2), but basalt was found at 516 feet. Under the north half of the Midway lagoon, volcanic rock was predicted between 0.63 and 0.71 km (2067 and 2329 feet), but the drill entered basalt at 1261 feet. George Shor, who was in charge of the preliminary seismic surveys and who made additional observations at Midway after the drilling was completed, is preparing a further report on this matter.
16. G. A. Macdonald, oral communication.
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20. The project discussed here was carried out under the auspices of the Hawaii Institute of Geophysics, University of Hawaii, with financial support (grant No. GP4728) from the National Science Foundation. Other agencies collaborating included the U.S. Geological Survey and the Office of Naval Research. In planning the work, Ladd was assisted by George P. Woollard and Gordon A. Macdonald, co-investigators in the project. In connection with planning, thanks are also due to Dr. William E. Benson of the National Science Foundation, V. C. Mickle of the George E. Failing Company, and Rear Admiral Charles W. Thomas (Ret.) of the University of Hawaii. During our stay at Midway, Captain F. D. Milner, Commanding Officer, and his associates cooperated fully. The cores and cuttings obtained during the drilling have been placed on permanent deposit at the Hawaii Institute of Geophysics, University of Hawaii. Publication of this report is authorized by the Director of the U.S. Geological Survey and by the Secretary of the Smithsonian Institution.

16 March 1967

Sudbury Structure, Ontario: Some Petrographic Evidence for Origin by Meteorite Impact

Abstract. *Unusual deformation structures, similar to those observed in rocks from known and suspected meteorite impact craters, are observed in inclusions of basement rock in the Onaping formation at Sudbury, Ontario. These features, which include planar sets in quartz parallel to the (0001) and $(10\bar{1}3)$ planes, suggest that the Onaping formation consists of shocked and melted material deposited immediately after a meteorite impact which formed the Sudbury basin.*

Recently, studies of rock specimens subjected to 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 (*1–3*). These effects include (i) high-pressure silica polymorphs, (ii) high-temperature fusion and decomposition reactions, (iii) multiple sets of planar lamellae in quartz, commonly oriented parallel to the (0001) and $(10\bar{1}3)$ planes, and (iv) intense disordering of single crystals of quartz and feldspar, often producing glasslike phases. Such effects, observed in rocks of older circular structures, have been cited as evidence of meteorite impact (*4–8*).

This report describes some unusual microdeformational features observed in rocks from the Sudbury structure in southern Ontario, Canada; these features are similar to those developed in rocks associated with accepted meteorite craters and with older circular structures for which an origin by meteorite impact has been proposed.

The Sudbury structure is a kidney-shaped basin approximately 60 km (37 miles) long in an east-northeast direction and 27 km (17 miles) across (Fig. 1). The basin is outlined, both topographically and geologically, by an igneous irruptive (*9*) between 2 and 5 km thick, which is divided into an upper felsic micropegmatite and a lower, more mafic norite. Whole-rock Rb-Sr methods have determined an age of approximately 1700 million years for the irruptive (*10*). The irruptive and the basin are surrounded by older rocks—metasediments on the south and east, granitic rocks on the north and west. Near the margin of the basin, these rocks are locally intensely shattered and brecciated, forming a unit called the Sudbury breccia (*11, 12*). The inner part of the basin is filled with a series of sediments (the Whitewater series) at least 1830 m (6000 feet) thick, composed of, in ascending order, the Onaping tuff-breccia, the Onwatin slate, and the Chelmsford sandstone.

Since the discovery of nickel 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 been the subject of a continuing geological debate concerning 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 (*13*).

The possibility that the Sudbury structure was formed by a large meteorite impact was formulated in detail by Dietz (*14*), who argued that such an origin would explain both the presence of the Sudbury breccia and some of the other puzzling structural features (*12*). Dietz also predicted and later discovered shatter cones, a possible indicator of impact, in the older rocks adjacent to the basin. Further investigations (*15*) indicated that a zone of shatter-coned older rocks surrounds the entire Sudbury structure to distances as great as 18 km. 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 that predated or immediately preceded emplacement of the irruptive (*16–18*). The Onaping formation has an estimated thickness of 1220 m and an estimated minimum volume of 630 to 1050 km^3 (150 to 250 cubic miles) (*16*).

