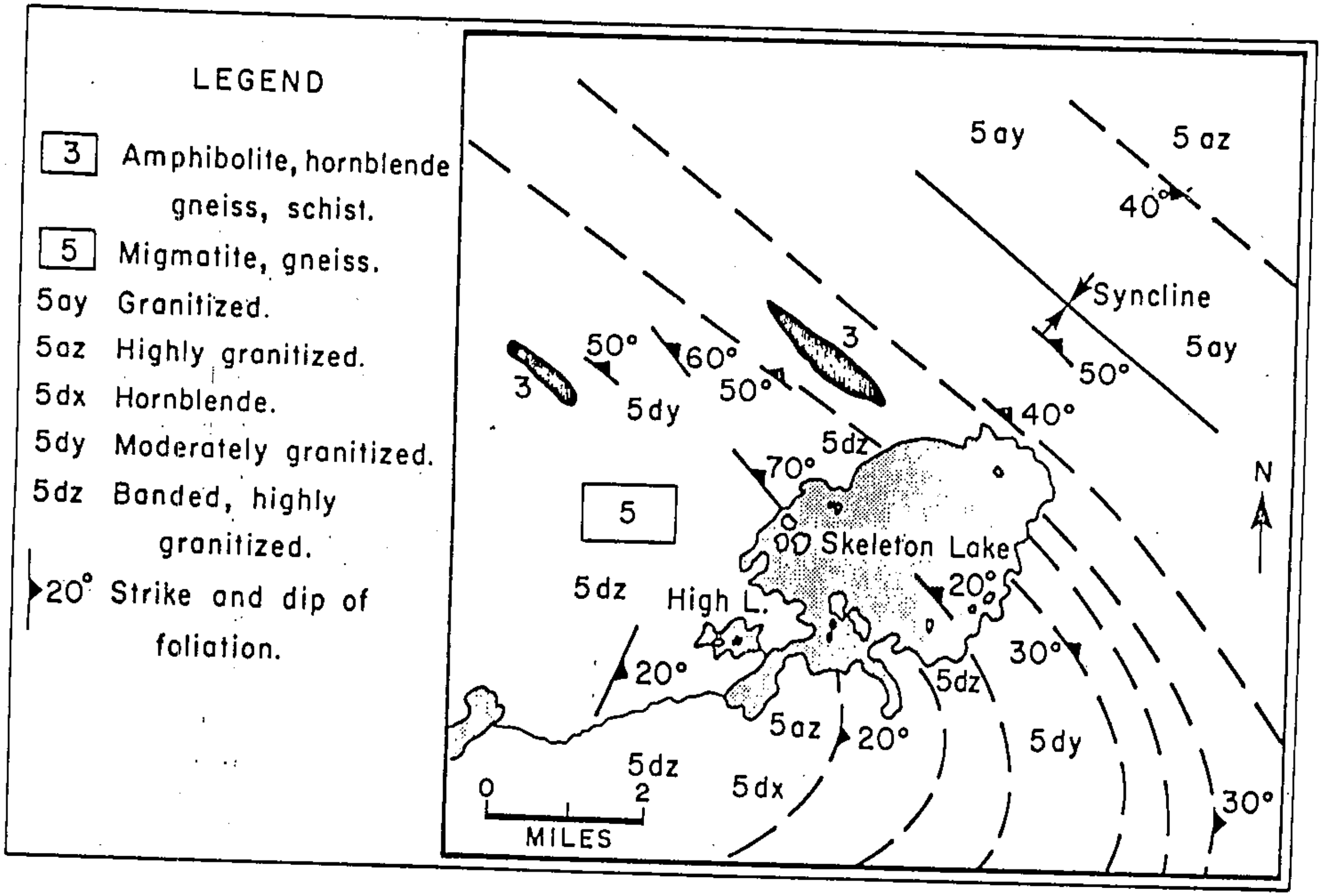

Fig. 1. Geological Sketch of Skeleton Lake area, after Hewitt (1967).

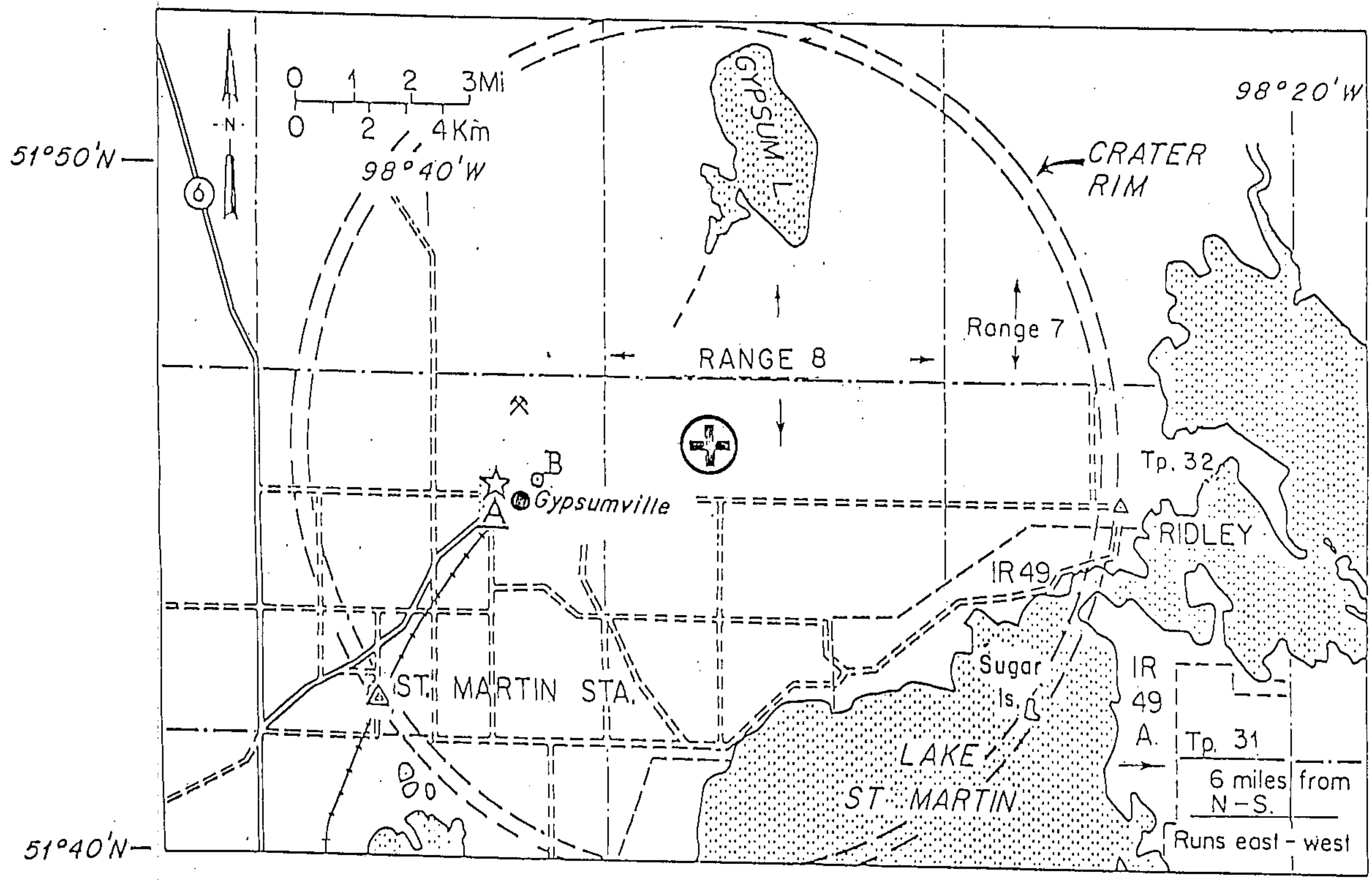

Fig. 2 Geographical location, L. St. Martin feature. Theoretical rim is shown to indicate size of crater. B is base station; the Gypsumville magnetic repeat station A (Table V) is 1 km west of 'B'.

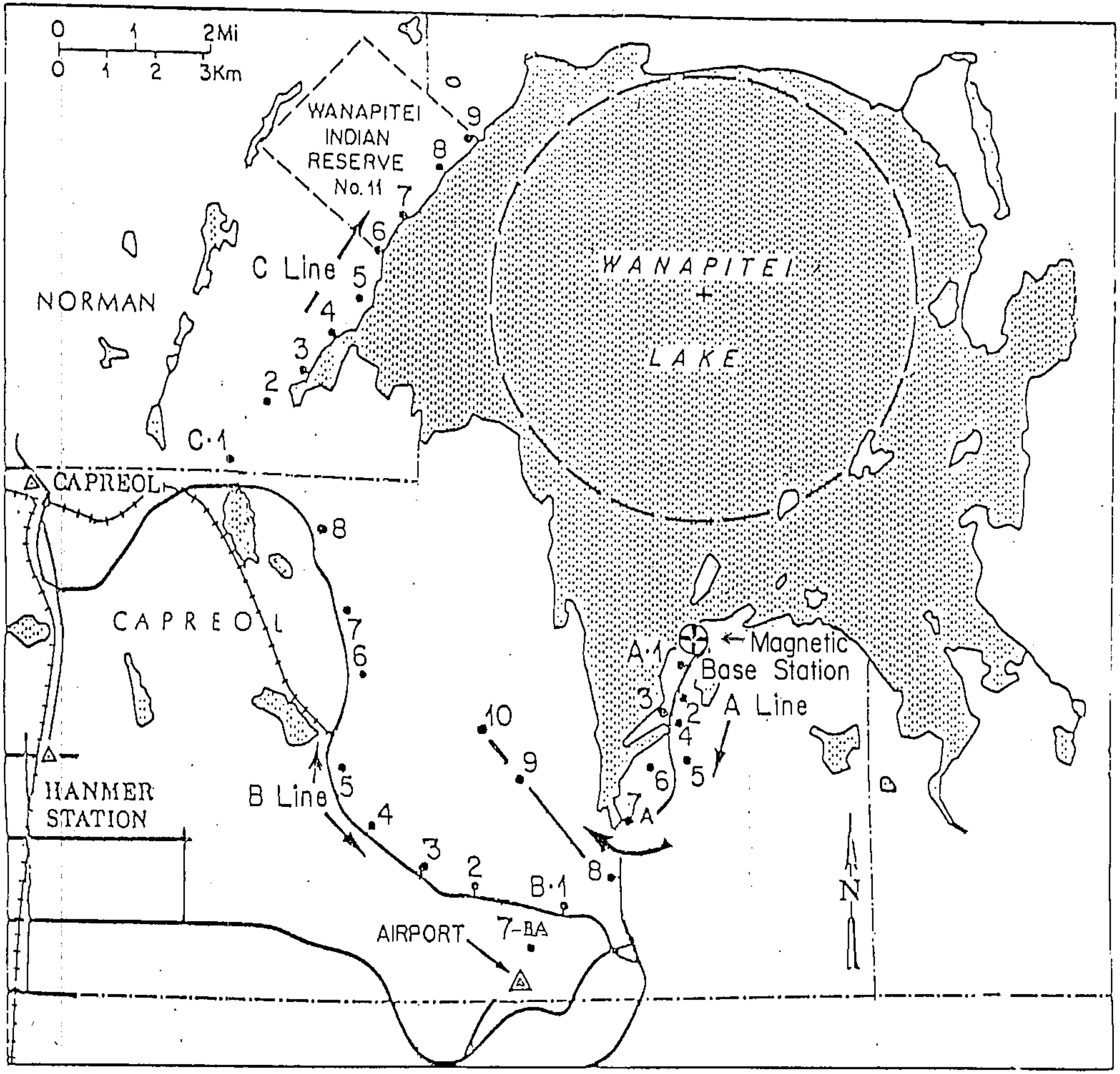

Fig. 3 Lake Wanipitei and environs, showing e.m. survey points on lines A, B, C.

