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SUDBURY STRUCTURE, ONTARIO: SOME PETROGRAPHIC EVIDENCE FOR AN ORIGIN BY METEORITE IMPACT

BY

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ABSTRACT

The Onaping formation, approximately 4000 feet thick, is the lowest member of the Whitewater series which occupies the center of the Sudbury basin in southern Ontario. The formation overlies the upper (micropegmatite) unit of the nickel-bearing Sudbury "irruptive," and is separated from it by a "quartzite breccia" composed of large blocks of quartzite with interstitial micropegmatite. Previous workers have identified the Onaping formation as a complicated series of extrusive fragmental volcanic rocks and possible flows, but its exact origin and relations to the nickel-bearing "irruptive" have not been definitely established.

It has been previously accepted that the Onaping formation: (1) contains numerous fragments of devitrified glassy material; (2) also contains numerous inclusions of various "basement" rocks up to tens of feet in size; (3) exhibits a gradation in fragment size, from large blocks at the base to fine material at the upper contact; (4) exhibits a concentric zonation in rock types with respect to the basin margin; (5) cannot be definitely correlated with formations outside the Sudbury basin; and (6) was apparently deposited as a single unit during a brief period of time.

Preliminary petrographic study by the writer provides evidence that inclusions of basement rocks in the Onaping formation show microscopic textures typical of rocks subjected to shock pressures generated by meteorite impact or by artificial explosions. These include: (1) planar features in quartz, concentrated at or near the (0001) and $(10\bar{1}3)$ planes; (2) intense deformation and development of additional planar features in associated feldspar; (3) unusual deformational "flow textures" in single feldspar crystals which may represent the results of selective "melting" by shock. These features are also rarely observed in smaller fragments which constitute the matrix of the inclusions.

These observations establish a strong similarity between Sudbury and other structures for which an impact origin is either proven or strongly indicated. Acceptance of an impact origin for the Sudbury structure would also imply: (1) that shock-induced petrographic features can be preserved for periods in excess of 1.5 billion years; (2) that shatter cones, which are common at Sudbury, may constitute a definite criterion for meteorite impact; and (3) that meteorite impacts may either produce or trigger igneous processes involving large volumes of magma and economic ore deposits.

SUDBURY STRUCTURE, ONTARIO: SOME PETROGRAPHIC EVIDENCE FOR AN ORIGIN BY METEORITE IMPACT

INTRODUCTION

Within the last few years, studies of rock specimens subjected to the hypervelocity shock waves generated by artificial explosions and by meteorite impacts have established some petrographic and mineralogical criteria which appear to be unique indicators of such processes (Short, 1966a; Chao, 1967a, 1967b). These effects, which appear distinctly different from those induced by normal geological deformation, include:

(1) Formation of high-pressure silica polymorphs such as coesite and stishovite (Chao, Shoemaker, and Madsen, 1960; Shoemaker and Chao, 1961).

(2) High-temperature fusion and decomposition reactions among opaque minerals, indicating temperatures probably in excess of 1500°C (El Goresy, 1965).

(3) Widespread cleavage in quartz (Bunch and Cohen, 1964).

(4) Multiple sets of planar lamellae in quartz, commonly oriented parallel to specific planes, notably c(0001) and $\omega(10\bar{1}3)$, together with development of analogous planar features in associated feldspar (Carter, 1965; Von Engelhardt and Stöffler, 1965; Bunch, 1966).

(5) Intense disordering of single crystals of quartz and feldspar, often with complete conversion to glasslike phases which preserve original grain boundaries and structures (Bunch, 1966; Chao, 1966; Bunch, Dence, and Cohen, 1967).

Recent interest in such shock-metamorphic features has been reflected by an increased amount of study, by the appearance of several recent comprehensive review articles (Short, 1966b; Chao, 1967a, 1967b), and by a recent (April, 1966) Conference on Shock Metamorphism of Natural Materials (French, 1966; French and Short, in preparation).

Comparison of natural rock specimens from known meteorite impact craters, from unusual disturbed circular ("cryptoexplosion") structures, and from specimens subjected to artificial shock by conventional or nuclear explosions has demonstrated strong similarities in textures and behavior of the minerals. It is generally accepted by geologists and experimenters that these textures have been formed by the passage of transient shock waves with peak pressures of from approximately 40 kb to above several hundred kb. It has also proved possible to establish, based on the nature and intensity of the deformation observed, a series of qualitative stages or facies of shock metamorphism (Stöffler, 1966; Chao, 1967a, 1967b). However, because of the complex character of the passage of shock waves through a heterogeneous medium, and because of the rapid reactions and disequilibrium textures developed, it has not been possible to relate these stages to quantitative values of peak pressure, temperature, and other parameters.

The occurrence of these petrographic and mineralogical effects, in structures of known meteorite impact origin (e.g., Meteor Crater, Arizona; Wabar, Arabia; Henbury, Australia) together with the high pressures apparently required for their formation, has led to their use as indicators of a meteorite impact origin for older circular structures where meteorites are absent (Shoemaker and Chao, 1961; Dence, 1964, 1965; Carter, 1965; Von Engelhardt and Stöffler, 1965). Opponents of this interpretation have argued (1) that the textures are not indicative of shock or, (2) that the shock pressures that produced them were generated by internal volcanic and tectonic forces (see, e.g., Bucher, 1963, 1965; Currie, 1965, 1967). At present, however, the only natural process that is known to produce such effects is the hypervelocity impact of meteorites.

The purpose of this paper is to describe some unusual microdeformational features observed in rocks from the Sudbury structure in southern Ontario, Canada (French, 1967). These features are similar to those developed in rocks associated with accepted meteorite craters and with older structures for which an origin by meteorite impact has been proposed. Several structures of the latter type also occur in Canada (Dence, 1964, 1965); the largest, the Manicuoagan-Mushalagan structure, is approximately 40 miles in diameter. The occurrence of these features at Sudbury implies that the theory of an impact origin for the Sudbury structure must at least receive consideration as a valid working hypothesis.

GEOLOGY OF THE SUDBURY STRUCTURE

The Sudbury structure in southern Ontario, Canada, is a kidney-shaped basin approximately 37 mi. (59 km) long in an east-northest direction and 17 mi. (27 km) across (Fig. 1). The basin is outlined, both topographically and geologically, by an igneous "irruptive" between two and five kilometers thick, which is divided into an upper felsic "micropegmatite" and a lower, more basic "norite." (Because of a long controversy about the origin, method of emplacement, and subsurface shape of this igneous body, the nongenetic term "irruptive" has come into

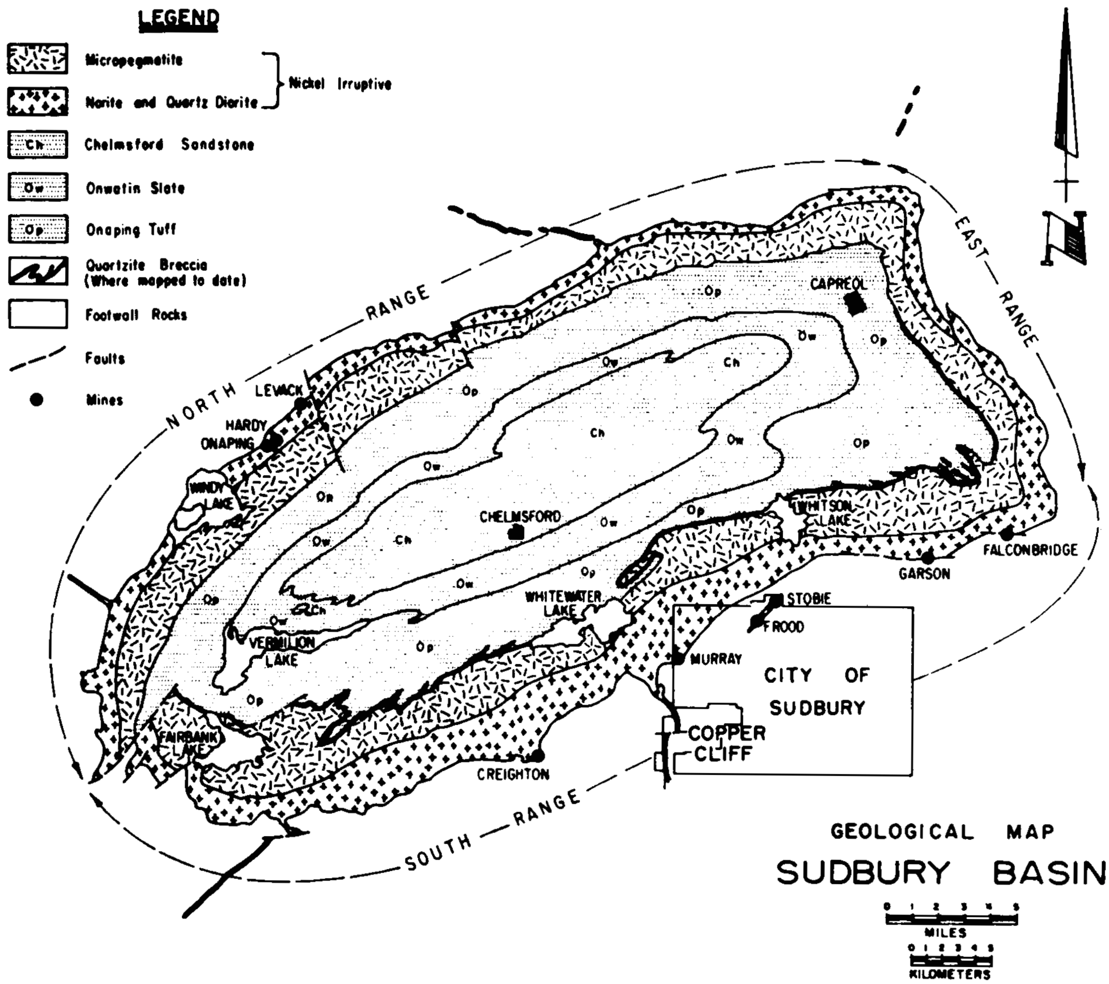

Figure 1—Index geological map of the Sudbury basin area (from Stevenson, 1963, Fig. 1), showing distribution of the Onaping formation and the basal "quartzite breccia" between the Onaping formation and the nickel irruptive. Older rocks which surround the Sudbury basin are not subdivided.

general use.) The age of the irruptive, as determined by whole-rock Rb-Sr methods on the micropegmatite, is approximately 1700 m.y. (Faure et al., 1964; Fairbairn, Hurley, and Pinson, 1965).

The irruptive and the basin are surrounded by older rocks, metasediments on the south and east, granitic rocks on the north and west (Fairbairn, Hurley, and Pinson, 1965). Near the margin of the basin, all these rocks have been locally shattered and brecciated, forming a complex unit known as the Sudbury breccia (Fairbairn and Robson, 1941; Speers, 1957). The inner part of the basin is filled with a series of sediments (the Whitewater series) composed of, in ascending order, the Onaping "tuff-breccia," the Onwatin slate, and the Chelmsford sandstone.

Since the discovery of ore in 1883, the mines associated with the Sudbury irruptive have produced several billion dollars worth of nickel, copper, iron, and platinum group metals. During this period, and especially within the last few years, the Sudbury structure has also generated a continuing geological debate about its origin and age, the timing of the igneous phenomena, the relationships with rocks outside the basin, and the origin of the ore deposits themselves. It is not possible to review here the bibliography, which has expanded continually since the early monographic studies (Coleman, 1903, 1904, 1905; Barlow, 1904). Several comprehensive reviews and bibliographies are available (Hawley, 1962; Card et. al., 1966), and detailed mineralogical studies on the ore bodies are continuing (Naldrett and Kullerud, 1967).

The possibility that the Sudbury structure was formed by a large meteorite impact was formulated in detail by Dietz (1964), who argued that such an origin would explain both the presence of the abundant Sudbury breccia and the origin of other puzzling structural features. Dietz also predicted, and subsequently discovered, shatter cones in rocks adjacent to the Sudbury basin (Figs. 2 and 3). Shatter cones are conical fracture features which Dietz believes to be unique indicators of meteorite impact. Subsequent studies (Dietz and Butler, 1964; Bray et al., 1966) have indicated that a zone of shatter coned older rocks is present around the entire Sudbury basin to distances as great as 11 mi. (17 km.) (Fig. 4).

SIGNIFICANCE OF THE ONAPING "TUFF-BRECCIA"

The development of a consistent theory for the origin of the Sudbury structure has been hampered by uncertainty about the origin of the Onaping formation, the lowest member of the Whitewater series, which lies within the Sudbury basin immediately above the irruptive (Fig. 1). This unit has generally been considered an unusual pyroclastic rock deposited by tremendous volcanic eruptions which occurred either long before, or immediately preceding, the emplacement of the irruptive itself (Burrows and Rickaby, 1929; Thomson, 1956; Williams, 1956; Speers, 1957). The Onaping formation has an estimated thickness of 4000 ft. (1220 m.) and an estimated minimum volume of 150 to 250 mi.^{3} (630 to 1050 km.^{3}) (Williams, 1956).

Various investigators (Bonney, 1888; Williams, 1891; Burrows and Rickaby, 1929; Thomson, 1956; Williams, 1956) have concluded that the Onaping formation: (1) contains numerous fragments of devitrified glassy material; (2) also contains numerous inclusions of "basement" rocks up to tens of feet (several meters) in size; (3) exhibits a uniform gradation in fragment size, with large blocks at the base and fine material at the upper contact; (4) exhibits a concentric zoning of

Figure 2—Well-developed shatter cones in the Mississagi quartzite. A large, intensely shatter-coned outcrop is located on the south shore of Kelly Lake, southwest of Sudbury on the South Range (Dietz and Butler, 1964). The cone axes are nearly parallel to the bedding, which, at this locality, dips steeply to the south, away from the observer. The shatter cones display the typical divergent "horsetail" striations and development of parasitic cones. The hammer in the foreground is 16 in. (41 cm.) long.

