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MAGNETIC SURVEY DATA AT METEORITIC IMPACT SITES IN NORTH AMERICA

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Dossier public de la Direction de la Physique du Globe No. 83-5
Earth Physics Branch Open File Number 83-5
Ottawa, Canada

Ministère de l'Energie, des
Mines et des Ressources du Canada
Direction de la Physique du Globe
Division de Séismologie et de
Géomagnétisme

Department of Energy, Mines and
Resources Canada
Earth Physics Branch
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Price/Prix: $7.50

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J.F. CLARK

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Magnetic Survey Data at Meteoritic Impact Sites in North America

CONTENTS

Abstract

A compilation of source references to magnetic survey data over proven, probable and possible meteorite impact structures in North America shows that more than half of the 58 structures listed have been surveyed magnetically. Several types of magnetic signature, depending on he complexity of the impact structure and also on the geological setting, have been identified. At small simple craters, the magnetic anomalies are generally weakly negative; at complex structures, there may often be intense anomalies associated with the central uplift. Structural interpretation using magnetic data is considered feasible at several sites.

Résumé

D'après une étude des documents faisant mention de données magnétiques relatives à des structures d'impact météoriques prouvées, probables et possibles en Amérique du Nord, près de la moitié des 58 structures énumérées ont fait l'objet d'un levé magnétique. Les chercheurs ont observé plusiers types de signature magnétique, qui dépendaiént de la complexité de la structure d'impact et du contexte géologique. Aux cratéres petits et simples, les anomalies magnétiques sont généralement faiblement négatives; aux structures complexes, il y a souvent des anomalies fortes qui sont associées avec la remontée centrale. On considère que l'interprétation structurale se servant de données magnétiques soit faisable, et on la recommande à plusiers sites.

Part I: Magnetic Survey Data at Impact Structures in Canada.

Introduction.

This part of the report is a compilation of available magnetic data, chiefly from aeromagnetic low-level surveys, over probable and suspected impact craters in Canada. It attempts to identify those sites which are associated with magnetic anomalies and for which structural interpretation seems feasible.

Grieve and Robertson (1979) have listed all known impact structures as proven, probable and possible meteoritic craters. These authors include a bibliography for each of these structures, which is not repeated here. To merit classification as a proven crater portions of the original meteorite must have been recovered. This has not occurred in Canada despite a systematic search because impact events which create craters greater than one km in diameter would melt or vaporize the meteorite. However, there are craters at twenty-three sites in Canada where shock metamorphism has been found in the rocks and these craters are considered to be of probable meteoritic impact origin. There are many other features where there is some evidence of impact origin, but no definitive shock metamorphism effects. Of these possible impact sites ten are listed in alphabetical order, with the latitude and longitude of the centre of each feature. See Fig. 1 for location of all sites in Canada, identified in the same order as in the text. The map numbers given in Part I are for the Geological Survey of Canada (GSC) aeromagnetic maps. Ogilvie et al. (1982) have given a summary of meteoritic impact features in Canada.

The simple craters are those structures less than about 4 km across; the complex craters have a distinct central uplift and slumped or depressed rim structure which is not present in the simple bowl shaped ones. Central uplift may occur in a sedimentary target when the diameter of the crater is 3 km or greater; in a crystalline rock target the minimum diameter is about 4 km.

Probable Meteoritic Craters

1. Brent, Ontario. 46°05'N, 75°29'W.

This crater is situated in the Grenville geological province and has been surveyed extensively by Millman et al. (1960). Multi-disciplinary studies - geology, magnetic, gravity, seismic and diamond-drilling - have been completed. Aeromagnetic maps are available and surface magnetic observations have been made. Smooth contours of total magnetic intensity, with gentle gradients, are typical over this ancient (450 m.y.) structure. Beyond the rim, gradients are steeper and the contours irregular. Shock metamorphism effects have been observed in rock specimens from the drill cores. The crater has been shown to be of simple morphology with a crystalline basement beneath the central depression. It is 3.8 km in diameter with the near-circular cavity partially filled with sediments and the waters of Lake Tecumseh and Gilmour Lake. The Ontario Heritage Foundation has erected a roadside marker indicating the conclusion that this crater was caused by a meteorite which fell to earth 450 m.y. ago. The magnetic maps are numbered 1457G and 1467G.

2. Carswell, Saskatchewan. 58°27'N, 109°30'W.

This structure has a diameter of about 37 km and has complex morphology. Magnetotelluric soundings were made by Pham Van Ngoc et al. (1976). The crater is aged about 485 m.y. and is located in late Precambrian terrain. The low level one mile/inch aeromagnetic maps of F have been examined. They show a smooth magnetic field with low lateral gradients and northerly trending lineations. The low magnetic relief over the central area varies by no more than 200 nT. Away from the central area there are positive anomalies of up to 500 nT. A noticeable 'high' exists over an oval area of 10 km extent on the SE perimeter and another lesser 'high' appears on the NE edge. Magnetic modelling of the crater would be feasible from these maps, which are 2684G, 2885G, 2700G and 2701G.

3. Charlevoix, Quebec. 47°32'N, 70°18'W.

Robertson (1975) describes this as a Palaeozoic (360 m.y.) impact site. The crater floor is exposed and partially sediment-filled, but these are pre-crater age sediments showing shock effects. About one half of the 46 km diameter feature is obscured by the St. Lawrence River. The aeromagnetic maps at scales of four miles/inch (7071G) and one mile/inch (1964G, 1965G) are available. This complex structure has been investigated extensively by various geophysical methods, especially seismic. No definite explanation for the abnormal seismic activity in the area is available; further tectonic interpretation is required. The highly variable magnetic contours over the north half of the exposed portion of the impact structure reflect the complex magnetic character of the gneissic rocks in situ. Although there is no specific magnetic signature or central anomaly there are positive anomalies of 500 nT around the northern margins. Over the southerly half of the crater the magnetic gradients are gentler with broadly east-west linears; the total field is depressed about 300 nT below normal here.

4. Clearwater Lakes, Quebec.

(a) East Clearwater 56°05'N, 74°07'W.

(b) West Clearwater 56°13'N, 74°30'W.

These features are a pair of craters formed by the same meteorite which broke into two parts shortly before impact. They are of the same age (290 m.y.). The diameters are 22 km for the East Lake and 32 km for the West Lake. The aeromagnetic maps have been published recently and the magnetic data are being interpreted by R.L. Coles (in preparation). There are a number of anomalies, with large regional trends superimposed on them, owing to the complexity of the geology in this part of the Canadian Shield. This area is counted as two sites. Maps 9024G, 9025G cover East Clearwater; 9026G, 9033G and 9034G cover West Clearwater Lake.