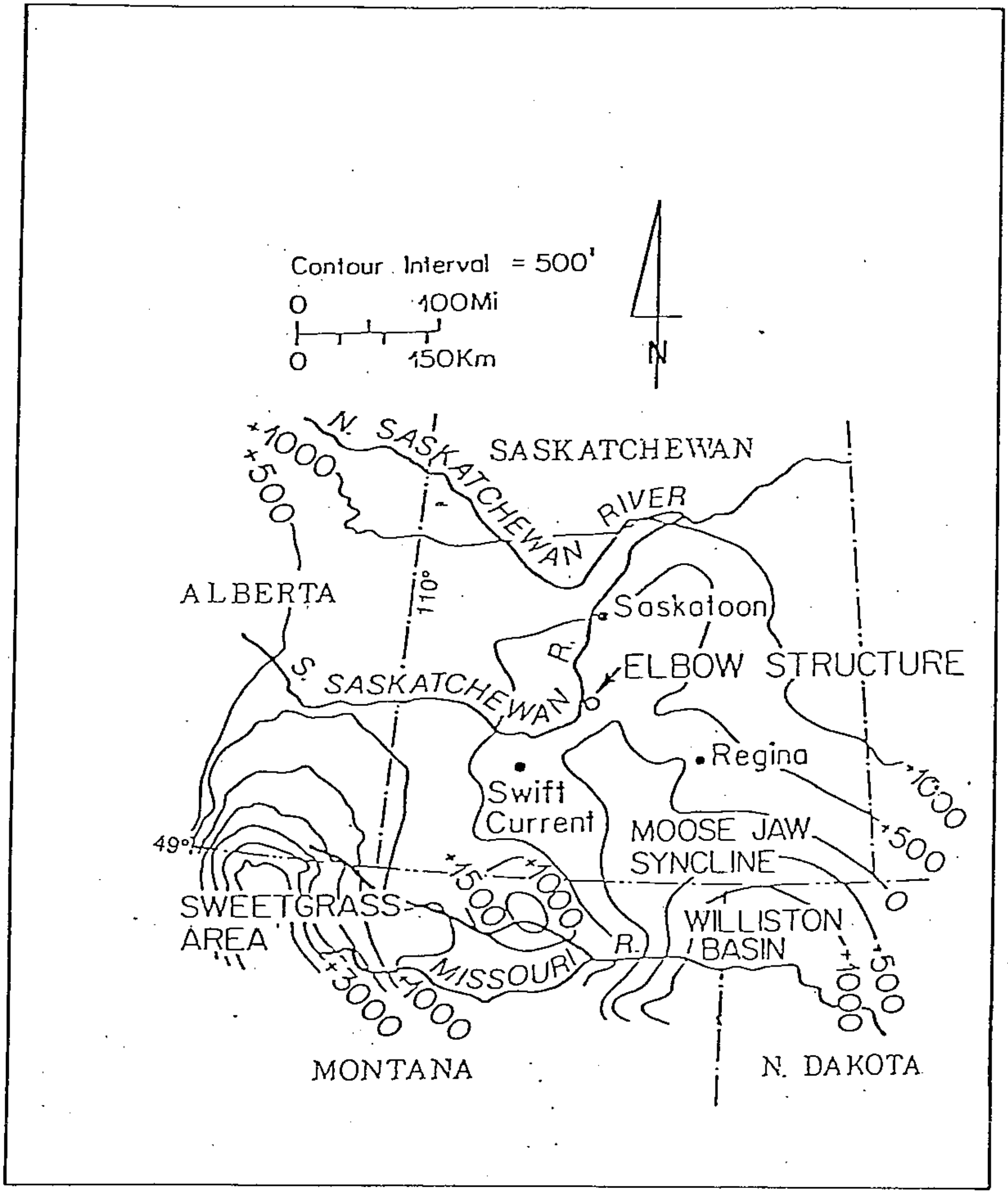

Fig. 4. Geographical location map, Elbow Structure.
Contours are depths in feet from surface to top of Colorado Group of Jurassic[145 m.y.]Sandstones.

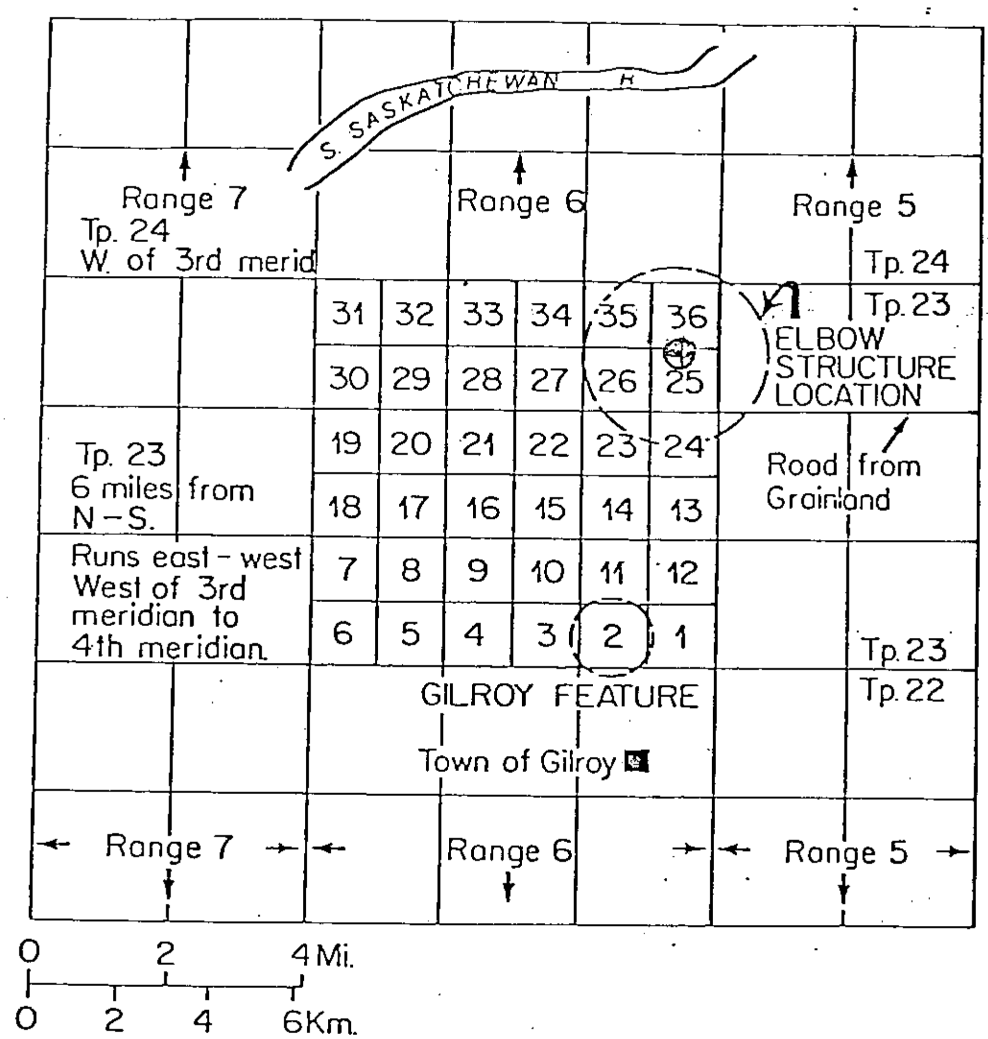

Fig. 5 Detailed location of Elbow Structure; squares are land sections, Dominion Land survey system. Centre is in Section 25, Range 6, Tp. 23, W. of 3rd Meridian.

