Geoscience Canada

Sudbury, Ontario, and the Meteorite Theory

John S. Stevenson and Louise S. Stevenson

Volume 7, Number 3, September 1980

URI: https://id.erudit.org/iderudit/geocan7_3art01

See table of contents

Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

Stevenson, J. S. & Stevenson, L. S. (1980). Sudbury, Ontario, and the Meteorite Theory. *Geoscience Canada*, *7*(3), 103–108.

Article abstract

The origin of the Sudbury Basin, Onta-rio, has been the subject of much con-troversy, and the controversy was reacti-vated for further discussion in the 1960swhen Dietz proposed the meteoritetheory. The proof of the Sudbury astro-bleme has depended largely on shattercones in the area and on planar featuresdetailed microscopically in quartz insome rocks. Literature is cited to showthat such evidence is not in itself proofof origin of meteorite impact. Also ques-tioned is whether the Sudbury ore camefrom outer space or from the Earth. Theunique geological setting of Sudbury,near the junction of the threeprovinces of the Canadian Shield,is also considered in relation to themeteorite theory.

Articles

Sudbury, Ontario, and the Meteorite Theory

John S. Stevenson and
Louise S. Stevenson
Department of Geological Sciences and Redpath Museum
McGill University
3450 University Street
Montreal, P.Q. H3A 2A7

Summary

The origin of the Sudbury Basin, Ontario, has been the subject of much controversy, and the controversy was reactivated for further discussion in the 1960s when Dietz proposed the meteorite theory. The proof of the Sudbury astrobleme has depended largely on shatter cones in the area and on planar features detailed microscopically in quartz in some rocks. Literature is cited to show that such evidence is not in itself proof of origin of meteorite impact. Also questioned is whether the Sudbury ore came from outer space or from the Earth. The unique geological setting of Sudbury, near the junction of the three provinces of the Canadian Shield, is also considered in relation to the meteorite theory.

Résumé

L'origine du bassin de Sudbury, en Ontario, a fait l'objet de beaucoup de controverses. Au cours des années '60, lorsque Dietz avança sa théorie météoritique, la controverse reprit et donna lieu à de nouvelles discussions. La preuve d'un astroblème à Sudbury était étayée principalement par les cones d'éclatement trouvés dans la région et les plans structuraux décelés au microscope dans les cristaux de quartz de certaines roches. On dénie, avec de nombreuses références à l'appui, que pareilles observations puissent, à elles seules, suffire à expliquer l'origine du bassin par la chute d'un météorite. La question se pose de savoir si le minerai de Sudbury est tombé du Ciel ou provient de la Terre. Le cadre géologique du gisement, aux confins de trois provinces du bouclier Canadien, est également étudié dans ses relations possibles avec la théorie météoritique.

Introduction

Until the 1960s it was generally assumed that the Sudbury Basin had been formed largely by volcanic explosive activity (Speers, 1957; Williams, 1956) during the middle Precambrian, with the original features altered by later deformation and metamorphism (Stevenson, 1979). Thus the Basin was presumed to have been formed by endogenous process.

However in 1962 Dietz, who had been impressed with the nickel content of the Sudbury irruptive emplaced in this structure, suggested that the Basin might have been formed by meteorite impact, and the nickel ore brought in as part of this event, from outer space (Dietz, 1964; Dietz and Butler, 1964). This presented problems, particularly in explaining the large copper content, which is approximately equal to that of nickel in the Sudbury ore. This gives it a very different composition from that of nickel-rich meteorites. Thus Dietz' hypothesis has been modified by Guy-Bray and others (Guy-Bray, 1972, p. 2) to suggest that the form of the Basin resulted from meteorite impact, but the ore itself included material that had been in the Earth when the meteorite fell. In this concept, the Basin was presumed to have been formed by exogenous rather than endogenous processes.

In its modified form, the meteorite theory has won acceptance by many geologists (Guy-Bray, 1972; Peredery and Naldrett, 1975). During the 1960s and 1970s a large number of papers were written on Sudbury as a meteorite crater. The tremendous interest in lunar exploration and in the effects of nuclear explosions led to an unprecedented availability of government funds for research, particularly in the United States, and Sudbury has been the scene of special interest because of its Precambrian age and large size (Fig. 1).

Of course there is no problem in recognizing as meteor craters the circular structures that contain meteorite fragments, but structures like Sudbury without such material must be classed as astroblemes or cryptoexplosion structures, and proof of origin is more difficult. In particular, the mode of origin must be compatible with the geological features of the area, as stressed by Card and Hutchison (1972).

