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POSSIBLE RELATIONS BETWEEN METEORITE IMPACT AND IGNEOUS PETROGENESIS AS INDICATED BY THE SUDBURY STRUCTURE, ONTARIO, CANADA

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ABSTRACT

Recent investigations indicate the importance of meteorite impact as a process which has operated throughout geologic time to produce numerous originally circular structures as much as 50 km in diameter. One such structure, at Sudbury, Ontario, is associated with large volumes of internally-derived igneous rock.

Geological and experimental studies have demonstrated that rocks subjected to intense shock waves produced by hypervelocity meteorite impacts and by nuclear or chemical explosions develop distinctive and unique shock-metamorphic features, including: (1) high-pressure minerals such as coesite and stishovite; (2) high-strain-rate crystal-lattice deformation features such as isotropic feldspar (maskelynite) and "planar features" (shock lamellae) in quartz; (3) ultra-high-temperature reactions such as decomposition of zircon to baddeleyite and melting of quartz to lechatelierite.

These petrographic features, currently regarded as unequivocal evidence for meteorite impact, can be preserved and recognized even in very old and deeply eroded structures. Such features have now been observed in more than 50 "crypto-explosion" structures ranging in size from 2 km to more than 60 km in diameter.

The recent discovery of shock-metamorphic features in rocks of the Sudbury structure, Ontario, indicates that this old and complex structure was also produced by a large meteorite impact. Petrographic shock effects are widespread in inclusions of "basement" rock in the Onaping "tuff," a unit now regarded as a fallback breccia deposited in the original crater immediately after impact. Similar shock effects also occur in the footwall rocks around the basin, associated with shatter cones and unusual Sudbury-type breccias. Study of Sudbury specimens has established grades of progressive shock metamorphism comparable to those recognized at younger impact structures (Brent, Ontario; Ries basin, Germany).

Igneous activity associated with known meteorite impact structures takes two forms:

(1) Direct production of impact melt. At many structures (e.g., Brent, Ontario; Lake Mien, Sweden; Clearwater Lakes, Quebec), breccias containing shock-metamorphic features occur with "sills" and "dikes" of fine- to medium-grained crystalline igneous rock. Such units, previously regarded as internal volcanic products, now appear to have been formed by complete fusion, injection, and rapid crystallization of large volumes of target rock during the impact event.

(2) Emplacement of internally derived magma. The presence of the clearly internally-derived Nickel Irruptive within the Sudbury basin indicates that large meteorite impacts may also control the emplacement of internally-generated magmas through "unroofing" or by the production of deeply-extending zones of weakness below the crater.

The inferred development of the Sudbury structure was a complex process involving: (1) impact of an asteroidal body approximately 2-4 km in diameter, releasing 10^{29} erg and forming a large (100-km) diameter crater with a central uplift; (2) subsidence of the central uplift and simultaneous emplacement of the Nickel Irruptive; (3) metamorphism, deformation, and erosion to its present appearance. The post-impact history of the Sudbury structure thus corresponds closely to that established for many ring-dike complexes and caldera subsidences.

Similar compound impact-igneous structures, in which internal igneous activity is superimposed on a large impact crater, probably exist on both the earth and the moon. Future examination of "roofed lopoliths" and "ring-dike structures" for shock-metamorphic effects, combined with serious consideration of the geophysical effects produced by large-energy meteorite impacts, will be a productive field for cooperative studies by astrogeologists and igneous petrologists.

POSSIBLE RELATIONS BETWEEN METEORITE IMPACT AND IGNEOUS PETROGENESIS, AS INDICATED BY THE SUDBURY STRUCTURE, ONTARIO, CANADA

I. INTRODUCTION

The last ten years represent a period in the history of the geological sciences in which geologists have become more aware of the earth, not as an isolated individual planet, but as a member of a planetary system with which it interacts. The most spectacular aspect of this trend has been the geological interest in the manned and unmanned exploration of the moon and other planetary bodies. Simultaneously, an increased consideration has been given to the geological effects of extraterrestrial agencies on the earth itself.

One major result of this latter area of investigation has been the rapid and amazing increase in regard for the effects of meteorite impact throughout geologic time (French, 1968a; French and Short, 1968). Not long ago, meteorite impacts were regarded as rare events whose only products were small ephemeral structures less than 100,000 years old. The last ten years have seen a combining of geological and experimental research on the effects of meteorite impact to the extent that current tabulations (O'Connell, 1965; Freeberg, 1966, 1969; Short and Bunch, 1968) consider more than 50 structures to have originated through meteorite impact. Some structures in this group, such as Sudbury, Ontario, and Vredefort, South Africa, are more than 50 km in diameter and nearly 2 billion years old, and have been the subjects of prolonged and extensive geological arguments about their origin.

This increased recognition of the effects of meteorite impact on the surface of the earth is in perfect concordance with estimates of the possibilities of meteorite and asteroidal impact on the earth that have been calculated from astronomical data (e.g., Shoemaker et al., 1962). Such calculations indicate that sufficient large impacts should have occurred in the past 2 billion years to produce, on the present land areas of the earth, approximately 100,000 craters larger than Meteor Crater, Arizona, approximately 6,000 larger than 5 km in diameter, and about 20 the size of Sudbury or Vredefort. When the effects of crater removal by erosion or burial are considered, astronomical and geological data both support the present existence of perhaps several hundred large impact craters on the land areas of the earth.

In older meteorite craters, the easily destroyed meteorite fragments no longer occur. The recent recognition of such structures has been based on unique megascopic and microscopic deformational effects produced in the target rock by the intense shock waves generated by the hypervelocity[1] impacts of such large meteorites. At the instant of impact, the kinetic energy of the meteorite is converted into intense shock waves which are transmitted through the target rock and are also reflected back into the meteorite (Shoemaker, 1963; Gault et al., 1968). Shock waves travel upward through the rock from the subsurface path of penetration of the meteorite and are reflected from the ground surface as tensional waves, fracturing the rock and excavating it from the rapidly forming crater. The mechanics of such crater formation have been studied in detail for both natural meteorite craters (Shoemaker, 1962, 1963), nuclear explosions (Short, 1965, 1966a), and laboratory hypervelocity impacts (Gault and Heitowit, 1963; Gault et al., 1968).

The chief characteristic of a hypervelocity meteorite impact is that it subjects the target rock to environmental conditions which cannot be produced by any endogenetic geological mechanism: (1) peak pressures may reach several Mb near the impact point, and large volumes of rock will be subjected to shock waves with peak pressures in excess of 100 kb; (2) relaxation temperatures produced after passage of the shock wave may reach several thousand degrees; (3) the time involved is virtually instantaneous: a few microseconds for passage of the shock wave through a hand specimen, and a few minutes for excavation of a crater 30 km in diameter.

These unique conditions of shock metamorphism produce equally unique <u>shock-metamorphic effects</u> in the target rocks, many of which can be preserved for billions of years and constitute unique evidence of meteorite impact (Beals et al., 1963; Dence, 1964, 1965; Short, 1965, 1966b; Chao, 1967a, 1967b, 1968; French and Short, 1968; Engelhardt and Bertsch, 1969). These criteria include: (1) high-pressure polymorphs such as coesite and stishovite; (2) high-strain-rate lattice deformation effects such as "planar features" (shock lamellae) in quartz and production of isotropic phases from feldspar (maskelynite) and quartz; (3) ultra-high-temperature reactions, such as melting of quartz to lechatelierite, decomposition of zircon to baddeleyite, and melting or decomposition of various opaque minerals (El Goresy, 1968); (4) unusual conical

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[1]The term hypervelocity impact designates an event in which the impact velocity of the meteorite is greater than the acoustic velocity in the target rock. Such a condition occurs only for larger meteorites (weight more than about 10^2–10^3 tons) which are not significantly slowed by the atmosphere and strike the surface at virtually their original geocentric velocity. Such velocities range from a minimum of about 9 km/sec to above 50 km/sec; calculations of energy release usually assume an average velocity of 15-20 km/sec, but impact velocities for cometary bodies could be higher.

fracturing patterns (shatter cones) (Dietz, 1959, 1968) whose association with more distinctive petrographic shock effects suggests that they also are unique products of meteorite impact, forming at lower levels of shock pressure at some distance from the center of impact. The extreme conditions of shock metamorphism, combined with the short time scale of the process, produce distinctive selective mineralogical changes (Chao, 1967a, 1967b) and also result in the general preservation of mineralogical and chemical disequilibrium in the shocked rocks.

The response of rocks to shock waves is strongly dependent on individual characteristics such as mineral composition, grain size, pore filling, and small-scale texture and structure. This characteristic prevents exact correlation of any given deformation feature with a definite peak shock pressure, although present data can be used to specify broad limits. Experimental studies of rocks subjected to nuclear explosions (Short, 1966a, 1968) or to laboratory experiments (Hörz, 1968; Müller and Défourneaux, 1968) indicate that the distinctive planar features in quartz develop at peak shock pressures above about 80-100 kb and occur in a pressure range of about 100-250 kb. At higher shock pressures, e.g. 300-500 kb, development of isotropic quartz and feldspar occurs. Pressures above 400-500 kb produce extensive melting of the rock. Shatter cones are probably produced by pressures below 50 kb (Roddy and Davis, 1969), but minimum and maximum pressures for their formation have not been established.

With the possible exception of shatter cones, the effects of shock metamorphism apparently require minimum pressures of 75-100 kb for their formation. It is generally believed that such high shock pressures cannot be produced by internal mechanisms such as volcanic explosions, for which maximum pressures of 3-5 kb have been calculated (Williams, 1954; Gorshkov, 1959, Roddy, 1968). It is therefore believed that the assemblage of unique petrographic effects arising from high shock pressures, occurring in a structure characterized by intense and often localized deformation, is unique evidence for meteorite impact.

The terrestrial impact craters so far identified can be separated into two general types which Dence (1968) has designated simple craters and complex craters (Figure 1). The smaller simple craters consist of a cavity whose depth is about 1/3 to 1/4 the diameter. The cavity is partly filled by slumping from the rim and by deposition of ejected material to form a breccia lens containing large amounts of distinctively shocked and melted rock fragments. Larger impact structures, which may be as much as 65 km in diameter, are of the complex type and exhibit a central uplift which exposes material originally present at depth below the crater floor. Complex craters are much shallower in proportion to their depth; a typical diameter: depth ratio (Figure 1) might be

TYPES OF METEORITE IMPACT CRATERS

(ADAPTED FROM DENCE, 1968)

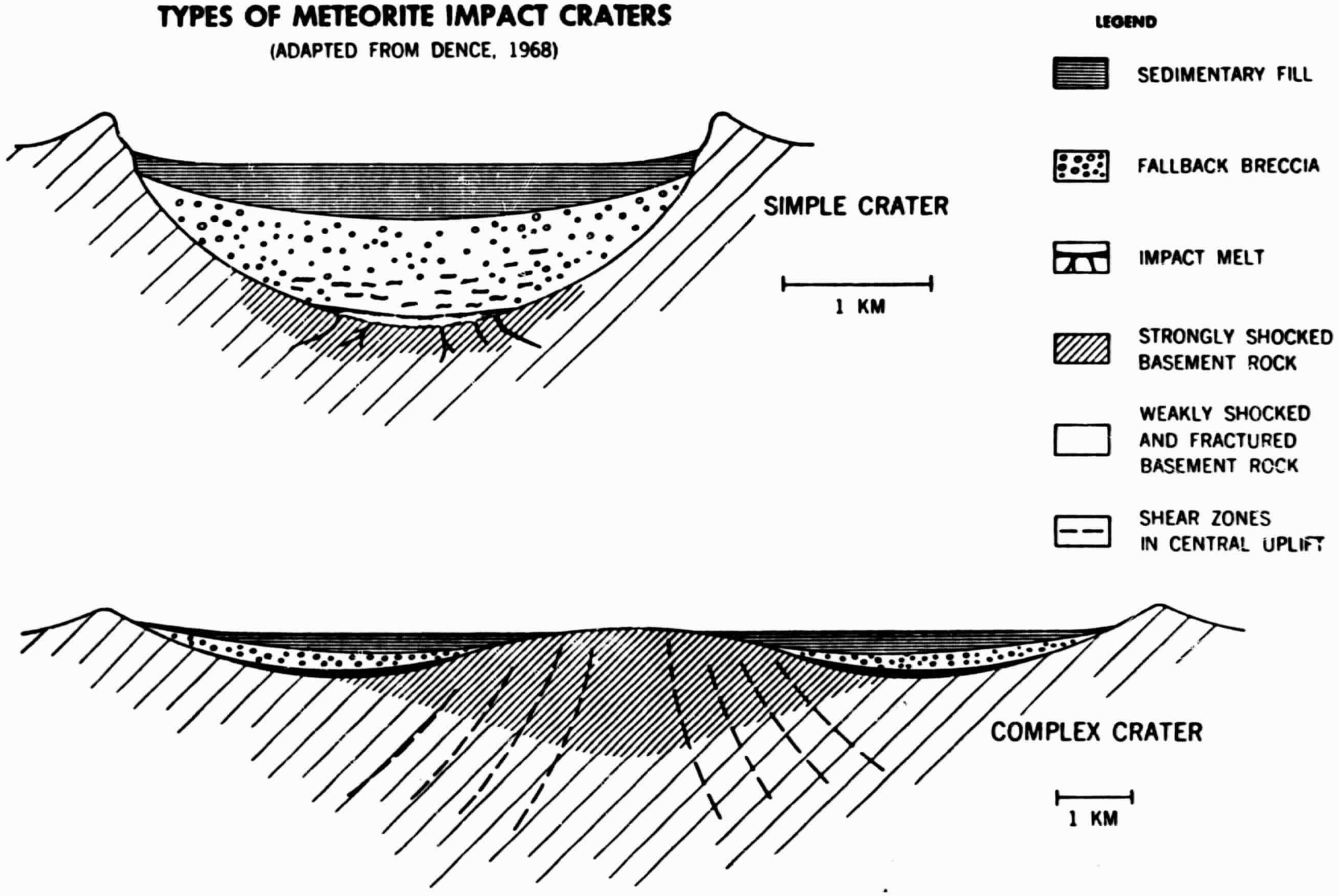


Figure 1—Schematic cross sections of simple and complex meteorite impact craters (adapted from Dence, 1968). Simple craters, (upper) such as Brent, Ontario, exhibit an original depth that may be as much as 1/4 to 1/3 the diameter and are partly filled by fallback breccia. In complex craters (lower), such as Clearwater Lakes, Quebec, inward and upward movement of the rocks below the crater in response to the impact produces a central uplift and results in a structure that is much shallower in comparison to its diameter. In simple craters, fallback breccia and impact melt are concentrated toward the center. In complex craters, these deposits are thickest in an annulus which surrounds the central uplift.