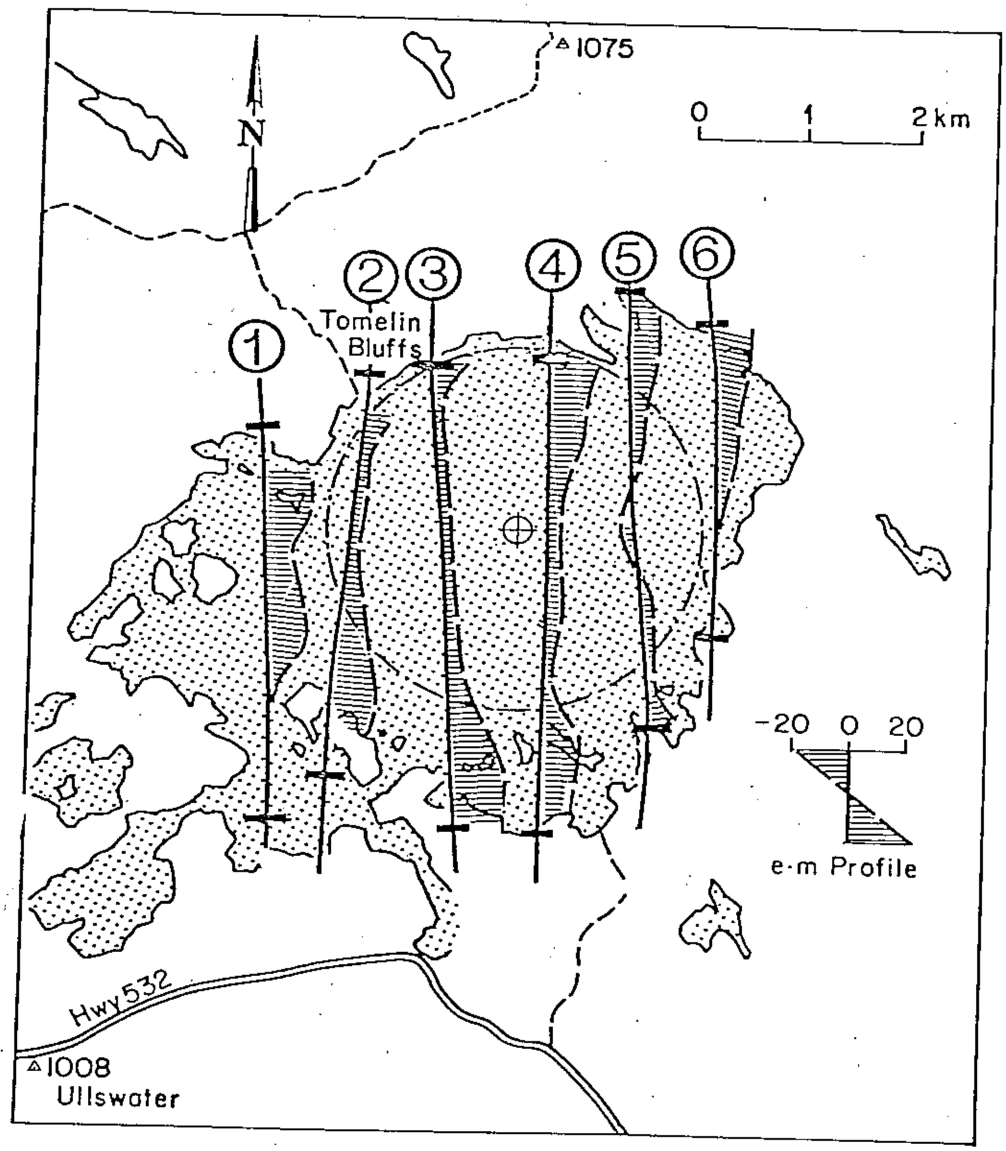

Fig. 6 Position of tracks of flight lines and surface surveys at Skeleton Lake; circle is hypothetical rim of crater; e.m. profiles plotted with tracks as baselines. Bars on tracks show length of profiles plotted in Figs. 11-16. The elevation for Ullswater is shewn in feet above mean sea level datum. Skeleton Lake is 920 feet [282m] aboves m.s.l.,North America Datum,1927.

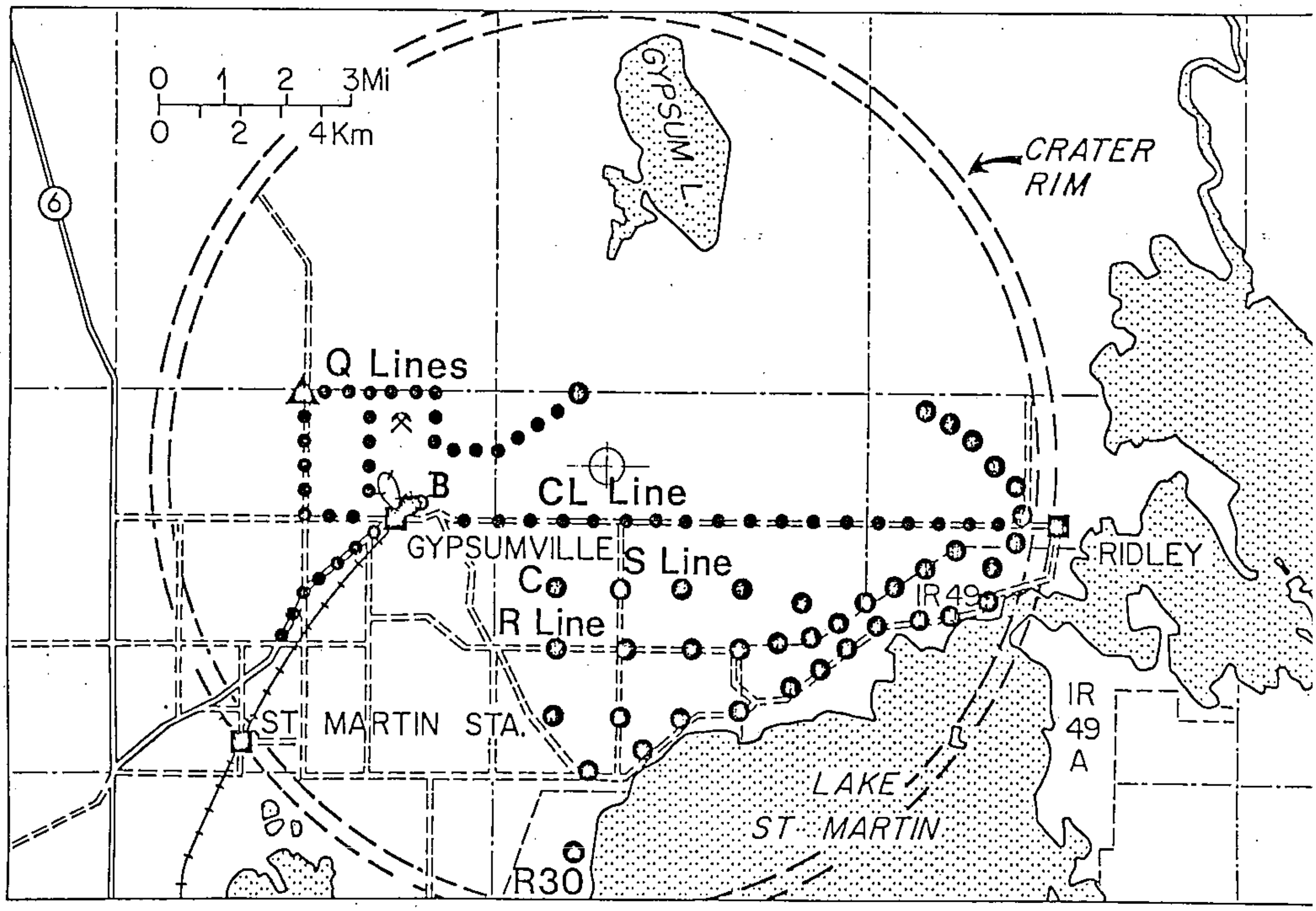

Fig. 7 Lake St. Martin, location of survey lines and main stations, total magnetic intensity. Small dots represent one station, large dots two stations. Squares are towns.

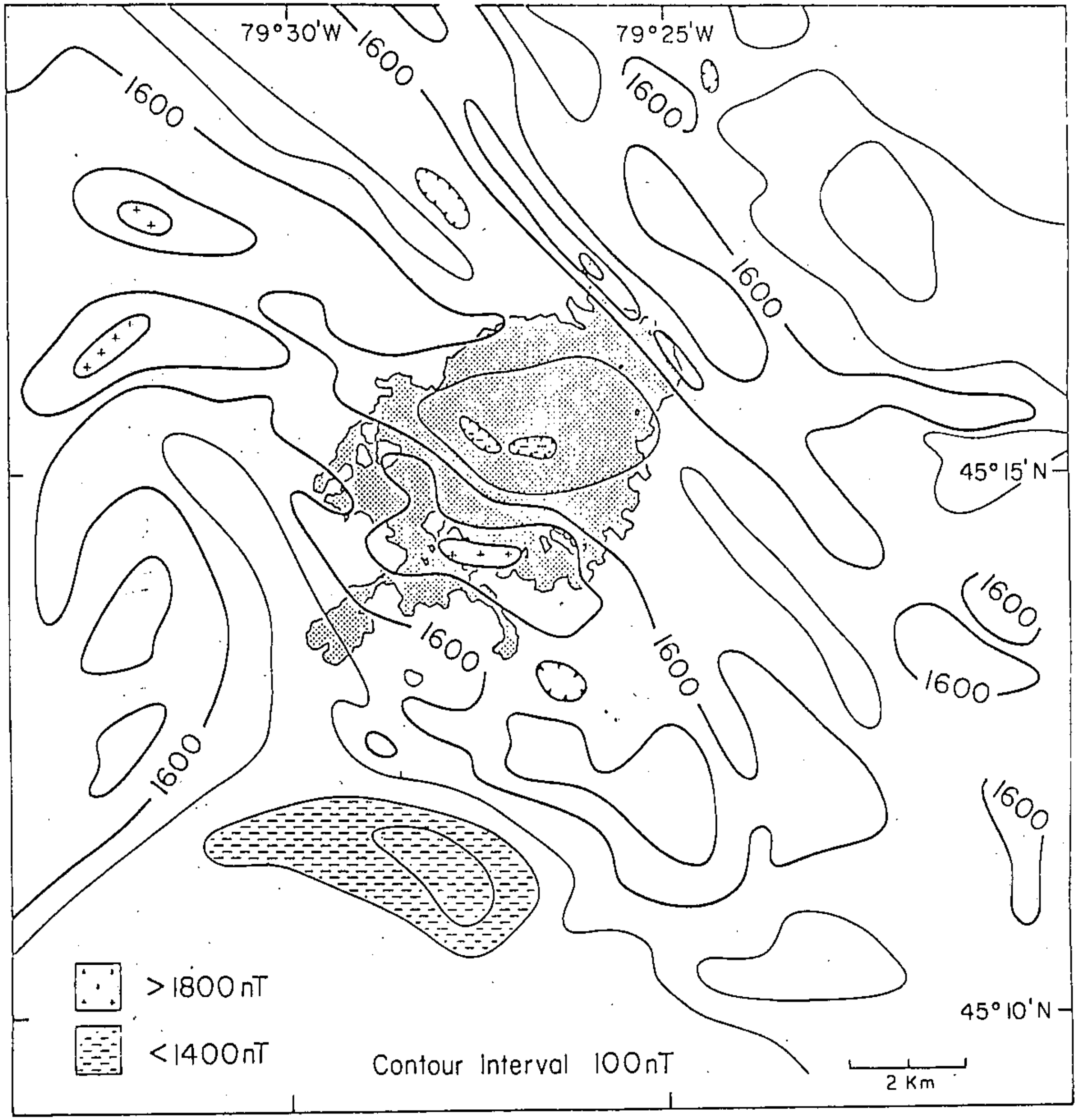

Fig.8 Aeromagnetic field over Skeleton Lake and environs derived from maps published by the Geological Survey ofCanada.