These authors point out that regionally the Basin is near the junction of the Superior, Southern and Grenville provinces of the Precambrian Shield. Sudbury is approximately 10 km northwest of the Grenville front zone, a major tectonic element. Furthermore, such major fault zones as the faults of the long-lived northeast-trending Murray and the north-northwest-trending Onaping systems are also part of the structural environment of the Sudbury Basin. Card and Hutchinson also point out that the Basin was established early above a major domal structure, where it was a centre of eugeosynclinal volcanic activity. Card (1978) concludes a discussion of the evolution of the Basin in this way: "These relationships indicate that the Sudbury structure is an integral part of its regional setting in space and time, and is not simply the product of a fortuitous meteorite impact at this particular site." (p. 196).

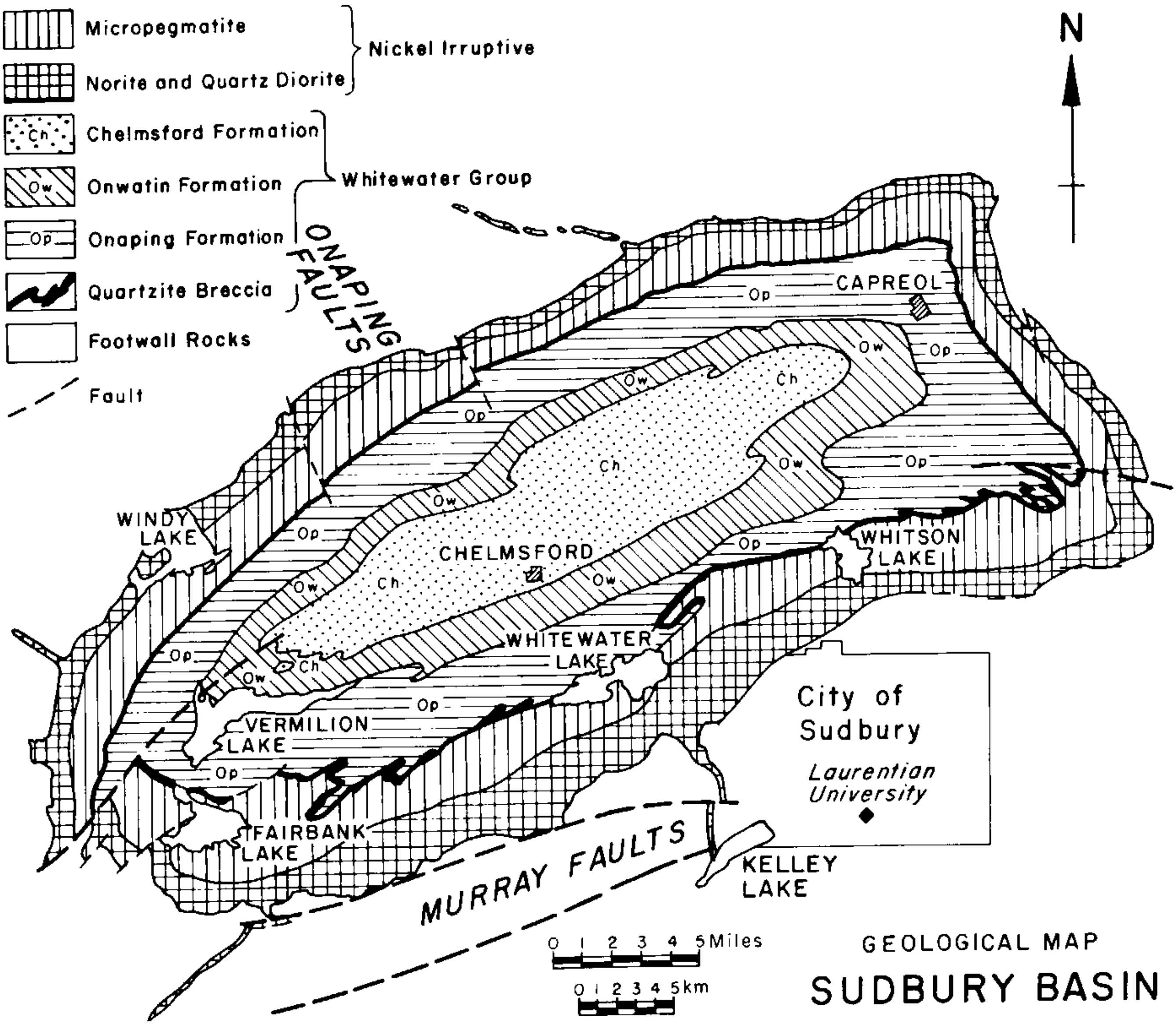

Figure 1
Generalized geological map of the Sudbury Basin with recent modifications by J. S. Stevenson after several published maps.