5. Deep Bay, Saskatchewan. 56°24'N, 102°59'W.

This 100 m.y. old crater forms a circular bay in the extreme southerly end of Reindeer Lake. It has been investigated by Innes (1957) and others. It is a complex structure in crystalline bedrock that manifests itself morphologically as a water filled depression. Geophysics Paper 7152G (4 miles/inch) indicates aeromagnetic contours in F which have little change in intensity over Deep Bay, except for a high area on the NE edge, where linear belts of higher gradients trend northerly across Reindeer Lake. The greater relief over Reindeer Lake is probably because of shallower water depths underlain by Archean basement rocks. Deep Bay has no clear magnetic signature.

6. Gow Lake, Saskatchewan. 56°27'N, 104°29'W.

This has the same regional geological background as Deep Bay, being about 90 km to the west. Geophysics Paper 7153G (4 miles/inch) indicates extensive magnetic lineations trending NE over much of the map area. Contours of F close in a semi-circle at the NE end of Gow Lake, interrupting the regional trend. The lake and coincident crater are about 5 km in diameter with an island about one km in extent near the centre. Magnetic relief over the whole feature is less than 100 nT. Morphology is complex although it is near the minimum diameter for such structures to occur. Modelling might be feasible using the detailed Hickson Lake aeromagnetic map sheet (2822G) although the arcuate signature is weakly defined.

7. Haughton Dome, Devon Island, N.W.T. 75°22'N, 89°40'W.

This structure of 22 km diameter was originally theorized to be an evaporite piercement dome but this superficial interpretation is now discounted after ground observations. Shatter cones have been found along with definitive planar features in quartz rock samples. The extent of the central stratigraphic uplift is consistent with its size. Aeromagnetic data are not available from GSC but one profile has been flown over the Dome commercially, and P.B. Robertson (personal communication) has recently detected a positive central magnetic anomaly of 300 nT over an area of 6 sq. km which he has attributed to the central uplift.

8. Holleford, Ontario. 44°28'N, 76°38'W.

This crater was discovered about 30 years ago in a systematic search through air photographs for circular features. It has received extensive study and has been accepted by the Ontario Heritage Foundation for a roadside point-of-interest sign which was erected in 1976.

Magnetic contour maps were obtained from Bethlehem Steel Co. initially and recently the GSC version (8392G) has been published. Clark's (1969) magnetic analysis shows a concentric negative anomaly of 200 nT amplitude after correction for regional trends.

9. Ile Rouleau, Quebec. 50°41'N, 73°58'W.

This crater is located near the northern boundary of Grenville Province in the Shield area of Quebec and is about 300 m.y. old. GSC aeromagnetic maps 1989G and 1990G cover the area of the crater which has a diameter of 4 km. On the maps there is a quasi-circular magnetic contour pattern in the southerly quadrant of the crater. In the central and northerly sectors there is lower relief and no definitive pattern. Total range of F is about 100 nT with a minor maximum near the centre. This may be localized fine structure but central uplift in a crater of this size is possible.

10. Lac Couture, Quebec. 60°08'N, 75°18'W.

This 420 m.y. old feature is in the Superior Province of the Shield with a crystalline target and complex morphology. Around the rim of the 8 km diameter structure there is evidence of block-faulting and down thrusting. Aeromagnetic surveys have been flown and GSC has published the map (8825G) which shows a central negative anomaly of 400 nT in an elliptical shape with the long axis north-south.

11. Lac la Moinerie, Quebec 57°26'N, 66°36'W.

This probable crater site is similar in age and size to Lac Couture, but is in the Churchill Province. Aeromagnetic data are available (8570G) and depict low magnetic relief over most of the lake. A band of higher relief trends NW across the westerly portion of the lake.

12. Manicouagan, Quebec. 51°23'N, 68°42'W.

This feature is second only to the Sudbury Irruptive Basin as the largest crater in Canada, being about 70 km in diameter with complex morphology, central uplift and crater-fill products partly preserved. Aeromagnetic maps (4964G, 4965G) have been used to analyze the magnetic characteristics of the crater by Coles and Clark (1978). There is a central positive anomaly of 2000 nT over an uplifted mafic rock unit.

13. Mistastin, Labrador. 55°53'N, 63°18'W.

This is a large, complex crater of 28 km diameter in a crystalline target of Precambrian rocks and is classified as a central peak basin. There is about one km of central stratigraphic uplift which is physically visible as an arcuate island in the centre of the lake. The age of the crater is estimated to be 38 m.y.; only remnants of crater-fill are preserved.

The aeromagnetic maps (6253G, 6254G) indicate a central anomaly of -800 nT within a circle of 2 km diameter. This is attributed to the uplift of highly magnetized basement rocks which later acquired reverse polarity. Another negative anomaly of larger areal extent, 4 km diameter is visible about 5 km SE of the centre; it varies in magnitude from 500 to 750 nT. The crater has been modelled by Clark using a computer program which calculates the morphology of a body, given certain magnetic properties, which would compensate for the original country rock that has been excavated by impact.

The best fit obtained is for a bowl-shaped body of diameter 25 km, a magnetic susceptibility of +.005 SI in a total magnetic field of 58,200 nT, and with a thickness of 5.6 km in the centre, and having allowed for reverse polarity.

14. New Quebec Crater, Quebec: Cratère du Nouveau Québec. 61°17'N, 73°40'W.

This nearly circular lake and well preserved crater of about 3 km diameter was noted from the air in the 1940s. Visited in 1950 by Fred Chubb, a prospector for whom it was named initially, it is geologically young (about 100 m.y.) and is preserved as a near-circular hemispheroidal structure. Hannaford took some surface magnetic observations at 4 locations in the area in 1953 and observed a range of 400 nT along the rim. Aeromagnetic maps 8748G and 8733G show low gradients across the crater with a total relief of 100 nT. A regional trend of 25 nT/km, increasing to the east, is superimposed on the field.

15. Nicholson Lake, N.W.T.. 62°40'N, 102°41'W.

This complex crater is 12.5 km in diameter and located in Churchill Province, in partially sedimentary but mainly crystalline rock targets. Aeromagnetic maps are available - 6883G and 7830G Corey Lake. The crater is substantially covered by the lake but there is a large promontory in the SW quadrant. Total magnetic relief across the crater is about 300 nT with an absolute F value of 61,600 nT occurring in the centre over an island. Central uplift is quite probable. A secondary 'high' of 61,500 nT is observed in the NE margin location. Average gradient in the locale away from the small central high is 50 nT/km. The lake is 280m above mean sea level and is situated about 50 m below surrounding terrain, with complex drainage systems of ground water entering the lake. The magnetic signature is not precise but does resemble that found at Manicouagan and St. Martin craters, i.e. low relief except for a strong localized central anomaly. Well beyond the site (10 km N, for example) there is a gradient of about 1000 nT/km in irregular trend lines, so the low relief over the crater is unusual in this geological setting.