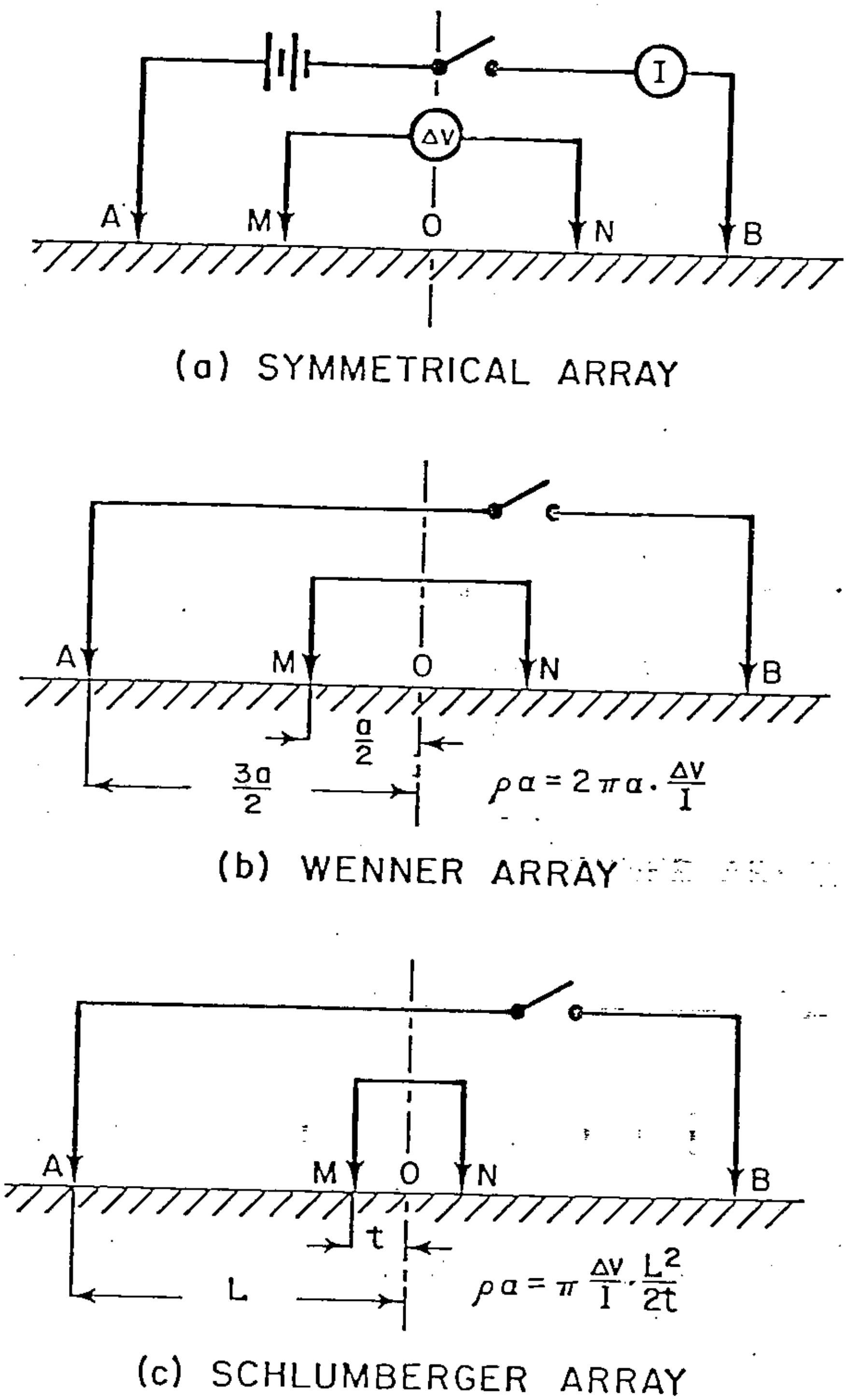

Fig.9 Electrical resistivity arrays. A,B denote current electrodes, M,N potential electrodes. O is centre of array. Current(I), Voltage(V) and power source symbols on (a) are assumed on (b), (c).

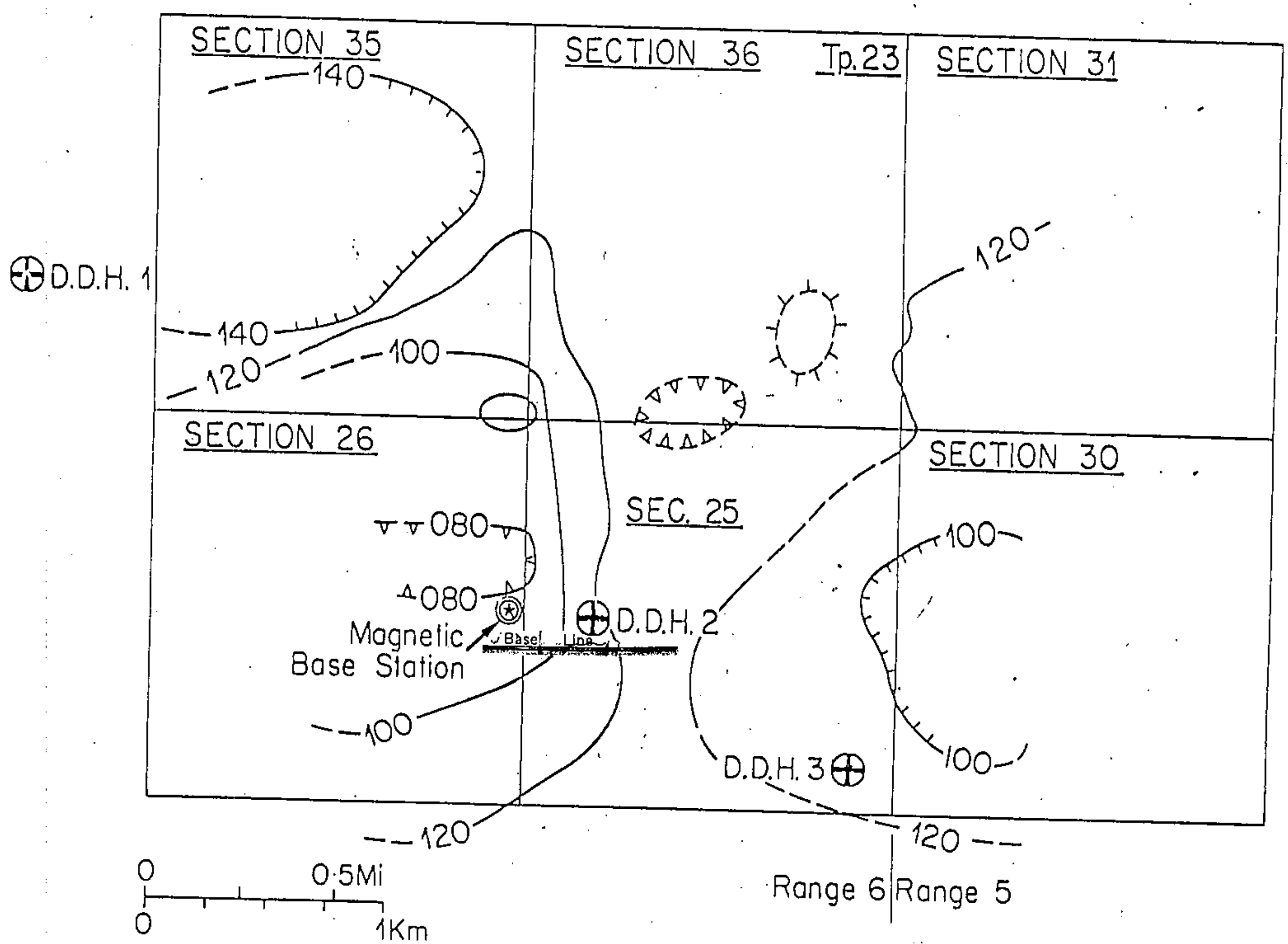

Fig. 10 Surface magnetic survey (F) contours, Elbow structure, Base station datum = 60,000 nT, contour interval 20 nT. Resistivity traverse is from base station to Diamond-drill hole 2. (D.D.H 2)

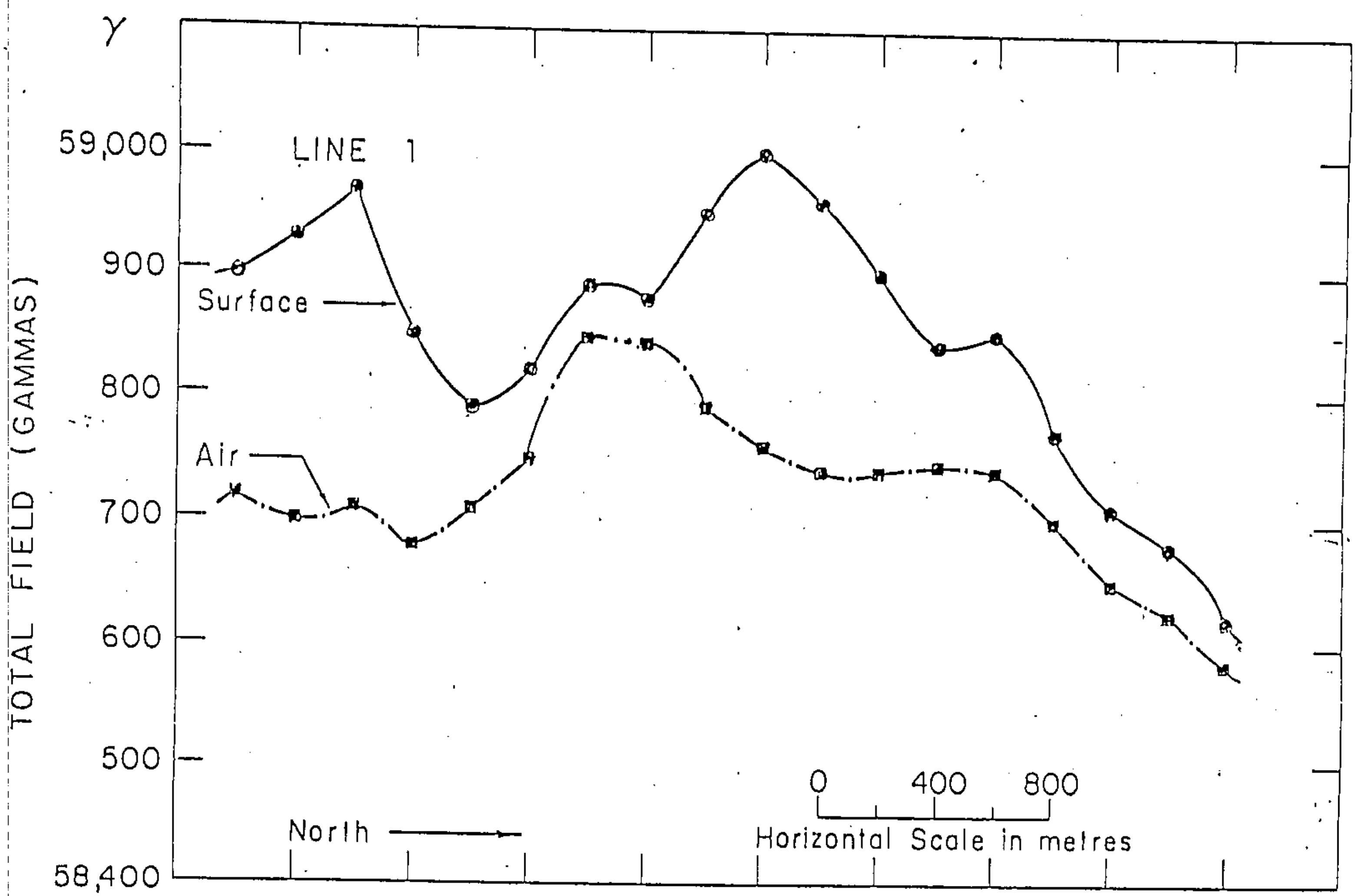

Fig. 11 Aeromagnetic and surface profiles of F along track 1, fig. 6.

