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The Allende, Mexico, Meteorite Shower

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ABSTRACT

Clarke, Roy S., Jr., Eugene Jarosewich, Brian Mason, Joseph Nelen, Manuel Gómez, and Jack R. Hyde. The Allende, Mexico, Meteorite Shower. *Smithsonian Contributions to the Earth Sciences* 5:1–53. 1970.—The Allende meteorite fell near Parral, Chihuahua, Mexico, between 0105 and 0110 Central Standard Time on Saturday, 8 February 1969. The fireball approached from the south-southwest (S37°W), and broke up in the atmosphere, producing thousands of fusion-crusted meteoritic stones. The smallest individuals were recovered 4 km east of Rancho Polanco (26°43′N, 105°28′W), and the largest near Rancho El Cairo (27°06′N, 105°12′W), some 50 km to the north-northeast across the Parral-Jiminéz highway. Specimen size increases generally as one moves to the north-northeast within the field, and many large specimens (5–15 kg) were recovered in and around the area enclosed by Pueblito de Allende, San Juan, Rancho Blanco, and Santa Ana. At least two tons of meteoritic stones have been recovered, with crusted individuals ranging in weight from approximately 1 g to one individual of 110 kg. Specimen shapes are mainly fragmental, due to one major disruption of the parent body, followed by minor subsequent fragmentation. Individual stones have primary and secondary fusion crust, and some fresh fracture surfaces due to late-stage breaking. A small percentage of stones shows strong ablative shaping due to oriented flight. The elongate strewnfield possibly exceeds 300 km^2 in area, making Allende the largest recorded stony meteorite fall both in its areal extent and in total weight of recovered meteorites. Allende fell near the sites of find of two major iron meteorites, Morito and Chupaderos.

Chemical and mineralogical compositions establish that Allende is a Type III carbonaceous chondrite. Three distinct components can be recognized: fine-grained black matrix (~60%), chondrules (~30%), and irregular white aggregates (~10%). The matrix consists almost entirely of iron-rich olivine (average 50% Fe_2SiO_4), with minor amounts of troilite, pentlandite, and taenite, rendered opaque by dispersed carbonaceous material. Most of the chondrules are magnesium-rich, and consist of olivine (average 9% Fe_2SiO_4) with minor amounts of clinoenstatite and some glass; a few chondrules are rich in calcium and aluminum, and are made up largely of anorthite, gehlenite, augite, and spinel. The irregular aggregates are also rich in calcium and aluminum, and contain anorthite, gehlenite, augite, spinel, nepheline, grossular, and sodalite (the last two minerals have not previously been recorded from meteorites). Complete chemical analyses have been made of the bulk meteorite, a dark inclusion, the matrix, a chondrule concentrate, two individual chondrules, and a single aggregate.

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The Allende, Mexico, Meteorite Shower

Introduction

In the early morning of Saturday, 8 February 1969 (between 0105 and 0110 Central Standard Time), a brilliant fireball was observed over much of northern Mexico and adjacent areas of Texas and New Mexico. The most spectacular phenomena were centered around the city of Hidalgo del Parral in the south-central part of the state of Chihuahua. The fireball approached from the south-southwest, and as it neared its terminal point the brilliant light was accompanied by tremendous detonations and a strong air blast. Thousands of individual meteoritic stones rained down over a large area of rural Mexico. One weighing 15 kg fell within four meters of a house in the town of Pueblito de Allende, 35 km east of Parral. This stone was broken up, and pieces taken to the office of the newspaper "El Correo de Parral" the same day; the news of an important meteorite fall was published that evening. Dr. E. A. King of the NASA Manned Spacecraft Center in Houston, Texas, heard of these events on the morning of 10 February 1969 and departed promptly for the scene. He returned with meteoritic material on the morning of 12 February, and he and his colleagues have published a preliminary report on their findings (King et al., 1969).

Our initial field investigation was undertaken after conferring by telephone with Ing. Diego Cordoba, Director del Instituto de Geologia, Mexico City. Roy S. Clarke and Brian Mason arrived in Parral on Wednesday, 12 February and spent the next five days investigating the fall and collecting material for research and preservation. Ing. Manuel Gómez of ASARCO Mexicana S. A., Parral, and Ing. César Gallardo of the University of Chihuahua joined the field party and contributed importantly to its success. Clarke returned to the field 24–27 May with Jack R. Hyde of the Smithsonian Institution's Meteorite Recovery Project, Lincoln, Nebraska. Hyde remained in the area for several weeks con-

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Acknowledgments

We are indebted to Ing. Diego Cordoba, Director del Instituto de Geologia, Mexico City, for permission to investigate the fall area and to collect material for scientific investigation; to R. C. Byrd, Superintendent, ASARCO Mexicana, Parral, for providing facilities for our work; to R. E. McCrosky and Gunther Schwartz of the Smithsonian Institution Astrophysical Observatory for field assistance and informative discussion and interpretation of phenomena of fall observations. Our co-workers within the Department of Mineral Sciences, National Museum of Natural History, have contributed to this work in various ways: John S. White, Jr. prepared many X-ray powder photographs; E. P. Henderson prepared photomicrographs and provided helpful discussion; Grover C. Moreland prepared critical sections for study; Sarah W. Scott cataloged field collections and assisted in preparation of the manuscript; and William G. Melson critically reviewed the manuscript and provided helpful discussion. We are indebted to the National Aeronautics and Space Administration for grants that covered part of the costs of this investigation.

ducting studies of specimen distribution, and he returned to the field for an additional three weeks in late October and November.

SPECIMEN RECOVERY AND DISTRIBUTION FOR STUDY.—Information related to the fall and recovery of the Allende meteorite was disseminated rapidly to interested scientists throughout the world by the Smithsonian Institution's Center for Short-Lived Phenomena, Cambridge, Massachusetts. Specimen material reached the Division of Meteorites, National Museum of Natural History, Washington, on 19 February, and its distribution to interested scientists began immediately. All reasonable requests were granted; scientists in thirty-seven laboratories in thirteen countries were sent material within a few weeks of the date of fall. Dr. E. A. King's group in Houston had also distributed material to other research laboratories.

Many individual meteorite specimens have been recovered from the strewnfield, and Allende material is now widely distributed in collections and research laboratories. We obtained about 150 kg of meteorites on our first trip into the field and smaller amounts on the second and third trips, and we were shown many large specimens that we were unable to acquire. Several other scientific groups from institutions in Mexico and the United States are known to have visited the area and acquired material, as has one Canadian group. Commercial and private collectors have been active in the area and have removed indeterminate amounts of specimen material. One dealer reported handling approximately 500 kg of Allende meteorites on a wholesale basis by early November 1969. An aggressive amateur collector visited the field in late February and obtained 110 kg of excellent material for his collection. Information of this type leads us to conclude that during the first five months after the fall two tons of meteorite specimens were removed from the strewnfield. The recovery of this large quantity of specimen material establishes the Allende meteorite as the largest stony meteorite shower on record.

PUBLISHED REPORTS.—The immediate and broad distribution of Allende meteorite specimens has resulted in the prompt publication of several studies that are not referred to directly in this paper. Fireman (1969) published a preliminary account on the field recovery and laboratory study of Allende. A report on the atmospheric collection of meteoritic debris associated with the Allende fireball has been prepared by Carr (1970). The study of a number of radionuclides in Allende by gamma-ray spectrometry has been reported by Rancitelli et al. (1969). Fireman et al. (1970) have reported several types of ages for Allende based on determination of rare gases, K, U and Th, and Durrani and Christodoulides (1969) have used thermoluminescence as a means of estimating an exposure age for Allende.

PROPOSED NAME.—We propose the name "Allende" for this meteorite, although "Pueblito de Allende" was used in the preliminary report of King et al. (1969), because this town was the location of the first stone known to have been recovered. The extent of the strewnfield was not fully realized at that early date, and it is now clear that the name Allende has an association with a large area in the heart of the strewnfield. Specimens have been recovered within a kilometer of the historic and beautiful town of Valle de Allende, from along a 15-km segment of the valley of the Rio del Valle de Allende, as well as in the environs of Pueblito de Allende. Hey (1966) comments in the introduction to his standard *Catalogue of Meteorites* that "meteorite names are essentially labels, of no intrinsic significance." Labels should be simple and concise, and the name Allende satisfies these criteria admirably. The name honors Ignacio José Allende (1779–1811), a Mexican army officer and patriot of the uprising of 1810–1811.

Strewnfield

The Allende fireball approached from the south-southwest, the azimuth of the radiant (direction of approach) being approximately 215° and its altitude 13° (preliminary values, McCrosky et al., 1969). The resulting meteorite strewnfield is located 540 km (340 statute miles) south (S10°E) of El Paso, Texas, and 200 km south (S20°E) of the city of Chihuahua, to the east of the Sierra Madre Occidental (Figure 1). Its head lies within and somewhat to the east of a small group of hills, the Sierra de Almoloya, just north of the Interamerican Highway (Route 45), halfway between the cities of Parral and Jiménez. Small individual meteorite specimens from the tail of the field have been recovered as far south as 4 km east of Rancho Polanco, 26°43′N and 105°28′W (Figure 2). Approximately 50 km to the north-northeast a large individual

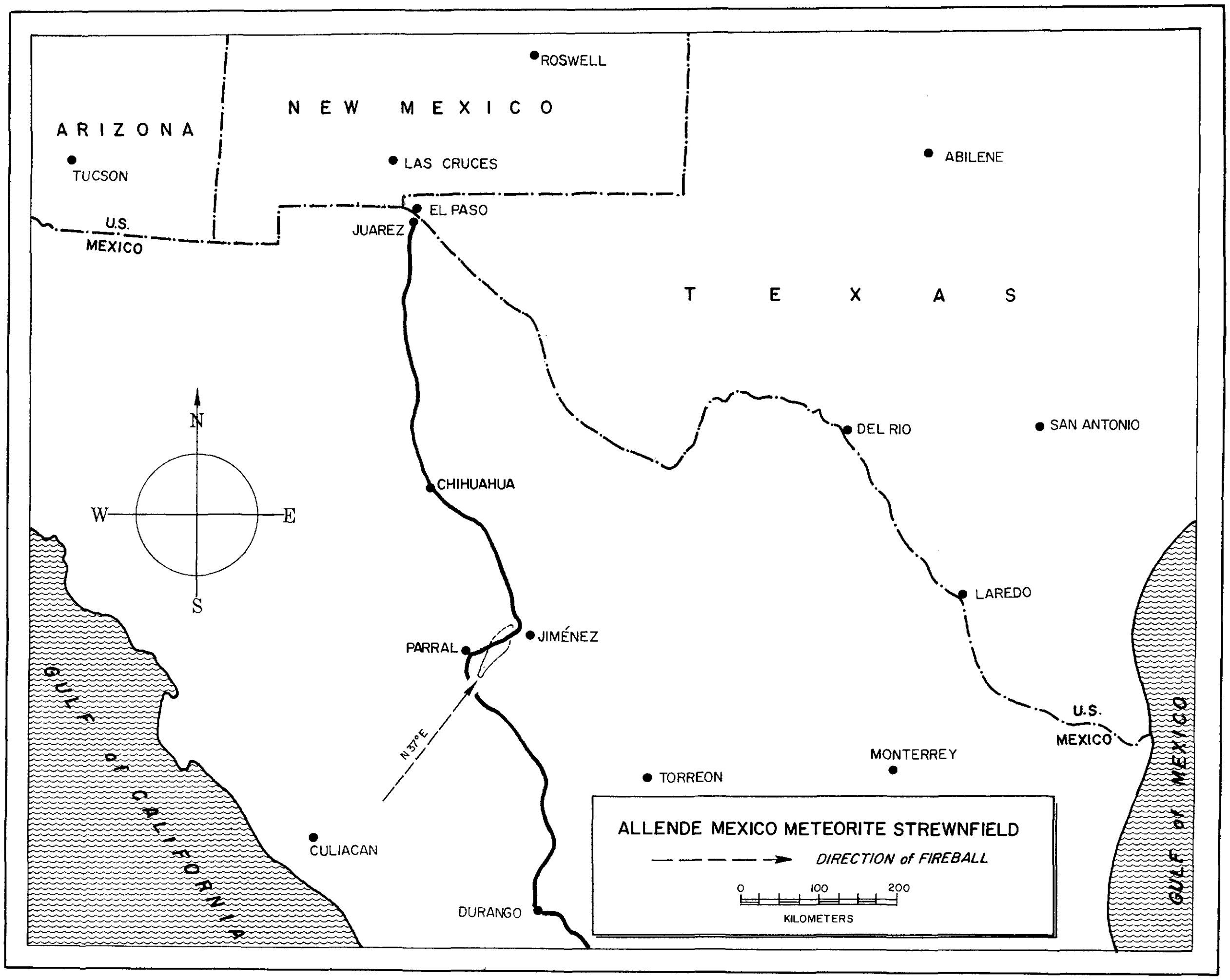


FIGURE 1.—Location of the Allende meteorite strewnfield, with direction of fireball approach indicated.

stone of approximately 110 kg, broken into many fragments on impact, was discovered at 27°06′N and 105°12′W, just to the east of the Sierra de Almoloya.

The specimen-rich Allende meteorite recovery area, 50 km in length and possibly exceeding 300 km² in area, is the largest stony meteorite strewnfield that has been studied in any detail.[1] The map presented here (Figure 2)[2] is based largely on our own field investigations and may not indicate the full extent of the field. We feel, however, that the general shape of the field and the nature of the distribution of samples within it are fairly well understood at this time. Large individual specimens may still be found, extending the field to the northeast and perhaps modifying the shape of that end

[1] The recent fall of the Belfast (Bovedy), Northern Ireland, meteorite resulted in the recovery of two stones separated by a distance of 62 km (Meighan and Doughty, 1969), and the suggestion that the main mass continued on for 150 km into the Atlantic Ocean (Hindley and Miles, 1970). Kulik (1922) reported that stones from the Saratov, Russia, meteorite fall were found over a distance of 130 km, but details are lacking. Nininger (1936) reported that specimens of the Pasamonte, New Mexico, meteorite shower were separated by a distance of 28 miles (45 km).

[2] The maps presented here (Figures 2 and 9) are based on 1:250,000 sheets compiled in 1964. They were prepared as a collaborative effort of the Departmento Cartográfico Militar de Mexico, the Inter-American Geodetic Survey, and the Army Map Service of the United States, based on aerial photographs taken in 1957–1958. They are available from the Mexican Government. The two sheets used were:

Hidalgo del Parral, Chihuahua. NG13–5, series F501.
Ciudad Camargo, Chihuahua. NG13–2, series F501.

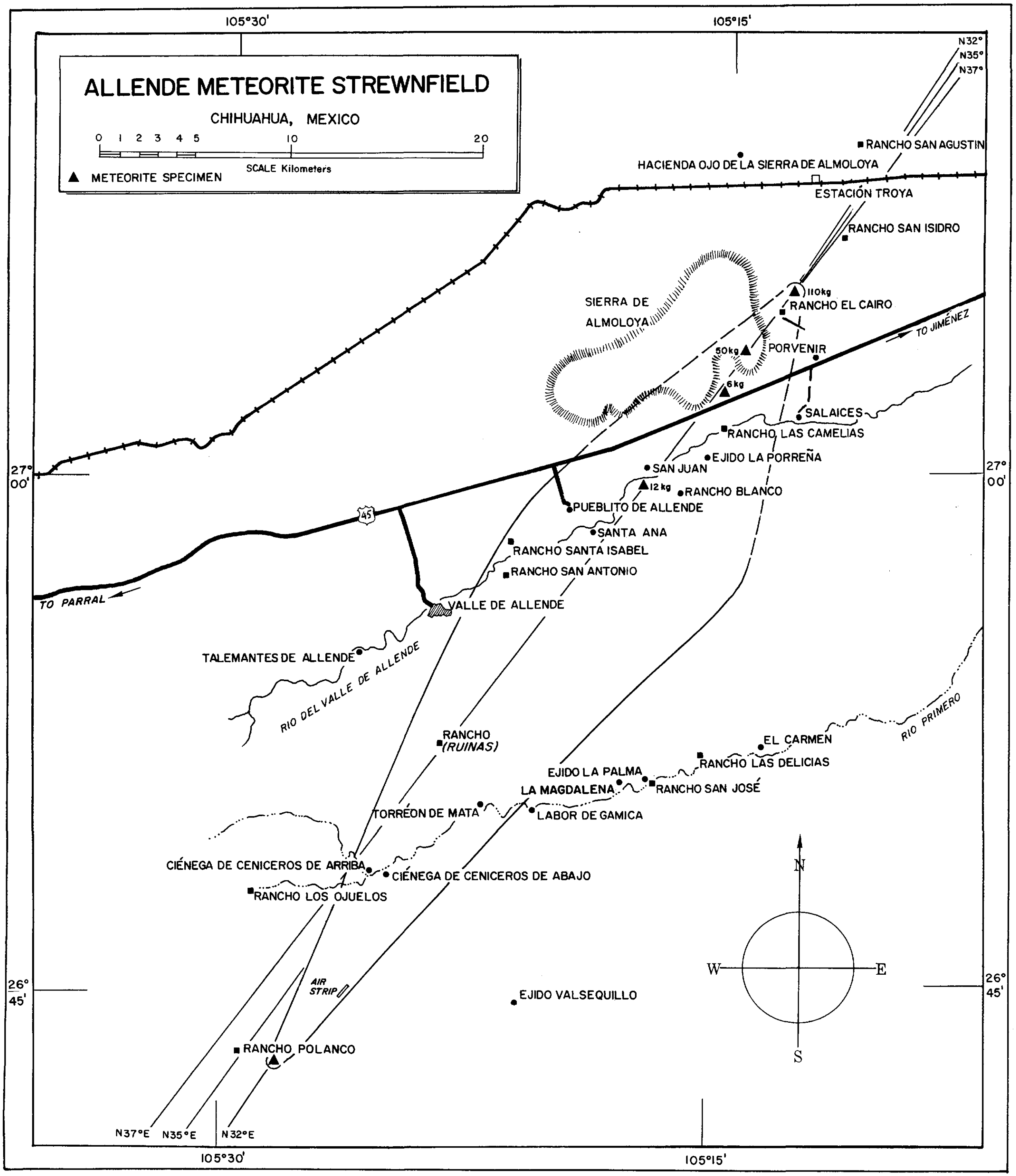


Figure 2.—Plan of the Allende meteorite strewnfield.

of the field somewhat. We do not expect subsequent work to require major changes in the shape of the field south of the Rio del Valle de Allende.

The map (Figure 2) shows the outline of the strewnfield and its relation to major geographic features and habitations. The strewnfield boundaries were arrived at largely on the basis of interviews with many local residents who had searched for specimens or who had knowledge of where they were recovered. Specimen collecting by the local people started immediately after the fall and continued with more or less enthusiasm for months. The intensity of this activity depended somewhat on the interest stimulated at a given period by outsiders and by the varying labor requirements of an agrarian economy. Meteorite collecting proved to be an interesting and profitable leisure-time activity for a few individuals in each community, and these collectors were a particularly reliable source of information needed to reconstruct the specimen distribution pattern. All of the habitations indicated on the map (Figure 2) were visited; the important ones on many occasions, and most at least several times over a period of weeks or months.

There is an unavoidable vagueness in much of the information obtained from local residents. Individuals were mainly open and frank in their reports to us, but their meteorite finds had not been documented with scientific precision. Specimens were collected over a period and kept together at home in a box, bag, or sack. Plastic bags which had previously been used for candy or meal and had not been well cleaned were a favorite storage method for collections of small specimens. Normally, a given individual collected from a relatively small area within the strewnfield. Collectors generally had sharp recollections of the location where unusual specimens or particularly large ones were found, but it was impossible to revisit each site. Distances and directions are also subject to question, our practice being to record reports as we received them. Landmarks are scarce in the chaparral country, possibly introducing another uncertainty. Occasionally, claims were made that seemed to be at variance with the developing pattern, and these reports were rejected unless corroborative evidence could be found. Generally speaking, we would receive numerous reports of meteorites being found in a given area, and equally numerous reports of their absence from other areas. In particularly critical areas, we conducted limited searches, normally with the assistance of local residents.

The degree of confidence we have in the boundaries developed is indicated on the map (Figure 2) by use of either a solid or broken line. The area of most uncertainty is north of the highway, where the two largest specimens have been found. Does the strewnfield really extend further to the northeast, perhaps even beyond the railroad? The area south of the highway between Rancho Las Camelias and the town of Salaices seems also to be in question, specimens so far not having been reported from there.

An axis of the strewnfield based on specimen recovery was drawn by joining the point where small specimens were found in the extreme southwest with the locations of the largest specimen (Figure 2). This line, N32°E, is in good agreement with the azimuth of 215° (N35°E) calculated by McCrosky et al. (1969) from fireball observations. The N35°E line is also indicated on the map, assuming the location of the largest specimen to be most representative of the fireball trajectory. It is interesting to note that the three specimens found north of the highway, separated by a maximum distance of 7 km, plot closely to both of these lines. The shape of the strewnfield and the distribution of specimens within it (discussed below) suggest that the N35°E line approximates the axis of the strewnfield corrected for preferential scattering of lighter specimens due to high-altitude winds. McCrosky et al. (1969) reported that data for the time of fall supplied by the United States Air Force indicated winds "predominantly from the west up to an altitude of 30 km except for the immediate surface layer where northeast winds may have been occurring." These west winds would be consistent with an eastward skewing of the tail of the strewnfield, a situation that seems to be borne out by the observed distribution of specimens.

The outline of the strewnfield might be somewhat easier to understand if one assumed that the actual trajectory of the fireball was from a slightly more westerly direction than the N35°E bearing of McCrosky et al. (1969). Justification for such an assumption can be derived from considerations of three key specimens from accurately known locations within the strewnfield. The 110 kg specimen from the head of the field has been mentioned above and its location is indicated in Figure 2. A 40–50 kg individual was found within the Sierra de Almoloya 5 km to the southwest of the largest specimen (Figure 2, and discussed below). The third specimen was found 12 km to the southwest of the 110 kg individual (NMNH 3527, discussed below), near San Juan (Figure 2). This specimen is a 12 kg aerodynamically oriented individual, and it seems reasonable to assume that a specimen of this type would fall with relatively little deflection during passage through the atmosphere, falling close to the fireball's actual trajectory. Similar assumptions for the other two specimens based on their size also seem reasonable. These three specimens lie on a straight line with a bearing of N37°E, a bearing that fits well the configuration of the strewnfield. The asymmetry of the field along this line can be reasonably explained as due to high-altitude winds. The light material that fell in the tail of the field may have been moved to the east by 4 km or more, while the eastern border of the main body of the field may have been skewed eastward by approximately 2 km. This picture seems reasonable to us on the basis of our field observations and study of specimen distribution (discussed below).