16. Pilot Lake, N.W.T. 60°17'N, 111°01'E.

This 6 km diameter crater in the Churchill Province of the Shield is 300 m.y. old. Map references are 1633G (1 mile/inch) and 7172G Fort Smith (4 miles/inch). The aeromagnetic map of Canada indicates a regional high of 200 nT in the area. Over Pilot Lake there is virtually zero magnetic gradient N-S and only 100 nT/km EW. Just beyond the postulated north rim there is an anomaly of +1400 nT, probably related to basic rocks. The lack of anomalies over the central zone is a signature usually caused by the excavation and removal of ferromagnetic rock.

17. Saint Martin, Manitoba. 51°47'N, 98°33'W.

Lake St. Martin waters partially cover the southern sector of this 23 km diameter buried crater. Geophysical surveys have been carried out and reveal a central negative anomaly of 1000 nT in an area 200 m by 250 m.

The structure is 100 km west of the Precambrian Shield boundary and is of Permian age. Diamond drilling has confirmed central uplift. Aeromagnetic maps 4184G and 4185G have been utilized in modelling programs which indicate that the central anomaly derives from an uplifted body which has acquired chemical remanence (CRM), as described by Coles and Clark, (1982).

18. Slate Islands, Ontario. 48°40'N, 87°00'W.

This large, complex feature in Lake Superior is about 30 km in extent with mainly crystalline target rock, and with the crater floor exposed but water-covered. Age is about 350 m.y. Some aeromagnetic coverage is available: Maps 7146G and 7088G (Schreiber, Ont.). Shatter cones have been discovered there. Apparently, there has been central uplift with the islands projecting above the original crater level. Differential erosion has left a circular semi-graben inside the rim remnants.

The Slate Islands, overall, exhibit a number of quasi-circular positive F anomalies with a gradient of 400 nT/km. Absolute F is 60,600 nT in the centre compared to a regional normal field of 60,000 nT. This is characteristic of centrally uplifted, older and more highly magnetized crystalline rocks, probably mafic in origin. There is a semblance of ring form. Where the waters of Lake Superior are deep, the total field F is a normal value. However, north of the theoretical rim, in shallow waters, steep gradients occur, and the magnetic field is anomalously high. This may be the effect of a peripheral graben caused by up-thrusting of ferromagnetic blocks along the Superior Province boundary; the site is partially in Southern Province. Palaeomagnetic studies denote a widespread secondary component of shock-induced magnetism (SRM) in the older rock units (H.C. Halls, personal communication).

19. Steen River, Alberta. 59°31'N, 117°38'W.

No aeromagnetic data from GSC are available but Geoterrex has some commercial aeromagnetic data. This feature is situated in the Interior Platform of the continental craton and could be suitable for magnetic modelling when more magnetic data become available. It is a buried crater with no obvious surface expression. Diamond-drilling has suggested a central uplift of 2 km in a crater of 25 km diameter (Grieve et al. 1981).

20. Sudbury, Ontario. 46°36'N, 8~~7~~1°11'W.

The Sudbury Irruptive Basin was formed by the release of magma from great depth (at the Moho discontinuity). This structure is located in the Shield near the boundary of Superior Province with Grenville Province. The Basin is attributed to events triggered by the hypervelocity impact of an asteroid with a target having a high thermal gradient. The original crater was about 80 km in diameter, 30 km deep and was formed about 1,800 m.y. ago. The mineralized rocks comprising the mines in the area are likely the result of the elevated impact melts interacting with the silicates to form sulphide ores. The aeromagnetic maps 1510G, 1511G, 1517G, 1518G indicate a signature which is variable and complex; there is an average 'high' in total magnetic field of 300 nT across most of the Basin.

21. Wanapitei, Ontario. 46°44' N, 80°44'W.

The crater itself is about 9 km diameter and lies beneath Lake Wanapatei which is about 12 km diameter. It is on the easterly flank of the Sudbury Basin but not related to it (age is only 37 m.y.). Its proximity is a happy coincidence since the same aeromagnetic maps cited for Sudbury also serve to cover Wanapitei. These maps show no strong signature over Wanapitei, however, when the regional trend (+50 nT/km N) is removed, the central area has very little relief, typical of a signature over a sediment-filled basin.

22. West Hawk Lake, Manitoba. 49°46'N, 95°11'W.

Aeromagnetic maps have been available for many years and a magnetic study has been carried out, with intercomparison of surface and airborne data. Pronounced shock metamorphic effects provide strong evidence that it is a meteoritic crater, and the surface and aeromagnetic data are supportive.

There is a pronounced signature with arcuate contours and a central negative anomaly of 250 nT, as determined by Clark (1980) using the aeromagnetic maps 1191G and 1192G.

Possible Impact Craters, Canada

a. Dumas, Saskatchewan. 49°55'N, 102°07'W.

This crater is about 4 km in diameter and less than 70 m.y. old. It is completely buried by several km of Cretaceous sediments filling the cavity. No aeromagnetic data are available at present.

b. Eagle Butte, Alberta. 49°42'N, 110°30'W.

This feature is about 10 km in diameter with a minor topographical surface expression of a crater in the form of a small circular depression. It is covered by several hundred m of sediments on the High Plains of the Interior Craton. It is less than 40 m.y. old and has been studied geologically by the University of Alberta, but no aeromagnetic maps are available (J. Steiner, personal communication).

c. Elbow, Saskatchewan. 50°58'N, 106°45'W.

This feature is 80 m.y. old, situated in the Western Plains. Rotary drilling for petroleum has indicated it to be a subterranean structural dome of one km, or greater, depth. No aeromagnetic data are available yet, but the surface magnetics have only a random pattern.

d. Hartney, Manitoba. 49°24'N, 100°40'W.

This circular structure is 6 km in diameter and is totally obscured by sediments of age 150 m.y. and thickness 700m. No aeromagnetic data are published; the structure was discovered by deep drilling for petroleum.

e. Lac Kakiattukalak, Quebec. 57°42'N, 71°40'W.

This feature is 6 km in diameter, of early Paleozoic age and is situated in the Superior Province. Map GSC 8594G covers the area. There is a negative central anomaly of 300 nT with easterly trending linears on the north side. The lake surrounding the crater is nearly circular with a diameter of 7 km. There is a magnetic contour pattern of concentric rings of gradients of 75 nT/km extending out to the rim. This pattern could be interpreted as the effect of central uplift. Beyond the rim on the north side gradients increase rapidly to 200 nT/km over land. The general physiographic configuration bears an evident resemblance to West Hawk Lake, on a larger scale. Glaciation has deposited sediments over the centre and on the southerly shores as the ice sheets moved southwards.

f. Meen Lake, N.W.T. 64°58'N, 87°40'W.