Although a number of interesting analogies have been made by geologists and astronomers between the Sudbury structure and meteorite craters, the main argument has been concentrated in the two areas here discussed: shatter cones and planar features in quartz.

Shatter Cones

Shatter cones are found in considerable abundance in the Sudbury area, and Dietz was the first to emphasize their importance as evidence of the meteorite origin of Sudbury. There is no disagreement on the fact that shatter cones are found there (Fig. 2): the controversy is whether or not such cones are indeed sure evidence of meteorite origin.

Although the term, "shatter cone", seems to have been first coined by Bucher (1936), the structures per se appear to have been described in 1905 and, later, in 1924, from the cryptovolcanic Upper Miocene Steinheim Basin in Germany. In North America they were described early from Wells Creek Basin, Tennessee, by Bucher (1936) and from Kentland, Indiana, by Shrock and Malott (1933), where they found numerous shatter cones in local quarries. Both Bucher and Shrock and Malott felt that these structures were the result of a sudden liberation of confined gases.

Later, Bucher followed with two papers (1963a, 1963b) in which he described in detail examples from Wells Creek, Tennessee, Vredefort, South Africa, and Steinheim Basin in Germany. He developed strong arguments against the formation of shatter cones by meteorite impact and rejected such an origin for these structures. The figures in his papers include excellent photographs of shatter cones from coal (1963b, p. 634). McCall (1964) strongly supported Bucher, basing his conclusions on experience in Europe, Africa and Australia.

In Canada in the 1950s, C. S. Beals, Dominion Astronomer, initiated a search for possible meteor craters and astroblemes, giving Canadian scientists an early lead in the study of impact craters (Grieve, 1979). Beals (1960) described the Holleford, Ontario, crater and his col-

Figure 2
Large shatter cones in Mississagi quartzite at type locality, Kelley Lake, south of the Sudbury Basin.

league, Millman (1960), the Brent, Ontario, crater. The careful presentation of facts by the Canadian astronomers was commended by McCall (1964) despite his criticism of other authors espousing the meteorite theory. Largely through Beals' efforts, the Canadian astronomical and earth physics programmes, which had long been underfunded, came to be generously supported by the Canadian and United States governments.

The Vredefort structure (ring or dome) in South Africa has many similarities to Sudbury, in particular the abundance of shatter cones. Because of this, it is frequently cited in the Sudbury literature, hence must be understood in an analysis of the Sudbury astrobleme concept. Like Sudbury, the origin of the Vredefort structure, whether endogenous or exogenous, has been and continues to be a subject of considerable discussion and disagreement.

Boon and Albritton (1937) discussed the origin of the Vredefort dome and concluded that "Impact and explosion of a gigantic meteorite could account for the salient features of the Vredefort area" (p. 63). This concept of an exogenous origin for Vredefort was expanded by Daly (1947) in a classic paper in which he summarized five commonly held endogenous theoretical explanations for Vredefort, and then elaborated his reasons for accepting the meteorite impact hypothesis. Daly's paper is an eloquent presentation of his philosophical concepts and illustrates the fact that the meteorite impact hypothesis is not recent in origin.

Dietz noted that this concept had not been generally accepted by South African geologists actually working in the mines of the area, and countered with his paper on the Vredefort ring structure (Dietz, 1961). This is a landmark paper because it included the first emphasis on the importance of shatter cones as a criterion for meteorite impact. In fact, he stated: "Shatter cones are a definite criterion for identifying meteorite scars or astroblemes" (1961, p. 499).

In a paper written slightly after Dietz' paper appeared in print, Hargraves (1961) suggested that the orientation of the Vredefort shatter cones was such as to suggest origin by an intense shock wave radiating from the centre of the ring and produced by a tremendous explosion. However, he was careful to state: "Whether the explosion was the culmination of a series of terrestrial igneous and/or tectonic events or the almost instantaneous result of meteorite impact remains to be proved." (p. 152).

