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GEOMAGNETIC SURVEYS AT WEST HAWK LAKE, MANITOBA, CANADA

J. F. Clark

Geomagnetic Series
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Ottawa, Canada 1980

Série géomagnétique
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Earth Physics Branch,
Energy, Mines and Resources Canada,
1 Observatory Crescent,
Ottawa, Canada K1A 0Y3

Catalogue No. M74-32/20E
ISBN 0-660-10690-6
ISSN 0704-3015

Canada: $1.00
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ABSTRACT

West Hawk Lake - Lat. 49.7°N, Long. 95.2°W - is a near-circular structure of impact origin. A contour map of magnetic total intensity (F) has been compiled from observations at 225 stations on the land surrounding the lake and about 300 stations over the lake in summer and winter. The contours have a circular form centered on the lake with a main low in F over the southern part of the lake and a secondary low over a northern sector. A comparison of F values obtained from an aeromagnetic survey of the area and the surface data indicates contour patterns and gradients consistent with an asymmetrical meteoritic crater whose diameter is 2.5 $\pm$ 0.2 km. Values of near-surface apparent resistivity measured close to the rim and shoreline are low ($\sim$ 100 ohm-m) but increase rapidly to about 8,500 ohm-m a few km outside the rim.

RÉSUMÉ

Le lac West Hawk - lat. 49.7°Nord, long. 95.2°Ouest - est une structure presque circulaire d'origine d'impacte. Le profil de l'intensité totale du champ magnétique a été tracé suivant des observations effectuées à 225 postes terrestres autour du lac, et d'environ 300 observations sur le lac en été et en hiver. La forme circulaire du profile est axée sur le lac; cependant, deux minima inégals d'intensité peuvent être observé, le principal se situant dans la partie sud du lac et le plus petit dans la partie nord. D'une comparaison des observations terrestres et des valeurs residuelles provenant d'un relevé aeromagnétique découle un modèle compatible avec un cratère météorique asymétrique dont le diamètre moyen serait de 2.5 $\pm$ 0.2 km. Les valeurs de résistivité apparent à la proche-surface près du bord et du littoral sont basses ($\sim$100 ohm-m) mais augmentent rapidement à environ 8,500 ohm-m à quelques km du bord.

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GEOMAGNETIC SURVEYS AT WEST HAWK LAKE, MANITOBA, CANADA

J. F. Clark

INTRODUCTION

Evidence has been presented by Halliday and Griffin (1963) in favour of a meteoritic origin for West Hawk Lake, Manitoba, Lat. 49° 46'N; Long. 95° 11'W. The lake is roughly circular, has a mean diameter of 3657 m and is remarkably deep for its diameter, as shown by a bathymetric survey, see map references. There are water depths of over 107 m for much of its area, with nearly concentric contour patterns; lakes of similar size in the Canadian Shield are normally less than 35 m deep. The shoreline is surrounded by exposed Precambrian rocks, is at an altitude of 332 m above m.s.l. and the surrounding wooded hills rise about 100 m above lake level. There are a number of islands in the lake, all situated outside of a central area of about 3 km diameter.

Shock metamorphosed rock samples are considered acceptable proof of the meteoritic impact formation of a structure, and for this crater such proof is given by Short (1970). His petrographic studies of diamond-drill cores have revealed numerous shock features, planar features in quartz, abundant glossy fragments and matrix-binding "melt", thus establishing beyond doubt that this is a meteoritic crater.

The diamond drilling operations which provided these data were carried out under the supervision of Halliday and Griffin (1967) and in their summary of results they indicate a nearly circular crater filled by consolidated sediments of depth 100 m underlain by breccia lenses. The greatest thickness of breccia is 300 m which in turn is underlain by 200 m of fractured bedrock in the centre. Several metres of soft mud and loose glacial debris cover the lake bottom. Since this is a sediment-filled crater with a great volume of the original country rock excavated away, one would expect to find rather low gradients in the magnetic field intensity across the central basin, probably as far out as the vestigial rim. At the rim location and beyond, where one encounters undisturbed country rocks of high magnetic susceptibility, one would expect steeper gradients of magnetic intensity and irregular isodynes. If the surveys indeed show that this occurs, they will have provided supporting evidence for the impact mode of origin of the feature.