Figures 11-16, corresponding to profiles on lines 1-6 incl. Profiles of F from aeromagnetic and surface data along same tracks, updated to epoch 1970.0. Aircraft elevation ~ 300 m above terrain.

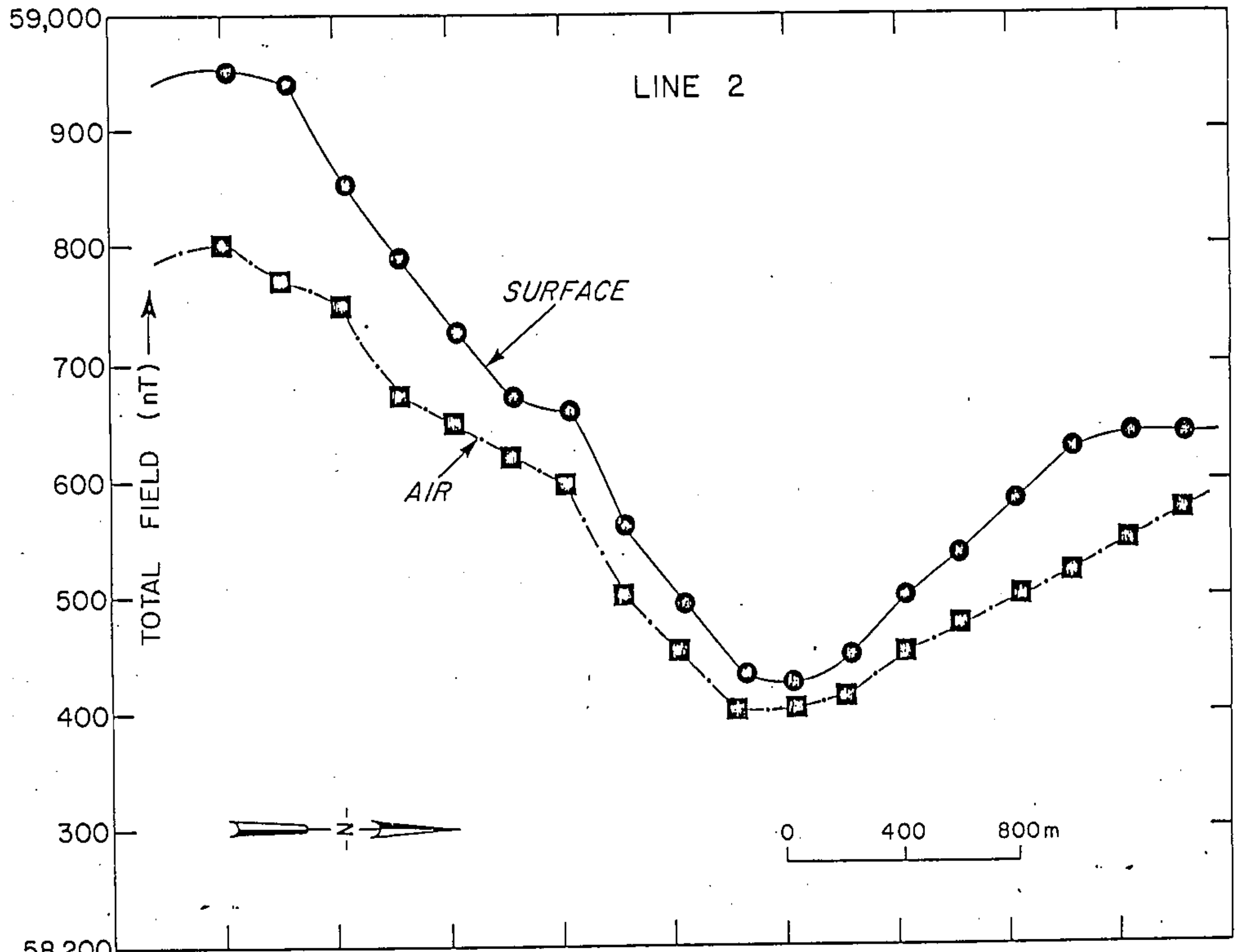

Fig. 12 Aeromagnetic and surface profiles of F, track 2 fig. 6.

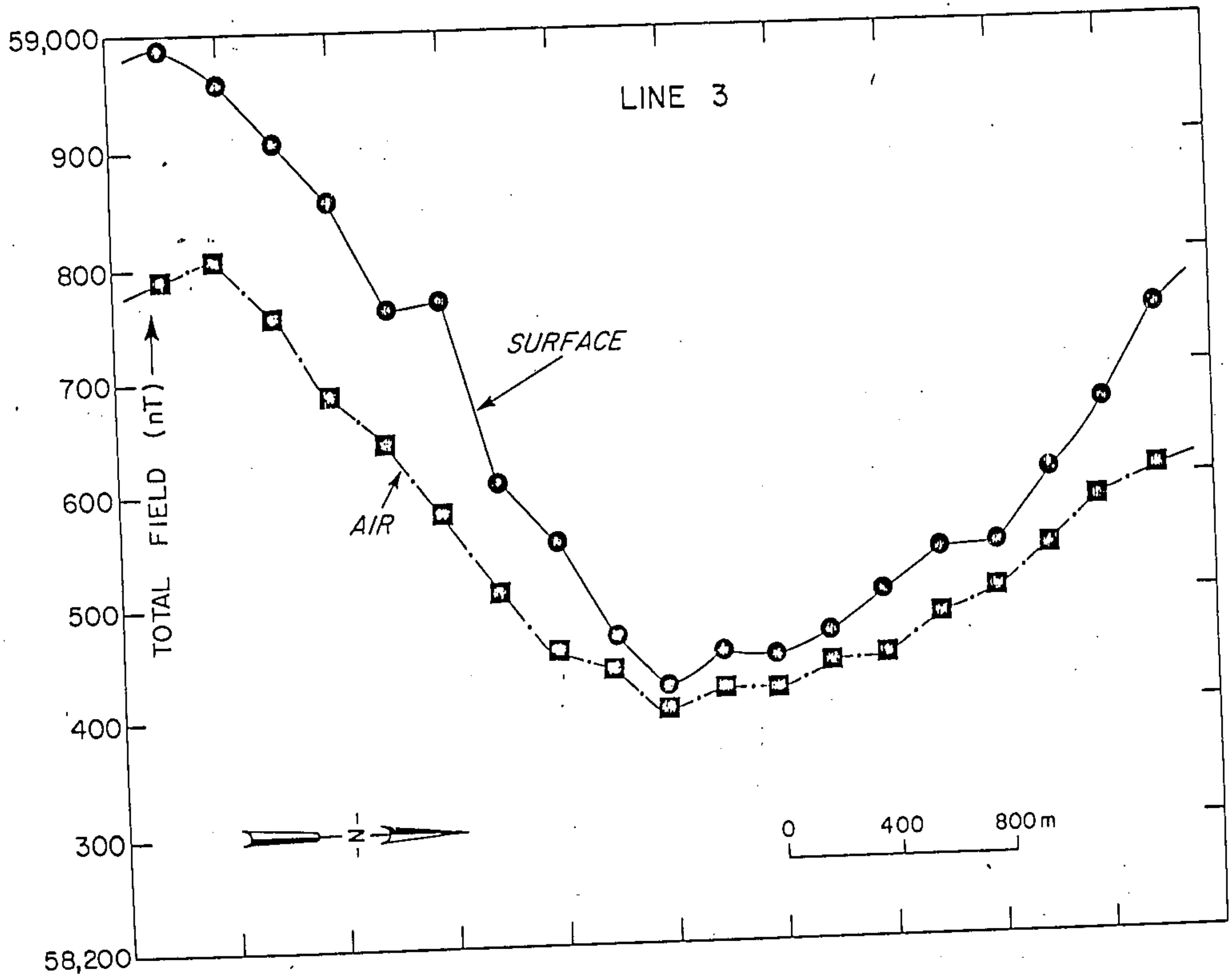

Fig. 13 Aeromagnetic and surface profiles of F, track 3.

