Geological Society of America
Special Paper 384
2005

Using vertical dikes as a new approach to constraining the size of buried craters: An example from Lake Wanapitei, Canada

E. L'Heureux*
H. Ugalde
B. Milkereit
Department of Physics, University of Toronto, 60 St. George, Toronto, Ontario M5S 1A7, Canada

J. Boyce
W. Morris
School of Geography and Geology, McMaster University, 1280 Main St. West, Hamilton, Ontario L8S 4K1, Canada

N. Eyles
Department of Physical & Environmental Sciences, University of Toronto at Scarborough, 1265 Military Trail, Toronto, Ontario M1C 1A4, Canada

N. Artemieva
Institute for Dynamics of Geospheres, Moscow, Russian Academy of Sciences, Leninskii pr. 38-6, Moscow 117334, Russia

ABSTRACT

Lake Wanapitei, located within the Southern Province of Ontario, Canada, provides the setting for a unique study of an impact crater situated within a shield environment. Evidence for the 7.5-km-diameter Wanapitei impact includes a circular Bouguer gravity low centered over the central area of the lake and features of shock metamorphism in samples of glacial drift found on the southern shores. Geophysical studies of craters in hard-rock environments are often limited by the lack of markers used for exploration; this may be overcome with the use of the large igneous dike swarms that characterize Archean terrains. The 1.2 Ga Sudbury dike swarm predates the impact that is suggested to have generated Lake Wanapitei and provides the setting for a study to constrain the size and location of the impact crater. The swarm is clearly visible on aeromagnetic maps as high amplitude, linear features, suggesting they could be used as vertical markers indicative of structural changes having an effect on target rock susceptibilities.

To fully establish the size of the crater, a total field magnetic map was produced to trace the Sudbury dikes through the proposed crater center. A gap in their signature, expressed as a 100 nT low, 2–3 km in width, constrains the size of the crater to <5 km. Numerical modeling suggests that a crater of this size will demagnetize target rocks, producing a low in the total magnetic field, up to a maximum diameter of 3 km. Dikes

*elizabeth.lheureux@utoronto.ca

L'Heureux, E., Ugalde, H., Milkereit, B., Boyce, J., Morris, W., Eyles, N., and Artemieva, N., 2005, Using vertical dikes as a new approach to constraining the size of buried craters: An example from Lake Wanapitei, Canada, *in* Kenkmann, T., Hörz, F., and Deutsch, A., eds., Large meteorite impacts III: Geological Society of America Special Paper 384, p. 43–50.

within the central crater structure will be excavated, vaporized, and melted down to a depth of 1.3 km.

Keywords: Wanapitei, dike swarm, Sudbury, impact structure, magnetic anomaly, Superior Province.

INTRODUCTION

Lake Wanapitei is located within the Huronian Supergroup of the Southern Province in northern Ontario, Canada, and is bounded on its west side by the eastern rim of the Sudbury impact structure (Fig. 1A). The lake was suggested to have been generated by a meteorite impact, with a resultant crater 7.5 km in diameter (Dence and Popelar, 1972). Identification of an impact crater is commonly based on crater morphology, macroscopic and microscopic shock metamorphic features, and the presence of specific lithologies such as suevitic breccias and geophysical anomalies. In stratified targets, marker beds help to deduce the degree of impact-induced tilting and faulting of the rocks. Identification of craters in crystalline rock environments such as the Canadian Shield is made more difficult by the lack of prominent marker horizons in geophysical data sets; identifying buried structures in a nonsedimentary setting often reduces diagnostic approaches to analysis of potential field data.

The Wanapitei region is transected by several Precambrian dike swarms, namely the Matachewan and Sudbury swarms. Archean provinces such as the Canadian Shield are generally characterized by these large swarms of igneous dikes that are thought to emanate from mantle plumes (Ernst et al., 1995). The geometrical and geophysical properties of these dikes can provide key constraints on any structural geological model. Evidence suggests that upon intrusion most dikes are near vertical and have a preferred orientation that corresponds to the regional stress field applicable at the time of intrusion (Morris and Tanczyk, 1978). By defining variations in the current geometry and orientation of a portion of a larger dike swarm it is possible to unravel complex tectonic histories (see Halls et al., 1994; or Siddorn and Halls, 2002). The vertical dikes extend several kilometers below the surface; hence, simple uplift is marked by a change in the width of the thermal contact aureole (Schwarz and Buchan, 1989). Traditionally, these large collections of vertical dikes have been used in studies of supercontinent cyclicity (Yale and Carpenter, 1998; Mertanen et al., 1999) or structural deformation (West and Ernst, 1991; Buchan and Ernst, 1994).