The character and use of the land within the strewnfield is largely controlled by elevation and drainage patterns. The area is traversed by the drainage systems of the Rio del Valle de Allende in the north and the Rio Primero in the south. The Rio Primero is an intermittent stream, dry for most of the year. Habitation is concentrated along these streams at the borders of areas of intense agricultural use. Agriculture and habitation account for 10–15 percent of the land use within the strewnfield, and there is some mining in the area. With only a slight rise in elevation away from these streams, the land changes to brush-covered range country known as chaparral. Much of the chaparral is relatively open, but it does include areas of dense brush, penetrable only with difficulty. To the southwest from the Rio del Valle de Allende, the country generally becomes more open and drier.

Changes of elevation within the strewnfield are generally gradual with the marked exception of the Sierra de Almoloya (2,044 meters maximum elevation). Elevations tend to increase to the southwest and range from 1,500 to 1,750 meters. The Rio del Valle de Allende meanders across the upper part of the field for a distance of almost 20 km, elevations along the river ranging from 1,550 meters east of San Juan and Rancho Blanco to near 1,600 meters just east of Valle de Allende. The elevation of the Rio Primero where it crosses the tail of the field near the twin villages of Ceniceros is 1,650 meters. From here elevations increase gradually to the southwest, reaching 1,750 meters just east of Rancho Polanco.

Distribution of specimens.—The weight distribution of individual, crusted Allende meteorite specimens within the strewnfield approximates the pattern that would be expected, assuming one major disruption of the parent meteorite followed by limited further breakup of smaller fragments during high-velocity flight. Atmospheric drag combined with the low angle of entry produced unusually effective size sorting over a long strewnfield. This is clearly demonstrated by the observed distribution of specimens on the ground and is further supported by morphological observations that will be discussed in a following section. Several of the largest individual pieces were apparently relatively undeflected in their flight through the atmosphere and traveled the greatest distance to the northeast after initial breakup, well beyond the bulk of specimens. Large- to medium-size fragments traveled less far and were apparently deflected by the atmosphere to an extent depending largely upon their individual shapes. This resulted in a broadening of the strewnfield in the area that produced most of the large specimens. Smaller specimens were retarded more promptly by atmospheric drag—falling many kilometers behind the largest individuals—and were not deflected far from the fireball's trajectory. This summary is, of course, an oversimplification, but it furnishes a useful framework for discussion of our field observations.

The largest specimen known to us is a 100–110 kg fragmented individual which was discovered eight months after the fall. It was found approximately 1.5 km N15°E of Rancho El Cairo (Figure 2), in and around a small hole. The second largest stone was found in early April in the Sierra de Almoloya 4 km north of Route 45 at a point north of Rancho Las Camelias. This was a 40–50-kg individual that also fragmented on impact. We know of only one other stone recovered north of the highway, a 6-kg individual. Two large stones were recovered south of the highway and within a few hundred meters of it, a 35-kg individual recovered northeast of San Juan (NMNH 3529, broken on impact) and a 17-kg individual recovered directly north of San Juan (NMNH 3509, broken on impact). A number of specimens in the 5–20-kg size range have been recovered around San Juan and Rancho Blanco and in the area extending southeast from Rancho Blanco for several kilometers. A somewhat isolated 18 kg individual was recovered in range country 7 km south of Rancho Blanco (Donald P. Elston, personal communication, 1969), and several other large individuals (5 to 11 kg) have been recovered 2 to 3 km to the north and northwest of this 18 kg individual. Many other large individuals have been found in the agricultural area enclosed by the four locations Pueblito de Allende, San Juan, Rancho Blanco, and Santa Ana. The largest individual that we know of that landed without damage was recovered at the edge of the river between Pueblito de Allende and Santa Ana (NMNH 3528, 18.5 kg). A 12-kg individual (Figures 3 and 14) was recovered in a freshly plowed field less than one kilometer south of San Juan (NMNH 3527, found by B. Mason on 17 February 1969). Small specimens have been found interspersed among the large specimens at the north end of the field, but in very limited numbers. An example is a 26 g completely crusted individual that was found within 2 to 3 km of Rancho Blanco (NMNH 4651). The range country south from Rancho Blanco and Santa Ana and extending west toward Rancho San Antonio produced many medium-size specimens (1 to 5 kg) and occasional larger ones. Specimens in this size range were also found as far south as several kilometers southeast from Valle de Allende, and 1-kg specimens have been found as far south as "Rancho (ruinas)."

South from Rancho (ruinas) and 10 km south of Valle de Allende is the comparatively isolated village of Torreón de Mata (population, approximately 50). This village has served as an important collecting point for the south-central region of the strewnfield. Specimens were recovered here immediately after the fall, but the local people do not appear to have been greatly impressed by the abundance of valuable meteorite material close at hand. Specimens were found within the village and on the farmland nearby, and in the range country to both the north and south. Some of the more enthusiastic residents of villages to the north walked or rode horseback from the vicinities of Pueblito de Allende and Valle de Allende to Torreón de Mata searching for specimens. This activity undoubtedly attracted attention, but the local people seem to have felt that the small specimens found in their area were of little value compared to the commercially attractive large specimens found to the northeast. Five kilometers farther to the southwest are the twin villages of Ciénega de Ceniceros de Arriba and Ciénega de Ceniceros de Abajo (combined population, approximately 500). They served as collecting centers for hundreds of small specimens recovered from the tail of the strewnfield. Little collecting was done in this area prior to the visits of Jack R. Hyde in June 1969. These visits stimulated searches that led to the recovery of an important research collection and to extending the strewnfield as far south as several kilometers east of Rancho Polanco.

The general trend of decreasing specimen size that was observed for the head and center of the strewnfield holds for the tail. This is demonstrated by calculating average specimen size for collections made (1) around Torreón de Mata, (2) the Ceniceroses, and (3) in the extreme tail of the field. Collections made around Torreón de Mata naturally include material collected toward the Ceniceroses, and the converse is true for collections obtained in the Ceniceroses. Torreón de Mata material, however, has a strong bias for areas to the north and northeast, while material from the Ceniceroses would not normally have been collected as far north as Torreón de Mata. The specimens from the tail of the strewnfield were collected at least 5 km south of the Ceniceroses and on to the end of the field. The approximately 200 specimens known to have been collected in the Torreón de Mata area range in weight from 6 to 537 g, with an average weight of 87 g. A somewhat larger collection of specimens known to have been collected around the Ceniceroses range in weight from 2 to 540 g, with an average weight of 32 g. The small group of specimens (17) from the tail of the field ranged in weight from 3.1 g (completely crusted individual) to 43 g, with an average weight of 12 g. Individual specimen weight on the average decreases as one moves to the southwest within the strewnfield.

It is tempting to try and estimate the amount of Allende meteorite material that reached the ground. We pointed out above that an estimated two tons of material was removed from the strewnfield during the first few months after its fall. What fraction of the material that actually landed does this represent? An important factor to consider is the effectiveness of search and recovery operations within the strewnfield. The areas of maximum concentration of large specimens fortuitously and fortunately coincided with or were contiguous to areas of maxi-

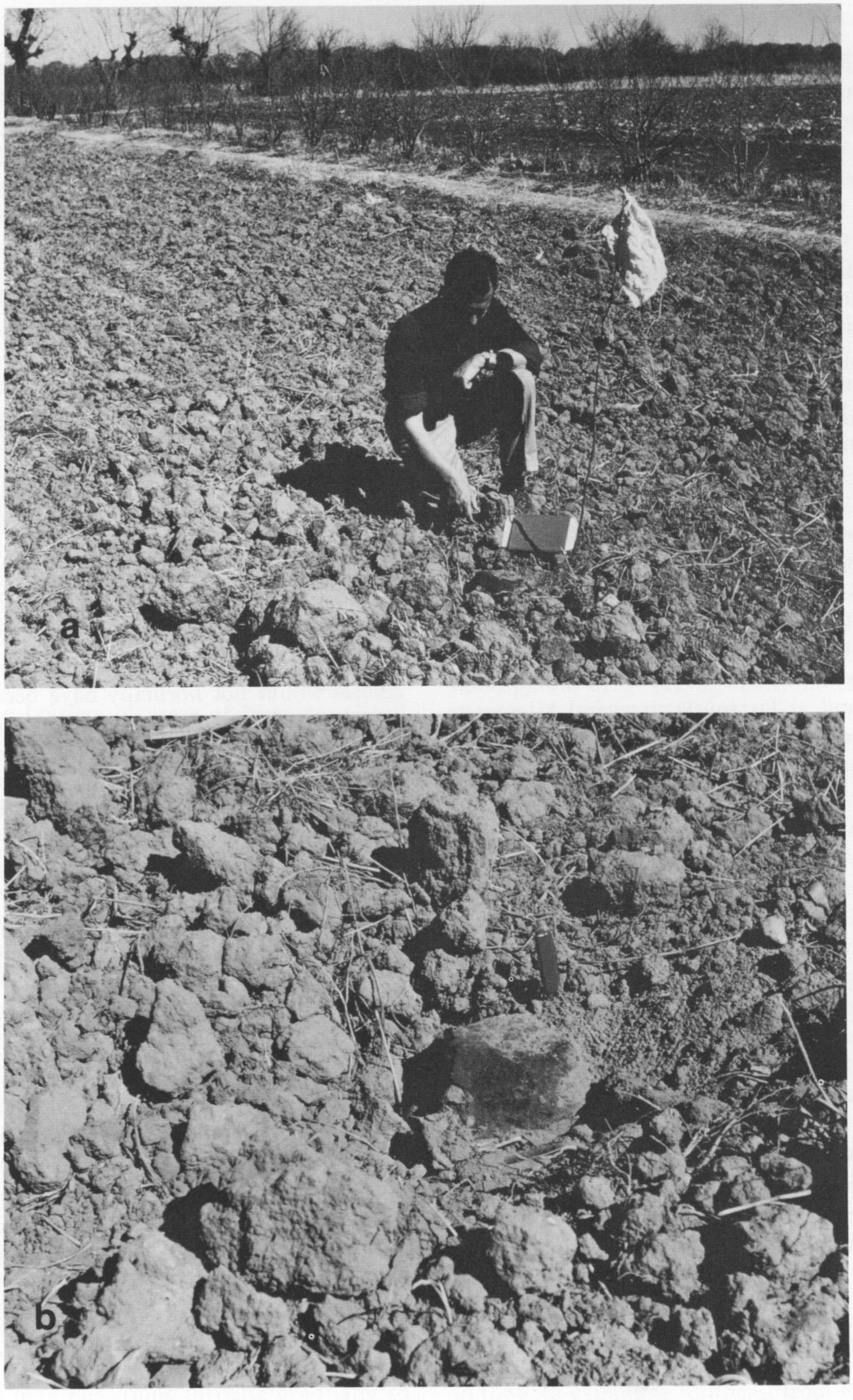


FIGURE 3.—The field recovery by Brian Mason of a 12-kg Allende specimen (NMNH 3527) 17 February 1969, approximately 0.7 km south of San Juan: *a,* specimen in front of notebook, nearly buried in recently plowed field; *b,* close-up of specimen in place, with pocketknife handle for scale. Two large pieces and several small fragments recovered. See Figure 14.

mum population density. These areas have been searched extensively by the local people, although little in the way of systematic searching has been undertaken. Large areas of the strewnfield have been given only cursory attention, while remote and impenetrable areas of the field remain essentially unexamined. An indication of the nature of the problem is the fact that the 110-kg specimen mentioned above was not discovered until eight months after the fall, and specimens as large as 5 kg were still being found in the intensively searched area around Rancho Blanco (NMNH 4646) and San Juan (NMNH 4655) in early June, four months after the fall. A 14-kg specimen was reported to have been found near Rancho Blanco in mid-November. Probably only 40 to 60 percent of the meteorite material that hit the ground has been recovered to date, leading us to suggest that the minimum amount of material that comprises the Allende shower was of the order of four tons. The possibility exists, of course, that this estimate is too conservative. Field investigation should be continued in the Allende strewnfield as long as significant amounts of meteorite material are recoverable.

Recovery of individual stones.—In this section notes are given on the circumstances of recovery of specific stones. The stones selected are from those for which we have particularly reliable information, and those that are of unusual interest in developing the distribution pattern within the strewnfield.

The largest specimen that has been recovered to date was not found until 8 October 1969, eight months after it fell. Guadalupe Juarez of Rancho Él Cairo was working in a bean field when he noticed a rabbit run into an adjacent uncultivated area. He got his gun and pursued the rabbit some 150 yards into the chaparral where he discovered the 110-kg fragmented meteorite. The soil was hard and consisted of compacted clay containing approximately 70 percent small stones. The meteorite had produced a spoon-shaped hole with a one- to three-inch raised rim at the north end. It was 13 inches deep at the north end, the bottom sloping smoothly to ground level at the south end. The hole was 32 inches wide, 52 inches long, and had an apparent axis of N21°E. The largest individual piece recovered was about 6 kg, and the larger pieces were mainly distributed 12 to 15 feet from the hole, around its north end. At least 20 kg of dust and pieces in the 1- to 3-g size range were recovered, mainly from within the hole.

Comments on individual specimens are given below:

NMNH 3491, 1.8 kg, approximately 3 km south to southeast of Rancho Santa Ana.

A completely crusted individual found in place by schoolboys in our party just prior to a brief but heavy rainstorm about noon on 13 February 1969 (Figure 4). It was embedded in hard ground, penetrating perhaps 5 cm at maximum. Figure 4*c* is a photograph of this specimen oriented similarly to the position shown in the ground. Thin fusion-crust development on the flat surface to the upper right in both photographs establishes that this was a posterior surface during high-velocity atmospheric flight. This specimen seems to have hit the ground at a high angle, falling close to the trace of the fireball's trajectory (Figure 2). A small amount of dirt adhered to the specimen as it was removed from the hole. It is one of many specimens found in contact with dry grass that showed no signs of charring.

NMNH 3492, 22 g, approximately 3 km south-southeast of Rancho Santa Ana, within a few hundred meters of NMNH 3491.

This specimen is a small fragment free of any obvious fusion crust. A cursory search of the immediate surroundings produced no additional material. It was found by a member of our party on the morning of 13 February 1969.

NMNH 3493, 7.5 kg, approximately 3 km south of Rancho Santa Ana.

This specimen was found by Manuel Gómez while running for shelter during the rainstorm about noon on 13 February 1969. It is a large, flatiron-shaped individual that landed on hard ground, making a shallow abrasion (Figure 5). The specimen broke into two large pieces (4.8 and 2.5 kg), a small piece (115 g), and several small fragments. The largest piece was found about 1.5 m from the impact point and the other large piece was an additional meter away. Some of the smallest fragments were found yet farther away and are being pointed out in the photograph (Figure 5b). The alignment of the pieces with the point of im-

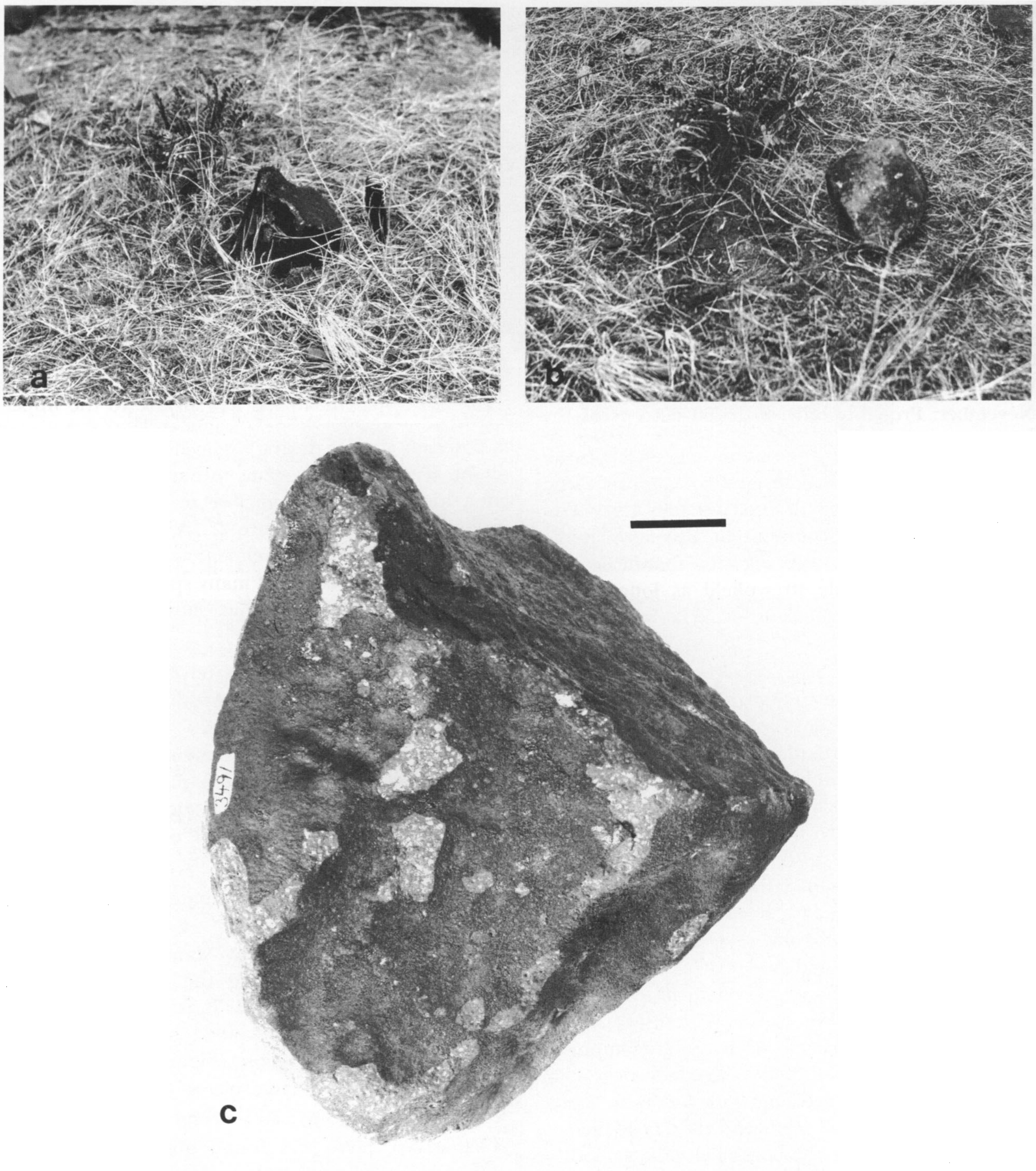


FIGURE 4.—A 1.8-kg Allende individual (NMNH 3491) found in place approximately 3 km south to southeast of Rancho Santa Ana, 13 February 1969; *a,* in place, pocketknife for scale; *b,* rolled out of hole; *c,* enlarged view oriented as in *a.* Scale bar in *c,* 2 cm.

FIGURE 5.—A 7.5-kg Allende individual found by Manuel Gómez on 13 February 1969 approximately 3 km south of Rancho Santa Ana (NMNH 3493). Specimen hit abraded area to right of boy's foot, *a*, Largest piece marked by sunglasses, a second large piece farther away and in line with impact point. Small fragments are being pointed to in *b*.

FIGURE 6.—A 7.0-kg Allende individual found partially embedded at base of cactus plant on 13 February 1969 (NMNH 3494). Sunglasses for scale. Found 3 to 4 km south of Rancho Santa Ana. See Figure 13.

pact was in the direction N40°E, in good agreement with the suggested strewnfield axis.

NMNH 3494, 7.0 kg, 3 to 4 km south of Rancho Santa Ana.

This specimen was found by a Mexican helper during the rainstorm on the morning of 13 February 1969 embedded at the base of a cactus plant. It is possible that the upper part of the plant was damaged by the essentially vertical descent of the specimen, but the damage may also have been caused by cattle (Figure 6). The specimen was buried approximately one-third its depth in the relatively soft earth at the base of the cactus.

NMNH 3495, 4.0 kg, approximately 2 km southeast of Rancho Santa Ana.

This specimen was sighted in a plowed field by a Mexican helper from a truck moving slowly along an adjacent road. The specimen was about 25 m from the road and had buried itself to about half its depth. It was found in the early afternoon of 13 February 1969.

NMNH 3502, 2.0 kg, approximately 200 m west of Rancho Blanco.

This completely crusted individual was found undisturbed on the afternoon of 14 February 1969 by a boy in our field party. It landed on hard, pebbly ground in a chaparral area and made virtually no impression (Figure 7). Only minor damage was done to the under side of the specimen.

NMNH 3509, 17 kg, approximately 1 km north of San Juan.

This large, completely crusted individual had been found north of San Juan within a few hundred

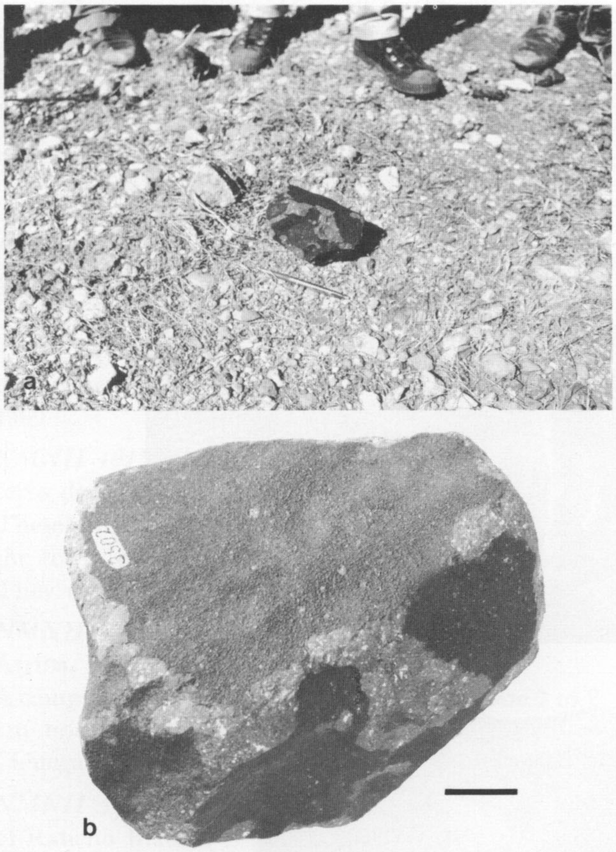


FIGURE 7.—A 2.0-kg Allende individual (NMNH 3502) found by local boy at edge of Rancho Blanco on 14 February 1969: *a*, in place, *b*, enlarged view; scale bar, 2 cm.

meters of the main road (Route 45). It was reported to have made a small depression in the ground and was recovered in three large fragments and three small ones. The fragments fit together neatly, reconstructing the original morphology. Surprisingly little damage was done other than the clean fractures through the body of the specimen. It is an eight-sided polyhedron, five sides of which were abraded by the soil. The fusion crust, however, is essentially intact.

