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GUIDE TO THE GEOLOGY OF SUDBURY BASIN,
ONTARIO, CANADA
(Apollo 17 Training Exercise, 5/23/72-5/25/72)

by

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# ERRATA

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<u>Page</u> ii. Add "(photograph by G. Mac G. Boone)" to caption.

iii. P. 2, line 5; delete "the" before "data".

iv. P. 1, line 3; add "of Canada, Ltd." after "Company".

iv. P. 1, line 7; delete "of Canada" after "Company".

v. Move entire section "aerial reconnaissance....etc..." 5 spaces to left margin.

1. P. 2, line 6; add "moderate to" after "dips are".

1. P. 2, line 13; change "strike" to "striking".

2. P. 1, line 2; change "there" to "these".

2. P. 2, line 7; change "(1) breccias" to "breccias (1)".

2. P. 3, line 3; add "slate" after "Onwatin".

4. P. 1, line 7; change "which <u>is</u>" to "which <u>are</u>".

7. P. 1, line 9; add "(fig. 3)" after "surveys".

7. P. 2, line 4; delete "(C)", add "the previous section" after "presented in".

11. P. 1, line 3; change "southwest" to "southeast".

28. P. 2, line 3; change "anomolously" to "anom<u>a</u>lously".

39. P. 7, line 3; add "and eastern Quebec" after "Ontario"

39. P. 9, line 1; add "silica" after "Lechatelierite".

40. P. 10, line 2; change "shear" to "fracture".

40. P. 13, line 1; change "shorted" to "sorted".

"The Sudbury nickel Irruptive furnishes a most interesting case of the painfully slow, caterpillar-like, yet logical way in which we grope our way to an understanding of big and intricate geological bodies" (W. H. Collins, 1934).

Shatter cones in quartzite at Kelley Lake, Sudbury, Ontario, Canada

## Foreword

This guide has been prepared in Ottawa, Canada and Flagstaff, Arizona for Apollo 17 flight crews participating in the Field Training Exercise in the Sudbury Basin on May 23, 1972 through May 25, 1972. The authors have departed from standard guidebook format with the intent of presenting the dynamic aspects of research centered on the Sudbury Basin. References to literature are not made in the text to avoid distractions and the use of geologic jargon has been kept to a minimum. A reference list and glossary are provided at the end of the guide, respectively to show sources of published data and to refresh geologic vocabularies. For the exercise we have adopted a "problem solving" approach in which the crews are encouraged to evaluate observations recorded in the literature, gather new data, and summarize their own interpretations, which may or may not agree with syntheses generated by others.

The evolution of thought during research in the Sudbury Basin illustrates the power of scientific rigor, first, in compiling field and laboratory data, and second, synthesizing these data into models. These models relate either to (1) orthomagmatic or (2) impact events. Neither the the data nor the models are complete, so that, at this time, neither model can be dismissed as obviously incorrect. We favor the unifying model of an impact event.

The field stops afford a brief synopsis of the geology of the Sudbury Basin; they have been chosen to display as many features as possible that we believe are fundamental to an understanding of the geology of the Basin. Crew members are encouraged to prepare themselves during the aerial reconnaissance and the field stops to evaluate the impact model and possibly to present alternatives.

ACKNOWLEDGMENTS AND SOURCES OF INFORMATION

The exercise is co-hosted by the Earth Physics Branch, Department of Energy, Mines and Resources of Canada and the International Nickel Company. We are grateful for the interest and help of Dr. John H. Hodgson, Director of the Earth Physics Branch who pledged his staff and Ottawa facilities to the conduct of the exercise. We are also grateful for the participation and help provided us by Dr. J. V. Guy-Bray and Don Phipps of International Nickel Company of Canada in arranging access, conference facilities, and logistical support for the exercise. J. D. Strobell, Jr. reviewed the manuscript and made many improvements.

This guide is abstracted from many sources, both published and unpublished. Those published are included in the list of selected references at the end of the guide. We have used considerable unpublished information from guides for field excursions run in conjunction with the annual meetings of the Geological Association of Canada and Mineralogical Association of Canada in Sudbury in May, 1971; a symposium volume resulting from these meetings is in press. We have also used information compiled in preparation for the International Geological Congress in Canada in August, 1972. Free use has been made of unpublished data from the ongoing work of M. R. Dence, M. J. S. Innes, J. Popelar, and D. P. Gold, all of the Earth Physics Branch, Department of Energy, Mines, and Resources at Ottawa; J. V. Guy-Bray, D. Phipps, and E. Pattison of the International Nickel Company; K. D. Card of the Ontario Department of Mines; and A. J. Naldrett and W. Peredery of the University of Toronto.

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# INTRODUCTION

## Sudbury as a classic example of interaction between observation and theory

The Sudbury Basin is the world's largest producer of nickel, and an important producer of other associated metals. Consequently, geologic study of the Basin has been intense, and excellent control in the vertical direction has been provided by mine workings and exploratory drilling. In spite of this, the genesis of the Basin itself and of certain of the rock units contained in it has been the subject of spirited debate for more than eighty years. An historical overview of this debate serves as an excellent example of the development of observation and hypothesis, and of the mutual effect of the one on the other.

## Outline of the geology of Sudbury Basin: facts[1/]

Sudbury Basin is an ellipsoidal structure whose major axis, measuring about 60 km, trends east-northeast (fig. 1). The minor axis measures about 27 km. The edges of the structure are defined structurally and topographically by resistant rocks of the Sudbury Irruptive, dated at 1.7 b.y. These rocks form ridges, e.g., the North Range and South Range (fig. 2). In most places, dips are steep and toward the center of the Basin. The direct structural control now available is compatible with either a spoon or a funnel form for the Basin (fig. 3). The youngest rocks preserved, in the center of the Basin, have an overall spoon-like form, and are thrown into broad folds whose axes parallel the long axis of the Basin. Numerous faults cut the Basin. The most important are high-angle dip-slip faults with the south side upthrown and strike approximately parallel to the major axis of the Basin. Folds and faults are shown on the Sudbury-Cobalt Sheet, Geological Compilation Series (Ontario Department of Mines and Northern Affairs Map 2188).

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1/ The outline presented above is no more than a thumbnail sketch. More detailed information on the various rock units and their contacts is given later.

The Sudbury Basin is surrounded by Precambrian rocks. To the north and west, there consist of granite and gneiss more than 2.5 b.y. old, to the south and east, of metasediments and metavolcanics of somewhat younger age. These younger rocks are intruded by sills, dikes and plugs of the Sudbury gabbro (2.15 b.y.) and were affected by orogenic events between 2.15 and 1.7 b.y. ago. Four to ten km southeast of the Sudbury Basin, a major northeast-trending structural lineament (the Grenville Front) separates these rocks from other Precambrian rocks differing in age of deformation (metamorphism), composition, and structural style (fig. 2).

The rocks immediately surrounding the Basin (collectively referred to as "footwall rock") have been brecciated in a zone up to 20 km wide. It is important to note that this type of brecciation does not affect the Sudbury Irruptive and younger rocks of the Basin. The brecciated footwall rock is referred to as the "Sudbury Breccia" as distinctive in appearance and genesis from (1) breccias at the base of the Irruptive and (2) in the rocks overlying the Irruptive.

The rocks within the Sudbury Basin are, in ascending order, (1) the Sudbury Irruptive, 2-3 km thick, (2) the Onaping Formation, about 1500 m thick, (3) the Onwatin, 800 m thick and (4) the Chelmsford sandstone, 850 m thick (figs. 1 and 3). The Onwatin and the Chelmsford have been dated at about 1.7 b.y. The Onaping, Onwatin, and Chelmsford comprise the Whitewater Group.

The Sudbury Irruptive is a massive, sheet-like igneous rock emplaced between footwall rocks and those of the Whitewater Group. It is differentiated into a more mafic basal unit (norite), 1/3 to 1/2 of the total thickness of the Irruptive, grading upward into a more siliceous upper unit called the "micropegmatite". A discontinuous layer of breccia, as much as 200 m thick, called the "sublayer" occurs at the base of the Irruptive. The sublayer has an igneous matrix which includes the sulfide mineralization of commerical grade and resembles an igneous breccia in contrast with the footwall breccia, which resembles fault breccia.