30:1. The breccia lens in complex craters is also relatively thinner than that in simple craters, implying that the majority of the ejecta was removed from the crater, either during the original impact or during the subsequent rise of the central uplift.

Formation of the central uplift of a large impact crater apparently involves plastic yeilding of the rock beneath and adjacent to the original crater (Dence, 1968) although the exact mechanism is not clearly understood. Development of the central uplift does involve absolute inward and upward movements of rocks in the crater floor, producing observable stratigraphic offsets in craters developed in sedimentary rocks (Roddy, 1968; Cook, 1968; Wilshire and Howard, 1968). Study of relations between the central uplift and the deposition of fall-back ejecta (Milton and Brett, 1968) support the view that production of the central uplift occurs relatively late in the impact event itself and is not due to subsequent isostatic readjustments over long periods of time.

The critical size division between simple and complex craters appears to be a function of rock strength and type. For granitic target rocks, the division occurs between crater diameters of 4 and 9.5 km (Dence et al., 1968, p. 359). However, in layered subhorizontal sediments, structures less than 3.6 km in diameter have well-developed central uplifts (Roddy, 1968), a characteristic which may reflect the relatively easier yielding provided by bedding planes. In even weaker materials such as alluvium, good central uplifts are observed in some explosion craters less than 100 m in diameter (Roddy, 1968).

A third type of structure, in which the original impact crater is modified by related internal igneous processes, has often been proposed. It has long been argued, generally in considering lunar craters, that large meteorite impacts could generate or control the emplacement of internally derived magma (Baldwin, 1949, 1963; Ronca, 1966; Salisbury and Ronca, 1966). The recent discovery of impact-induced shock-metamorphic features at Sudbury, Ontario (Dietz, 1964; French, 1967, 1968b) has provided the first definite correlation between a large meteorite impact structure and the occurence of large volumes of internally-derived magma (the Sudbury Nickel Irruptive). The existence of one example of this third type of meteorite impact structure indicates that other examples may exist on both the earth and moon. It is therefore necessary to consider the possible relations between meteorite impact and the production of igneous rocks, and to examine other "igneous" structures for traces of their possible impact origin.

2. DIRECT PRODUCTION OF IGNEOUS ROCKS BY METEORITE IMPACT: IMPACT MELTS

During a large meteorite impact, a relatively small volume of rock near the impacting body will be subjected to shock pressures in excess of 500 kb, sufficient to produce melting of the rock. Such impact-melted material has been found in several forms, both around the resulting crater and in the breccias deposited within it: (1) individual bodies composed of mixtures of glass and rock and mineral fragments, which are ejected from the crater and aerodynamically shaped before deposition. The impactite of Meteor Crater, Arizona (Nininger, 1954) and the Fladen of the Ries, Germany (Hörz, 1965) are examples. (2) glass-rich breccias containing numerous shocked rock fragments, which make up part of the breccia lens within the crater (Dence, 1964, 1965, 1968). Melted material occurs in these deposits both as glassy fragments or as partly or completely crystalline matrix. (3) relatively thick and uniform layers resembling sills, associated with the breccias, but composed of completely crystalline rock with few or no inclusions. These latter units have been considered to be internally derived volcanic rock and have been cited as evidence for an endogenetic origin of the structures.

(The term igneous here designates rocks formed by partial or complete crystallization of a silicate melt and does not imply any particular mechanism by which the original melt was formed. The term impact melt designates, material formed by direct fusion of target rock by meteorite impact.)

The amount of melt that can be produced by a meteorite impact depends chiefly on two factors: (1) the total amount of energy of the impact, which is equal to the kinetic energy of the impacting body; (2) the partition of this energy, or the percentage which actually is used to melt rock.

Because the mass and velocity of the original impacting meteorite are not known, several investigators have attempted instead to develop a mathematical relationship between the energy of a meteorite impact and the diameter of the resulting crater. Most of these calculations involve the use of scaling laws based on small craters produced by nuclear and chemical explosions (Baldwin, 1949, 1963; Innes, 1961; Shoemaker et al., 1962; Shoemaker, 1963; Short, 1965; Beals, 1965). It is generally considered that the diameter of a crater is proportional to the energy raised to some power between 1/3 and 1/3.4, but the extrapolations in energy and diameter for large meteorite craters are so great that energies calculated for a given crater diameter may differ by one or two orders of magnitude. (e.g., for a 30-km diameter crater, calculated energies range from 6×10^{27} to 2×10^{29} erg.).

The fraction of impact energy used to melt rock is almost equally uncertain. From small-scale hypervelocity impacts, Gault and Heitowit (1963) estimate that about 20 per cent of the impact energy is transmitted to the target rock as waste heat, but much of this energy will be dissipated without raising the rock to its melting point.

Calculation by Beals (1965) of rock melted by meteorite impacts show good agreement with melt volumes estimated from studies of several Canadian craters (Dence, 1965). Beals' calculations used the scaling equation of Baldwin (1963, p. 176):

$$\log D\ (km) = 0.3284 \log E\ (erg) - 7.9249$$

in which D is the crater diameter in km and E is the impact energy in ergs. The calculated melt volumes and melt thickness (Figure 2) were derived assuming that 5 per cent of the impact energy is effective in melting rock. The calculated melt volumes are in good agreement with the empirical observations of Dence (1965, p. 954) that the value of the ratio V_m/D^3 is 1/400 to 1/500 for several Canadian craters (V_m is the volume of impact melt, and D is the diameter of the crater).

A significant fraction of the melted rock now occurs as individual glassy fragments or as crystalline matrix in parts of the breccia lens. The intimate association of these types of melt with shocked rock fragments is good evidence for their origin by impact. However, part of the melt in several craters, notably Brent, Clearwater Lakes, and Manicouagan (Dence, 1965) occurs as discrete, completely recrystallized layers which resemble sills. These units have been considered by some workers as products of internal volcanism.

Dence (1968) has suggested that these impact melt layers are material melted close to the penetrating meteorite and that their location indicates the approximate depth of penetration of the meteorite into the target rock. The bodies are generally sill-like in shape and are overlain by breccias containing distinctively shocked glasses and rock fragments. They are generally concordant with the crater floor, although small dikes believed to be impact melt have been identified at the Tenoumer crater, Mauritania (French et al., 1969) (Figure 3). In simple craters, such as that at Brent, Ontario (Dence, 1968), the melt layer occurs at the low point in the center of the crater. In complex craters, such as Clearwater Lakes and Manicouagan (Dence, 1965, 1968), the melt layer forms an annular ring between the central uplift and the rim, suggesting that the central uplift had formed before the melt had completely solidified.

Considered individually, these melt layers strongly resemble internally derived sills and dikes. They may be as much as several hundred meters thick and range in character from medium-grained to aphanitic. They are often completely crystalline, consisting chiefly of laths of feldspar and pyroxene with accessory minerals (Dence, 1968, p. 176), but they may contain variable amounts of glass. In detail, however, these impact melt layers reflect

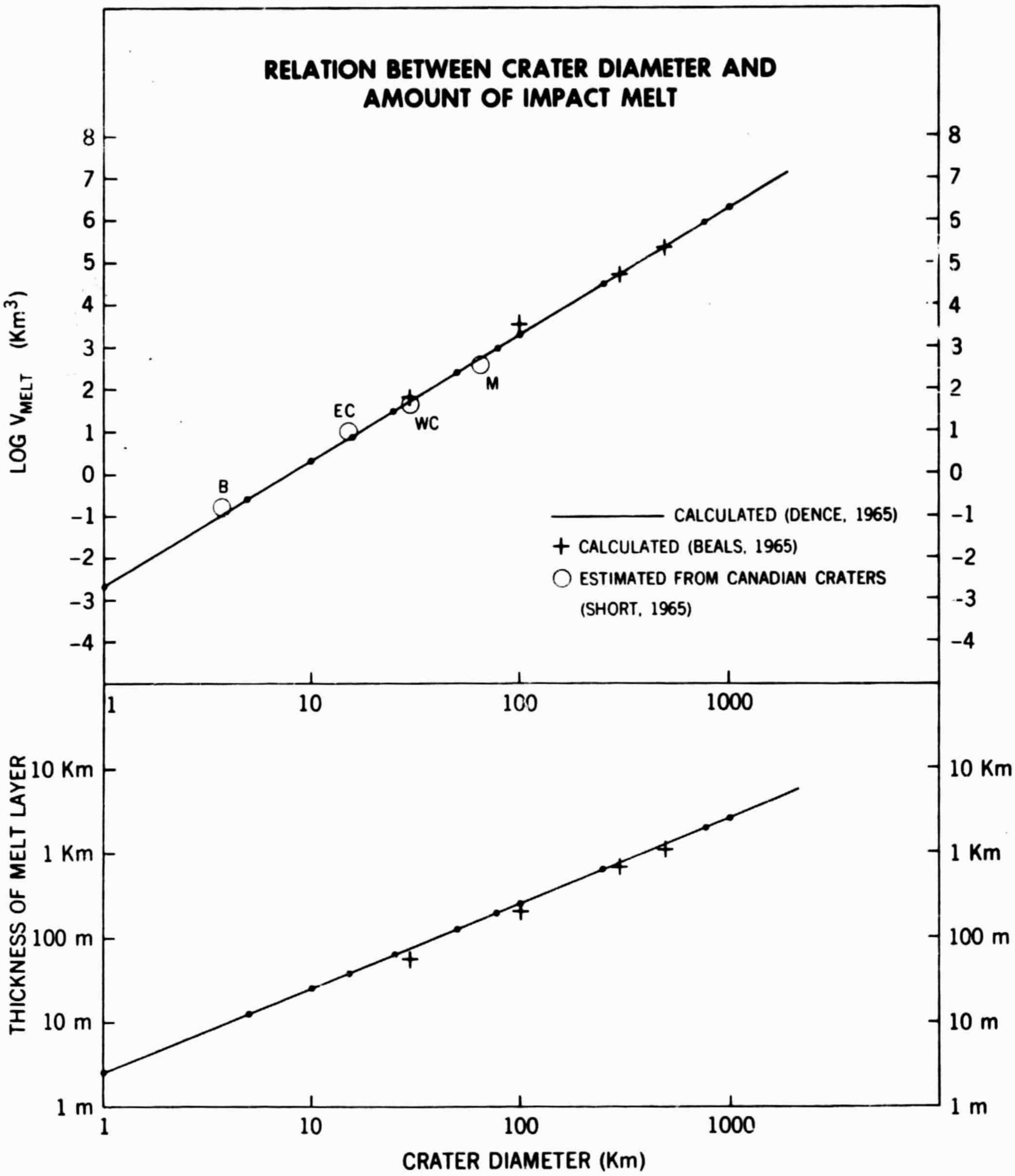


Figure 2–Relations between crater diameter and amount of impact melt formed by direct fusion of target rock. The straight line is based on estimated melt volumes at known Canadian craters, using the relation, $V_{melt} = 0.002\ D^3$ where D is the crater diameter in km (Dence, 1965). Crosses are calculated from Baldwin's energy equations, assuming a five percent use of energy to melt rock (Beals, 1965). Large open circles are estimated melt volumes for several Canadian craters: B, Brent, Ontario; EC and WC, East and West Clearwater Lakes, Quebec; M, Manicouagan, Quebec (Short, 1965).