This very old (600 m.y.) 4 km in diameter structure, is located in the Churchill Province and is of simple morphology. The GSC federal-provincial aeromagnetic low level surveys have been flown and the map has been published recently. The map (8375G) shows a definitive magnetic signature comprising a central low with an amplitude of 180 nT, with concentric contours except in the NE sector.

g. Merewether, Labrador, Nfld. 58°02'N, 64°02'W.

This is one of the smallest craters in the group. It is 200m in diameter and 10,000 years old. It is in Churchill Province. Aeromagnetic data are not available.

h. Poplar Bay, Manitoba. 50°23'N, 95°47'W.

This 3 km diameter crater is located in the Interior Platform of the Great Plains. However, it is near the Shield boundary and sedimentary cover is thin. It is aged 75 m.y. The crater has formed a large bay within Lac du Bonnet, somewhat similar to Deep Bay in Reindeer Lake. Aeromagnetic maps have been secured and examined. They indicate signatures favourable to meteoritic impact formation with circular contours, low gradients and a total relief of 100 nT. Map numbers are 4070G and 7124G Pointe du Bois.

i. Skeleton Lake, Ontario 45°15'N, 79°26'W.

This crater has been examined with geophysical methods over the past decade. Rock specimens analysed by the Earth Physics Branch have not shown clear evidence of shock metamorphism and further work is required. Aeromagnetic and surface magnetic data have been correlated by Clark (1981). The crater is about 3.5 km in diameter. It is in the Muskoka District of Ontario, near the southerly edge of Grenville Province. A clearly recognizable magnetic signature on the maps shows a slightly asymmetrical, circular anomaly of -300 nT. Map numbers are 112G, 126G, 127G and 148G.

j. Viewfield, Saskatchewan. 49°35'N, 103°04'W.

This is another of the fossilized craters noted in the sedimentary cover of the Interior Platform. No aeromagnetic data are published. The feature is 2.5 km in diameter and of Permian age. Ground magnetic surveys could be carried out since it is readily accessible. It is deeply buried by about 1 km of Cenozoic and Mesozoic sediments, and was discovered by deep structure drilling during petroleum exploration.

The Geological Survey of Canada (GSC) has bedrock geology coverage for the region and some surficial maps as well. Some provincial geological studies are also available. The low-level (300 m above terrain) aeromagnetic survey program is continuing.

Comments

After examination of the aeromagnetic maps and other evidence which is available, one is able to recommend further detailed study of four probable impact structures and one possible impact structure in Canada.

The locales which warrant structural interpretation by a magnetic modelling program are listed in Table 1 in alphabetical order. Poplar Bay, Manitoba, is the only one of these sites for which shock metamorphism is not known to be present, possibly because the crater was discovered only quite recently. A tabulation of the average magnetic anomaly is given for each location. These sites are in addition to more than a dozen in Canada which have already been studied using magnetic data, as shown by Grieve and Robertson (1979) and also as described in this review.

Table 1

Name	Lat.	Long.	Diameter (km)	F. Anomaly	Remarks
Carswell, Sask.	58°27'N	109°30'W	37	+500 nT	Good contrasts
Mistastin Lake, Labrador, Nfld.	55°53'N	63°18'W	28	-800 nT	Central negative anomaly
Nicholson Lake, N.W.T.	62°40'N	102°41'W	12	+300 nT	Complex patterns
Pilot Lake, N.W.T.	60°17'N	110°01'E	6	+250 nT	Low relief
Poplar Bay, Man.	50°23'N	95°47'W	3	+100 nT	Small gradients

* * * * *

PART II: Data at Impact Structures, U.S.A.

In the United States of America there are three craters of proven meteoritic impact origin.

1. Barringer Meteor Crater, Arizona 35°02'N, 111°01'W.

This crater has a mean diameter of 1.2 km and was formed by the impact of an iron meteorite on the Arizona desert about 50,000 years ago.Much of the original meteorite, estimated to be 60m in diameter, has been recovered and analyzed, see Nininger (1952). Magnetic data are available for meteoritic fragments and the crater itself; the structure is well documented. The first natural occurrence of coesite, a high-pressure polymorph of SiO_2, was identified here in sheared Coconino sandstone. Owing to dissemination of magnetite, very little magnetic expression is now visible.

2. Haviland, Kansas, 37°35'N., 99°10'W.

This crater is only eleven meters in diameter and was caused by a meteorite about one m in diameter. Nininger (1956) has excavated the site. An aeromagnetic map of Kansas (Steeples and Bickford, 1981, Yarger, 1981) indicates the area to be one of little magnetic relief.

3. Odessa, Texas, 31°45'N., 102°29'W.

This is a cluster of 3 craters , the largest being 168m in diameter. Actually, there are other proven 'craters' or pits, but they are less than 9m in diameter (too small to have structural implications) and are not considered in this review. No magnetic signature has been found.

Eleven features in the U.S.A. satisfy the criterion for <u>probable</u> impact structures and twelve others are identified as being <u>possible</u> impact structures, as listed by Grieve and Robertson (1979). Their references are not repeated here but some significant additional sources of information are cited. The probable structures are discussed alphabetically, with the geographical position of the centre given in latitude and longitude respectively, rounded to the nearest minute.

The possible structures follow, also in alphabetical order. Ages given are the best available estimate at present. See Fig. 2 for location of all sites in the United States.

U.S.A Probable Impact Structures

1. Bee Bluff, Texas. 29°02'N. 99°51'W. It has an age of 40 m.y., a diameter of 2.4 km and is filled in by sedimentary rocks. No magnetic data are available.

2. Crooked Creek, Missouri. 37°50'N., 91°23'W.

The crater has a diameter of 5.6 km and an age of 320 m.y. It is a complex structure in a sedimentary target. Evidence of shock metamorphism has been found in the remnants of crater-fill. No anomalous magnetic signature is evident in the magnetic map contoured from the transcontinental geophysical survey carried out as part of the Upper Mantle Project by Zietz and Kirby (1968). However, compared to the highly disturbed field in the environs, the magnetic field is lower and more uniform over the crater, which is at least a partial signature.

3. Decaturville, Missouri. 37°54'N, 92°43'W.

This feature is similar in size (6 km) and age to Crooked Creek and is located about 75 km west of it. The Palaeozoic sediments were displaced by impact and a topographic map of the area shows a depression surrounded by the rugged hills of the Ozarks. An aeromagnetic contour map shows a variation of only 200 nT across the feature with gentle gradients of total intensity.

However, at Lat. 37°53'N and Long. 92°39'W., there is a positive anomaly of 400 nT over a circular area within the crater which could be modelled.