NMNH 3513, 138 g, approximately 200 m southwest of Rancho Blanco.
This is a completely crusted individual that is unusually small for this area of the strewnfield. It was purchased 15 February 1969.

NMNH 3514, 202 g, approximately 200 m southwest of Rancho Blanco.
A nearly complete individual that is small for this area of the strewnfield. Probably less than 10 percent of the specimen is missing. It was purchased 15 February 1969.

NMNH 3517, 8.2 kg, approximately 200 m southwest of schoolhouse in San Juan.
The specimen was found in a plowed field near the school in San Juan (Figure 8). It has a large broken surface that is free of fusion crust, suggesting it separated into two major portions after the terminal point of its high-velocity flight. It was purchased from the finder 16 February 1969.

NMNH 3527, 12.0 kg, approximately 0.7 km south of San Juan.
This completely crusted individual was found undisturbed by Brian Mason about noon on 17 February 1969 (Figures 3 and 14). It was in a plowed field, having penetrated the ground to approximately its own depth. One large piece (11.0 kg), one small piece (1.0 kg), and several small fragments were removed from the hole.

NMNH 3528, 18.5 kg, approximately 0.5 km south-southeast of Pueblito de Allende.
This specimen was found at the edge of the Rio del Valle de Allende between Pueblito de Allende and Santa Ana in late February 1969. It is a completely crusted individual that landed undamaged in the stream bed. It is the largest sample that we know of that landed without breaking.

NMNH 3529, 33 kg, approximately 2 km northeast of San Juan.
This specimen was found fragmented near the main highway 2 km northeast of San Juan during February 1969. The fragments were collected by Manuel Gómez by purchase from residents of San Juan. The largest fragment weighed 14 kg and five other fragments were in the 1- to 5-kg range.

NMNH 3531, 9.3 kg, near Santa Ana.
An excellent, completely crusted individual found near Santa Ana. It was presented to the Smithsonian Institution 16 February 1969 by Mr. and Mrs. R. C. Byrd of Parral.

NMNH 3681, 281 g, near Porvenir.
A fragment purchased in late May 1969 near Porvenir. The owner reported that it was part of the 50-kg individual found earlier in the Sierra Almoloya.

NMNH 3682, 617 g of fragments, near El Cairo.
This collection of small fragments was purchased

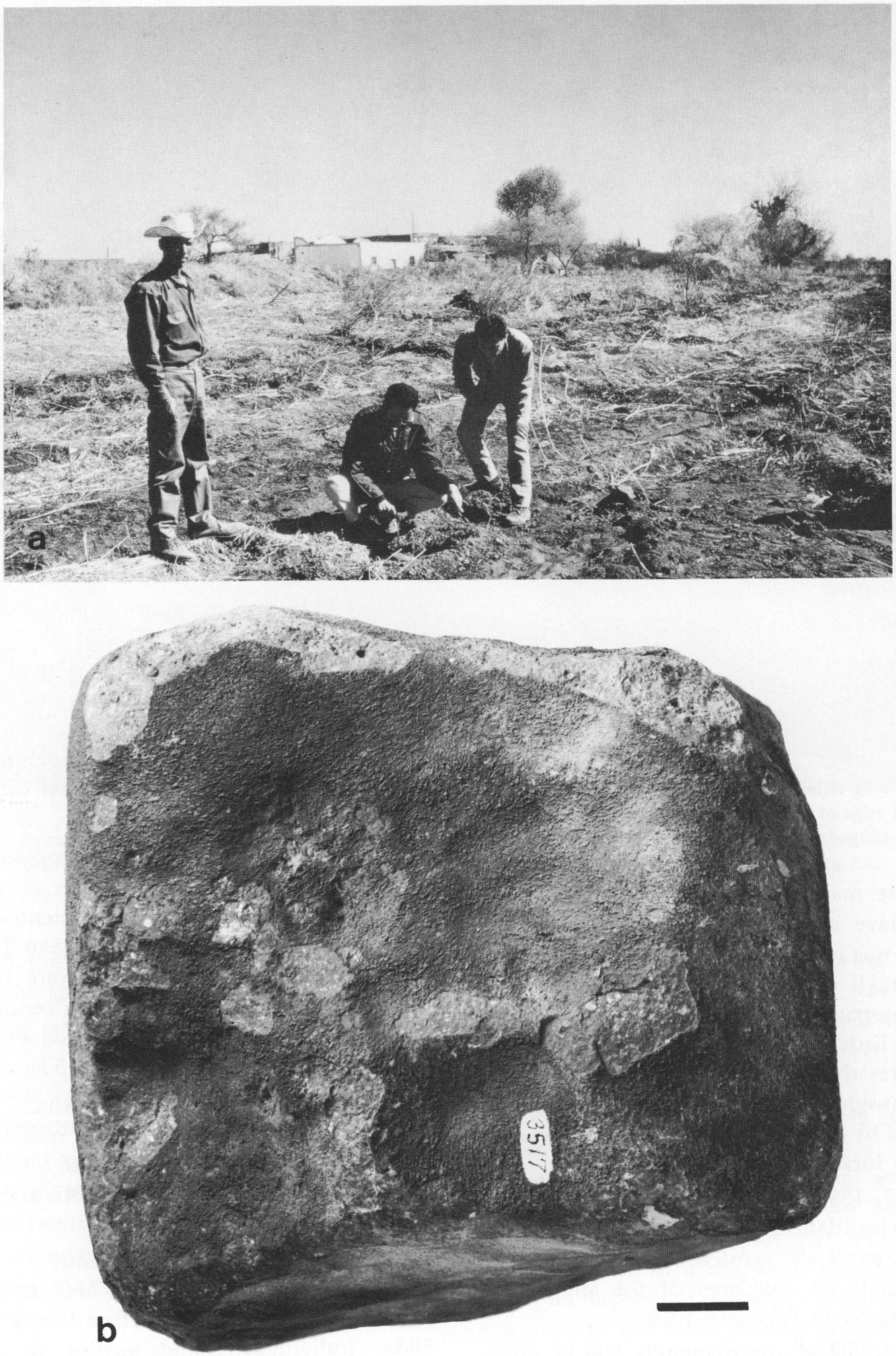


FIGURE 8.—An 8.2-kg Allende individual (NMNH 3517) found approximately 200 m southwest of schoolhouse (white building) in San Juan: *a*, finder with Manuel Gómez, kneeling, and César Gallardo, right, examining hole from which specimen had been recovered earlier. *b*, photograph of specimen; scale bar, 2 cm.

near El Cairo in late May 1969. The owner reported they were part of the 50 kg individual found earlier in the Sierra Almoloya.

NMNH 3935, 1.8 g, Torreón de Mata–Rancho (ruinas) area.
An unusually small, completely crusted individual. One surface of the specimen is a late break covered with light fusion crust. Purchased in June 1969.

NMNH 4006, 540 g, in riverbed directly north of Ciénega de Ceniceros de Abajo.
This platy specimen is unusually large for this area of the strewnfield (Figure 20). Purchased in June 1969.

NMNH 4015, 41 g and 39 g, in Ciénega de Ceniceros de Abajo.
These two specimens were both recovered within the town, one on a rooftop and one from a patio. They were purchased in June 1969.

NMNH 4289, 2 g, near Ciénega de Ceniceros de Arriba.
A completely crusted individual found in zone 1 to 2 km north to 1 to 4 km south and southwest of Ciénega de Arriba. Purchased during June 1969.

NMNH 4646, 4.36 kg, approximately 1.5 km east of Rancho Blanco.
This completely crusted large individual was found near Rancho Blanco—an area that had been intensively searched from the date of fall—in mid-June 1969. It was purchased within a day or two of the date it was found.

NMNH 4651, 26 g, from an area 1 to 3 km south of Rancho Blanco.
This completely crusted individual is an unusually small specimen for this part of the strewnfield. It was purchased in early June 1969.

NMNH 4655, 4.7 kg, at south edge of San Juan.
This completely crusted individual was found in the stream at the south edge of San Juan on Sunday, 8 June 1969. It was purchased shortly thereafter.

NMNH 4789 to 4799, 11 small specimens, tail of strewnfield.
These specimens were found in 1.5 km^2 area southwest of airstrip at tail of strewnfield. Eight of the specimens were completely crusted individuals, ranging in weight from 7.2 to 16 g. They were collected by Jack R. Hyde and local helpers in June 1969.

NMNH 4801 to 4809, 8 small specimens, tail of strewnfield.
These specimens were found in a 3 km^2 area to the southwest of the group above, at the extreme end of the strewnfield. Seven of the specimens can be considered complete individuals, and they range in weight from 3.1 to 43 g, with an average weight of 10 g. If the 43 g specimen is rejected, the average weight is 5 g. These specimens were collected by Jack R. Hyde and helpers in June 1969.

NMNH 5183, 1.1 g, near the Ceniceroses.
This is the smallest completely crusted individual in our collection. It is from a large group of specimens collected by a single person within an area 4 km to the northeast of Ciénega de Ceniceros de Arriba and Abajo extending 4 km to the south. This specimen was among a group purchased in November 1969.

NMNH 5240, 697 g, 4 km south of Valle de Allende.
This specimen was found during the first week of November 1969 partially buried in a field. It is a major part of an individual with one large fracture surface and fairly large areas where the fusion crust had spalled. Areas of the specimen that were unprotected by fusion crust and protruding from the ground were covered with a fine-grained white material tinged with blue and green. X-ray powder diffraction analysis showed that this material was largely hexahydrite ($MgSO_4 \cdot 6H_2O$). This specimen was purchased from its finder in November 1969.

NMNH 5268, 1.5 kg, south edge of Pueblito de Allende.
This specimen was found on 15 November 1969 on the south edge of Pueblito de Allende in the mud at the side of an irrigation ditch. It has large areas that were unprotected by fusion crust and apparently not buried completely in the mud. These areas are heavily covered with a coating of fine-grained white material tinged with blue and green. X-ray powder diffraction analysis showed this material may be mainly hexahydrite ($MgSO_4 \cdot 6H_2O$). This specimen was purchased in mid-November 1969.

OTHER METEORITES FROM THE PARRAL–JIMENEZ AREA.—Mexico is a country well-known for its many meteorite finds (Fletcher, 1890; Farrington, 1915;

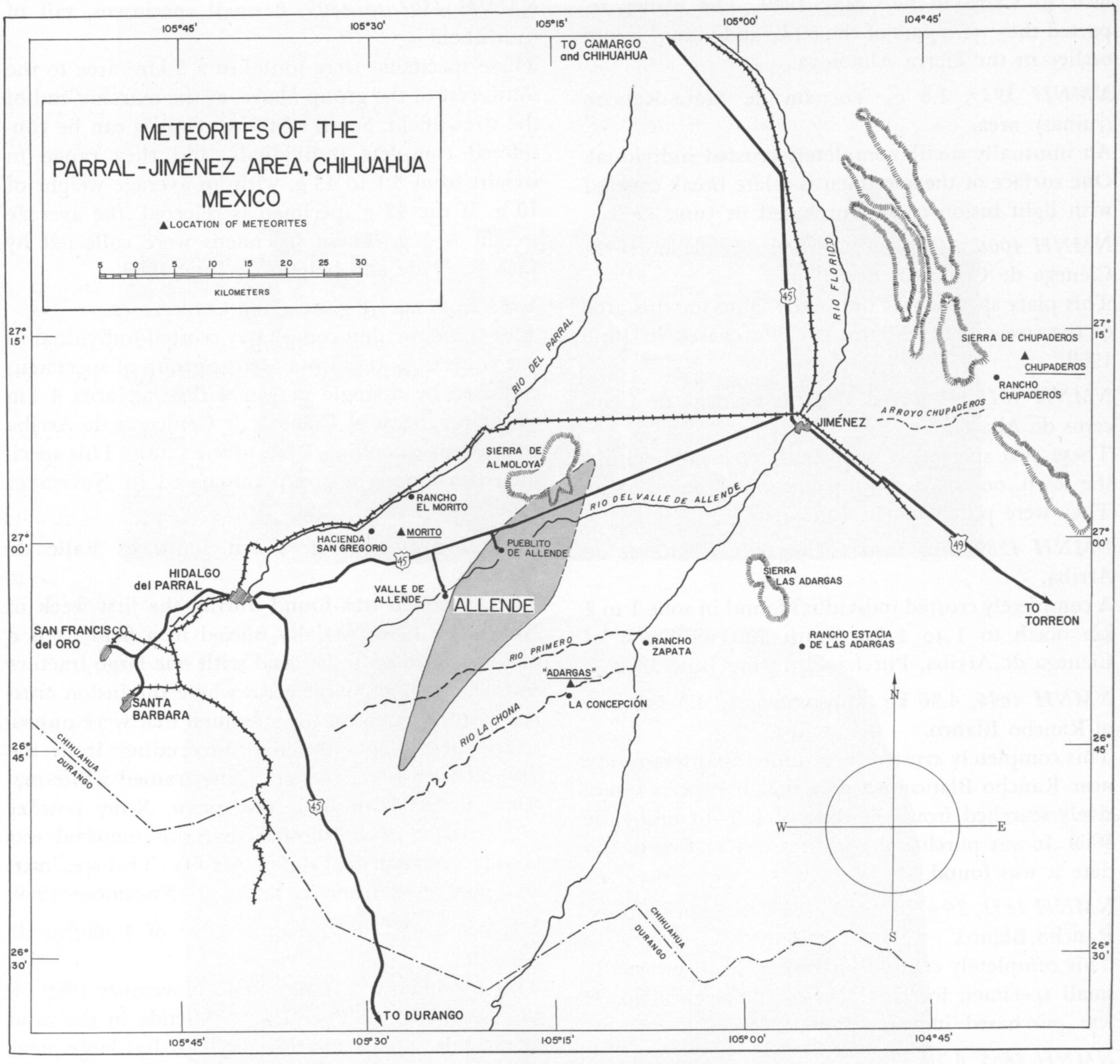


FIGURE 9.—Location of meteorites of the Parral–Jiménez area of Chihuahua, Mexico. The Allende meteorite fell between two of the largest iron meteorites known, Morito and Chupaderos.

Buchwald, 1968). Three out of the ten largest individual meteorite masses known are from Northern Mexico, and two of these, the Morito and Chupaderos irons, are from the Parral–Jiménez area of southern Chihuahua. The Allende meteorite, the largest stony meteorite yet observed, fell in between these two ancient falls, seemingly attesting to the "peculiar property, difficult of explanation which the Mexican soil has in attracting meteoritic" material (Barcena, 1876).

Morito is a single 11-ton conical mass of iron, a medium octahedrite (IIIA), known as early as 1600. It was found on Rancho El Morito (approximate location of find, latitude 27°00′N, longitude 105°28′W) and at an early date moved to Hacienda San Gregorio (Figure 9). It has since been moved to Mexico City and is preserved there in the School of Mines. The three Chupaderos irons are medium octahedrites (IIIB) that have been known for centuries (Figure 9). The two largest masses, 14 and 6.5 tons, were found on the east slope of the Sierra de Chupaderos (approximate location of find, latitude 27°10′N, longitude 104°40′W). The probable site of find of the Morito meteorite and the site of the two Chupaderos masses are separated by approximately 85 km. A third mass of the Chupaderos meteorite is the "Adargas" specimen (Buchwald, 1968). "Adargas" is a 3.4 ton mass that was moved at an early date to La Concepción (Figure 9), possibly coming originally from the area of the Sierra Las Adargas.

The Parral–Jiménez area is undoubtedly among the richest meteorite-producing areas in the world. Within the relatively small area of approximately 4,000 km^2, three of the world's major meteorites have been recovered: the 11-ton Morito iron, the 24 tons of Chupaderos irons, and several tons of the Allende stony meteorite. The area per meteorite find for North America as a whole is 30,000 km^2, many times the area of recovery of the Morito–Allende–Chupaderos meteorites.

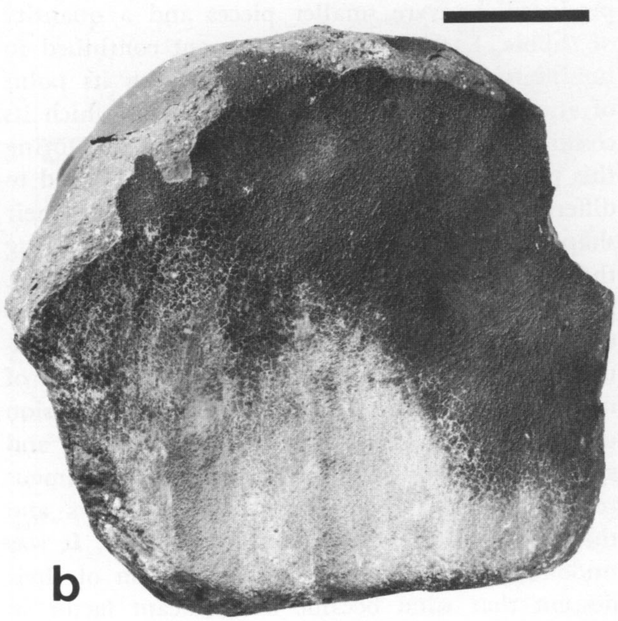
The place-names used in our map (Figure 9) are all taken from the modern base maps described above. Important names relating to the history of the Morito and Chupaderos irons have changed in a number of instances since the early reports and maps were prepared. Jiménez or Ciudad Jiménez was known earlier as Huejuquilla (an Indian name, pronounced Wa-hu-ke-yah), and a number of variations on this spelling have been used. Valle de Allende was previously known as El Valle de San Bartolomé, and simply as El Valle. The Rio del Valle de Allende has been known as Rio de Allende and Rio de San Bartolomé. The Rio la Chona has been referred to as the Rio de la Concepción.

Three other meteorites are listed in the literature as coming from the Parral–Jiménez area: Parral, Tule, and Sierra Blanca (Hey, 1966). All three of these meteorites have recently been examined by V. F. Buchwald (personal communication, 1969) as part of his comprehensive examination of iron meteorites. Buchwald reports that Parral appears to be a fragment of Morito, Tule is a pseudometeorite, and Sierra Blanca may be a transported fragment of the Toluca shower.

Morphology

The individual Allende meteorite specimens preserve in their ablation crusts and gross morphology a partial record of the meteoroid's passage through the atmosphere. This information, combined with the observed specimen distribution pattern (discussed above), allows us to derive a probable sequence of events. The meteoroid entered the atmosphere at a low angle as a single large body with cosmic velocity (greater than 11 km/sec. and probably less than 18 km/sec., McCrosky et al., 1969). Friction between it and the increasingly dense atmosphere produced ablation and initiated the luminous fireball stage. Continued penetration into the atmosphere was followed by a major disruption—an explosion of the parent body—at a relatively great altitude. Many large blocky fragments were produced, as were smaller pieces and a quantity of rubble. Each individual fragment continued in luminous, ablative flight until reaching its point of atmospheric retardation, the point at which its cosmic velocity was completely dissipated. During this part of the flight, fragments were subjected to differential atmospheric drag depending on their shape and orientation, resulting in size sorting along the trajectory and lateral broadening of the cluster. It was during this interval between initial disruption and retardation that fragments became individual crusted meteorite specimens. The recovery of numerous specimens with areas of secondary fusion crust indicates at least minor fragmentation and spallation subsequent to initial breakup. Specimens reached their individual retardation points and then continued to the ground in free fall. It was undoubtedly during the free-fall portion of their descent that wind became a significant factor in distorting the symmetry of the field (Figure 2). The largest specimens traveled the farthest and shattered on impact, making small holes in the ground, while small specimens generally fell far behind, producing no damage and being recovered unscathed. Large- to medium-size specimens were recovered between the two extremes, their condition on recovery depending on such factors as preexisting weakness in the specimen and whether it landed on hard or soft ground. Many remarkably fragile features ablated on Allende meteorite fusion crust survived descent.

Individual stones are typically ablation-modified



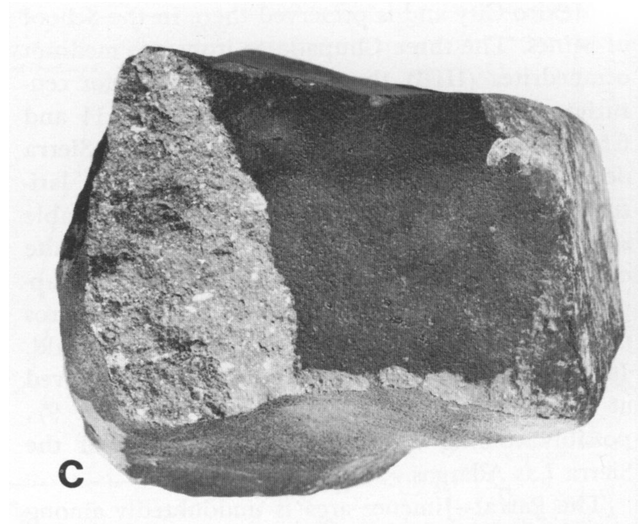


FIGURE 10.—A 11.4-kg blocky, crusted Allende individual (NMNH 3523) found between Pueblito de Allende and San Juan. Scale bar, 5 cm.

fragmental shapes; blocky, pyramidal, and occasionally lenticular. They are covered with a dull black fusion crust that tends to be chipped or spalled away at edges, revealing either fresh fracture surfaces or fracture surfaces covered with a light secondary fusion crust that is frequently reddish in hue. The fusion crust contains occasional lustrous spots above the calcium and aluminum-rich aggregates which are characteristic of the meteorite, and infrequent sooty areas above fine-grained black inclusions. The amount of aerodynamic shaping of an individual fragment is related to the stability of its orientation during ablative flight. A small percentage of the individuals shows evidence of oriented flight and heavy ablation both in the gross shape of the specimen and in the character of fusion-crust development on anterior and posterior surfaces. A particularly curious feature of Allende specimen morphology is the presence on five specimens of hollow filaments of fusion crust encapsulating an as yet unidentified material, apparently a colorless hydrocarbon. In the following section individual specimens that illustrate many of these features will be described.

NMNH 3523, 11.4 kg, found between Pueblito de Allende and San Juan.