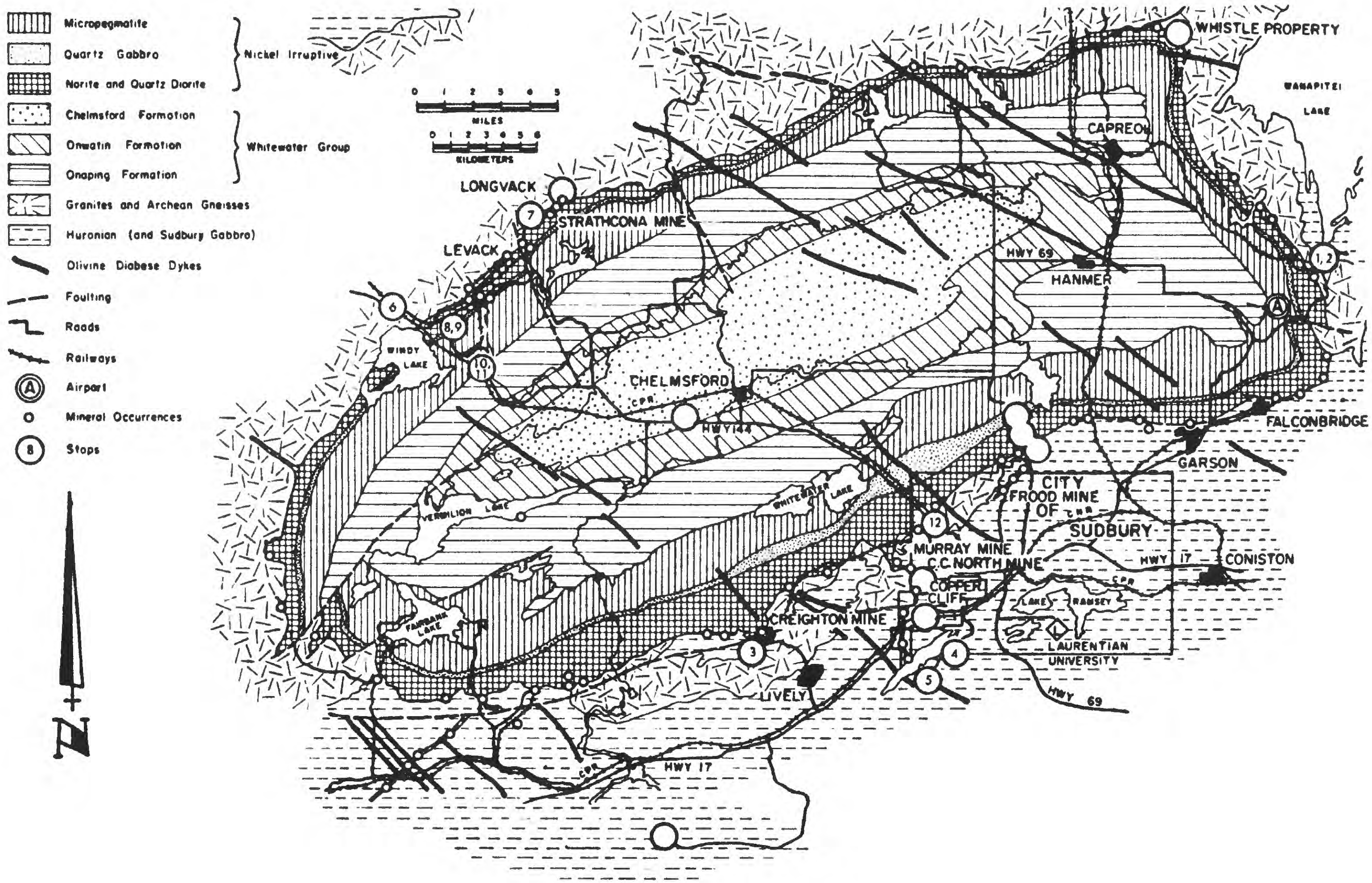



Figure 1. Geology of the Sudbury Basin showing field stops (from Guy-Bray and others, 1972).

The Onaping Formation is divided into three subunits, in ascending order the "basal" or "quartzite breccia", the "gray" Onaping, and the "black" Onaping. The quartzite breccia shows some textural similarities to the sublayer breccia, but differs greatly in composition. It also varies in thickness from almost zero to about 200 m. Clasts from less than 1 m to more than 50 m across are of quartzite and granite gneiss, some of which is shocked, and held in a partly igneous, partly recrystallized clastic matrix. The composition of clasts and matrix is similar. The gray Onaping, 200-300 m thick, is characterized by glassy clasts associated with clasts of country rock, some shocked, in light gray hornfelsic clastic matrix. This unit grades upward into the black Onaping, about 1000 m thick, which is generally similar to the gray Onaping, but contains smaller and less altered clasts in a fine-grained black matrix characterized by several percent of carbonaceous material. Minor sulfide (pyrrhotite) is dispersed throughout the matrix.

The black Onaping grades upward into the Onwatin slate, which is chemically similar and consists of fine-grained, carbonaceous, pyritic argillite and local beds of laminated limestone and chert.

The Onwatin grades upward into the Chelmsford sandstone, a carbonaceous subgraywacke with well developed bedding and abundant marine sedimentary structures.

Younger material includes diabase dikes of late Precambrian age cutting all rock units of the Basin, and alluvial and glacial deposits of Quaternary age.

## Evolution of tectonic and stratigraphic model for the Sudbury Basin: interpretations

The overview presented here is a concise summary of the history of study of the Sudbury Basin. More extensive treatments can be found in many of the papers listed in the bibliography.

The history of geologic study of the Basin can be divided into phases based upon the problems that were of chief interest,

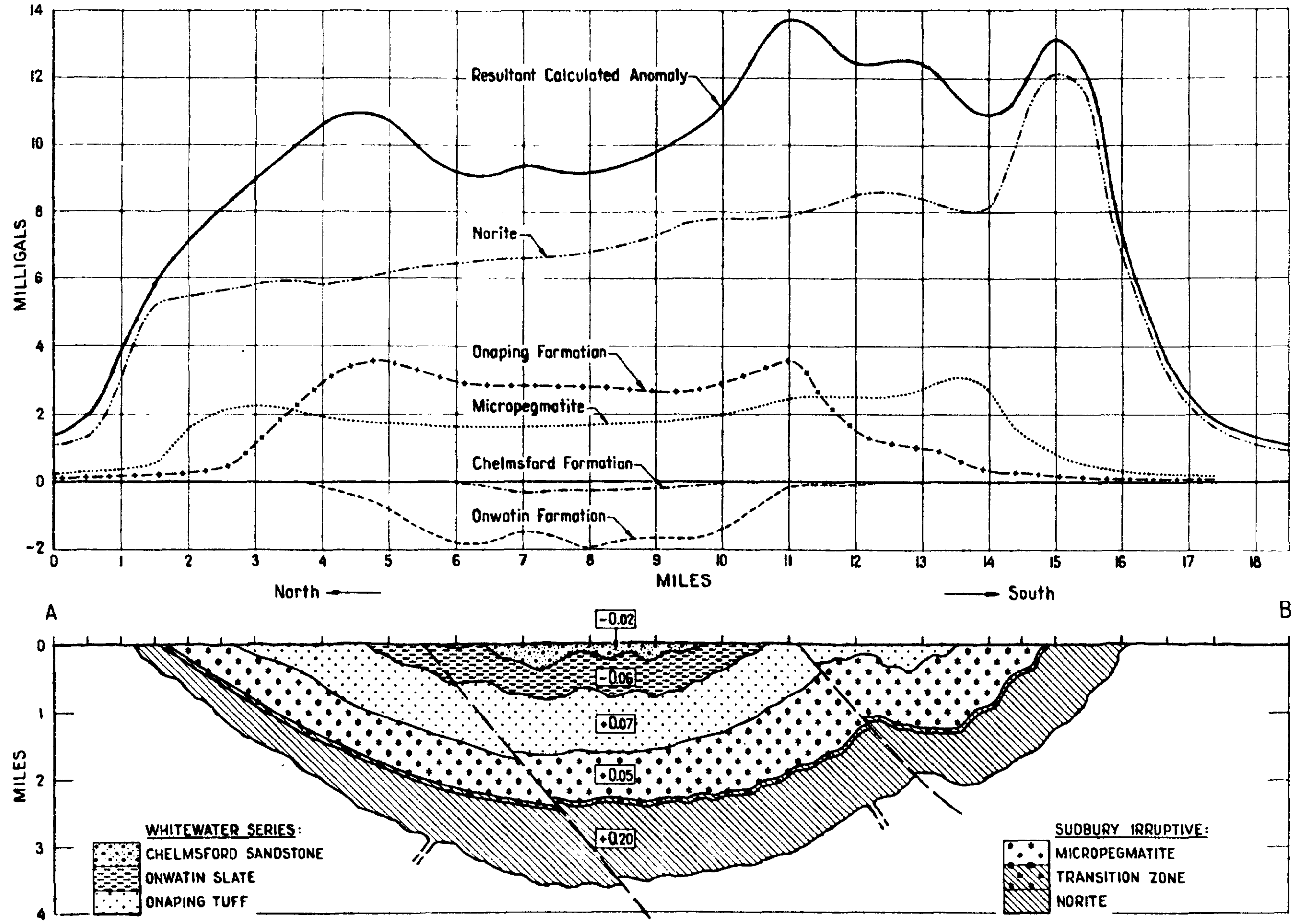



Figure 3. Gravity profiles and calculated profile of the Sudbury Basin (from Miller and Innes, 1955).

the critical observations that were made, and the hypotheses that were generated.

Recognition phase: 1890-1910

The discovery of metallic ores during railway construction in 1883 sparked an initial period of prospecting. By 1890 scientific studies were underway. During this phase the Sudbury structure was recognized as a structural basin, and the main stratigraphic units within the Basin were defined and named. Interest centered on the relation between rocks within the Basin and those outside, and on the nature and mechanism of emplacement of the Irruptive. The Irruptive was regarded as a folded sill, and the norite, micropegmatite and ores were interpreted as the result of magmatic differentiation within this sill.

Detailed study phase: 1910-1955

This phase consisted chiefly of extending the scope and depth of observations, largely within the framework of previously established hypotheses. Interest centered on detailed study of individual rock units, the origin of the ore bodies, the three-dimensional shape of the Basin, interpretation of the Onaping Formation, including the contact with the micropegmatite as well as the basal breccia, the mechanism of emplacement of the Irruptive, and on whether the norite and micropegmatite represent magmatic differentiation or two separate intrusions. Metamorphic contacts were documented at both the base and the top of the Irruptive. The Basin itself was variously interpreted as a syncline formed by folding and faulting of originally flat-lying deposits, or as a volcano-tectonic complex consisting of ring dikes with or without a collapsed center. The Onaping Formation was interpreted as a volcanic unit, commonly a pyroclastic one, with a basal unit of conglomerate or volcanic breccia. Breccias in the country rock were considered to be connected with either the intrusion of the Irruptive, or the later orogenic deformation.

New syntheses: 1955-1964

New concepts and new techniques were brought to bear on the problem of the genesis of the Irruptive and the Onaping, modifying or challenging previous interpretations. The Irruptive was interpreted by some as a funnel-shaped lopolith similar to other layered complexes with an ultramafic zone at depth. Others considered the Basin to be a volcano-tectonic depression surrounded by ring dike complexes, later folded into a spoon shape and then intruded concordantly and in two stages by the Irruptive. Gravity surveys showed that values in the center of the Basin, although high, are not high enough to support the lopolith (or funnel-shaped) model. Isotopic age determinations showed that the Irruptive is about the same age as the Whitewater Group. Paleomagnetic studies showed a 30° difference in pole position for the same units on the north and south sides of the Basin, confirming structural deformation after emplacement. For the first time, the Onaping Formation was regarded as the product of a single, catastrophic event: the basal breccia was interpreted as autobrecciated material of rhyolite domes and dikes that fed glowing avalanches whose products constitute the rest of the formation. From studies of the breccia and regional structure, the Basin was seen as a caldera collapse structure in the center of a broad domal uplift.

