REPORT OF THE METEORITE COMMITTEE

E. Anders, Chairman, and A. A. Yavnel', Past Chairman

Work on meteorites has slowed perceptibly since 1969, because many meteoriticists are now working on lunar samples. Nonetheless, progress has been made. Meteorites are providing new clues to traditionally astronomical questions, such as early stellar evolution, interstellar molecules, and composition of comets and asteroids.

Numerous reviews have appeared in 1971–72, and the present report will therefore be brief. The 1967–71 U.S. report to the IUGG is a well-referenced, comprehensive source of information (though restricted mainly to U.S. work), with excellent reviews on noble gases (Bogard, 1971), ages (Burnett, 1971), chondrites (Dodd, 1971), and other meteorite classes (Wasson, 1971a). Reviews concerned mainly with meteorites and the early solar system were written by Pellas (1972), Wasson (1972), and Anders (06.107.002; 1972a, b). Interrelations with asteroids and comets as well as with orbital data were discussed by Wetherill and Anders (*Coll.* **12**). A variety of cosmochemical topics are covered in a book by Sobotovich (1971). Data on the chemical composition of meteorites are compiled in a handbook edited by Mason (06.003.027).

More specialized reviews or monographs have been published on the following topics: Canyon Diablo meteorite (Vdovykin, 1971), diamonds in meteorites (03.003.133), composition of basaltic achondrites (06.003.031), ureilites (03.105.075), carbonaceous chondrites (05.105.062; Van Schmus and Hayes, 1973), meteorites and interstellar molecules (Anders, 1972c), trace elements in meteoritic minerals (Mason and Graham, 1970), and meteorite craters (05.105.088; Hörz and Ronca, 1971).

To conserve space, the reference list comprises only reviews and books. Papers are cited in the text by year only, but the reader can trace them through the sources given or through *Astronomy and Astrophysics Abstracts*.

Chondrites and the solar nebula

There is a growing consensus that the chondrites developed most of their properties in the solar nebula. Much of the effort in meteorite research has therefore been directed toward reconstruction of events and physical conditions in the solar nebula.

A widely held view is that chondritic matter condensed from a cooling solar gas under equilibrium conditions at 10^{-3}–10^{-5} atm. The first phases expected to condense are calcium-, aluminum-, and titanium-rich and silicon-poor minerals (Larimer and Anders, 1970; Grossman, 1972a, b). Such minerals have actually been found in carbonaceous chondrites (Christophe, 1968, 1969; Keil *et al.*, 1969; Kurat, 1970; Marvin *et al.*, 1970). Their chemistry and texture agree strikingly well with predictions of the equilibrium condensation model (Grossman, 1972a; Grossman and Clark, 1972). Noble metals of high boiling point (iridium, osmium, rhenium) also seem to be enriched in the early condensate (Grossman, 1972b; Yavnel', 1970; Müller *et al.*, 1971).

It seems that fractionation of the early condensate is a fairly widespread process in nature. Gast (1972) has noted that the Earth and the Moon are enriched in calcium, aluminum, titanium, etc. by factors of 3–10. Herbig (1970a) has pointed out that the interstellar gas is depleted in the same elements, presumably owing to removal of an early condensate.

Nickel-iron and magnesium silicates are the next phases to condense, at about 1300 K (Larimer and Anders, 1970; Vinogradov, 1971; Grossman, 1972a; Lewis, 1972). They continue to equilibrate with the gas on cooling, until the process is terminated by accretion.

Attempts have continued to estimate accretion temperatures of the Earth, Moon, and meteorites, using volatile metals such as thallium, bismuth, and indium as cosmothermometers. (Accretion temperature, as defined here, refers to the temperature of the dust at the time it became isolated from the nebula and ceased to react chemically with the gas). Values for most objects cluster around 450 K, with a total spread of 420–500 K (Keays *et al.*, 1971; Laul *et al.*, 1972a, b; Larimer, 1973). Very similar values, 445–480 K, were obtained with a newly developed oxygen isotope cosmothermometer (Onuma *et al.*, 1972a). It is curious that the Earth, Moon, and most meteorites give essentially the same temperature, although they formed at manifestly different distances from the Sun. This

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suggests a very flat temperature distribution in the solar nebula. Only C1 and C2 carbonaceous chondrites give lower temperatures, 360-380K(Onuma *et al.*, 1972a; Lancet and Anders, 1973a). More detailed discussions of this topic are given in the reviews of Anders (06.107.002; 1972b).