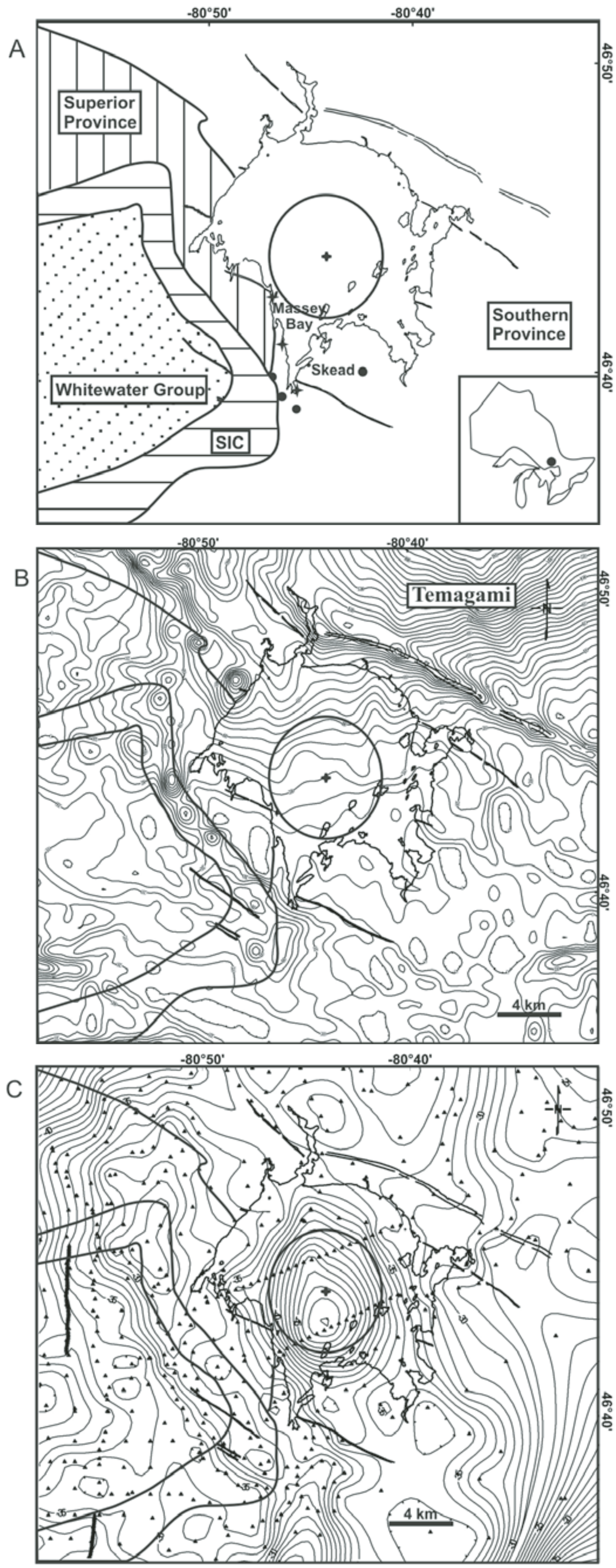
Igneous dike swarms are commonly associated with prominent magnetic features that can be traced over several kilometers and are easily imaged on aeromagnetic maps (see Fig. 1B). In the Wanapitei region, dikes of the Sudbury swarm were intruded ca. 1.2 Ga (Krogh et al., 1987), prior to the suggested impact that lead to the formation of Lake Wanapitei. In this study, we took advantage of the geological setting offered by the Sudbury dike swarm to investigate a buried meteorite impact crater, using the dikes as vertical markers for constraining crater dimensions.

Geologic Setting and Evidence for Impact

The impact crater studied lies entirely within the central, circular portion of the 12 km diameter Wanapitei Lake, and is believed to be of medium size (with a diameter of ~7.5 km; see Fig. 1) (Dence and Popelar, 1972). The lake is situated on the border between the Southern and Superior Provinces, with target rocks of early Proterozoic age (Dressler and Reimold, 2001). It is surrounded by Huronian sedimentary rocks that are intruded by the northwest-trending Sudbury dikes, aged 1238 Ma (Krogh et al., 1987). Dence and Popelar (1972) were the first to present topographic, petrographic, and geophysical evidence in support of the impact theory. The circular shape of Lake Wanapitei was one of the first and most obvious clues indicating its origin. The authors used this observation as well as the drainage pattern of the lake to support their approach, citing a concentric pattern of streams and smaller lakes within 5 km of Wanapitei as further proof. This pattern is most obvious on the western side of the lake and coincides with the indented eastern rim of the Sudbury basin (Fig. 1). Dressler (1982) observed an apparently concentric pattern of joints and fractures peripheral to the lake as well as shatter cones on the islands and up to 5 km northwest of the lake. However, it is not clear whether the shatter cones should be attributed to the Wanapitei or the Sudbury impact events as the lake is located within the larger Sudbury structure.

The most conclusive evidence for an impact origin of the Wanapitei structure comes from petrographic studies of cobbles and boulders of suevitic breccias found in glacial drift south of Lake Wanapitei. These breccias contain impact melt fragments and clasts that exhibit shock metamorphic features. The first samples were found by M.R. Dence in the area south of the lake, north of Skead, followed by more discoveries around the Massey Bay area (see Fig. 1A). Dence and Popelar (1972) argued that the breccias originated from the bottom of the lake, stating that the boulders are weakly compacted and disintegrate upon handling. The boulders are also concentrated around the southern shores of the lake: Pleistocene glaciation is suggested to have scoured the bottom of the lake and transported the boulders of breccia southward.