This large, blocky specimen was purchased in Pueblito de Allende on 16 February 1969. Its fragmental shape appears to be relatively unmodified by ablation, but its surfaces are essentially covered with a well-developed fusion crust (Figure 10). Spalling has occurred along edges, and many of these spalled areas are partially or completely covered with a thin reddish secondary fusion crust that does not show clearly on the photographs. One fairly large fragment appears to have broken off at a late stage, leaving a fresh fracture surface (Figure 10*c*). Inclusions in the matrix revealed on this fracture surface appear to have a parallel alignment, an

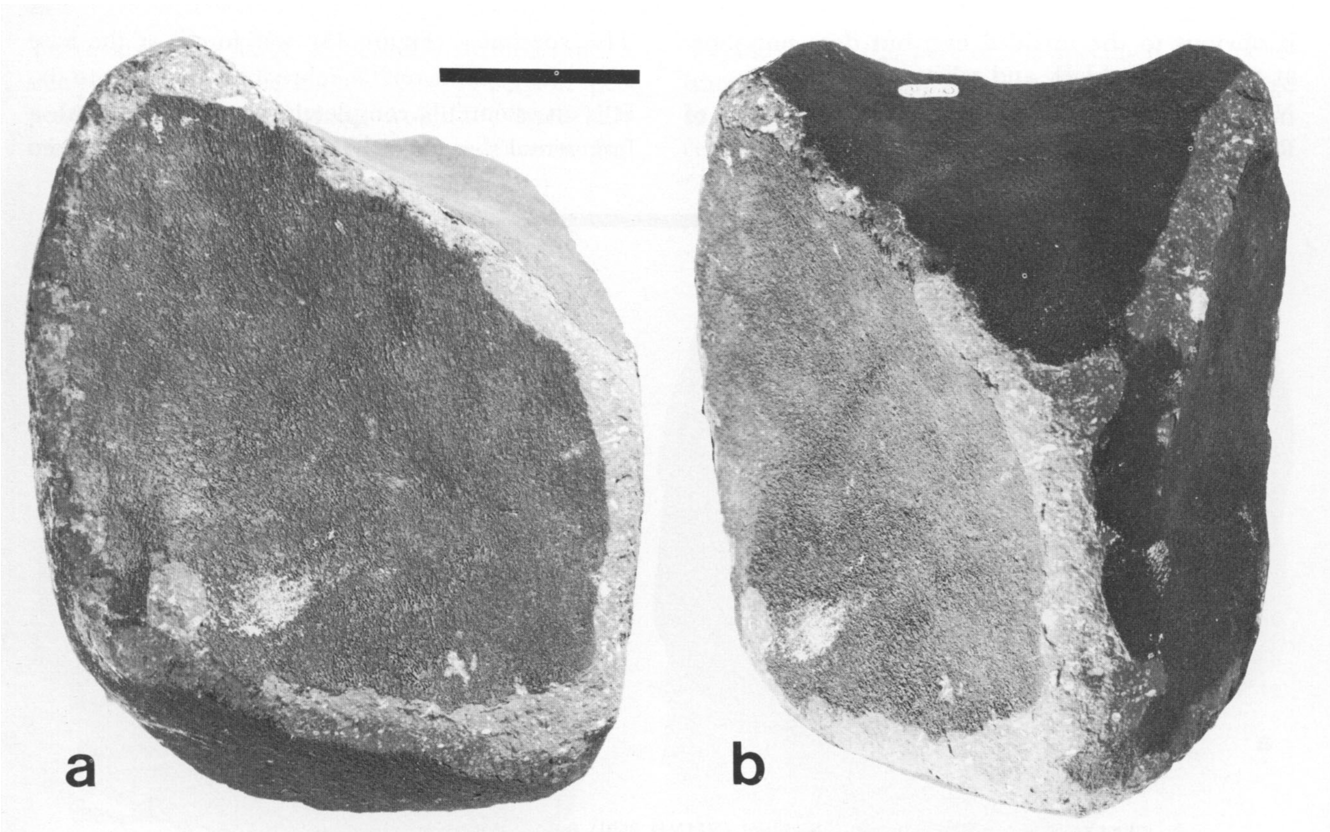


FIGURE 11.—A 6.2-kg Allende individual (NMNH 3500) found approximately 700 m southwest of Rancho Blanco. Scale bar, 5 cm.

alignment that is also parallel to the top and bottom exterior surfaces in this photograph (Figure 10*c*). This suggests that the fracture pattern of the rock may well be related to its internal fabric. The lower part of Figure 10*b* shows the effect of colliding with the ground. Light-colored clay soil is embedded in the fusion crust, but the crust survived essentially intact. At the upper part of the light-colored area a well-developed polygonal craze pattern is emphasized by soil filling small cracks. This surface craze is observed on specimens recovered very soon after they fell, but is much more pronounced on some specimens that have been exposed to the elements for a few months.

NMNH 3500, 6.2 kg, found approximately 700 m southwest of Rancho Blanco.

This large specimen was purchased in Rancho Blanco on 14 February 1969. It is a fragmental shape only slightly modified by atmospheric ablation; a rectangular base, two trapezoidal sides, and triangular ends (Figure 11). The rectangular surface is indicated in profile in Figure 11*b*. Several of the surfaces are slightly convex, and they are all covered with a well-developed fusion crust. Spalling of fusion crust at edges, a common feature in Allende specimens in general, is particularly pronounced on this stone.

NMNH 3501, 4.3 kg, found approximately 2 km southwest of Rancho Blanco.

This complete individual was purchased in Rancho Blanco on 14 February 1969. It is a nine-sided figure, comprising three triangular and six trapezoidal surfaces (Figure 12), suggestive from certain aspects of a distorted octahedron (Figure 12*a*). Its flat surfaces are all heavily crusted, but there are relatively numerous areas of spalled crust at edges. Most of these spalled areas are covered with a thin reddish secondary fusion crust. The apex area in Figure 12*a* is covered with this very thin crust that is obvious to the unaided eye, but does not show at all on these black and white photographs.

NMNH 3494, 7.0 kg, found 3 to 4 km south of Rancho Santa Ana.

This specimen (Figure 13) was found at the base of a cactus plant on 13 February 1969 (Figure 6). It is an essentially completely crusted individual, a fragmental shape relatively unmodified by ablation.

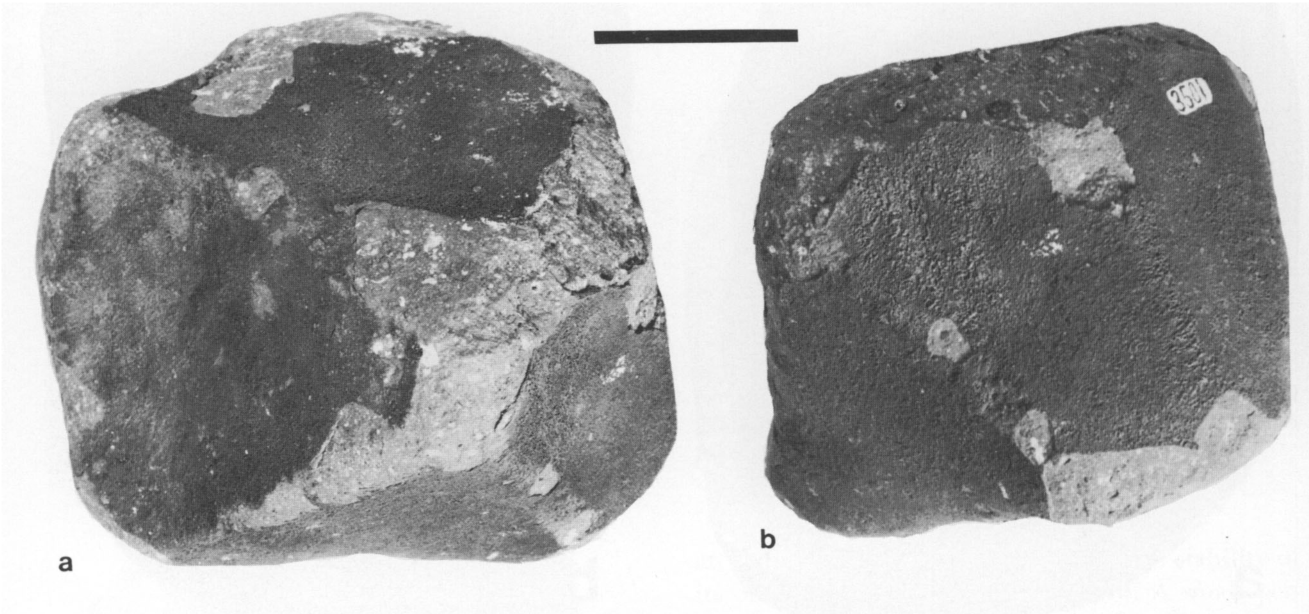


FIGURE 12.—A 4.5-kg Allende individual (NMNH 3501) found approximately 2 km southwest of Rancho Blanco. Scale bar, 5 cm.

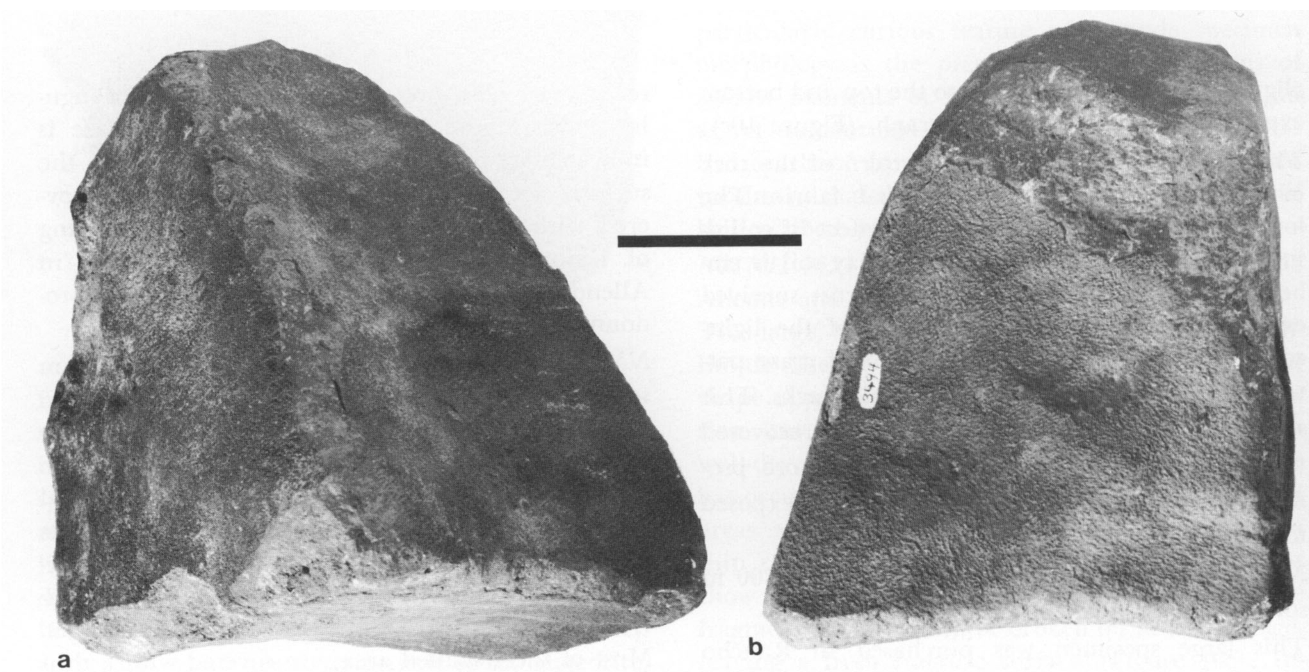


FIGURE 13.—A 7.0-kg Allende individual (NMNH 3494) found at base of cactus 3 to 4 km south of Rancho Santa Ana. See Figure 6. Scale bar, 5 cm.

There are three large trapezoidal surfaces and a small one at the specimen's apex. A section perpendicular to these surfaces would be essentially triangular. The corner and bottom surface in Figure 13*a* shows the part of the specimen that penetrated the ground on landing. Only slight damage to the specimen seems to have resulted. Fusion crust appears to have spalled off of most of the

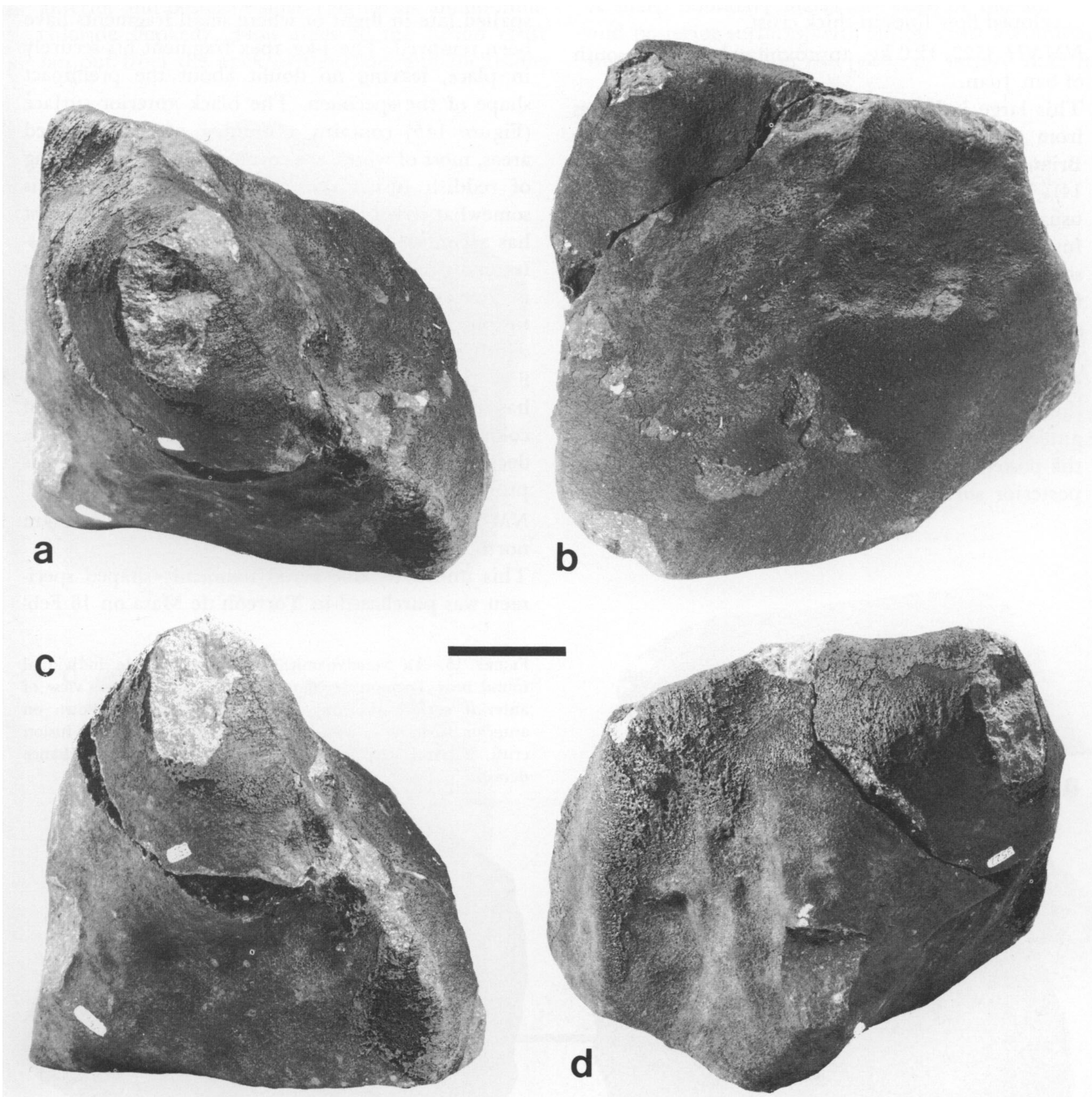


FIGURE 14.—An unusually large oriented Allende individual (NMNH 3527). Found in place approximately 0.7 km south of San Juan (see Figure 3), broken into 1.0-kg and 11.0-kg pieces: *a*, anterior surface to right, zone of fusion-crust accumulation diagonally from left to right, and posterior surface to left; *b*, anterior surface; *c*, posterior surface and zone of fusion-crust accumulation; *d*, posterior surface and zone of fusion-crust accumulation. Scale bar, 5 cm.

edges of the specimen, and most of the spalled areas have a thin coating of secondary fusion crust. One surface (Figure 13*b*) has a large area of spalled fusion crust, the edges of which have this secondary coating. The large surfaces in Figure 13*a* have well-developed flow lines in thick crust.

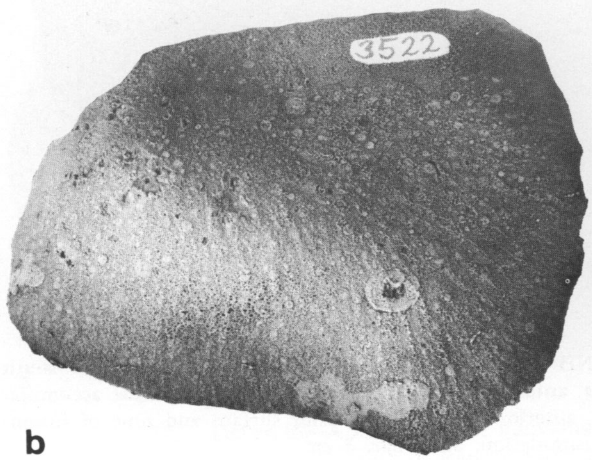
NMNH 3527, 12.0 kg, approximately 0.7 km south of San Juan.

This large individual was recovered in two pieces from a plowed field, buried to its own depth, by Brian Mason on 17 February 1969 (Figures 3 and 14). It is of particular interest because it is an unusually large oriented individual with spectacular fusion-crust development. The specimen's basic shape is a distorted pyramid with one domed surface. All of the photographs in Figure 14 show the specimen sitting on the same surface. Figure 14*a* was taken looking down on the specimen, showing the edge of the anterior (upper right) and posterior (lower left) surfaces. Figure 14*b* is of the complete anterior surface, while Figure 14*d* shows much of the posterior area. Figure 14*c* shows one side of the posterior surface, a portion of the zone of fusion-crust accumulation, and an edge of the anterior surface. The surface not shown is a posterior surface also containing a zone of fusion-crust accumulation. This specimen is essentially completely crusted, but it does have a number of small areas where crust spalled late in flight or where small fragments have been removed. The 1-kg apex fragment fits securely in place, leaving no doubt about the preimpact shape of the specimen. The black anterior surface (Figure 14*b*) contains a number of small spalled areas, most of which are covered with a thin coating of reddish fusion crust. This anterior surface is somewhat irregular, and thick vesicular fusion crust has accumulated in depressions. A zone of the posterior surface along the edge of the anterior surface is covered with a thick vesicular accumulation of fusion crust (Figure 14*a,c,d*). This zone has a width of 6 cm in some areas and shows a distinct flow pattern. The posterior surface (Figure 14*c,d*) has a much thinner fusion crust that is lighter in color than that on the anterior surface, having a decided brownish hue. A polygonal craze pattern is pronounced on this thinner crust.

NMNH 3522, 188 g, found approximately 2 km north of Torreón de Mata.

This unusually fine aerodynamically shaped specimen was purchased in Torreón de Mata on 16 Feb-

a



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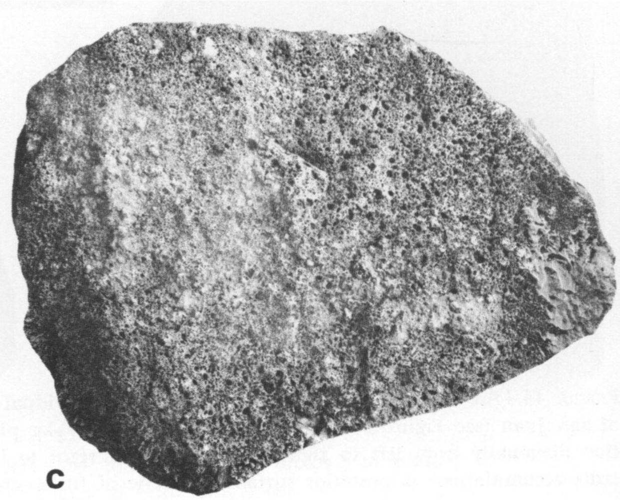


c

FIGURE 15.—An aerodynamically shaped Allende individual found near Torreón de Mata (NMNH 3522): *a,* side view of anterior surface showing cone shape; *b,* looking down on anterior surface; *c,* posterior surface with vesicular fusion crust. Natural size, ammonium-chloride smoked to enhance detail.

ruary 1969. It appears to have entered upon independent flight in the atmosphere as a plate-shaped fragment. Orientation was maintained and aerodynamic sculpturing smoothed forward edges and produced a cone-shaped specimen with pronounced anterior and posterior sides (Figure 15, ammonium-chloride smoked). Flow lines in the fusion crust fan out from the apex of the cone, and inclusions within the meteorite produced a patchy appearance due to varying crust composition (Figure 15 *a,b*). The outline of chondrules produced a pronounced pattern on the anterior surface, and small depressions in this surface developed areas of vesicularity. A sharp boundary marks the edge of the anterior and posterior surfaces, with fusion crust accumulating preferentially on the posterior surface near its

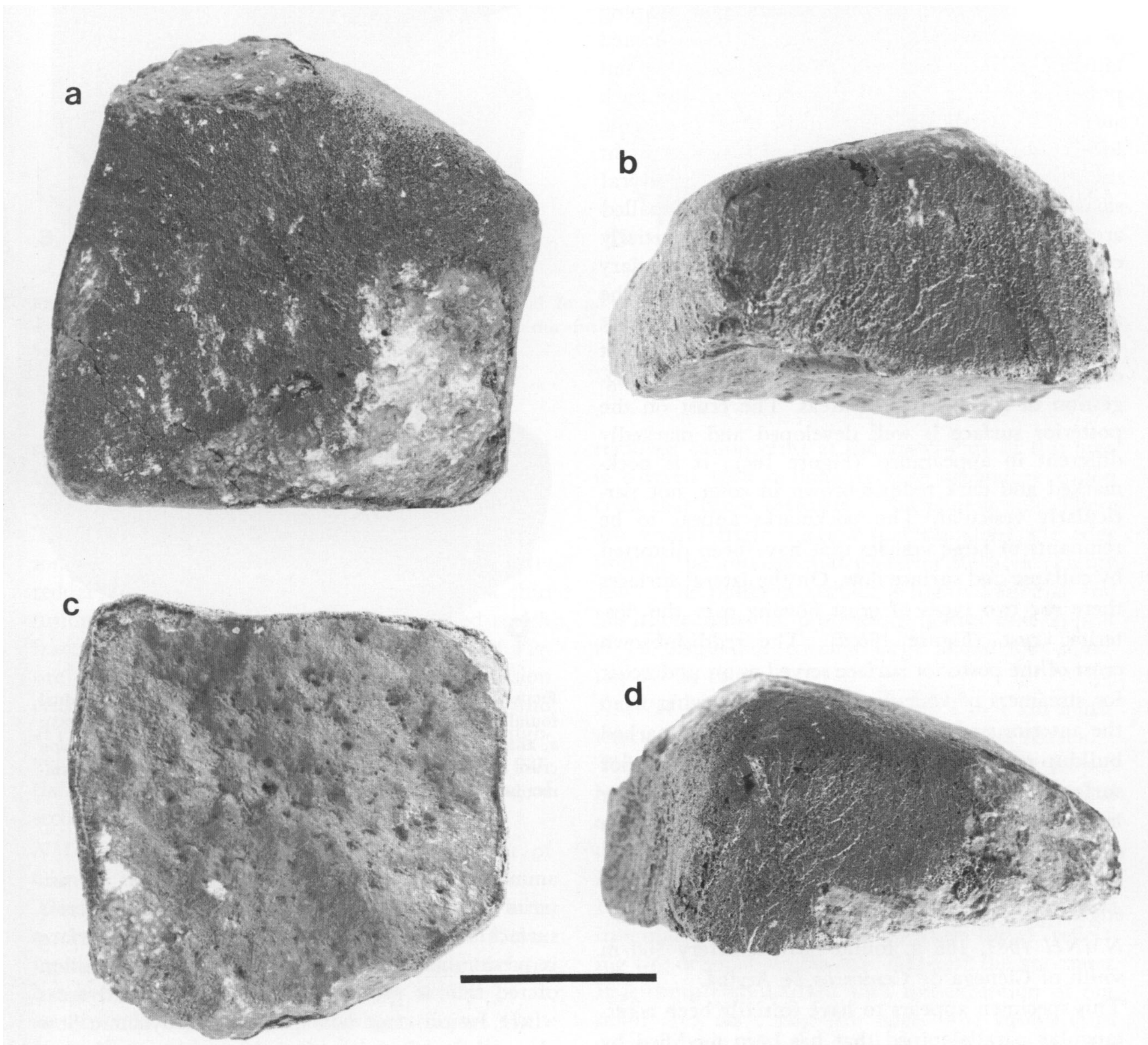


FIGURE 16.—An aerodynamically shaped Allende individual from the area of the Ceniceroses (NMNH 4018): *a*, looking down on anterior surface; *c*, posterior surface with fusion-crust accumulation at edges; *b* and *d*, side views showing flow of fusion crust. Scale bar, 2 cm.

edge. The posterior surface is uneven, undoubtedly a result of initial fragmentation. It is completely covered with a highly vesicular fusion crust that is somewhat thinner toward the center of the surface. Fusion crust in general on the posterior surface is considerably thicker than on the anterior surface.