Lewis (1972) has calculated the density of the condensate at different distances from the Sun, on the assumption that the *P-T* distribution in the nebula followed Larson's (1968) adiabat. He obtains strikingly good agreement with the densities of the planets, but is forced to assume that the meteorites originated between the Earth and Mars, rather than in the asteroid belt. He must also make special assumptions to explain the low density of the Moon.

Blander (1971) argues that condensation took place under conditions of extreme supercooling, rather than at equilibrium. He postulates widespread mixing of materials of different grain size from different environments, so that no sample of condensed matter has a single, meaningful condensation temperature. Arrhenius and Alfvén (1971) propose that the medium is a plasma, not a neutral gas. In order to keep pressures low enough to prevent recombination of the ions, they assume that planetary matter was never located in a massive solar nebula, but was injected gradually over 10^7–10^8 yr from surrounding space. Neither of these two models has thus far been worked out in sufficient detail to permit quantitative comparison with the meteoritic evidence.

Debate on the origin of chondrules continues, with most authors favoring remelting of a primary condensate over direct condensation of supercooled droplets (Nelson *et al.*, 1971). Whipple (1972) has shown that an asteroid moving through the nebula at moderate velocity would accrete chondrules in preference to fine dust grains, which would be carried away by the slip stream. The high chondrule content of chondrites thus may reflect selective accretion, not high abundance in the nebula. In fact, Whipple has suggested that chondrules may form by impact during the accretion process itself, as proposed by Fredriksson and other authors. Chondrule formation may have been widespread during accretion of the planets, judging from the fact that the inner planets consist largely of volatile-poor material.

Arguments on the reality of metamorphic reheating after accretion have abated, and the discussion now centers on details of the reheating process. Application of oxygen-isotope thermometry (Onuma *et al.*, 1972b) has given reheating temperatures of 600–900 °C for most ordinary chondrites, consistent with earlier estimates by other methods. The chemical changes accompanying metamorphism are still being debated: Wasson (1972) and Dodd (1968) favor extreme loss of volatiles, while other authors concede only minor redistribution (Keays *et al.*, 1971; Laul *et al.*, 1972b).

'Cosmic' abundances

The redetermination of the oscillator strength of iron (Garz and Kock, 1969) has removed the long-standing discrepancy between the abundance of iron in the solar photosphere (Goldberg *et al.*, 1960) and in carbonaceous chondrites (Cameron, 1968). Confidence in the meteoritic abundances is further strengthened by their agreement with cosmic-ray abundances (Price, 1972) and by their consistency with nuclear and cosmochemical systematics (05.061.013; Suess and Zeh, 1968). A careful analysis of 8 type 1 carbonaceous chondrite sample for 17 trace elements shows that their composition is far more uniform than was heretofore believed (Krähenbühl *et al.*, 1973). Some authors continue to believe, however, that no class of carbonaceous chondrites is inherently more primitive than any other (Schmitt *et al.*, 1972).

Irons, stony irons

Goldstein and Doan (1972) have brought a century-old quest to a successful conclusion by producing a Widmanstätten pattern (albeit on a microscopic scale) in the laboratory. Phosphorus turned out to be a key ingredient, as first predicted by R. Vogel in the 1930s, but for different reasons.

Wasson (1970, 1971b) has continued his monumental study of the trace-element content of iron meteorites. These data, together with those of other authors (e.g., Crocket, 1972; Gibson and Moore, 1971) have been used to develop an unambiguous and precise classification of iron meteorites.

Scott (1972) and Yavnel' (1970, 1972) have discussed the chemical trends. Most trends seem to reflect fractionations during accretion of the parent bodies, not differentiation within the body.

Fricker *et al.* (1970) have made detailed calculations of the cooling rates of asteroidal bodies as a function of size and depth. From their data and from metallographically determined cooling rates, it is possible to estimate parent-body sizes. Between six and eleven parent bodies of $R = 25 \pm 5$ to 260 ± 40 km seem to be required (Anders, *Coll.* **13**). Jain and Lipschutz (1970, 1972) have continued their efforts to relate iron meteorites to each other through a common shock history.

Mesosiderites have suprisingly low cooling rates ($\sim 0{\cdot}1$ K Myr^{-1}), according to metallographic studies by Powell (1968, 1971). It is not clear that this result should be taken at face value.