GEOLOGY

The area is underlain by rocks of Precambrian age and is about 16 km east of the contact between the Precambrian Shield and Paleozoic sediments of the prairies. The geology as shown in Figure 1 has been mapped by Davies (1954) and further discussed by Davies and Mills (1962). The southern boundary of West Hawk Lake is underlain chiefly by dense volcanic greenstones of Archaean age including basic and ultrabasic types. The exposed rocks are chiefly andesite and basaltic lava flows (Springer 1952). The band extending around the northern edge of the lake consists primarily of clastic sedimentary types of Keewatin age, underlain by granites and gneisses which outcrop to the north at a Precambrian contact. Near the middle of West Hawk Lake basalts and slates are folded in an easterly trending anticline, the apex of which is situated between West Hawk Lake and Falcon Lake, where the folds plunge 35°

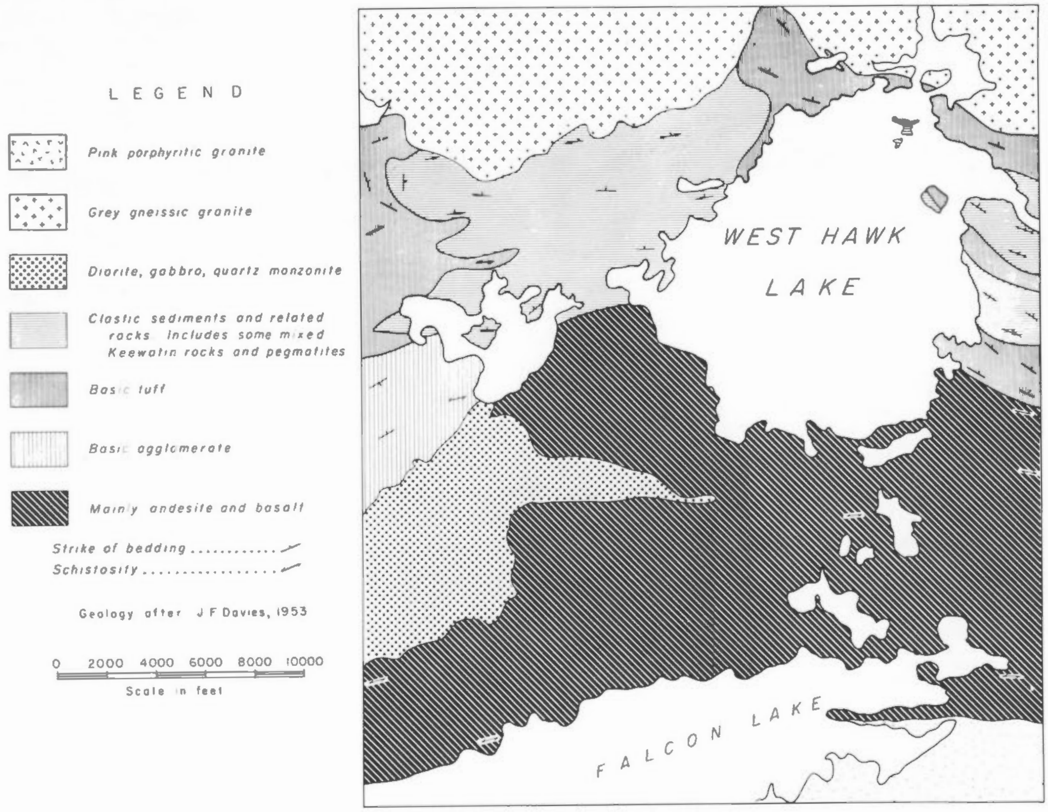

Figure 1. Geological map, West Hawk Lake area, after Davies (1954).

to the northeast. There are some sheared and mineralized zones on the northwest quadrant surrounding West Hawk Lake, dipping north 70°-80°. Glacial Lake Agassiz covered the site for a considerable time; there has been intense erosion since then, caused by the Wisconsin ice sheet moving south.