The ensuing discussion of Hargraves' paper indicated considerable opposition on the part of many South African geologists to his concepts of the origin of shatter cones there. The controversy was similar to that which has ensued concerning Sudbury shatter cones. Brock (1961) forcefully objected to Hargraves' resuscitation of Daly's meteorite impact theory for Vredefort. Apparently Daly's meteorite theory continued to be objected to most strongly by many South African geologists.

More specifically in respect of shatter cones, Ramsay (1961) felt that there was good evidence at Vredefort that the cones were developed late in the formation of the major structures. This is very much in line with the current thinking of Fleet (1979) concerning Sudbury. Ramsay also pointed out that "structures resembling shatter cones may be produced by axial compression of rock cylinders in the laboratory" (1961, p. 156).

Brink and Knight (1961) in their discussion of Vredefort shatter cones suggested a mode of formation that is well known in the testing of concrete in cement and soil specimens in civil engineering laboratories. They further suggested that the cones might be related to shear phenomena and intense folding.

Although Hargraves made a rebuttal to these objections, it would seem from the discussion that shatter cones do not necessarily constitute a definitive criterion for identifying meteorite impact structures.

Poldervaart (1962) presented field evidence and arguments against a meteorite origin for Vredefort. While admitting that shatter cones are characteristic of shock, he felt that shock might have been induced by surface or near-surface explosions and not by meteorite impact origin. Poldervaart concluded his remarks by saying that the main tenets of his paper were, "that the geology and fracture pattern of the Vredefort Structure are incompatible with an origin of meteor impact" (p. 251).

Manton (1965) in a detailed study of shatter cones in the Vredefort Ring, listed a number of objections to shock wave origin, concluding by saying, "It now seems possible that shatter coning may be formed not only by violent shock but also by slow stress and may no longer be considered a criterion of meteor impact." (p. 1044).

Interest in Vredefort as a possible astrobleme was reactivated by Hamilton (1970). This prompted very strongly opposing papers by several South African geologists, particularly Cousins (1970) and Hunter (1973). Both believed that strictly geological reasons, structural and sedimentological, explained features seen in the Bushveld-Vredefort region.

When thinking of analogies between Sudbury and Vredefort, it is valid to note that, just as Sudbury is very important in the economy of nickel, so the Vredefort structure is very important in the economy of gold. As Brock (1961) pointed out, "The Vredefort structure is a factor in controlling the shape of the depository of the greatest known accumulation of gold in the world" (p. 155).

Nicolaysen (1972) presented evidence against meteorite impact for the origin of shatter cones and planar features in quartz. He showed that shock deformation features can be produced both experimentally and naturally without invoking meteorite impact, but may be interpreted as diapirs which obtained release from strong lateral compression.

Many geologists specifically interested in the Sudbury problem have been concerned with the apparent absence, in general, of shatter cones from volcanic environments. This has been emphasized by Dietz (1959, p. 500): "Shatter cones seem to be completely absent from rocks which have been definitely subjected to volcanic explosion." However, to give one example, Elston and Lambert (1965) have described shatter cones of presumed non-meteorite impact at Cerro Colorado, a small Tertiary volcanic vent near Albuquerque, New Mexico. They concluded that the striated cones there were almost certainly formed by volcanic processes and that volcanic explosions sufficiently powerful to form shatter cones have occurred on earth in historic time.

Among examples of shatter cones closer to Sudbury are those found, with planar features, in Precambrian rocks of the Slate Islands, in northeastern Lake Superior. These islands are presumed to represent the central uplift of a meteorite impact crater.However, as with Sudbury, there is a lively discussion going on about the origin of the Slate Islands structure. For example, Grieve and Robertson (1976, 1979) have proposed a meteorite impact origin, while Sage (1978) has advocated an endogenous origin. Sage suggests that the disagreement between the two groups results, in part, from their different approaches to the same problem. Those proposing endogenic processes base their conclusions on field observations and field data, while those proposing astrobleme origins support their hypothesis with the recognition of shock metamorphism features and the *a priori* assumption that such features can be caused only by meteoritic impact. He feels that the meteorite hypothesis fails to explain the closely associated local and regional structures and associated evidence for magmatic activity.

It seems to have been the discovery of shatter cones in the Sudbury area in the early 1960s that gave impetus to the belief that the Sudbury structure might have been formed by meteorite impact (Dietz, 1964; Dietz and Butler, 1964). Following the pioneer work of Dietz, a very comprehensive paper by Guy-Bray specifically on shatter cones at Sudbury appeared (Guy-Bray *et al.*, 1966). Several papers followed, many by scientists working for astronomical observatories or for agencies related to the space programme.