Revolution: 1964-present

An entirely new concept--impact--has revolutionized previous interpretations and has led to new observations and syntheses. The initial discovery of shatter cones led to an interpretation similar to the volcano-tectonic one presented in (c), but with volcanism triggered by impact. The Onaping Formation was still considered a volcanic unit, the only melt resulting directly from impact was thought to be represented by the sublayer igneous rock, and the metals of the ore were thought to be derived from the projectile. It was soon confirmed that shatter cones occur all around the Basin in rocks predating the structure. By 1967 deformation lamellae or planar elements as well as other evidence of shock metamorphism had been found in clasts within the Onaping. Detailed studies of the Irruptive, the sublayer and quartzite breccias, have confirmed magmatic differentiation of the main Irruptive, but have shown that the sublayer is a distinct unit. Recent gravity data confirm the spoon-shape model for the Irruptive and also that displacement on faults has resulted in as much as three miles of uplift of South Range relative to North Range. Wanapitei Lake basin has been recognized as an impact structure. Currently favored hypotheses are variants of the following: a meteorite struck the area of Sudbury Basin, which was then probably receiving sediments under water. The impact brecciated the country rock, excavated a deep crater, produced some direct melt, and large amounts of impact breccia (Onaping) some of which fell back into the crater, and some slumped in or was brought in later by normal geologic processes. The impact triggered melting, either in the crust or the mantle, which produced the stratiform complex of the Irruptive. The target area may already have been unusually hot in incipient orogenesis before impact. After normal geologic processes became reestablished, the crater continued to be filled, first by reworked material of the ejecta blanket, then by sand and other detritus carried in by turbidity currents. Some geologists, however, continue to favor a volcano-tectonic hypothesis for the genesis of the Basin.

Future work

Work will continue on resolving definitively whether the impact or one of the volcanic hypotheses is correct, and on clarifying many details that are still enigmatic. These include, among others, the mechanism of obtaining the present shape of the Basin from an initially circular one, and the question of how much of the Irruptive can be accounted for by direct impact melting, and where and how the balance was generated. Detailed comparisons will be made on a world-wide basis with other circular structures and stratiform complexes. Comparative studies will also be made with appropriate features on the moon, Mars, and other planets.

# AERIAL RECONNAISSANCE OF SELECTED STRUCTURES IN THE PRECAMBRIAN SHIELD AND OF THE SUDBURY BASIN: THE SYNOPTIC OR MEGASCOPIC VIEW

## Purpose

Erosion of the Precambrian Shield has produced physiographic patterns and lineaments (fig. 2) that express the interaction of fold belts, faults, intrusions, meteorite impacts, and glaciation. An aerial overview is taken to establish the regional structural and physiographic context of the Sudbury Basin and to demonstrate that some circular features can be explained by intrusive mechanics while others are impact sites. The flight will provide a view of three different impact features (Sudbury, Brent, and Wanapitei) among the several presently identified on the Shield (fig. 4).

## General flight plan

The flight is southeasterly from Sudbury Airport over the Grenville Front to Lake Nipissing thence easterly over alkalic intrusive complexes at the Manitou Islands and Callander Bay about 200 km to Brent Crater. The return is westerly along the south shore of Lake Nippissing, thence northwesterly back over the Grenville Front to Sudbury. The Sudbury Basin is then circled clockwise to the Wanapitei Lake impact structure, after which the aircraft will return to Sudbury Airport. The total elapsed flight time is estimated to be 2-1/2 hours. An explanation of the geological features seen along the flight line will be given by site geologists.

## Principal features observed

### Grenville Front

A major structural boundary between Precambrian terranes that differ in lithology, geologic history, and, to some extent, in age, occurs 8 km southeast of Sudbury. These terranes have had different tectonic histories as shown by contrasting deformation patterns. The rocks northwest of the Front have been deformed

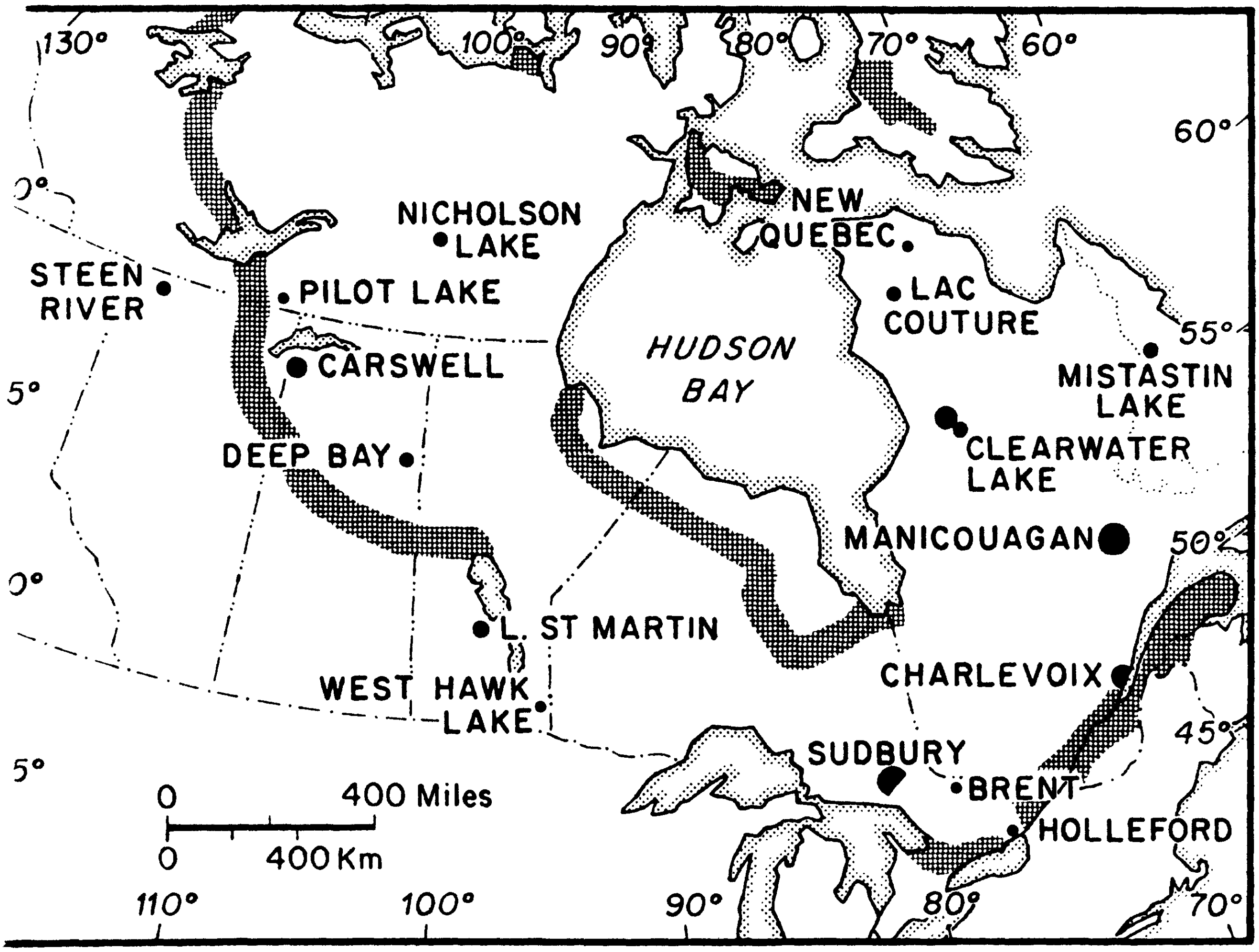



Figure 4. The distribution of probable impact structures on the Canadian Shield.

principally by faulting (shown by strong east-west and northeast linears) with some folding near the Front. The rocks on the southwest are deformed by a combination of folding and faulting (shown by major swirls truncated by linears). Rocks southeast of the Front tend to be somewhat younger, but age correlations have been made between some rock units on either side. Thus, the Front is more properly classified as a tectonic boundary than as a time boundary.