Various investigators (*16–18*) have concluded that the Onaping formation: (i) contains numerous fragments of devitrified glassy material; (ii) also contains numerous inclusions of basement rocks up to tens of feet (several meters) in size; (iii) exhibits a uniform gradation in fragment size, with large blocks at the base and fine material at the upper contact; (iv) exhibits concentric zoning of rock types with respect to the basin margin; (v) cannot be definitely correlated with formations outside the Sudbury basin; (vi) was apparently deposited as a single unit during a brief period of time; and (vii) has been involved in at least one period of postdepositional deformation and metamorphism.

The long-accepted volcanic origin of the Onaping formation has recently been unsettled by the discovery (*19, 20*) that a unit at the base of the formation, originally identified as rhyolite feeder dikes (*16, 17*) is composed of large blocks of quartzite in a matrix of micropegmatite (*21*). The present research was undertaken to examine the 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 fall-back breccias from other probable impact structures (*4*) would be a likely place to search for preserved shock-metamorphic effects.

At the type locality (*22*), the Onaping formation is a dense, massive, dark gray to black, structureless rock that sometimes exhibits crude conchoidal fracture. The formation contains inclusions ranging in size from submicroscopic to larger than 20 cm enclosed in a black, opaque, and featureless matrix (*16–18*). The inclusions show no apparent alignment. In outcrop, the majority of inclusions greater than 5 cm in size are light green, aphanitic, and irregular in shape; they commonly display contorted flow structure. Inclusions of recognizable basement rocks are also common; the majority appear to be granites, granite gneisses, and feldspathic metaquartzites, all of which occur surrounding the Sudbury basin. Rarely, inclusions are observed that have a core of apparently crystalline basement rock surrounded by a greenish, aphanitic, and flow-banded rim. The Onaping formation, observed in outcrop, has a general resemblance to both conventional pumiceous tuffs and the suevite breccias described from the Ries crater and other proposed impact structures (*4, 8*).

In thin section, the Onaping formation consists of diverse, very poorly sorted fragments in a black, opaque, and unresolved matrix that commonly forms as much as 15 to 25 percent by volume of the specimens observed