Petrographic studies reveal target rock clasts in the suevitic breccias that exhibit planar deformation features in quartz and feldspar, and glass fragments with lechatelierite (Dence and Popelar, 1972; Dence et al., 1974; Grieve and Ber, 1994; Dressler et al., 1997). Coesite, a high pressure modification of silica, was identified by Dence and Popelar (1972) in a strongly shocked quartzite. Dressler (1982) observed planar deformation features in quartz grains in bedrock at only three locations southwest of the lake (Fig. 1A). Based on glass samples and the



necessary pressure for the formation of coesite, Dence et al. (1974) estimated that minimum shock pressures were between 40 and 50 GPa. Dressler et al. (1997) estimated shock pressures to be 50–60 GPa and temperatures to be >1700 °C, based on the absence of feldspar and the presence of glass in samples. A study was performed by Winzer et al. (1976) to determine the age of three samples consisting of breccia with glass veins, showing no visible signs of recrystallization or alteration. Two K/Ar dates were obtained from one glass vein and one whole rock glassy boulder: these revealed ages of 37.8 ± 1.6 Ma and 36.0 ± 1.6 Ma, respectively. Bottomley (1982) dated the samples at 36.1 ± 0.5 Ma based on ^{40}Ar-^{39}Ar dating of what appeared to be "melt textured rock." Evan et al. (1993) studied samples from the collection of Dence and Popelar and found evidence suggesting that the impacting body was chondritic (LL, L, or C1). Wolf et al. (1980) analyzed samples from the collection of the Gravity and Geodynamics Division, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, Canada, for Ir and Os abundances. Interelement ratios suggest a C1-C2 or an LL-chondrite as an impacting body.

As the crater is submerged, there are few constraints on its actual size: until recently, its suggested diameter has been based on one gravity survey performed on the ice covered lake in 1969 (Dence and Popelar, 1972) (Fig. 1C). The data were corrected for water mass using 1968 bathymetry measurements from the Ontario Department of Lands and Forests; however, no terrain corrections were applied. From the final Bouguer anomaly map, a circular low of ~15 mGal was observed covering almost the entire area of the lake. The 11-km-diameter bowl-shaped anomaly is of significant amplitude, yet constrained by only a few observations (see Fig. 1C). The relatively uniform magnetic field, as seen by aeromagnetic maps flown at a line spacing of 800 m (Fig. 1B), did not seem to indicate the presence of an intrusive body (Dence and Popelar, 1972).

Vertical Markers

The study of impact craters by geophysical methods often focuses on the recognition of offsets of local features such as seismic reflectors; such offsets can be used to trace faults. Seismic surveys make use of contrasting lithologies to map the tilting of slumped blocks or overturned strata at the rim of the crater, to

Figure 1. Lake Wanapitei regional setting. Northwest-trending lines represent Sudbury dikes and the 7.5-km-diameter circle indicates the impact crater proposed by Dence and Popelar (1972). (A) Geology. Stars indicate locations of planar deformation features in quartz; dots indicate samples of suevite and shock metamorphosed rocks (extracted from Dressler et al., 1997). SIC—Sudbury Igneous Complex. (B) Regional magnetic field; contour interval is 50 nT. The large Temagami magnetic anomaly extends southward into Lake Wanapitei. (C) Regional Bouguer gravity; contour interval is 1 mGal. Triangles indicate station locations. The circular anomaly has an amplitude of −15 mGal. Lake outline and dikes extracted from Dressler (1982).

trace a central uplift, and to identify zones of breccia infill (Mazur et al., 2000). Potential field anomalies reveal impact structures by their typically circular geometry, accompanied by disruptions in local trends. To study the Wanapitei impact, we used dikes of the Sudbury swarm as well-defined vertical markers indicative of such disruptions. The Precambrian olivine diabase dikes have a maximum width of 120 m in the lake area and exhibit a strong, linear total field magnetic anomaly (Figs. 1B and 2B). They appear to be more resistant to erosion than surrounding rocks in the immediate vicinity of the lake and are found in several outcrops on both the east and west shores.

A total field magnetic survey was conducted on Wanapitei in an attempt to track the diabase dikes through the proposed crater location. According to Ugalde et al. (this volume), the magnetic signature observed over large impact structures is primarily the combination of three effects: (1) composition and properties of target rocks; (2) modification of magnetic carriers due to high *P-T* conditions; and (3) natural remanent magnetization (NRM). It was our goal to constrain the outline of the crater based on a comparison of the measured magnetic field to models of pressure effects on the magnetic signature of the dikes (Fig. 3). To map the submerged dikes as well as to constrain gravity and magnetic anomalies, the thickness of young sediments was monitored with a high frequency single channel seismic survey (see Fig. 2C).

The results of the magnetic survey are shown in Figure 4A. 48 north-south lines were surveyed with a spacing of 500 m over