SURVEY OBSERVATIONS

Total force observations were taken around the perimeter at 225 points and over the surface of the lake during the 1967 season at 100 positions. These readings were made with a Barringer proton precession magnetometer with a resolution of 10 nT. On land the readings were made along roads or lines through the bush with positioning obtained from topographical maps. On the lake the instrument was carried in a non-magnetic boat travelling in straight traverse lines in both north-south and east-west directions. Locations of stations are plotted from dead reckoning and map inspection using known topographical features, islands, promontories or other reference objects on shore. Each measurement comprised 5 readings over a time frame of 30 seconds, stations being about 100 m apart. In February 1968, 200 more F observations were made on lake ice which was about 2 m thick - a motorized toboggan provided transportation. Distribution of observations is shown in Figure 2.

An apparent resistivity survey was carried out around the lake using the standard Wenner-Lee array with a Sharpe SP-5-R unit. Wyder (1967) has described the survey method used here. About 60 measurements in all were made around the western perimeter and near the base station, using this equipment and method with electrode spacings from 10 to 80 metres. The data for 80 m spacings are summarized in the interpretation section. The longest traverse line was in the Moonlight Bay region, see Figure 4.

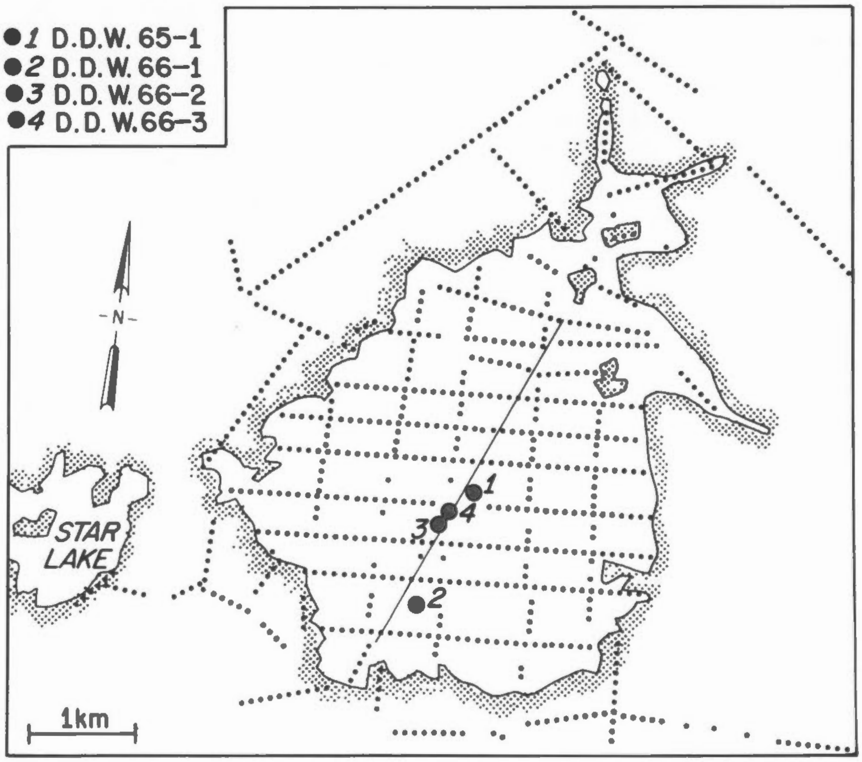

Figure 2. Distribution of total force observations and location of diamond-drill holes, West Hawk Lake area. N-S line is track of control traverse. D.D.W. 65-1 is 1965 drill hole, others are in 1966.