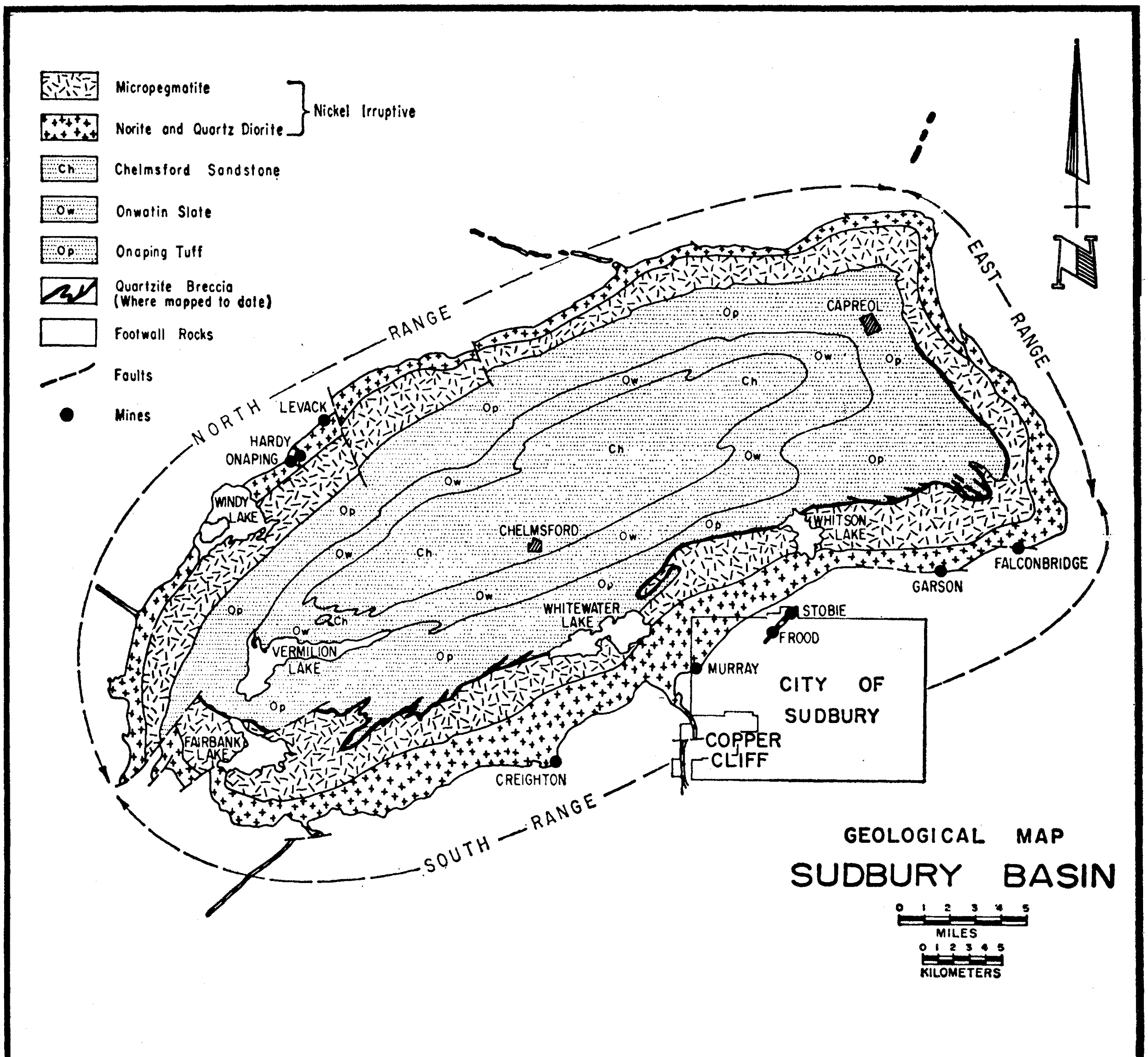

Fig. 1. General geologic map of the Sudbury basin [from Stevenson (*20*, Fig. 1)], showing distribution of Onaping formation and basal quartzite breccia. Older rocks surrounding the basin are not subdivided.