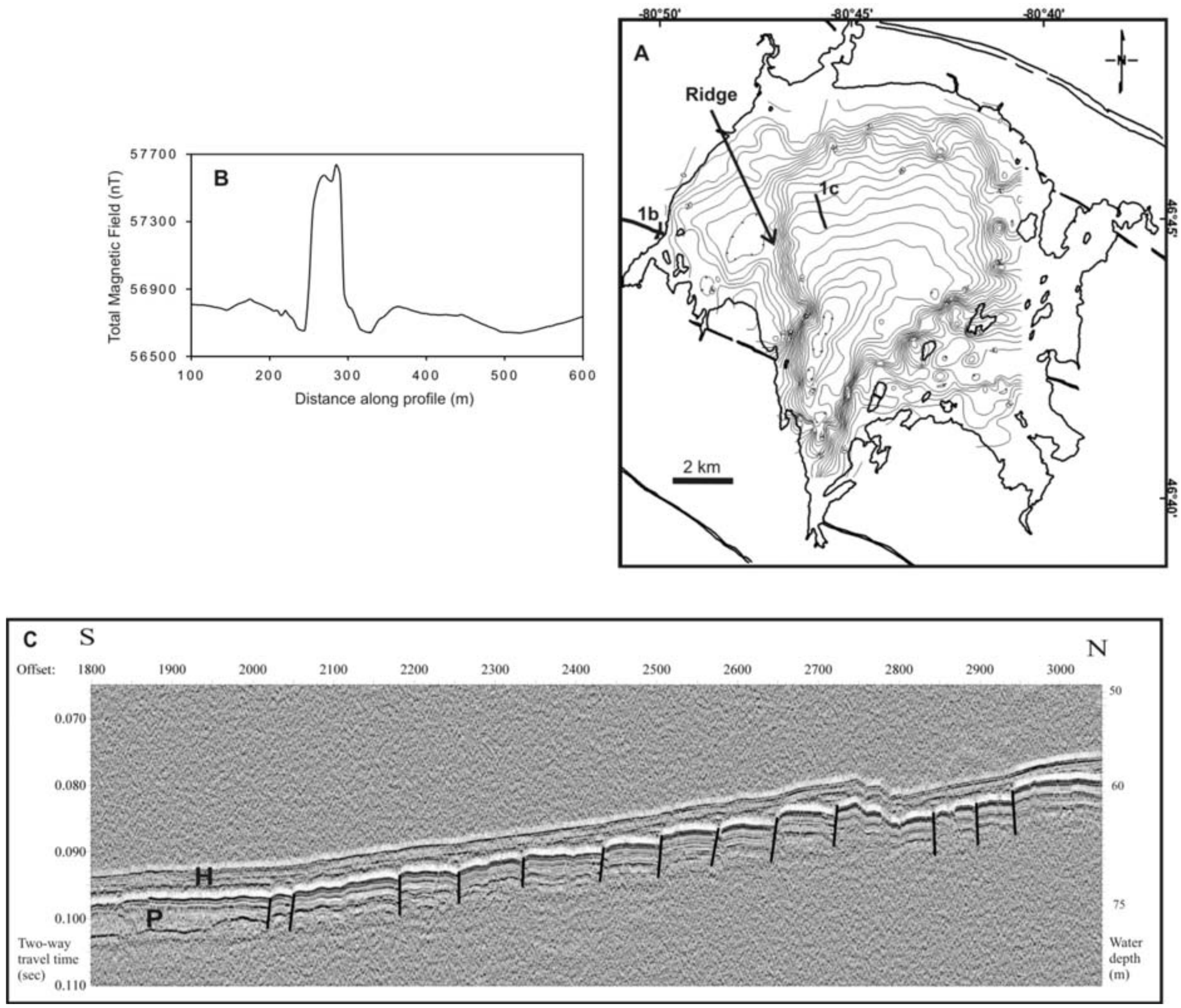


Figure 2. (A) Bathymetry over Lake Wanapitei (5 m contour lines) acquired with a 200 kHz echo sounder. The deepest part of the lake runs through the southern bay and reaches depths of ~100 m. Black lines labeled 1b and 1c indicate the locations of the magnetic and seismic profiles shown in B and C, respectively. (B) Magnetic signature of the Sudbury dike located on the west side of the lake. The dike exhibits a maximum amplitude of 1000 nT as compared to its granitic host rocks. (C) High frequency, single channel seismic profile through the central basin of Lake Wanapitei. Profile is ~1200 m in length, reaching up to 70 m water depth. Faulting occurs in Pleistocene sediments. H—Holocene sediments; P—Pleistocene sediments.

the entire area of the lake, and 12 east-west lines with uneven spacing were collected for leveling purposes. The data were acquired with a proton precession magnetometer with a sampling rate of 4 Hz, corresponding to a 1.4–2.4 m inline sample spacing. Bathymetry (Fig. 2A) was monitored concurrently with a 200 kHz echo sounder and global positioning system (GPS) positioning. The seismic data were collected with a high resolution digital sub-bottom profiler, with a depth penetration reaching up to 60 m after processing. Results show that the thickness of Pleistocene and Holocene sediments varies greatly throughout the lake, with maximum thicknesses of ~40–50 m in the western section of the lake (west of the ridge indicated in Fig. 2B). Furthermore, an area of ~5–6 km in diameter in the center of the lake is characterized by a thin, faulted layer of Pleistocene sedimentation (Fig. 2C).

DISCUSSION OF RESULTS

The total magnetic field over the lake correlates with the aeromagnetic map; it is dominated by the large Temagami magnetic anomaly to the north, which extends southward to cover approximately half of the lake area (see Figs. 1B and 4). The anomaly, situated in the Precambrian aged rocks of the Southern Province (Milkereit and Wu, 1996), is not affected by the Wanapitei impact. Toward the southern end of the lake, the magnetic field continues to decrease in amplitude. The Sudbury dikes are imaged as discontinuous, linear 75–100 nT anomalies trending northwest (Fig. 4). The gap in their signature coincides with an ~100 nT low in the magnetic field of 2–3 km in diameter. There is no evidence for a central uplift or coherent melt body in the magnetic field. Although direct evidence of the impact is not seen in the shallow penetrating seismic data of this study, profiles show that the area described by the gap in dike signature is covered by a thin, faulted and disturbed sediment layer of Pleistocene age (Fig. 2C). This may be the result of differential compaction and slumping of post-impact sediments above brecciated target rocks and fallback material. The same effect is observed in seismic profiles over the 10 km diameter impact crater in Lake Bosumtwi, Ghana. Lacustrine sediments overlying the crater are vertically fractured in the area of the faulted central uplift (Scholz et al., 2002), indicating that structural damage due to an impact has an effect on deposition and compaction of post-impact sediments.