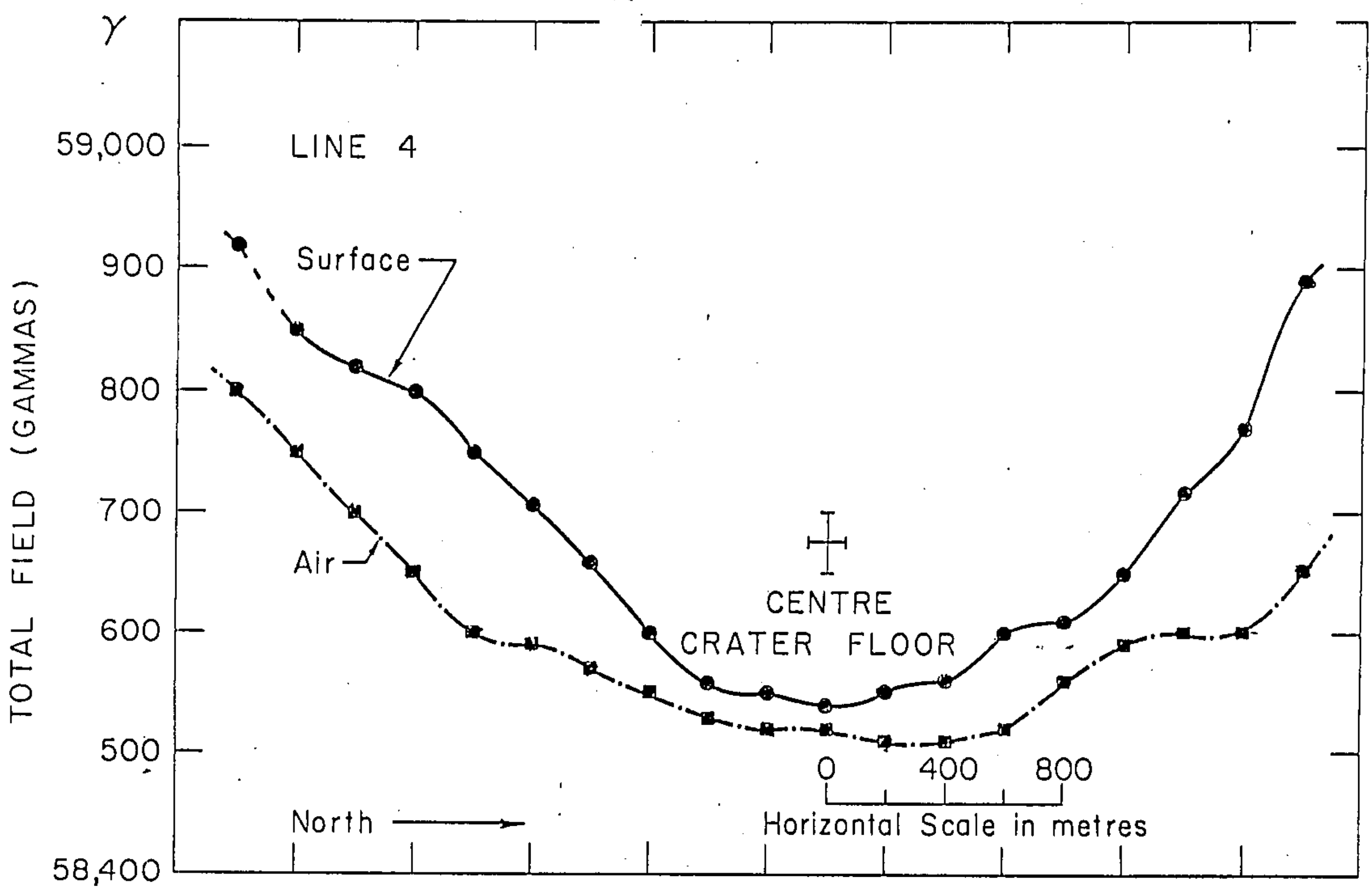

Fig. 14 Aeromagnetic and surface profiles of F, track 4, for gammas read nT.

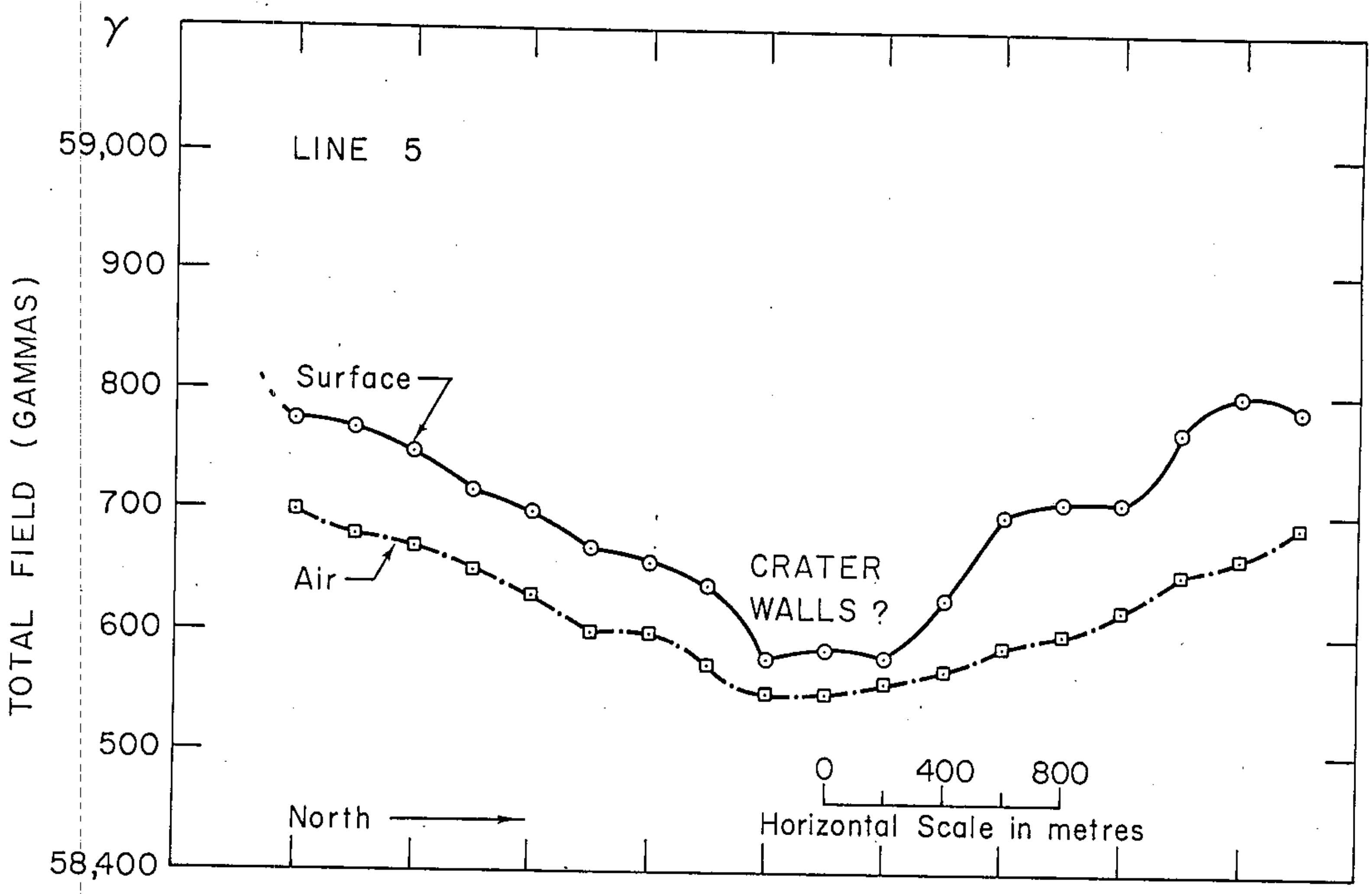

Fig. 15 Aeromagnetic and surface profiles of F, track 5.

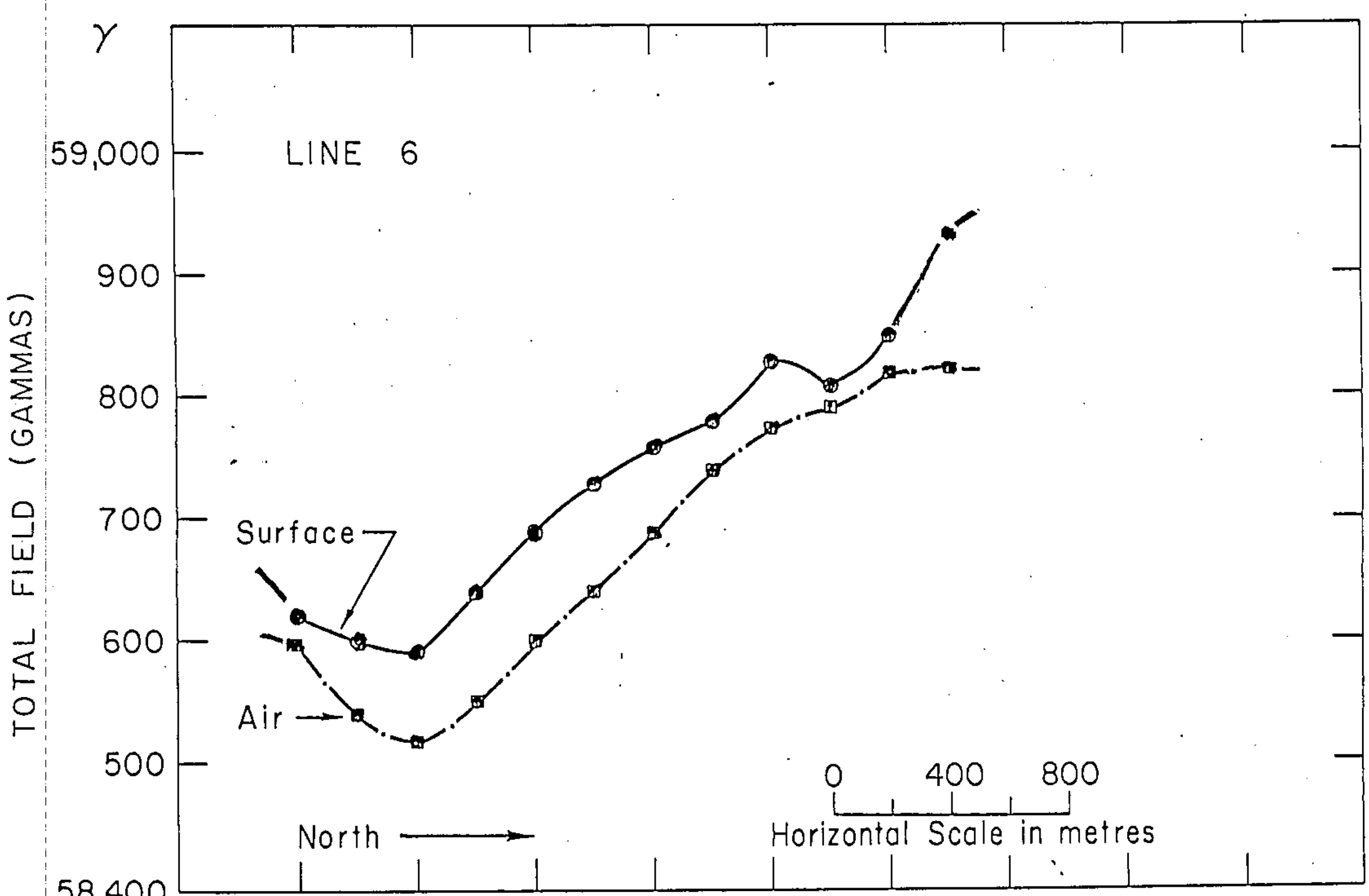

Fig. 16 Aeromagnetic and surface profiles of F, track 6.