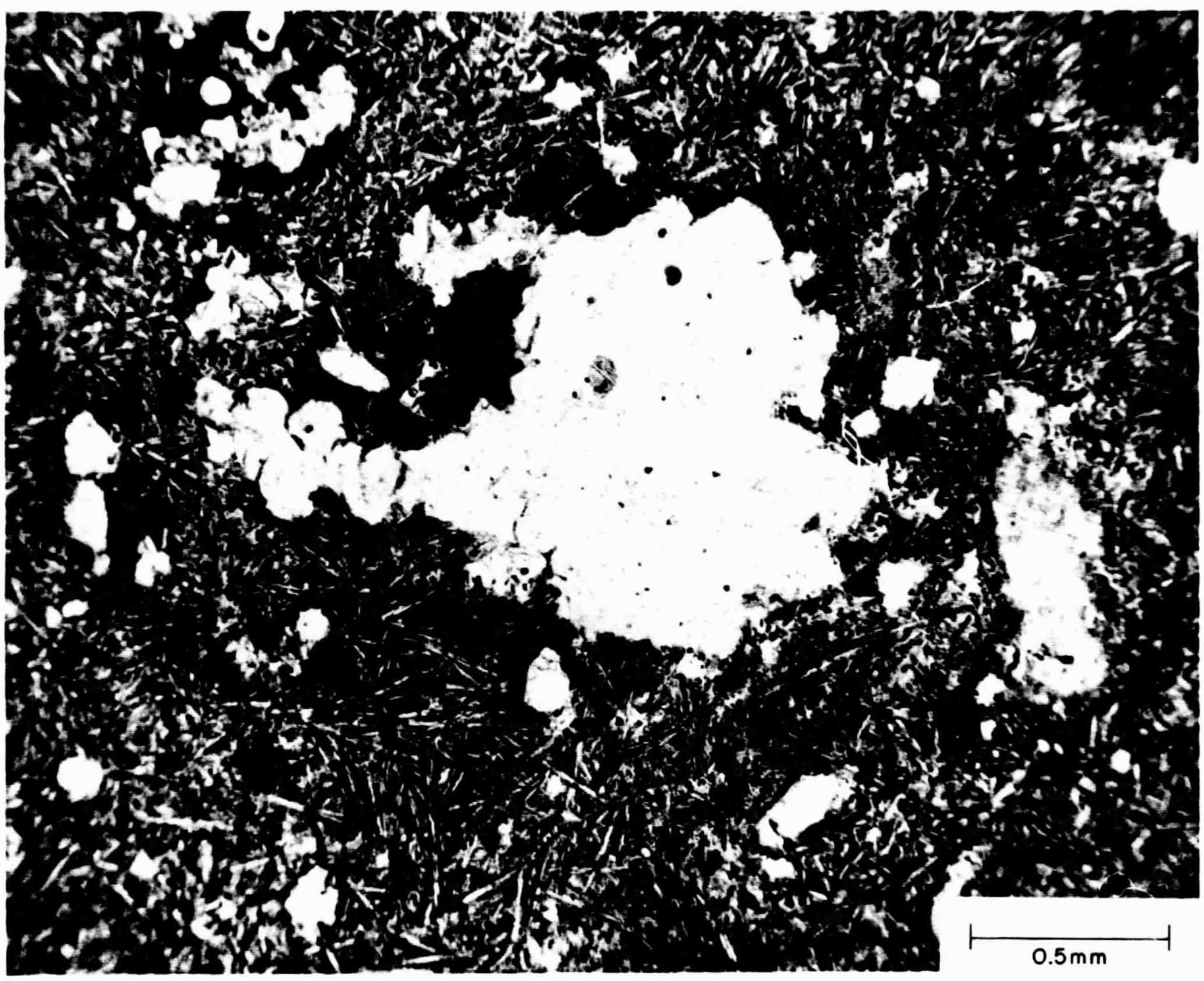


Figure 3–Large irregular lechatelierite inclusion (clear) in partly crystalline impact melt from the Tenoumer crater, Mauritania. These inclusions apparently result from high-temperature fusion of shocked quartz grains in the target rock. The lath-like feldspar crystals in the melt are associated with pyroxene and brown interstitial glass; quench textures are common. The lechatelierite inclusion itself encloses a small inclusion of brown matrix glass and feldspar. At the contact between lechatelierite and melt, matrix glass indents and penetrates the lechatelierite, indicating that both glasses were molten simultaneously.

their formation by sudden high-temperature fusion of the underlying rock, rapid injection, and rapid cooling. Their characteristics (Dence, 1968, p. 176) include: (1) chemical composition similar to that of the underlying target rock; (2) considerable secondary hydrothermal alteration and zeolitization; (3) absence of phenocrysts; (4) absence of flow structure, indicating crystallization virtually in place; (5) generally fine grain with numerous quench textures in the glassy varieties; (6) presence of occasional shocked inclusions or lechatelierite derived from fused quartz grains (Figure 3) (Taylor and Dence, 1969; French et al., 1969); (7) association with distinctively shocked and shock-melted breccias.

These impact melt layers are geochemically important. The severe fusion involved in their production appears sufficient to remove original radiogenic argon, and such melt units apparently give K/Ar ages corresponding to the time of formation of the structure (Dence et al., 1968; Rondot, 1968; Taylor and Dence, 1969; French et al., 1969). By contrast, the original Sr^{87}/Sr^{86} ratio is unchanged by such fusion. For impact craters developed on geologically old terrains, the impact melt will be enriched in original radiogenic Sr^{87}. The Sr^{87}/Sr^{86} ratio of the impact melt will not only be identical to that of the underlying basement rock, but will also be much higher than that of fresh magma generated in the mantle (Faure and Hurley, 1963). This discrepancy provides a potential method of recognizing impact melt units produced by meteorite impacts on relatively old terrains (P. M. Hurley, personal communication, 1968; French et al., in preparation).

3. EVIDENCE FOR IMPACT ORIGIN OF THE SUDBURY STRUCTURE, ONTARIO

A. Geology

Although several impact structures exhibit associated melt units derived directly by fusion of the target rock, the recent discovery of shock-metamorphic effects at Sudbury, Ontario (Dietz, 1964; French, 1967, 1968b) provides the first example of a correlation between meteorite impact and internal igneous activity. The discovery of shock-metamorphic effects in a structure of such great age and complicated geological history indicates that: (1) shock-metamorphic features can be preserved for periods approximating two billion years to provide unequivocal evidence of meteorite impact; (2) the impact theory may provide a resolution of puzzling and complex geological and structural relations (Dietz, 1964); (3) meteorite impact can apparently initiate large-scale igneous activity combined with the emplacement of tremendously valuable ore deposits.

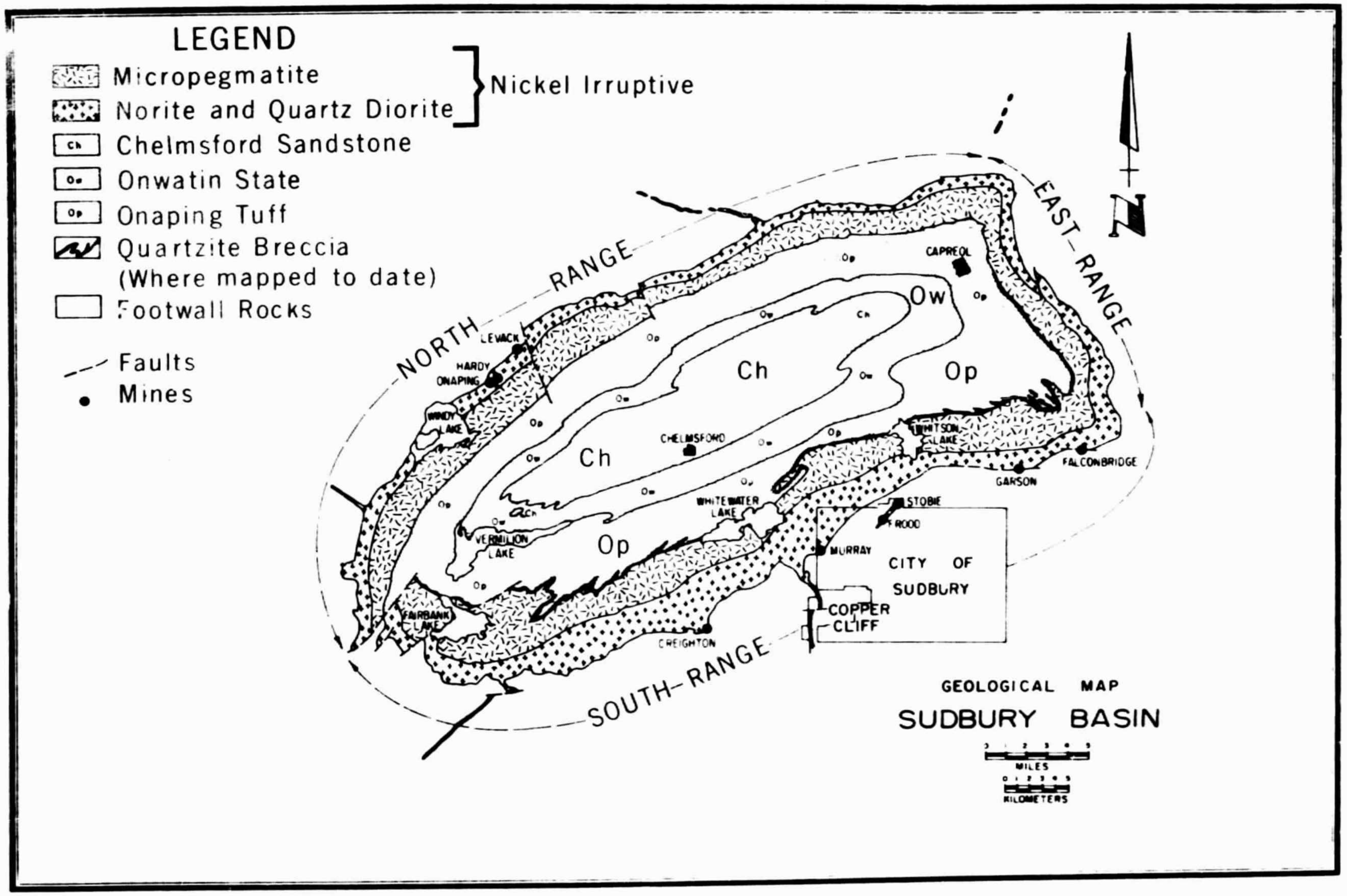


Figure 4—Index geological map of the Sudbury structure, Ontario (from Stevenson, 1963, Fig. 1). Older rocks outside the Irruptive are not subdivided. At the base of the Onaping formation (Op) is the "quartzite breccia" (black) previously considered to represent feeder dikes for the Onaping and now recognized as a complex unit containing large blocks of basement rocks.

The Sudbury structure in southern Ontario, Canada (Figure 4) has produced more than $9 billion worth of nickel, copper, and iron since discovery of the ore deposits there in 1883. It has also produced, during the same period, a continuing geological controversy about the origin of the structure, the Nickel Irruptive, and the associated ore deposits (for detailed bibliographies, see Hawley, 1962; Card, 1967).

The Sudbury structure (Figure 4) is outlined, both topographically and geologically, by the outcrop belt of the Sudbury Nickel Irruptive (Burrows and Rickaby, 1929; Thomson, 1956; Williams, 1956).[2] This unit forms a kidney-shaped basin approximately 37 mi (59 km) in a NE-SW direction by 17 mi (27 km) across. The basin is emplaced in older rocks, granites and granitic gneisses on the north and east, Huronian metasediments whose age is estimated at greater than 2.2 b.y. along the east and southeast. These wallrocks have been intensely shattered and brecciated to form a unit called Sudbury-type breccias (Speers, 1957). The intensity of this deformation increases inward and is a maximum near the lower contact of the Irruptive itself.

The rocks of the Whitewater series underlie the interior of the Sudbury basin. Immediately above the Irruptive is the Onaping formation, about 4000 feet (1200 m) thick, previously regarded as pyroclastic volcanic deposits. The Onaping is overlain by the Onwatin "slate" or argillite, about 1000 feet (300 m) thick, a unit believed to be derived by subaqueous reworking of the uppermost part of the Onaping formation. Overlying the Onwatin is the Chelmsford sandstone, a sequence of graywacke beds with a minimum thickness of about 1000 feet (300 m). The sediments within the Sudbury basin have been deformed into folds whose axes trend parallel to the long axis of the basin.

The Sudbury Nickel Irruptive separates the Whitewater series from the older basement rocks. At its lower contact, it is emplaced discordantly against the granites, gneisses, and metasediments which surround it. At its upper contact, the Irruptive has apparently metamorphosed the adjacent Onaping formation, suggesting an intrusive relationship.