Numerical modeling was used to simulate pressure conditions in a crater with a final diameter of 5 km (Ugalde et al., this volume) (Fig. 3). The model crater was generated with a stony asteroid projectile of 260 m in diameter striking vertically into a crystalline target at a velocity of 15 km/s. For a more complete description of the numerical model, please see Ugalde et al. (this volume). The results show that the originally vertical markers representing the Sudbury dikes are affected by the impact in the complex crater as follows:

1. Strain: the vertical markers in the center of the complex structure are removed by excavation and vaporization down to a depth of 500 m below the original target surface (0 level in Fig. 3). Markers located at 1000 m from the center of the structure are displaced outward down to a depth of 800 m.

2. A decrease in susceptibility and natural remanence: elevated pressures and temperatures are assumed to correlate with a reduction in susceptibility. Thus, we can infer that a decrease in susceptibility occurs as far down as 1000 m (where pressures are

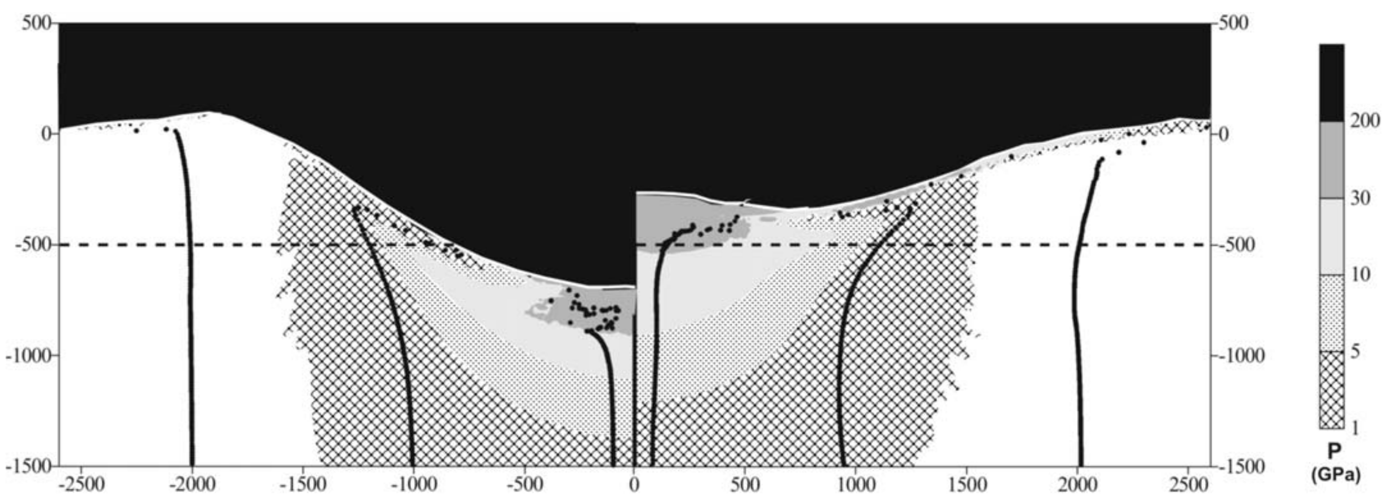


Figure 3. Results of a numerical model displaying pressure conditions in a 5-km-diameter impact crater (based on Ugalde et al., this volume). Pressures are in GPa, distances in m. The left half of the figure represents a simple crater; the right half is a complex crater. The dashed line indicates the assumed present erosion level (Dence and Popelar, 1972); thick vertical lines represent the Sudbury dikes. 1 GPa < P < 5 GPa = fracturing and brecciation (French, 1998). P < 10 GPa = existing remanence demagnetized (Cisowski and Fuller, 1978). P > 10 GPa = susceptibility depletion (Pilkington and Grieve, 1992). P > 30 GPa = magnetic resetting. Material above 200 GPa is vaporized. Dikes are demagnetized or vaporized in a central area with a diameter of ~3 km.