NMNH 4018, 121 g, found in an area extending 4 km south and southeast of the Ceniceroses.

This specimen resulted from aerodynamic shaping of a blocky fragment (Figure 16). It has a domed anterior surface, four lateral surfaces, and a flat posterior surface. Two of the corners of the back surface are nearly right angles, the other two being less regular. A fairly large area of fusion crust at the apex of the dome has spalled, as have several smaller areas of crust at edges. One small spalled area on the anterior surface has been partially covered with a light coating of reddish secondary fusion crust. Most of the white material on the anterior surface is foreign matter due to contact with the ground (Figure 16*a*). The fusion crust on the forward surface is black with a slight suggestion of red in limited areas. The crust on the posterior surface is well developed and markedly different in appearance (Figure 16*c*). It is pockmarked and dark reddish-brown in color, not particularly vesicular. The pockmarks appear to be remnants of large vesicles that have been distorted by collapse and surface flow. On the lateral surfaces there are two types of crust flowing over the posterior crust (Figure 16*b,d*). The reddish-brown crust of the posterior surface served as an undercoat for streamers of vesicular black crust flowing from the anterior surface. There is a particularly marked buildup of fusion crust at the edge of the posterior surface (Figure 16*c*), resulting from flow along the lateral surfaces. Small beads of black glass were carried on to the posterior surface by airflow and can be seen with moderate magnification near the edge.

NMNH 4083, 165 g, found near cemetery 300 m south of Ciénega de Ceniceros de Arriba.

This specimen appears to have initially been a rectangular parallelepiped that has been modified by oriented flight and one major late-stage fracture. It has four distinct surface types; anterior, lateral, posterior, and fracture. Figure 17 gives views of ammonium-chloride smoked surfaces; (a) the anterior surface, and (b) the edge of the anterior surface and a lateral surface. The anterior surface is predominantly black in color with a suggestion of red that is pronounced in the few small areas where fusion crust has spalled. Aerodynamic flow along the surface is recorded as stringers of glass in the fusion crust (Figure 17*a*). A surface pattern due to differential melting of chondrules and matrix is evident. Figure 17*b* is of an edge of the anterior

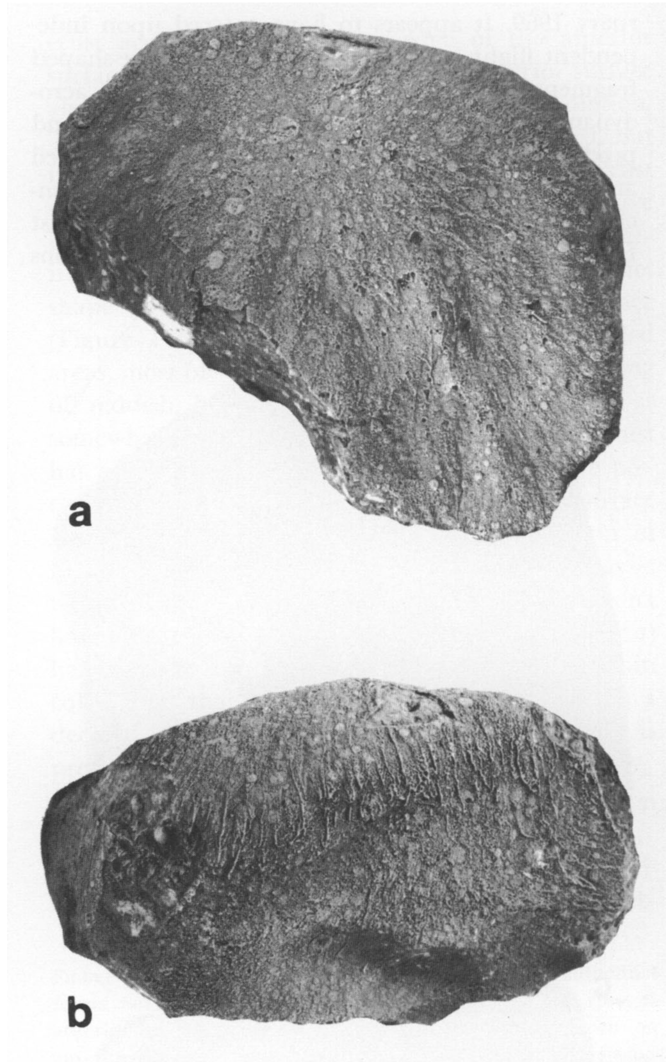


FIGURE 17.—An aerodynamically shaped Allende individual found near Ciénega de Ceniceros de Arriba (NMNH 4083): *a,* anterior surface; *b,* side view, showing streamers of fusion crust at the edge of the anterior surface. Natural size, ammonium-chloride smoked to enhance detail.

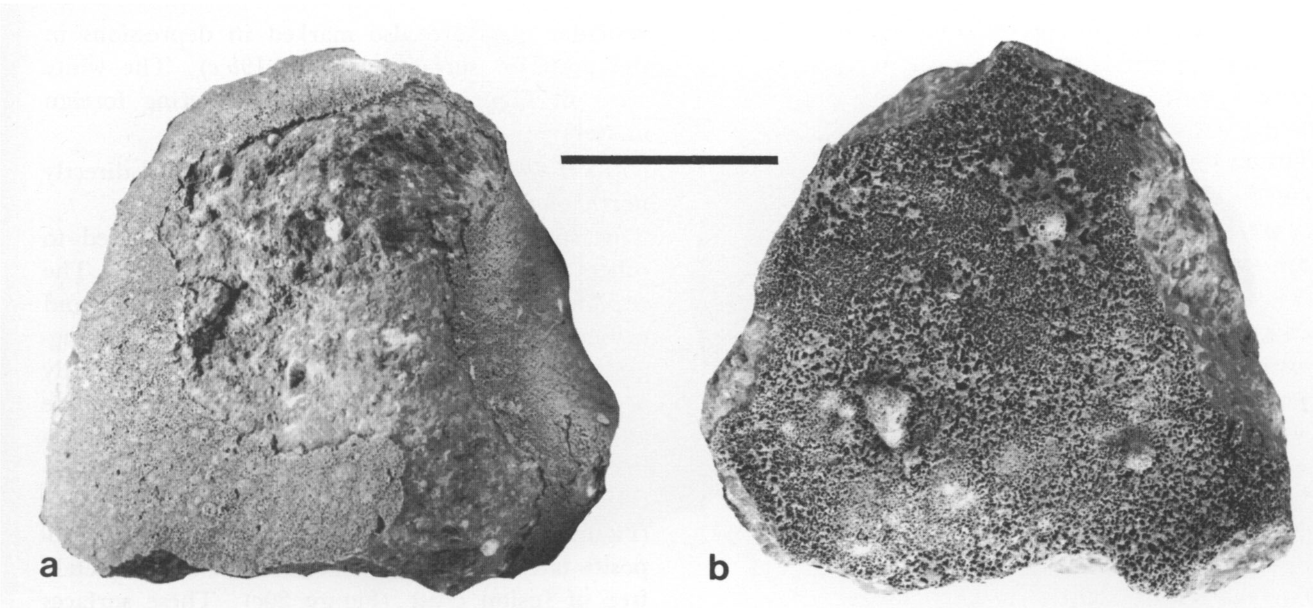


FIGURE 18.—An aerodynamically shaped Allende individual found southwest of Ciénega de Ceniceros de Abajo (NMNH 4084): *a*, Anterior surface with spalled apex; *b*, vesicular posterior fusion crust. Ammonium-chloride smoked to enhance detail. Scale bar, 2 cm.

surface and a lateral surface. The accumulation of fusion crust marked by stringers of glass in the photograph marks the edge of the lateral surface. The fusion crust on the lateral surface below the zone of accumulation is thinner and noticeably redder in color. The posterior surface has a thin fusion crust covering a relatively unmodified rough fracture surface. The area in the lower left of Figure 17*a* is a late fracture surface, free of fusion crust. There are areas on the posterior surface and at edges where fusion crust has spalled late in high-velocity flight, and some of these are covered partially or completely with a light, reddish coating of secondary fusion crust.

NMNH 4084, 87 g, found 1½ km southwest of Ciénega de Ceniceros de Abajo.

The basic shape of this specimen seems to have been a somewhat irregular tetrahedron (Figure 18, ammonium-chloride smoked). One set of three surfaces has been smoothed into an anterior surface of an aerodynamically oriented individual (Figure 18*a*). Its anterior and posterior surfaces are clearly defined by the character of their fusion-crust development. The anterior surface has fusion crust over about half of its area, spalling late in flight having removed fusion crust at the apex. Part of this area is covered with a light, reddish secondary fusion crust that is not revealed in the photograph. There are several fresh fracture surfaces along the edge joining the anterior and posterior surfaces (Figure 18*b*). The posterior surface is highly vesicular and has three unusual protruding bodies that appear to be fusion-crust-covered large chondrules standing out in relief.

NMNH 4157, 15 g, found in area 1 to 4 km southwest to south of Ciénega de Ceniceros de Arriba.

This initially small fragment was markedly shaped by aerodynamic ablation (Figure 19). It is typical of a number of small individuals recovered from the strewnfield, generally south of the Torreón de Mata area and frequently south of the Ceniceroses. It has a domed anterior surface (Figure 19*a*) and irregular posterior surfaces (Figure 19*b*,*c*) reflecting the original fragmental shape of the specimen. It is completely crusted with the exception of one small area on a posterior edge. The fusion crust on the anterior surface is comparatively thin, with a number of fine cracks. Fusion-crust accumulations developed at edges of the posterior surface due to flow from the anterior surface. Accumulations of

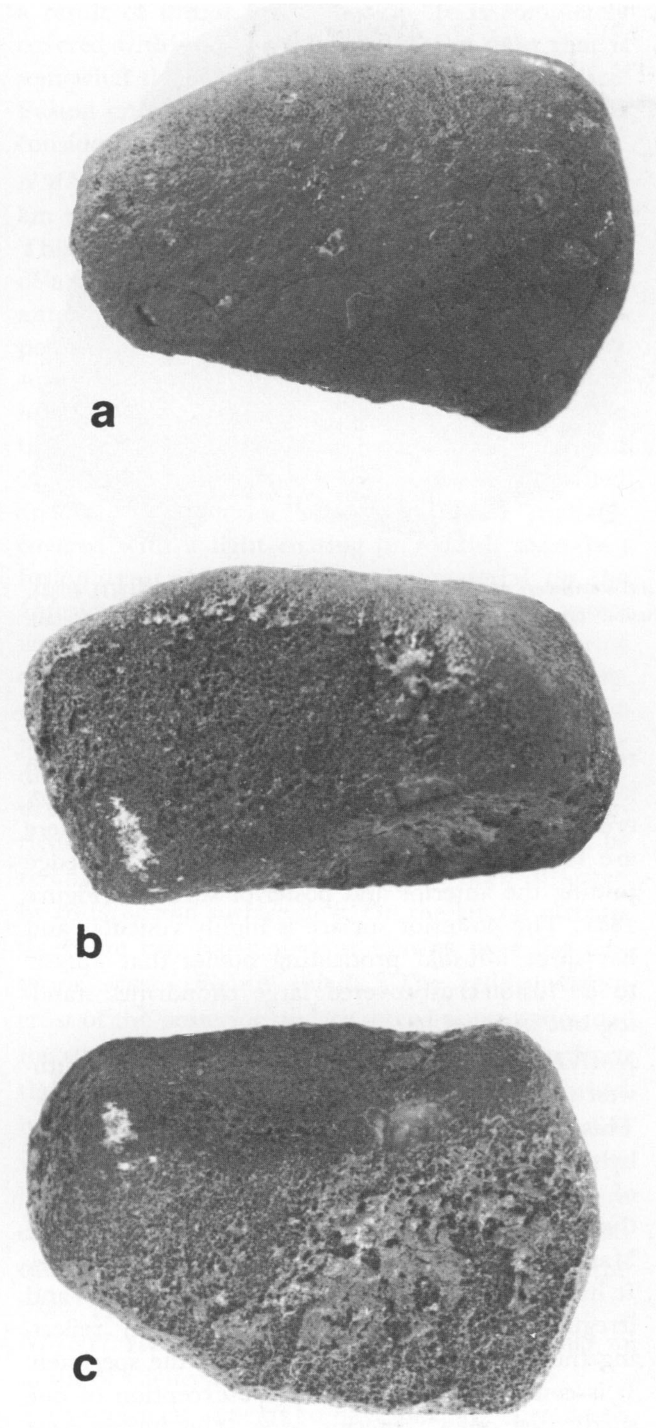


FIGURE 19.—A small aerodynamically shaped Allende individual (NMNH 4157) found southwest of the Ceniceroses: *a*, anterior surface; *b*, side view; *c*, posterior surface. Twice actual size.

vesicular glass are also marked in depressions in the posterior surfaces (Figure 19*b*,*c*). The white areas in Figure 19*b* and *c* are adhering foreign matter.

NMNH 4006, 540 g, found in the riverbed directly north of Ciénega de Ceniceros de Abajo.

This specimen is remarkably heavy compared to others found so far south in the strewnfield. The explanation is undoubtedly atmospheric drag, and evidence from the specimen itself supports this suggestion. The specimen was undoubtedly initially a platy fragment that presented to the atmosphere an exceptionally large surface area in relation to its mass (Figure 20). Fusion-crust development indicates clearly an anterior (Figure 20*b*) and posterior (Figure 20*a*) surface. Fairly large areas on two opposite lateral surfaces are recent breaks, completely free of fusion crust (Figure 20*c*). These surfaces demonstrate that the area presented to the atmosphere during high-velocity flight was certainly somewhat greater than the area of the present anterior surface. The edges of the anterior surface that do not join recent fracture surfaces are rounded (Figure 20*b*), and flow lines within the fusion crust on lateral surfaces indicate flow toward the posterior surface. In several areas where lateral surfaces join the posterior surface there are accumulations of vesicular crust (Figure 20*a*) on the posterior surface. Fusion crust on the anterior surface is relatively thin and noticeably reddish in color. The posterior-surface fusion crust is similar, but it is spattered in streaks with a black lustrous glass, suggestive of snail tracks, undoubtedly derived from areas of fusion-crust accumulation. The result is that the posterior surface has a sheen that is not noticeable on the anterior surface.

Of the specimens available to us from the area of the Ceniceroses, less than 6 percent weigh more than 100 g, less than one percent more than 200 g, and less than 0.1 percent more than 300 g. The four heaviest specimens are: NMNH 4006, 540 g, discussed above, NMNH 4007, 272 g; NMNH 4533, 257 g; NMNH 4575, 232 g. Three of these (NMNH 4006, 4533, 4575) are aerodynamically shaped specimens with a large ratio of anterior surface area to weight of specimen. This would appear to be a clear demonstration of atmospheric sorting on the basis of shape as well as on the basis of mass.

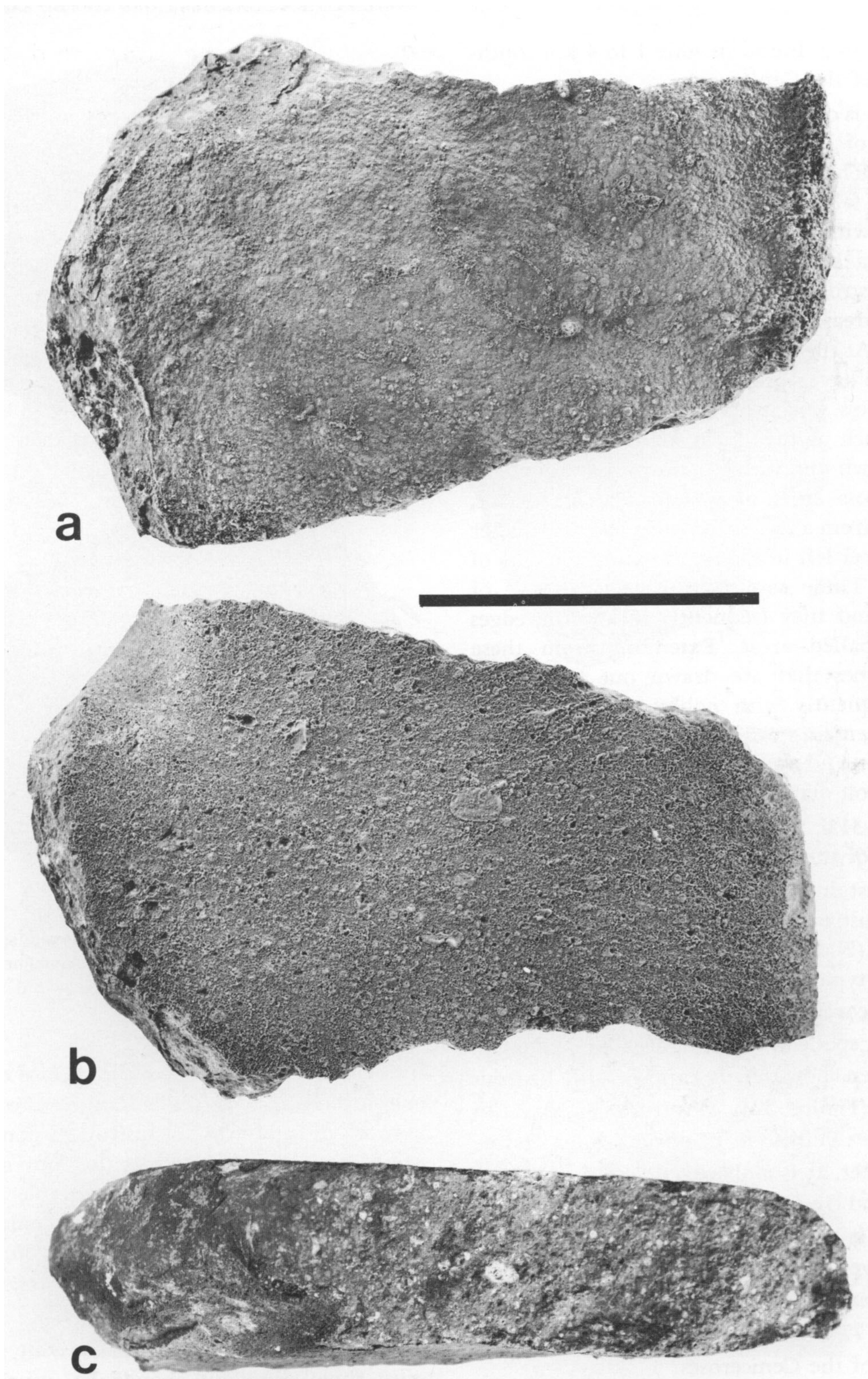


FIGURE 20.—An unusually large Allende individual (NMNH 4006) found near Ciénega de Ceniceros de Abajo. The flat shape resulted in high drag and retardation: *a,* posterior surface; *b,* anterior surface; *c,* broken surface on bottom side of *b*. Scale bar, 5 cm.

NMNH 3812, 46 g, found in zone 1 to 4 km southeast to north of the Ceniceroses.

This specimen is one of a group of five displaying an unusual type of lustrous fusion-crust development (Figure 21). The specimen has areas of normal fusion crust (~30%), spalled areas that are partially covered with secondary fusion crust (~50%), and areas of a black, lustrous, blistery appearing crust. This lustrous crust appears in part to have flowed over areas of regular fusion crust on to spalled areas. At the edges of these areas of flow the crust seems to have accumulated to a greater than normal thickness, and it has a resinous appearance. From areas such as this, crust material appears to have been drawn out, forming straps that adhere to or bridge across areas of spalled matrix surface, jumping gaps from a few millimeters to a centimeter in length (upper left in Figure 21*a* and right side of Figure 21*b*). These ropy straps are suggestive of drawn taffy, and they frequently follow the edges of concave spalled areas. Extending from these straps are spines that are drawn out to delicate filaments, frequently with nobby ends. Filaments on this specimen are translucent and amber in color when very thin, and apparently encapsulate a colorless hydrocarbon material.

NMNH 3813, 34 g, found in zone 1 to 4 km southeast to north of the Ceniceroses.

