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See table of contents

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The Sudbury Structure: A CCDP Workshop Report

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The Canadian Continental Drilling Program is presently nearing the end of its initial two-year planning phase. As part of the planning process the proposals received by the program, following its announcement, are being examined in open workshops. The first such workshop, on the lower crust in general and the Kapuskasing Structure in particular was held at the University of Toronto in February 1988 (Percival, 1988). A full report of that meeting is available from the planning office (CCDP Report 88-1). The second workshop was held at Laurentian University, Sudbury, on 6-7 October 1988. Its purpose was to examine two proposals for drilling in the Sudbury Structure.

The Sudbury Structure is a major feature of the Canadian Shield. It is on the boundary between Archean and Proterozoic cover near the Grenville Front. The Sudbury Structure was formed by a catastrophic explosive event at about 1850 Ma (Krogh *et al.*, 1984). The location of the Sudbury Structure has led some authors (*e.g.*, Card and Hutchinson, 1972; Stevenson and Stevenson, 1980) to suggest that it is of endogenic origin. However, Dietz (1964) suggested that the high nickel content of the Sudbury sub-layer might be of exogenic origin, the result of a large meteorite impact. Since Dietz's suggestion, much work has been done on the origin of the Sudbury Structure, and although there is by no means a consensus, the exogenic origin is the majority view. The undisputed recognition of widespread breccia with shock effects, shatter cones and planar features in quartz in basement rocks and in the Onaping Formation has been a strong impetus to the development of this view.

Coupled with the scientific interest in the Sudbury Structure is its major importance as the world's largest economic source of Ni-Cu sulphides. Hence the structure has been intensively explored and several tens of thousands of boreholes have been drilled into it. Geological mapping at a scale of 1:50,000 has been completed. There is thus a wealth of information to be drawn upon.

Geologically, the structure contains several units: micropegmatite, norite and sublayer forming the irruptive Sudbury Igneous Complex (SIC); the Onaping Formation, which contains large volumes of material very similar to the fallback debris found in other impact craters (Peredery and Morrison, 1984); the Onwatin Formation consisting of mudstone, and the Chelmsford Formation, consisting of turbidites. The SIC has been interpreted as a magmatic melt body that was emplaced shortly after the Sudbury Structure was formed (Peredery and Morrison, 1984), but Nd/Sm data suggests it was derived mainly from crustal rocks (Faggart *et al.*, 1985). It is possible that the meteorite impacted into a tectonically active terrane, which led to anorogenic modification of the impact crater (Peredery and Morrison, 1984).

Two proposals concerning the Sudbury Structure were received by CCDP. The first, entitled "Preliminary research proposal for a deep borehole in the Sudbury Basin", was submitted by a team of university, industry and Ontario provincial government scientists, headed by Don H. Rousell. The principal scientific objectives were: (1) to obtain complete sections through the Whitewater Group and SIC, in order to resolve the nature of the SIC (funnel-shaped lopolith or sagged sill); (2) to obtain information on the structure of the basin at depth; (3) to examine the nature of the crust beneath the SIC; (4) to examine the bottom configuration of the basin, and look for a central uplift; (5) to develop techniques for determining the stress field at depth; and (6) to look for Zn-Pb-Cu-Ag mineralization at the base of the Onwatin Formation, and Ni-Cu mineralization at the base of the SIC. It was hoped that the borehole would indicate the nature and configuration of the feeder for the SIC, and also shed light on the apparently deep-seated magnetic and gravity anomaly.

The second proposal was submitted by a team from the Geological Survey of Canada, headed by Dr. R.A.F. Grieve. It was entitled "Proposal to drill selected impact structures in Canada", and suggested drilling in both the Sudbury and Manicouagan Structures. The proponents noted that despite the occurrence of shock metamorphic effects, such as shatter cones and microscopic planar features in quartz, the impact origin of the Sudbury Structure is probably the most controversial of all impact structures in Canada. As with the Rousell *et al.* proposal, Grieve *et al.* suggested a drill site in the centre of the basin, to address the questions: does a feeder system exist for the SIC, and what is the nature of the high-density body at depth below the Complex? They noted that the answers to those questions would also answer the more fundamental question of the origin of the Complex itself, either as the result of internal igneous activity or impact melting.