In a more recent paper, Dietz (1972) stated that the Sudbury shatter coning had achieved full status as a criterion of shock uniquely caused by meteorite impact. However, he regrets that the second part of his theory, that the Sudbury ores themselves are of meteoritic parenthood, has apparently received no adherence. He has presented interesting arguments in favour of his hypothesis, and has suggested that the Sudbury bolide might have been neither a usual meteorite nor a comet head, but an Apollo asteroid, a Sudbury "moon".

Since publication of Dietz' and Guy-Bray's papers on Sudbury shatter cones, such features have been found farther afield in the area, beyond the probable influence of a Sudbury meteorite impact. For example, they have been observed in Mississagi quartzite in the vicinity of Espanola, some 35 km from the nearest edge of the intrusion (Church, 1979).

Pattison (1979) in a recent paper continues to accept Dietz' meteorite proposal as proven by shatter coning, while rejecting the second part of Dietz' hypothesis regarding the bolide. In fact he states that such ideas "are opposed by the nearly unanimous opinion of the geological fraternity" (p. 259).

Fleet (1979) has recently studied the conical fracture surfaces that define the Sudbury shatter cones, specifically those at the type locality at Kelley Lake (Fig. 2) and those on the campus at Laurentian University. His petrographic studies convince him that the layers of biotite and chlorite of these conical fractures cross-cut the principal deformation features of the host Mississagi quartzite, and these features are logically associated with the Penokean orogeny. He states that "the conical fractures in the Southern province rocks of Sudbury cannot be a cryptoexplosion feature associated with a meteorite impact event immediately prior to emplacement of the nickel intrusion." (p. 1180). From additional textural evidence seen in the mineralized conical fractures, he further states that these are the result of rock deformation at low strain rates. Fleet concludes that the shatter cones at Sudbury therefore cannot be used as evidence for the origin of the Sudbury structure by hypervelocity meteorite impact.

Lamellar Quartz

In addition to shatter cones, the occurrence of lamellar quartz (quartz lamellae, planar structures in quartz) is the second principal criterion used in the support of an origin of cryptoexplosion structures by hypervelocity meteorite impact. However, as French (1966) has said, "Although these unique deformation lamellae may constitute the surest and most obvious criterion for identifying shocked rocks, there is much debate about their character and origin." (p. 905). Since lamellar quartz is present in many structures, its presence may not by itself prove meteorite impact.

Lamellar structures have long been known but their formation had usually been thought of as due to deformation during regional metamorphism. Up until the 1960s they had been studied in only a very general way, but with the development of the meteorite impact theory at that time and the finding of lamellar quartz in the rocks of many impactites, more attention was paid to their occurrence and specifically to certain crystallographic orientations of the lamellae, thought of as being unique to shock metamorphism.

McIntyre (1962) described deformation lamellae in quartz in the impact breccias of Clearwater Lake, Quebec. Bunch and Cohen (1963) found lamellar quartz expressed as deformation by fracturing along rational crystallographic planes from shocked quartz in breccia in the Holleford Crater. Dence (1964) reported quartz lamellae from breccia in the Brent and Holleford craters.

Shortly after Dence's papers were published, two papers appeared describing the experimental production of deformation lamellae in quartz, Carter *et al.*, (1964) and Christie *et al.*, (1964). Carter (1965) came out strongly in support of such lamellae as the result of shock metamorphism produced by meteorite impact.

The Vredefort dome is famous not only for its shatter cones, but also for the occurrence of lamellar quartz. Carter (1965) appears to have been the first to emphasize the occurrence of lamellar quartz at Vredefort in support of a meteorite impact origin for that structure. In a detailed paper, Carter (1968) said that he regarded naturally formed basal deformation lamellae as a reliable indicator of shock deformation due to impact, but did include the cautionary note that the suggested origins of the miscrostructures were to be regarded as speculative.

Many of Carter's conclusions in respect of quartz lamellae at Vredefort were challenged by Nicolaysen (1972).

In this paper Nicolaysen made a case for the origin not only of shatter cones but also of lamellar quartz by the operation of endogenous as opposed to exogenous processes.