This is the most dramatic of the five specimens with the type of lustrous fusion-crust development described above (NMNH 3812). In most respects, this specimen is a typical small individual, much of its surface being covered with ordinary and secondary fusion crust or spalled areas (Figure 22*b*). One end of the specimen, however, is capped with lustrous fusion crust (Figure 22*a*). Protruding from this area is a spine reminiscent of an antler, extending a full centimeter. It is amber in reflected light, but light yellow and translucent when backlighted (Figure 22*c*). It is remarkable that features of this delicacy survived landing, recovery by a local resident, and shipment to Washington.

NMNH 3814, 77 g, found in zone 1 to 4 km southeast to north of the Ceniceroses.

A large part of the surface of this specimen is free of fusion crust (Figure 23*b*), while other areas are covered with a normal thick, and in part vesicular,

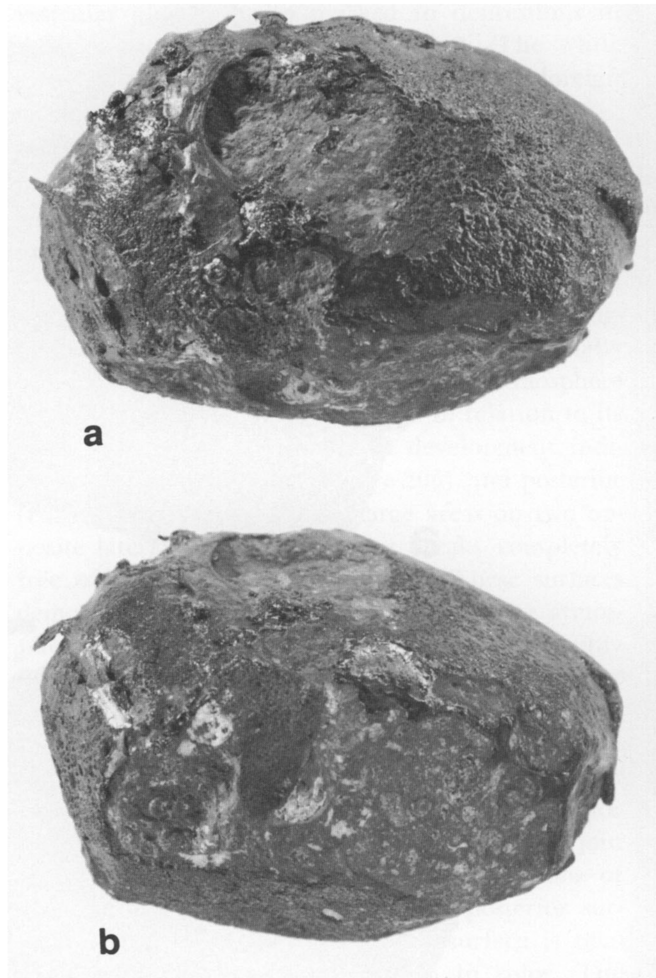


FIGURE 21.—One of a small group of Allende specimens with an unusual, lustrous fusion-crust development. Found near the Ceniceroses (NMNH 3812). Twice actual size.

fusion crust. About half of the surface of the specimen, overlying both spalled and crusted areas, is a network of ropy straps of lustrous fusion crust (Figure 23*d,e*). In several places the ropy material has lifted from the surface of the sample and can be seen in silhouette. Figure 23*a* is an enlargement of the area in the upper left of Figure 23*b*, and Figure 23*c* is an enlargement of an area in the upper right of Figure 23*b*.

Broken surfaces and surfaces with thin fusion crust show abundant chondrules, usually about 1 mm in diameter, but sometimes much larger. Broken surfaces of a single large fragment from a 33 kg individual are illustrated in Figure 24

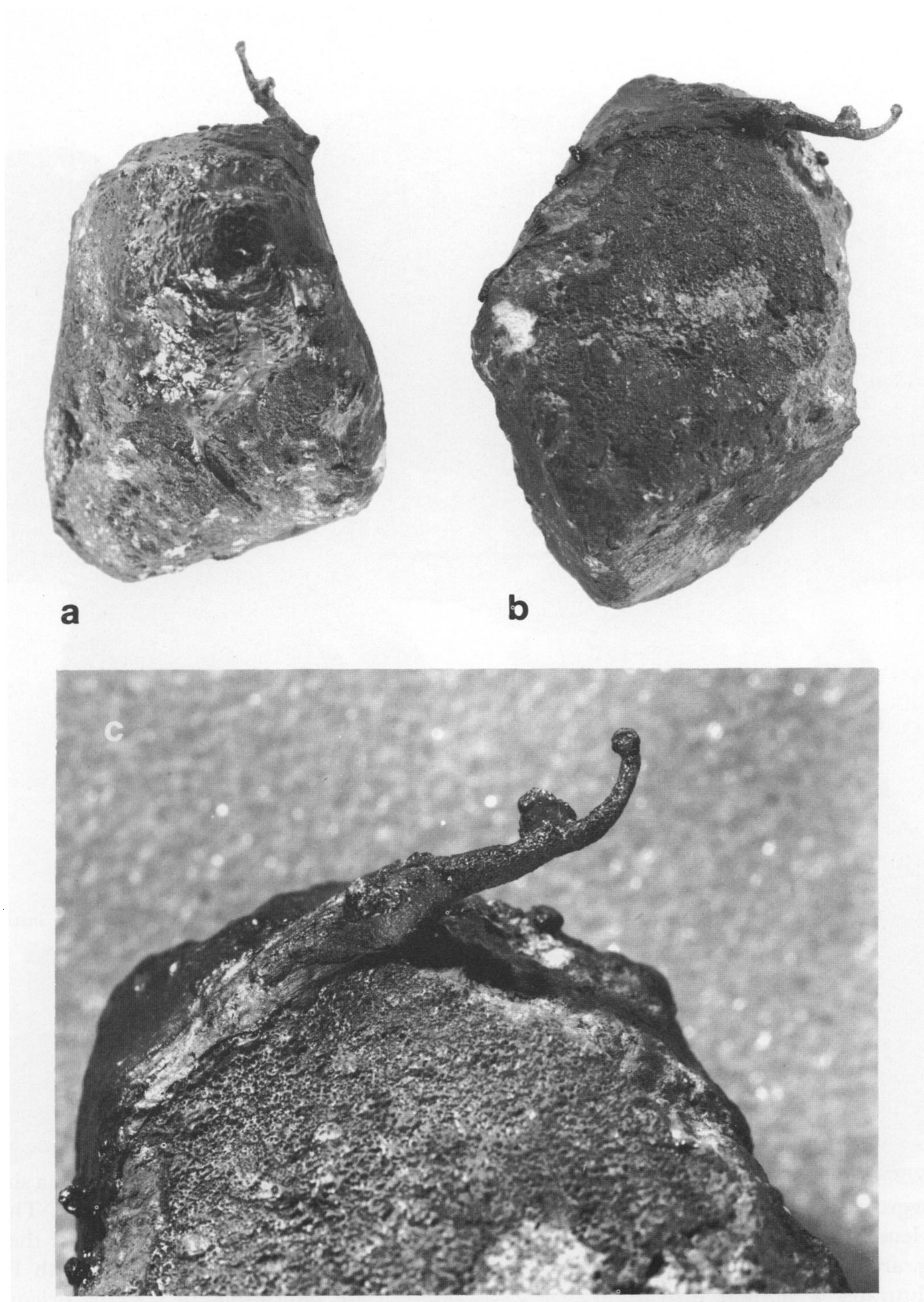


FIGURE 22.—An Allende individual from the area of the Ceniceroses (NMNH 3813) with a horn of lustrous, translucent fusion crust: *a, b,* twice actual size; *c,* horn at four times actual size.

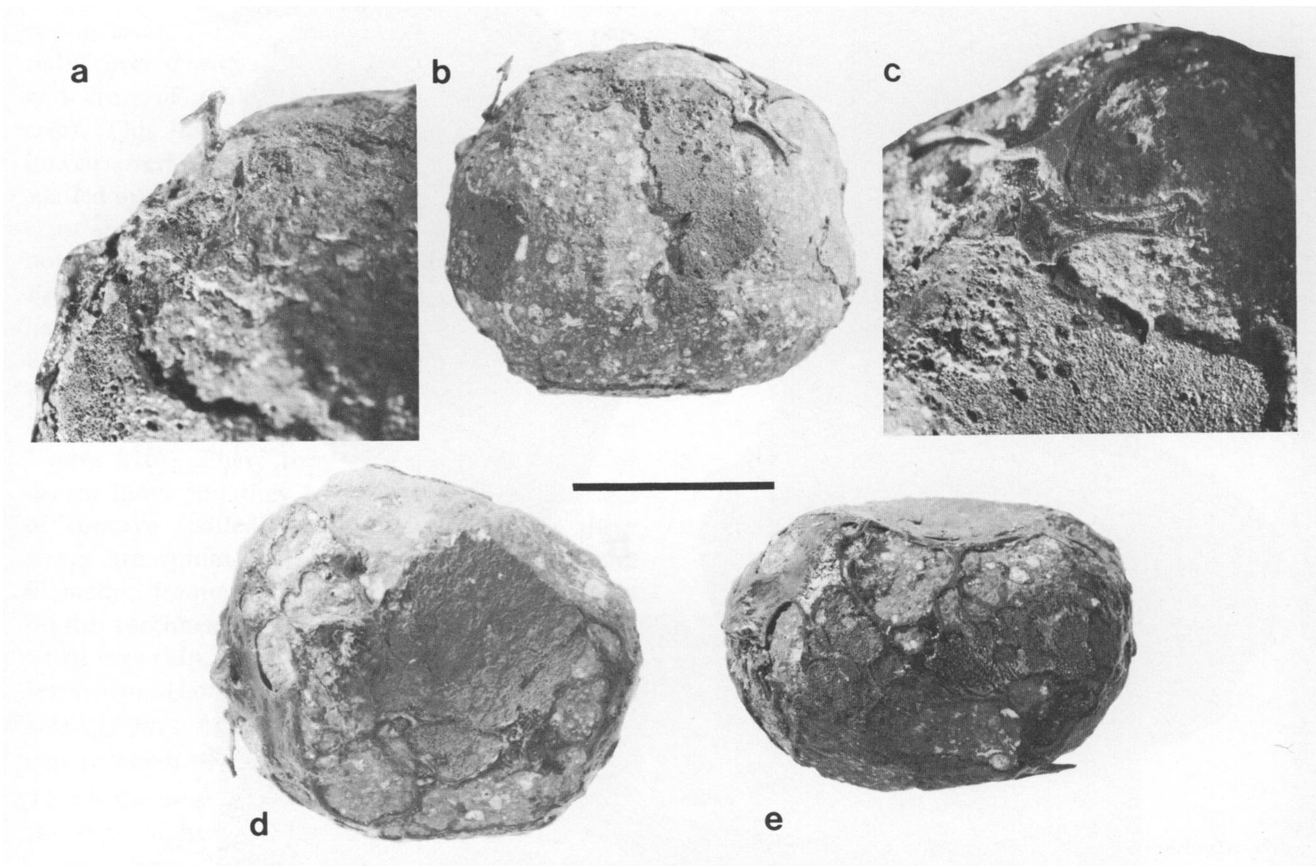


FIGURE 23.—An Allende individual from the area of the Ceniceroses (NMNH 3814) with a network of ropy, lustrous fusion crust over spalled and crusted areas. Scale bar 2 cm for *b, d, e;* 1 cm for *a, c.*

(NMNH 3529, found 2 km northeast of San Juan). Irregular aggregates, white to pink in color and sometimes lensoid in shape, up to several millimeters long, are common in the black matrix. Figure 24*a* illustrates a normal distribution of aggregates, while the reverse side of the same piece (Figure 24*b*) show a preferential accumulation of aggregates and large chondrules. A large polished surface from this same individual is shown in Figure 25. Chondrules, aggregates, and a single large dark inclusion (see below) are shown. This surface would be considered representative if the dark inclusion were excluded. Present in both Figures 24 and 25 are indications of a vague oriented fabric suggested by subparallel elongation of aggregates. These elongations may represent an original flattening, or a secondary flattening produced by later deformation.

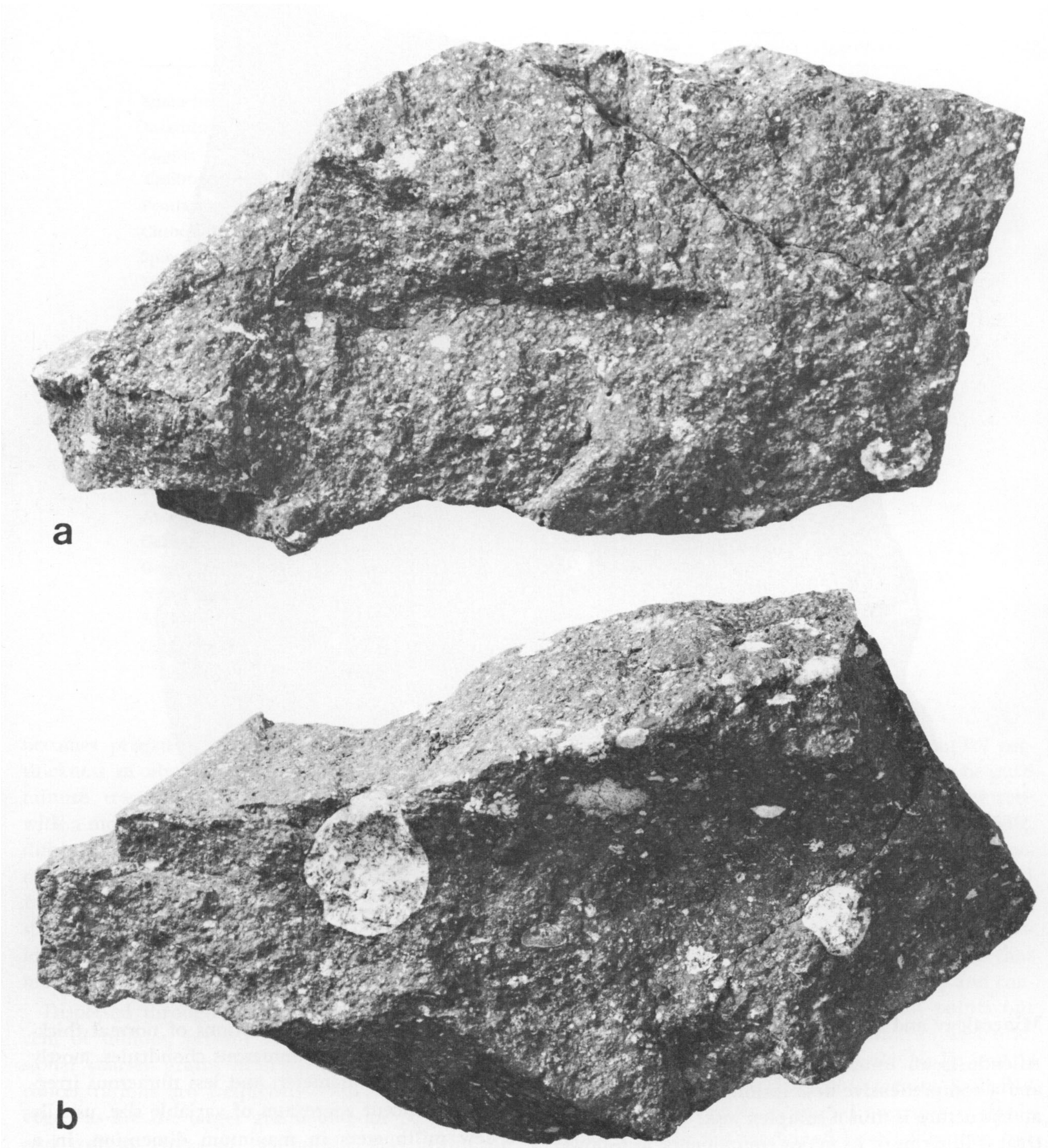


FIGURE 24.—Two views of broken fragment from a large Allende specimen (NMNH 3529): *a*, normal distribution of aggregates and chondrules. *b*, preferential accumulation of aggregates and large chondrules, and a vague oriented fabric. Actual size.

FIGURE 25.—A polished surface of slice of a large Allende individual (NMNH 3529). Note large dark inclusion at bottom of photograph. Actual size.

Mineralogy and Petrography

Allende is an unusually heterogeneous meteorite, and a comprehensive description of its composition and structure is thus a complex task. We propose to treat it in terms of its major components, as follows: (a) matrix; (b) chondrules; (c) irregular aggregates; (d) dark inclusions. It has a remarkably diversified mineralogy; a list of the minerals so far identified is given in Table 1.

Under the microscope, sections of normal thickness (0.03 mm) show numerous chondrules, mostly 0.5 to 2 mm in diameter, and less numerous irregular translucent aggregates of variable size, usually a few millimeters in maximum dimension, in a black opaque matrix. Point-counting on one section gave the following results: chondrules, 34 volume percent; aggregates, 9 percent; matrix, 57 percent. As a section is reduced in thickness, the matrix

TABLE 1.—*Minerals in the Allende meteorite*

Name	Formula	Mineral location: Matrix	Chondrules	Aggregates
Kamacite	(Fe,Ni)		x	
Awaruite	Ni_3Fe	x	x	
Copper	Cu	x		
Troilite	FeS	x	x	
Pentlandite	$(Fe,Ni)_9S_8$	x	x	
Chromite	$FeCr_2O_4$	x		
Spinel	$MgAl_2O_4$		x	x
Hercynite	$FeAl_2O_4$			x
Perovskite	$CaTiO_3$			x
Olivine	$(Mg,Fe)_2SiO_4$	x	x	
Enstatite	$MgSiO_3$			x
Clinoenstatite	$MgSiO_3$		x	
Clinohypersthene	$(Mg,Fe)SiO_3$	x		
Diopside	$CaMgSi_2O_6$			x
Augite (fassaite)	$Ca(Mg,Al,Ti)(Al,Si)_2O_6$		x	x
Ferroaugite	$Ca(Fe,Mg,Al)(Al,Si)_2O_6$			x
Anorthite	$CaAl_2Si_2O_8$		x	x
Gehlenite	$Ca_2Al_2SiO_7$		x	x
Grossular	$Ca_3Al_2Si_3O_{12}$			x
Nepheline	$NaAlSiO_4$		x	x
Sodalite	$Na_4Al_3Si_3O_{12}Cl$		x	x
Cordierite	$Mg_2Al_4Si_5O_{18}$			x

becomes progressively more translucent, and at a thickness of about 0.01 mm is seen to consist of minute transparent equant crystals, interspersed with a moderate amount of opaque material. X-ray diffraction shows that the matrix consists largely of iron-rich olivine (~50 mole percent Fe_2SiO_4). Electron micrographs (courtesy Dr. K. M. Towe) show that many of the minute olivine crystals are idiomorphic, one to a few microns in greatest dimension (Figure 26).

Dispersed throughout the matrix is several percent of sulfides, present as pentlandite with occasional coarser grains of troilite. Localized sulfide concentrations are frequently found at chondrule edges, as are the larger grains of both pentlandite and troilite. Areas of pentlandite and grains of troilite sufficiently large for microprobe analysis were examined. The nickel content of the pentlandite ranges between 16.5 and 21 percent, with an average value around 19 percent, and about 0.7 percent cobalt is present. The troilite appears to be pure FeS, without detectable nickel and cobalt. The rare grains of metal are generally rich in nickel (67–68% Ni and 1.6% Co by microprobe), although an occasional grain of low nickel kamacite was observed within chondrules. These nickel-rich grains would normally be described as taenite, but Dr. E. P. Henderson (personal communication) has noted that the microhardness of these grains is notably and consistently less than that of taenite, and points out that the composition is similar to that of awaruite. Awaruite approximates the formula Ni_3Fe and is an ordered structure in contrast to taenite. Kullerud and El Goresy (1969) note that awaruite is stable below 503°C in the condensed Fe–Ni–S system, but cannot coexist stably with troilite. Electron microprobe investigation established, however, that in the Allende meteorite metal of awaruite composition

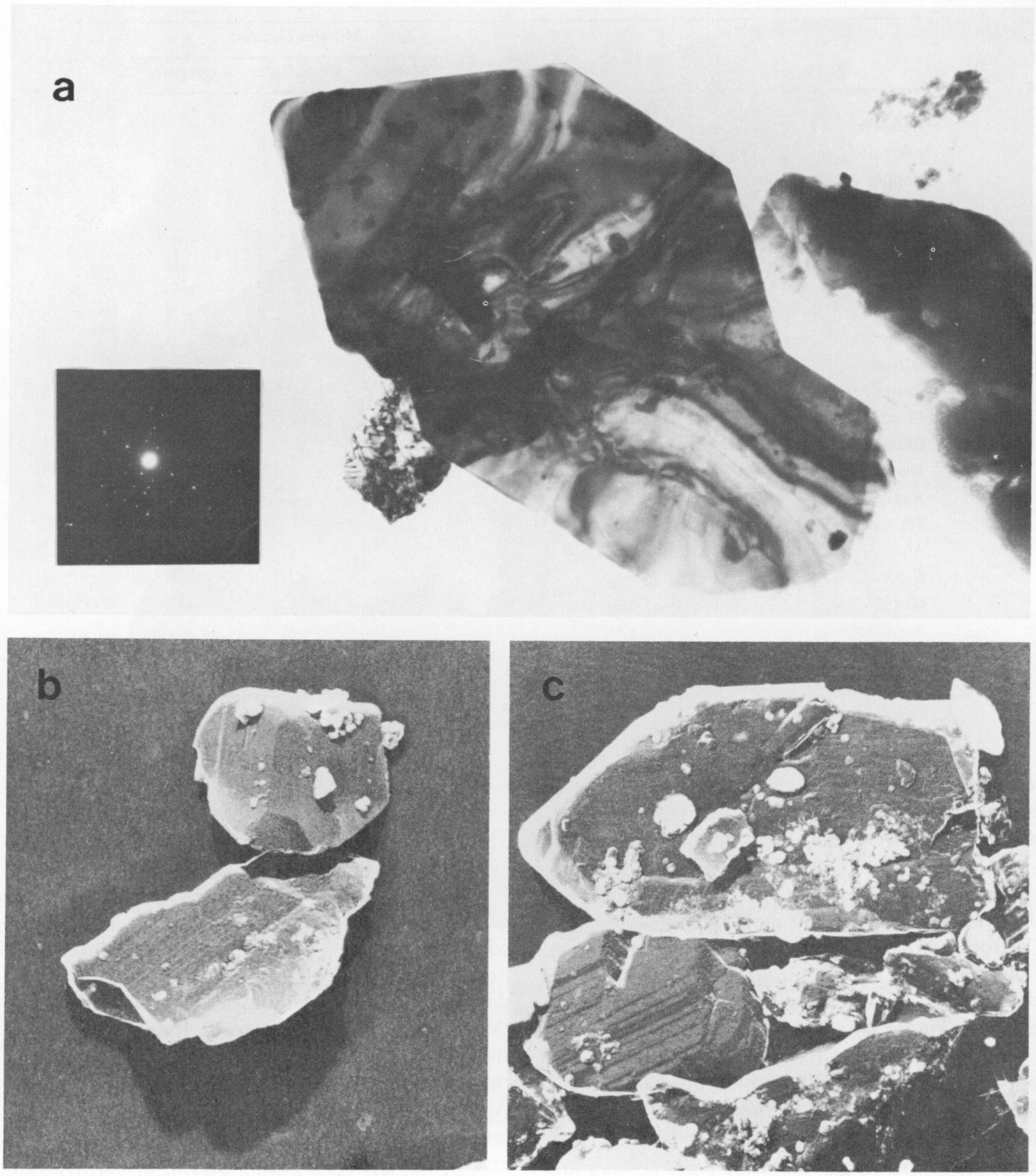


FIGURE 26.—Electron micrographs of Allende meteorite matrix, courtesy of Dr. K. M. Towe: *a,* transmission micrograph of idiomorphic olivine crystal (× 68,000), with electron diffraction pattern (inset). *b, c,* platinum-carbon replica micrographs of representative matrix grains, probably olivine (× 30,000).

exists in intimate association with both pentlandite and troilite. Other minerals included in the matrix are minute amounts of chromite, native copper, and possibly mackinawite (Dr. G. Kullerud, personal communication). The carbonaceous matter cannot be recognized as such except by the uniform black coloring of the matrix; it probably exists as a thin film coating the individual crystallites of olivine and other minerals.