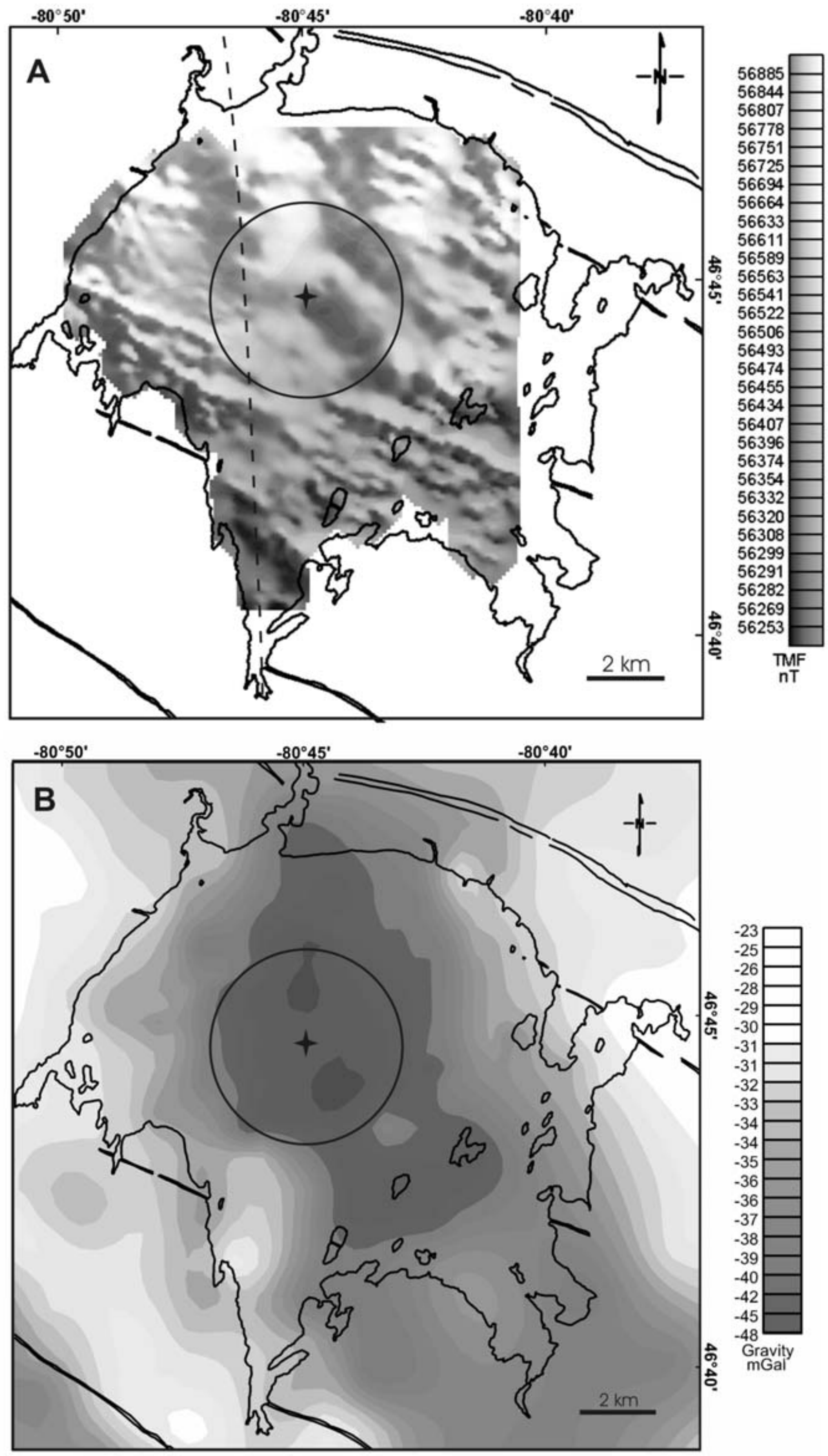


Figure 4. (A) Total magnetic field map over Lake Wanapitei. Sudbury dikes are imaged as linear, 75–100 nT anomalies striking northwest. Map is shaded from 45° declination, 0° inclination. A 5 km crater where the dike signature is disrupted and the location of a possible fault zone running north-south through the western part of the lake are indicated. (B) New gravity data collected during the winters of 2003 and 2004 (Ugalde et al., 2004). Increased sampling shows that the shape of the anomaly is concordant to the regional geologic framework rather than simply circular.

greater than 10 GPa [Pilkington and Grieve, 1992]). Remanence demagnetization (at pressures less than 10 GPa [Cisowski and Fuller, 1978]) affects the target structure down to ~1300 m below the target surface and as far as 1200 m from the center. Subsequently, these rocks may reacquire remanence through NRM as they cool.

3. Low magnetization sedimentary infill: post-impact sediments may fill the crater basin up to a depth of 300 m and out to a radius of 2000 m. Unless they build up significant detrital remanent magnetization (DRM), they will have a lower magnetic susceptibility and NRM than the crystalline basement.

4. Hydrothermal alteration: fracturing and brecciation intensively occur in a pressure interval of 1–5 GPa (French, 1998), out to a radius of 1500 m and depth >1500 m. The fractured rocks provide space for fluid circulation, and a hydrothermal system driven by small inclusions of melt could either increase or decrease the original magnetization (Ugalde et al., this volume).

The results of the model indicate that the processes generating an impact crater with a final diameter of 5 km have enough energy to decrease the magnetization of the vertical dikes out to a diameter of 3 km. The low in the magnetic field is the combined result of susceptibility depletion as described, excavation of the upper portion of the dikes (with subsequent infill of suevitic breccia and post-impact sediments), and brecciation of target rocks producing a randomization of magnetic vector orientations. Magnetic forward modeling of target rocks after the impact demonstrates that although the dikes may still be present at a depth of 500 m below the present-day surface, their magnetic signature is greatly reduced due to the petrophysical changes induced by the impact (Ugalde et al., this volume). Although the observed discontinuity in the magnetic anomaly of the dikes does not cross the center of the structure (Fig. 4), the possible location and size of the Wanapitei impact crater can be roughly constrained by projecting the gap in the magnetic field toward the center of impact. Based on the previously described model and the absence of a dike signature in the central part of the lake, we propose that the Wanapitei impact crater is less than 5 km in diameter. The magnetic discontinuity is located within the central section of the lake (Fig. 4), coinciding with the greatest depths (see bathymetry in Fig. 2A). The unconsolidated and faulted material below and above the impact crater will produce a negative gravity anomaly in the center of the lake.

Recently, new gravity data was collected that provides a finer sampling of the anomaly over Lake Wanapitei (Ugalde et al., 2004). The final Bouguer map, including terrain corrections, shows a smaller, less circular low in the central area of the lake (Fig. 4B). The anomaly no longer has the large characteristic bowl shape that distinguished it from the regional field.