### Faults and folds

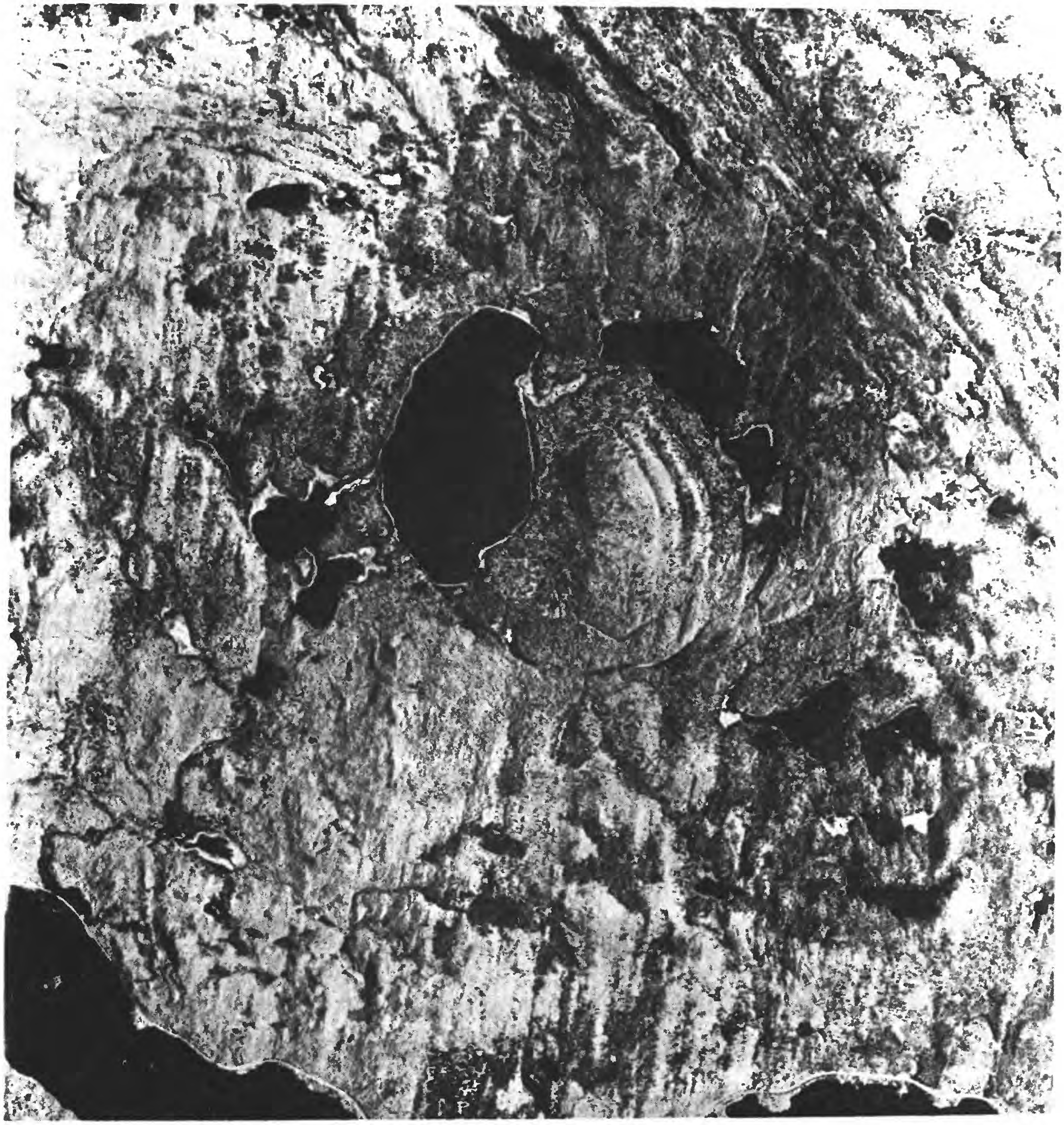
Rocks of the Grenville province southeast of the Front are cut by conspicuous extensive linears associated with faults oriented west-northwest, northeast, and east. The east-trending faults are dominant, and some to the east are recently active. The alkalic intrusive complexes in eastern Lake Nipissing basin are aligned with some of the east-trending faults. The overall style of faulting and the resultant blocks are reminiscent of the structural pattern of the Sinai Peninsula and Red Sea. Fold belts in metamorphic rocks between major fault segments are shown by intricate swirl patterns resembling wood grain and produced by differential erosion of the layered sequence. Segments without patterns are likely dominated by plutonic rocks, which erode more uniformly.

### Alkalic complexes

The groups of islands including the Manitou Islands in Lake Nipissing and Callander Bay on the eastern shore result from erosion of alkalic intrusive complexes. The Manitou Islands and Callander Bay are remarkably circular and could reasonably be mistaken for impact features if data obtained from the ground were not available.

### Brent Crater

Not all circular features have an explanation that is obvious from the ground. Extensive drilling was required to establish the nature of the Brent structure (fig. 5). This



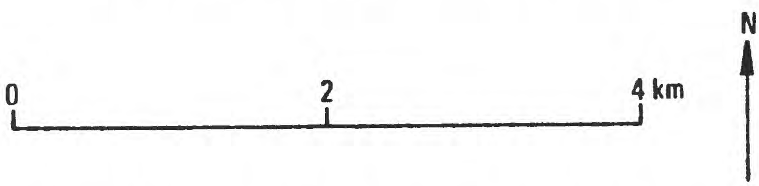



Figure 5. Aerial photograph of Brent Crater showing outline and regional linears produced by bedrock structure and glaciation.

structure is currently the best documented impact structure on the Shield--if not the world. The structure was produced during the middle Ordovician, then later buried by continued Paleozoic sedimentation. Stratigraphic and mineralogic evidence suggests that the surface has been lowered about 1000 feet to the present level since accumulation of the youngest sediments.

Sudbury Basin

Erosion-resistant concentric ridges cored by the Irruptive outline the Basin which has a flat interior underlain by the metasedimentary rocks of the Whitewater Group. The Grenville Front, several kilometers to the south, is marked by a prominent valley. The rocks outside the ring are massive in appearance in contrast with the disrupted appearance of the Irruptive ring itself. The north-trending fault system is displayed in prominent linears--especially where the faults cross the North Range. The northeasterly faults are not as conspicuous, but fold deformation within rocks of the Whitewater Group is manifested by "wood grain" effects similar to those in the Grenville rocks. It is notable that no conspicuous large structural features, such as ring fractures, that can be attributed directly to an impact event can be seen outside the ring. Assuming that Sudbury originated as an impact, the shock energy probably was largely absorbed by movements along pre-existing disjunctures rather than by forming new ones.

Wanapitei Lake

The circular depression and concentric arrangement of linears associated with Wanapitei Lake are impressed upon the structure of the Sudbury Basin. Whatever mechanism produced the Wanapitei structure also emphasized pre-existing fractures in such a way as to produce a concentric pattern. Surface mapping as well as magnetics and gravity data (presented in the following section) do not support a plutonic origin. Mineralogic and petrologic data, on the other hand, support an impact origin.

If the Sudbury Basin is assumed to be of impact origin, then the Wanapitei structure presents the only known terrestrial example of a smaller impact impressed upon a larger one.

# SELECTED FIELD OBSERVATIONS IN THE SUDBURY BASIN: THE MESOSCOPIC OR OUTCROP VIEW[1/]

## Wanapitei Lake: an impact crater?

Wanapitei Lake is irregular in shape, and about 16 km in maximum dimension (fig. 6). The northeastern part of the lake shore defines a segment of a circle. The lake is more than 350 feet deep (fig. 6). Linears are arranged concentrically around the lake for a distance of more than one crater diameter, and define a circular structure (fig. 7). Geophysical traverses across the lake show a strong negative gravity anomaly, but no magnetic anomaly (fig. 8). Bedrock in the area of the lake consists of metasedimentary, metavolcanic, and crystalline rocks of Precambrian age. These rocks are locally mylonitized. Glacial drift near the lake contains boulders of rock showing effects of shock metamorphism, intermixed with boulders of unshocked country rock. No shocked rock has been found in the outcrop. The Wanapitei circular structure appears superposed on the Sudbury Basin. Its age is estimated at about 200 m.y. but with considerable uncertainty. The Wanapitei structure is currently considered of impact origin.

<u>Stop (1) Bowlands Bay. Mylonitized host rock: pre crater</u>?--Mylonite is developed in Precambrian host rock, and is believed to have been formed before the Wanapitei impact event, but after the Sudbury event. It would therefore represent a tectonic, non-impact breccia. Criteria which have led to this conclusion are: the matrix has a strongly lineated, augen-like fabric typical of cataclastic rocks and not of impact breccias; the matrix is very fine grained and dense, but not glassy; the clasts look "normal" and only show some fracturing. No features typical of shock-type deformation and metamorphism can be seen.

1/ In this section, the general description of an individual rock unit is followed by the comments for the stops at which that unit will be examined.

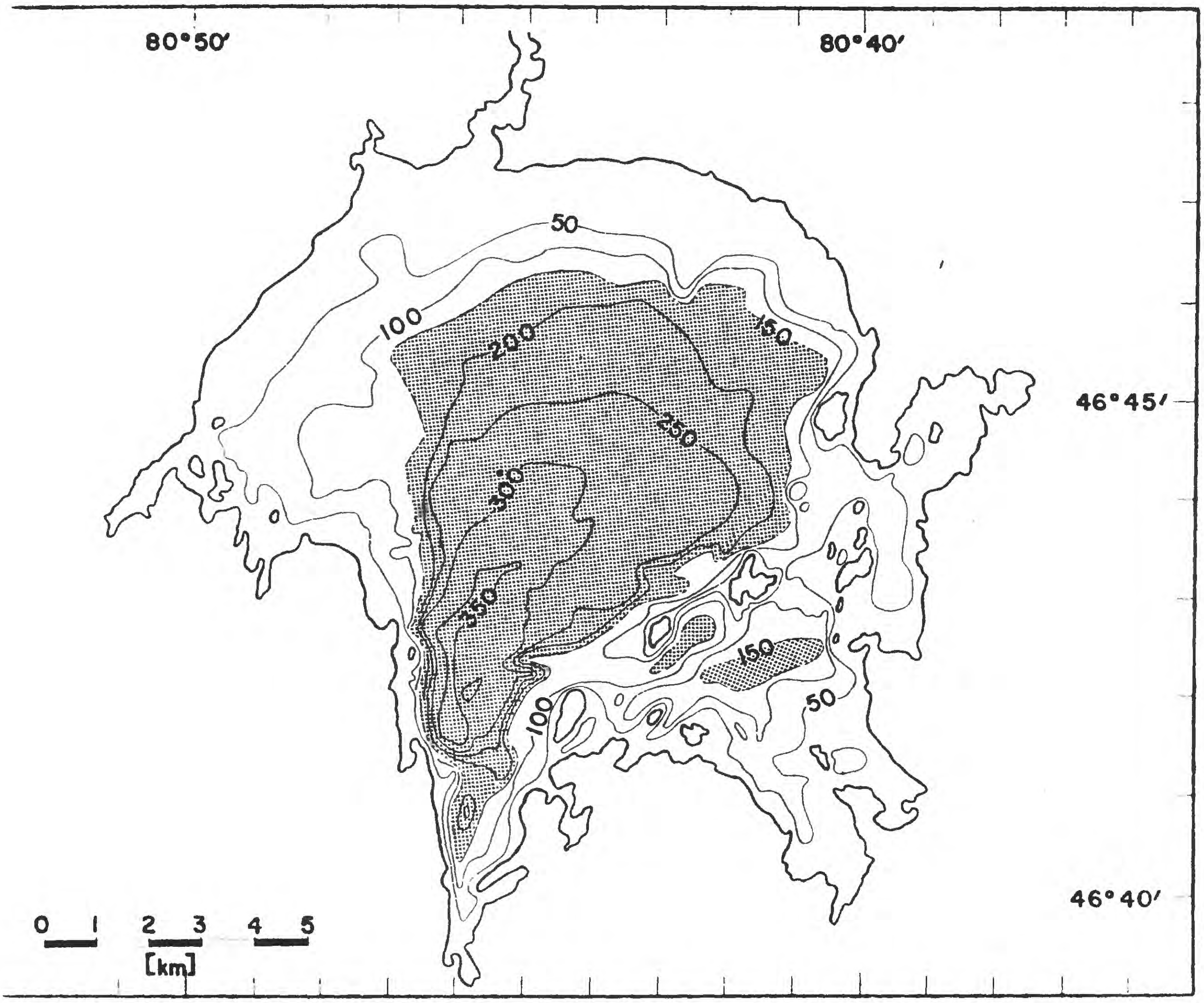



Figure 6. Dimensions and depths of Wanapitei Lake
(from Dence and Popelar, 1972).