Extinct radionuclides

Efforts are continuing to resolve the chronology of the early solar system by means of extinct radionuclides. Podosek and Hohenberg (1970) noted that three primitive chondrites did not give precise isochrons by the I^{129}–Xe^{129} method, perhaps because these meteorites had retained the iodine-xenon record of an earlier stage. Alexander *et al.* (1971) confirmed that the fission-produced xenon in achondrites was indeed derived from 82 Myr Pu^{244}. This has led to further efforts to develop a chronology based on this nuclide.

Schramm and Wasserburg (1970) have shown that the presence of Xe^{129} implies an interval of only 75–250 Myr between cessation of nucleosynthesis and onset of Xe^{129} retention in meteorites. Other parameters, such as the duration and rate of nucleosynthesis, are not well determined, however.

Clarke *et al.* (1970) found a slight enrichment of Mg^{26} in aluminum-rich meteoritic minerals, and attributed it to a very short-lived extinct radionuclide often mentioned as a heat source for melting of asteroids, 0·74 Myr Al^{26}. Later work by Schramm *et al.* (1970) did not confirm the enrichment, however. All meteorites in this study were highly evolved, i.e., achondrites or type 6 chondrites. Apparently no detectable amounts of Al^{26} were present when the feldspar in these meteorites ceased exchanging magnesium with other meteorite phases, but this negative result does not preclude the possibility that significant amounts of Al^{26} were present several million years earlier. Theoretical considerations show, however, that none of the known processes are likely to yield enough Al^{26} to serve as a major heat source in the early solar system (Schramm, 1971).

Bhandari *et al.* (1970) have found an excess of long nuclear tracks in several achondrites, which they attribute to extinct, superheavy elements of $Z \approx 114$ to 126. This conclusion depends entirely on the reliability of their corrections for cosmic-ray and Pu^{244} fission tracks, and needs to be further confirmed. Evidence for a superheavy element in carbonaceous and unequilibrated chondrites is appreciably stronger. Anders and Larimer (1972) have shown that the amount of fission xenon attributed to this nuclide correlates with accretion temperatures, and have attempted to estimate the heat of vaporization of this element. They conclude that elements 111 to 116 are the most likely candidates. Sabu and Manuel (1971) have questioned the fission origin of this xenon, however.

Ages

An excellent general review of the field has been given by Burnett (1971) and so only a few recent papers will be discussed. Oversby (1970) has reexamined the puzzling occurrence of radiogenic lead in some iron meteorites and concludes that it represents nothing but terrestrial contamination. Thus the multitude of high and low ages reported for irons in the 1950s and 1960s has once again given way to the magic number of $4{\cdot}6 \times 10^9$ yr. The only confirmed exception is the iron Kodaikanal, of rubidium-strontium age $3{\cdot}8 \times 10^9$ yr.

Some long-standing questions about the meaning of cosmic-ray exposure ages are also being resolved. A major paradox has been the scarcity of stones with exposure ages greater than 70 Myr, only one case in ~ 300 (Norton Co.) being known. Monte Carlo calculations for a variety of origins (Arnold, 1965; Wetherill, 1968; Mellick and Anders, 1969, 1973) have consistently shown a longlived residuum in the 10^8- to 10^9-yr interval, comprised of meteorites perturbed into orbits of low collision probability with the planets. Some process other than planetary capture is needed for eliminating old stones, e.g., space erosion or collisional destruction, but neither of these mechanisms appears to be capable of eliminating meteorites fast enough, e.g., with a mean life of 10–20 Myr.

However, a careful reevaluation of the destruction time, on the basis of new experimental cratering data (Gault and Wedekind, 1969) and steady-state models of the asteroid belt (Dohnanyi, 1969, 1971) indeed brought it down to the required value, $\lesssim 10^7$ yr. This was fortunate, because the paradox was soon heightened by the discovery that exposure ages of stones had been overestimated by a factor of 1·24, owing to errors in the production rates (Herzog and Anders, 1971a), and that the oldest stony meteorite, Norton Co., had a radiation age of only 86 Myr, not 220–500 Myr (Herzog and Anders, 1971b).

Lavrukhina and Ibraev (1972) have estimated preatmospheric sizes of meteorites from noble-gas data. Kolesnikov *et al.* (1972) have found further evidence for multiple breakups in the history of Sikhote-Alin 450 ± 20 and 145 ± 11 Myr ago.