A remarkable variety of chondrules has been observed in this meteorite (Figures 28–34). They can be divided into two groups (I and II) on the basis of chemical and mineralogical composition, and into many different textural types. The chemical groups are:

I. Magnesium-rich chondrules. These consist of magnesium-rich olivine, sometimes with clinoenstatite and interstitial glass (which may be partly devitrified). Individual olivine crystals are frequently zoned, with cores of almost pure Mg_2SiO_4 and increasing iron content towards the surface. An X-ray diffractometer trace shows a sharp peak corresponding to a composition of Fa_9, with a broadened base indicating some variation in composition. The average of the microprobe analyses (100 points) is Fa_6 (Figure 27), the commonest value being Fa_{0-1}. The clinoenstatite is close to $MgSiO_3$ in composition. Microprobe analyses of the glass show that it is rich in calcium and aluminum; a typical analysis is (weight percent): SiO_2, 47.8; Al_2O_3, 24.7; CaO, 17.5; MgO, 6.3; FeO, 0.7; Na_2O, 2.0; K_2O, 0.2. The chondrules usually consist entirely of silicate minerals. A few contain small amounts of sulfides, which occasionally are present as spherical aggregates. Some chondrules are rimmed with small grains of sulfides.

A great variety of textures has been observed in these chondrules. The commoner types can be grouped as follows, in approximate order of abundance:

1. Granular olivine (Figure 28). A tightly packed aggregate of euhedral olivine crystals. Within a single chondrule the individual crystals are fairly uniform in size, but this size varies from chondrule to chondrule; the range measured is

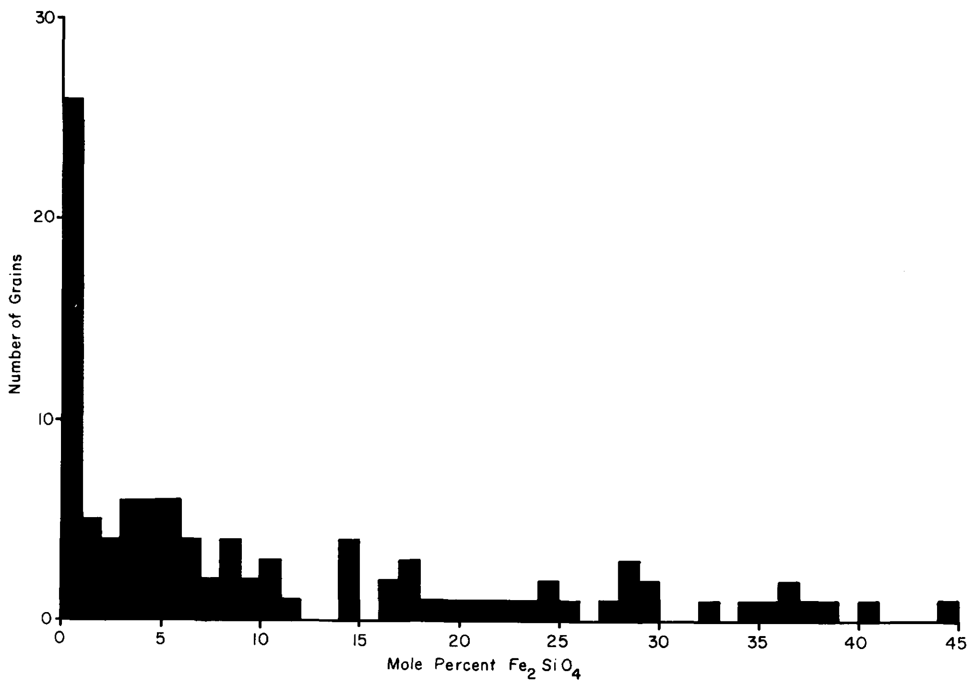


Figure 27.—The composition of individual olivine grains in Allende chondrules, determine by electron microprobe analysis.

from 0.02 to 0.5 mm in different chondrules. Some chondrules have a core of coarse crystals and a mantle of much smaller grains.

2. Granular olivine plus clinoenstatite. Like 1, but containing minor amounts of clinoenstatite. Frequently, the grains of clinoenstatite are concentrated near the surface of the chondrule and then show a "snowball" effect, the clinoenstatite prisms being arranged tangentially to the surface. Clinoenstatite crystals within the chondrules may be comparatively large and poikilitically enclose grains of olivine.

3. Barred olivine chondrules (Figures 29, 30). Long prisms of olivine are interspersed with bars of glass or devitrified glass. The olivine prisms may be parallel throughout the chondrule, may show a fan-shaped arrangement, or may form two or more nonparallel sets. Frequently, a barred chondrule will have a mantle of olivine, which may be in optical continuity with the core olivine.

4. Monosomatic olivine chondrules. These chondrules consist of a rounded single crystal of olivine, usually about 0.5 mm in diameter; sometimes this rounded single crystal is surrounded by an aggregate of small olivine grains.

5. Pyroxene-rich chondrules. These are rare in Allende; this is reflected in the low content of normative pyroxene, as shown by the chemical analysis of a chondrule concentrate (Table 3, column 6, on page 45).

II. Calcium- and aluminum-rich chondrules. These are comparatively rare, making up less than five percent of the total chondrules, but show unusual chemical and mineralogical compositions. Three distinct types have been recognized, and probably others remain to be discovered. The mineralogy of the three types is as follows:

a. Gehlenite–fassaite–anorthite–spinel.

b. Anorthite–forsterite–spinel.

c. Nepheline–sodalite–fassaite–olivine.

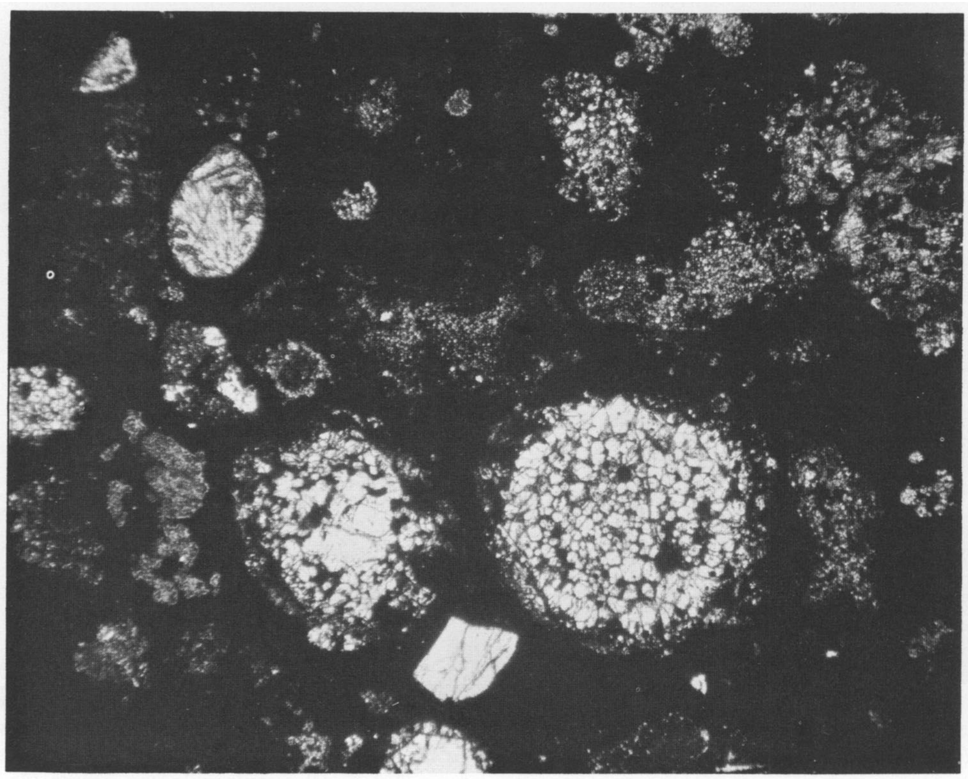


FIGURE 28.—Irregular aggregates and chondrules in black matrix of the Allende meteorite; diameter of the largest chondrule (granular olivine) is 1.4 mm. Transmitted light.

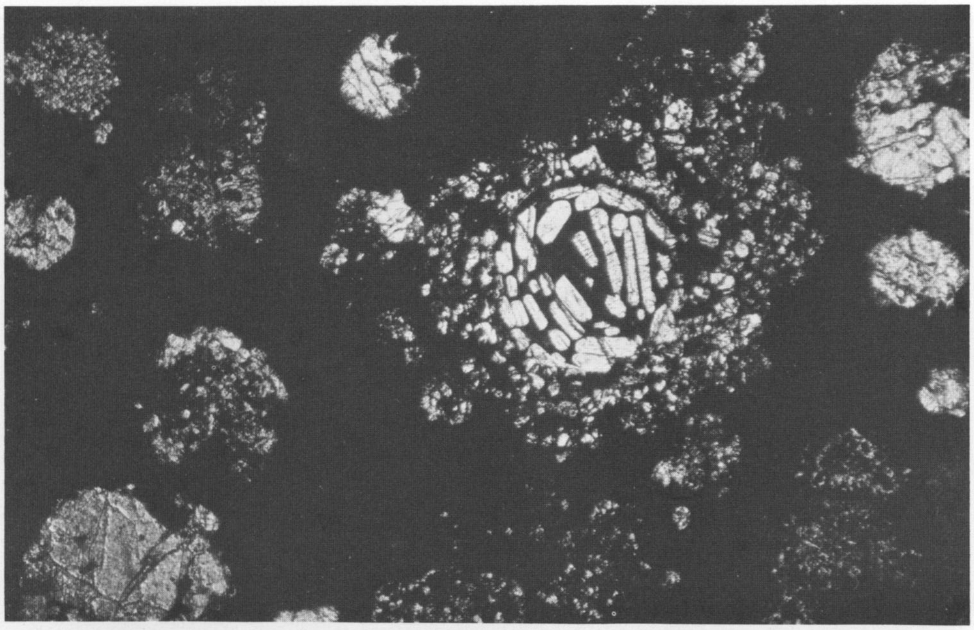


FIGURE 29.—Allende chondrule (0.7-mm diameter) of prismatic olivine crystals in dark glass, with a halo of small olivine crystals. Transmitted light.

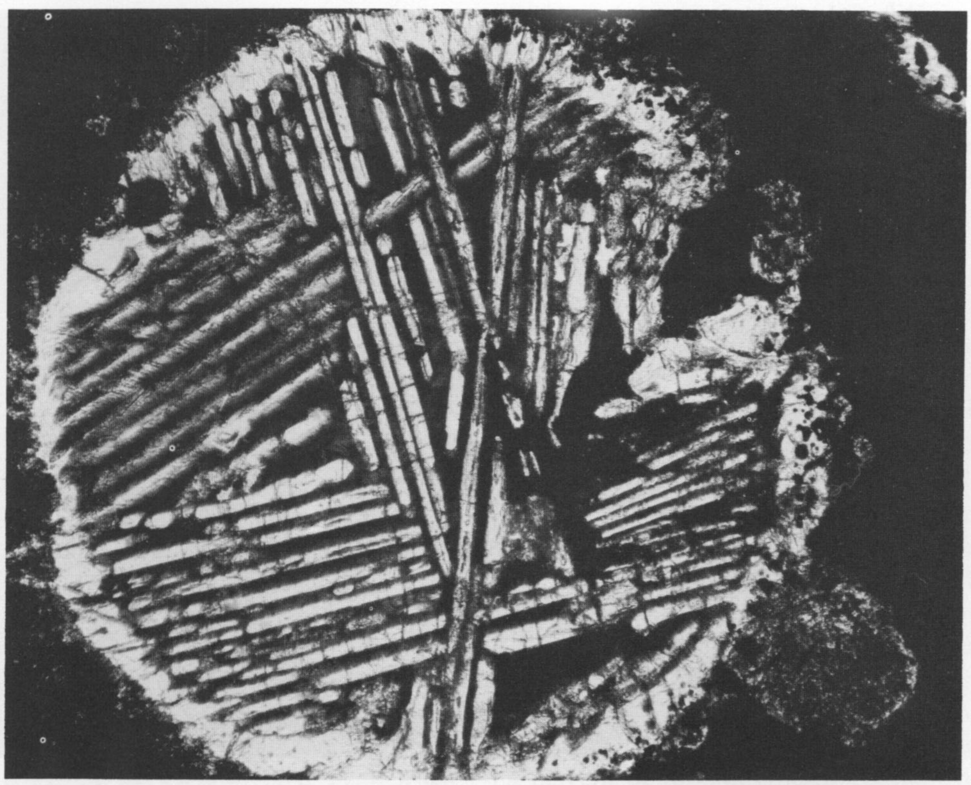


FIGURE 30.—Barred olivine chondrule with a narrow continuous rim of olivine in Allende meteorite; diameter 1.2 mm. Transmitted light.

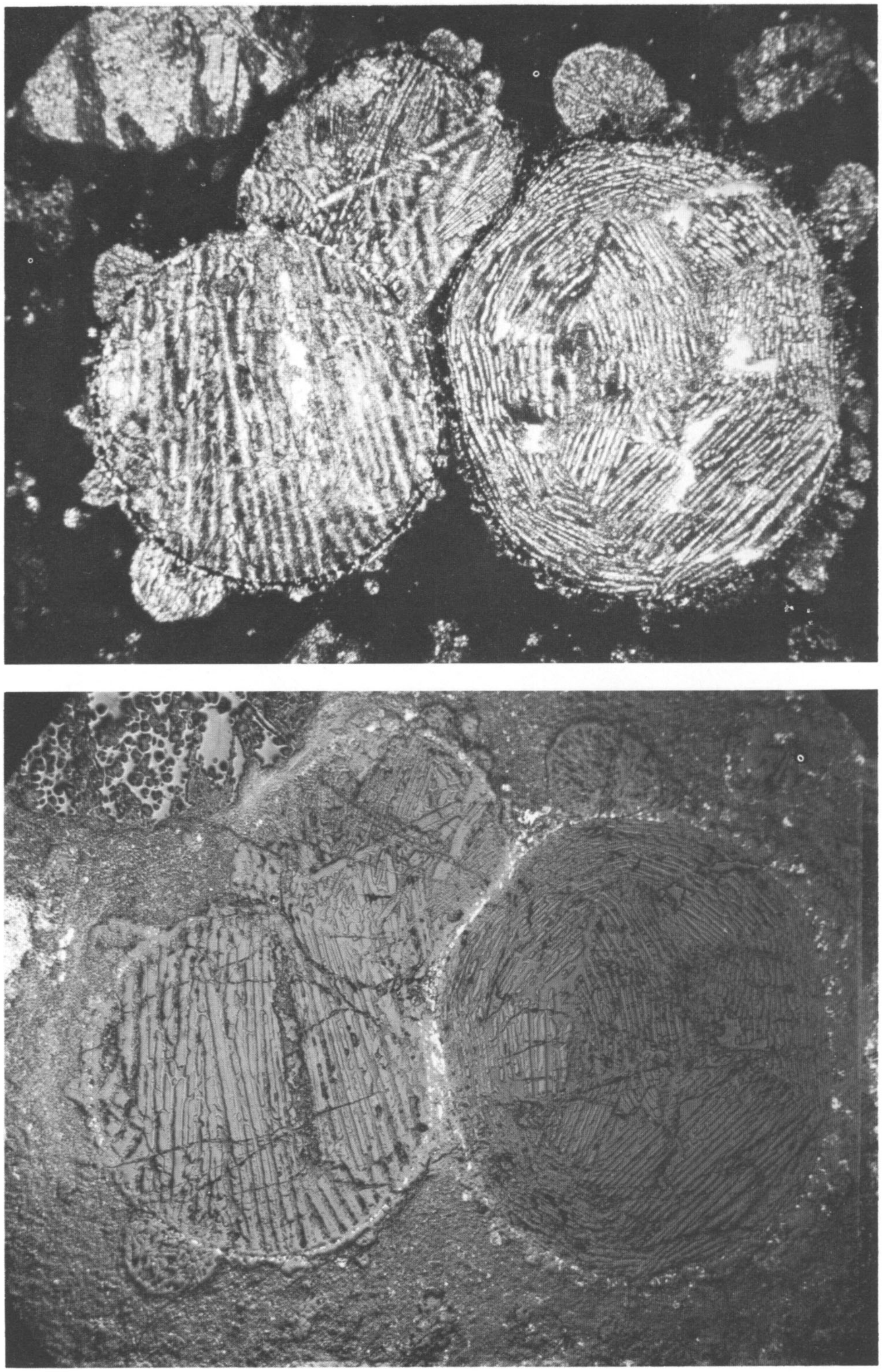


FIGURE 31.—Three juxtaposed barred chondrules in the Allende meteorite, in transmitted (upper) and reflected (lower) light; the reflected light photograph shows tiny sulfide grains (white) on the surface of the chrondrules (largest chrondrule is 1.7-mm diameter).

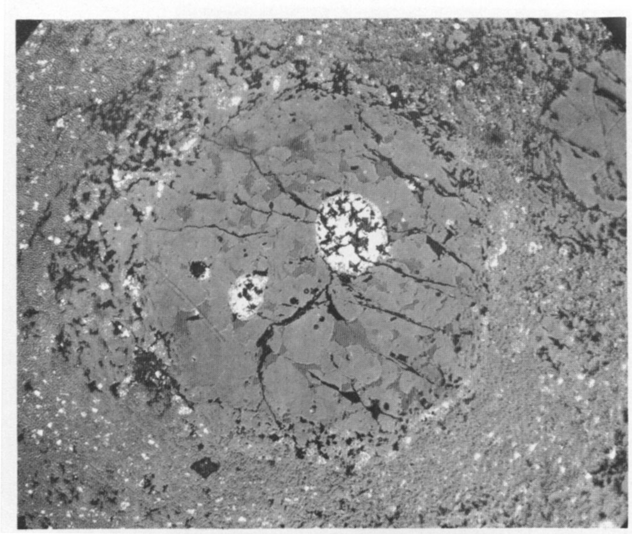


FIGURE 32.—Allende meteorite granular olivine chondrule (1.3 mm diameter) in reflected light, showing two spherical sulfide inclusions.

Type *a* form prominent chondrules, being unusually large, one (Figure 33) measuring 24 mm in diameter. This provided material for both bulk chemical analysis (Table 3, column 7) and for microprobe analyses of the individual minerals (Table 2). Gehlenite is the most abundant mineral (~40 percent), and is present as large prismatic crystals; its refractive indices are $\omega = 1.660$, $\epsilon = 1.655$. The microprobe analysis shows that it is close to pure gehlenite in composition, with a moderate amount of the akermanite component ($Ca_2MgSi_2O_7$). Pyroxene forms about 30 percent of the chondrule, and is an unusual type, being highly aluminous and also titanium-rich; in terms of components, it contains about 59 percent $CaMgSi_2O_6$ by weight, 24 percent $CaAl_2SiO_6$, and 17 percent $CaTiAl_2O_6$. Its refractive indices are $\alpha = 1.705$, $\beta = 1.713$, $\gamma = 1.735$; it is colorless and nonpleochroic, in marked contrast to the purple titaniferous clinopyroxene in the Angra dos Reis meteorite, and in terrestrial igneous rocks. Dr. Joan Clark of the United States Geological Survey has determined its cell dimensions, with the following results (in A): a = 9.725±0.004; b = 8.828±0.003; c = 5.306 ±0.003; $\beta = 105°55' \pm 10'$; $V = 438.1 A^3$. Pyroxene with a considerable content of the $CaAl_2SiO_6$ component is termed fassaite. Other minerals in the chondrule are anorthite (about 10 percent), and spinel (about 20 percent).

TABLE 2.—*Microprobe analyses of gehlenite, fassaite, and anorthite in a large chondrule (type a, Figure 33) from the Allende meteorite (J. Nelen, analyst). Values given in weight percent*

	Gehlenite	*Fassaite*	*Anorthite*
SiO_2	27.0	39.8	43.4
TiO_2	0.1	5.5	0.1
Al_2O_3	27.7	18.2	35.8
MgO	3.1	9.7	0.0
CaO	41.0	25.4	20.2
	98.9	98.6	99.5

Iron and sodium were looked for but not detected above the trace level.

The composition of this type *a* chondrule is closely similar to the compositions studied by Prince (1954) in the CaO-MgO-Al_2O_3-SiO_2 system. Using his diagram for the 10 percent MgO plane in this system, a melt of approximately the composition of this chondrule would begin to crystallize spinel at about 1550°C, followed by gehlenite at about 1400°C, anorthite at 1250°C, pyroxene at 1235°C. The textural relations of these minerals in the chondrule are consistent with this sequence of crystallization. Small euhedral crystals of spinel are included within all the other minerals. Gehlenite is present as large prismatic crystals, suggesting crystallization over a considerable temperature interval, whereas the anorthite and fassaite occur as smaller xenomorphic grains in the interstices of the gehlenite crystals, and are evidently a late crystallization product.

A type *b* chondrule is illustrated in Figure 34. This chondrule, 2 mm in diameter, consists largely of prismatic crystals of anorthite, notably larger in the outer part than in the core. Tiny crystals of colorless spinel are included within the anorthite crystals. A little forsterite, interstitial to the anorthite prisms, is present. The anorthite contains about 0.5 percent Na_2O, corresponding to about 5 percent of the $NaAlSi_3O_8$ component.