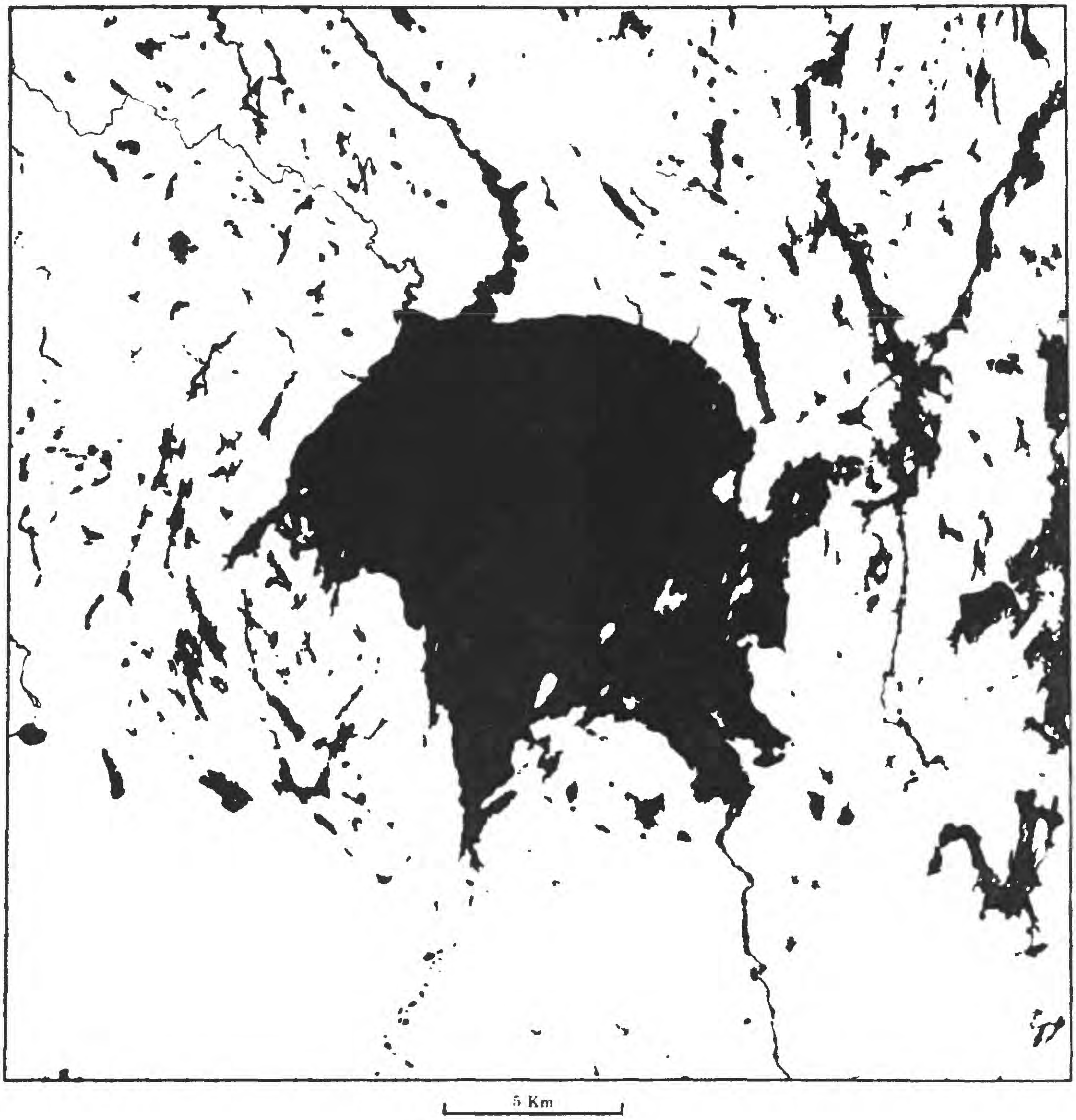



Figure 7. Linears defining circular structure around Wanapitei Lake (from Dence and Popelar, 1972).

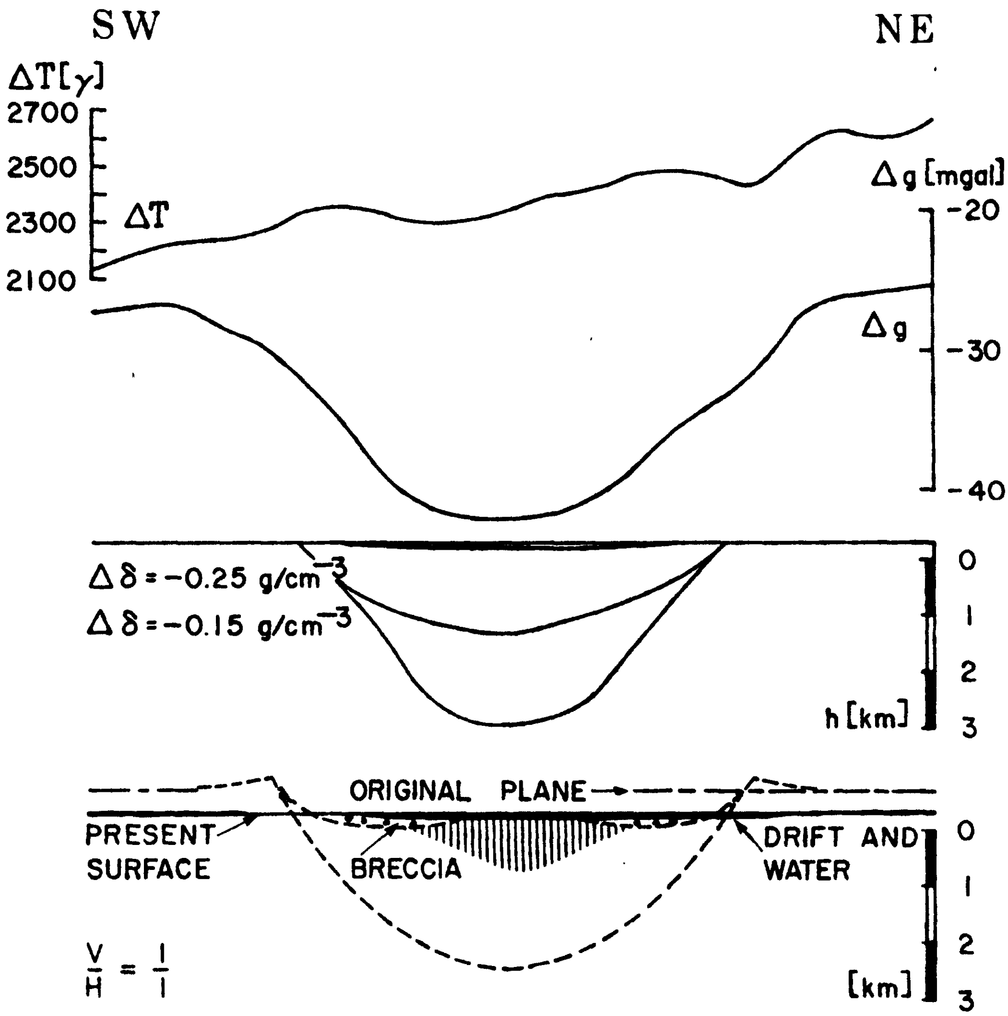



Figure 8. Magnetic and gravity profiles of Wanapitei Lake with resulting density and crater models (from Dence and Popelar, 1972).

Stop (2) Maclellan Mine. Breccia preserved as boulders in glacial drift: impact breccia?--Pebbles and cobbles of breccia inferred to be an impact breccia have been found in glacial drift near the Maclellan Mine. This rock has not been found in place. Criteria used to establish an impact origin are: i) great variation in the size, shape, and composition of the clasts; ii) open, porous, massive fabric of matrix, with little or no lineation; iii) typically, low density, in contrast with higher density of other, non-impact, rocks in the drift; iv) friability in contrast with the coherence of the other, non-impact, rocks in the drift, indicating that these rocks cannot have been transported far; v) presence of glass in some cases; vi) presence of coesite, frothed feldspar, and lechatelierite, all indicative of shock metamorphism.

## Sudbury Basin. Major lithologic units

### Sudbury breccia (also called footwall breccia)

The Sudbury breccia consists of deformed country rock. It occurs in all pre-Irruptive rocks for distances as great as 20 km outside the Irruptive. The country rock has been disrupted, invaded by matrix, and in thin section shows weak shock effects. Shatter cones are common; their axes converge toward the center of the Sudbury Basin. Breccia lenses, irregular in map view, range in thickness from meters to millimeters. Within 2-3 km of the Irruptive, the breccia typically forms up to 1/3 of any given outcrop. The lenses or veins commonly are subvertical, although all attitudes are present. Clasts of the breccia typically are meters to centimeters in diameter, angular to subrounded, some distinctly rounded. Clast boundaries are sharp. Clast/matrix ratio is high. There is no preferred orientation. Clasts commonly are of local rock types, with a wide variety of lithologies represented in any one outcrop (polymict breccia). The matrix typically is very fine grained, dark gray, massive. Flow texture is developed in places. Composition parallels that of nearby country rock. This matrix is not a magma but pulverized, mobilized and injected country rock. "Pseudotachylite" is a name often applied to this type of rock.

Diagnostic features for recognition of the Sudbury breccia are i) its occurrence in footwall rocks outside the Irruptive, ii) the character and intrusive nature of the matrix, iii) the wide variety of clasts derived from local country rock, and iv) the presence of shatter cones.

