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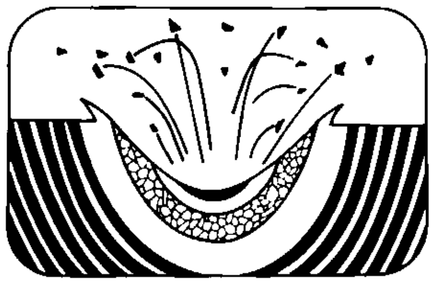

The Meteoritical Society at Sudbury, 1978

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The Meteoritical Society had its inception in the 1930s with a small but enthusiastic group of American "meteoriticists", most of whom were astronomers or geoscientists, and others simply amateurs interested in the discovery, collection and preservation of meteorites. The Society has greatly expanded, particularly since the birth of the space age in the 1960s, to a major international group whose interests still range from the recovery of meteorites, through every facet of analysis lending evidence to their origin and the evolution of the solar system, to entry phenomena and the formation of hypervelocity impact craters on the earth and other planets. The increasingly international aspect of the Society is reflected in the alternating venues of the annual meetings since 1970 between North America and Europe.

The 41st annual meeting of the Meteoritical Society was held at Laurentian University, Sudbury from August 14 to 17, 1978. This meeting, the second of the Society in Canada, was co-sponsored by the University and by the National Research Council of Canada. Whereas many of the previous meeting sites were chosen for their association with an institute or university closely connected with research related to the topics, or for the scenic and touristic attractions of the region, Sudbury was selected for its location within what is considered by many as one of the largest ancient impact craters in the world. Coincidentally, the hypothesis that the Sudbury basin was a meteorite impact site was originally proposed by Dietz 15 years earlier, when the Society met at Ottawa. Although this hypothesis still raises controversy the topic was not discussed during the technical sessions. However, the two-day field trips traversing the Sudbury Basin, led by Ed Pattison (INCO) and Mike Dence (EMR), enabled those less familiar with the subject to examine and consider many of the salient points in developing their own opinions. The other field trip visited the Brent crater, in northern Algonquin Park, one of the smallest of recognised terrestrial impact sites. There is little to be seen at the surface here, compared to Sudbury, but the amount of data obtained from Brent through drilling and geophysical methods makes this one of the world's most thoroughly investigated simple craters.

The 171 papers presented in a series of two concurrent sessions reflected the balance of research in these fields, with a fair proportion of German, French, Indian, British, Japanese and Canadian speakers complementing the large American representation. The geochemists dealt with meteorites and parent bodies, the astronomers talked about meteors and orbits, the geologists expounded on impact craters and the physicists and mathematicians presented detailed models for a variety of structures and processes. A common ground for discussion was provided by Jim Arnold's (University of Califronia, San Diego) provocative and entertaining evening lecture sponsored by Falconbridge Nickel Mines Ltd., on "Near-Earth Resources", outlining the merits and feasibility of using the moon and asteroids in establishing nearby, extraterrestrial colonies. Arnold emphasized that the option is being seriously considered by those familiar with megascale funding and felt that, though ambitious, the venture would eventually be attempted because it is part of man's nature to accept these challenges.

Although certain aspects of meteoritics continue to be discussed, as in all disciplines the emphasis or direction constantly varies. Fewer papers were given concerning lunar materials at this meeting in comparison with those of recent years. However, the expertise developed through the Ranger and Apollo programs has now been readily adapted to the studies of meteorite samples and to remote bodies in the solar system. Petrography, chemistry and geochronology of meteorites still receive attention, emphasizing the direction towards an understanding of their source and evolution, rather than the simple cataloguing of descriptions of individual meteorites.

The extraordinarily rich and complex data from Allende and other carbonaceous chondrites was the subject of two sessions and was the main basis for a third focussed on early processes in the solar system. The latter was led by an invited address by Anders (Chicago) who reviewed the ancient noble gas components in chondrites in terms of a "normal" planetary component, a "fission" Xe component, which may come from a volatile superheavy element, and a new, apparently presolar component, which shows evidence of being from dust grains generated by nuclear reactions in red giant stars. Runcord (Newcastle) also argued in favour of superheavy elements in the early solar system by reasoning that a short-lived radioactivity was needed to give early melting of the moon and hence an early lunar magnetic field. Ballard and others (Missouri) contended that correlations between noble gas isotopes were best explained by the explosion of a single star, concentric with the sun, which went through a supernova stage, rather than by injection of anomalous material into the early solar system.