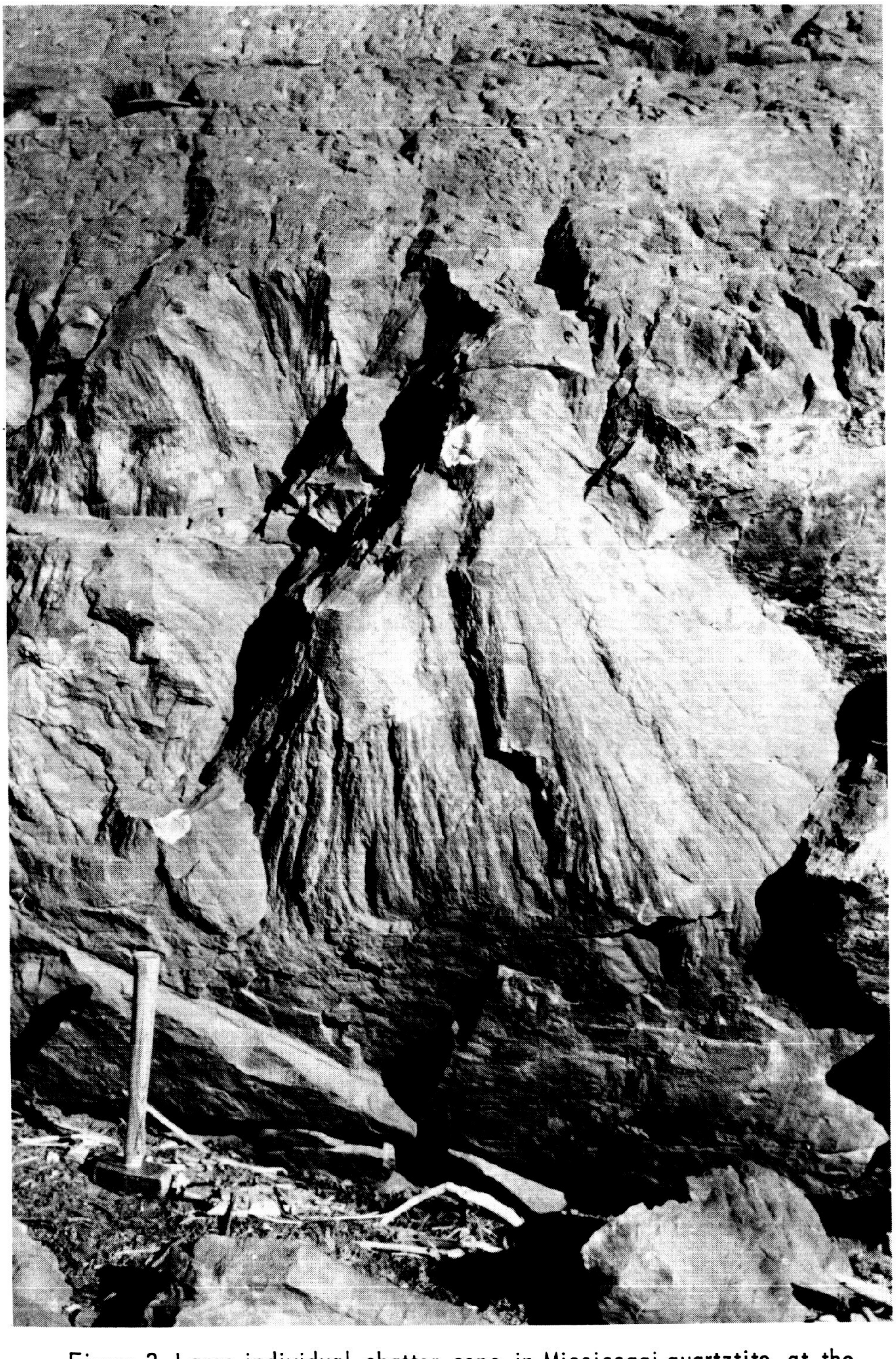

Figure 3—Large individual shatter cone in Mississagi quartztite, at the same outcrop shown in Fig. 2. Other areas of the outcrop where cones have not developed display curved, striated surfaces. Hammer in lower left in 16 in. (41 cm.) long.

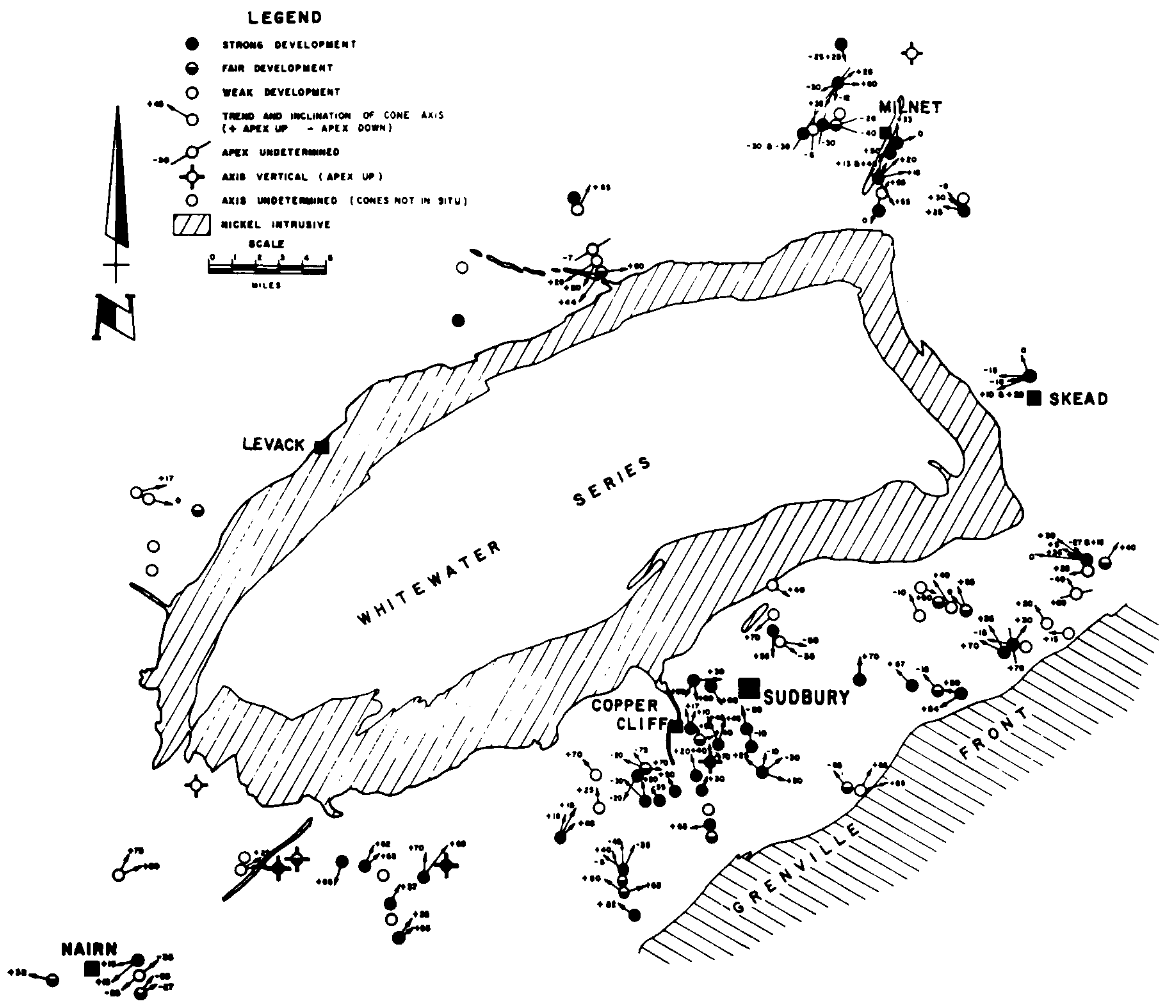

Figure 4—Distribution of shatter cones in older rocks around the Sudbury basin (from Bray et al., 1966, Fig. 1). Each symbol designates an outcrop of shatter-coned rock located during a reconnaisance study. No correction has been made for the dip of older shatter-coned sediments, but there is a general tendency for cone apices to point inward toward the center of the Sudbury basin.

rock types with respect to the basin margin; (5) cannot be definitely correlated with formations outside the Sudbury basin; (6) was apparently deposited as a single unit during a brief period of time, and (7) has been involved in at least one period of postdepositional metamorphism.

The long-accepted interpretation of the Onaping formation as a volcanic unit has recently been unsettled by the discovery (Stevenson, 1960, 1961, 1963) that a unit at the base of the formation, originally identified as rhyolitic and andesitic "feeder dikes" for the rest of the formation (Williams, 1956; Thomson, 1956) is composed of large blocks of quartzite in a matrix of micropegmatite. This unit (designated "quartzite breccia" in Fig. 1) contains isolated blocks of quartzite as large as 250 ft. (75 m) in long dimension (Stevenson, 1960). Such large exotic blocks do not seem restricted to the lowermost parts of the Onaping formation; recently (J. Guy Bray, personal communication, 1966) a block of quartzite at least 90 by 50 feet (27 by 15 m) has been discovered in the upper part of the Onaping formation, approximately 3400 ft. (1040 m) stratigraphically above the lower contact.

Dietz (1964), who proposed that the Onaping formation represented the top of an "extrusive lopolith" emplaced in and near the crater floor after the impact, suggested that this basal "quartzite breccia" should be examined for shock effects and coesite. The present research was undertaken to examine the alternative possibility that the Onaping formation might represent an accumulation of material excavated by the meteorite impact and immediately redeposited. Such a unit, corresponding to the "allochthonous breccias" or "fallback breccias" from other impact structures (Shoemaker, 1963; Dence, 1964, 1965), would be composed of shocked and melted "basement" rocks and would be a likely place to search for preserved shock-metamorphic effects.

GENERAL CHARACTER OF THE ONAPING FORMATION

A series of road and railroad cuts in Dowling Township, in the northwest part of the Sudbury basin, expose fresh Onaping formation generally regarded as typical by past investigators (Bonney, 1888; Williams, 1891; Walker, 1897; Burrows and Rickaby, 1929; Thomson, 1956; Williams, 1956). The specimens examined were collected by the writer from fresh roadcuts along the Copper Cliff – Levack highway (Route 144), about 5.8 mi. (9.2 km) south of the town of Levack, immediately west of High Falls on the Onaping River.

This study, which is concerned only with the Onaping formation, is based on the examination of material collected at this "type locality" and on additional specimens from this locality and from other exposures which were generously supplied by Dr. J. Guy Bray of the International Nickel Company of Canada, Ltd.

At this locality, the Onaping formation is a dense, massive, dark gray to black, structureless rock which sometimes exhibits crude conchoidal fracture (Fig. 5). The formation contains inclusions ranging in size from microscopic to larger than 20 cm, enclosed in a black, opaque, and featureless matrix (Bonney, 1888; Williams, 1891; Burrows and Rickaby, 1929; Thomson, 1956; Williams, 1956). The inclusions show no apparent alignment.

Figure 5–Typical Onaping formation, exposed in road cut at the "type locality" on Hwy. 144, south of Levack, and west of High Falls on the Onaping River. The rock shown here is so-called "black tuff," dark gray to black in color, very massive, with a crude conchoidal fracture and a typical fragmental character. (Photograph courtesy of J. Guy Bray).

In outcrop, the majority of inclusions are greenish, aphanitic, irregular in shape, and commonly exhibit a contorted flow structure (Fig. 6). Inclusions of recognizable "basement" rocks are also common; the majority of these appear to be granites, granitic gneisses, and feldspathic metaquartzites, all of which occur surrounding the Sudbury basin (Fig. 8). Occasionally, unusual inclusions are observed which consist of a core of crystalline "basement" rock surrounded by a greenish, aphanitic, and often flow-banded rim (Fig. 9). In outcrop and in hand specimen, the Onaping formation exhibits a general similarity to conventional pumiceous tuffs and tuff-breccias. However, its general character and the appearance of some of the inclusions which it contains also resemble the suevite breccias described from the Ries basin, Germany (Shoemaker and Chao, 1961; Hörz, 1965) (Figs. 7 and 10) and other proposed impact structures (Dence, 1964, 1965). The megascopic appearance of the Onaping formation is not distinctive enough to decide which of the two methods of origin is correct.

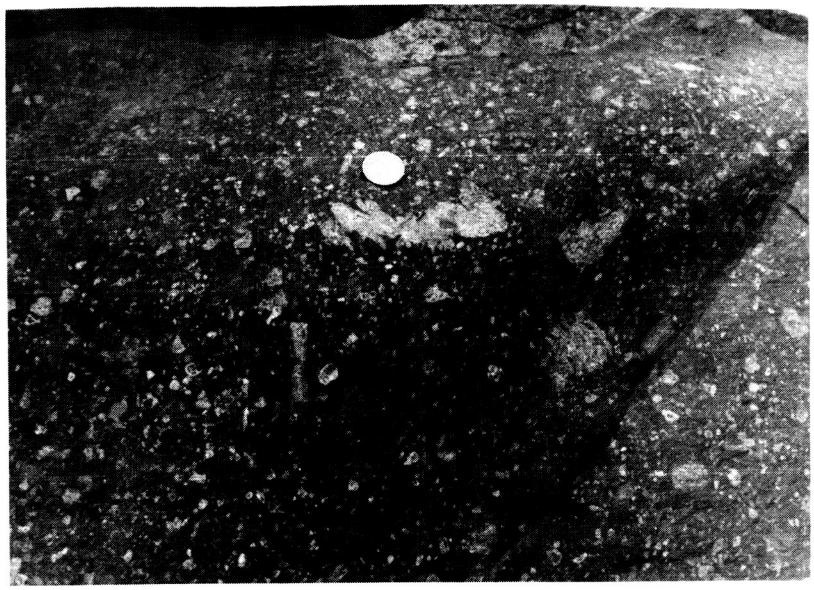

Figure 6—Typical Onaping formation, from the same locality, showing contorted, light-colored inclusions in a dark matrix. Coin diameter is about 1 in. (2 cm.). (Photograph courtesy of J. Guy Bray.)

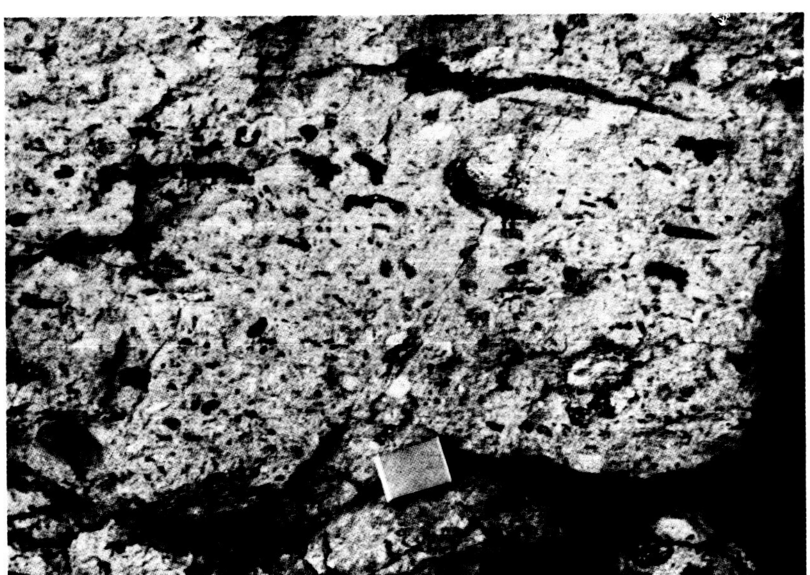

Figure 7—Outcrop of suevite from the Ries crater, Germany (Hörz, 1965, Fig. 1); Otting quarry. The fragmental deposit from this generally-accepted impact crater consists of dark, distorted inclusions of glass in a light, friable, and fragmental matrix. Some inclusions, such as the one in the lower right, consist of a rim of dark glass around a light-colored core of crystalline rock. Height of photograph approximately two feet. Compare textures with those shown in Fig. 6.