Structural Deformation Unrelated to the Impact

Further interpretation with respect to the structure of Lake Wanapitei and a possible relation to the eastern rim of the Sudbury basin (Fig. 1A) can be derived from the results of these surveys. The most apparent feature is seen in the bathymetry of the lake (Fig. 2): a ridge separating the central basin from the western "lobe." This separation has a distinct north-south trend and coincides with the southeastern shore of the lake, as well as with an inferred fault running through Massey Bay (Dressler, 1982). It may be the extension of the regional Onaping-Matagami fault zone that runs more than 450 km northward (Buchan and Ernst, 1994) and produces 7–8 km of left-lateral offset. This fault is between 2.2 and 1.9 Ga in the Sudbury-Wanapitei region (Buchan and Ernst, 1994), thereby predating the formation of the dikes, but it may have gone through subsequent periods of reactivation. It is therefore suggested that a large fault zone runs north-south through Wanapitei Lake (Fig. 4B), exerting control over the emplacement of the Sudbury dikes as well as acting as a zone of weakness influencing Pleistocene glacial activity. Valleys of glacial till extend more than 25 km to the south of the lake along the same path (Burwasser, 1979). It is estimated that up to 500 m of erosion have affected the area since the emplacement of the Wanapitei crater 37 Ma (Dence and Popelar, 1972). The trend of the whole lake structure is comparable to the eastern rim of the Sudbury basin (see Fig. 1), suggesting that the present-day shape and size of Wanapitei Lake is due rather to regional deformation and glacial action than to the original meteorite impact.

CONCLUSIONS

By modeling the effects of impact on the magnetic signature of a crystalline target, it is possible to estimate the extent of the crater making use of markers in the terrain. In the case of the Wanapitei structure, vertical dikes with a characteristically high, linear total field magnetic anomaly were used as indicators to outline the crater. The method proved useful in reducing the estimated diameter of the crater based on attenuation of the dikes' magnetic signature. Large swarms such as the Sudbury dikes exist in most Archean craton environments and have typically been used for large scale deformation or continental studies. It has been demonstrated here that through detailed images of the dikes, small disruptions in their signature can be identified and related to impact events.

The detailed magnetic field map over Lake Wanapitei serves to constrain the possible location of the impact crater by the gap in the linear signature of the Sudbury dikes, which are used as vertical indicators of the structural damage produced by meteorite impact. The area delineated by the gap is characterized by a faulted layer of sediment and is located in the central part of the lake's main basin. The ridge that separates the lake into eastern and western sections follows a north-south trend that is comparable to that of the East Range in the Sudbury Igneous Complex. It corresponds to the extension of a documented fault zone that runs for several kilometers north of the Wanapitei area (Buchan and Ernst, 1994). Glacial scouring has produced valleys of till that reveal the zone of weakness associated with the fault and the excavation by glaciers during the Pleistocene (see Burwasser, 1979). It is our conclusion that the Wanapitei impact crater is confined to an area less than 5 km in diameter and that the character of the magnetic and gravity fields over the lake suggests a simple geometry (there is no evidence for a central uplift). The lake itself takes its semi-circular shape from regional deformation associated with faulting and glacial scouring.

ACKNOWLEDGMENTS

We thank Mike Doughty for conducting the seismic survey, Wei Qian for the magnetometer surveys, and Erick Adam for his help with seismic data processing. Comments and suggestions from T. Kenkmann, B. Dressler, and an anonymous reviewer were greatly appreciated. Data collection on Lake Wanapitei was funded by the National Sciences and Engineering Research Council (Canada).

REFERENCES CITED

Bottomley, R.J., 1982, ^{40}Ar-^{39}Ar dating of melt rock from impact craters [Ph.D. thesis]: Toronto, University of Toronto, 103 p.

Buchan, K.L., and Ernst, R.E., 1994, Onaping fault system: Age constraints on deformation of the Kapuskasing structural zone and units underlying the Sudbury structure: Canadian Journal of Earth Sciences, v. 31, p. 1197–1205.

Burwasser, G.J., 1979, Quaternary geology of the Sudbury basin area, district of Sudbury: Ontario Geological Survey Report 181, 103 p.

Cisowski, S.M., and Fuller, M., 1978, The effect of shock on the magnetism of terrestrial rocks: Journal of Geophysical Research, v. 83, no. B7, p. 3441–3458.

Dence, M.R., and Popelar, J., 1972, Evidence for an impact origin for Lake Wanapitei, Ontario, *in* Guy-Bray, J.V., ed., New developments in Sudbury geology: Geological Association of Canada Special Paper 10, p. 117–124.

Dence, M.R., Robertson, P.B., and Wirthlin, R.L., 1974, Coesite from the Lake Wanapitei crater, Ontario: Earth and Planetary Science Letters, v. 22, p. 118–122, doi: 10.1016/0012-821X(74)90071-5.

Dressler, B.O., 1982, Geology of the Wanapitei Lake area, district of Sudbury: Ontario Geological Survey Report 213, 131 p.

Dressler, B.O., and Reimold, W.U., 2001, Terrestrial impact melt rocks and glasses: Earth Science Reviews, v. 56, p. 205–284, doi: 10.1016/S0012-8252(01)00064-2.