The Irruptive has a stratigraphic thickness varying between one and three miles (2-5 km) (Wilson, 1956). The section exposed on the south side of the basin (South Range) is thicker than that on the north (North Range). On the South Range, where considerable subsequent deformation has taken place, the

[2]Because of considerable debate about the origin, mode of emplacement, and subsurface shape of this igneous body, the nongenetic term "irruptive" has come into general use.

contact between the Irruptive and the older rocks is steep to vertical and generally dips toward the center of the basin. On the North Range, where deformation has been comparatively minor, the same contact dips basinward at about 30°-45°. Preliminary paleomagnetic studies (Sopher, 1966), suggest that the original dip of the Irruptive may have been about this value.

Lithologically, the Irruptive is broadly divided into two major units: a lower more mafic norite (approximately 55 percent SiO_2), and an upper more felsic micropegmatite (approximately 66 percent SiO_2) (Knight, 1923; Collins, 1934). A thinner transition zone is recognized between the two major units, and more recent studies have allowed further subdivision (Stevenson and Colgrove, 1968). A whole-rock Rb-Sr age determined on the micropegmatite gave a value of 1.72 b.y. (Faure et al., 1964; Fairbairn et al., 1965).

The origin of the Irruptive and its associated ore deposits has been the subject of continuing debate. The irruptive itself is unusual in combining an apparently lopolithic shape with an anomalously high silica content and a general absence of obvious mineralogical layering (Stevenson and Colgrove, 1968). The Irruptive has been variously regarded as a flat lens, subsequently folded (Coleman, 1905), a ring-dike (Knight, 1917), a subsurface part of a caldera complex (Williams, 1956), a lopolith (Wilson, 1956), and the remnant of a much larger lopolith (Hamilton, 1960b). A similar uncertainty has existed regarding the origin of the ore deposits, and still exists in recent studies (Naldrett and Kullerud, 1967; Souch et al., in press).

Subsequent to emplacement of the Irruptive, the Sudbury area has undergone at least one major period of metamorphism (Card, 1964, 1969). During the "Grenville event" at about 1200 m.y., the structure was compressed from the southeast, developing numerous northeast-trending thrust faults roughly parallel to the South Range. This event was also accompanied by emplacement of diabase dikes which trend in a generally northwestward direction.

Prior to the discovery of shock-metamorphic features at Sudbury, the current interpretation of the structure as a caldera complex (Thomson, 1956; Williams, 1956) had been unsettled by the discovery that a unit at the base of the Onaping formation, previously regarded as feeder dikes for the formation (Williams, 1956) actually consists of a breccia of large blocks of quartzite and granite in a matrix of micropegmatite (Stevenson, 1960, 1963). Subsequently, Dietz (1964) noted that the intense structural deformation around the basin (Speers, 1957) could be explained by meteorite impact, and suggested that the Sudbury structure had been produced by the impact of a 4-km-diameter asteroid, 1.7 b.y. ago, in an event that released 3×10^{29} erg, or about a million megatons of energy and formed a crater 30 miles in diameter. Dietz also proposed that the Irruptive was emplaced as an "extrusive lopolith" into the crater and that the

Onaping formation developed as a "cap" of weided tuffs above the Irruptive Finally, Dietz (1964) predicted and then discovered shatter cones around the basin and suggested the "quartzite breccia" at the base of the Onaping formation might contain petrographic shock features.

The subsequent discovery of petrographic shock effects in inclusions of basement rock in the Onaping formation (French, 1967, 1968b, 1969) confirmed Dietz' ideas about the impact origin of Sudbury. However, these results indicated that the Onaping formation was equivalent to the "breccia lens" in other craters and that it was composed of material that had been shocked and melted by the impact and immediately redeposited in the crater. Subsequent studies at Sudbury have verified predictions made on the basis of the impact theory. Shatter-coning has been discovered to be widespread in the older rocks around the basin (Dietz and Butler, 1964; Bray et al., 1966), and petrographic shock effects have been observed in inclusions and wallrock associated with the Sudbury-type breccias (French, 1969). Except for the preservation of the "fallback breccia" (Onaping formation) and the presence of the Irruptive itself, the general structure and shock-metamorphic features at Sudbury are very similar to those observed at the Vredefort structure, South Africa (Daly, 1947; Dietz, 1961; Hargraves, 1961; Manton, 1965).

B. Shock-metamorphic Effects in the Onaping Formation.

The origin, characteristics, and petrographic study of the Onaping formation have been crucial in the recognition of Sudbury as an impact structure. The formation was long regarded as a volcanic rock whose esistence provided evidence for the internal origin of the Sudbury structure, and its true character as an impact-produced "fallback breccia" was not established until distinctive petrographic shock effects were recognized in basement rock inclusions (French, 1967, 1968b, 1969). The nature of the Onaping formation and the methods used to establish its impact origin are important, not only in the study of Sudbury, but also for the recognition of similar impact-produced structures now regarded as purely internal in origin.

Previous investigators (Burrows and Rickaby, 1929; Thomson, 1956; Williams, 1956) regarded the Onaping formation as an accumulation of pyroclastic rocks deposited during the intense early explosive phase of development of the Sudbury structure. The formation has an estimated thickness of about 4000 feet (1200 m) and a preserved volume of 600-1000 km^3 (Williams, 1956). Earlier investigators concluded that the Onaping formation: (1) contains numerous fragments of devitrified glassy material; (2) also contains numerous inclusions of basement rocks up to 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 rock types with respect to the basin; (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; (7) has been involved in at least one period of postdepositional metamorphism.

Although several varieties of Onaping formation can be distinguished (Burrows and Rickaby, 1929; Thomson, 1956; Williams, 1956; Stevenson, 1960, 1963), the most common variety is a dark gray to black, poorly sorted, fragmental rock containing numerous inclusions (French, 1967, 1968b). The formation has been mildly metamorphased (chlorite grade). Many of the inclusions have clearly been molten and these constitute the evidence for the original identification of the Onaping formation as a pyroclastic rock (Bonney, 1888; Williams, 1891). Occasionally, so-called "cored" inclusions have been observed (French, 1968b), which consist of a core of basement rock surrounded by a rim of glassy material. These composite fragments have apparently originated by mixing of melted and unmelted rock fragments in the air before deposition and may be diagnostic for meteorite impact. In its general appearance, the Onaping formation is not dissimilar from volcanic tuffs and tuff-breccias (French, 1968b) and definite evidence for its origin by meteorite impact is supplied by the petrographic shock effects in the numerous inclusions of basement rocks which it contains.

Distinctive petrographic effects of shock are widespread in inclusions collected from various parts of the Onaping formation. On the basis of study of numerous such inclusions, it has been possible to recognize stages or grades of progressive shock metamorphism (French, 1969) that are comparable to those established by studies at other impact structures such as Brent, Ontario (Dence, 1968; Robertson, et al., 1968), and the Ries basin, Germany (Stöffler, 1966; Chao, 1967a, Engelhardt and Stöffler, 1968).

The majority of inclusions observed in the Onaping formation are medium- to course-grained quartzofeldspathic rocks such as granites, granitic gneisses, and feldspathic metaquartzites. Such rock types are sensitive indicators of shock metamorphism and develop distinctive shock effects over a range of temperatures and pressures (Stöffler, 1966; Robertson et al., 1968). The grades of shock metamorphism discussed below are based on the progressive destruction of the original fabric of these inclusions. A few inclusions of other rock types from the Onaping formation have been examined, but either too few have been studied to distinguish grades of shock damage (gabbroic and diabasic inclusions) or no distinctive shock effects have been observed (fine-grained sandstones and argillities).

The stages of shock metamorphism recognized in the Sudbury inclusions are transitional and may grade into each other even within a single thin section. Detailed descriptions are further hampered by the extensive recrystallization in the inclusions, which has resulted from either postdepositional cooling or from later unrelated metamorphism. No isotropic material has been observed in any inclusion, and the term "glass" is used here to designate recrystallized material which may have been either: (1) shock-produced isotropic phases such as maskelynite; (2) molten material produced by fusion of the rock.

The following stages of shock metamorphism can be recognized in quartzofeldspathic inclusions collected from the Onaping formation:

(0) Fracturing, crushing, and granulation: These deformation effects can be produced by both shock waves and normal geological processes. Such textures could have been present in the target rocks before impact, or they could have been produced by low-intensity shock waves at a distance from the impact point. In some inclusions, these features are accompanied by definite shock effects, but they do not, by themselves, constitute evidence of impact.

(1) Planar features in quartz and feldspar. The first distinctive evidence of shock metamorphism (French, 1967, 1968b) is the production of distinctive sets of "planar features" (shock lamellae) in quartz and feldspar grains without serious destruction of the original grain fabric. Two broad subdivisions of this stage can presently be made: (a) planar features in quartz only (dominantly with basal orientation), associated with kink banding in mica, and generally observed in footwall rocks and inclusions in the Sudbury-type breccias (French, 1969); (b) planar features in quartz (multiple sets, including the distinctive $\{10\bar{1}3\}$ orientation) (French, 1967) accompanied by planar features in associated feldspar. This second type may represent higher peak shock pressures (Robertson et al., 1968), and further subdivision of this stage based on petrofabric studies (Robertson et al., 1968) may be possible.

(2) Selective recrystallization of feldspar. In such inclusions the quartz contains multiple planar features, while associated feldspar has been recrystallized to small crystals, possibly from a pre-existing shock-produced isotropic phase. Such mineralogical selectivity is characteristic of shock metamorphism (Chao, 1967a), but the effects observed in these inclusions could also be the result of rapid and incomplete melting of the inclusion produced by low-pressure superheating. An inclusion transported through the "fireball" immediately after impact would be heated above the melting point of its consitutent minerals. Under such conditions, the lower-melting feldspar would fuse, but would be quenched and recrystallized before fusion of the quartz or extensive reaction between quartz and feldspar could occur. Some of these inclusions exhibit the effects of such ultrahigh temperatures, such as partial melting of grains of sphene (M.P. 1385°C) associated with the recrystallized feldspar (Figure 5).

Figure 5—Shock-metamorphosed inclusion (Stage 2) from the Onaping formation, Sudbury, Ontario, showing selective transformation of feldspar and partial fusion of sphene. Plane polarized light. Quartz grains (upper and lower center) exhibit several sets of planar features. Original feldspar grains (lower right) appear clear and glassy and are completely recrystallized to fine-grained aggregates. In the area of recrystallized feldspar, a euhedral grain of sphene has been partly melted, producing a train of small droplets of sphene or of titanium oxide minerals. The melting point of pure sphene is about 1400 °C, and such textures provide evidence for ultrahigh temperatures produced by meteorite impact. The needlelike material at the quartz-feldspar contacts is probably secondary amphibole.

(3) Plastic deformation of feldspar and recrystallization of quartz. Feldspar crystals in this stage of deformation exhibit strong plastic deformation, producing unusual extinction patterns and striking bent-twin structures in plagioclase (French, 1968a, Figs. 25-28). Many of the feldspar grains are now completely recrystallized and may have originally been isotropic. The associated quartz grains are completely recrystallized to mosaics of unstrained crystals.

(4) Eutectic melting between quartz and feldspar. In inclusions exhibiting strongly deformed feldspar, patches of glassy material containing quenched

microlites occur along original grain boundaries, generally between plastically deformed feldspar and recrystallized quartz (Figure 6). The microlites are apparently both feldspar and opaque minerals, and their existance suggests the formation of locally heated areas in which adjacent quartz and feldspar grains were partly dissolved to form a small amount of eutectic melt at the contacts, followed by rapid quenching. Such textures are consistent with the elevated temperatures that can be produced by shock-wave action, and the location of the melt areas may reflect locally high temperatures produced by the effect of shock waves on original grains of opaque minerals. Similar eutectic melting is observed in granitic inclusions superheated in lavas (Hawkes, 1929; Knopf, 1938; Larsen and Switzer, 1939), but such textures lack the intense deformation produced by shock waves and observed in the remnants of quartz and feldspar in the Sudbury specimens.

(5) Heterogeneous melting. At extremely high shock pressures ($\gtrsim$ 500 kb), the residual temperatures will not only exceed the eutectic temperatures of the system, but will exceed the individual melting points of all minerals present. Under such conditions, each mineral melts independently to form an inclusion composed of several distinct types of glass of differing color and refractive index (Figure 7), each area corresponding to an original mineral grain. Incipient flow, when observed, is turbulent and contorted and generally extends for less than a few grain diameters. In some inclusions, shock heating has apparently been great enough to produce vesiculation.

(6) Complete melting, mixing, and accretion. At the highest detectable shock levels, rock fragments are completely melted, with sufficient superheat to allow the development of nearly laminar flow over distances of several centimeters. This melted material is ejected from the crater, mixed with other rock fragments showing varying shock effects, and redeposited. These individual bodies, such as the Fladen at the Ries basin, Germany (Hörz, 1965) may be aerodynamically sculptured before deposition.