Figure 8—Small inclusion of coarsely-crystalline granitic rock (below coin) in typical Onaping formation. Coin diameter about 1/2 in. (1 cm.). (Photograph courtesy of J. Guy Bray).

In thin section, the Onaping formation can be seen to consist of diverse fragments set in a black, opaque, and unresolved matrix which commonly forms as much as 15 to 25 per cent by volume of the specimens observed (Fig. 11). The fragments, which do not appear to form a self-supporting framework, may be divided into three general types. The majority, including many of the larger ones, appear to be devitrified glass. They are irregular, often spinose, in shape, and exhibit both vesicular texture and flow structures, although they are rarely in contact and generally display no collapsed vescicles or eutaxitic structures characteristic of pumice fragments in partly- to strongly-welded ash-flow tuffs (Ross and Smith, 1961). These inclusions presently consist of finely-crystalline material, probably quartz and feldspar, in zoned or spherulitic arrangements suggestive of devitrification textures; no isotropic material was observed.

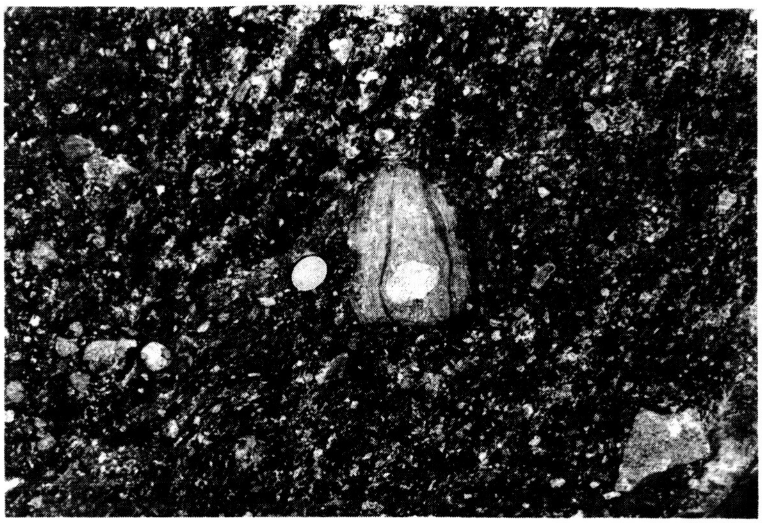

Figure 9–Typical Onaping formation, containing a fine-grained quartzofeldspathic inclusion (lower right), and a compound inclusion (to right of coin) consisting of a central core of crystalline rock (light), surrounded by aphanitic and flow-banded glassy material. Coin diameter about 1/2 in. (1 cm.). (Photograph courtesy of J. Guy Bray).

Figure 10–Glassy, flow-banded inclusion from the Ries suevite, Bollstadt quarry (photograph courtesy of F. Hörz). These inclusions, called Flädler (= "pancakes") consist of a mixture of shocked and unshocked rock fragments and molten material. The specimen here contains a large block of shocked granite (light) in darker, flow-banded material. The specimen is about 6 in. (12-15 cm.) long. Compare with the "compound" inclusion in Fig. 9.

Figure 11–Photomicrograph of typical Onaping formation; plane polarized light. The larger, irregular fragments of apparently devitrified glass exhibit flow structures; original vesicles are now filled with chlorite (gray). Smaller fragments include sharp and angular single crystals of quartz and feldspar as small as 5μ, enclosed in a black, opaque matrix.

A second type of fragment contains both finely-crystalline devitrified glass and either cores or irregular areas of coarser-grained xenoblastic aggregates of quartz, K-feldspar, and plagioclase (Fig. 12). The textures of these inclusions are extremely complex and may vary greatly even between adjacent fragments. The following observations seem applicable to most inclusions of this type: (1) the coarser crystals do not show euhedral outlines and often appear as corroded remnants within the finely-crystalline devitrification products; (2) spherulitic or chalcedonic textures are common in the finely-crystalline material, indicating either rapid crystallization or subsequent divitrification of a rapidly quenched glass; (3) areas of apparently devitrified glass are often hetereogenous with regard to structure or color, suggesting the original presence of glasses of differing compositions. The appearance of this group of inclusions gives the impression that they have been formed by the partial fusion of coarsely-crystalline granitic rocks, followed by devitrification and replacement by secondary minerals.

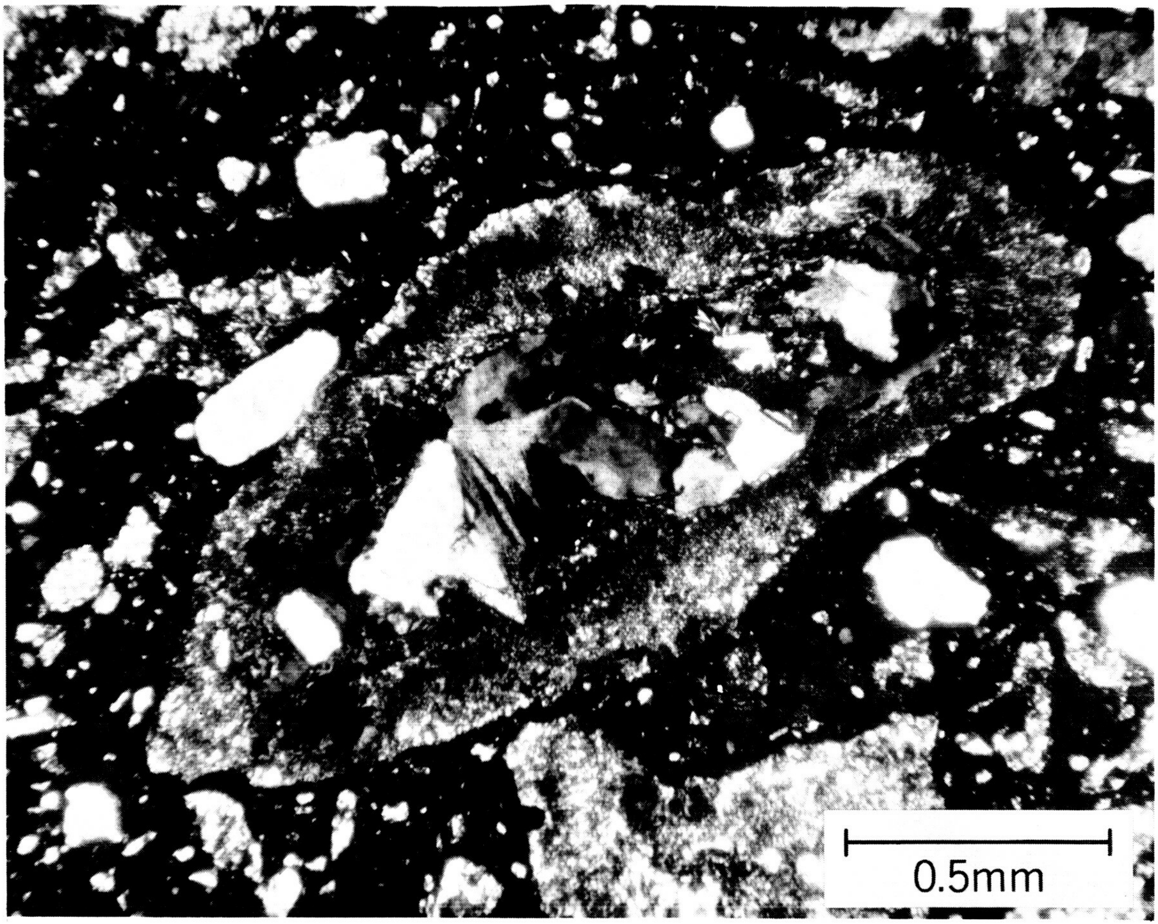

Figure 12—Small inclusion in Onaping formation, consisting of a central core of xenoblastic crystals of quartz, K-feldspar, and plagioclase, surrounded by a rim of finely-crystalline material which displays chalcedonic textures suggestive of rapid quenching or devitrification. The finely-crystalline rim cuts sharply across the larger crystals in the center. Crossed polarizers.

A more interesting group of this second type of compound inclusions consists of those in which a rim of apparently devitrified glass surrounds a core of crystalline rock (Figs. 9 and 12). In these inclusions, the contact between the crystalline core and the glassy rim is sharp, even though there may be well-developed flow structure in the material immediately adjacent to the inclusion. There is no evidence of gradual transition, suggesting that the glassy rims have not been derived by fusion of the crystalline core which they surround. The glassy material is extremely heterogenous in one specimen examined (Fig. 13) and contains several distinct structural and textural types of devitritifed glass, together with crystalline inclusions ranging in size from sharp individual fragments

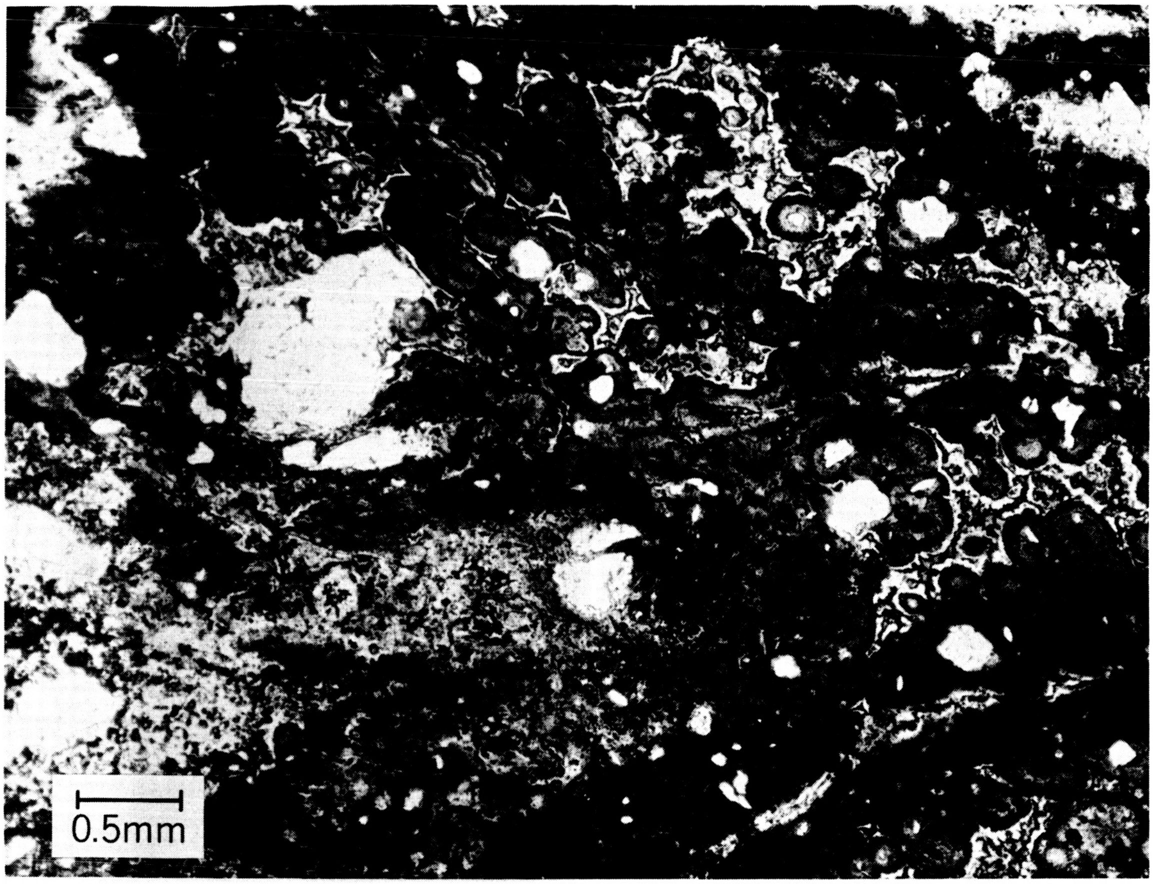

Figure 13—Photomicrograph of greenish, glassy material surrounding a core of quartzofeldspathic rock, to form an inclusion in typical Onaping formation. The glassy material shown here (plane polarized light) is extremely heterogeneous and consists of rock and crystal fragments (light, overexposed), mixed with diverse glass fragments of differing color and texture. The spherical, red-brown bodies often contain small crystal fragments in their interiors, suggesting that they developed as discrete bodies before being incorporated into the glassy rim around the rock fragment. No euhedral crystals or textures typical of volcanic rocks are observed in this material.

a few microns across to large xenoblastic polycrystalline inclusions several mm. in diameter. None of these crystalline inclusions shows any euhedral character; the impression is that the crystalline material has been mixed in with the glass rather than crystallizing from it.

In the specimen shown in Figure 13, the small dark red-brown spherulites are of particular interest. These appear to consist of devitrified glass exhibiting both radial and concentric structures, generally enclosing at or near the center, a smaller, irregular fragment of quartz or feldspar. These textures suggest that the molten material actually condensed on a small core in much the same manner as an oölite will grow around a similar nucleus in an agitated marine environment. The fact that these spherulites are distorted and even obliterated by the contorted flow structure present in this glassy rim suggests that they were present as discrete particles while the rim was still molten.

The glassy rims which occur around such crystalline cores are of particular significance in evaluating the Onaping formation and the Sudbury structure. Analogous materials, in which heterogenous aggregates of molten glass and fragmented rock have been plastered onto larger cores of rock, occur at both Meteor Crater, Arizona (Nininger, 1954; 1956, p. 117-134) and at the Ries basin, Germany (Hörz, 1965; Fig. 10). In both structures they are interpreted as collections of shattered and molten material thrown out of the crater through the explosion cloud immediately after impact.

A third type of inclusion in the Onaping formation consists of small rock fragments analogous to the large inclusions of "basement rock" observed in outcrop. The most common varieties are quartzofeldspathic rocks similar to the cores and remnants observed in the glassy inclusions. Less commonly observed rock types include oolitic quartzite, shale or slate, and possible amphibolite. Sharp and angular single crystals or small groups of the component minerals comprise smaller fragments; individual crystal fragments as small at 5μ can be distinguished in the matrix (Fig. 11).

In no specimens of the Onaping formation studied were any crystalline textures typical of volcanic rocks observed. Such features as euhedral crystal outlines, zoned feldspars, corroded quartz crystals, and eutaxitic or trachytic textures were uniformly absent. Based on petrographic study of the Onaping formation, it is possible to advance the interpretation that the unit is composed of a heterogeneous mixture of fractured and partly- to completely-melted fragments of granitic rocks typical of those which underlie the Sudbury basin. It should be remembered, in evaluating this interpretation, that the original identification of the Onaping formation (Bonney, 1888; Williams, 1891) was based on the recognition of glassy "pumice" fragments rather than on the presence of typical volcanic rock fragments such as might be expected in a normal tuff-breccia.