REDUCTION OF DATA

Total magnetic intensity measurements made with the Barringer model 100A unit have a resolution of 10 nt for an individual reading. By taking 5 observations at fixed tripod stations on land the probable error of the mean value at each station was normally $\pm$ 5 nT.

Observations offshore in a boat have a greater scatter as computed from a series of looping experiments. Proceeding from a shore station to the bow of the boat, taking readings and returning to the shore station as quickly as possible gave a probable error estimate of $\pm$ 20 nT for lake measurements.

Distance errors in absolute positioning of stations over the water are in the order of $\pm$ 30 m, negligible within the graphical limitations of plotting results. Contours were drawn for 100 nT intervals with the various observations (from the several surveys) reduced to a common epoch of 1967.5, using appropriate corrections from known annual change data. Observations were reduced for diurnal variation but not for disturbance. The corrections were found to be in the order of 10 nT or less. Comparisons of readings made on land, e.g. on islands, or on a beach close to the boat with those made in the boat, indicate an average difference of $\pm$ 20 nT in individual readings made with the instrument mounted forward in the boat, as compared to the probable error of $\pm$ 5 nT for readings on land, as described above.

Examination of K indices from magnetograms at Meanook, see Cook and Sprysak (1967), reveal low magnetic activity (K index = 2.1) on the days of observation.

The regional trend is an increase in total magnetic intensity of approximately 2 nT per km to the north; the westerly gradient is virtually zero, (E. Dawson, Personal Communication). The necessary corrections were applied to observations made on the north-south tracks and to the other observations according to their location. Geographically the relative positions of the contour lines are accurate within the limits of drafting at the large scale in use. Although no continuously-recording magnetometers were available, a permanently marked base magnetic station was established near the southwest shore of West Hawk Lake in 1963 and reoccupied as a 'repeat' station. Observations of declination and inclination with a fluxgate magnetometer, and of total intensity with a proton precession magnetometer, supplied diurnal variation and annual change data and served as a base datum for control of the local anomaly surveys by a base-looping method.

The values of the magnetic elements at the base station for epoch 1967.5 are shown in Table 1, Appendix, and the diurnal F curve is available. The magnetic results at the base station indicate that the terrestrial magnetic field is of normal strength as compared with values shown on maps and chart publications for the area. The low-level (300 m) GSC aeromagnetic maps (Total Force) cover the whole region in fine detail.

INTERPRETATION

The absolute values of F on the GSC charts have been compared with the surface measurements across the feature, see Figures 3 and 4. After allowance for different elevation and times of observation the agreement is generally quite good, especially over the central crater area. There is normal attenuation, or smoothing, of the magnetic field which occurs when observing from an aircraft. Beyond the immediate crater area the gradients and pattern of surface vs. airborne are considerably different, but the magnetic relief of about 100 nT across the crater is visible on both contour maps.

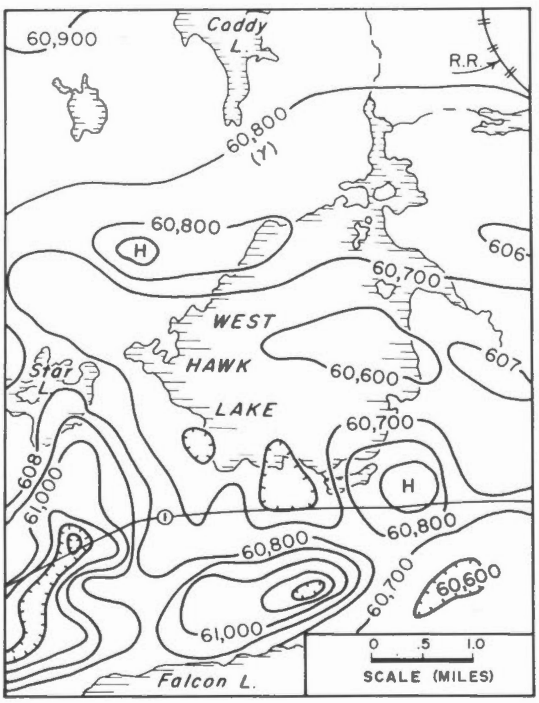

Figure 3. Contour map of total magnetic intensity, epoch 1962.5, West Hawk Lake. GSC aeromagnetic map low level (300 m); contour interval selected is 100 nT. An absolute value of F is derived relative to a base datum.