The shatter cones and the orientation of their axes, the petrographic evidence of shock metamorphism, the pseudotachylite matrix, and the distribution around and outside the Irruptive all contribute to make the Sudbury breccia a strong argument in favor of an impact origin for the Sudbury Basin.

<u>Stop (3) Creighton</u>.--Layers of Sudbury breccia cut across inclusion-rich granite. The inclusions consist of quartzite, greenstone, and layered fine-grained sedimentary rocks. The granite shows coarse-grained and fine-grained phases. Note especially the contact relations between the Sudbury breccia and the granite, the characteristics of the pseudotachylite matrix, and the characteristics and contact relations of the clasts.

<u>Stop (4) Kelley Lake</u>.--Here the Sudbury breccia is developed in metasedimentary rocks. Shatter cones are not uncommon. Note contact relations between breccia and country rock, characteristics of the pseudotachylite matrix, characteristics and contact relations of clasts, and the shatter cones.

<u>Stop (5) Kelley Lake: shatter cones</u>.--This outcrop has the most conspicuous shatter cones in the Sudbury District. The rock is a coarse subarkosic sandstone.

<u>Stop (6) Windy Lake</u>.--Exposed here is the Sudbury breccia typical of the North Range. The country rock is gneiss and migmatite. There has been less recrystallization in the breccia than is common in the South Range, and consequently petrographic

evidence of shock metamorphism in the clasts and country rock has been preserved. Rocks showing such evidence have been collected in this vicinity as much as 8 km from the Irruptive. Note that the clasts are somewhat smaller than in the previous stops. A good feeling for the shape in three dimensions of the breccia lenses can be obtained from these outcrops.

Sudbury Irruptive

The Sudbury Irruptive is a resistant body of rock that underlies the hills ringing the Sudbury Basin. The Irruptive is a sheet-like body, 2-3 km thick, of massive igneous rock differentiated into a more mafic lower part (norite), which forms 1/3 to 1/2 of the total thickness of the Irruptive, and a more siliceous granophyric upper part (micropegmatite). The contact between the two is gradational. At the base of the Irruptive, and in contact with the footwall rock, is the sublayer, an irregular body of breccia as thick as 200 m. The contact between the sublayer and the footwall is irregular but distinct and carries evidence of heating. The upper contact of the Irruptive--between the micropegmatite and the basal Onaping--is complex. It is essentially conformable, although the micropegmatite locally intrudes the Onaping. These relationships have been taken as evidence of the intrusive nature of the Irruptive, but are also compatible with the basal unit of the Onaping being emplaced shortly after the micropegmatite while the latter was still hot.

The sublayer is characterized by the variety of clast lithologies, including exotic mafic and ultramafic rocks. The matrix is of quartz norite or gabbro composition and coarser grained than that of the Sudbury breccia. The sublayer includes most of the ore of commercial grade, although in some mines there are important deposits in the footwall breccias beneath the mafic sublayer.

The norite, the lower part of the main Irruptive, is a grayish, massive, homogeneous crystalline rock, with visible plagioclase laths. Mafic minerals, mostly interstitial, are pyroxene and minor hornblende. The micropegmatite is a light gray to pinkish granophyre generally similar in appearance to the norite, but lighter colored, less mafic, and with the plagioclase laths less well defined.

The Irruptive is one of the most studied and best known, though not fully understood, stratiform complexes in the world. Compared to the Stillwater (another well known stratiform complex), the Irruptive is considerably more siliceous in overall composition. Detailed studies show that it varies in a subtle though continuous fashion in chemical composition (cryptic variation), but lacks the rhythmic layering at the outcrop scale characteristic of most stratiform complexes. Its unusual composition and texture suggest unusual initial melting conditions and an exceptionally quiet environment during cooling. These features suggest that the Irruptive is an impact melt, but the volume of the Irruptive seems too large to be accounted for solely by this mechanism.

Stop (7) Near Strathcona Mine: contact between Sudbury breccia and sublayer.--Visible at this locality are the Sudbury breccia of the footwall, the sublayer breccia, and the contact between the two. The Sudbury breccia, mostly barren, contains clasts derived chiefly from local crystalline rocks and from rocks originally higher stratigraphically. Mafic clasts are present in minor amount. The sublayer breccia, by contrast, is mineralized and contains chiefly mafic clasts presumably derived from below. Its matrix is recrystallized and much coarser grained than that of the Sudbury breccia. Note contact between the two units.

Stop (8) Near Onaping: norite.--Note crystalline, homogeneous, massive nature of rock, the plagioclase laths, and the color.

Stop (9) About one mile south of Onaping: micropegmatite.--Note that the micropegmatite is generally similar in appearance to the norite, but lighter colored, with fewer mafic minerals, and more poorly defined plagioclase crystals. The norite and the micropegmatite are currently considered by most geologists as gravity differentiates of a single initial melt.

Stop (12) Discovery site: norite, sublayer, and adjacent footwall.--At this locality the Sudbury (footwall) breccia, the sublayer breccia, and the norite are all exposed, although the contacts between them are not. The footwall breccia consists of greenstone locally recrystallized to hornfels and criss-crossed by amphibole veins containing coarse crystals of hornblende.

The sublayer breccia consists of rounded clasts of exotic mafic and ultramafic rocks in an abundant matrix of nearly massive sulfide ore. The norite is in striking contrast, being massive, free of clasts, and virtually devoid of sulfides.

Onaping Formation

The Onaping Formation, about 1500 m thick, is less resistant to erosion than the Irruptive, and therefore underlies terrain of less relief. It is subdivided into three units, in ascending order the quartzite breccia, the gray Onaping, and the black Onaping.

The quartzite breccia is widely distributed, very variable in thickness, and at most 200 m thick. The quartzite breccia seems invaded by the micropegmatite at its lower contact, which is sharp, irregular, and with evidence of thermal metamorphism. The upper contact, with the gray Onaping, is also sharp. The unit is characterized by large inclusions, up to a few meters in diameter, of rocks from the upper levels of the country rock, and by the near absence of clasts derived from depth. The material of the unit is therefore inferred to have been emplaced from above. Many of the clasts are recrystallized. Some of those that are not show evidence of shock metamorphism. The matrix is medium to light gray, in part with recrystallized clastic fabric, in part with igneous fabric. The rock with the igneous, melted, matrix forms irregular bodies that occur in the basal breccia as well as in the overlying units up to and including the black Onaping. These bodies have chilled and brecciated contacts, and contain rounded inclusions of country rock.

The gray Onaping forms about 1/4 to 1/3 of the total thickness of the Onaping, or about 200 to 300 m. It is recrystallized at its lower contact (with the quartzite breccia), and grades upward into the black Onaping. In outcrop, the unit resembles a pumiceous tuff or tuff breccia. It is characterized by glassy clasts which are highly contorted, devitrified, recrystallized, and typically angular. Intermixed are clasts of country rock, some of which show shock metamorphic features, others a glassy rind. The matrix was once fragmental, but has been recrystallized to a fine grained, light gray, felsitic material.

The black Onaping is about 1000 m thick. It grades upward very gradually into the Onwatin slate, which is similar chemically. The black Onaping generally resembles the gray, but differs in having clasts that are smaller, less altered and recrystallized, though similar in composition. The matrix resembles that of the gray Onaping, but is made black by the inclusion of a few percent of carbonaceous material, which indicates deposition by normal sedimentary processes. The sulfide pyrrhotite is common in small amounts. In outcrop the unit appears heterogeneous, fragmental, and massive.

The basal quartzite breccia has been interpreted variously as an autobrecciated volcanic rock, a conglomerate, and a tectonic breccia. The gray and black Onaping have been considered a pyroclastic tuff or ignimbrite. The Onaping is now regarded as a suevite, and thus serves as critical evidence for the impact model. Under this theory, the quartzite breccia would be ejected material including bodies of impact melt that slid or fell back into the crater immediately after excavation of the crater. The gray Onaping would be unmodified fall out material of the ejecta blanket that may also have slid into the crater from higher up on the rim. The black Onaping would be reworked ejecta blanket material with an admixture of foreign sediment, and would mark the resumption of normal geologic processes in the area of impact.

Stop (10) High Falls locality: micropegmatite, quartzite breccia, gray Onaping.--This is a complicated stop involving its own mini-excursion and several stations. For this reason, only skeletal information is presented here. An extensive discussion will be carried out in the field by the leaders of the trip. The features that will be seen are, in sequence: i) micropegmatite, here somewhat darker in color than elsewhere. ii) Contact between micropegmatite and quartzite breccia. Note sharp but irregular contact, local intrusion of breccia by micropegmatite, abundance of basement rock fragments and recrystallization of breccia matrix. iii) Contact between quartzite breccia and breccia with melt matrix. Contact is chilled and brecciated. Note character of melt matrix, and the smaller size and greater rounding of clasts. These clasts locally show preferred orientation. Nearby are quartzite blocks in which shock features are preserved. iv) Contact between breccia with melt matrix and gray Onaping. Chilled margins at contact in melt, recrystallization in gray Onaping. Note glassy angular clasts, felsitic matrix, lack of preferred orientation of clasts, and massive nature of the gray Onaping.

Stop (11) Highway near High Falls: black Onaping.--Note heterogeneous, fragmental nature, complete lack of bedding, matrix similar to that of gray Onaping, but black. Glassy clasts are still present, as are clasts of basement rock. Both typically are smaller than in gray Onaping. The larger rock clasts show shock features: it was in specimens from this vicinity that petrographic evidence of shock metamorphism was first discovered in the Sudbury area.

On the way to Stop 12, note the Chelmsford Formation, which is the sandy filling of the crater. Beds are well developed, each consisting of a turbidity current depositional unit. Well preserved sedimentary structures give current directions. Note also the broad folds, which postdate the Sudbury Basin, and the well developed axial plane cleavage.

## SYNTHESIS OF A MODEL FOR THE SUDBURY STRUCTURE

Any model of the formation and history of the Sudbury Basin must satisfy certain boundary conditions that result from data currently available. These conditions are sufficiently restrictive to justify only two models, the orthomagmatic and the impact, but not restrictive enough to select one model over the other unequivocally. Nevertheless, we feel that the impact model explains more features of Sudbury Basin than does the orthomagmatic one, although we recognize that many problems remain unsolved by either model. Table 1 summarizes the critical observations currently available on the Sudbury structure and evaluates them relative to both an orthomagmatic and an impact model.