Quartz, potassium feldspar, and plagioclase are the most common minerals observed in the inclusions; the composition of the latter, estimated by the Michel-Levy method, is approximately An_{30}/An_{35}. The minerals occur as xenoblastic aggregates in rock fragments and in partly-glassy inclusions, as isolated fragments of single crystals up to a few mm in size, and as devitrification and recrystallization products in altered inclusions. Chlorite and a green actinolitic amphibole commonly occur as secondary minerals in recrystallized inclusions. The chlorite occurs as greenish aggregates which fill vesicles and occasionally replace larger feldspar crystals. The actinolite occurs as radiating or matted sheaves and aggregates of slightly pleochroic fibrous green crystals as much as 0.5 mm long, which penetrate both crystals and devitrified glass in many of the inclusions. Minor, apparently secondary components include sphene, which occurs as strings and patches of small crystals; epidote as small isolated crystals; and sulfide minerals, which occur as irregular patches in both inclusions and matrix.

The apparent freshness and lack of extreme metamorphic effects in the Onaping formation have long been recognized (Bonney, 1888; Williams, 1891; Burrows and Rickaby, 1929; Thomson, 1956; Williams, 1956), although near the micropegmatite contact, both thermal and cataclastic metamorphic effects have been observed (Stevenson, 1960, 1961, 1963). Specimens from the type area show virtually no recrystallization; crystal fragments a few microns across are still distinct within the matrix. Some of the larger crystalline fragments have developed a rim of actinolite a few microns thick at the contact with the matrix; actinolite also penetrates many inclusions. Many of the recrystallization textures of the larger inclusions vary widely, even in a single thin section and often between adjacent inclusions, suggesting that many of the presently observable textures in the Onaping formation may have developed during or soon after deposition of the individual fragments.

There is independent evidence for at least two major metamorphic events affecting the Sudbury basin after deposition of the Onaping formation: the "Penokean" orogeny at about 1600 m.y. (Card, 1964), and deformation and diabase intrusion associated with the "Grenville event" at about 1100-1200 m.y. (Burrows and Rickaby, 1929; Thomson, 1956). The mineralogy of the Onaping formation is consistent with mild metamorphism to the chlorite grade. Whole-rock X-ray diffraction patterns show the presence of quartz, K-feldspar, plagioclase, actinolite, and chlorite; no detectable amount of micas or clay minerals occur in the matrix.

SHOCK-METAMORPHIC FEATURES IN THE ONAPING FORMATION

Introduction

Typical specimens of the Onaping formation, which consist of small fragments in a black matrix, rarely show any textures uniquely indicative of shock metamorphism. Most of the component fragments are either underformed or have been completely melted (Fig. 11), so that their history is uncertain. The evidence to be discussed is found in study of larger inclusions of granitic rock contained within the Onaping formation, and includes unusual planar features in quartz and feldspar, together with more unusual deformational textures observed in some inclusions.

Rarely, small fragments in thin sections of typical Onaping formation show poorly-developed planar sets in quartz and feldspar similar to those which occur throughout larger inclusions; such small fragments typically occur at a rate of about one to three per thin section and can easily be overlooked except for the corroborative evidence from larger inclusions. An unusual, striking example of a deformed feldspar crystal is shown in Figure 14. The original crystal, about 4 mm long, has been converted completely into an aggregate of disoriented microcrystalline domains without destroying the general shape of the crystal. Crosscutting zones of apparent melting have developed in the crystal without fragmenting it, and the indented character of some areas of the outer margin suggest the crystal has been molten, or at least plastic, for a brief period of time, sufficient to destroy the original crystalline character but brief enough so that the outline of the crystal and the gross aspects of the structure have not been obliterated. Such pervasive deformation is also common in many of the inclusions studied (see below, p. 31).

Planar Features in Quartz and Feldspar as an Indication of Shock Metamorphism

Since the inference of a meteorite impact origin for the Sudbury structure rests in a large part upon the planar features observed in quartz and feldspar from inclusions in the Onaping formation, it is desirable to discuss the use of such features as criteria of shock metamorphism.

Numerous studies of artificially and naturally shocked rocks have shown that one effect of moderate levels of shock pressure is the development of unusual sets of planar features in the constituent quartz and feldspar (Short, 1966a, 1966b; Chao, 1967a, 1967b; Carter, 1965; Bunch, 1966; von Engelhardt and Stöffler, 1965). The features most commonly occur as multiple sets of closely-spaced parallel planes oriented parallel to distinct crystallographic directions in the host crystal (Figs. 15 and 16). The individual planes are generally less than 2μ in width and often so closely-spaced that individuals cannot be distinguished. In unaltered crystals from artificial explosions or from young meteorite craters, the planes may appear as distinct lamellae possessing a sharp contact against the host quartz and exhibiting birefringence effects. In older structures, the planes are represented by discontinuous arrays of small discrete inclusions, and have been designated "decorated" planar features (Dence, 1964, 1965; Bunch, 1966; Carter, 1965).

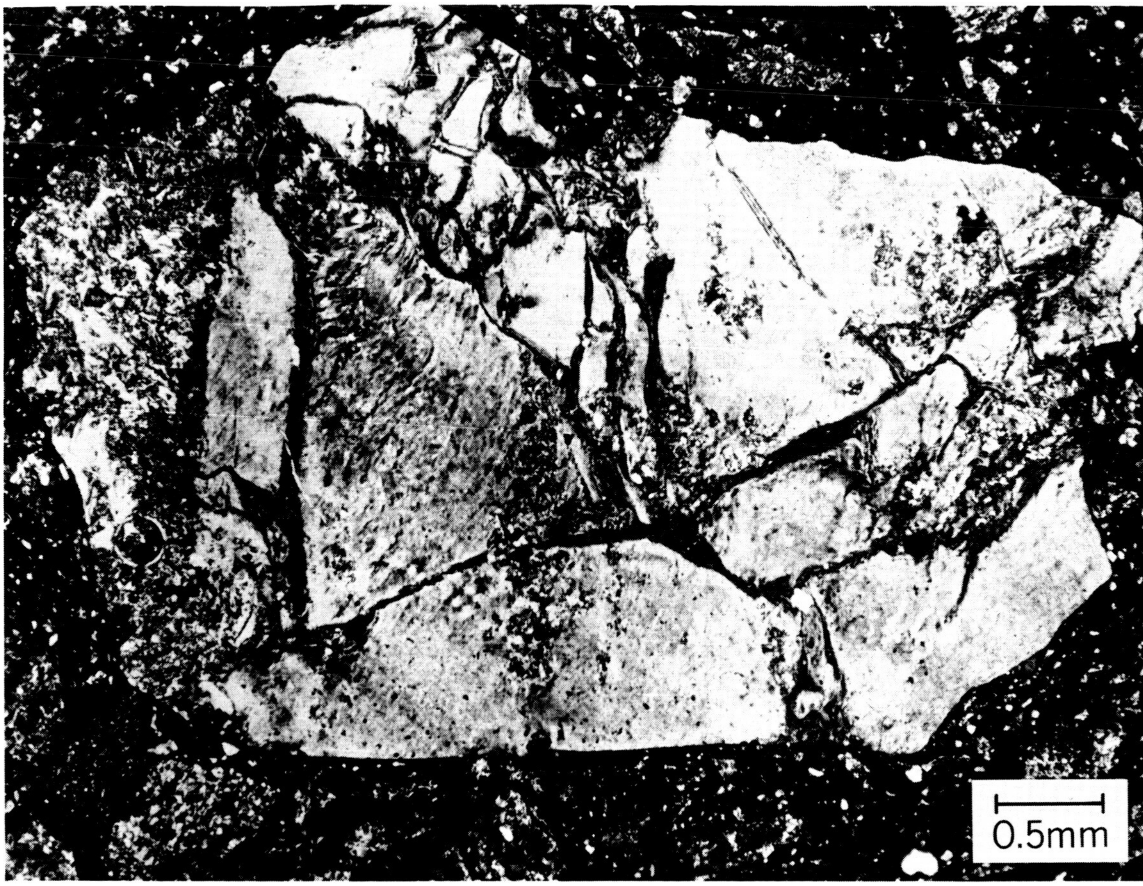

Figure 14—Intense, throughgoing crystalline deformation exhibited by a single feldspar crystal fragment about 4 mm. long in typical Onaping formation (crossed polarizers). The entire crystal has been converted, without disruption, into a mosaic of small crystalline areas. Dark veins through the crystal are apparently zones of localized melting without fracturing of the crystal. Indented areas in the crystal, surrounded by apparent strain (top, center) suggest that the entire crystal may have been glassy or plastic for a brief period.

There is still considerable debate about the exact nature of the planar features, particularly whether they are actual lamellae of a distinctly different phase, perhaps analogous to "slip planes" in deformed metals, or whether they represent open fractures developed during unloading of the grains after passage of the shock wave.

Regardless of these uncertainties, the planar sets, particularly those in quartz which have been most studied, seem to possess several characteristics that distinguish them from "deformation lamellae" or "Böhm lamellae" which form in quartz deformed during metamorphism at geologically slow strain rates:

Figure 15—Highly shocked quartz crystal from the Ries crater (Zipplingen) (from von Engelhardt and Stöffler, 1965, Fig. 1). The single grain exhibits several planar sets; those parallel to A are $(10\bar{1}3)$ and related planes; those parallel to B are related to $(10\bar{1}1)$. (Crossed polarizers).

Figure 16–Shocked plagioclase feldspar crystal from the Ries crater (Zipplingen) (from Stöffler, 1966, Fig. 4). Original albite polysynthetic twinning runs NE-SW; deformation lamellae have developed across the original twins (NW-SE) to produce a distinctive "ladder-like" texture. The lamellae have formed in alternate twins; the intervening twins have been converted to isotropic material. The upper and lower left-hand areas of the crystal have been changed to isotropic material in which relics of twins and deformation lamellae can be seen.

(1) Multiplicity. Planar sets in shocked quartz are generally multiple. It is not uncommon to find between three and seven distinct sets of planes in quartz grains from breccias associated with both known meteorite craters (e.g., Meteor Crater, Arizona and the Ries basin, Germany) (Fig. 15) and older circular structures. The present record is eleven planar sets in a grain from the Brent structure, Canada (M. R. Dence, personal communication, 1967).

(b) Orientation. The strong orientation of planar sets in quartz parallel to distinct crystallographic directions is the most striking difference between shock deformation features and the lamellae produced by normal metamorphic deformation of quartz. In shocked quartz, planar sets are oriented parallel to discrete planes, commonly (0001), $(10\bar{1}3)$, $(10\bar{1}2)$, $(10\bar{1}1)$, $(11\bar{2}1)$, and $(10\bar{1}0)$ (von Engelhardt and Stöffler, 1965). In lightly-shocked quartz with only a few planar sets, (0001) and $(10\bar{1}3)$ orientations are common, and development of planar sets parallel to these planes has been used as an indicator of extremely high strain rates and consequently of meteorite impact (Carter, 1965; von Engelhardt and Stöffler, 1965).

The effects of this distribution can be seen in a plot of the angle between the pole to the planes and the quartz c-axes. Shocked quartz displays a series of maxima corresponding to one or more of the particular planes. Lamellae in quartz from metamorphic rocks display a diffuse, "bell-shaped" distribution, generally with a maximum at 15 to 25° and a skewed tail toward higher angles (Ingerson and Tuttle, 1945; Tuttle, 1949; Carter, 1965; Carter and Friedman, 1965; Scott, Hansen, and Twiss, 1965; Short, 1966b).

(c) Distribution. In a given specimen or inclusion of shocked rock, planar features in quartz or associated feldspar are generally distributed through virtually every grain in the inclusion.

(d) Fabric. In shocked rocks, the crystallography of each individual grain seems to be the determining factor in orientation of planar features. Such features do not cross grain boundaries and may be strongly disoriented in adjacent grains. The orientation of such shock lamellae does not seem to reflect the slow imposition of an external anisotropic stress (Carter, 1965), although there is a strong relation between the orientation of lamellae and the crystal structure of each individual grain.

Analogous planar features developed in feldspar have, at present, been less studied, although they seem to show a similar crystallographic control and appear oriented parallel to planes of low crystallographic index. The occurrence of these planes across preexisting albite polysynthetic twinning (Fig. 16) produces a "ladder-like" texture typical of feldspars from the Ries crater (Stöffler, 1966) and other Canadian structures (Dence, 1964, 1965).

Planar Features in Granitic Inclusions from the Onaping Formation

Planar features in quartz and feldspar were originally detected in an inclusion of granitic gneiss collected from the Onaping formation at the "type locality" near High Falls on the Onaping River. The inclusion, about 15 cm in diameter, consists of quartz, K-feldspar, and plagioclase; no mafic accessory minerals were observed. The specimen displays bands from one to several cm thick, resulting from mineralogical and textural variations. The thicker bands consist of plagioclase (50 to 70 percent by volume), K-feldspar (10 to 20 percent), and quartz (20 to 40 percent), which occur as anhedral grains generally 0.2 – 1.0 mm in size. In the narrower bands, K-feldspar becomes dominant and the average grain size increases to several mm.

The inclusion is cut by a thin vein of light brown glasslike material, which pinches out at one end and reaches a maximum width of a few mm. In thin section, this material appears as a heterogenous, finely-crystalline aggregate suggestive of massive devitrified glass (Fig. 17). Irregular patches and strings of fine quartz crystals occur isolated in a brownish matrix which apparently consists of fine crystals of feldspar. At the margins of the vein, there is often a gradual transition between the glassy material of the vein and the larger crystals which border it; locally, patchy birefringence in the crystals grades into the glassy material of the vein (Figs. 17 and 18).

The appearance of the glassy vein suggests that it was derived by sudden and localized fusion of the constituent quartz and feldspar and does not represent extraneous material emplaced in a fracture. This interpretation is consistent with the heterogenous character and composition of the glassy material and with the apparently gradational contacts between the vein and the adjacent crystals. Deformation in the remainder of the inclusion, indicated by strained extinction and by brittle fractures which commonly offset and rotate original polysynthetic twinning in plagioclase, apparently becomes more intense toward the margin of the vein. The material in this vein is strongly similar to the "pseudotachylite" reported in shocked granitic rocks from other Canadian structures (Dence, 1964, 1965).

Multiple sets of planar features are developed in both quartz and feldspar crystals in this inclusion. These features occur in virtually every observable quartz grain and can be recognized in the majority of both K-feldspar and plagioclase crystals. Identical features have also been observed in over half of a series of about a dozen granitic inclusions collected at random from the same locality after the original discovery of planar features. (The remainder of this suite showed even more intense deformational effects, described below, p. 31). It is therefore believed that the features described are typical of textures developed in granitic inclusions contained in the Onaping formation, and do not represent an isolated occurrence.