Details of solar nebula condensation processes were deduced by several groups from the mineralogy of Allende inclusions, and by others from the fractionation of siderophiles in iron meteorites. Allen and Grossman (Chicago) examined compositional zoning in several minerals from a hibonite-rich Allende inclusion and concluded that the heterogeneity present was evidence that different grains grew in gases of different pressure, temperature and/or composition before the grains amalgamated. Condensation of refractory metals from a nebula was considered by Blander and colleagues (Argonne National Laboratory) by comparing Allende inclusions rich in refractories with condensation calculations. In contrast to the generally favoured solid-gas or liquid-gas equilibrium models, their model seeks to explain many observations by a mechanism of silicates coating metal particles, allowing supersaturation of the nebula gas with respect to metal and local variations in composition.

Nebula processes were also evoked to explain elemental fractionations among iron meteorites. Scott (Cambridge) pointed out that abundancy - volatility plots for irons were markedly similar to those for common stony meteorites as predicted by Wai (Idaho) and Wasson (UCLA). The latter favoured a multicomponent model with significant ranges in grain size allowing a spread of equilibration temperatures and efficiencies of accretion. Condensation of oxide or silicate melts from nebula gases was examined by Wagner and Larimer (Arizona State) who argued that an oxide melt may achieve sufficient stability to be an initial condensate. They concluded that the bulk compositions of CaAℓ-rich inclusions follow the solid-gas condensation path but most chondrules follow gas-liquid condensation paths.

The nature and composition of chondrules, the distinctive spherical bodies in most stony meteorites, was the subject of a separate session. Keil and associates (New Mexico) presented many chemical data on both chondrules and their matrix, documenting the decrease in compositional variance with increasing degree of recrystallization. Several studies sought to determine whether chondrules showed evidence of independent existence in space before incorporation into meteorites. Wilkening and others (Arizona) were unable to discover unusual radiation features in chondrule rims or differences in composition between rims and interiors of chondrules. The New Mexico group also examined chondrule surfaces by SEM, noting fine dendrites as evidence for very rapid cooling but an absence of zap pits common on objects in the lunar regolith. Only low relative velocity impacts seem to have occurred between chondrules. The role of impact in the formation of chondrules continues to be debated.

Isotopic and chronologic studies were less strongly represented at Sudbury than at previous meetings of the Society, but a representative set of papers extending over one and one half sessions were given. Many were concerned with the determination of cosmic ray exposure ages, led by an assessment by Marti and Regnier (University of California, La Jolla) of ages obtained by ^{81}Kr-Kr methods, which they conclude are reliable, although in some cases they appear to disagree systematically with ages obtained by other methods. Results were given on the Innisfree, Alberta, meteorite by Hensser and colleagues (Heidelberg) and Goswami and colleagues (Ahmedabad, India). The results show good agreement with the reported pre-entry mass calculated from dynamic and photometric measurements (see below) but raise questions as to the galactic cosmic ray intensity which may be lower now than over the previous 500 years.

Meteorite ages were discussed by Allègre (Paris) in terms of ^{87}Rb-^{87}Sr systematics of L chondrites, basaltic achondrites and enstatite chondrites. He identified many departures from the reference "primitive isochron" defined by H chondrites. Disturbances possibly related to thermal events were also reported by the Heidelberg group continuing their effort to obtain I-Xe ages from a wide range of ordinary chondrites, and by Turner and colleagues (Sheffield) who reported on further ^{40}Ar-^{39}Ar studies of chondrites. Their objective was to test the idea of interpreting low temperature ^{40}Ar-^{39}Ar age plateaus in terms of recent reheating events.