Zietz and Henderson (1948) Sander et al. (1964) and Godby et al. (1966) have discussed methods of interpretation of magnetic surveys to enable an estimate of depth of sources of magnetic anomalies to be made.

These methods which have been applied chiefly in geophysical exploration of ore bodies are based on the principle that where the lateral gradients of change of magnetic intensity are steep, the source of magnetic variation is close to the surface, whereas when the lateral gradients are shallow the source of variation is at greater depth. Sander has used the half-slope method in a study of the Deep Bay meteorite crater in 1964 and his procedure has been followed here. One assumes that the boundary between the strongly and weakly magnetized rocks is fairly sharp. Then, since it is known that the great majority of magnetic anomalies originate from the top surface of basement rocks, one is able to estimate depth to crystalline basement rock from the shape and magnitude of magnetic anomalies observed on the surface. Computations have shown that the vertical depth to source of anomaly is one-half the horizontal distance across the main anomaly as plotted graphically at the surface. Over the West Hawk Lake crater the negative anomaly is 249 nT. Measuring radial distances from the centre across contours corresponding to this change in F one obtains a mean distance close to 1500 m. Therefore, the estimate of depth to undisturbed bedrock at the centre of the crater is 750 m. One would expect this to decrease gradually as one proceeds outwards to the rim, becoming nearly zero at the rim. This estimate is in close agreement with the drill-hole depth to bottom of breccia at 727 m.

The central negative anomaly or 'contrast' is 249 nT, as mentioned above. This has been determined by a comparison between the mean F over the crater area and the mean F in an annulus 1 km wide outside the crater rim (shown on Figure 4). Although this is not a really large anomaly it is significant, and is compatible with formation of the central depression by meteorite impact. The removal of ferromagnetic rock and subsequent replacement by sediments has been sufficient to result in this anomaly. Halliday and Griffin (1966) have estimated the deficiency of the original country rock over an area of 6 km^2.

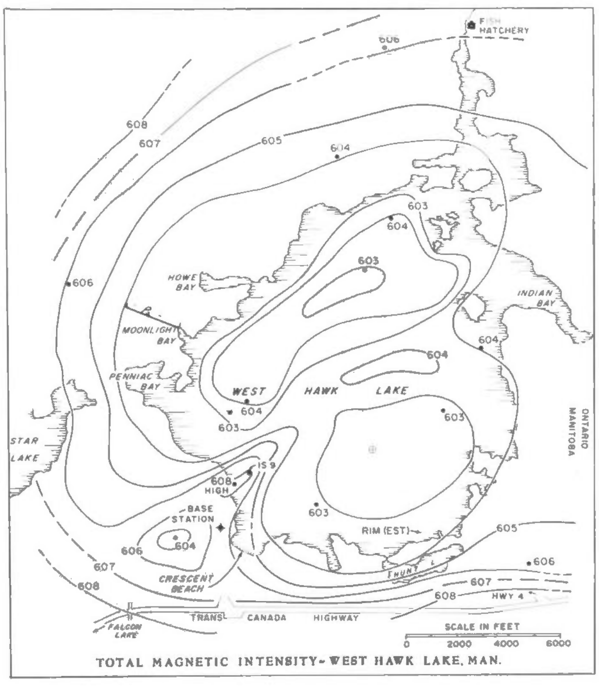

Figure 4. Surface magnetic surveys, epoch 1967.5 - contour interval 100 nT. Dots refer to points where more numerous observations were taken, i.e. at grid intersections.