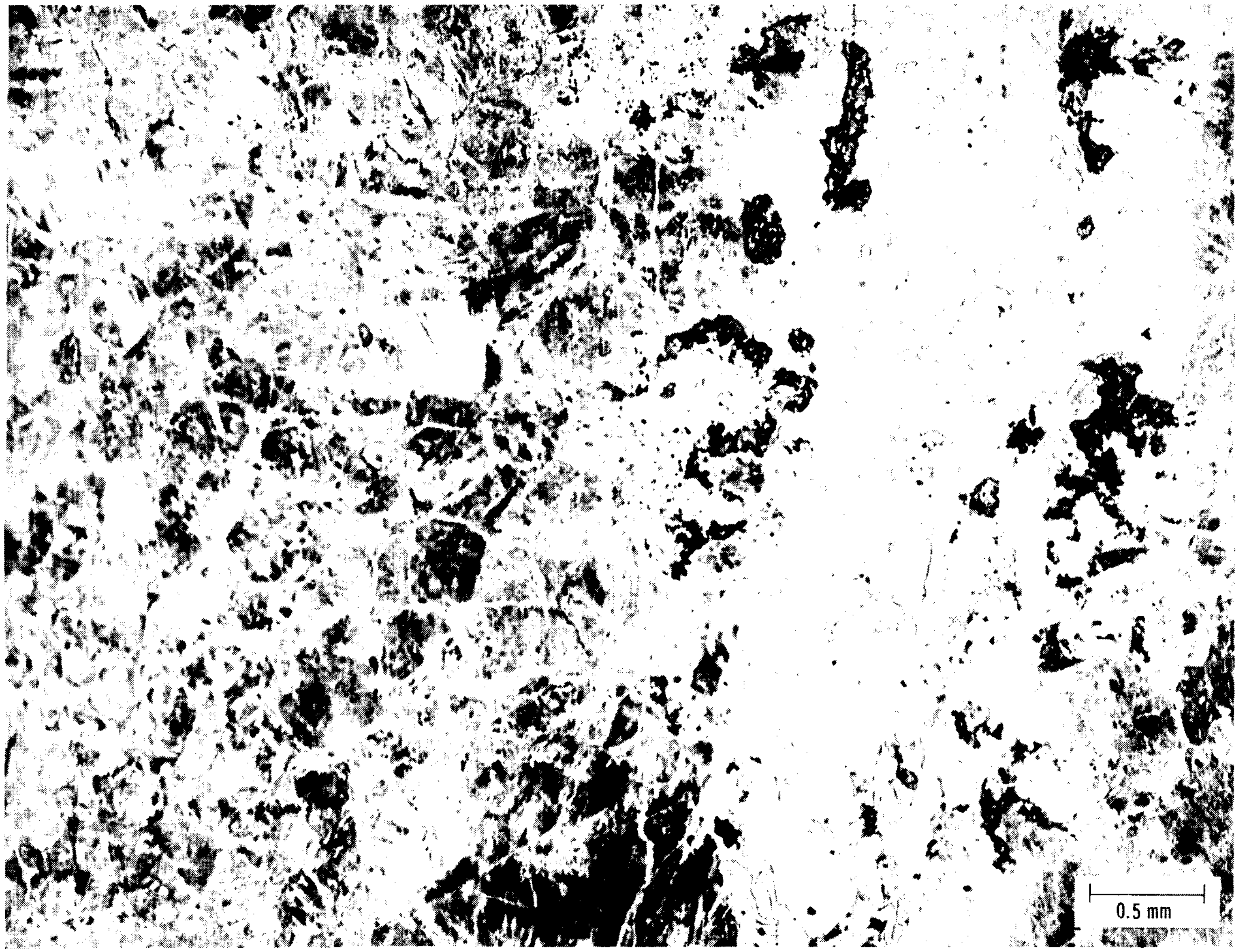

Figure 17–Inclusion of granitic rock from typical Onaping formation (specimen CSF-66-39) (plane polarized light). The granitic fabric is cut by a light brown glass vein (right) which consists of heterogenous material now represented by finely-crystalline quartz (light "islands") and feldspar (light gray areas). Contacts of this "pseudotachylite" vein are gradational, and crystals adjacent to the vein show enhanced deformation.

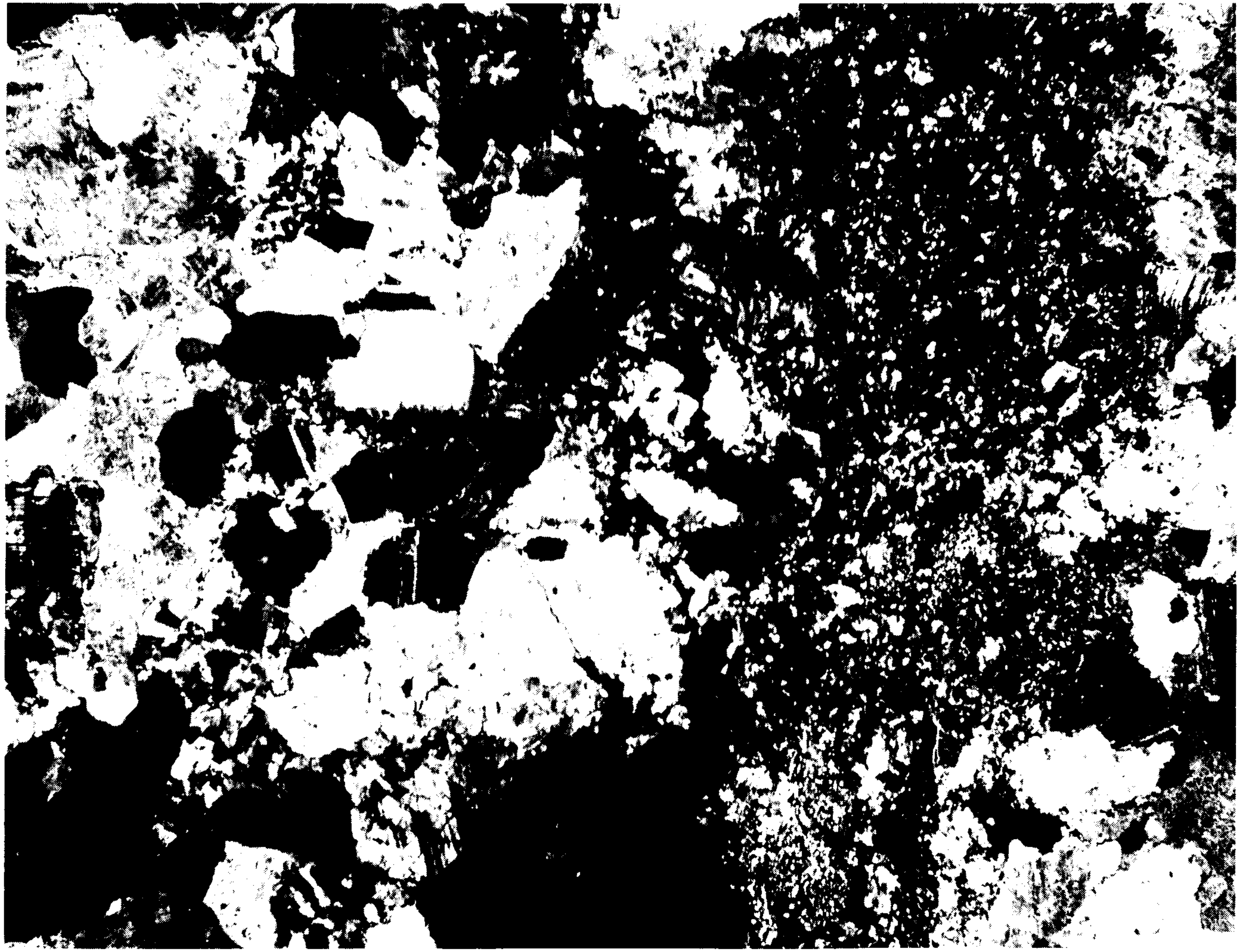

Figure 18—Same view as Fig. 17, crossed polarizers. Notice the gradational character of the contact between crystalline material and the pseudotachylite vein; in the upper right, material which appears glassy in plane polarized light shows significant birefringence and crystal structure.

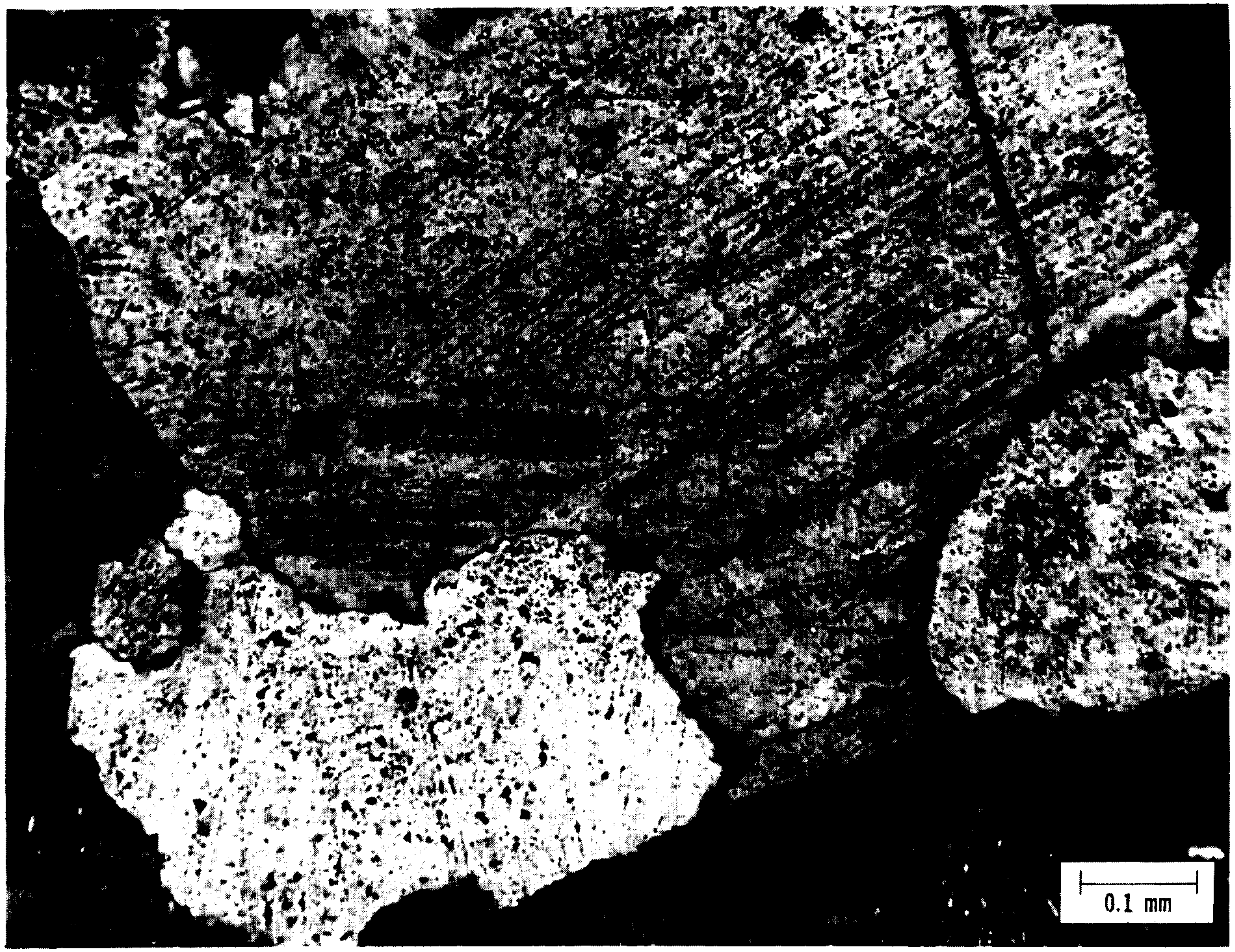

Figure 19—Photomicrograph of planar features in quartz in an inclusion of granitic rock from the Onaping formation (specimen CSF-66-39). The planes consist of discontinuous arrays of small inclusions. The large grain exhibits three distinct sets, oriented NE-SW, E-W, and ENE-WSW. The smaller grains at the bottom contain two sets each, strongly disoriented from the direction of the sets in the larger grain. (Crossed polarizers).

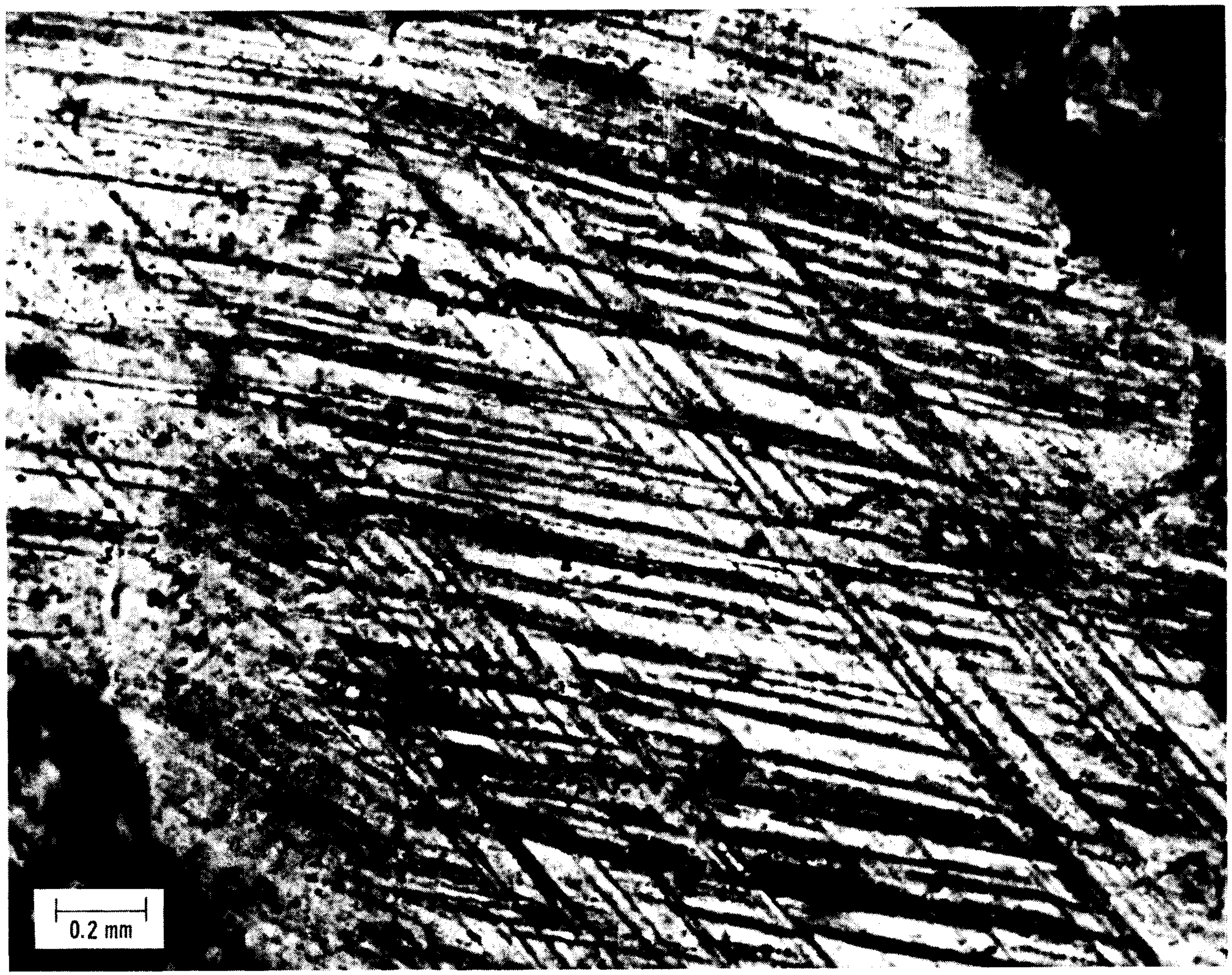

Figure 20–"Decorated" planar features in a quartz grain from the breccia at the Brent crater, Canada (photograph courtesy of M. R. Dence). Two sets of planar features are somewhat discontinuous and exhibit isolated inclusions arranged along the trend of the plane. (Crossed polarizers).