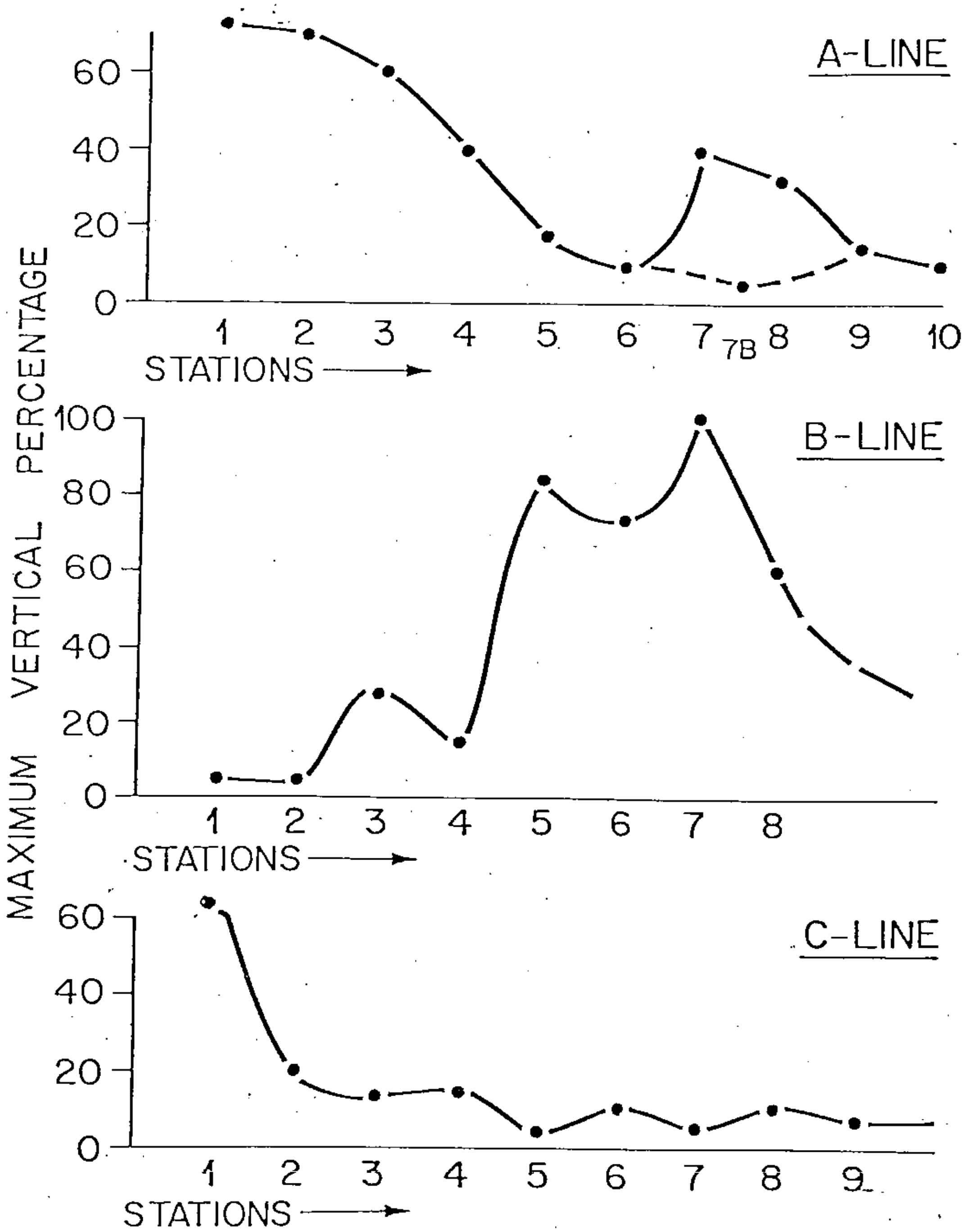

Fig. 17. Lake Wanapitei e.m. readings;profiles of intensity of vertical phase.Low vector ordinals imply high electrical conductivity values.Station 7-B[plotted on A-line to extend it] is located 2 km south of station A-9.

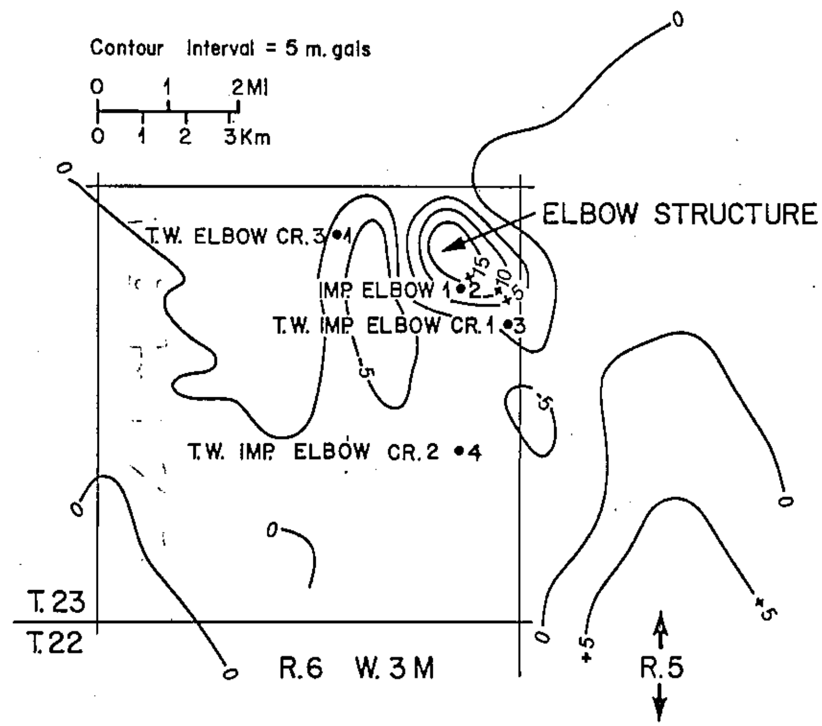

Fig. 18 Gravity anomaly contour map, Elbow Structure.

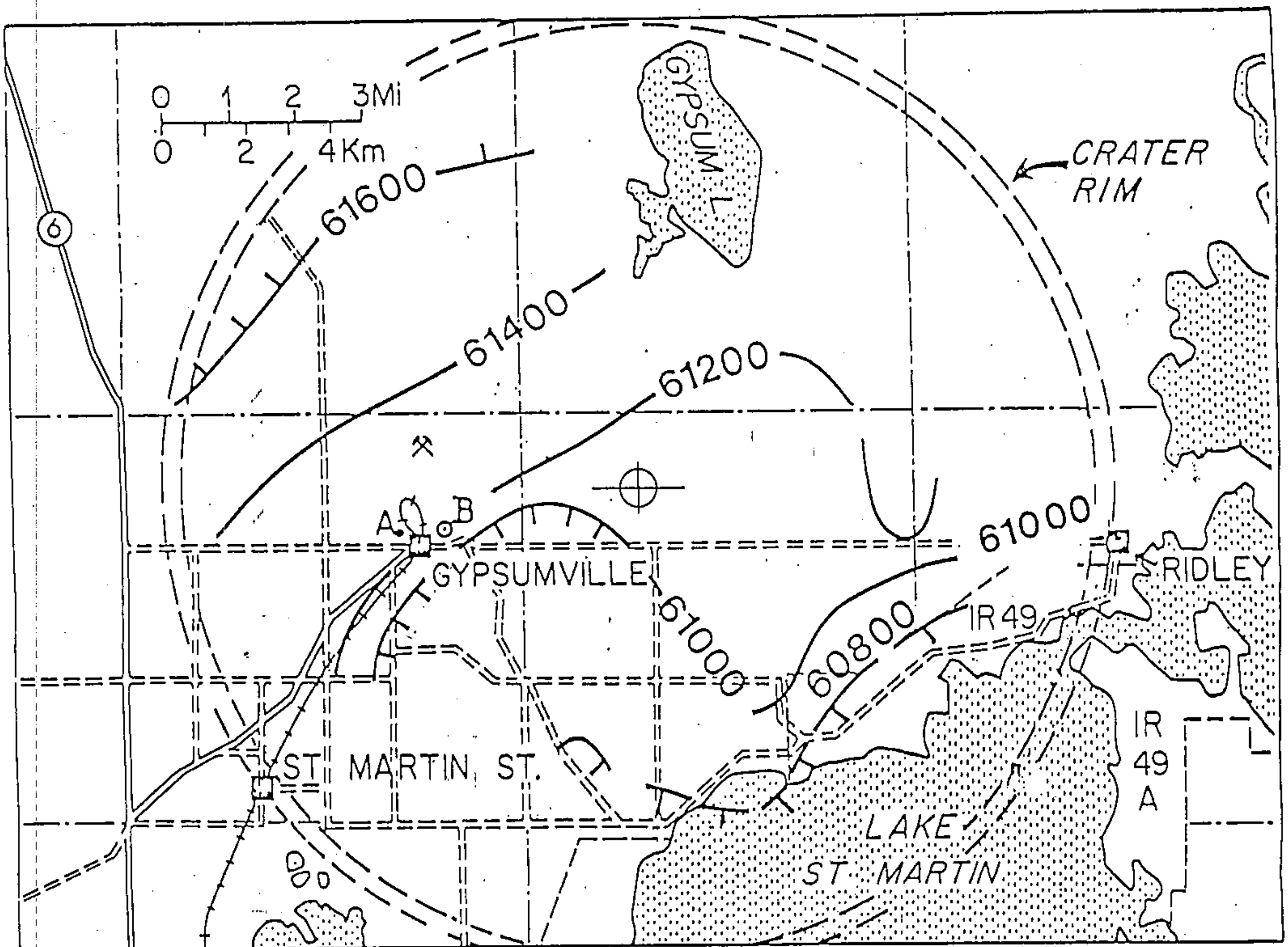

Fig. 19. L.St.Martin surface magnetic survey, total intensity F.
Contour interval is 200 nT, epoch 1970.5.