Such inclusions in the Onaping formation, composed of once-molten glass with varying amounts of rock and mineral fragments, were responsible for the original identification of the Onaping formation as a volcanic rock (Bonney, 1888; Williams, 1891). The inclusions are greenish in color and generally recrystallized to quartz, chlorite, and amphibole, but the original flow structure can still be distinguished and can be seen to wrap around the included fragments (Figure 8). The content of rock and mineral fragments varies widely, ranging from a few percent in the more glassy fragments (Figure 8) to the so-called "cored inclusions" (French, 1968b) which may consist of only a thin rim of glass around a large core of basement rock. In general appearance, these fragments resemble glassy volcanic ejecta. However, the absence of phenocrysts, combined with the presence of rock and mineral fragments differing

Figure 6–Shock-metamorphosed inclusion (Stage 4) from the Onaping formation, Sudbury, Ontario, showing incipient eutectic melting at quartz-feldspar contacts. Plane polarized light. Original quartz (lower right) is completely recrystallized. Original feldspar (clear areas in upper left) shows strong plastic deformation, flow structure, and recrystallization. At the contacts between grains, areas of eutectic melt (dark patches in upper right and lower left) have developed, in which quench textures produced by lath-like feldspar and opaque minerals can be seen.

Figure 7–Shock-metamorphosed inclusion (Stage 5) from the Onaping formation, Sudbury, Ontario, showing complete and individual melting of component minerals to produce heterogeneous glasses which are now largely recrystallized to secondary quartz, chlorite, and amphibole. Plane polarized light. Incipient flow has developed in some areas (center), but does not extend for long distances.

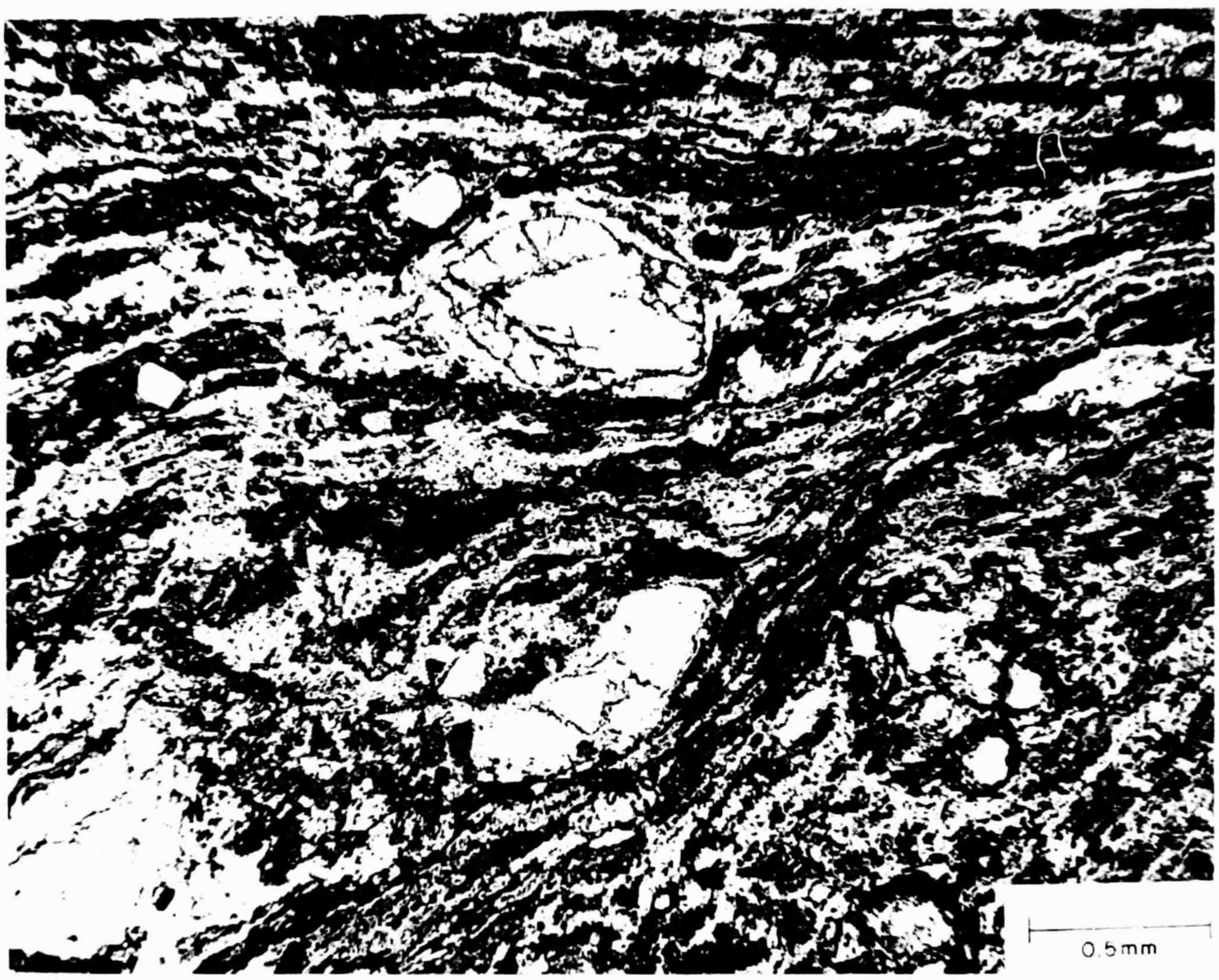


Figure 8—Composite glassy inclusion (Stage 6) from the Onaping formation, Sudbury, Ontario, produced by mixing and accretion of impact melt and diverse rock and mineral fragments. Plane polarized light. Fragments of quartz have irregular outlines and are not phenocrysts; the upper fragment exhibits poorly preserved planar features. Flow structure is heterogeneous, but laminar flow persists over distances of several mm, although turbulent flow occurs in other areas of the same inclusion. Inclusions of this type are completely recrystallized, but the original flow structure is still recognizable.

in both lithology and degree of shock metamorphism, indicates that these inclusions have formed by accretion of originally separate fragments of shocked and shock-melted rock.

The size of these glassy inclusions is similar to the size of the rock fragments with which they are associated, and shows a similar decrease in size upward from the base of the Onaping formation. At the base occur large "cored bombs" (Williams, 1956, p. 76-81), aggregates of rock fragments and glassy material that are more than 20 m in size. Above this basal zone, the fragments generally range from a few millimeters to about 50 cm in size, although larger compound blocks tens of meters across are occasionally found in the upper parts of the formation.

The discovery at Sudbury of a range of shock-metamorphic effects which can, despite their metamorphism and recrystallization, be compared with those from other structures, provides a strong and consistent body of evidence for the impact origin of the Sudbury structure. Some of the textures involving incipient melting (Stages 4-6) resemble features observed in inclusions superheated in high-temperature igneous rocks, but the extensive crystal deformation and the presence of ultra-high-temperature decomposition reactions are convincing evidence that such heating has occurred as a result of meteorite impact. The high-pressure polymorphs coesite and stishovite have not been detected (French, 1968b, p. 406); it is unlikely that they would have been preserved during the subsequent burial and metamorphism of the Onaping formation.

C. Emplacement of the Sudbury Nickel Irruptive.

The location of the Sudbury Nickel Irruptive is strongly controlled by the structure of the Sudbury basin itself. It invariably occupies a zone immediately beneath the Onaping formation and immediately above the most intensely shattered and deformed footwall rocks (Speers, 1957). This close association has indicated to all investigators that the origin of the Sudbury basin and the origin and emplacement of the Irruptive are closely and genetically related.

If the Sudbury structure is regarded as a large impact crater, the Irruptive occupies the zone between the breccia lens and the intensely shocked basement rocks which form the original crater floor (see Figure 1). Subsequent to formation of the crater, this contact would be a natural zone for emplacement of magma generated at depth.

It is generally agreed that most, if not all, of the Irruptive represents internally derived magma rather than primary impact melt. Values of the Sr^{87}/Sr^{86} ratios for the micropegmatite are much lower than would be produced by primary fusion of the near-surface basement rocks (Faure et al., 1964). Further, the volume of the Irruptive far exceeds the amount of melt that could be expected from a meteorite impact.

If one assumes that the Nickel Irruptive underlies the Sudbury basin with an average thickness of 1.5 mi. (Collins, 1934; Wilson, 1956), the calculated present volume is between 800-1000 mi^3 (3300-4200 km^3). This minimum value does not allow for erosion, but it is still far in excess of the melt volume of about 225 km^3 to be expected from a 30-mi-diameter crater (Beals, 1965) (Figure 1). Since the glassy material in the Onaping formation is believed to represent primary impact melt, the calculated melt volume of 225 km^3 would correspond to 10-20 volume per cent of the Onaping formation at deposition, a figure which is in reasonable agreement with the present character of the Onaping formation. It is clear that the amount of impact melt to be expected from the Sudbury event can be accounted for as glassy fragments in the Onaping formation, while the bulk of the Irruptive itself must have been internally derived.

The detailed development of the history of the Sudbury structure and the emplacement of the Irruptive is not presently possible because information is lacking on several vital problems:

1. Interval between the impact and emplacement of the Irruptive. The age of 1.72 b.y. determined for the micropegmatite (Faure et al., 1964) has been tacitly assumed to date the impact as well (Dietz, 1964; French, 1967, 1968b). There has been no independent dating of the time of impact itself, although it has been shown that the Whitewater series is contemporaneous with the Irruptive (Fairbairn et al., 1968). However, the possibility exists that these ages might be metamorphic ages, since the Sudbury area exhibits a long and complex metamorphic history between about 2.2 and 1.5 b.y. ago (Card, 1964, 1967, 1969). At present, the interval between impact and the emplacement of the irruptive cannot be stated, and because of the great age of the rocks involved, a definite interval could not be recognized unless it were greater than about 50-100 m.y.

2. Subsurface shape of the Irruptive. Both the subsurface shape and the location of feeder channels for the Irruptive are entirely unknown. Preliminary gravity data (Miller and Innes, 1955) provide no evidence for the existence of large feeders in the center of the basin or for the presence of thick ultramafic layers at depth, but no other limitations on possible shape and source of the Irruptive have been established.

3. Depth of intrusion of the Irruptive. Intrusive relations of the Irruptive against the Onaping formation are indicated by the existence of contact-metamorphic effects in the Onaping formation (Burrows and Rickaby, 1929; Stevenson,

1960, 1963). The inferred formation of tridymite near the contact (Stevenson, 1963) indicates that the load pressure at the time of intrusion did not exceed about 3 kb and thus the possible sedimentary cover could not have been much greater than about 10 km. The preserved cover over the Irruptive (Onaping, Onwatin, and Chelmsford formations) is about 6000 ft (1.8 km). However, the Chelmsford formation represents an episode of renewed deposition after the Onwatin (Burrows and Rickaby, 1929; Thomson, 1956) and it is not definitely known whether it was deposited before, during, or after emplacement of the Irruptive.

Available geochronology (Faure et al., 1964; Fairbairn et al., 1968) suggests that the Irruptive was intruded soon after the deposition of the Whitewater series, with an interval less than 100 m.y. Such a period would be sufficient for the deposition of a large quantity of clastic sediment in the basin, so that it is possible that the Irruptive was intruded into the contact between the basement rocks and the Onaping formation at a time when the Onaping was completely lithified and was covered by as much as several kilometers of younger sediments.

4. PROPOSED GEOLOGICAL HISTORY OF THE SUDBURY STRUCTURE

A. Geological Considerations

The Sudbury structure is presently unique, since it combines evidence of a large meteorite impact with undoubtedly internal igneous activity. Any analysis of the history of the Sudbury structure must be speculative, partly because of the absence of comparable structures, and partly because of serious gaps in our information about Sudbury itself.

The recognition of shock-metamorphic features at Sudbury strongly suggests that the initial event in the Sudbury history was the impact of an asteroidal body about 2 b.y. ago. However, this new view of the impact origin of Sudbury, while accounting for the intense structural deformation (Speers, 1957; Dietz, 1964), leaves a number of apparent paradoxes for resolution:

(1) First and foremost, the structure outlined by the Nickel Irruptive is not circular, as would be expected for a meteorite impact crater. Much of the eccentric shape of the Sudbury basin reflects compression from the southeast during the "Grenville Event", but the sharp bends in the contact, particularly at the northeast corner of the basin, suggest that part of the Irruptive may not have followed the original floor and rim of a large impact crater.

(2) The Onaping formation represents part of the original ejecta that filled the impact crater. Such units are deposited near the surface and are extremely thin in comparison to the crater diameter (Dence, 1965) (Figure 1). In a

30-mile-diameter crater, such a unit would be expected to be less than about a mile thick. Estimates for the amount of erosion at Sudbury since formation of the structure range from a minimum value of about 3 mi. (8 km) (Souch et al., in press) to 6-10 mi. (10-16 km). Under normal circumstances, such erosion would be sufficient to completely remove the original crater fill, and some special mechanism is required to explain the preservation of the Onaping formation and the rest of the Whitewater series within the basin.