The multiple sets of planar features in quartz consist of planar arrays of small, spherical to elliptical inclusions, which generally extend discontinuously across 10 to 20 percent of the trace of the plane in thin section (Fig. 19). The inclusions range in size from about 2 μ down to submicron dimensions; under high magnification, they have a slightly brownish color and exhibit a lower refractive index than that of the host quartz. The planes do not cross grain boundaries and are often oriented at sharp angles to each other in adjacent grains. The number of observable planar sets varies between one and four per grain, with an average of about two per grain for the inclusion studied.

The quartz grains containing the inclusions show uniform to mildly strained extinction of a character not unusual in metamorphosed granitic rocks. Recrystallization of the host quartz grains after formation of the planar sets is evident in thin section. The planar sets commonly have a patchy distribution over larger grains, and, in a few grains, irregular areas of clear quartz truncate and transect the planar sets. (Fig. 21).

The Sudbury planar sets are not completely identical in appearance to planar features observed in quartz from artificially shocked rocks and in materials from young meteorite impact craters. The planar arrays observed thus far in Sudbury material are not lamellae sensu strictu; they have no sharp planar contacts against the host quartz and do not constitute continuous bands of finite width. No anomalous birefringence properties have been observed associated with the planar features. The Sudbury features most closely resemble "decorated" planar features observed in quartz from older structures (Dence, 1964, 1965; Carter, 1965) (Fig. 20). The production of such "decorated" features by the effects of recrystallization and annealing of original deformation lamellae has been noted in both naturally and artificially deformed quartz specimens (Carter, 1965; Carter and Friedman, 1965). It should be remembered, in evaluating these features in the Sudbury specimens, that the Onaping formation has been subjected to long burial and to at least one metamorphic event, and that recrystallization and annealing effects are apparent in the quartz grains containing the planar features.

The Sudbury planar features exhibit a strong preferred crystallographic orientation similar to that observed for both true lamellae and for "decorated" features in shocked rocks from known and suspected meteorite impact craters. Orientations of the planes of inclusions with respect to the quartz c-axes were determined by conventional universal stage methods for several hundred planes in quartz grains whose c-axes were measurable (i.e., oriented at less that 40° to the plane of the thin section). Because of the relatively large uncertainty in orienting the planar arrays in a true vertical direction, no refraction corrections were made, and the angles between the quartz c-axes and the poles to the planes are considered accurate only to ±4°. The histogram of these angles (Fig. 22)

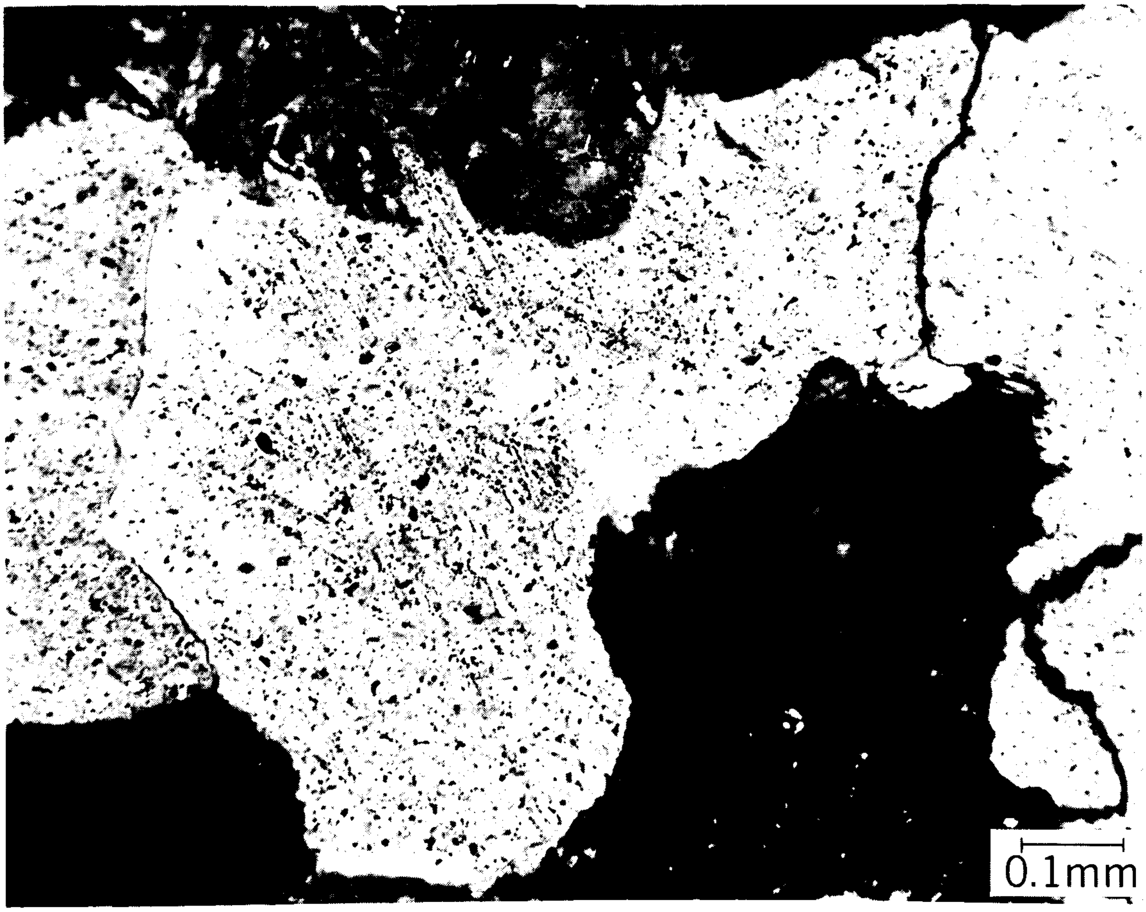

Figure 21—Planar features in another quartz grain from the same granitic inclusion shown in Fig. 19. The planar sets are discontinuous, and a sinuous area of clear quartz cuts across and partly destroys the planar sets in the center of the grain, indicating that the quartz grains have undergone annealing and recrystallization since the planar sets were formed. (Crossed polarizers).

shows a strong concentration of planes near the angle corresponding to the $\omega(10\bar{1}3)$ plane and strongly resembles similar plots for unaltered planar features from Clearwater Lake (Carter, 1965) and other Canadian structures (M. R. Dence, personal communication, 1967). There is, in addition, a subordinate orientation parallel to c(0001), similar to that exhibited by deformation lamellae in shocked rocks (Carter, 1965).

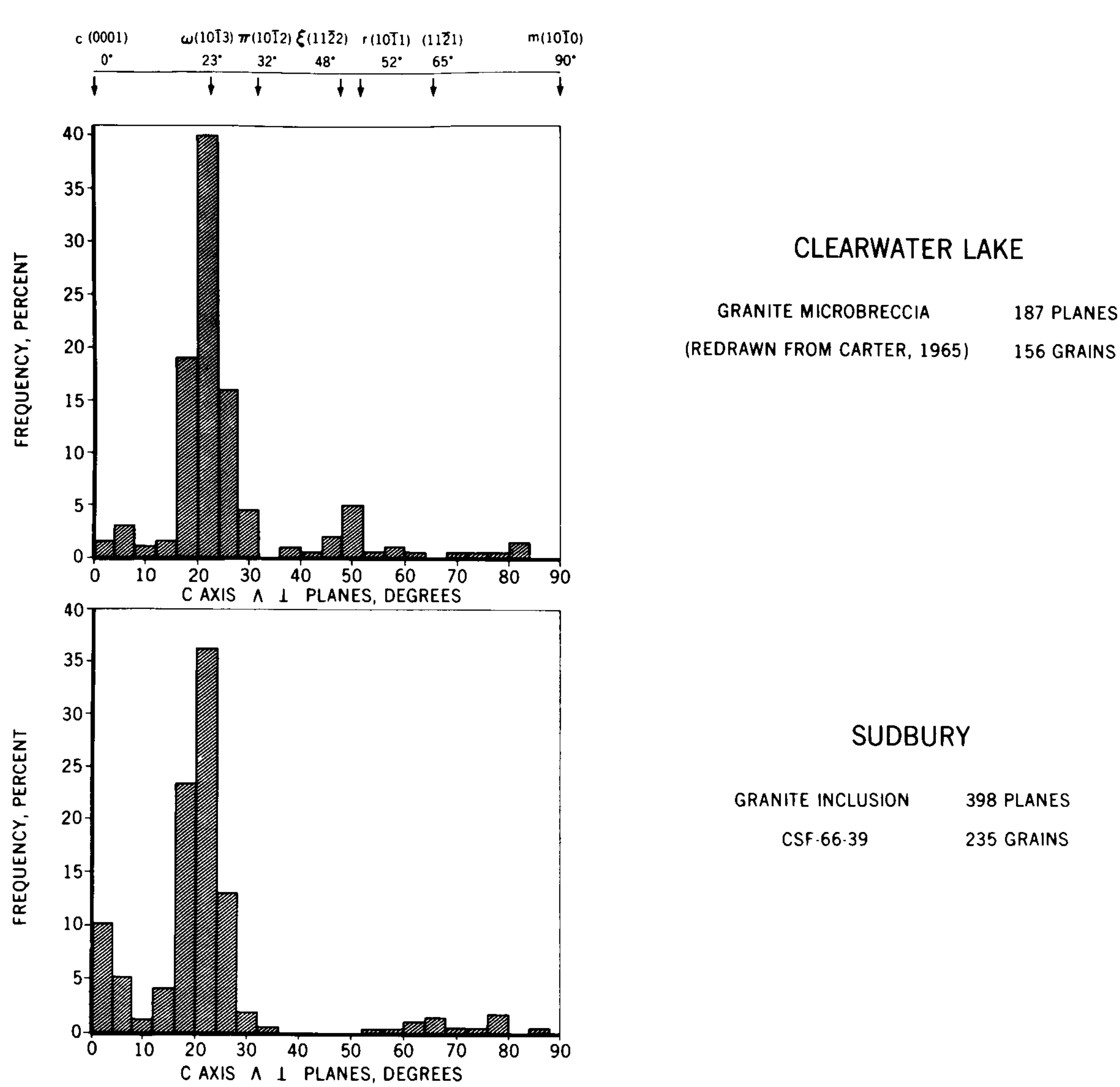

Figure 22—Histograms of measured angles between quartz c-axes and poles to the planar features. Measurements for the Sudbury specimen show a strong concentration at angles corresponding to the ω (10$\bar{1}$3) and c (0001) planes. The data for unaltered planar features in quartz from the Clearwater Lake structure (Carter, 1965, Fig. 3) have been recalculated to a 4° increment for comparison.

The problem of evaluating the nature and orientation of the planar sets in the associated feldspar crystals is complicated by the greater crystallographic complexity of feldspar, by the relative lack of comparative data on feldspars from known impact craters, and by incipient alteration which has occurred in the Sudbury specimens. The planar features which occur in both K-feldspar and plagioclase appear as relatively continuous planes only a few microns in width rather than as arrays of inclusions. The planes are filled with a brownish-red material (clay minerals plus hematite?) which gives the feldspar crystals a reddish color in hand specimen and a brownish, cloudy appearance in thin section. As many as three distinct sets have been observed in large K-feldspar crystals, but the orientation with respect to crystal directions is unknown (Fig. 23). Locally, plagioclase crystals have developed planar sets transverse to alternating albite twins, producing a distinctive, ladder-like texture (Fig. 24) similar to that exhibited by deformation lamellae in shocked plagioclase from younger structures (Fig. 16) (Stöffler, 1966; Short, 1966b).

Intense Unusual Deformation in Granitic Inclusions from the Onaping Formation

More intense deformational features were observed in a group of coarse-grained quartzofeldspathic inclusions collected from the Onaping formation at the same "type locality." The inclusions consist dominantly of grains of quartz, K-feldspar, and plagioclase, from 2 to 10 mm long, together with accesory mica, apatite, sphene, and opaques, and minor, apparently secondary, actinolitic amphibole. In hand specimen, although the granitic fabric is recognizable, the appearance of the minerals is unusual; feldspar crystals exhibit either a pronounced red-orange color or a black, glasslike appearance, while quartz crystals have a dull, milky aspect.

In thin section, the feldspar grains show the effects of intense, pervasive, and small-scale deformation. Original single crystals can be seen, under crossed polarizers, to be composed of a mosaic of fine, irregular, and strongly disoriented crystalline domains which blurs, distorts, or even obliterates original features such as albite twinning or larger areas of optical continuity (Figs. 25 and 26). In other specimens, or in other areas of the same specimen, original feldspar crystals appear to have been completely converted *in situ* to a glassy material now represented by a fine-grained, heterogeneous aggregate of very small crystals. More uniformly crystalline areas of feldspar also exhibit intense deformation, either by intensely strained or mosaic extinction, or by the physical bending or distortion of the entire crystals through large angles (Figs. 27 and 28).

(I am indebted to O. F. Tuttle for neatly characterizing the appearance of these strongly deformed feldspar crystals in the phrase, "looking as though they had been squeezed out of a toothpaste tube.")

Figure 23–Planar features in feldspar from a granitic inclusion in typical Onaping formation. Twins of a plagioclase grain (center) have developed a transverse, "ladder-like" arrangement of planar sets (compare with Fig. 16). A K-feldspar grain (upper right) exhibits two rectilinear sets. The planar features in the feldspar grains appear to be relatively continuous and filled with a fine reddish, unresolved material. Length of photograph about 2 mm. (Crossed polarizers). (Photograph courtesy of N. M. Short).

Figure 24–A grain of plagioclase feldspar (center), from the same inclusion as shown in Fig. 23. Irregular, discontinuous twin lamellae, oriented horizontally, exhibit transverse planar sets. Length of photograph about 2 mm. (Crossed polarizers). (Photograph courtesy of N. M. Short).

Figure 25–Photomicrograph of a coarse-grained inclusion of granitic rock in the Onaping formation, composed of elongate quartz (gray) and glassy-appearing feldspar (light gray to white). (Plane polarized light).

Figure 26–Same view as in Fig. 25, under crossed polarizers. The feldspar crystal (left) is represented by a deformed mosaic of disoriented crystallites which surround remnant areas of greater optical continuity (upper left). The associated quartz appears slightly polycrystalline, but not as deformed as the adjacent feldspar.