The CCDP workshop on the Sudbury Structure brought together a diverse group of experts from industry, universities and government agencies. The workshop was opened by Mr. Sterling Campbell, MPP, of the Government of Ontario, assistant to the Ontario Minister of Mines. Mr. Campbell welcomed the participants, and noted the economic significance of the Sudbury Structure. Malcolm Drury explained the purposes of the workshop: to allow proponents to present their ideas in an open forum; to allow full and open discussion of the proposals; and to allow other scientists other than those initially associated with the proposals to become involved.

The first presentation, by B. Dressler (Ontario Geological Survey (OGS), Toronto), was a review of the nature and origin of the Sudbury Structure. He outlined the reasons for drilling a deep hole: (1) to obtain a complete section through the mafic-ultramafic Sudbury Igneous Complex; (2) to obtain a section through deep crustal granulite facies gneisses of the Levack Complex; (3) to examine the economic significance of the Vermillion Member and Cu-Ni sulphide bodies at depth; (4) to test geophysical and geological models; (5) to achieve a better understanding of the origin of the Sudbury Structure. He proposed a 7 km hole in the western part of the basin.

R.A.F. Grieve (GSC) discussed the Sudbury Structure as an impact structure. He noted that impact cratering is an important process in planetary accretion, crustal, surface and biological evolution. There are, at present, 120 known impact craters on Earth, with 3 or 4 new ones being discovered each year. Sudbury is the largest and oldest impact structure in North America and, in the context of terrestrial impact structures, the SIC is unique. The volume of melt is estimated to be 5.5-13.7 × 10^3 km^3, and structural uplift is estimated to be 14-19 km. Potential drilling targets would be at the centre of the structure, to examine shock levels and cratering mechanisms, and a 5 km hole to penetrate the SIC and allow study of the sub-floor of the structure and uplifted lower crust.

Shock metamorphic features were discussed by B.M. French (NASA), who was the first to point out petrographic evidence for the impact origin of the Sudbury Structure (French, 1968). Detailed studies of shock effects in core could be used to (1) identify key units, such as the Onaping Formation; (2) recognize shock-produced breccias and melt rocks; (3) determine the vertical distribution of shock effects within and below the structure; (4) characterize the decay of shock-wave pressure beneath the Sudbury Structure; and (5) estimate the shape of the original structure before subsequent deformation. G. Morrison discussed the nature of the Sudbury Structure at depth. He offered models of the Sudbury Basin in terms of a meteorite impact origin. The models differ considerably from the classical funnel-shaped lopolith model. The models presented also attempt to explain some of the more subtle features of the Sudbury Basin, such as the emplacement of base metals along the Onaping-Onwatin contact and the distribution of the sub-layer.

The location of the original centre of the crater was discussed by J.P. Golighty (Inco Ltd.). The melt volumes are compatible with a crater transient radius of approximately 40-50 km. The orientation of shatter cones, impact breccia dykes and originally radial ore-bearing footwall troughs all indicate that the original centre of the crater was under the southern half of the basin.

R.S. Dietz (U of Arizona), who is the originator of the concept that the Sudbury Structure is an astrobleme (Dietz, 1964), noted that his interpretation is now the preferred one, although there is still not a consensus. Subsequent work has shown that his original model required considerable revision; for example, there is no need to invoke triggered volcanism because shock melting of the crust can account for all phases of the Sudbury Structure. Further, the original crater was about 200 km in diameter, and the present Sudbury Basin is only the foundered eye. He still believes that the SIC is an extrusive lopolith. The further resolution of the impact event by a combination of deep drilling and geological and geophysical studies is a highly deserving enterprise.

Direct analogy with impact structures on terrestrial planets led H.R. Butler (Consultant Geologist, Sudbury) to suggest that the Sudbury Structure is multi-ringed. Concentric lineaments can be recognized on topographic maps and Landsat images. The lineament classification approach would help elucidate whether rings elsewhere in the Shield are endogenic or exogenic.