The occurrence of lamellar features in minerals as a definitive criterion for meteorite impact has been further challenged by Currie (1971, 1972). In his paper on the Mistastin Labrador crater, Currie (1971) pointed out that shock metamorphism may be developed at volcanic temperatures and pressures. In his paper describing the Manicouagan caldera, Quebec, Currie (1972) noted that experimental evidence refutes the claim by Carter (1968) that certain unique orientations of deformation lamellae on shocked rocks are petrographically distinct from those on unshocked rocks. He stated, "The claim that deformation lamellae, or any feature of them, is indicative of impact is not supported by experimental evidence" (p. 49).

French (1966, 1967a, 1967b, 1968 and 1972) was the first to use planar structures in quartz specifically as found in clasts in the Onaping Formation as proof of the origin of Sudbury by hypervelocity meteoritic impact. Dence (1972) invoked the similarity of planar features found in quartz in the Onaping as well as out in the footwall rocks of the North Range to those in Vredefort in support of his belief that the Sudbury structure, like the Vredefort, was due to meteorite impact.

Although specimens showing planar structures in quartz are by no means common in Sudbury rocks, their occurrence has indeed been confirmed (Fig. 3). Through the kindness of French and others, one of us (J. S. S.) was able in 1966 to work with specimens which best illustrated planar features. These specimens seemed to have been through more than one major deformation and certainly had been subjected to localized deformation. During a review of this material in 1979, we again noted the abundance of planar features in quartz and of quartz strained to a block-mosaic structure. However, it did not appear to be necessary to invoke shock metamorphism and other evidences of meteorite impact for the features seen in these thin sections.

Conclusion

The interpretation of the Sudbury Basin as an astrobleme is a controversial one which rests largely on evidence from shatter cones and planar features in quartz. That such features do exist at Sudbury is definitely confirmed; their significance must be analysed and further research continued in the context of the entire geological setting of the Sudbury Basin.

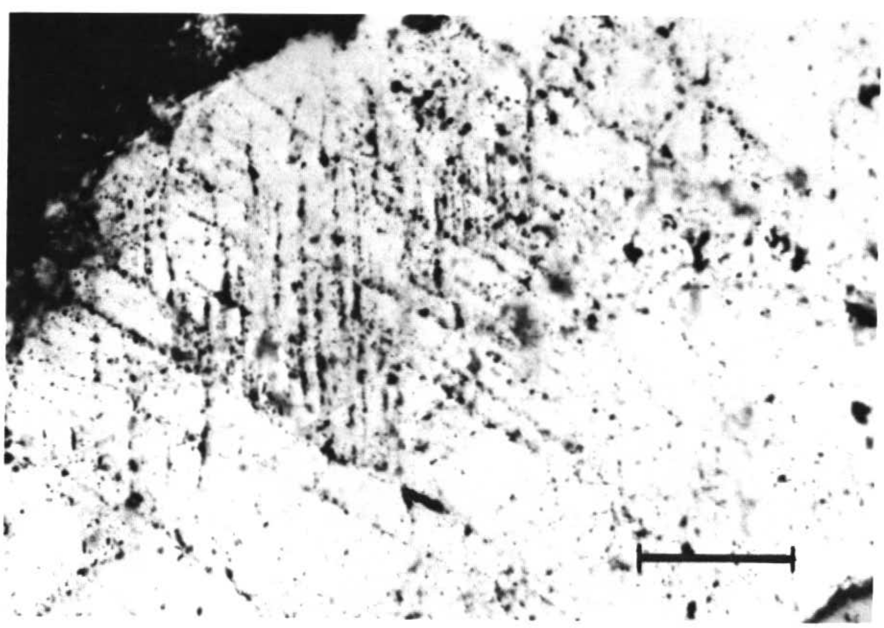

Figure 3
Multiple sets of planar structures (lamellae) in large quartz grain in quartzite from a lens in black tuff, Onaping formation, Morgan township, North Range, Sudbury. Crossed polars. Scale bar 0.1 mm.

References

Beals, C. S., 1960, A probable meteorite crater of Precambrian age at Holleford, Ontario: Publ. Dominion Observatory, Ottawa, v. 24, p. 117-147.

Boon, J. D. and C. C. Albritton, Jr., 1937, Meteorite scars in ancient rocks: Field and Laboratory, Southern Methodist University, v. 5, p. 53-64.

Brink, A. B. A. and K. Knight, 1961, Shatter cones in the rocks of the Vredefort ring - Discussions: Geol. Soc. South Africa Trans., v. 64, p. 157-158.