Efforts are continuing to determine the dates of major impacts. These can serve as genetic markers indicating a common origin. Taylor and Heymann (1969, 1970, 1971) and Christophe (1969) have correlated shock effects with potassium-argon and uranium-helium ages, primarily for L-chondrites involved in the 520-Myr outgassing event. Carver and Anders (1973a) have shown that meteorites of three other classes (Serra de Magé, Zagami, and Bondoc) have fission-track ages of the same order and were presumably involved in the same event. Wetherill (1971), on the other hand, has questioned the reality of the L-chondrite event, while Fisher (1969, 1972) favors a lower age, 400 Myr, rather than 520 Myr.

Orbits

A photographic orbit was obtained for the H-chondrite Lost City, which fell on 3 January 1970. The elements are $a = 1{\cdot}66$ AU, $e = 0{\cdot}42$, $i = 12°$ (05.105.081). An approximate orbit of the L-chondrite Bruderheim was estimated from its Na^{22}–Al^{26} content, on the assumption that the production rate of these cosmogenic radionuclides was greater above than below 2 AU. The radioactivity content suggests that the meteorite spent 20–27% of its period at less than 2 AU from the Sun; combining this result with the visual radiant, one obtains $a = 2{\cdot}5$ AU, $q' = 4$ AU for a preatmospheric velocity of 16 km s^{-1} (Lavrukhina *et al.*, 1972). Owing to uncertainties in the cosmic-ray flux gradient, this method needs to be calibrated against meteorites of known orbit before it can be considered fully reliable.

Carver and Anders (1973b) have studied nuclear tracks in the howardite Washougal, for which the exceptionally high v_∞ of 55 ± 3 km s^{-1} had been reported. They obtained a preatmospheric radius of 36 ± 5 cm, implying a ratio of postatmospheric to preatmospheric mass greater than 1/3000. From ablation theory, this corresponds to $v_\infty < 38$ km s^{-1}.

Radioactivity

Fireman and Goebel (1970) have continued their efforts to infer the space and time dependence of cosmic radiation from cosmic-ray-produced radionuclides in meteorites. For Lost City, they estimate a positive gradient of 62 ± 17% per AU, for energies above 400 MeV. Begemann (1972) obtained markedly different results, however, and concluded that the radial gradient was of the order of 15% or less.

Cressy (1971) has estimated production rates of Al^{26} from various neighboring elements and found that the calcium-rich achondrites were systematically lower in Al^{26} than expected. He attributes this to an orbit of small eccentricity, with $a \approx 1$ AU.

Primordial noble gases

Black (1971, 1972a, b) has argued that primordial gas in meteorites consists of up to five distinct components: three 'solar' (recent and ancient solar wind and flares), one 'planetary' (from the solar nebula), and an elusive fifth component located in what may be surviving interstellar grains. Extensive studies of primordial gas in carbonaceous chondrites have been reported by Mazor *et al.* (1970) and Jeffery and Anders (1970).

Some progress has been made in explaining the origin of planetary gas. Fanale and Cannon (1972) attribute it to adsorption, while Lancet and Anders (1973b) explain it by equilibrium solubility. Neither of these mechanisms can account for the isotopic fractionations in planetary gas. Manuel *et al.* (1970, 1972) have argued that these fractionations were caused by some mass-dependent process.

The Tunguska fall

Korobeinikov *et al.* (1971) have made an elaborate attempt to reconstruct the Tunguska event, using shock-wave theory. They found that a trajectory inclined 30° from the horizontal, with an end height of 5 km and a sharply peaked energy release at the end, satisfactorily reproduced the destruction pattern in the forest. Further theoretical analyses of the fall were given by Bronšten (1972) and Zotkin (1972).

Vasil'ev *et al.* (1971) examined peat layers deposited in 1908 for silicate spherules. They found increased concentrations of 15- to 120-μm spherules 12–15 km from the epicenter and spherules smaller than 20 μm some 300 km from the epicenter. Electron microprobe analyses showed more SiO_2 (65–76%) and Na_2O+K_2O (12·5–15·4%) and less MgO ($\sim$ 0·5%) than in local terrestrial rocks or meteorites (Dolgov *et al.*, 1971).