W.M. Shanks (U of Toronto) described the characteristics of a 40 km long ductile shear zone that cuts rocks of the Onaping Formation and the SIC. Differential uplift, with the South Range being uplifted more than the North Range, would explain the preponderance of economic deposits in the South Range. Post-impact generation of pseudotachylites in the basin attest to shearing following the intrusion of the SIC.

P.D. Lowman Jr. (NASA) compared the Sudbury Structure with impact craters on the Moon and Mars. He noted the existence of elliptical craters on the Moon with all the characteristics of primary impact structures, *e.g.*, Schiller, which has a length:width ratio of 1.9. He suggested that three questions could be addressed by drilling in the Sudbury Structure: (1) the location and nature of the impact melt; (2) the relation of the structure to true magmatism; and (3) the nature of the lower crust. These considerations suggest a drilling site in the northwest part of the structure, in the Levack area.

The use of radar studies in the Sudbury Basin was discussed by V.R. Slaney (GSC). The basin, and the Superior, Huronian and Grenville rocks surrounding it, were chosen as a major North American test site for the European Space Agency's Earth Resource Satellite (ERS-1). As part of the preparatory work for this project, the Canada Centre for Remote Sensing has surveyed the test site with its C-band radar. Early results show that the radar mosaic provides a very clear overview of the regional morphology, and contains a wealth of structural information.

A.M. Jessop (GSC) described a geothermal experiment in the Sudbury Basin between 1967 and 1969 (Jessop and Lewis, 1978). Heat flow was measured in exploration boreholes. Three boreholes in the northwest margin of the basin gave an average heat flow of 43 ± 2 $mW \cdot m^{-2}$, before correction for Pleistocene glaciation effects. Three holes on the southwest margin gave an uncorrected heat flow of 49 ± 3 $mW \cdot m^{-2}$. A single hole near Copper Cliff gave an uncorrected value of 43 $mW \cdot m^{-2}$. The heat flow on the southwest margin is significantly higher than at the other two locations, probably because of a greater total radiogenic heat production in the crust beneath the southwest margin.

S.A. Kissin (Lakehead U, Thunder Bay, Ontario) presented data on fluid inclusions from several impact sites. Impact melts appear to trap meteoric water at high temperatures. Inclusions in shock features are of meteoric water, but inclusions of metamorphic origin are CO_2 rich. This observation can be used to differentiate between the two, and could, therefore, be applied in determining the origin of the Sudbury Structure.

The results of a high resolution seismic survey in the North Range were presented by W.M. Moon (U of Manitoba). In general, seismic velocity information derived from samples in the laboratory over-estimates the real near-surface velocity for most lithological units in the study area. The final processed data clearly map several geological boundaries that may be crucial in exploration for deep-seated ore bodies.

J. Kieley (Quantech Consulting Ltd., Toronto) stated the case for using magnetotelluric (MT) soundings in deep crustal soundings. Three types of MT method, each with different ranges of frequency, and therefore penetration, may be used. The natural energy source used in low frequency (1 mHz) to 20 Hz) MT soundings originates from micropulsations in the Earth's magnetic field. Audio-frequency magnetotelluric (AMT) soundings use natural energy from sferic activity, in the range of 15 Hz to 20 kHz. Controlled-source magnetotellurics (CSAMT) use applied field sources, in the frequency range 0.1 Hz to 8 kHz. The lower the frequency the greater the depth of penetration. In high resistivity environments of the Canadian Shield it is feasible to achieve penetration depths greater that 20 km. Magnetotelluric surveys should be an integral part of drill site selection.

A. Basu (U of Rochester) discussed the geochemical signature, particularly ε_{Nd}, of probable impact-generated volcanism, with examples from Sudbury, the Deccan Traps and Columbia River (Oregon, USA). The SIC appears to be heavily contaminated with, if not entirely derived from, pre-impact crust, since ε_{Nd} is approximately −7.5. The Deccan Trap lavas may similarly have a significant crustal component, although the wide variation in ε_{Nd} (+8 to −16) implies assimilation of different crustal segments. The Columbia River basalts show a similar ε_{Nd} range.