Since the central negative anomaly is nearly circular one may assume a point pole source, in effect a reduction of magnetic pole strength over a hypothetical circle of diameter approximately 250 m at the surface. This may be modelled by a long narrow cylinder parallel to the earth's total magnetic field vector with the bottom of the cylinder sufficiently remote (theoretically at infinity) to render the effect of the lower poles negligible at the place of observation.

The minor low over the northern part of the lake is quasi-elliptical. One could postulate this is due to a number of simple dipoles curved in a gentle arc following the curve of the anomaly pattern. Another possibility is to assume there is a long thin magnetized dike, curved and dipping steeply. For the complete feature (crater plus area of the lake to the north of it) an asymmetrical, sediment filled basin would satisfy the various requirements, (Dence 1965).

Could an asymmetrical basin have been created by a meteorite striking the surface at a low vertical angle? Dence et al. (1968) conclude that the direction of approach and angle of fall make little, if any, difference to the symmetry of the hemispherical transient cavity. A low vertical angle of fall ($< 30°$) could result in some portion of the meteorite being imbedded in the rim. In the case of a 'stone' there would be no detectable magnetic effect; in the event the meteorite was an 'iron' there could be some magnetic expression. However, since the age of the crater from dating of drill cores is Mesozoic (100-150 m.y.), magnetized fragments probably have been disseminated and largely removed by erosion and glacial transport long ago. This process has been discussed in a text by Heide (1957).

Further interpretation was attempted based on a combination of gravity and magnetic data following the methods of Innes (1949, 1961) and Garland (1951).

A gravity map of the area by Halliday and Griffin (1963) reveals a negative gravity anomaly of 6 mgls centred over West Hawk Lake but distorted by a strong regional gravity field. The deep glacial gouge which breached the crater rim on the northwest edge has allowed water to flow in from this direction, with deposition of moraine debris of less density than the underlying basement, which may in part explain the gravity anomaly over the crater. The gravity 'low' shown by Halliday and Griffin agrees quite well with the magnetic low in the same area, probably due to a deficiency of material of high density and high susceptibility respectively.

In the southern half of the lake there is a magnetic pattern consistent with meteoritic impact, assuming about the same diameter crater as suggested by Halliday and Griffin of 2500 m rim to rim. The central region is relatively flat magnetically with the field depressed about 250 nT below the normal or background field as measured beyond the rim and lakeshore. By interpreting all the available data, one obtains a hypothetical model of the crater as shown in Figure 5. The rim is shown for a crater diameter of 2.5 km which is the magnetic method estimate, with a probable error of 10 per cent, i.e. 2.5 ± 0.25 km.

Consulting Figure 4 one notices an intense high magnetic anomaly localized around Island No. 9, a granitic islet of 50 m diameter located about 1 km northeast. of the base station and on the westerly rim, which is probably a remnant of a ring of islands on the original rim; presumably differential erosion has removed all previous islands or reefs which were composed of softer rock.

Another check on the schematic composite model, Figure 5, is to refer to the least squares regression lines plotted by Grieve and Robertson (1979) which define empirical depth-diameter relationships. The depths obtained by substituting a diameter of 2.5 km in their formulas agree very well with known data from drilling.