4. Flynn Creek, Tennessee. 36°16'N., 85°37'W.

This structure is 4 km in diameter with an unusually complex morphology for a small feature. It is near the southeasterly edge of the American Great Plains craton with 1500m of Palaeozoic and younger sediments overlying the Precambrian basement rocks. The New York-Alabama Piedmont tectonic lineament covers this area and an anomalously high magnetic linear crosses the feature trending NE. This signature is probably related to deep geological structure on a large scale. Age of crater is about 360 m.y. A magnetic anomaly map has been published by Haworth et al. (1980). There is no prominent signature but some anomalously high zones are visible.

5. Kentland, Indiana. 40°45'W., 87°24'W.

The geological environment here is similar to the first three structures in this section. There are platform sediments of Ordovician age, with a maximum depth of 1 km. The magnetic anomaly map (Dempsey et al. 1951) shows a positive anomaly of 300 nT in oval shaped contours centred over the feature, with uniform gradients of 50 nT/km. The structure is about 13 km in diameter and exhibits complex morphology. Geological information has been supplied by State Geologist Dr. E. Biggs, (personal communication, 1981).

6. Manson, Iowa. 42°35'N., 94°31'W.

This is one of the largest probable craters in the U.S.A., being 32 km in diameter. It is situated in sedimentary rock 500m thick, of age 70 m.y. The morphology is the complex, multi-ring type with crater fill preserved. A detailed aeromagnetic map of the Manson Anomaly has been published by Henderson et al. (1973). This map shows a central positive anomaly of 900 nT over several km , decreasing to an average of +500 nT over the remainder of the crater. This reinforces the hypothesis of central uplift.

7. Middlesboro, Kentucky. 36°37'N., 83°44'W.

Although only 6 km in diameter this feature has a complex, central uplift morphology with shock metamorphism evident in the sedimentary rocks which were uplifted. Sedimentary cover has filled in much of the crater and a magnetic high of about 500 nT prevails over most of the central area, but is interrupted by some local geological faults.

8. Redwing Creek, North Dakota. 47°40'N., 102°30'W.

This is another fairly large, (9 km diam.) complex structure, which has been investigated by Brenan et al. (1975). It lies within the Williston Basin and is obscured by great depths (3 km) of sediments of Palaeozoic age and later which are present in jumbled blocks up-thrust as much as 900m above regional subsurface elevations. This has masked any surface expression. Detailed magnetic data are not yet available.

9. Serpent Mound, Ohio. 39°02'N., 83°24'W.

Reidel (1975) considers this to be a cryptoexplosion structure of age 300 m.y. It is 6.4 km in diameter with the rim largely eroded away leaving the central uplift exposed. Complex magnetic anomalies occur in a way difficult to interpret.

10. Sierra Madera, Texas. 30°36'N., 102°55'W.

The structure is 13 km in diameter, of age 100 m.y., in a sedimentary setting. The site is near the southerly edge of the West Texas Basin which contains sediments up to 3 km thick. A profile from the Project Magnet aeromagnetic survey passes over the feature in a N-S line about 2.5 km east of the centre. Total magnetic intensity increases from 50540 nT at the southerly edge to 50,600 nT at the north side, a gradual change of only about 4 nT/km, as measured at an elevation of 500m. This magnetic signature is typical for a sediment filled basin.

11. Wells Creek, Tennessee. 36°23'N., 87°40'W.

This site has about the same dimensions as the Sierra Madera (14 km) structure. It is older (about 200 m.y. old), more eroded and has sedimentary thicknesses of up to 1500m. It has a complex, multi-ring form. The aeromagnetic field map shows a smooth oval pattern with low gradients and no definitive signature.

U.S.A. Possible Impact Structures

1. Amak, Alaska. 55°44'N 163°09'W. The diameter is 0.16 km, and the age is unknown. There are no magnetic data.

2. Des Plaines, Illinois. 42°02'N. 87°56'W.

Enrich and Bergstrom (1962) have described this feature as a crypto-explosion structure 9 km in diameter. It is within the Michigan Basin, overlain by sediments from Mississipian to early Ordovician age. An aeromagnetic survey analysis has been published by Beck (1965), which concludes that this structure was formed by meteoritic impact.

3. Dycus, Tenn. 36°22'N., 85°45'W.

The magnetic anomaly map of the Appalachian Orogen shows a positive anomaly with an amplitude of 500 nT. The complex geology of the New York-Alabama lineament has largely obscured any surface expression, and the margin is not well defined.

4. Glasford, Ill. 40°22'N., 89°48'W.

Busbach and Ryan (1963) examine the original hypothesis of an uplifted dome structure. Diamond drilling has been carried out which has retrieved approximately 900m of sheared and brecciated core specimens. They conclude that the structure is an astrobleme. It is about 4 km in diameter. Regional maps of vertical magnetic intensity (McGinnis and Heigold, 1961) show only a small anomaly (+100 nT), centred over the structure.

5. Glover Bluff, Wisconsin. 43°55'N., 89°35'W.

This is a 'simple' feature of 0.4 km diameter and located in a Precambrian setting. The crater itself may be of Mesozoic age. No detailed magnetic data are available.

6. Howell, Tennessee, 35°15'N., 86°35'W.

This crater of 2.4 km diameter is on the crest of the Appalachian Orogen uplift with a positive magnetic anomaly superimposed over it. The aeromagnetic map (TVA, 1976) shows moderate gradients (100 nT/km) decreasing uniformly from south to north with east-west trends.

7. Jeptha Knob, Kentucky. 38°11'N., 85°07'W.

This feature has a circular form and is about 5 km in diameter with indications of uplift centrally and peripheral down-faulting. It is on the westerly slope of the Appalachian lineament with its regional high magnetic field. A map by Black et al. (1977) shows Bouguer anomalies, magnetic contours and structural geology of the area in detail. However there is very little gravity or magnetic relief associated with the complex geological faulting.

8. Kilmichael, Mississippi. 33°30'N., 89°33'W.

This structure is about 13 km wide with a topographic expression of a shallow depression of about 30 m relative to surrounding terrain. There are no magnetic maps available at present.

9. Sithylemenkat L., Alaska. 66°07'N., 151°23'W.

This was the first discovery of a crater in Alaska. It is 12.4 km in diameter and estimated to be 10,000 years old (post-glacial). No magnetic data are available yet.

10. Upheaval Dome, Utah. 38°26'N., 109°54'W.

This was originally thought to be a structural dome of 5 km diameter, but is now considered to be a possible sub-surface meteorite crater. It has been well documented, see Joesting and Plouff (1958). Their aeromagnetic map is dominated by two prominent, symmetrically rounded highs, each of about 500 nT, across the feature. Depth of the structure is estimated to be about 700m.

11. Versailles, Kentucky. 38°02'N., 84°45'W.

This site appears on the same map as Jeptha Knob (Black et al. 1977) where it is called the Versailles cryptoexplosion structure. Here also, there is very little gravity or magnetic expression associated with the crater, although the geological map shows about 200 m of very recent sediments above Tyrone limestone of Ordovician age in a circular area of 2 km diameter.