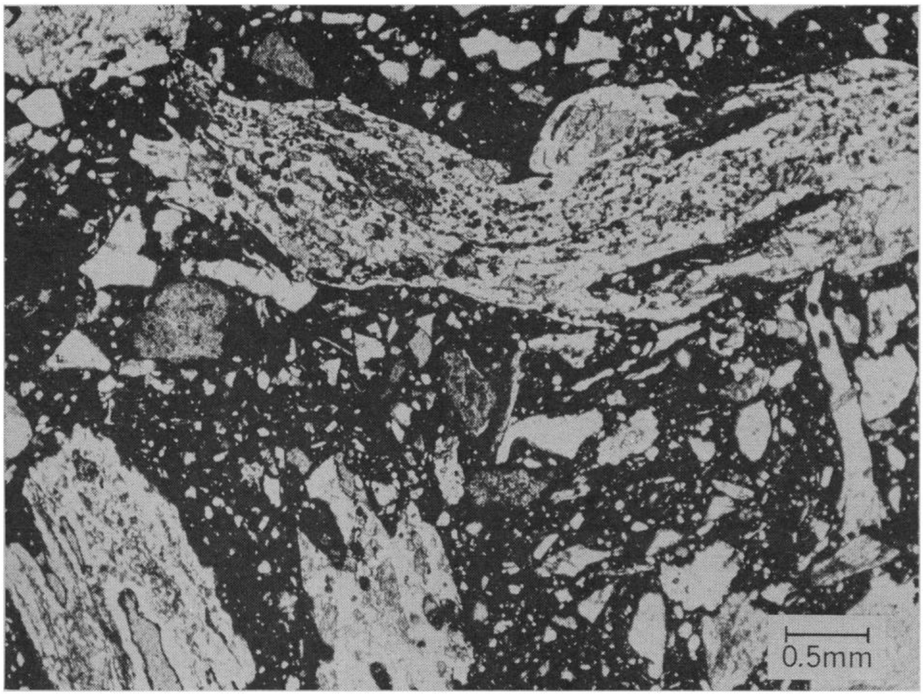

Fig. 2. Photomicrograph of typical Onaping formation in plane-polarized light. Larger irregular fragments of apparently devitrified glass exhibit flow structures. Smaller fragments include sharp and angular grains of single crystals of quartz and feldspar as small as 5 μ, enclosed in a black, opaque matrix.

(Fig. 2). 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 structure. They presently consist of finely crystalline material in zoned or spherulitic arrangements suggestive of devitrification textures. A second type contains finely crystalline devitrified glass surrounding cores or irregular areas of coarser-grained xenoblastic aggregates of quartz, K-feldspar, and plagioclase. The third type consists of small rock fragments analogous to larger inclusions of basement rock observed in outcrop. Sharp and angular single crystals or small groups of the component minerals occur as smaller fragments; individual crystal fragments as small as 5 μ can be distinguished in the matrix. In no specimens of Onaping formation were any crystalline textures typical of volcanic rocks observed. Such features as euhedral crystal outlines, zoned feldspars, corroded quartz crystals, or trachytic textures were uniformly absent. Quartz, K-feldspar, and plagioclase are the major minerals of the Onaping formation. Chlorite and green actinolitic amphibole commonly occur as secondary minerals in recrystallized inclusions, together with traces of sphene, epidote, and sulfide minerals. 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 micas or clay minerals occur in either inclusions or matrix.

Planar features in quartz and feldspar were detected in an inclusion of granite gneiss about 15 cm in diameter, composed of quartz, plagioclase, and K-feldspar, with a trace of muscovite. 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 a group of about a dozen similar inclusions collected at random at the same location. 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. The sets of planar features in quartz consist of planar arrays of small, spherical to elliptical inclusions that generally extend discontinuously over 10 to 20 percent of the trace of the plane in thin section (Fig. 3). The inclusions range in size from a maximum of about 2 μ down to submicron dimensions; under high magnification, they have a slightly brown color and exhibit a refractive index