Organic matter

Considerable progress has been made in this area. It appears that most compounds reliably identified in meteorites can be made by catalytic reactions of CO, H_2, and NH_3 in the presence of meteoritic dust: hydrocarbons (Studier *et al.*, 1972), amino acids (Yoshino *et al.*, 1971; Hayatsu *et al.* 1971), and nitrogen compounds such as adenine, guanine, and porphyrin-like pigments (Hayatsu *et al.*, 1972). Lancet and Anders (1970, 1973a) have shown that the same reaction also accounts for the inexplicably large isotopic fractionation between organic and inorganic carbon in meteorites (Smith and Kaplan, 1970; Krouse *et al.*, 1970; Belsky and Kaplan, 1970). Catalytic reactions of this type presumably took place in the solar nebula, in the region where the carbonaceous chondrites originated. The formation temperature of organic compounds estimated from C^{12}/C^{13} ratios, 360 K (Lancet and Anders, 1973a), agrees exactly with the formation temperatures of their minerals based on O^{18}/O^{16} fractionation (Onuma *et al.*, 1972a). Herbig (1970b) has suggested that interstellar molecules might have been made by the same process in other preplanetary nebulae. Indeed, 9 of the 12 interstellar molecules with 3 or more atoms have been seen in these catalytic syntheses (Anders, 1972c).

The recent fall of two carbonaceous chondrites has intensified experimental work in this area. Kvenvolden *et al.* (1970, 1971) have shown by an elegant, contamination-proof technique that indigenous amino acids do occur in meteorites. Hodgson and Baker (1969) have found compounds similar to porphyrins in several meteorites. Ponnamperuma and Pering (1970), Belsky and Kaplan (1970), and Gelpi *et al.* (1970a, b) have made thorough studies of meteoritic hydrocarbons. Some of them turned out to be contaminants, however.

Meteoritic material on the Moon

Comparison of lunar samples with meteorites shows that neither mare nor highland rocks are represented among known meteorites. Apparently hypersonic impacts are much less efficient in accelerating decimeter-sized fragments to lunar escape velocity (2·3 km s^{-1}) than was formerly believed. Thus, the Moon is mainly a collector, not a source, of meteoritic material.

Lunar soils and breccias from all landing sites are enriched in a number of trace elements (gold, iridium, rhenium, bismuth, etc.), apparently reflecting addition of a meteoritic component similar to carbonaceous chondrites (Ganapathy *et al.*, 1970; Laul *et al.*, 1971; Morgan *et al.*, 1972a, b; Baedecker and Wasson, 1971). The amount is about 1·0–1·5% at all landing sites, corresponding to an average influx rate of $2{\cdot}4 \times 10^{-9}$ g cm^{-2} yr^{-1}. This rate agrees within a factor of four with a similar estimate for the Earth, based on the iridium and osmium content of ocean sediments (Barker and Anders, 1968), and with the influx rate of meteors (Dohnanyi, 1970). If this material represents micrometeorites, and if they are largely of cometary origin (as is widely believed), then the lunar data provide an important clue to the composition of comets.

Some lunar breccias (especially from the Apollo 14 site, and norites and anorthosites from other landing sites) contain a different meteoritic component, low in volatile elements (Ganapathy *et al.*, 1972; Morgan *et al.*, 1972b). It seems to be derived from planetesimals that fell on the Moon in the last stages of accretion. Studies of lunar samples may thus yield clues to the composition of the ancestral material of the planets.

Meteorite craters

Apart from a review by Millman (05.105.088), several papers on general topics have appeared, e.g., impact melts (Dence, 1971), deposition of sediments in craters (Beals and Hitchen, 1970), and crater-scaling laws (Gault, 1972; White, 1971). Among new craters described, the Popigai basin in Northern Siberia is of special interest because of its large diameter, 70-80 km (Masaitys *et al.*, 1971, 1972). Studies of individual craters have been published by Blau *et al.*, French *et al.* (1970, 1971), Guppy *et al.* (1971), Hodge (1970), Hodge and Wright (1971), Kurat and Richter (1972), Milton *et al.* (1972), and Short (1970). Hörz and Ronca (1971) have described a new classification of craters. Storzer *et al.* (1971) and Sekiguchi (1970) have investigated the tidal breakup of meteoroids during approach to a planet, which can lead to multiple craters. Fission track ages show that the Ries and two neighboring structures, the Steinheim basin and Stopfenheim Kuppel, were formed in a triplet cratering event 15 Myr ago (Storzer *et al.*, 1971). Hartung *et al.* (06.105.041) have determined a potassium argon age of 414±20 Myr for the Brent crater.

Results of recent expeditions to the Sikhote-Alin crater field have been reported by Krinov (1970, 1971, 1972), Nekrasov and Tsvetkov (1970), Aaloe (1970, Zaslavskaja (1970), and Tsvetkov (1972).

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