12. Wetumpka, Alabama. 32°32'N., 86°14'W.

The feature is nearly circular, 6.5 km in diameter and about 100 m.y. old. It is described by Neathery et al. (1976) as a cryptoexplosion structure. They present evidence favourable to formation by the impact of a meteorite. This evidence comprises a detailed geological survey, studies of shock deformation features in quartz and feldspars, and an aeromagnetic field map. This regional map shows a deep magnetic low coinciding with the western part of the structure. The configuration of the total magnetic anomaly, however, correlates more with the regional geological structure than with any specific aspect of the Wetumpka astroblême.

Comments

The features at Crooked Creek, Missouri, Flynn Creek, Tennessee, Kentland, Indiana and Manson, Iowa are recommended as deserving further study including surface magnetic surveys and analysis.

Among the possible craters, Glasford, Illinois and the Upheaval Dome, Utah, would be suitable for further interpretation.

In addition to the references cited there is a considerable amount of other published material on file, as well as the address of each official source of further information.

The IGRF (International Geomagnetic Reference Field) has been computed for the above significant features and has been utilized, along with other magnetic data, to remove the main regional field, obtaining the magnetic anomalies for the craters as shown in Table 2.

Table 2

Place	Lat.°	Long.°	Altitude* (km)	Epoch (Date)	Anomaly F (nT)
1. Crooked Creek, Missouri	37.9N	91.4W	1.5	1968.5	-200
2. Flynn Creek, Tennessee	36.3N	85.6W	2.0	1975.0	+400
3. Kentland, Indiana	40.75N	87.4W	2.5	1965.0	+300
4. Manson, Iowa	42.6N	94.5W	1.2	1971.5	+700
5. Glasford, Illinois	40.4N	89.8W	0.1	1961.5	+450
6. Upheaval Dome Utah	38.4N	109.6W	3.0	1962.5	+600

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* Altitude is elevation above ground for which theoretical IGRF is computed.

Conclusions

Magnetic data are available at 48 of the 58 structures investigated in this report. There is a recognizable magnetic signature at 37 of these 48 sites. The signatures vary depending on the size of the feature, the amount of crater-fill, if any, and the geological setting.

Over the proven craters, which are small, simple ones, there is an absence of any strong anomaly in the total magnetic field. Anomalies present are invariably negative owing to the ejection of magnetized rock. The contour map has a pattern which is ideally circular or arcuate but may be irregular if distorted by variable structure beneath the crater floor. Over simple craters which are unproven, one expects similarly small negative magnetic anomalies, 100-200 nT, with patterns similar to those over the proven structures.

Over larger, complex structures greater than about 4 km in diameter there is usually central uplift of magnetic, mafic rock units. This causes a central magnetic anomaly of about 400 nT or greater as size increases. The anomaly may be positive or negative depending on whether there was a reversed magnetic field at the time of impact. Structures which are greater than about 25 km in diameter may have a ring or multi-ring form with a stronger central uplift signature. In addition, one may note a signature related to the surrounding peripheral graben and also an anomaly over the ring-like 'outer' rims. In the Precambrian Shield settings craters generally have a clearer signature than those in younger geological surroundings since the latter ones tend to be masked by sediments and other cover.

Gravity surveys have been carried out over most of the Canadian land-mass on a regional scale of about 10 km between stations. These are published in the gravity map series showing the Bouguer anomalies in contour format. Localized gravimetric surveys have also been made at many craters and are useful in modelling the structures' dimensions. It is desirable to have a good density contrast (0.20 g/cm^3) between the original rock and the basin, especially if it is filled by breccia, sediments, or both.

Seismic reflection surveys have been undertaken at several sites and are useful in estimating depths to crystalline basement. They work well as long as there is no high reflectivity horizon near the surface. There are other disciplines e.g. palaeomagnetism and rock physics, which contribute to a better understanding of the structure of impact craters.

The magnetic methods provide useful supportive evidence for correlation with data from these other disciplines. Even when a magnetic signature is not visible, the measurement of rock properties such as susceptibility, anisotropy and strength of magnetization can assist in the total structural interpretation. This may be of more practical importance than attempting to prove or disprove the mode of formation of a structure with the aid of these methods.

Acknowledgements

Drs. E.R. Niblett and P.B. Robertson provided valuable guidance during the compilation of this review and Dr. M.D. Thomas gave a thorough critique. Dr. P.A. Camfield reviewed the paper and made helpful comments. The World Data Centre at Boulder, Colo. furnished a magnetic tape containing Project Magnet data and many colleagues in North America supplied useful information.

REFERENCES

Beck, M.E. (1965) Aeromagnetic map of northeastern Illinois, USGS Map GP-523. Illinois State Geol. Surv., Champaign, IL.61820.

Black, D., G.R. Keller and R.W. Johnson (1977), Geological Map of the Northwest Sheet, Central Kentucky. Kentucky Geol. Surv., Frankfort, Ky, 40506. Map GQ-303.

Brenan, R., B.L. Peterson and H. Smith, (1975), Origin of the Redwing Creek Structure. Wyoming Geol. Assoc. Bulletin, Vol. 8, No. 3, pp 1-41, Cody, Wyo.

Buschbach, T.C. and R. Ryan (1963), Ordovician Explosion Structure at Glasford, Illinois. Am. Soc. of Petr. Geologists, Vol. 47, no. 12, pp. 2015-2022.

Coles, R.L. and J.F. Clark (1978), The central magnetic anomaly at Manicouagan Structure, Quebec. J. Geophys. Res., 83B, 2805-2808.

Coles, R.L. and J.F. Clark (1982), Lake St. Martin Impact Structure, Manitoba, Canada: Magnetic Anomalies and Magnetizations, J.Geophys. Res. Vol. 87, No.B8, pp. 7087-7095.

Clark, J.F. (1969), Magnetic profiles at Holleford crater, eastern Ontario. Proc. Geol. Assoc. of Canada, 20, pp. 24-29.

---------(1980), Geomagnetic Surveys at West Hawk Lake, Manitoba, Canada. Geomagnetic Series, Earth Physics Branch, EMR, No. 20, 1980.

----------(1981) Geomagnetic Surveys at Four Canadian Craters, E.M.R., E.P.B. Geomagnetic Report 81-1. Ottawa, Can.

Dempsey, W.J., J.R. Henderson and N. Dufferin (1951), Newton County Purdue-52 aeromagnetic map. USGS, Bloomington, Indiana, 47405.

Emrich, G.H. and R.E. Bergstrom (1962), Des Plaines Disturbance, Northeastern Illinois, Bull. Geol. Soc. America V. 73, p. 959-968.