Most of the meteorites which have been extensively investigated over the years, Allende and Shergotty for instance, receive attention because of their unique chemical or textural properties. Much of the recent limelight, however, has been focussed on a couple of meteorites which are relatively common chondrites. Innisfree, photographed by the Canadian MORP camera network before recovery 140 km east of Edmonton in 1977, and Lost City are, along with Pribram, the only "falls" which have been photographed in flight and then recovered. From aero-dynamic theory and the multi-station data on Innisfree and Lost City, Revelle (Carnegie Institute) calculated a pre-atmospheric mass of about 20 kg and about 60 kg, respectively, for these two bodies, indicating 70 per cent to 90 per cent mass loss by atmospheric ablation. The mass for Innisfree agrees within limits with the photometric analysis estimate of 50±20 kg by Halliday (NRCC), and the intersection of end-height versus ablation coefficient by McIntosh (NRCC) which gave 40±19 kg. Bhandari (Ahmedabad, India), from measurements of cosmic ray track densities in 160 meteorites to determine "shielding depths", found that mass ablation values range from 27 per cent to 99.9 per cent with a mean near 85 per cent. Ablation is a direct function of pre-atmospheric velocity so that Rajan (Carnegie Institute) calculated velocities from 12.4 to 16.5 km/sec for several of the meteorites in which cosmic ray tracks gave mass loss of from 41 per cent to 83 per cent respectively. Earlier estimates of pre-atmospheric mass were based on Öpik's luminous efficiency theory but there was no way of directly calibrating this method. The Carnegie group combined the Innisfree and Lost City photographic data with theoretical mass ablation values from the cosmic ray track method and concluded that photometric masses have been earlier over-estimated by a factor of five to 10.

Estimates of annual meteoritic influx for objects one kg or larger, have increased from about 500 in 1960, to perhaps double this number when the Prairie Network data became available. A figure of 200,000 was proposed by Huss (Meteorite Laboratory, Denver) extrapolated from a mean terrestrial residence age on samples of small meteorites accumulated in the soil of an arid region in Texas. This figure would be more comparable with earlier estimates if a similar minimum sample size were chosen and an older residence age assigned.

The subject of meteorite sources or parent bodies is approached from three directions: restrictions on their location in the solar system, remote sensing of asteroids and meteors to assess surface compositions, and analysis of the meteorites themselves to formulate evolutionary development. The Apollo and Amor objects with their earth-crossing or earth-grazing orbits are a likely meteorite source. They probably comprise extinct cometary nuclei as well as material from the asteroid belt, but it has been argued that the 300-500 m.y. shock metamorphism ages of many meteorites preclude a cometary source. Wetherill (Carnegie Institute) finds a steady-state equilibrium in the number of Apollo-Amor objects with about half replaced approximately every 25 m.y. from the Mars-crossing group. The latter have a median age closer to 200 m.y. so that collisional events of this age are to be expected regardless of whether they are cometary or asteroidal objects. The earth's atmosphere efficiently obscures the nucleus of periodic comets preventing effective earth-based studies. Wilkening (Arizona) spoke for members of a group who have recommended the development of a space probe to orbit and maneuver about a comet (Tempel 2 or Encke) for more direct measurement of cometary properties.

Gaffey and McFadden (Hawaii) are using visible and near-infrared reflective spectra to quantify mineral abundances in asteroids and comets. To this end they have calibrated a relationship between absorption band depth and relative abundance of equilibrium pyroxene-plagioclase assemblages using basaltic achondrites and lunar samples. So far their group has discovered unique surface assemblages on Ceres, Pallas, Phobos and Deimos which may be iron-poor analogues of C1-C2 chondritic material not represented in meteorite collections.

John Wood (Harvard-Smithsonian), who was this year's recipient of the Society's Leonard Medal, proposed a new and controversial model for meteorite parent bodies. Because many meteorites display very slow metallographic cooling rates they had been interpreted as originating at about 100 km depths in asteroidal bodies, i.e., in large parental bodies. This requires initial heating/melting and continuous slow cooling which is difficult to reconcile with their old ages. Small planets, 40 km diameter, could melt by ^{26}A1 decay, differentiate and rapidly cool through upper temperature ranges. Accreted particulate matter would in time, insulate the interior and internal cooling would diminish to the metallographic rates determined. However, the size of parent bodies can also be estimated from the FeS geobarometer. Hutchison and Scott (Toronto) derived equations relating temperature and pressure from FeS in sphalerite in equilibrium with troilite. Assuming an equilibrium temperature, pressures for type IA irons give burial depths of 75 to 380 km, and for enstatite chondrites, 0 to 200 km.

Evolution of parental body regoliths has been formulated from particle track studies Bagolia's (Ahmedabad) work on a C2 chondrite indicates a very thin regolith and slow mixing over five m.y., whereas Macdougall (Scripps), using C1 chondrites, deduced a quick burial in a rapidly accreting regolith. Housen and colleagues (Arizona) agree with the latter scenario based on the relative scarcity of impact glass, agglutinates, microcraters, solar gases and solar flare tracks in gas-rich meteorites. The rapid regolith build up results from crater ejecta blankets and will be most effective on small bodies where low surface gravity allows each impact to distribute material over the entire surface.