Dressler, B.O., Crabtree, D., and Schuraytz, B.C., 1997, Incipient melt formation and devitrification at the Wanapitei impact structure, Ontario, Canada: Meteoritics & Planetary Science, v. 32, p. 249–258.

Ernst, R.E., Head, J.W., Parfitt, E., Grosfils, E., and Wilson, L., 1995, Giant radiating dyke swarms on Earth and Venus: Earth Science Reviews, v. 39, p. 1–58, doi: 10.1016/0012-8252(95)00017-5.

Evan, N.J., Gregoire, D.C., Grieve, R.A.F., Goodfellow, W.D., and Veizer, J., 1993, Use of platinum-group elements for impactor identification: Terrestrial impact craters and Cretaceous-Tertiary boundary: Geochimica et Cosmochimica Acta, v. 57, p. 3737–3748, doi: 10.1016/0016-7037(93)90152-M.

French, B.M., 1998, Traces of catastrophe: A handbook of shock-metamorphic effects in terrestrial meteorite impact structures, LPI Contribution no 120: Houston, Lunar and Planetary Institute, 120 p.

Grieve, R.A.F., and Ber, T.J., 1994, Shocked lithologies at the Wanapitei impact structure, Ontario, Canada: Meteoritics, v. 29, p. 621–631.

Halls, H.C., Palmer, H.C., Bates, M.P., and Phinney, W.C., 1994, Constraints on the nature of the Kapuskasing structural zone from the study of Proterozoic dyke swarms: Canadian Journal of Earth Sciences, v. 31, p. 1182–1196.

Krogh, T.E., Corfu, F., Davis, D.W., Dunning, G.R., Heaman, L.M., Kamo, S.L., Machado, N., Greenhough, J.D., and Nakamura, E., 1987, Precise U-Pb isotopic ages of diabase dykes and mafic to ultramafic rocks using trace amounts of baddeleyite and zircon, *in* Halls, H.C. and Fahrig, W.F., eds., Mafic dyke swarms: Geological Association of Canada Special Paper 34, p. 147–152.

Mazur, M.J., Stewart, R.R., and Hildebrand, A.R., 2000, The seismic signature of meteorite impact craters: CSEG Recorder, v. 25, p. 10–16.

Mertanen, S., Halls, H.C., Vuollo, J.I., Pesonen, L.J., and Stepanov, V.S., 1999, Paleomagnetism of 2.44 Ga mafic dykes in Russian Karelia, eastern Fennoscandian shield—implications for continental reconstructions: Precambrian Research, v. 98, p. 197–221, doi: 10.1016/S0301-9268(99)00050-9.

Milkereit, B., and Wu, J., 1996, Seismic image of an early Proterozoic rift basin: Tectonophysics, v. 264, p. 89–100, doi: 10.1016/S0040-1951(96)00119-9.

Morris, W.A., and Tanczyk, E.I., 1978, Precambrian dykes: A preferred orientation of intrusion: Nature, v. 275, p. 120–121.

Pilkington, M., and Grieve, R.A.F., 1992, The geophysical signature of terrestrial impact craters: Reviews of Geophysics, v. 30, p. 161–181.

Scholz, C.A., Karp, T., Brooks, K.M., Milkereit, B., Amoako, P.Y.O., and Arko, J.A., 2002, Pronounced central uplift identified in the Bosumtwi impact structure, Ghana, using multichannel seismic reflection data: Geology, v. 30, p. 939–942, doi: 10.1130/0091-7613(2002)0302.0.CO;2.

Siddorn, J.P., and Halls, H.C., 2002, Variation in plagioclase clouding intensity in Matachewan dykes: Evidence for the exhumation history of the northern margin of the Sudbury Igneous Complex: Canadian Journal of Earth Sciences, v. 39, p. 933–942, doi: 10.1139/E02-003.

Schwarz, E.J., and Buchan, K.L., 1989, Identifying types of remanent magnetization in igneous contact zones: Physics of the Earth and Planetary Interiors, v. 58, p. 155–162, doi: 10.1016/0031-9201(89)90051-4.

Ugalde, H., L'Heureux, E., Milkereit, B., and Lachapelle, R., 2004, Measuring gravity on ice: an example from Wanapitei Lake, Ontario, Canada [expanded abstract]: SEG International Exposition and 74th Annual Meeting.

West, G.F., and Ernst, R.E., 1991, Evidence from aeromagnetics on the configuration of Matachewan dykes and the tectonic evolution of the Kapuskasing structural zone, Ontario, Canada: Canadian Journal of Earth Sciences, v. 28, p. 1797–1811.

Winzer, S.R., Lum, R.K.L., and Schuhmann, S., 1976, Rb, Sr and strontium isotopic composition, K/Ar age and large ion lithophile element abundances in rocks and glasses from the Wanapitei Lake impact structure: Geochimica et Cosmochimica Acta, v. 40, p. 51–57, doi: 10.1016/0016-7037(76)90193-9.

Wolf, R., Woodrow, A.B., and Grieve, R.A.F., 1980, Meteoritic material at four Canadian impact craters: Geochimica et Cosmochimica Acta, v. 44, p. 1015–1022, doi: 10.1016/0016-7037(80)90289-6.

Yale, L.B., and Carpenter, S.J., 1998, Large igneous provinces and giant dike swarms: Proxies for supercontinent cyclicity and mantle convection: Earth and Planetary Science Letters, v. 163, p. 109–122, doi: 10.1016/S0012-821X(98)00179-4.

Manuscript Accepted by the Society 9 August 2004