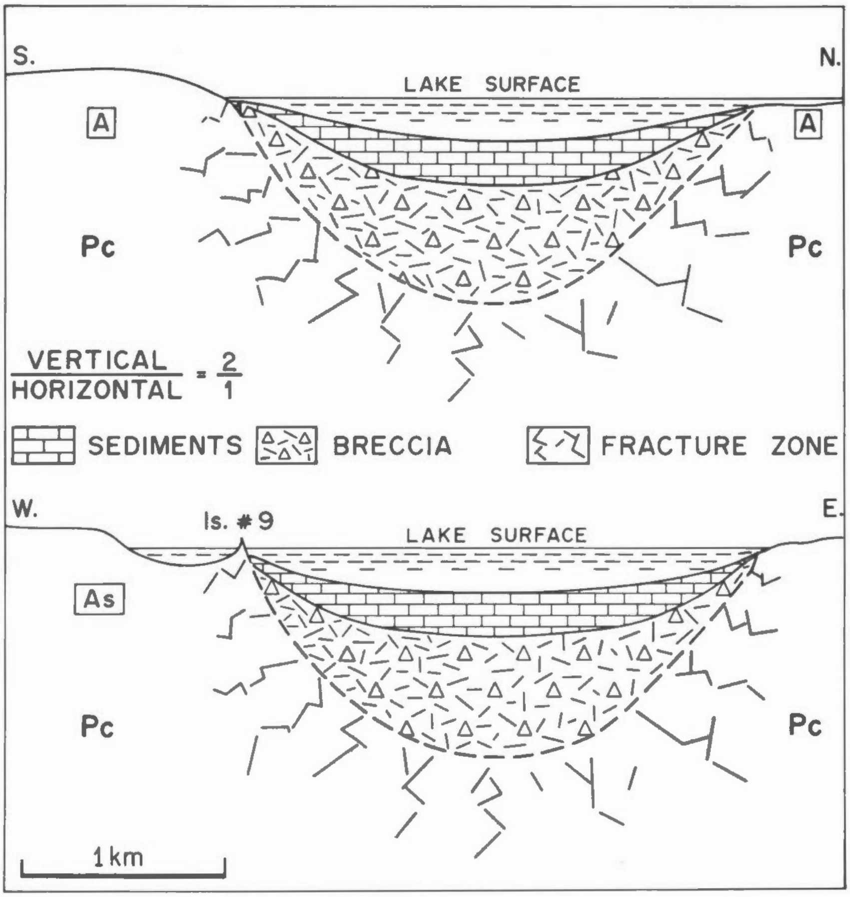

Figure 5. Model of West Hawk Lake crater. Top shows N-S section, bottom is E-W cross section. Island No. 9 is near west rim, marked IS* 9. Not all of lake is shown on north side.

The results from the resistivity survey have been examined to see if they confirm the location of the rim.

Twenty-four measurements of the apparent resistivity were obtained around the westerly and southerly perimeter of West Hawk Lake using a Wenner-Lee array and electrode separation of 80 metres. These data are plotted in Fig. 6 and represent near-surface values of apparent resistivity corresponding to the centre point of arrays from Moonlight Bay on the west side to the southeasterly shoreline. This method should help to verify the position of the crater rim as shown in Figure 5. Assuming there is fractured rock or broken melt-rock in the vicinity of the rim then one should be able to detect a considerable reduction in the values of apparent resistivity as one approaches the rim from the exterior. This effect is expected if larger pore spaces, cracks and fissures in this rim material are filled with conducting pore fluids, causing lower resistivity here than in the surrounding bed-rock. Such an effect does seem to occur (Figure 6) although there is considerable scatter due to overburden and inhomogeneous rock types. Values from 50 - 300 ohm-m are found closest to the rim and shoreline, rapidly increasing to a maximum of about 8420 ohm-m several km remote from the rim.

An airborne resistivity survey as described by Collett (1965) would be useful to confirm this trend over portions of the crater where surface measurements are not feasible.