(3) Despite the apparent preservation of a nearly complete section of fall-back breccia (Onaping formation), no unit comparable to the layer of impact melt observed in other large impact structures (Dence, 1965, 1968) has been recognized at Sudbury.

Speers (1957) pointed out that the Sudbury basin itself lies on a larger structural dome surrounded by a roughly circular peripheral depression, about 60 miles in diameter. The depression is presently indicated by the existence of patchy Huronian sediments to the west, north, and east of the structure. Dence (personal communication, 1968) suggested that this peripheral trough could be an integral part of a much larger impact structure about 60-75 mi (100 km) in diameter and that the present Sudbury basin corresponds approximately to the location of the central uplift of the crater. Thus, there would be no requirement that the present outcrop belt of the Irruptive be parallel to the originally circular crater rim.

This interpretation of the original Sudbury structure allows the development of a history which is consistent with the known geology and which also explains the paradoxes mentioned above. In this model, formation of the Sudbury structure begins with a large meteorite impact crater and involves subsequent subsidence of the central part of the crater and intrusion of the Irruptive to form the present Sudbury basin (Figure 9). In this view, the Sudbury structure is a combination of two types of structure, each with several known examples. Large meteorite craters in the 50-100-km diameter range with central uplifts have been identified, the best examples being Vredefort (Daly, 1947; Hargraves, 1961; Dietz, 1961), Clearwater Lakes, and Manicouagan (Dence, 1965). Similarly, there are numerous igneous structures of the "cauldron subsidence" or "ring-dike subsidence" type, in which subsidence of a central block is accompanied by extrusion of magma.

B. Stages in the development of the Sudbury structure

This proposed history of the Sudbury structure can be subdivided as follows:

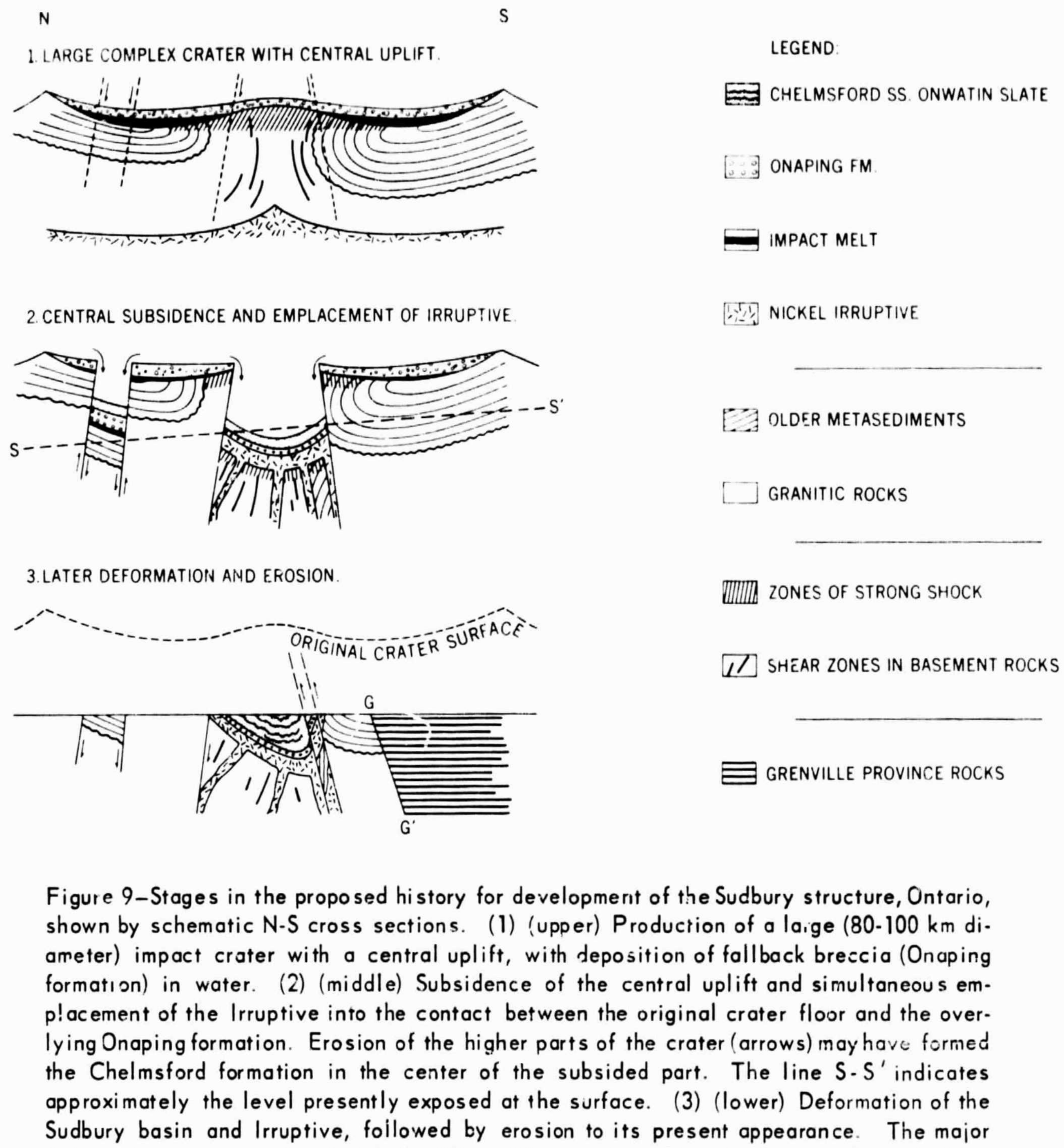


Figure 9—Stages in the proposed history for development of the Sudbury structure, Ontario, shown by schematic N-S cross sections. (1) (upper) Production of a large (80-100 km diameter) impact crater with a central uplift, with deposition of fallback breccia (Onaping formation) in water. (2) (middle) Subsidence of the central uplift and simultaneous emplacement of the Irruptive into the contact between the original crater floor and the overlying Onaping formation. Erosion of the higher parts of the crater (arrows) may have formed the Chelmsford formation in the center of the subsided part. The line S-S' indicates approximately the level presently exposed at the surface. (3) (lower) Deformation of the Sudbury basin and Irruptive, followed by erosion to its present appearance. The major deformation was associated with the "Grenville event" and involved strong thrust faulting from the southeast. The line G-G' represents the Grenville Front to the south of the Sudbury structure.

(1) Large impact crater with a central uplift. The original Sudbury crater is believed to have been about 100 km in diameter. It was formed about two billion years ago by the impact of an asteroidal body about 4 km in diameter. The amount of energy released, estimated from Baldwin's equation (1963, p. 176) is 2×10^{30} erg (about 5×10^{7} megatons). (For comparison, the annual energy loss from the earth by heat flow, volcanism, and earthquakes, is about 10^{28} erg). The crater developed in basement granites and gneisses on the north side and in Huronian metasediments on the south. A central uplift about 40 km in diameter was formed, together with a peripheral trough depression containing downfaulted Huronian sediments that is still recognizable to the northwest and northeast of the present Sudbury basin. At this stage, the Sudbury structure would have been generally similar to Vredefort.

The upper part of the Onaping formation is transitional into clearly subaqueous sediments, and some petrographic evidence suggests that most if not all of the Onaping formation may have been deposited in water (Stevenson, 1960, 1963). These data suggest the possibility that the original impact site could have been covered with as much as several thousand feet of water. Such a cover would not affect formation of the crater in the underlying rocks, but subsequent deposition of ejecta would occur in a tremendously agitated subaqueous environment (Enever, 1966). It is possible that some of the unusual characteristics of the Onaping, such as its extremely poor sorting and the absence of a discrete impact melt layer, resulted from deposition in agitated water. Such a proposal would fit the interpretation that the original site of the Sudbury structure was on or near the continental shelf (Dietz, 1964, p. 432).

The relatively large amount of organic material in the Onaping formation may represent a contribution from unconsolidated sediments involved in the impact, or it may have been introduced during deposition in a restricted basin formed by the crater. It has been suggested (Hochstim, 1965) that interaction between the shock wave and water could produce organic material as a direct result of impact. At present, the Onaping formation is the only known possible example of such a process.

The direct products of the original impact event include shatter cones, Sudbury-type breccias, the Onaping formation, and the reworked material from it which constitutes the Onwatin "slate." If the impact and deposition did occur under water, the poor sorting and uniform decrease of grain size of the Onaping upwards would be explained. The fallback deposits would be thinnest over the central uplift and would be thickest in the depressed annulus surrounding it (see Figure 1). Much of the fallback material would have been swept outward from the crater by the strong currents existing immediately after impact and deposited beyond the original crater rim.

The central uplift would contain numerous shock effects (Dence, 1968), including shatter cones and Sudbury-type breccias. As deposition proceeded after impact, the uplift was covered by a relatively thin layer composed of fallback material and fragments of an original melt layer broken up and redeposited by the intense current action. As the current intensity decreased, the grain size of the Onaping formation decreased upward, and in its upper part, definite bedding developed. Finally, under quiet-water conditions, reworking and redeposition of fine material from the upper Onaping formation, combined with deposition of the finest ejecta, would produce the Onwatin "slate."

(2) Subsidence of the central uplift: The production of central uplifts in large impact craters (Dence, 1968) requires substantial and rapid inward and upward movement of the rocks beneath the crater floor. The intensity of this movement produces zones of intensely crushed, sheared, and frictionally melted rock (pseudotachylite). These zones of potential weakness could localize further movement under stress. After formation, the central uplift of the original Sudbury crater contained numerous such zones, generally consisting of surfaces dipping steeply outward from the central uplift (Dence, 1968).

The crucial step in the development of the Sudbury structure requires subsidence of the greater part of the original central uplift along these zones of weakness at some time after deposition of the Onaping and Onwatin formations. Such subsidence could result from isostatic disequilibrium of the raised central uplift and existence of weak zones of pseudotachylite, if the rock beneath the crater was not rigid enough to support the central uplift.

The development of the Sudbury structure beyond the stage of a large impact crater apparently involves special conditions in the rocks at depth below the structure. Such subsidence and related igneous activity have not apparently occurred in the similar Vredefort structure. Two mechanisms for producing such subsidence and magma generation are possible:

(a) The impact occurred on a thin continental crust and completely excavated it, exposing more plastic zones of potential magma generation in the upper mantle. The original depth of the Sudbury crater before the rapid development of the central uplift may have been as much as 1/5 the diameter, or 10-15 miles, ample to penetrate any but a thick continental crust.

(b) The impact occurred on a thick continental crust. The crust was not completely penetrated, but the unloading and zones of weakness produced by excavation were sufficient to remove support for the central uplift and to promote the generation of magma beneath the crater.

The subsidence of the central uplift would begin an episode of renewed deposition in the basin, as materials from the crater rim and the more stable parts of the uplift itself were swept into the newly-formed depression (Figure 9). This process may have produced the Chelmsford graywacke beds which overlie the Onwatin and which represent a sharp break in the depositional history. The possibility that the deposition of the Chelmsford may have occurred during subsidence of the central uplift and before emplacement of the Irruptive makes this formation of great interest for further studies.

(3) Emplacement of the Irruptive. At the end of the second stage, the central uplift of the original Sudbury crater had begun subsidence along vertical to steeply outward-dipping surfaces. As subsidence continued, the subsiding part of the central uplift would have been subjected to horizontal tension, producing normal faults within the subsiding block and converting the contact between the central block and the overlying Onaping formation into a generally convex-downward surface.

As this subsidence continued, magma produced at depth ascended along the fractures and spread out along the contact between the basement rocks and the Onaping formation. It is not known whether the present norite and micropegmatite have resulted from differentiation in place or from multiple intrusions. It has also been suggested (Stevenson and Colgrove, 1968) that the micropegmative was produced largely by assimilation of brecciated basement rocks by the norite. Such a process would be likely if the norite itself was emplaced as a superheated magma at the contact between fallback breccia and brecciated basement rocks below. In any case, emplacement of the Irruptive was a relatively rapid process. Precipitation of sulfides (which are believed to be entirely internal in origin) began before or at the time of intrusion and continued during the early part of emplacement.

During emplacement, the presently-preserved portion of the Irruptive was roofed by as much as 3-6 km of sediments (Onaping, Onwatin, and Chelmsford formations) (Figure 9). The ascending magma could have broken through this roof to the surface, forming extrusive rocks of the same age as the Irruptive, but any such rocks have been removed by erosion. As intrusion continued, withdrawal of magma from below the central uplift would accelerate subsidence until some sort of stability was reached.