Models for the Sudbury Basin must simultaneously reconcile a broad spectrum of fact within the constraints provided by geometry, energy, physics, and chemistry. Definition of processes alternative to those suggested that can produce features such as shatter cones, shock effects, and brecciation concentric to the basin could change the variables in the system.

The energy required to produce the Sudbury structure in either an impact or endogenic event is estimated to be $10^{30}$ ergs. This work is equivalent to the energy released from $2.5 \times 10^{6}$ megatons of detonated TNT or at least 2 orders of magnitude greater than that produced by the largest known non-impact natural event (estimated to be $10^{27}$ ergs). The annual work from all sources on earth is probably less than $10^{30}$ ergs, yet it is probable that the energy required to produce the Sudbury structure necessarily had to be released in a very short time.

Petrographic changes similar to those attributed to shock metamorphism could be produced in "natural" systems at lower strain rate and pressure and higher temperature then are typical of shock metamorphism. Here, however, three serious constraints are encountered.

(1) Any workable system requires pressures ($\sim$10 kb) which are above those available under natural

processes other than shock.

(2) System temperatures (~800°C) required as far away as 25 km from the center of structure are not recorded in mineral facies.

(3) Required strain rates and the total energy budget are not available in normal orogenic/metamorphic events.

The Irruptive alone poses problems in "normal" processes of magmatic differentiation and crystallization. Among these problems are (1) the bulk silica content is anomolously high for normal mafic rock series; (2) the anomalous silica content is distributed throughout the differentiated body of the Irruptive; (3) the origin of the sublayer breccia and history of ore-mineral crystallization indicate unusual circumstances of formation. Unusual circumstances apparently generated the magma of the Irruptive and later governed its emplacement, crystallization, and differentiation.

The present shape of the Sudbury Basin poses a problem of understanding the nature of the deformation that modified an original shape (assumed to be bowl-like). The mapped fold dislocations and fault offsets are not sufficiently well documented to account for the transition from bowl to spoon. Furthermore, the bifurcation of the axis of the Basin at the northeast end (fig. 1) cannot be explained as a modification by the Wanapitei Lake structure. It could therefore be an early effect related to the major deformation of the Basin.

The exact genesis of the pseudotachylite within the footwall (Sudbury) breccia is not adequately explained at present. Its association with shatter cones suggests that both were formed under the very high rates of strain produced by impact, but correlating the pseudotachylite either with a process of crushing and mobilization during fracture deformation or with gas fluidization remains a problem. The presence of dikes of sublayer breccia within the footwall breccia is a problem that parallels that of the origin of the pseudotachylite.

Table 1. Summary of observable features in the Sudbury Basin and their probable relationship to orthomagmatic and impact models.

| Observation | Orthomagmatic Model | Impact Model | Comments |
|---|---|---|---|
| 1. Shatter cones in footwall rocks | Questions | Strongly supports | At present the best evidence for impact. |
| 2. Shock metamorphism in Onaping Formation | Questions | Supports | At present the best evidence for impact. |
| 3. Shock metamorphism in footwall rocks | Questions | Strongly supports | At present the best evidence for impact. |
| 4. Anomalous silica in Irruptive | Non-diagnostic | Supports | A normal magmatic emplacement and cooling history is not indicated. |
| 5. Energy budget calculations | Questions | Supports | An extraterrestrial source is indicated by work/time considerations |
| 6. Spoon-shape geometry of Irruptive and Basin | Problematical | Problematical | Tectonic modification of original circular impact structure required. |
| 7. Volume of melt represented by Irruptive and sublayer | Supports | Problematical | The melt is excessive for impact; therefore, a source either in the mantle or in the lower crust (which was near the melting point) is required. |
| 8. Similar isotopic ages for Irruptive and country rock | Supports | Non-diagnostic | The region could have been undergoing metamorphism and plutonism during the time of impact. |
| 9. Ultramafic inclusion in Irruptive sublayer | Supports | Problematical | This source is probably related to that of the excess melt. |
| 10. Intrusion of sublayer into country rock | Problematical | Supports | Probably requires tectonics or a catastrophe. |
| 11. Pseudotachylite in Sudbury breccia | Problematical | Supports | Probably requires tectonics or a catastrophe. |
| 12. Bifurcation of Basin axis at northeastern end | Problematical | Problematical | Shape of northeast part of Basin cannot be explained by the Wanapitei event; therefore, other severe tectonic modification is required. |
| 13. Melt fractions in the quartzite breccia of Onaping | Problematical | Non-diagnostic ? | Melting cannot be accounted for in contact metamorphism by irruptive |

Figure 9. Main rock units of the Sudbury complex diagrammatically compared (not to scale) with units of a standard large complex impact crater. The main units are:

i) Basement crystalline rocks (crosses) mildly shocked (shatter cones), fractured, and cut by pseudotachylite breccia veins (black matrix).

II) Lower breccia unit: sub-layer breccia of mafic inclusions with quartz diorite/norite-sulfide matrix; basal breccia (standard) of shocked basement rocks including shock melted glasses.

iii) Igneous rock unit: Sudbury Irruptive with norite at base (varying in composition), transition zone and micropegmatite; melt rocks (standard crater) with fine grained, inclusion-rich margins and coarser grained center.

iv) Upper breccia unit: Quartzite breccia (Sudbury) of weakly shocked quartzite and granitic boulders in a partially molten matrix; Bunte breccia (standard crater) or equivalents of weakly shocked upper target rocks in a clastic matrix.

v) Fallout breccia unit: Onaping Formation (Sudbury) of variously shocked and melted fragments in a matrix which grades upwards into sedimentary rocks; suevite (standard crater) breccia of variously shocked and melted fragments.

vi) Sedimentary fill unit: Onwatin slate (Sudbury); clastic or chemical sedimentary rocks (standard crater).

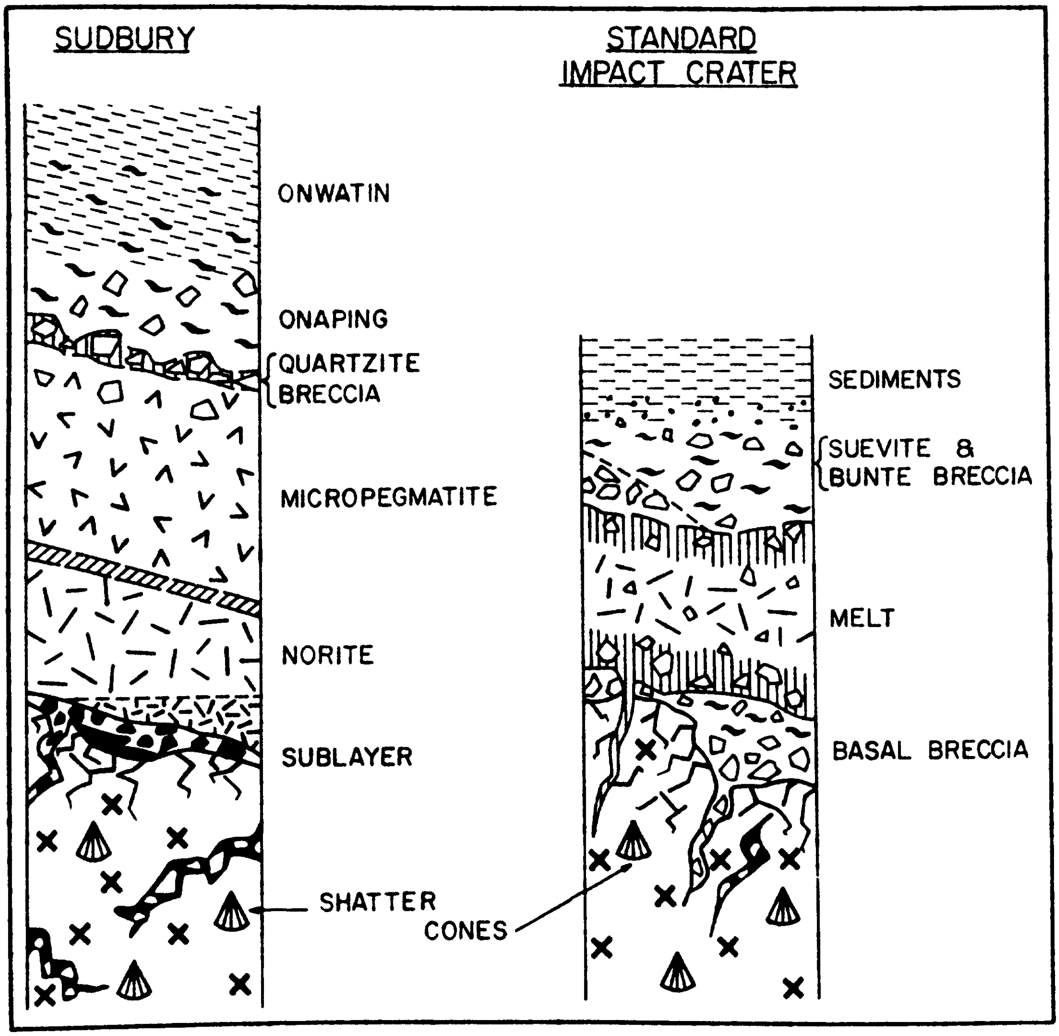

SUDBURY
STANDARD IMPACT CRATER
ONWATIN
ONAPING
QUARTZITE BRECCIA
MICROPEGMATITE
NORITE
SUBLAYER
SHATTER CONES
SEDIMENTS
SUEVITE & BUNTE BRECCIA
MELT
BASAL BRECCIA

Figure 10. Diagrammatic representation along a northwest-southeast profile of the possible sequence of events forming the Sudbury structure.

(a) Hypervelocity impact of a cosmic bolide, depicted here as a stony asteroid.