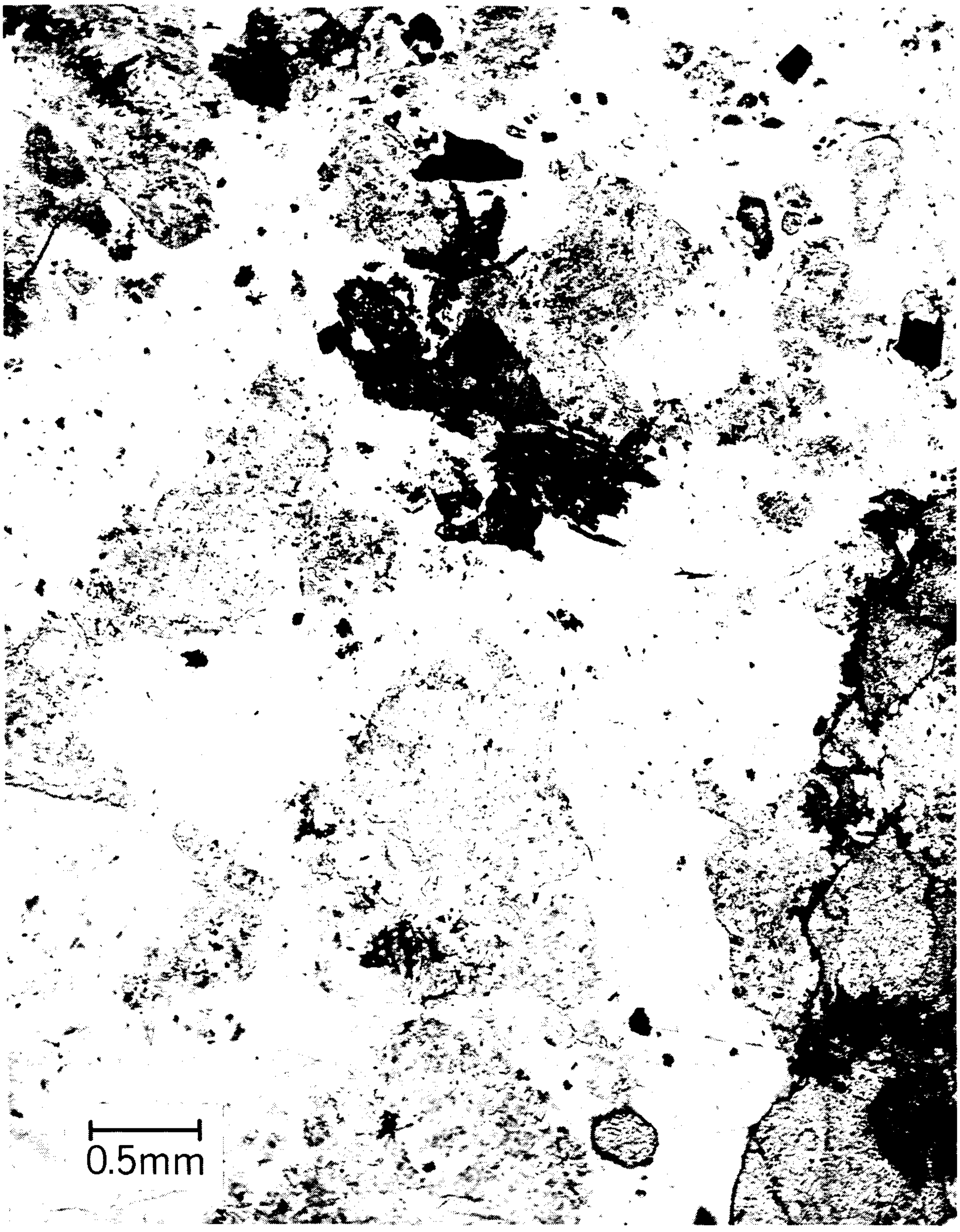

Figure 27–Coarse-grained granitic inclusion from typical Onaping formation, composed of anhedral quartz grains (gray), glasslike feldspar (white), and minor amphibole and opaques (dark gray and black). A few hexagonal apatite crystals (gray, high relief, lower right) are present. Note that the granitic fabric seems undisturbed. (Plane polarized light).

Figure 28—Same view as Fig. 27, under crossed polarizers. The quartz is present as a polycrystalline mosaic of small grains. Much of the feldspar is now present as finely-crystalline material suggestive of devitrified glass (upper right). Two plagioclase crystals (left center and right center) have been bent as units through large angles; the striped portions of the grains are remnants of original polysynthetic twinning. Note that the large apatite crystal in the lower right is neither recrystallized, fractured, nor distorted, despite the intense deformation and recrystallization of the feldspar adjacent to it.

The quartz associated with the deformed feldspar crystals is now present as a mosaic of fine grains which appears to preserve the original shape of larger, anhedral grains (Figs. 25-28). No intense deformation or strain effects are present in the quartz grains; they may represent either relatively less intense deformation of original quartz or relatively more complete recrystallization of a strongly deformed or glassy product.

Petrographic features strongly similar to these inclusions have been described from fragments of similar rocks in the Sudbury breccia which cuts the older rocks around the basin. Speers (1957, p. 502-503) observed that:

> "Some plagioclase fragments are angular, and the polysynthetic twinning is straight and extends from one side of the grain to the other, whereas other plagioclase fragments are rounded and their polysynthetic twinning is distorted and broken; parts of these crystals appear isotropic under crossed Nicols...
>
> "In some fragments the feldspar twin lamellae are very distorted, as if the feldspar crystals had flowed; in other fragments the feldspar twin lamellae are perfectly straight but fade out a fraction of a millimeter before reaching one or both sides of the fragment. Some light-colored subangular inclusions are composed of relatively large grains of quartz in a clear, nearly isotropic matrix, within which hazy, distorted plagioclase fragments with undulatory extinction can be recognized. Other light-colored fragments are composed of aggregates of hazy, rounded shapes which show nearly perfect crosses under crossed nicols. Still other light-colored fragments have faint fibrous structures."

The microscopic appearance of this group of inclusions suggests the operation of a process by which the feldspar crystals were partly or completely converted <u>in situ</u> to a glassy material which subsequently devitrified and recrystallized. Such a selective "melting" process appears more consistent with the effects of shock on quartzofeldsparthic rocks (Short, 1966b; Chao, 1966, 1967a, 1967b) than with conventional fusion under pyrometamorphic conditions. There is no indication of initial or preferential melting at grain boundaries; further, deformation has occurred throughout virtually every crystal without distorting or obliterating the original grain fabric of the inclusion.

No isotropic material was observed in the inclusions examined. It is possible to interpret the unusual textures in the feldspar as the result of conversion by shock of original feldspar crystals into a glassy or nearly-isotropic phase (maskelynite) (Dence, 1964, 1965; Bunch, 1966; Chao, 1967a; Bunch, Dence, and Cohen, 1967). It has proved possible to convert natural maskelynite back into single feldspar crystals by heating (Bunch, 1966); an analogous process may have occurred in the Sudbury feldspars during long-duration, low-temperature metamorphism. This interpretation could be strengthened by the discovery of (a) preserved isotropic material (unlikely) or (b) anomalous optical and crystallographic properties of the feldspar crystals.

A range of inferred intensities of deformation can be observed in inclusions of this type, not only between different granitic inclusions collected from the same locality, but also within a single inclusion. In a few specimens, a rapid transition can be observed (sometimes within a single thin section) between relatively undeformed grains of quartz and feldspar which exhibit only planar features, and more intensely-deformed regions where both quartz and feldspar appear to have undergone more intense deformation and recrystallization. These latter zones may, in turn, grade into areas composed almost entirely of a mosaic of fine quartz and feldspar crystals, within which intergranular flow has apparently taken place. It is possible that many of the flow-banded, originally completely molten, inclusions in the Onaping formation represent an additional stage of this progressive deformation.

EVIDENCE FOR AN IMPACT ORIGIN OF THE SUDBURY STRUCTURE

Introduction

This petrographic study of granitic inclusions in the Onaping formation, and particularly the observation of unusual planar features in quartz, serves, at the very least, to establish a firm similarity between the Sudbury structure and other circular structures in Canada and elsewhere for which an origin by meteorite impact has been proposed. The problem of the origin of the Sudbury structure thus becomes part of the larger problem of the origin of a number of unusual, disturbed, circular structures whose rocks exhibit extremely unusual petrographic features.

The interpretation of a meteorite impact origin for this group of structures, based on the study of the rocks associated with them, rests on two working assumptions: (1) that the unusual petrographic features observed require, for their production, the operation of transient shock waves of extremely high peak pressures, and (2) that hypervelocity meteorite impacts are the only natural method of generating the required shock waves. Opponents of the impact theory have based their arguments largely on the premise that these assumptions, particularly the second one, have not been conclusively proven, so that it is worthwhile to discuss them in some detail before evaluating the evidence provided by structural and petrographic features associated with the Sudbury structure.

Sufficient experimental evidence already exists, accumulated by the study of rocks subjected to shock waves generated by nuclear and chemical explosions, to indicate that such shock waves do produce the unusual textures observed, including both the development of planar features in quartz and the entire in situ transformation of quartz and feldspar to glassy phases (Short, 1966a, 1966b; Milton and DeCarli, 1963). Because of the complexities of shock-wave phenomena in heterogenous solids, it has not as yet proved possible to establish a rigorous calibration of peak pressures with observed textures. Such preliminary data as are available indicate that, qualitatively, the development of multiple planar sets may reflect peak shock pressures in the 50-150 kb range, (Carter, 1965; Short, 1966a) while intense disordering of the crystal structure apparently occurs at peak pressures in the 100-400 kb range and above. There has as yet been no reported occurrence of such features in rocks naturally or artificially deformed at slow strain rates or in undisputed volcanic or tectonic environments (e.g., Carter, 1965), so that the assumption that such textures in rocks require the operation of shock pressures in excess of about 50 kb appears justified at present.

An explosive meteorite impact can easily generate shock waves with peak pressures as high as several megabars (Shoemaker, 1963). In addition, the textures described have been observed at generally accepted meteor impact craters where meteorites have been found (e.g., Meteor Crater, Arizona; Wabar, Arabia; Henbury, Australia) (Chao, 1966, 1967a, 1967b). Thus, the argument that a meteorite impact is capable of producing such unusual textures in target rocks appears beyond question.

It is of course difficult to prove that a meteorite impact is the only method of generating such pressures. However, advocates of a volcanic origin are faced with two difficulties: (1) the lack of a detailed or obviously possible mechanism for concentrating pressures of hundreds of kilobars in a near-surface environment and then releasing them explosively in a small, relatively shallow area; (2) the fact that, despite the long history of study of explosive volcanic rocks, such textures have never been described from any structure whose origin by explosive volcanism is generally accepted, while the uniqueness of deformational textures observed in meteorites and in Coconino sandstone at Meteor Crater has been commented on more than sixty years ago (Tschermak, 1872; Merrill, 1907).

With the present state of knowledge, it is possible to say that meteorite impact represents the only known natural method of producing the unusual deformational textures observed in rocks from these structures. Future studies might demonstrate that other origins, involving internal geological processes, are possible. However, such results, for which there is no evidence at present, will not change the present conclusion that such deformational features can result from hypervelocity meteorite impact. It seems fair to state that, where such unusual features are observed in rocks associated with disturbed circular structures, an origin by meteorite impact must be considered as a valid possibility, even in the cases of structures as large or as complex as Sudbury.

Structural Evidence

Much of the present uncertainty in evaluating the complex structure of the Sudbury basin with regard to a possible origin by impact stems from the fact that there is, as yet, no clear-cut picture as to what a 30-mile-diameter impact crater, formed 1700 m.y. ago and subsequently deformed and metamorphosed, should look like. There are, however, many distinctive structural features of the Sudbury basin which are consistent with an origin by meteorite impact, even though they may not be unequivocal evidence. As Dietz (1964) has pointed out, many of the structural features considered most puzzling by earlier workers provide the strongest support for an impact origin. These include:

(1) an approximately circular original shape (if known post-basin deformation is considered).

(2) apparent overturning of stratified beds on the southern rim during formation of the basin, before the irruptive and the Whitewater series were emplaced.

(3) extensive shattering and brecciation of older rocks around the basin margin, with formation of the Sudbury breccia.

(4) strong similarities between the Sudbury breccia and the Onaping formation (Speers, 1957, p. 509).

(5) emplacement of the nickel irruptive in a trough- or bowl-like structure corresponding to the contact between the Sudbury breccia and the overlying Onaping formation (Speers, 1957, p. 509), and against the <u>underside</u> of the overturned rocks on the south rim.

Significance of the Onaping Formation

According to the hypothesis of impact origin discussed here, most, if not all of the Onaping formation represents an accumulation of shocked, fractured, and partly- or completely-melted basement rocks that were excavated by the meteorite impact and subsequently redeposited, lithified, metamorphosed to the chlorite grade, and deformed by later folding and faulting.

There are numerous structural, lithologic, and petrographic characteristics which are consistent with this interpretation, many of which have been considered puzzling from the point of view of a conventional volcanic origin for the unit. These include:

(1) the large amount of heterogeneous glassy material, combined with a general absence of typical volcanic rock fragments.

(2) the great amount of lithic fragments, ranging from tens of feet down to a few mm in size.

(3) an apparent gradation in fragment size from the bottom of the formation upwards, together with a general concentric zoning of rock types with respect to the basin margin.

(4) lack of correlation with any units outside the Sudbury basin.

(5) apparent rapid deposition during a brief period of time.

In addition, many features of the Onaping formation discussed in this study provide positive evidence for shock metamorphism and for a meteorite impact origin for the Sudbury basin. These include:

(1) planar features in quartz which exhibit strong preferred orientations parallel to the planes (0001) and $(10\bar{1}3)$.

(2) analogous planar features in associated feldspar crystals.

(3) intense, throughgoing, and apparently *in situ* deformation of feldspar and quartz in many granitic inclusions.

(4) the presence in the formation of compound inclusions which consist of a core of crystalline basement rock surrounded by a glassy rim which has apparently been deposited on the core as a heterogeneous mixture of molten and crystalline fragments.

The present observations apply to only a small protion of the Onaping formation; further petrographic and mineralogical study of the formation and its inclusions is mandatory before firm conclusions can be stated. It is however, possible to make certain predictions and suggestions for further study which will help indicate the exact nature of the Onaping formation. These include:

(1) search for high-pressure polymorphs. Treatment of samples of typical Onaping formation and of two shocked inclusions with an HF separation method by J. J. Fahey of the U. S. Geological Survey yielded negative results. The absence of phases such as coesite and stishovite cannot, however, be considered as evidence against a meteorite impact, and there are two possible explanations for their absence in the specimens studied: (a) the material examined was not intensely shocked enough for coesite to develop (Chao, 1967a, 1967b), or (b) any coesite originally formed was removed by subsequent metamorphism; stishovite would not be expected to survive even mild metamorphism (Skinner and Fahey, 1963).