(4) Metamorphism and Later Deformation. After solidification of the Irruptive, the Sudbury area was affected by at least two major metamorphic episodes. One, at about 1.6 b.y., was largely thermal (Card, 1964, 1967, 1969) and its effects on the Irruptive are not clear. Major deformation in the second "Grenville" event involved compression from the southeast and produced

numerous northeast-trending thrust faults. Northwest-trending diabase dikes were also intruded at about this time. The chief effect of this deformation was to raise the South Range 2-3 miles (3-8 km) vertically relative to the North Range and to produce considerable shearing and recrystallization in both the Irruptive and the Onaping formation along the South Range (Stevenson and Colgrove, 1968; Souch et al., in press).

Subsequent erosion to the present time has removed at least two and perhaps as much as 6-10 miles (10-16 km) of cover from the Sudbury area. This erosion has removed all trace of the original Sudbury crater except for the remnant of the central uplift surrounding the Irruptive and the peripheral depression which surrounds it (Speers, 1957). Except for the preserved section of Onaping formation which was downdropped during subsidence of the central uplift, all ejecta from the original crater and any extrusive equivalents to the Irruptive have been eroded away.

C. Discussion. The history outlined here is speculative, and the available geological information permits alternate histories for the time after the original meteorite impact. For instance, it is possible the original impact unroofed deep zones of magma generation, and that the emplacement of the norite magma into the crater was the counterpart of the process that would have developed a central uplift on a thicker, cooler crust. This possibility cannot be evaluated until some limits can be placed on the time interval between impact and emplacement of the Irruptive.

The theory discussed above has the advantage of combining processes observed in other structures, i.e., large meteorite craters and igneous subsidence structures. Except for initiation of the Sudbury structure by a large meteorite impact, the theory is similar to others proposed to explain the origin of the Irruptive, most notably that of Knight (1917, 1923) who regarded it as a ring-dike structure.

This theory does not contradict any known geological information. As long as the subsurface shape of the irruptive and the location of its feeder channels remain unspecified, no theory of its origin can be proven. This theory would imply that the Irruptive should be underlain at depth by shocked and fractured granitic rocks or metasediments (Figure 9). Much more study by geophysical methods (gravity, paleomagnetics, etc.) will be required to resolve the question.

This theory does explain the paradoxes mentioned above. Since the fractures along which subsidence of the central uplift occurred were probably not exactly concentric to the crater rim, there is no need for the Irruptive outcrop pattern to have been exactly circular, even before the distortion produced by later metamorphism. Secondly, the preservation of the originally near-surface

Onaping formation is explained by the subsidence of the central uplift. A consequence of this theory is that the presently-preserved volume of Onaping formation represents a small fraction (perhaps 5-10 percent) of the original ejecta.

Except in its initial events, the theory outlined here is comparable to conventional igneous theories proposed by other workers. Such conventional theories have also been hampered by the unusual characteristics of the Sudbury structure, about which there has been relatively little agreement. In addition to explaining the post-impact history of Sudbury, this proposed origin involving an original meteorite crater larger than the present basin explains two other major problems of Sudbury geology: (1) the occurrence of a subsidence igneous structure on a large structural dome (Speers, 1957); (2) the occurrence of shock-metamorphic features in both the Onaping formation and in the footwall rocks around the Irruptive (French, 1967, 1968b, 1969). Further evaluation of this theory will require additional geological and geophysical work, but the recognition of a meteorite impact in the history of Sudbury may be the first necessary step toward evolving a complete and consistent theory for its formation and evolution.

5. GENERAL CHARACTERISTICS OF SUDBURY-TYPE STRUCTURES PRODUCED BY METEORITE IMPACT

A. Magma Generation by Meteorite Impact

It seems likely that the Sudbury structure, at present the only example of internal igneous activity generated and localized by a large meteorite impact, is by no means unique. Considering the potential for large meteorite impacts on all the larger bodies of the solar systems, it is probable that structures of similar origin will be found, not only on the earth, but on the moon and other planets as well.

The idea of igneous activity localized by large meteorite impacts is by no means new. It has been proposed chiefly to explain the formation of lunar maria (Baldwin, 1949, 1963; McCauley, 1967; Mackin, 1969), but it has also been suggested as a process important in the early history of the earth (Donn et al, 1965; Ronca, 1966; Salisbury and Ronca, 1966). Several mechanisms have been suggested by which large meteorite impacts on the surface of a planetary body could influence the generation and emplacement of magma (Carr, 1964; Dietz, 1964; Ronca, 1966):

(1) Direct removal of overlying thin crust to expose zones of active magma generation.

(2) Partial fusion of material upon release of lithostatic pressure caused by removal of material (off-loading). Such a process will not be significant unless the underlying material is already near its melting point (Carr, 1964; Ronca, 1966). However, under such conditions, superheating will result from the lowering of the melting point as a result of suddenly decreased pressure. Ideally, such superheat would be sufficient to melt a significant fraction of the underlying material, but to be effective, such a process requires an anomalously high thermal gradient beneath the crater at the time of impact.

(3) Production of a high thermal gradient after impact. Such a gradient, developed by insulation of the ambient heat flow by the breccia lens within the crater (Carr, 1964; Ronca, 1966; Mackin, 1969), might become high enough to induce melting.

(4) Development of channels for ascending magma by fracturing of rock beneath the crater. This process, combined with melting produced by release of overburden over a zone of active magma generation, is probably most effective in localizing emplacement of magma within and near the crater itself. Such fracturing would extend to a depth of between 1/4 to 1/2 crater diameter (Innes, 1961; Beals, et al., 1963; Dietz, 1964) and would provide a path of ascent for magma present below this depth.

The most favorable conditions for the production of such compound impact-igneous structures appear to involve the impact of large meteorites on areas of the earth characterized by high thermal gradients or by active magma generation at depth. Under these conditions, the development of rock fracturing at depth by the impact, combined with melting produced by removal of overburden and release of lithostatic pressure, would promote the migration of magma upwards toward the crater. The fractured rock beneath the crater would provide a natural path of ascent. On reaching the level of the crater, magma would tend to intrude preferentially along the unconformable contact between the shocked and brecciated basement rocks constituting the crater floor and the overlying lens of fallback breccia.

B. Possible Types of Impact-Induced Igneous Structures

It is obvious that, by combining the direct near-surface generation of igneous impact melt with the subsequent introduction of magma from below a variety of apparently internal igneous structures will be produced, some of which may show little or no trace of their impact origin. A range of igneous rock types may be developed, including: (1) isolated fragments and crystalline breccia matrices composed of impact melt; (2) an impact melt layer resembling a small sill, which marks the approximate limit of original meteorite penetration;

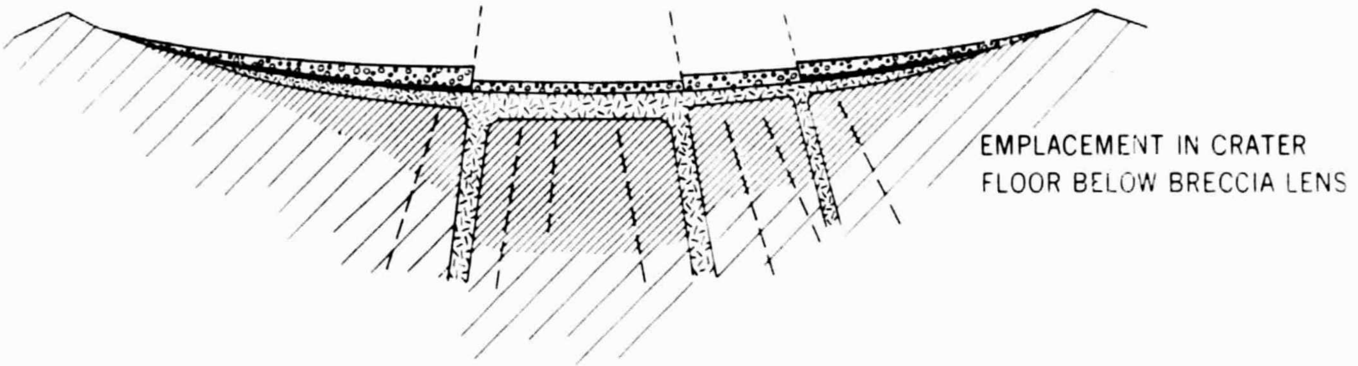
(3) internally-derived intrusive units appearing as large younger sills or lopoliths; (4) internally-derived extrusive rocks produced at the same time by penetration of the magma through the crater fill and onto the surface. Only the first type of rock will show widespread shock-metamorphic features by which its impact origin can be immediately recognized.

Possible structures displaying this diverse suite of igneous rocks are: (1) simple craters, with or without a discrete layer of impact melt (Figure 1); (2) complex craters which will generally exhibit an annular impact melt layer around the original central uplift (Figure 1): (3) complex craters in which internally-derived magma has been emplaced, either by subsidence of an original central uplift or by immediate introduction of deep magma into the crater as part of the impact process itself (Figure 10).

Two variants of the third type of structure may be distinguished (Figure 10), depending on whether the intruded magma is contained below the crater fill or breaks through onto the surface to form extrusive flow units or pyroclastic tuffs that are correlative with the intruded rocks below.

The recognition of the impact history of an igneous structure and its classification will be strongly influenced by the amount of erosion. In the structures shown in Figure 10, it is clear that relatively minor erosion would remove all evidence for the existence of any extrusive units, leaving in doubt the original character of the structure. Such a situation is, in fact, the case at Sudbury. Deeper erosion would transform the surface appearance of the same structure from that of a lopolith or sill into that of a ring-dike. Because meteorite impacts are relatively shallow structures, extensive erosion may remove all trace of the distinctively shocked rocks that are the key to recognizing the presence of an impact (Beals, et al., 1963; Beals and Halliday, 1965). It is possible that there exist on the earth impact-produced igneous structures in which no shocked rocks remain, and distinguishing such impact-localized magma from that produced under normal geological processes will be a difficult future problem for igneous petrologists.

The complexities involved in such impact-produced igneous structures and the difficulties involved in their recognition can be illustrated by an arbitary stratigraphic column (Figure 11) through the more complex structure shown in the lower part of Figure 10. The variety of extrusive and intrusive igneous rocks and related sediments present would indicate an early phase of explosive activity followed by intrusion of the thick igneous body ("main sill"). It is possible to interpret such an assemblage of rocks in terms of both a conventional igneous history and in terms of an igneous history initiated by meteorite impact, but the distinctive petrographic and structural effects of meteorite impact would be



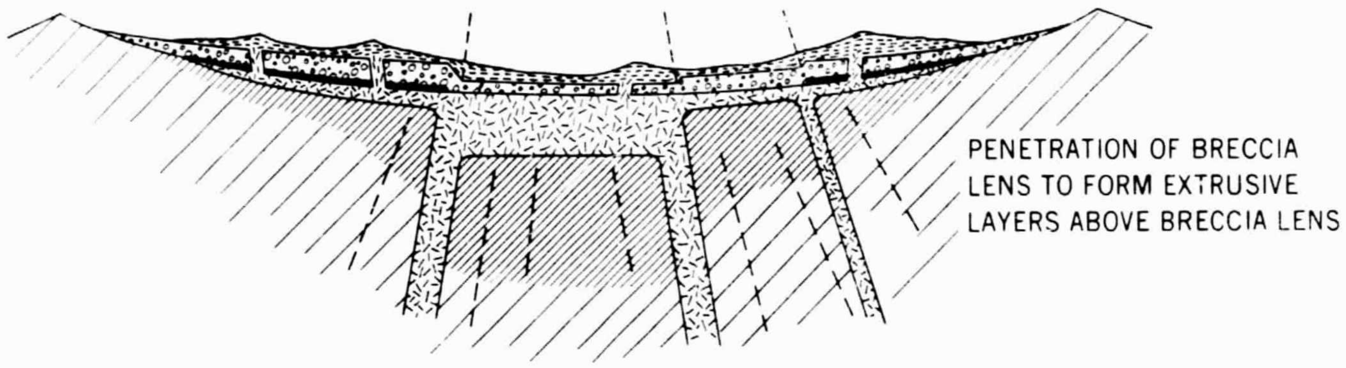
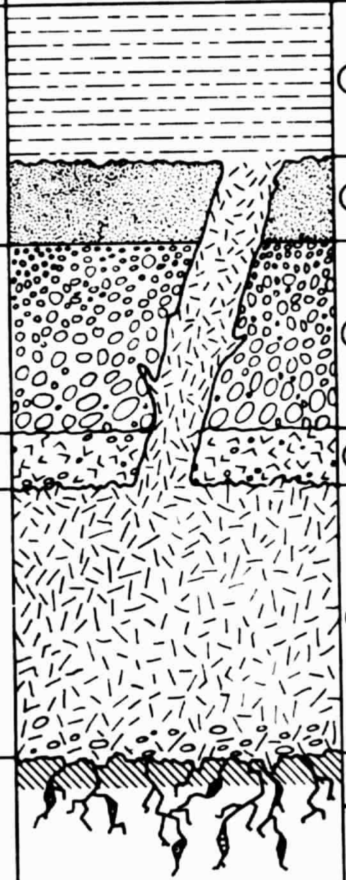


Figure 10—Schematic cross sections of structures formed by emplacement of internally derived magma into large impact craters, according to the mechanism of central subsidence proposed for the Sudbury structure. In both cases, the magma intrudes preferentially along the contact between the original crater floor and the breccia lens. The lower figure indicates possible formation of extrusive units by penetration of the magma through the breccia lens although such units may be removed by later erosion. Note that both these structures would appear either as flat lopoliths or as ring-dikes, depending on the level of erosion. Lithologic symbols are the same as those in Figure 1.