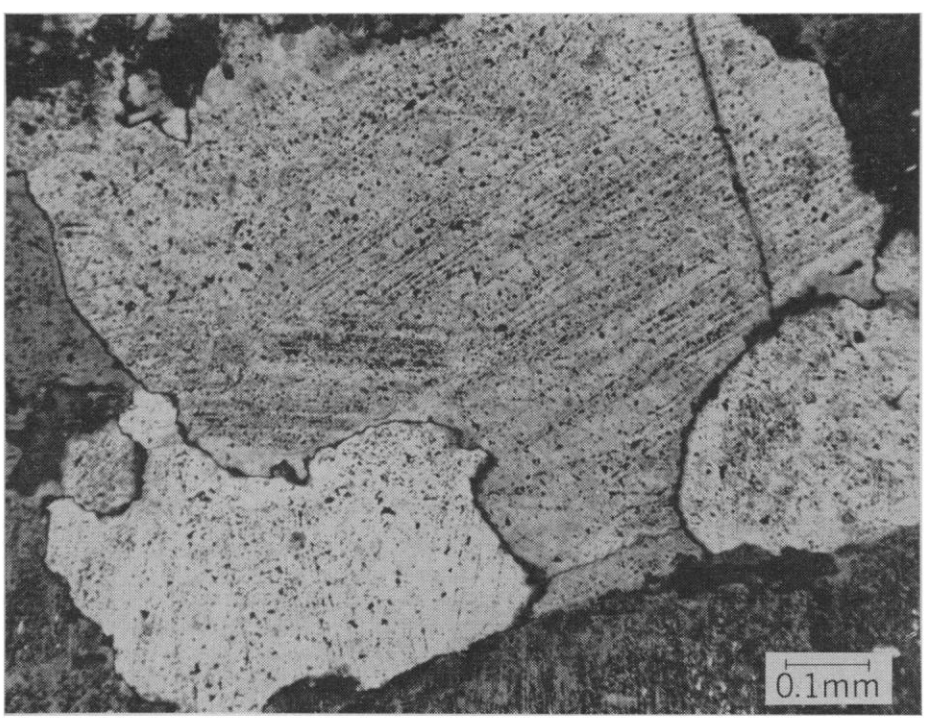

Fig. 3. Planar features in quartz grains from an inclusion in the Onaping formation; crossed polarizers. Planes are discontinuous arrays of small inclusions; the larger grain exhibits three distinct sets.

lower than that of the host quartz. The planes do not cross grain boundaries and are often oriented at sharp angles in adjacent grains (Fig. 3). The number of observable sets varies between one and four per grain, with an average of about two per grain in the inclusion studied. Recrystallization of the host quartz after formation of the planar sets is evident in thin section. The sets generally have a patchy distribution over larger grains, and, in a few grains, irregular areas of clear, unstrained quartz truncate and transect the planar sets. The Sudbury planar sets are not completely identical in appearance to structures observed in quartz from artificially shocked rocks and from young meteorite craters. The planar arrays observed thus far in Sudbury material are not lamellae in the narrow sense; they have no sharp planar contacts against the host quartz and do not constitute continuous bands of finite width. The Sudbury features most closely resemble decorated planar features observed in quartz from older circular structures (*4*, *6*). The production of such decorated features through recrystallization and annealing of deformation lamellae has been observed in both naturally and artificially deformed specimens (*6*, *23*). It must be remembered, in evaluating these features, that the Onaping formation has been subjected to long burial and to at least one period of metamorphism and that recrystallization and annealing effects are directly evident in many of the quartz grains.

The Sudbury planar features exhibit a strong preferred crystallographic orientation similar to that observed for both unaltered lamellae and decorated features in shocked rocks from known and suspected impact craters. Orientations of the planes of inclusions with respect to the quartz *c*-axis were determined by conventional universal stage methods for several hundred planes in grains whose *c*-axes were accessible (that is, oriented at less than 40 deg to the plane of the thin section). Because of the relatively large uncertainty in orienting the planes in a true vertical direction, measured angles between the quartz *c*-axes and the poles of the planes are considered accurate to only ±4 deg. The histogram of these angles (Fig. 4) shows a strong preferred orientation at the angle corresponding to the ω $(10\bar{1}3)$ plane in quartz, similar to orientations exhibited by unaltered planar features from Clearwater Lake, the Ries, and other structures (*5*, *6*). The Sudbury features also exhibit a subordinate concentration parallel to (0001), similar to that observed for deformation lamellae in shocked rocks (*6*).