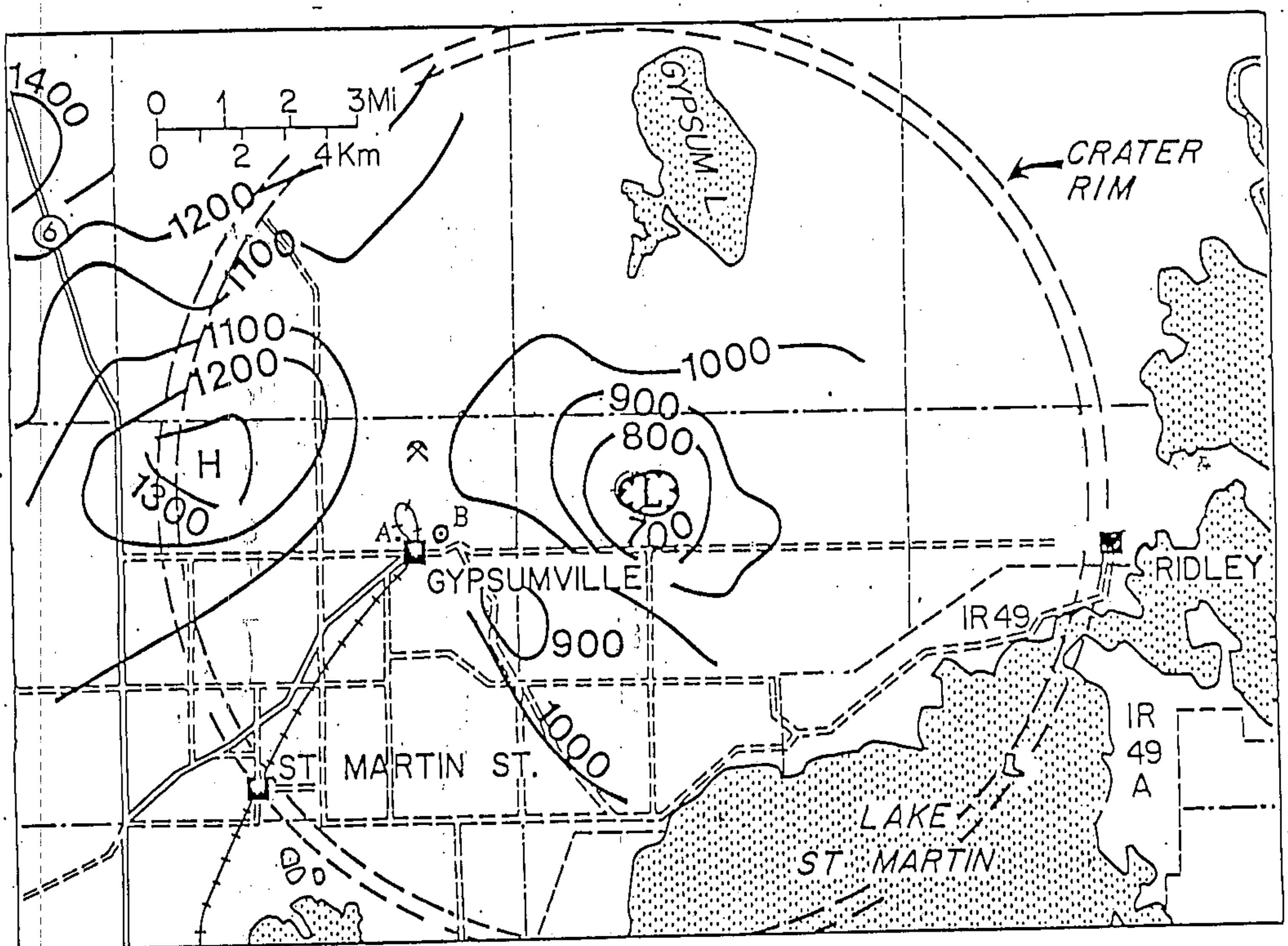

Fig.20 L.St.Martin aeromagnetic field map, contour interval 100 nT. Updated to epoch 1970.5 and adjusted for regional trend.

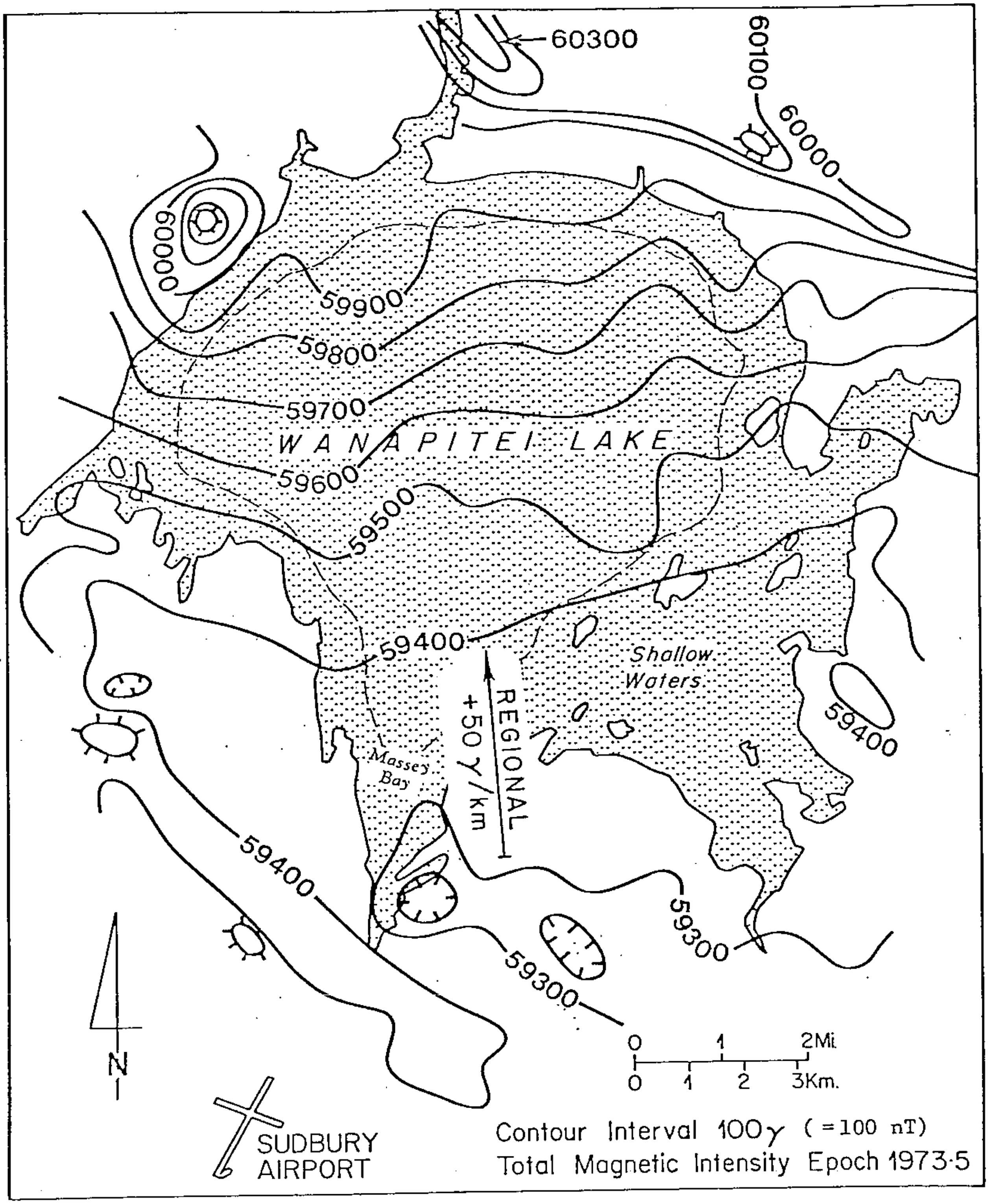

Fig. 21 Aeromagnetic survey L. Wanapitei, total force in absolute units (nT) from maps published by the Geological Survey of Canada.

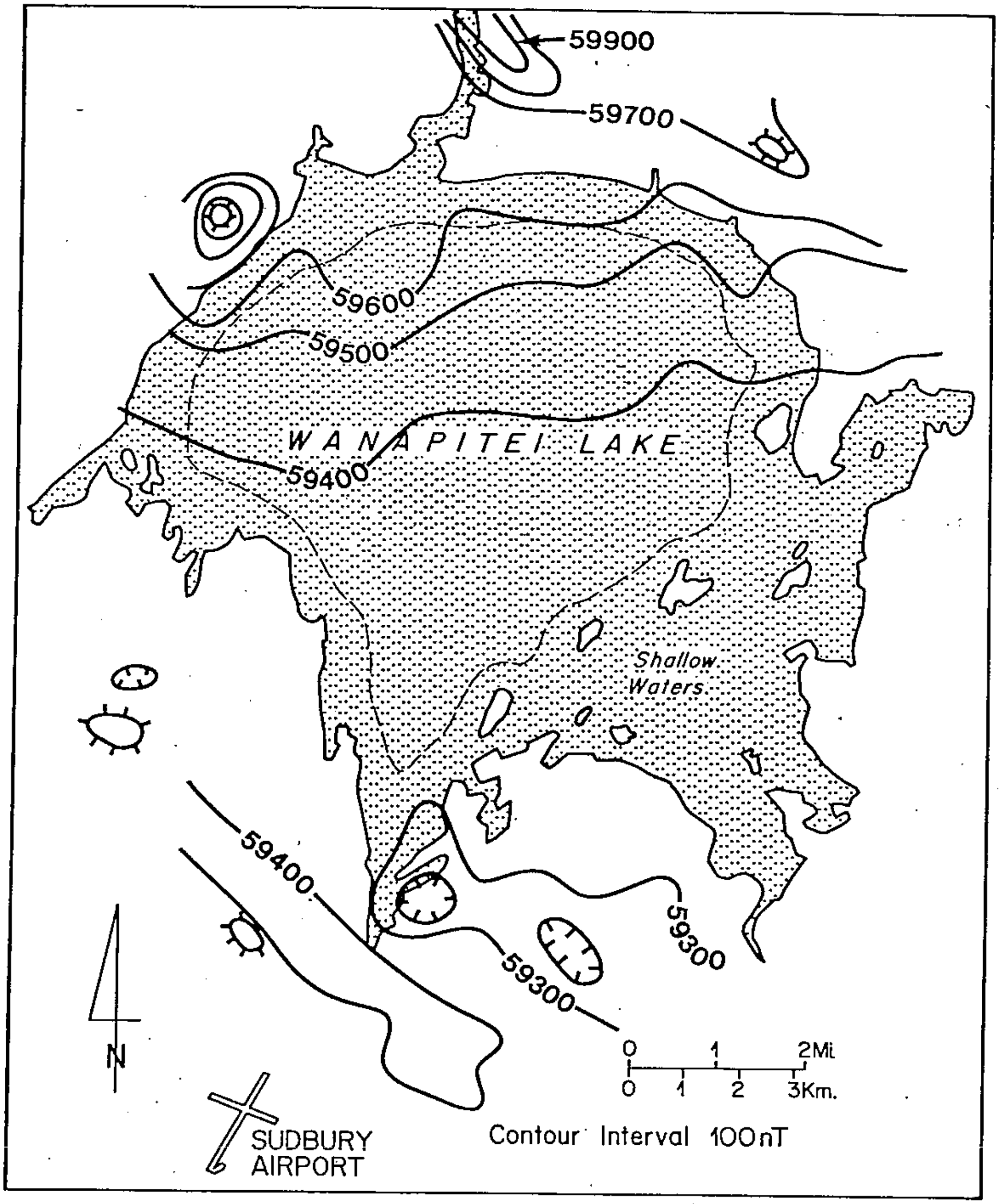

Fig. 22 Magnetic Residuals map of Lake Wanipitei, showing low gradients of total magnetic field over centre.