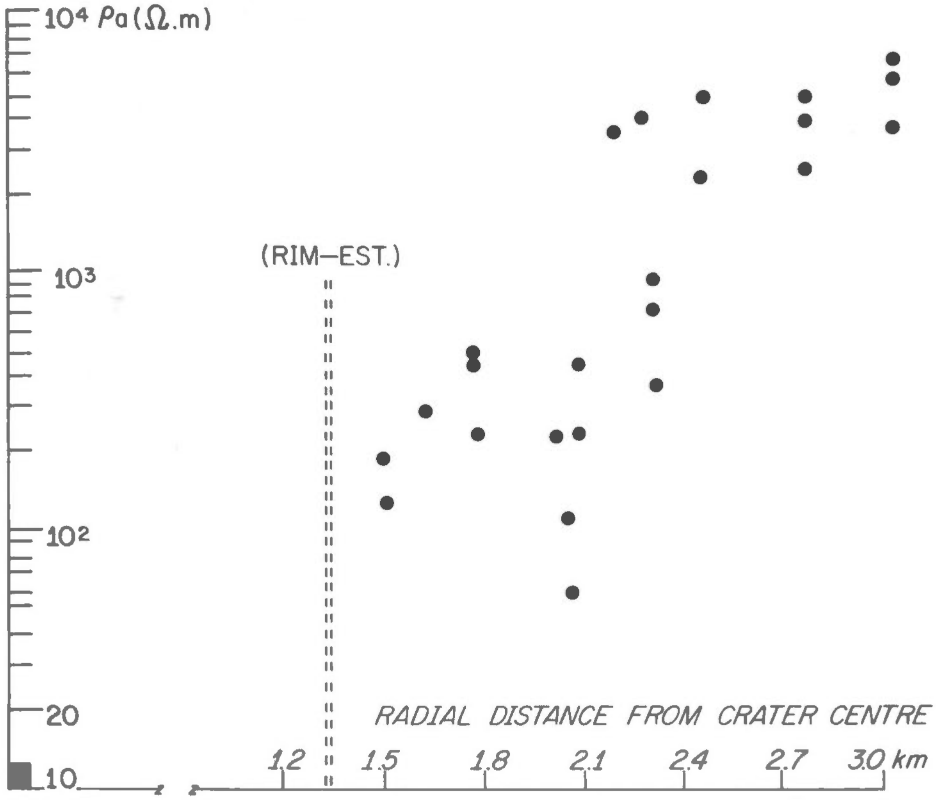

Figure 6. Plot of Apparent resistivity values at 24 points from Moonlight Bay around lake to SE quadrant. Wenner-Lee array, electrode separation 80 m.

COMMENTS

The New Quebec Crater has been described for the layman by Schrag (1958). It is nearly the same size (diameter 3.6 km) as West Hawk Lake and is believed to be of fairly recent origin - Pleistocene age. One would expect some similarities between the two features, and to verify a superficial comparison it would be useful to drill to basement at the theoretical centre of West Hawk Lake. This site is 200 m southerly from the 1966 d.d.h. No. 2. A greater depth of sediments should be found here than at d.d.h. No. 2 and if such is the case the true centre could be assigned with great accuracy along with the other parameters. Intercomparison of the two features might lead to verification of the models for simple craters of this size.

ACKNOWLEDGEMENTS

Dr. C.S. Beals of Manotick has kindly read the paper and offered helpful comments. Dr. P.H. Serson, Director of the Division of Geomagnetism, has reviewed the magnetic interpretation and E. Dawson and L.R. Newitt have assisted in organizing the material. Dr. E.R. Niblett has critically read and edited the Ms; D. Trigg and F.C. Plet assisted the author in the field. Thanks are extended to the operators of the WPU and to the Drafting office and Photo Unit of EPB.

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* Now Earth Physics Branch, Deparment of Energy, Mines and Resources, Ottawa, Canada.

APPENDIX

TABLE 1

West Hawk Lake: Lat. 49°45.9'N; Long. 95°12.3'W

Epoch 1967.5

Element	Base Station Mean
Magnetic Declination D	6°42.0' East
Magnetic Inclination I	76°49.0' North
Total magnetic intensity F	60,550 nT
Horizontal Intensity H*	13,810 nT
Vertical Intensity Z*	58,954 nT

* Computed from F and I.

To update the absolute quantities in Table 1, the following annual change increments may be applied to obtain values for epoch 1970.0.

D = 0.5' West
I = -2.5' North
F = -10 nT

Refer to Isogonic Charts (Canada 1970), Department of Energy, Mines and Resources.