Grieve, R.A.F. and P.B. Robertson, (1979), The terrestrial cratering record. I: Current state of observations. Icarus. 38, 212-229.

Grieve, R.A.F., P.B. Robertson and M.R. Dence (1981), Constraints on the formation of ring impact structures, based on terrestrial data. Proc. Lunar Planet. Sci. 12A, p. 35-57.

Haworth, R.T., D.L. Daniels and Isidore Zietz (1980), Magnetic Anomaly map of the Appalachian Orogen. Memorial University of Newfoundland, St. Johns, Nfld. Map sheets 1,2-scale 1:1,000,000.

Henderson, J.R., W.B. White and I. Zietz (1973), Interpretation of an aeromagnetic survey in north-central Iowa, USGS, Denver, Colo. 80225. Aeromagnetic map no. GP-476.

Innes, M.J.S. (1957), A possible meteorite crater at Deep Bay, Sask., Jour. Roy. Astron. Soc. Canada, Vol. 51, No. 4, p. 235-240.

Joesting, H.R. and D. Plouff (1958), Geophysical studies of the Upheaval Dome Area, San Juan County, Utah, USGS, Denver, Colo. (Guidebook g).

Millman, P.M., B.A. Liberty, J.F. Clark, P.C. Willmore, and M.J.S. Innes, (1960). The Brent Crater, Pub. Dom. Obs. Vol. 24, No. 1.

McGinnis, L.D. and Paul C. Heigold (1961), Regional maps of vertical magnetic intensity in Illinois, Illinois State Geol. Surv. Circular #495, Urbana, Ill.

Nininger, H. (1952), 'Out of the Sky' Dover Publications Inc.,180 Varick Street, New York, U.S.A.

---------(1956) Arizona meteorite crater. American Meteorite Laboratory, Denver, Colo.

Neathery, T.L., R.D. Bentley and G.C. Lines (1976), Cryptoexplosive structure near Wetumpka, Alabama. Bull. Geol. Soc. America, V. 87, pp. 567-573.

Ogilvie, B.Y., P.B. Robertson and R.A.F. Grieve (1982). Meteorite Impact Features in Canada - An inventory and an evaluation. Library, EPB, EMR. Ottawa, 180 pp.

Pham van Ngoc, W. Telford and A. Becker (1976), Magnetotelluric Trials, Carswell Dome, Sask. Note 76-1, McGill University, Montreal, Mineral Exploration Research Institute Library.

Reidel, S.P. (1975), Bedrock Geology of the Serpent Mound cryptoexplosion structure, Ohio Geological Survey, Columbus, Ohio, 43224. Geological Report No. 95.

Robertson, P.B, (1975), Impact Structures in Canada. Jour. Roy. Astron. Soc. Canada No. 69 , pp. 1-21.

Steeples, D.W. and M.E. Bickford (1981), Piggyback drilling in Kansas: An example from the Continental Scientific Drilling Program. EOS, vol. 62, no. 18, May 1981.

TVA (1976) Total Intensity Aeromagnetic Map, Fayetville Area.Tennessee Valley Authority, Knoxville, Tenn. U.S.A., 37902.

Yarger (1981) Aeromagnetic Survey of Kansas EOS, vol. 62, No. 17, pp. 173-78

Zietz, Isidore and J. Kinsley (1968), Aeromagnetic and gravity profiles of the United States along the 37th parallel of longitude. GP-597, USGS, Reston, Va. 22092.

----------and J.R. Kirby (1968b), Transcontinental Geophysical Survey, USGS Map I-534-A. USGS, Reston, Va.

----------F.P. Gilbert and J.R. Kirby (1976), Aeromagnetic Map of Iowa: Colour coded intensities, Map GP-476, USGS, Reston, Va.

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METEORITE IMPACT CRATERS IN CANADA

Caption for Fig. 1

I. Probables (evidence of shock metamorphism)

1. Brent
2. Carswell
3. Charlevoix
4. Clearwater East and Clearwater West
5. Deep Bay
6. Gow Lake
7. Haughton
8. Holleford
9. Ile Rouleau
10. Lac Couture
11. Lac La Moinerie
12. Manicouagan
13. Mistastin Lake
14. Cratère de Nouveau Québec (New Quebec Crater)
15. Nicholson Lake
16. Pilot Lake
17. St. Martin
18. Slate Islands
19. Steen River
20. Sudbury
21. Wanapitei Lake
22. West Hawk Lake

II. Possibles (evidence of shock metamorphism not discovered)

a. Dumas
b. Eagle Butte
c. Elbow
d. Hartney
e. Kakiattukallak
f. Meen Lake
g. Merewether
h. Poplar Bay
i. Skeleton Lake
j. Viewfield

Note: Stippled area on map denotes the Precambrian Shield.