The potential for isotopic studies of rocks, ores and brines from a deep borehole were discussed by R.H. McNutt (McMaster U, Hamilton, Ontario). A deep hole that penetrated the deepest, least contaminated material in the SIC, would provide material from which, by analysis for Os, Sr, Nd, and Pb radiogenic isotopes and H, O, C and S stable isotopes, the extent of the mantle signature in the SIC rocks could be determined. Interest in brines, which occur in large volumes at depths > 1 km in the Canadian Shield, centres on the possibility that they may represent residual ore fluids or metamorphic fluids.

S. Maloney (Laurentian U) addressed the geomechanical aspects of deep well drilling, in particular well stability and the problems of coring. A potential problem is discing, caused by stress redistribution produced by the drilling. Discing might be expected to occur in the Sudbury Structure at depths greater than approximately 3 km. At greater depths, disc thickness may decrease until only fragments are recovered. Depending on stress magnitudes, it may prove impossible to recover representative core for strength assessment.

L.S. Pascoli (Longyear Canada Ltd.) described a technique for continuous wireline coring in oil and gas exploration holes. A pilot project in the United States using a Longyear HD600 drill showed that overall costs were comparable to conventional oil patch drilling.

A discussion of current LITHOPROBE plans was led by A.J. Naldrett (U of Toronto), who is assembling a working group from mining companies and academia to assess the feasibility of a transect through the Sudbury Structure. This is one of several possible transects of the Abitibi-Grenville LITHOPROBE project.

In the general discussion on the further development of the proposals, attention was focussed on the need for much more detailed surface geophysical surveys, principally seismic reflection and refraction, and magnetotellurics. High resolution seismic work has been done in the North Range. Data acquisition there is difficult because of terrain conditions, but useful data have been obtained. They tie in quite well with available surface and subsurface data. The Abitibi-Grenville LITHOPROBE transect that has been designed to cross the Grenville Front could also cross the Sudbury Basin. Based upon the results of that transect, a seismic reflection and refraction programme should be designed to assist in the locating of the hole (or holes) to be drilled. It was suggested that several shallow holes might be drilled in order to help solve some local geological problems before recommendations could be made regarding the location and drilling of a deep hole.

A full report of the workshop, including abstracts of the presentations, is available from the CCDP Planning Office on request (CCDP Report 88-2).

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The Industrial Associate Members of CCDP are currently: BP Canada, Bradley Bros. Ltd., Chevron Canada Resources, Esso Minerals Canada, Falconbridge Ltd., Heath and Sherwood Drilling (1986) Ltd., Inco Gold Co., JKS/Boyles Industries Inc., Longyear Canada Inc., Midwest Drilling, Newmont Exploration Ltd., Noranda Explorations Ltd., Petro-Canada Inc., Teck Explorations Ltd. and Tonto Drilling Company.

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The Study of Major Faults in Canada by Drilling: A CCDP Workshop Report

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The third of a series of thematic workshops sponsored by the Canadian Continental Drilling Program (CCDP) was held at the Pacific Geoscience Centre of the Geological Survey of Canada, Sidney, BC, 19-20 October 1988. The workshop was attended by 32 participants, drawn largely from universities and government in Canada but also with representation from industry and the United States. The principal aim of the workshop was to encourage open discussion of five proposals submitted to CCDP for the examination and sampling of fault structures by drilling. Other presentations provided background information on the geophysical response of faults, especially as regards seismic reflection profiling, and on current ideas of the importance of major faults as conduits for fluids and the loci of mineralization.

The workshop began with an outline of the objectives and progress of CCDP. James M. Hall (Dalhousie U, Halifax, Chairman, CCDP Steering Committee) described the status of the process of the review of proposals, the links CCDP had made within the geological community in Canada through recognition of its Steering Committee as a Standing Committee of the Canadian Geoscience Council, and the successful Industrial Associate program which has led to 15 major companies in the petroleum, mining, drilling and service industries becoming associated with the program.

John A. Percival (Geological Survey of Canada (GSC), Ottawa) presented his proposal for the examination by drilling of the structural break between the deep-crustal granulites of the Kapuskasing Structural Zone and greenstone-granite terrane of the Abitibi Belt to the east. The LITHOPROBE seismic profiles obtained in 1988 clearly image