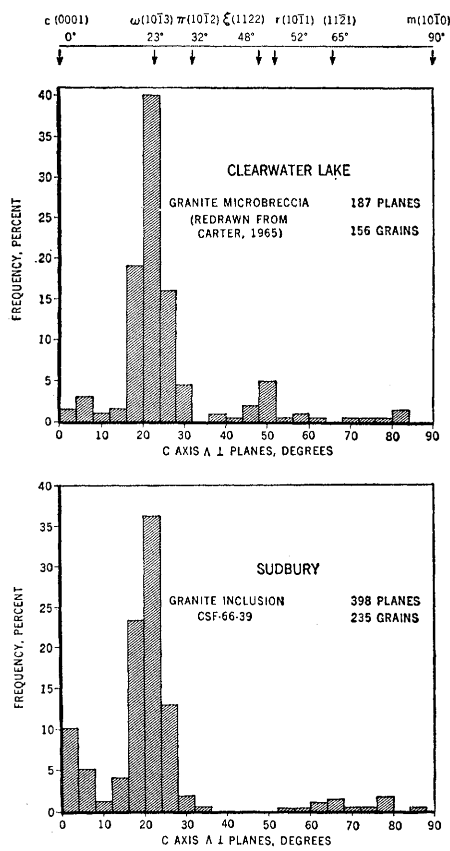

Fig. 4. Histogram of measured angles between quartz *c*-axes and poles to planar features. Measurements for the Sudbury specimen show a strong concentration at angles corresponding to the ω $(10\bar{1}3)$ and (0001) planes. Data for unaltered planar features in Clearwater Lake quartz (*6*) have been recalculated to a 4-deg increment for comparison.

This preliminary petrographic study of granitic inclusions in the Onaping formation at Sudbury, and particularly the observation in quartz of planar features oriented parallel to the (0001) and $10\bar{1}3$) planes, serves to establish a firm similarity between Sudbury and other structures in Canada and elsewhere for which an origin by meteorite impact has been proposed. These results, together with other petrographic and structural characteristics of the Onaping formation, are consistent with the view that some or all of the unit represents an accumulation of shocked and melted basement rocks, excavated by a meteorite impact and subsequently redeposited, lithified, and metamorphosed to the chlorite grade. This interpretation of the Onaping formation is consistent with other structural features of the Sudbury basin that have previously been advanced (*14*) in support of an impact origin. These observations apply only to a small portion of the Onaping formation; further petrographic and mineralogical study of the formation and its inclusions is mandatory before firm conclusions can be established. Although geological evidence strongly indicates a genetic relation between the basin and the ore-bearing irruptive, the exact details are still uncertain. At present it can only be suggested that a large meteorite impact may trigger or localize magmatic activity from within the earth (*24*), at some time subsequent to the actual impact.

The acceptance of a meteorite impact origin for the Sudbury structure has important implications for the study of Sudbury and of similar terrestrial and lunar structures: (i) Shock-induced petrographic features can survive long periods of burial and even mild metamorphism and provide geologists with a method for recognizing and studying ancient meteorite impact structures. (ii) The association of shatter cones with deformation features at Sudbury supports the view that shatter cones themselves may be a unique indicator of meteorite impact. (iii) The original shape of the Sudbury basin must have been approximately circular, like all impact craters. If it can be established that the irruptive outlines the original crater rim, it may be possible to evaluate geologically the amount of deformation by compression or tilting, or both, required to produce the present elliptical shape (*14*). (iv) High-energy meteorite impacts on the earth and moon, although infrequent, may act to generate or localize igneous processes that involve large volumes of magma and economically valuable ore deposits.

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21. In this basal unit, Stevenson observed quartzite blocks as much as 75 m long. Recently, a block of quartzite at least 27 by 15 m has been discovered in the upper part of the Onaping formation, approximately 1040 m stratigraphically above the lower contact (J. G. Bray, personal communication).
22. A series of road and railroad cuts in Dowling township, in the northwestern part of the Sudbury basin, expose unmetamorphosed Onaping formation generally regarded as typical. The specimens studied were collected from roadcuts on the Copper Cliff–Levack highway (Hwy. 144), about 9.2 km south of the town of Levack, immediately west of High Falls on the Onaping River.
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25. The assistance given me by many individuals does not necessarily reflect agreement with the conclusions reached in this report. The data, interpretations, and conclusions are my own, as are any errors contained in them. I am particularly grateful to J. G. Bray and to other individuals of The International Nickel Co. of Canada, Ltd., for providing geological information and for supplying many of the specimens. I also acknowledge helpful comments, suggestions, and criticisms from many individuals with a great diversity of views about Sudbury, including J. S. Stevenson, R. L. Smith, N. M. Short, M. R. Dence, E. C. T. Chao, W. von Engelhardt, P. R. Brett, and A. J. Naldrett.
26. A longer version of this report, including additional petrographic data and photomicrographs, is being prepared as NASA document X-641-67-67.