The theory that the moon was derived from the earth's mantle received support from Wänke and others (Max-Planck, Mainz), but not from all his audience. He interprets high Ni/Co ratios in highland breccias as due largely to indigenous rather than meteoritic Ni. The indigenous Ni from primary lunar material, Wänke takes as indicative of an early Ni/Co ratio comparable with that of the earth's mantle.

Several of the technical sessions were devoted to discussions of a wide range of physical and chemical properties of various meteorite classes (irons, achondrites, chondrites, carbonaceous chondrites). A common approach was by analysis for one or more trace elements to determine the evolutionary path of an individual meteorite but papers of this nature rarely developed and carried a particular theme beyond one or two presentations. A few studies outlined critical variations, not only between meteorites of the same class, but between pieces of the same meteorite fall, cautioning against the use of a single set of observations to formulate the character or history of a class of samples. Hewins (Rutgers) analyzed kamacite in the matrix, primary clasts and melt rocks of seven howardites (a relatively uncommon group) and found that large Ni/Co variations suggested quite different thermal histories and source materials. In particular, the equilibration of Ni and Co in the Petersburg howardite indicates deeper burial than for others in this group. The Bur-Ghelaui chondrite, represented by more than 100 individual specimens, provides a valuable source to assess heterogeneity within a meteorite. King and Maras (Houston) interpreted variation in olivine and orthopyroxene compositions as evidence that two portions equilibrated under slightly different conditions. The Kohar chondrite comprises several specimens; the one examined by Woolum and colleagues (California State, Fullerton) is particularly rich in Bi compared with its kin, and is believed to have equilibrated in a volatile-rich part of its parent body. Woolum's use of the particle track radiography method for determining distribution of trace elements confirmed for Bi, but contradicted for Pb, predictions that these elements would exhibit siderophilic behaviour.

The nature of mesosiderites, meteorites with various silicate rock clasts in a metal (Fe-FeS) matrix, was explained by Floran (Oak Ridge) as due to impact on a differentiated parent body with a stony-iron surface. A homogeneous impact melt engulfed shocked fragments and the melt split into two immiscible fractions (metal and silicate). Floran cited the variety of silicate fragments and the varying degrees of recrystallization and assimilation as evidence for this process. Additional evidence for shock metamorphism is provided by the Shergottites. Shergotty is the type specimen for eucrites with maskelynite (shock produced plagioclase glass). Martin and Barber (Essex) have now found maskelynite in smaller grains in the eucrites Zagami and Padvarninkai, along with intense fine-scale twinning in pyroxene, most likely also produced by shock.

A very early topic which has unexpectedly returned to prominence is the circumstances of discovery, recovery and classification of new meteorite finds. This is due to the recent, unparalleled discoveries by Japanese (Yanai, National Institute Polar Research, Tokyo) and American (Cassidy, Pittsburgh) teams of about 1300 meteorite fragments in Antarctica. The number of separate meteorites may be somewhat reduced from this as individual specimens may become recognized as pieces from the same fall, but it is nonetheless impressive when considered in terms of the world's previous total of less than 2300 meteorite falls and finds. The ratio of irons to stony meteorites in the Antarctica collections, about .01, is somewhat less than, but reasonably comparable with the ratio determined from recovered historic "falls". The Antarctic meteorite falls are distributed over the continental ice sheet. In places, the coastward-moving sheets are arrested by mountain ranges. Here, continuous sublimation and blue ice swept clear of snow exposes an everaccumulating collection of transported fragments. Canadian investigators are looking to the Arctic to determine whether similar conditions for accumulation exist. With the large number of samples there is the anticipation of discovering material previously not represented in meteorite collections. The primary value, however, stems from the preservation of these samples in a cold, clean, slow-weathering environment. As a consequence, from early results Kirsten and Ries (Max-Planck, Heidelberg) have found residence ages as old as 1.46±2.0 m.y., and this on a chrondrite, a type which rarely survives more than a few thousand years in other climates. The fate and treatment of the meteorites will rival that afforded the lunar samples, as NASA will use its lunar receiving facilities for their examination and storage under simulated Antarctic conditions and will act as the worldwide distribution agency.