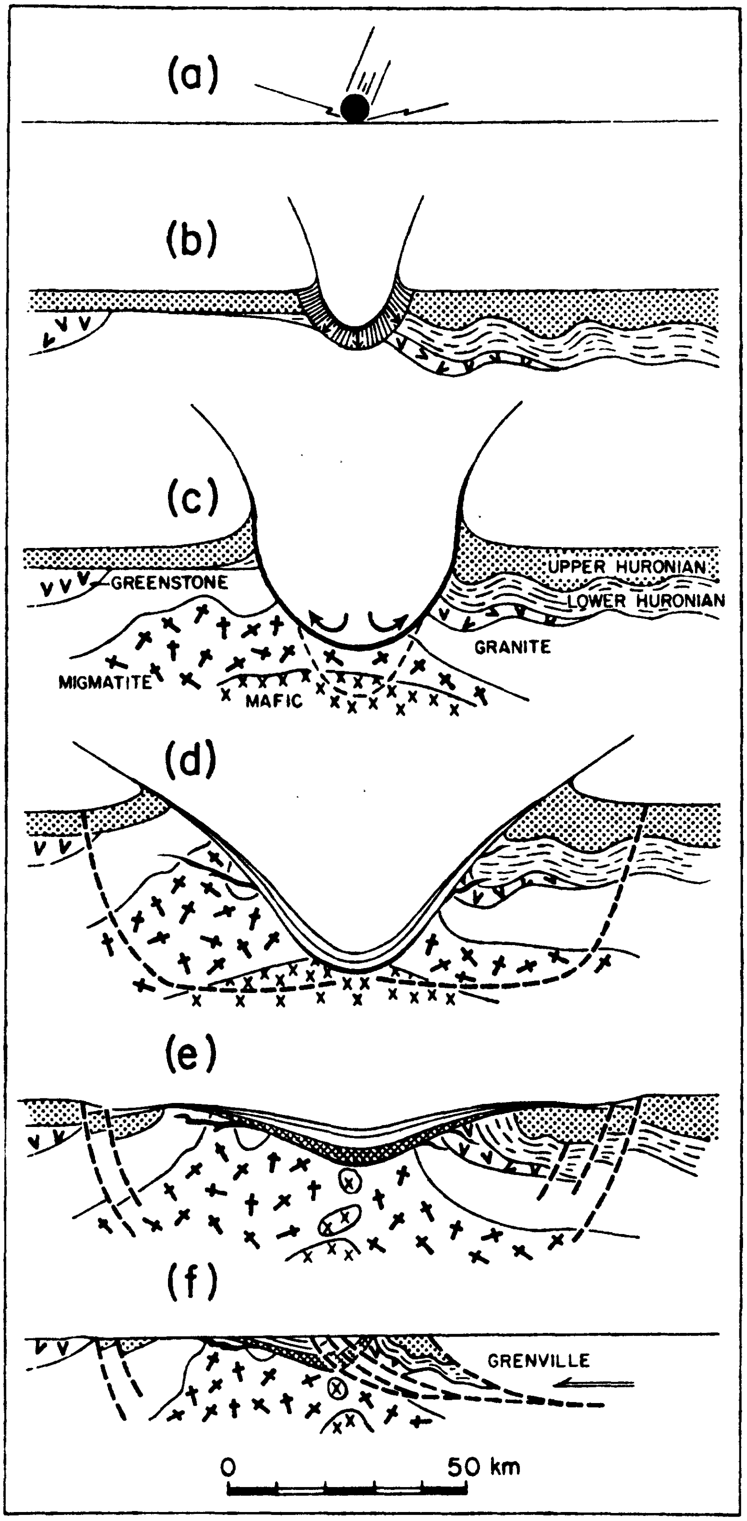
(b) Initial excavation of the crater by the high pressure shock wave and its rarefactions. At this stage the heavily shocked bolide is smeared out to line the growing cavity, and the target materials behind the expanding shock front are largely molten.

(c) Continued growth of the transient cavity. The cavity lining is now a relatively thin ($\sim 1$ km thick) layer of impact melt and breccia with fragments of moderately shocked country rocks. Normally the rocks underlying the cavity, having been shock metamorphosed at about 200 kb, would remain solid and there would be little further downward growth of the crater. However, it is postulated that at Sudbury the initial thermal gradient was high and the rocks outlined by the dashed line were brought to the melting point, allowing excavation of an exceptionally deep cavity.

(d) Maximum dimensions of the primary crater. Addition of melt below to initial impact melt is symbolized by a double lining of the cavity. Sublayer breccia (black), consisting of fragments and melt derived from the deeper levels of the cavity walls, formed the lowest layer of the cavity lining and was also mobilized and forced upwards. Collapse of the uplifted rim under gravity initiated faulting along planes indicated by heavy dashed lines, with consequent modification of the crater structure by inward and upward movement of the cavity walls, and generation of pseudotachylites (Sudbury breccias).

(e) Form of the Sudbury crater after equilibrium was attained. The rim has collapsed to form a peripheral graben of downfaulted Huronian rocks. A subdued ring uplift inside the graben, comparable to the island ring of West Clearwater Lake surrounds a central depression underlain by melt rocks which differentiate into noritic rocks (cross hatched) and micropegmatites. The entire crater is blanketed by returned ejecta (Onaping Formation), much of it redeposited in the central depression.

(f) Present form of the Sudbury structure after deposition of the Whitewater sedimentary rocks, orogenic activity involving overthrusting of the Grenville from the southeast, and general erosion.


(a)
(b)
(c)
UPPER HURONIAN
LOWER HURONIAN
GREENSTONE
GRANITE
MIGMATITE
MAFIC
(d)
(e)
(f)
GRENVILLE
0
50 km

The ultramafic inclusions in the sublayer breccia pose a problem of source because they have no known counterparts in the Irruptive. Their source probably is related to that of the Irruptive. The volume of the latter requires a melt source that is far in excess of what can result from direct impact melting. Therefore, an additional source for the excess melt is required in either the lower crust, heated near the melting point, or in the mantle.

A summary of the major features of the Sudbury Basin, shown in columnar section, is compared with that of a standard impact crater in Figure 9. The comparisons are reasonably close except for the difficulties caused by the Irruptive. One hypothesis that accounts for the emplacement of the Irruptive requires that the Sudbury impact occurred in a region where the lower crustal rocks were near or at the melting point. This could occur in a region with relatively high heat flow within the early synkinematic phase of metamorphism. The additional heat energy from impact could then trigger instantaneous melting and mobilization of a magma of quartz gabbro composition and emplace it as the Irruptive, there to cool and differentiate as a single sheet but at a rate relatively rapid compared to that of a normal stratiform complex. The sequence of events envisioned in this hypothesis is presented in Figure 10.

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## GLOSSARY

Argillite: mildly metamorphosed siltstone, claystone, or shale.

Autobrecciated: applied to igneous rocks in which early-formed consolidated crusts have broken up and incorporated into the still flowing magma.

Cataclastic: pertaining to rocks in which minerals have been fragmented by shear stresses--a consequence of friction along faults.

Deformation lamellae: planar strain features occurring in quartz as a result of tectonic stress or shock metamorphism.

Footwall: country rock outside the Sudbury Basin proper. Thus, outside and below the Irruptive.

Granophyre: fine-grained porphyritic granite characterized by a groundmass showing irregular intergrowth of quartz and feldspar.

Grenville Front: major structural boundary between different geologic provinces of Precambrian age in southeastern Ontario, Canada.

Hornfels: fine-grained, non-schistose metamorphic rock resulting from contact metamorphism.

Lechatelierite: glass produced by shock metamorphism.

Linear: straight or gently curved physiographic crease, trench, or escarpment.

Lopolith: large, floored intrusive whose center has sunk into the form of a basin.

Mafic: poor in silica and rich in iron and magnesium. Term applied to both minerals and igneous rocks.

Magmatic differentiation: the process by which different types of igneous rock are derived from a single parent magma, or by which different parts of a single molten mass assume different compositions and textures as the mass solidifies.

Micropegmatite: colloquial term, applied to granophyric part of Sudbury Irruptive.

Migmatite: rock produced by the injection of sheets of granite into schist.

Mylonite: fine-grained, laminated rock formed by extreme microbrecciation and milling of rocks during movement along shear surfaces.

Norite: hypersthene gabbro

Orogenic: pertaining to mountain-building processes that entail combinations of deformation, metamorphism, and intrusion.

Orthomagmatic: pertaining to normal plutonic or volcanic processes.

Pseudotachylite: pulverized, mobilized, and injected rock similar in appearance to mafic volcanic glass. Commonly considered a product of impact events or faulting.

Pyroclastic: applied to rocks made up of material explosively or aerially ejected from a volcanic vent.

Pyrrhotite: ferrous sulfide containing dissolved sulfur. Magnetic pyrite.

Quartzite breccia: lowest part of Onaping Formation. Irregular in thickness. Contains clasts of country rock in recrystallized or melted matrix.

Ring dike: arcuate dike with steep dip. Several ring dikes commonly are associated and form a circular or elliptical structure.

Shatter cone: structure produced by high strain rates and manifested by shear planes outlining a cone. Considered typical of impact structures.

Sill: tabular, concordant intrusive body emplaced parallel to bedding of host rock.

Stratiform complex: thick sheet of mafic igneous rock, compositionally layered, commonly in cyclic fashion.

Subgraywacke: poorly shorted sandstone containing quartz, feldspar, rock fragments in matrix of fine-grained micas and clay.

Sublayer: lowest, brecciated, irregular part of the Irruptive. Contains most of the commercial grade ore.

Sudbury breccia: brecciated country rock, occurring near Sudbury Basin.

Suevite: rock resembling a pumiceous tuff or tuff breccia in the outcrop, but considered to be of impact origin.

Synkinematic: taking place during deformation.

Turbidity currents: slurry-like currents impelled by differences in density, and moving along bottom slope of a body of standing water.

Ultramafic: containing 45% silica, virtually no quartz or feldspar, and composed essentially of ferromagnesian silicates, metallic oxides and sulfides, and native metals. Applied to igneous rocks.

Volcano-tectonic complex: a complex of related volcanic and plutonic rocks, generally associated with subsidence forming a large basin or graben.

Whitewater Group: of Precambrian age. Includes, in ascending order, the Onaping, Onwatin, and Chelmsford formations.