(2) search for high-temperature decomposition textures. Examination of the glassy material to detect reactions such as the decomposition of zircon to baddeleyite (El Goresy, 1965) would be desirable, since such textures provide independent evidence of an impact origin by indicating temperatures well above 1500°C, much higher than are attained by normal geological processes.

(3) geochronology of glassy material in the Onaping formation. If the glassy fragments in the Onaping formation do in fact represent mixed and melted pieces of basement rock, it may be possible to demonstrate that they show inherited Rb-Sr "isochron" ages significantly greater than the 1.7 b.y. established for the micropegmatite. Evidence of this type, establishing that the glassy "pumice" fragments are not related to the micropegmatite, would strongly support the theory of impact origin for the basin.

(4) existence of Onaping formation outside the basin. The future discovery of outcrops of Onaping formation outside the Sudbury basin would not constitute evidence against an impact origin. Obviously, ejecta from the impact would be spread beyond the present basin margin; for instance, at the Ries basin in Germany, the presently accessible suevite outcrops occur as a thin patchy layer around the structure (Hörz, 1965; Stöffler, 1966; Chao, 1967b). The existence of such outcrops, which should lie unconformably on the upturned older rocks, would allow estimations to be made of the amount of deformation and erosion since the Onaping was deposited. It is also possible to speculate that the distinctive glassy inclusions from the Onaping formation might have spread widely from the basin and could be used as a stratigraphic marker if they had become incorporated in sediments of the same age.

It is also fair to suggest that, considering the evidence for an impact origin of the Onaping formation, the term "tuff-breccia", with its genetic connotations, may be inappropriate. There is no generally accepted term for a glassy breccia produced by meteorite impact; the type material, the suevite from the Ries crater, was originally considered a volcanic rock, as was the Onaping. Similar deposits from impact craters have been described as "suevite-like" or as "fall-back breccias." It is possible to argue that the Onaping formation could be called a "metasuevite." However, the author prefers to use nongenetic terms such as "breccia" or "formation" until the questions of general nomenclature and of the origin of the Onaping formation have been resolved; certainly a proliferation of names for equivalent rocks from different structures is not warranted.

SUBSEQUENT HISTORY OF THE SUDBURY STRUCTURE

Emplacement of the Nickel Irruptive

The clearly intrusive nickel irruptive which lies between the Onaping formation and the Sudbury breccia in the rim of the basin (Thomson, 1956; Speers, 1957; Stevenson, 1963) represents a feature which appears unique to large structures for which an impact origin has been proposed; it is perhaps fair to say that the evidence for an impact origin at Sudbury might be more clear-cut if the irruptive were not present.

Although there is much geological evidence to indicate that the formation of the Sudbury basin and the emplacement of the nickel irruptive are closely related, there is no evidence available to indicate that either the irruptive or the associated nickel deposits contain any extraterrestrial material, or that they were formed as a primary result of the impact. There is considerable evidence to indicate that the irruptive has been intruded against both the Onaping tuff and the Sudbury breccia after they were formed; extensive metamorphic aureoles exist adjacent to both the upper and lower contacts (Burrows and Rickaby, 1929; Speers, 1957; Stevenson, 1963). In addition, the volume of the irruptive appears far too great to have been produced by fusion of the target rocks during the impact.

There is also no present reason to believe that the ore deposits themselves represent meteoritic material; they consist of a pyrrhotite-pentlandite-chalcopyrite assemblage (Hawley, 1962) which is similar to ore deposits associated with gabbroic intrusions in many parts of the earth. Although the tonnage of an assumed nickel-iron meteorite of sufficient size to form the Sudbury basin (about 4 km diameter; Dietz, 1964) would be sufficient to form the ore deposits, there are many mechanical and chemical difficulties in converting the original meteorite into the present sulfide deposits.

The greatest problem would be to convert the nickel-iron metal to sulfide minerals and to provide a source for the large amount of copper found as chalcopyrite in the deposits. In addition, it is unlikely that much of the impacting material would be distributed along the margins of the basin, because, as both theoretical investigations and studies of modern meteorite craters indicate, much of the impacting body would be ejected as fragments from the crater (Shoemaker, 1963). The history of the irruptive and the associated ore deposits is complicated and requires much further study; there is, for example, evidence that the ore minerals may have been emplaced after the majority of the irruptive had formed (Naldrett and Kullerud, 1967).

The strong geological relations between the formation of the Sudbury basin and the emplacement of the irruptive and its ore deposits indicate that any theory for the origin of one must also account for the other. If the impact origin for the Sudbury basin is correct, the emplacement of the irruptive must be somehow related to the impact, although the irruptive itself has apparently been internally derived. At present, it is only possible to suggest that large meteorite impacts may trigger or localize conventional magmatic activity from within the earth at some relatively short time after the impact itself (Baldwin, 1949; Dietz, 1962a; Lowman, 1963; Ronca, 1966a, 1966b). The exact mechanism of such a process would be complicated and might include: (a) fusion of rock below the crater by (1) pressure release from unloading, or (2) dissipation of shock-wave energy in the rocks below the crater; (b) localization of magmatic activity in zones of crushed and brecciated rock below the crater which provide a channel for ascending magma.

Subsequent Deformation of the Sudbury Structure

The original outline of a meteorite impact crater should be approximately circular (Shoemaker, 1963); the present elliptical outline of the Sudbury basin cannot have been the original shape.

The Sudbury basin has been affected by at least two metamorphic episodes since the irruptive was emplaced; a strong metamorphism, dated at about 1600 m.y. in the rocks to the southwest (Card, 1964), and a later "Grenville" event of deformation and minor igneous intrusion at about 1100-1200 m.y. (Burrows and Rickaby, 1929; Thomson, 1957; Speers, 1957). Strong compressive deformation from the southeast is indicated in the Sudbury area by thrust-faulting along the south rim and by the development of narrow, northeast-trending folds in the Whitewater series (Thomson, 1956). Considering this deformation implies that the original shape of the Sudbury basin must have been more circular (Dietz, 1964).

It is difficult to estimate whether the deformation involved would have been sufficient to produce the present ellipse from an original circular shape. It is quite possible, for instance, that the present irruptive may not outline the original basin rim. Further, it is possible to convert a circular basin into an ellipse by noncompressional tilting if the floor is sufficiently flat, or if, as in many large impact structures (Dence, 1964, 1965), a central uplift has developed. There is evidence for such tilting from the south rim of the basin, where apparently deeper levels of the irruptive are exposed than at the corresponding elevation on the north rim (Naldrett and Kullerud, 1967).

It is possible to say that the known structural history of the Sudbury basin is consistent with the production of the present elliptical shape from one more circular, although the correlation cannot as yet be made quantitative. The present elliptical shape of the Sudbury basin is thus not definite proof against an impact origin, but further structural studies will be necessary before any detailed consistence can be established. It might prove possible to estimate the extent of deformation in the region, based on the assumption of original circularity for the Sudbury basin.

SUMMARY AND CONCLUSIONS

The results of the present preliminary examination of the lithology and microstructures within the Onaping formation support the view (Dietz, 1964) that the Sudbury basin was formed by the impact of a large meteorite approximately 1700 m.y. ago, producing an explosive event estimated at 3×10^{29} erg (or about 7.5 million megatons) and forming a crater originally 30 miles across and 2 miles deep. According to the theory developed here, the Onaping formation represents a "fallback breccia" composed of material excavated by the impact and immediately redeposited. The emplacement of the irruptive between the Onaping formation and the Sudbury breccia (Speers, 1957) was a subsequent event, probably triggered or localized by the impact and formation of the crater. Subsequent compression and tilting during later metamorphic episodes converted the originally near-circular outline into the present elliptical shape (Dietz, 1964).

This interpretation is consistent with present knowledge about the structure of the Sudbury basin and the character of the Onaping formation. In fact, the impact theory explains many of the more puzzling geological problems of structure and of the Onaping tuff (Dietz, 1964), and is not inconsistent with any present information. The problems of the generation and emplacement of the irruptive represent a large area of uncertainty in any theory; however, such phenomena are not necessarily inconsistent with large meteorite impacts.

It has long been accepted that, whatever the origin of the Sudbury basin, its formation was an extremely rapid and violent event. Speers' (1957, p. 513) reconstruction of the formation of the basin states that:

"Volcanic gases burst through the center of the dome along major rifts and thus ushered in one of the most violent periods of explosive volcanic activity ever recorded in the rocks of the earth's crust. The actual eruption was continuous and may have taken place in a relatively short period of time. Tilting and undulation of the surface, resulting from the eruption, caused multitudes of tension fractures to open and close like jaws on giant crushers. Fragments which sloughed from the walls of the gaping fissures or which tumbled into the fractures from the rubble-covered surface were crushed and ground to fine sizes."

This description could, without serious modification, apply to the explosive aftereffects of a large meteorite impact (Shoemaker, 1963). The debate over the origin of the Sudbury structure thus concentrates less on the nature of the events, and more on the source of the energy required to produce them. Future study will have to resolve whether the explosive energy came from the impact of an extraterrestrial body or by an unusual concentration of internal volcanic energy. The solution of the problem may lie in the discovery of features, both structural and petrographic, which are clearly inconsistent with one or the other modes of origin.

IMPLICATIONS FOR THE ORIGIN OF SIMILAR STRUCTURES

It has generally been accepted that there are strong similarities between the Sudbury structure in Canada and the Vredefort and Bushveld structures in South Africa which suggest a similar mode of origin. If one can accept a meteorite impact origin for the Sudbury structure, it is necessary to examine the possibility that these two structures have also originated the same way.

The Vredefort Ring consists of a central zone of uplifted granite about 40 km in diameter, surrounded by a ring of uplifted and overturned sediments. There is evidence for uplift in excess of 40,000 feet, together with a large amount of brecciation and formation of a "pseudotachylite" which cuts the granite and the surrounding sediments in veins and stringers. Although the Vredefort Ring lacks any basin-shaped irruptive with a cover of volcanic-like rocks, it has been related to the Sudbury structure on the following bases: (1) evidence for domal uplift in both structures (Speers, 1957); (2) strong similarity between the character of the Vredefort pseudotachylite and the Sudbury breccia (Shand, 1916; Speers, 1957).

The widespread evidence for intense, relatively-localized deformation at Vredefort has led to consideration of meteorite impact as a possible origin (Daly, 1947). More recent work has established further similarities between

Vredefort and Sudbury which are considered to point directly to an origin by meteorite impact. These include: (1) the discovery of a widespread ring of shatter-coned rocks around the central granite core; apices of the cones point inward and upward when the beds are restored to the horizontal, indicating propagation of the shock wave from that direction (Dietz, 1961; Manton, 1965); (2) detection of deformation lamellae in quartz from shatter coned quartzites. Basal lamellae appear dominant (Carter, 1965), but a smaller amount of lamellae parallel to $(10\bar{1}3)$ are observed (M. R. Dence, personal communication, 1966).

These additional similarities strengthen the belief that Sudbury and the Vredefort structures have a common origin and favor the interpretation of meteorite impact for both. The absence of units in the Vredefort Ring corresponding to the nickel irruptive and the Onaping formation at Sudbury may reflect relatively deeper erosion of the Vredefort structure.

The Bushveld Complex to the north of the Vredefort Ring appears as an elliptical to pear-shaped basin more than 250 miles long from east to west and about 125 miles across (DuToit, 1954). The structure has long been considered similar to Sudbury because of: (1) a similar, but much larger intrusive, consisting of layered gabbroic rocks in the lower part and thick granitic rocks in the upper part; (2) a great development of magmatic ore deposits, consisting of chromite, platinum metals, and copper-nickel sulfides; (3) a unit of "volcanic breccias and volcanic rocks," with interbedded sediments (the Rooiberg series) above the igneous rocks which are not found outside of the Bushveld basin. The Bushveld structure appears contemporaneous with the Vredefort Ring (Nicolaysen et. al., 1959; Nicolaysen, Burger and Van Niekerk, 1963) so that any theory must consider the two structures together, despite their dissimilarities. Dietz (1962b) suggested a twin impact to form both structures.

The Bushveld structure apparently lacks the extensive marginal uplift and brecciation so pronounced at Sudbury and Vredefort. Furthermore, no structural or petrographic textures indicative of meteorite impact have as yet been reported. It should be remembered, however, that shatter cones were not recognized around the Vredefort and Sudbury structures until they were predicted and then specifically sought for (Dietz, 1961, 1964). More detailed study might discover shatter cones in the wall rocks around the Bushveld or in the huge "fragments" of basement rock within the intrusion. It is also possible that the Rooiberg series might be equivalent to the Onaping formation and might yield similar petrographic features indicative of shock metamorphism. It seems apparent that further study of the Bushveld structure will produce modifications in the theories of origin; for example, gravity surveys of the body (Cousins, 1961) suggest that the "lopolith" may actually be a series of discrete intrusions analogous to ring dikes around the basin. If this is the case, the large "fragments" of basement rock in the center might represent central uplifts rather than large isolated blocks. Further study of both the Bushveld and Vredefort structures and comparison of them with Sudbury is strongly desirable.

SOME GENERAL IMPLICATIONS OF AN IMPACT ORIGIN FOR THE SUDBURY STRUCTURE

Acceptance of a meteorite impact origin for the Sudbury structure as at least a valid working hypothesis leads to a number of implications for further study in the field.

(1) Similar structures of equal or larger size should be found on the surface of the earth. These implications for the Bushveld and Vredefort structures in South Africa have been discussed; the evidence for other large structures of a meteorite impact origin is discussed elsewhere (Dence, 1964, 1965; for compilations, see O'Connell, 1965; Freeberg, 1966).

(2) The discovery of shock-metamorphic features at Sudbury, in rocks about 1700 m.y. old, and in rocks of approximately similar age at Vredefort (Carter, 1965) indicates that such criteria can be preserved over long periods of time to provide geologists with a method of identifying ancient meteorite structures. Equally encouraging for the study of such ancient structures is the preservation of some shock-metamorphic features (such as planar sets) in the Onaping formation despite metamorphism to the chlorite grade which would be expected to have destroyed other diagnostic features (e.g., stishovite).

(3) The association of microscopic shock-metamorphic criteria with well-developed shatter cones at Sudbury and Vredefort supports the view that shatter cones themselves may be unique indicators of meteorite impact. Such a view would increase greatly the number of accepted meteorite impact structures by including the shatter-coned "cryptoexplosion" structures. It should be expected that some of these latter structures will also show petrographic indicators of shock; the Gosses Bluff structure in Australia (Cook, 1966; Crook and Cook, 1967) may be an example of a "cryptoexplosion" structure with good petrographic evidence for shock metamorphism.

(4) Finally, and perhaps most important for the study of the earth and other planetary bodies, the recognition of an impact origin for the Sudbury structure provides concrete indication that large meteorite impacts may trigger or localize internal magmatic activity, developing a type of large circular structure whose origin is due to impact, but whose subsequent morphology and history reflect volcanic processes. Such a view may help to reconcile the active controversy as to the impact or volcanic origin of large circular structures on the moon and Mars, as well as some of the larger and economically important structures on the earth.

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