Brock, B. B., 1961, Shatter cones in the rocks of the Vredefort ring - Discussions: Geol. Soc. South Africa Trans. v. 64, p. 155.

Bucher, W. H., 1936, Cryptoexplosion structures in the United States: Proc. 16th Internatl. Geol. Cong., Washington, D.C., v. 2, p. 1055-1084.

Bucher, W. H., 1963a, Are cryptovolcanic structures due to meteorite impact?: Nature, v. 197, p. 1241-1243.

Bucher, W. H., 1963b, Cryptoexplosion structures caused from without or within the earth?: American Jour. Sci., v. 261, p. 597-649.

Bunch, T. E. and A. J. Cohen, 1963, Coesite and shocked quartz from Holleford crater, Ontario: Science, v. 142, p. 379-380.

Card, K. D., 1978, Geology of the Sudbury-Manitoulin area, Districts of Sudbury and Manitoulin: Ontario Geol. Survey, Rept. 166, 238p.

Card, K. D. and R. W. Hutchinson, 1972, The Sudbury structure: its regional geological setting: in J. Guy-Bray, ed., New Developments in Sudbury Geology, Geol. Assoc. Canada Spec. Paper 10, p. 335-380.

Carter, N. L., 1965, Basal quartz deformation lamellae - a criterion for recognition of impactites: American Jour. Sci., v. 263, p. 786-806.

Carter, N. L., 1968, Dynamic deformation of quartz: in B. M. French and N. M. Short, eds., Shock Metamorphism in Natural Materials, Mono Book Corp., Baltimore, p. 453-474.

Carter, N. L., J. M. Christie and D. T. Griggs, 1964, Experimental deformation and recrystallization of quartz: Jour. Geol., v. 72, p. 687-733.

Christie, J. M., D. T. Griggs and N. L. Carter, 1964, Experimental evidence of basal slip in quartz: Jour. Geol., v. 72, p. 734-756.

Church, W. R., in Fleet, Michael E., 1979, Tectonic origin for Sudbury, Ontario, shatter cones: Geol. Soc. America Bull. Pt. I, v. 90, p. 1181.

Cousins, C. A., 1970, Discussion of paper by Hamilton: Geol. Soc. South Africa Spec. Publ. 1, p. 374-375.

Currie, K. L., 1971, Mistastin Lake, Labrador, a resurgent cryptoexplosion crater: Geol. Survey Canada Bull. 207, 62p.

Currie, K. L., 1972, Geology and Petrology of Manicouagan resurgent caldera: Geol. Survey Canada Bull. 198, 153p.

Daly, R. A., 1947, The Vredefort Ring structure of South Africa: Jour. Geol., v. 55, p. 125-147.

Dence, M. R., 1964, A comparative structural and petrographic study of probable Canadian meteoritic craters: Meteoritics, v. 2, p.249-270.

Dence, M. R., 1972, Meteorite impact craters and the structure of the Sudbury Basin: in J. Guy-Bray, ed., New Developments in Sudbury Geology, Geol. Assoc. Canada Spec. Paper 10, p. 19-28.

Dietz, R. S., 1959, Shatter cones in cryptoexplosion structures (meteorite impact?). Jour. Geol., v. 67, p. 496-505.

Dietz, R. S., 1961, Vredefort ring structure: meteorite impact scar?: Jour. Geol., v. 69, p. 499-516.

Dietz, R. S., 1964, Sudbury structure as an astrobleme: Jour. Geol., v. 72, p. 412-421.

Dietz, R. S., 1972, Sudbury astrobleme, splash emplaced sublayer and possible cosmogenic ores. in J. Guy-Bray, ed., New Developments in Sudbury Geology, Geol. Assoc. Canada Spec. Paper 10, p. 29-40

Dietz, R. S. and L. W. Butler, 1964, Shatter-cone orientation at Sudbury: Nature, v. 204, p. 280-281.

Elston, W. E. and P. W. Lambert, 1965, Possible shatter cones in a volcanic vent near Albuquerque, New Mexico: Annals New York Acad. Sci., v. 123, p. 1005

Fleet, Michael E., 1979, Tectonic origin for Sudbury, Ontario, shatter cones: Geol. Soc. Amer. Bull. Pt. I, v. 90, p. 1177-1182.

French, B. M., 1966, Shock metamorphism of natural materials. Science, v. 154, p. 903-906

French, B. M., 1967a, Sudbury structure, Ontario: some petrographic evidence for origin by meteorite impact: Science, v. 156, p. 1084-1088.