Just as acceptance of the concept that meteorites are pieces of interplanetary material required many decades, it has taken a comparable length of time to convince the scientific community that very large meteorite craters, similar to those clearly visible on the moon, were formed and preserved in varying degrees on the earth. Ralph Baldwin (Oliver Machinery) was among the scientific pioneers in this field and in an address highlighting the Society's annual banquet, outlined the development of cratering and shock metamorphic studies over the past half-century.

There is no problem in recognizing the origin of circular craters containing meteorite fragments (there are 13 such sites, none in Canada), but the class of structures variously called "astroblemes", "cryptoexplosions craters" or "probable impact craters" still generates some controversy. These latter structures (78 worldwide) display the evidence for shock metamorphism found in authenticated meteorite bearing craters, but lack recognizable meteorite fragments. This is in part simply a matter of erosion, but in many cases the kinetic energy of impact was high enough to vapourize or melt the impacting body, incorporating it with the melted target rocks which now form bodies of impact melt. Detailed geochemistry of the melt rocks at Brent and East Clearwater Lake by Grieve (EMR) and Palme (Max-Planck, Mainz) indicate a contamination by the impacting body, considered, from proportions of siderophile trace elements, to be a chondrite in both cases. These discoveries significantly strengthen the hypothesis that astroblemes are caused by meteorite impact. Those favouring an endogenic origin for Brent had considered the potassium values of up to 12 per cent K_2O in the melt rocks as evidence for alkalic magmatism. Grieve discovered that the K-enrichment resides not in the melt but in shocked gneissic inclusions and postulated a post-impact, alkali-exchange process between shock damaged feldspar and the saline waters of a transgressive Ordovician sea.

Without any doubt the most thoroughly studied impact structure is the Ries, Germany, yet it continues to spawn significant new research. Wagner and Miller (Max-Planck, Heidelberg) performed fission track analyses on zircon, sphene and apatite from several distinctive rock units in the crater. In addition to obtaining ages for the cratering event and the country rocks in accord with those from other methods, they established a post-shock temperature profile through the crater, from >520°C for ejecta to about 200°C below the crater floor, the reverse of a normal geothermal gradient. The suevite breccia at the Ries is reversely magnetized with respect to the basement gneisses and the overlying crater-filling sediments. As the sediments are only slightly younger than the crater, Pohl (Munich) feels the coincidence of the impact and magnetic reversal has a causal relationship. However, Dachille (Pennsylvania State) showed by theory and experiment that impact energy is partially converted to an intense plasma of ions and electrons; the ion-electron mass difference creates a mass separation and therefore a charge separation, resulting in a transient electro-magnetic field. Could this field provide the conditions for the apparent Ries reversal?

Nuclear and chemical explosion cratering have been studied for many years by physicists and mathematicians, and only recently has there been renewed interaction with geologists involved with terrestrial impact structures. This burgeoning relationship appears beneficial to both groups. Using cratering calculations, Kreyenhagen and Schuster (California Research and Technology) were able to successfully model early- and intermediate-stage processes in a hypothetical simple crater formation. Bryan (Lawrence Livermore) employed similar techniques to incorporate the mass and velocity of the Canyon Diablo meteorite, and achieve a model in good agreement with Barringer Crater, Arizona. As yet, computational modelling is not able to simulate shallow nuclear craters or late-stage modification events which lead to central uplift formation, though encouraging progress is being made.

This sampling of topics discussed at the meeting is indicative of the lively state of research in meteoritics. Once again the main effort on extra-terrestrial materials is being taken up by meteorite research as the exciting ideas about the origin of the solar system, the nature and origin of the asteroid population and the possible future uses of these bodies develop. Extended abstracts of presented papers will be published in Meteoritics, v. 13, no. 4, and the Society will next meet in Heidelberg, Germany, in September, 1979.

Contribution from the Earth Physics Branch No. 766.
MS received December 15, 1978.

Note

We regret that the article by R. W. Macqueen in Volume 6, No. 1 had the following omissions. 1) Abstract, line 14, page 3, should read "Ore, in comparison, appears to require coincidence of a specific set of circumstances: these are a cavity system, a fluid carrying metals, and an agency of precipitation as sulphides." 2) Line 24, page 8, should read "On a graph of atomic hydrogen, carbon versus atomic oxygen/carbon ratios, most of these kerogens plot close to the origin, indicating that the zone of organic metamorphism has been reached (Saxby, 1976, p. 125)."

Also note that Figure captions 1 and 2 on page 44 of the "Secretary's Report" are reversed.