VOLCANIC INTERPRETATION	ROCK UNITS	IMPACT INTERPRETATION	SUDBURY EQUIVALENT
FLOWS, FLOW BRECCIAS, AND ASSOCIATED SEDIMENTS	①	**FLOWS, FLOW BRECCIAS, AND DIKES** EMPLACED IN OR ABOVE CRATER FILL.	NONE OR ERODED
	②	**SEDIMENTARY CRATER FILL** ABOVE BRECCIA LENS.	**CHELMSFORD** SANDSTONE **ONWATIN** SLATE
VOLCANIC AGGLOMERATES AND TUFF-BRECCIAS WITH NUMEROUS GLASSY BODIES AND BASEMENT ROCK INCLUSIONS (EARLY EXPLOSIVE PHASE)	③	**BRECCIA LENS IN CRATER** ACCUMULATION OF "FALLBACK" BRECCIA SHOCKED BASEMENT ROCK INCLUSIONS SHOCK-MELTED ROCK FRAGMENTS	**ONAPING** FORMATION BASAL "QUARTZITE BRECCIA" - ? - - - - ? - - - - ? - - - - ? - -
FELSITE OR TRACHYANDESITE SILL ASSOCIATED WITH VOLCANIC BRECCIAS	④	**IMPACT MELT LAYER** APPROXIMATE LEVEL OF ORIGINAL METEORITE PENETRATION.	NOT RECOGNIZED
LOPOLITH OR MAIN SILL INCLUDING ASSOCIATED DIKES (LATER INTRUSIVE PHASE BETWEEN VOLCANIC BRECCIAS AND BASEMENT ROCKS) MAY BE STRATIFIED OR DIFFERENTIATED BRECCIA ZONE AT LOWER CONTACT	⑤	**LOPOLITH OR MAIN SILL** EMPLACED FROM BELOW AT CONTACT BETWEEN ORIGINAL CRATER FLOOR AND BRECCIA LENS POSSIBLE DIFFERENTIATION IN PLACE SINGLE OR MULTIPLE INTRUSIONS	**NICKEL IRRUPTIVE:** MICROPEGMATITE TRANSITION ZONE NORITE BASAL BRECCIA UNIT
FRACTURED AND BRECCIATED BASEMENT ROCKS (DEFORMATION DURING EARLY EXPLOSIVE PHASE)	⑥	**STRONGLY SHOCKED BASEMENT ROCKS** – WIDESPREAD PETROGRAPHIC INDICATORS	ABSENT OR CONTACT-METAMORPHASED
	⑦	**WEAKLY SHOCKED AND FRACTURED BASEMENT ROCKS** SPORADIC PETROGRAPHIC INDICATORS TENSIONAL AND INTRUSIVE BRECCIAS SHATTER CONES.	**FOOTWALL ROCKS** SUDBURY BRECCIAS

Figure 11—Theoretical stratigraphic section through a structure formed by emplacement of internally derived magma in a large meteorite impact crater. A structure similar to that shown in the lower part of Figure 10 is assumed, in which extrusive rocks have been deposited above the breccia lens by penetration of dikes of magma through the breccia lens. The series of rocks produced is complex and can be interpreted as either a conventional volcanic structure (left column) or an impact structure (right column). In searching for evidence of meteorite impact in structures hitherto regarded as volcanic, note that only the breccia lens (unit 3) and the shocked basement rocks (units 6 and 7) can be expected to show distinctive shock effects. The column at the far right correlates this section with the rocks observed at the Sudbury structure.

found at only a few specific horizons in the structure, chiefly as shock features produced in inclusions of basement rock in the breccias and in the basement rocks at the base of the structure.

The recognition of terrestrial structures similar in origin to Sudbury will chiefly depend on the discovery of shock-metamorphic features in rocks of presently known structures hitherto regarded as completely internal in origin. Such possible structures are characterized by an association of intrusive igneous rocks and apparently pyroclastic flows or volcanic breccias. Two types may be distinguished:

(1) Relatively wide and shallow bodies of intrusive rock, often layered, apparently covered by their own extrusive equivalents ("roofed lopoliths"). The Sudbury structure has hitherto been regarded (Wilson, 1956) as such a structure, and it has often been compared with the Bushveld structure, the Wichita complex, the Duluth gabbro complex, and others (Wilson, 1956; Hamilton, 1960a, 1960b). Many of these structures may be completely unrelated to impact or may no longer show traces of impact origin. However, the ability of a large meteorite impact to suddenly remove great thicknesses of crust over large areas indicates that its part in the generation of such structures should be carefully considered. Even the Skaergaard structure, considered a type example for gravitative settling of internally-derived magma, appears to have been emplaced in a short episode involving the sudden removal of several kilometers of overlying crustal rocks, and it has been compared to the Ries crater in Germany (Wager and Brown, 1967, pp. 20-21, 204-206).

(2) Ring-dikes and cauldron subsidences. The structures shown in Figure 10, could, after relatively deep erosion, appear as ring-dikes around a centrally subsided block. Numerous structures of this type, in which the ring-dikes are associated with volcanic breccias and apparently extrusive rocks and with structural deformation in the basement rocks, are known from the British Tertiary Province (Richey, 1961; Taubeneck, 1967), from the White Mountain series of New Hampshire (Noble and Billings, 1967), and from other areas.

Some of the structures in both these groups may, on future detailed examination, exhibit distinctive shock-metamorphic effects, indicating that they, like the Sudbury structure, have been initiated by large meteorite impacts. Definite evidence for such conclusions will tend to be concentrated in two units: (1) in the "volcanic breccias," as inclusions of melted basement rock without phenocrysts (Fladen), cored inclusions, and inclusions of basement rock exhibiting petrographic shock effects; (2) in the basement rocks in which the structures are emplaced, as such features as Sudbury-type breccias, shatter cones, and petrographic effects of weaker shock metamorphism, if these have not been destroyed by contact-metamorphism produced by the later igneous activity. In most of these structures, the units of supposedly extrusive volcanic tuffs and breccias are the most likely and rewarding place to search for shock-metamorphic effects.

The recognition of this class of compound igneous structures, in which internal igneous activity is superimposed on a large meteorite crater, has considerable importance in the increasing discussions of lunar geology which have developed over the past few years as a result of the information obtained by both manned and unmanned space missions. The existence of at least some large meteorite impacts on the moon is generally accepted, and the theory that many lunar features are the result of impact-triggered volcanism (Baldwin, 1949, 1963; Carr, 1964; McCauley, 1967; Mackin, 1969) may go a long way towards resolving the present controvery over the impact-or-igneous origin of large lunar craters. The crater Tsiolkovsky (Figure 12) (Lowman, 1969, p. 48-49), with its generally circular shape, slump terracing, central uplift, and filling of dark material may prove to be a prototype for such a process acting on the moon. The demonstration that impact can produce volcanism on the lunar surface will have considerable implications for the nature and history of the lunar interior as well, and it may be possible to infer more about the lunar interior by examining the origin of some of its surface features that it will be possible to learn by direct geophysical measurement for some time to come.

6. CONCLUSIONS

Within the past few years, a number of different and seemingly unrelated areas of research have provided a strong body of evidence to indicate the importance of meteorite impact as a geological process. Geological applications of experimental results on the shock metamorphism of natural materials have indicated that at least 50 "cryptoexplosion" structures, many of which have been the subject of long geological controversy, have originated through the impact of large meteorites. In one of these structures, Sudbury, Ontario, an association between large meteorite impact and internally-generated magma and ore deposits has been demonstrated, raising the possibility that many other "igneous" structures owe their initial development to similar impacts, and requiring consideration of the possible relations between meteorite impact and igneous petrogenesis.

The production of igneous rocks by meteorite impact can occur in two ways:

(1) Direct melting of the target rock by meteorite impact. In large craters, this process alone can produce as much as several hundred cubic kilometers

Figure 12–APOLLO 8 photograph of the crater Tsiolkovski, about 250 km in diameter, one of the few isolated areas of mare material on the far side of the moon. This circular structure, with the central uplift and widespread peripheral slumping, is partially floored by dark material which may represent internally-derived magma. Tsiolkovski is one example of a lunar structure which may have formed by a process of combined meteorite impact and volcanism analogous to that which formed the Sudbury structure

of melt, which is usually emplaced in and around the original crater as: (a) isolated melt fragments in the breccia lens; (b) recrystallized melt matrix of breccias consisting of shock-metamorphosed target rock; (c) discrete layers of impact melt which resemble sills and which are believed to mark the approximate depth of original meteorite penetration.

(2) Indirect production or channeling of internally-derived magma. Several effects of large meteorite impacts may promote magma generation and emplacement within the original crater: (a) production of anomalous near-surface heating as a result of the insulating effect of the breccia lens; (b) production of melting by sudden pressure release above a region of magma generation; (c) production of paths of ascent for subsurface magma by rock fracturing and by the presence of a natural unconformity between the base of the crater and the breccia lens. The last two effects appear to be most important, and the introduction of internal magma into a large crater will be most likely if the impact occurs on a area exhibiting an unusually high geothermal gradient or active magma generation at depth at the time of impact.

The sudden unroofing and excavation of material produced by a large meteorite impact could be equally effective in initiating geological processes not involving magma generation. Such a sudden release of lithostatic pressure could be effective, for instance, in initiating the rise of salt domes or of diatremes.

Future studies of the relationships between large meteorite impacts and igneous structures will involve several problems:

(1) Detection of other igneous structures related to meteorite impact. The existence of shock-metamorphic effects in rocks and minerals as unique indicators of ancient meteorite impacts provides present means by which the impact origin of other igneous structures hitherto regarded as internal in origin can be recognized. New studies of igneous structures in which lopolithic bodies or ring dikes are associated with supposedly extrusive rocks should be undertaken to detect shock-metamorphic features in the associated breccias or in the basement rocks in which the structures occur. The Sudbury structure is broadly similar to so many other igneous structures that it seems unlikely that its impact origin is unique.

(2) Geophysical effects of meteorite impacts. An extraterrestrial process which can release on the surface of the earth in a few minutes, a hundred or a thousand times more energy than the earth itself releases in a year, can be expected to have geophysical effects beyond the simple formation of a crater. One such effect, the localization of internally-generated magma, seems well

established in the case of the Sudbury structure. Other such effects, such as the growth of continental nuclei through meteorite impact (Donn et al., 1965; Salisbury and Ronca, 1966) need to be considered in more detail, now that the case for the occurence of large meteorite impacts on the earth has been satisfactorily established.

(3) Distinction between ordinary and impact-induced magmas. Deep erosion of an impact-produced igneous structure will remove all traces of shock metamorphism produced by the impact event. Any recognition of the impact origin of such a structure will have to be based on a study of the internally-derived igneous rocks themselves. The conditions of production and emplacement of magma as a result of meteorite impact will involve sudden unloading and pressure drops, superheated and perhaps disequilibrium melting, and rapid migration and emplacement. Such conditions might produce a magma of distinctively unusual composition or character which would itself indicate a meteorite impact origin. It should be remembered that the unusual character of the Sudbury Irruptive in comparison with other lopolithic bodies was commented upon long before the impact origin of the Sudbury structure itself was seriously considered.

The new importance of meteorite impact in geology is only one example of the changes that have been produced as geology has broadened and swung outward to become astrogeology or planetology. It is likely that past or present extraterrestrial agencies will be found to have the same importance in other areas of geology as they have been shown to have in structural geology and igneous petrogenesis. One might speak of the geological effects of meteorite impact as the "New Catastrophism," by which large complicated geological structures can be produced in a few minutes by a mechanism which, although it seems catastrophic on the large scale, is possibly more Uniformitarian than many terrestrial processes (French, 1968a, p. 7-8).

It remains to be seen whether the catastrophic effects of large meteorite impacts have importance for the earth beyond the production of individual and unrelated structures. It has been suggested that certain unusual igneous changes, apparently restricted to certain times, such as the "anorthosite event" (Herz, 1969) may have been related to extraterrestrial processes such as large meteorite impacts or to the proposed earth-moon separation. The resolation of such questions is still far in the future, but it is reasonable to believe that we have only begun to realize how much of the earth's history remains to be discovered by considering its relations with the rest of the solar system of which it has been so long a member.

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