4 April 1967

Excitation of Surface Waves by Events in Southern Algeria

Abstract. *Surface-wave magnitudes* (M_s) *of 4.1 and 3.2 are determined for two events in southern Algeria. The corresponding body-wave magnitudes* (m_b) *are 5.8 and 4.9, respectively. The surface waves from these events are much smaller than would be expected from most earthquakes of comparable body-wave magnitudes, which fact suggests that these waves were generated by underground explosions.*

This paper reports study of the excitation of body and surface waves by two events in southern Algeria. The epicentral data and magnitude determinations for these two events are given in Table 1. These events appear to be underground explosions, a conclusion based on newspaper reports and on the geographical coordinates, which place the events in an aseismic area. The same data are also given for Long Shot, a nuclear explosion detonated beneath Amchitka Island in the Aleutian Island chain on 29 October 1965 (*1, 2*).

The body-wave magnitude (m_b), which is based on the amplitude of short-period P waves recorded at teleseismic distances (*3*), is used as a measure of the short-period excitation. The surface-wave magnitude (M_s), which is based on the vertical amplitude of Rayleigh waves with periods of about 20 seconds (*4, 5*), is used as a measure of the excitation of the long-period waves. Båth (*5*) has emphasized the importance of measuring the amplitude of waves with periods within 2 to 3 seconds of 20 seconds even if this does not represent the maximum amplitude on the record; Richter (*6*) has found that determinations of M_s based on other periods tend to diverge from the standard scale. M_s and m_b measurements were obtained for these two events from the records of the World-Wide Standardized Seismograph Network (WWSSN) established by the United States Coast and Geodetic Survey (USCGS). No M_s values were obtained at stations where surface waves could not be seen above the noise levels. Thus, our M_s values represent an upper limit.

For the event of 27 February 1965, we have determined the body-wave magnitude to be $m_b = 5.8$ from the average of measurements at 50 individual stations, and the surface-wave magnitude to be $M_s = 4.1$ from measurements at 34 stations. From previous work on the relationship of M_s to m_b for earthquakes (*3, 7*), we would have expected $M_s \geqq 5.3$ from an earthquake of $m_b = 5.8$. The stations which recorded this event were distributed in all four quadrants of azimuth from epicenter to station and range in distance (Δ) from 15° to 101° from the epicenter.

For the event of 1 December 1965, we determined m_b to be 4.9 from the average of measurements at eight stations, and M_s to be 3.2 from measurements at seven stations. We would have expected $M_s \geqq 3.8$ from an earthquake of $m_b = 4.9$. The stations which recorded this event covered about 180° of azimuth and 17° to 77° in epicentral distance. As can be seen from the individual station magnitudes listed in Table 2, the m_b's for both of these events are not changed if the magnitudes for stations at $\Delta \leqq 20°$ are excluded.

The data from the two events in Algeria are represented by the large solid circles in Fig. 1, which is a plot of surface-wave (M_s) versus body-wave (m_b) magnitude. The smaller circle represents the same determination for Long Shot (*2*), the underground nu-

Table 1. Epicentral and magnitude data for events in Algeria and an underground nuclear explosion in the Aleutian Islands. Data for origin time, latitude, longitude, and m_b (USCGS) for events in Algeria reported by the United States Coast and Geodetic Survey. Data for origin time, latitude, longitude for Long Shot (29 October) are taken from the shot report (*1*). M_s and m_b were computed by the authors from copies of the original seismograms. Number of stations used in the determination of magnitudes is given in parentheses.

Date of event (1965)	Origin time	Latitude	Longitude	m_b (USCGS)	m_b	M_s
27 February	11:29:59.0	24.2 N	5.1 E	5.8	5.8 (50)	4.1 (34)
1 December	10:29:58.0	24.0 N	5.1 E	5.0 (8)	4.9 (8)	3.2 (7)
29 October	21:00:00.1	51.4 N	179.2 E	6.1 (32)	6.1 (56)	3.9 (56)