French, B. M., 1967b, Sudbury structure, Ontario, some petrographic evidence for an origin by meteorite impact: Goddard Space Center, NASA document X-641-67-67, p. 1-56

French, B. M., 1968, Sudbury structure, Ontario: some petrographic evidence for an origin by meteorite impact: in B. M. French and N. M. Short, eds., Shock Metamorphism of Natural Materials, Mono Book Corp., Baltimore, p. 383-412

French, B. M., 1972, Shock-metamorphism features in the Sudbury structure: a review: in J. Guy-Bray, ed., New Developments in Sudbury Geology, Geol. Assoc. Canada Spec. Paper 10, p. 19-28

Grieve, R. A. F., 1979, When giant meteorites land on earth: Canadian Geographic, v. 99, p. 52-55.

Grieve, R. A. F. and P. B. Robertson, 1976, Variations in shock metamorphism at the Slate Islands impact structure, Canada: Contrib. Min. and Petrol., v. 58, p. 31-49.

Grieve, R. A. F. and P. B. Robertson, 1979, Observations on Terrestrial craters. Icarus, v. 38, p. 212-229.

Guy-Bray, J., and Geological Staff, International Nickel Co., 1966, Shatter cones at Sudbury: Jour. Geol., v. 74, p. 243-245.

Guy-Bray, J., 1972, Introduction: in J. Guy-Bray, ed., New developments in Sudbury geology, Geol. Assoc. Canada Spec. Paper 10, p. 1-5.

Hamilton, W., 1970, Bushveld complex - product of impacts?: Geol. Soc. South Africa Spec. Publ. 1, p. 367-374.

Hargraves, R. B., 1961, Shatter cones in the rocks of the Vredefort ring: Geol. Soc. South Africa Trans., v. 64, p. 147-161

Hunter, D. R., 1973, The Bushveld complex: a review: Econ. Geol. Research Unit, Univ. of Witwatersrand, Johannesburg, Information Circular 74, 12p.

Manton, W. L., 1965, The orientation and origin of shatter cones in the Vredefort ring: Annals New York Acad. Sci., v. 123, p. 1017-1049

McCall, G. J. H., 1964, Are crystalline structures due to meteorite impact?: Nature, v. 201, p. 251-254.

McIntyre, D. B., 1962, Impact metamorphism at Clearwater Lake, Quebec: Jour. Geophys. Res., v. 67, Pt. 2, p. 1647.

Millman, P. M. *et al.*, 1960, The Brent crater: Publ. Dominion Observatory, Ottawa, 24, p. 1-43.

Nicolaysen, L. O., 1972, Cryptoexplosion structures, interpreted as diapirs which obtain release from strong lateral confinement. Geol. Soc. America Mem. 132, p. 605-620

Pattison, E. F., 1979, The Sudbury sublayer. Canadian Mineral., v. 17, p. 257-274.

Peredery, W. W. and A. J. Naldrett, 1975, Petrology of the upper irruptive rocks, Sudbury, Ontario. Econ. Geol., v. 70, p. 164-175

Poldervaart, A., 1962, Notes on the Vredefort dome: Trans. Geol. Soc. South Africa, v. 65, p. 230-251.

Ramsay, J. G., 1961, Shatter cones in the rocks of the Vredefort ring - Discussions: Geol. Soc. South Africa Trans. 64, p. 156-157.

Sage, R. P., 1978, Diatremes and shock features in Precambrian rocks of the Slate Islands, northeastern Lake Superior: Geol. Soc. America Bull., v. 89, p. 1529-1540.

Shrock, R. R. and C. A. Malott, 1933, The Kentland area of disturbed Ordovician rocks in northwest Indiana. Jour. Geol., v. 41, p. 337-370

Speers, E. C., 1957, The age relation and origin of common Sudbury breccia: Jour. Geol., v. 65, p. 497-514.

Stevenson, J. S., 1979, Geological concepts developed in the Precambrian of Sudbury, Ontario: in W. O. Kupsch and W. A. S. Sargeant, eds., History of Concepts in Precambrian Geology, Geol. Assoc. Canada Spec. Paper 19, p. 224-244.

Williams, Howel, 1956, Glowing avalanche deposits of the Sudbury Basin. Ontario Dept. Mines, Ann. Rept., v. 65, pt. 3, p. 57-89

MS received May 6, 1980