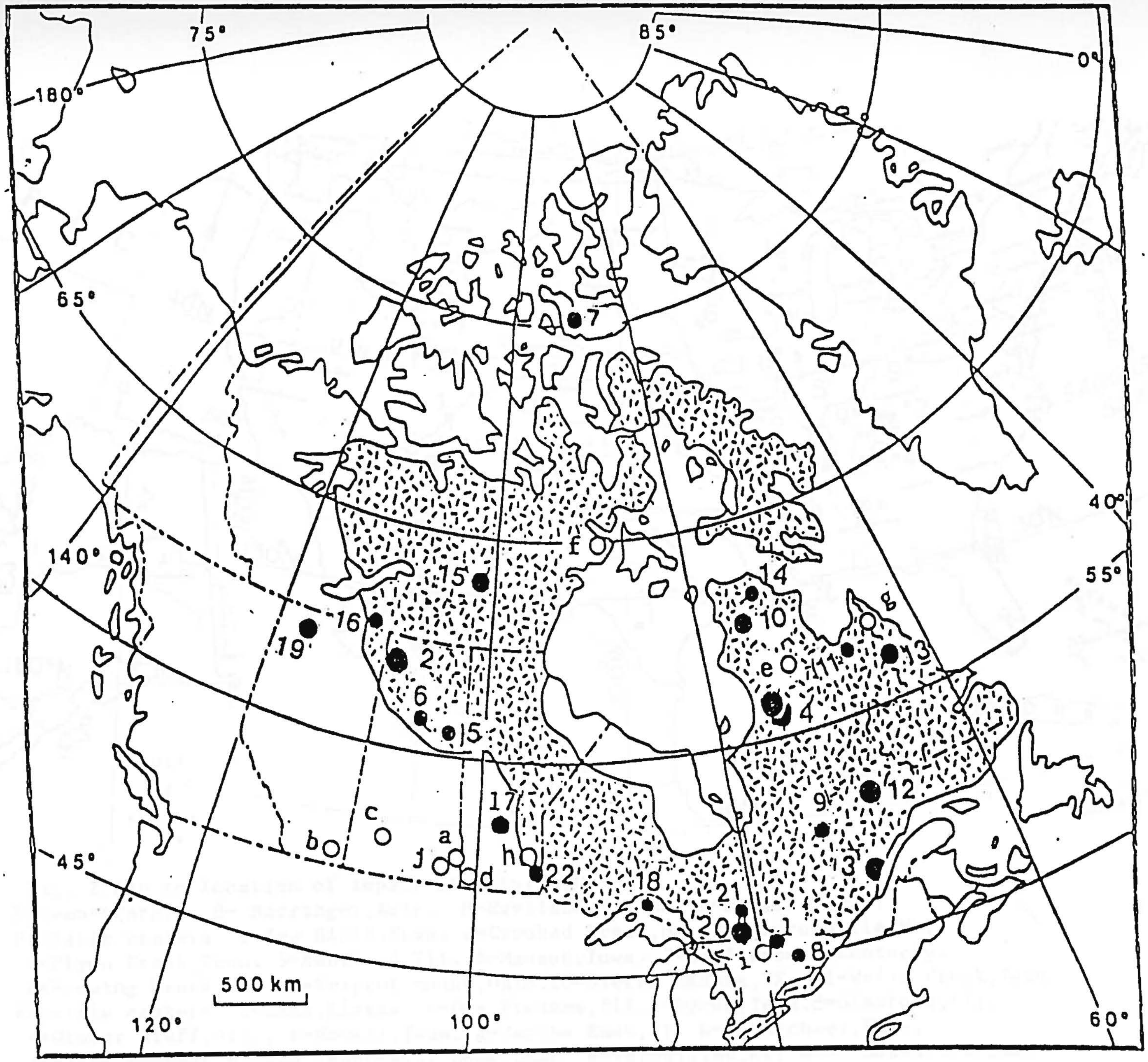

FIGURE 1. CANADA-KEY TO LOCATION OF CRATERS

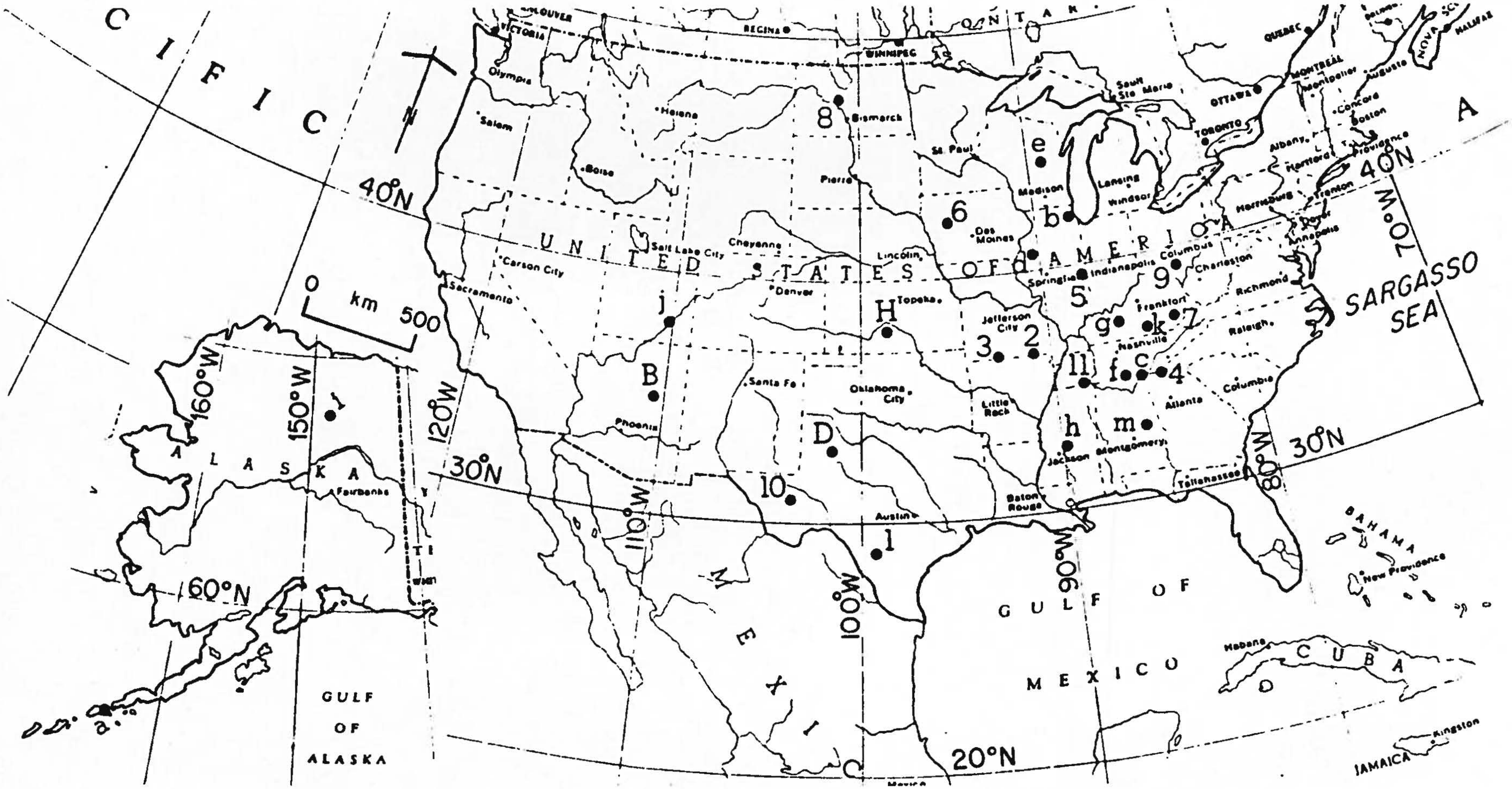

Fig. 2. Key to location of impact structures, U.S.A.

Proven craters B= Barringer, Ariz. H=Haviland, Kansas. D=Odessa, Texas.

Probable craters 1=Bee Bluff, Texas 2=Crooked Creek, Mo. 3=Decaturville, Mo.
4=Flynn Creek, Tenn. 5=Kentland, Ill. 6=Manson, Iowa. 7=Middlesboro, Kentucky.
8=Redwing Creek, N.D. 9=Serpent Mound, Ohio. 10=Sierra Madera, TX. 11=Wells Creek, Tenn.

Possible craters a=Amak, Alaska. b=Des Plaines, Ill. c=Dycus, Tenn. d=Glasford, Ill.
e=Glover Bluff, Wisc. f=Howell, Tenn. g=Jeptha Knob, KY. h=Kilmichael, Miss.
i=Sithylemenkat, Alaska j=Upheaval Dome, Utah. k=Versailles, KY. m=Wetumpka, Alabama.