A single chondrule of type *c* has been found. It was observed on a broken fragment of the meteorite,

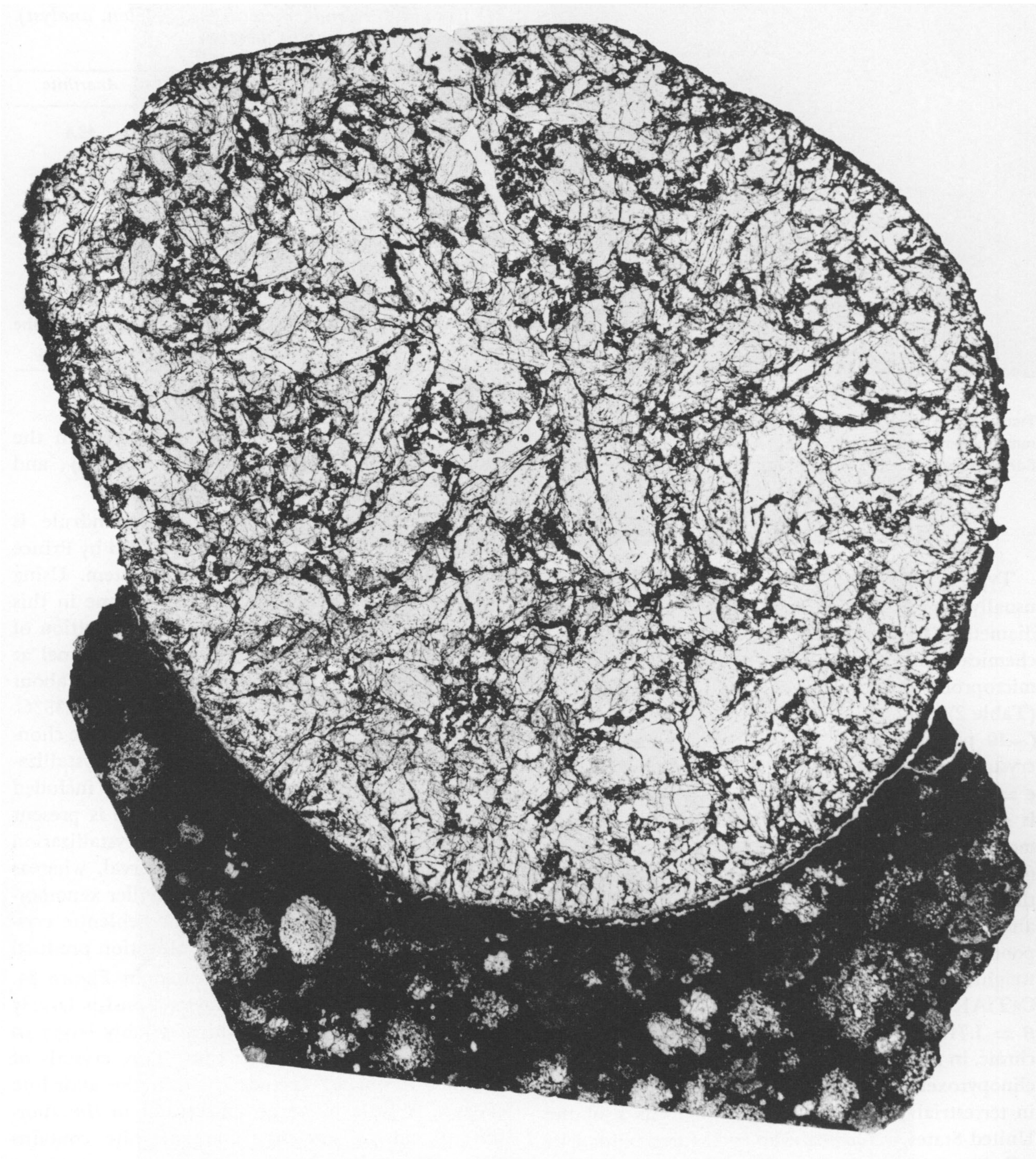


FIGURE 33.—Gehlenite-anorthite-fassaite-spinel chondrule (type *a*) in the Allende meteorite, 24 mm in diameter; gehlenite is the major phase and is present as large prismatic crystals, fassaite and anorthite occur as equant grains interstitial to the gehlenite, and the spinel is disseminated as small crystals throughout the other minerals. Transmitted light.

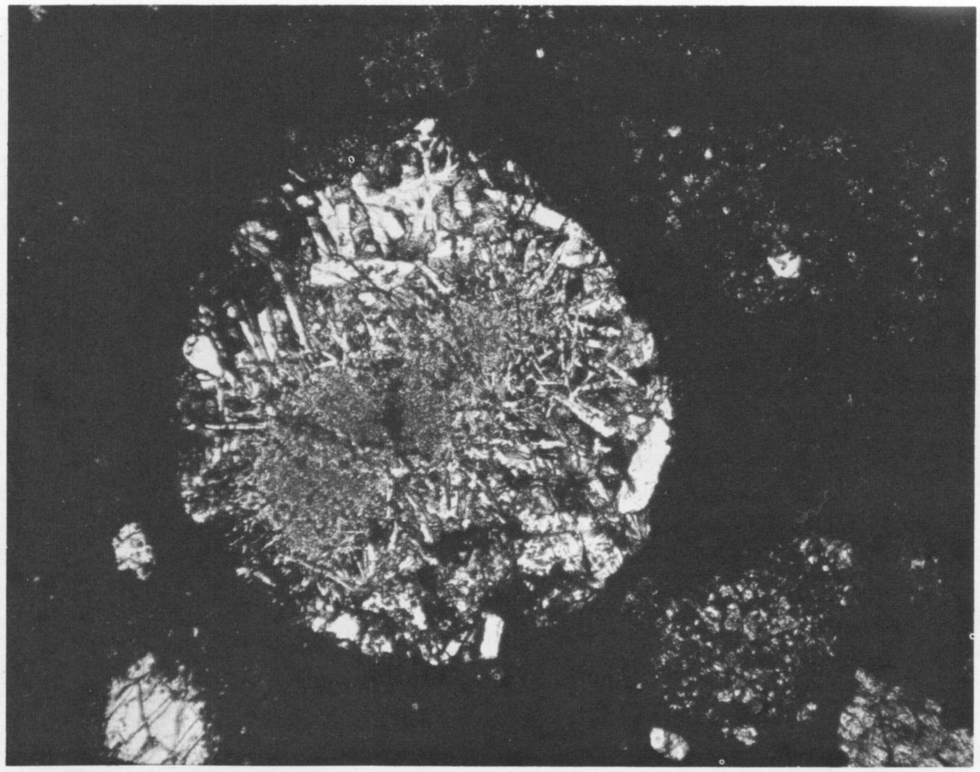


FIGURE 34.—Anorthite-forsterite-spinel chondrule type *b* in the Allende meteorite (2.1-mm diameter); white prismatic crystals are anorthite, the spinel is finely dispersed throughout the chondrule, and the forsterite is interstitial to the anorthite crystals. Transmitted light.

being unusually large (8 mm in diameter) and a uniform chalky-white color. It is so fine-grained that the individual minerals could not be identified in grain mounts in immersion oils. X-ray powder photographs provided positive identifications for sodalite, nepheline, clinopyroxene (probably fassaite), and olivine, and this mineralogy is consistent with the bulk chemical composition of the chondrule (Table 3, column 8). By the X-ray procedure of Yoder and Sahama (1957) the composition of the olivine was found to be Fa_{26}, in good agreement with the FeO/FeO+MgO ratio in the chemical analysis. This occurrence of sodalite ($Na_8Al_6Si_6O_{24}Cl_2$, with 7.3 percent Cl), the first recorded from a meteorite, is particularly intriguing, since the chlorine content of stony meteorites is usually low (of the order of 100 ppm) and combined as chlorapatite. Microprobe analyses have confirmed the presence of nepheline and sodalite, and have provided some significant compositional data; in particular, potassium is notably fractionated between the two minerals, the nepheline containing 1.5 percent K and the sodalite less than 0.1 percent. The extremely fine-grained texture of this chondrule suggests that it solidified as a glass and subsequently devitrified.

The calcium- and aluminum-rich chondrules frequently show narrow reaction rims against the matrix, whereas the magnesium-rich chondrules do not. This can probably be ascribed to the contrast in composition between the calcium-rich chondrules and matrix, whereas the magnesium-rich chondrules are compositionally similar to the matrix. The occurrence of reaction rims implies that either the chondrules or the matrix, or both, were quite hot when the material aggregated.

A prominent feature of the Allende meteorite, and one seen in few other chondrites, is the presence of irregular aggregates, white, pale gray, or pale pink, usually up to a few millimeters in maximum dimension. Many of the aggregates are somewhat elongated or lensoid, and on large surfaces there is a suggestion of subparallel arrangement of the individual aggregates. Frequently the aggregates show narrow but distinct rims against the matrix; these rims probably represent reaction zones with the matrix.

Under the microscope these aggregates are seen to be very fine-grained, the only prominent mineral being rounded grains of pinkish spinel, which are set in a microgranular aggregate of isotropic or weakly birefringent material. X-ray diffraction, supplemented by chemical analysis, has elucidated the mineralogy. A bulk analysis of one 250-mg aggregate (Table 3, column 9) shows that it is composed essentially of calcium and magnesium alumino-silicates, the composition being comparable with the gehlenite-anorthite-fassaite-spinel chondrules. These minerals are also prominent constituents of the aggregates. In addition, some of them contain nepheline and sodalite, their occurrence evidently being conditioned by the presence of appreciable amounts of sodium in these aggregates. Some aggregates contain considerable amounts of grossular, this mineral also previously unrecorded in meteorites. The identification of grossular rests on its X-ray powder photograph, giving a cell dimension of 11.85A, identical with that of pure $Ca_3Al_2Si_3O_{12}$; it is evidently too fine-grained to be recognized either optically or with the microprobe, although it is certainly abundant in some aggregates. Fuchs (1969) has described one aggregate consisting largely of cordierite, with associated aluminous enstatite, anorthite, spinel, and sodalite. Marvin et al. (1970) have identified spinel, hercynite, gehlenite, anorthite, nepheline, diopside, fassaite, ferroaugite, and perovskite from these aggregates.

The presence of grossular has considerable significance in the interpretation of these aggregates. Grossular is not known to crystallize from a melt; it decomposes above 800°C into a mixture of wollastonite, gehlenite, and anorthite. Yoder (1954) crystallized it from a glass of the requisite composition at 800°C. The extremely fine-grained nature of the aggregates suggest devitrification of a glass, and the presence of grossular indicates that this devitrification took place in some of them at or below 800°C.

On broken surfaces of the Allende meteorite one occasionally sees small areas somewhat darker than the enclosing matrix; these areas are fine-grained and have no visible chondrules, in contrast to the highly chondritic matrix (Figure 25). They are usually angular in outline, and range in size up to about 3 cm across. In thin section under the microscope these inclusions are seen to differ from the surrounding material only in chondrule size; they are essentially the same as the main mass of the meteorite except that the chondrules are much smaller, ranging up to 0.5-mm diameter, and are somewhat sparser; the same irregular aggregates are also present. The overall similarity is confirmed by a chemical analysis (Table 3, column 4), which is not significantly different from that of the bulk meteorite. An X-ray diffractogram shows good olivine peaks indicating a composition of Fa_{48}, the peaks however being somewhat skewed towards lower Fa values.

Fusion crust.—A unique feature of the Allende meteorite is the lustrous fusion crust discussed above in the section on morphology (Figures 21–23). This type of crust covers both spalled surfaces and areas of normal fusion crust, indicating that it developed late in the individual stone's passage through the atmosphere. Its translucency and amber color led us to assume first that it was a silicate glass of unusual composition. One of our specimens (NMNH 3811) was sectioned on this basis for microscopic and electron microprobe investigation. It was a great surprise to learn from preliminary examination of these sections that this strange crust actually consisted of a thin film of silicate fusion crust encapsulating comparatively large volumes of a material tentatively identified as a hydrocarbon. Our main supporting evidence for this identification is semiquantitative electron microprobe analysis indicating that this "hydrocarbon" contains approximately 85 percent carbon and no other elements detectable by the microprobe. It contains less carbon than graphite and considerably more carbon than the plastic mounting medium used in preparation of the section. The material is essentially colorless and is very soft, suggestive of paraffin. Until definitive work can be done, we will refer to this material as a hydrocarbon.

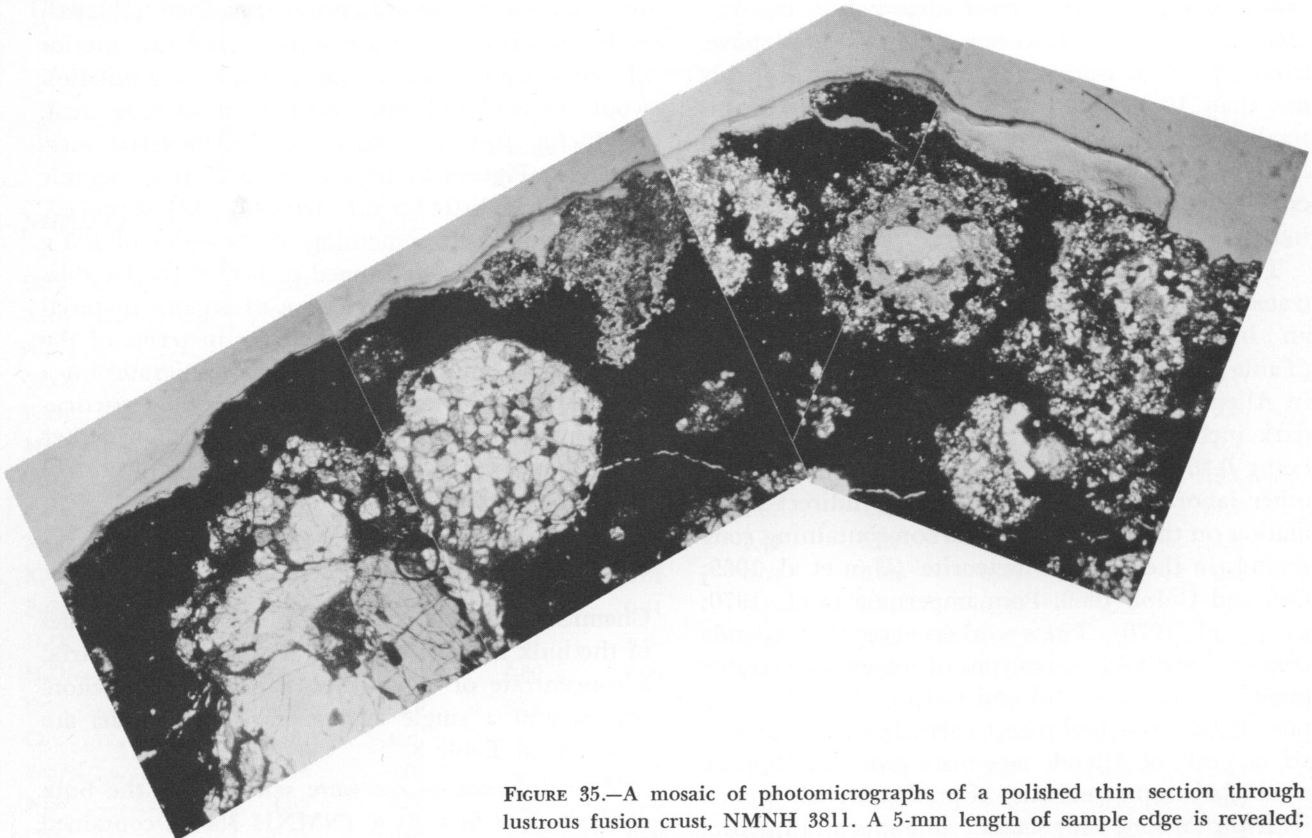


FIGURE 35.—A mosaic of photomicrographs of a polished thin section through lustrous fusion crust, NMNH 3811. A 5-mm length of sample edge is revealed; transmitted and reflected light.

Figure 35 is a mosaic of low-magnification photomicrographs of one of the polished thin sections through lustrous fusion crust, revealing a 5-mm length of sample surface. Lustrous fusion crust overlies all but the extreme right edge of the area shown. The area of fusion crust at the right of the photomicrograph is lustrous material extending out from the meteorite matrix approximately 0.2 mm and bridging it for a distance of 1 mm. Smaller areas are seen to the left, and in places this lustrous crust thins to the point where it cannot be distinguished from the edge of the matrix. It is, however, continuous under higher magnification. The outer edge of this crust assemblage is a thin film of silicate glass containing a few matrix fragments and heat-precipitated magnetite. The glass is too thin to be seen in the photomicrograph, ranging in thickness from 10 to 30 microns. Underneath the outer glass layer is a region of hydrocarbon material that may be continuous with the matrix, or may adhere to the glass crust, but be separated from the matrix by voids. The rim seen in the photograph consists largely of hydrocarbon material colored by a thin film of dark glass lying mainly below the surface of the section.

The lustrous fusion crust spine protruding at the left side of Figure 21*a* detached itself from specimen NMNH 3812 during the course of this preliminary investigation, providing material from a second stone for examination. A longitudinal section was prepared that yielded a trough-shaped volume of sample with a surface 4 mm long and from 0.5 to 1 mm wide, ranging from 0.2 to 0.5 mm in depth, with a total volume of hydrocarbon material of approximately 0.8 mm^3. The total volume of hydrocarbon in this one spine prior to loss of material during section preparation was certainly greater than 1 mm^3. The glass crust surrounding this volume was similar in thickness to that noted above, from 10 to 30 microns, accounting for probably less than 10 percent of the total volume. If this small fragment and the sections from specimen NMNH 3811 are representative of lustrous fusion crust in general, a large concentration of apparently indigenous hydrocarbon material is present.

The source of the hydrocarbon material concentrated under the crust of specific Allende stones is an intriguing problem. Bulk carbon analyses (Table 3) indicate that essentially all of the carbon in Allende is associated with matrix material and dark inclusions, average values of several analyses being 0.36 and 0.37 percent respectively. Work in other laboratories has yielded some indirect information on the nature of the carbon-containing compounds in the Allende meteorite (Han et al. 1969; Oró and Gelpi, 1969; Ponnamperuma et al., 1970; Levy et al., 1970). These workers agree that Allende contains negligible quantities of solvent-extractable organic substances. Oró and Gelpi (1969) have reported, however, that direct volatilization or pyrolysis, or both, of Allende meteorite produces 10 to 20 ppm of a complex mixture of predominantly aromatic hydrocarbons with smaller amounts of aliphatics and other compounds. This result is confirmed by Ponnamperuma et al. (1970). The conclusion of Han et al. (1969) that an upper limit of 0.1 parts per billion of possible indigenous organic matter in Allende seems unwarranted, and our observation of organic matter concentration within fusion crust suggests a possible alternative to terrestrial contamination as a source of some of the organic material they found in surface samples.

The mechanism by which large quantities of organic material are concentrated under the fusion crust of specific Allende stones presents a second intriguing problem. The work on pyrolysis of Allende material suggests that volatile organic compounds may have been formed by pyrolysis during ablation. A portion of this material would be expected to be lost to the atmosphere, while a part of it would be driven into the porous meteorite. A steep temperature gradient with depth into the stone would account for condensation and accumulation of volatiles slightly below the molten surface. This zone of accumulation would move into the meteorite as ablation progressed, concentrating volatiles from large volumes of pyrolized (ablated) meteorite. When ablation stopped and the interior of the sample warmed, the organic accumulation would expand and flow under the hardening crust, producing features similar to the observed morphology (Figures 21–23). If 10 to 20 ppm organic product is realistic for this natural pyrolysis process, one would expect something of the order of 100 g of meteorite to be consumed or heated by the ablation process for each milligram of organic material accumulated. This seems excessive in terms of the observed accumulations of several milligrams on a small surface and leads us to wonder if these particular stones were not associated with inclusions richer in volatile-producing compounds than normal Allende material.

Chemical Composition

Chemical analyses have been made of two samples of the bulk meteorite, a dark inclusion, the matrix, a concentrate of chondrules, two individual chondrules, and a single aggregate. These results are reported in Table 3.

Two different pieces were selected for the bulk analysis. The first, 81 g (NMNH 3509), contained several white aggregates; the second, 45 g (NMNH 3511), appeared more homogeneous. The samples were ground in a tungsten-carbide mortar to pass 100 mesh. Several metallic grains larger than 100 mesh—totaling, however, less than 0.01 percent of the sample—remained on the sieve. A split of each sample was then analyzed for major and minor constituents, following the general procedure outlined in an earlier paper (Jarosewich, 1966). The two analyses are in excellent agreement with the one exception that the first sample has somewhat more Al_2O_3, undoubtedly due to the presence of white aggregates.

Noteworthy features of the bulk composition of the Allende meteorite are the minute amount of free metal, the presence of most of the nickel as sulfide (a microprobe test of sulfide-free matrix showed no detectable nickel in the silicates), the high content of Al_2O_3 and CaO (about 50 percent greater than in the common chondrites), and the low values for Na_2O and K_2O (about half that in the common chondrites). The analysis is very similar

TABLE 3.—*Analytical data on the Allende meteorite (E. Jarosewich, analyst). Values in weight percent unless otherwise indicated*

	1	2	3	4	5	6	7	8	9
	Bulk Analyses		*Average of 1 & 2*	*Dark Inclusion*	*Matrix*	*Chondrules*	*Chondrule (Type a)*[4]	*Chondrule (Type c)*[5]	*Single Aggregate*[6]
NMNH Cat. Nos.	3509	3511		3509	3510	3510	3529	3509	3510
SiO_2	34.20	34.26	34.23	33.42	33.11	41.87	29.79	40.2	33.7
TiO_2	0.16	0.14	0.15	0.13	0.13	0.26	0.99	0.12	1.3
Al_2O_3	3.36	3.18	3.27	2.56	3.07	5.57	31.61	17.8	26.6
Cr_2O_3	0.51	0.53	0.52	0.56	0.55	0.47	0.06	0.2	0.1
FeO	27.22	27.09	27.15	31.48	29.68	9.44	0.37	8.8	2.3
MnO	0.18	0.18	0.18	0.26	0.22	0.14	0.02	0.1	0.0
MgO	24.50	24.75	24.62	23.91	21.42	34.34	10.82	15.2	13.1
CaO	2.65	2.57	2.61	3.00	2.67	4.06	26.76	5.3	21.6
Na_2O	0.44	0.45	0.45	0.34	0.44	0.82	0.11	10.6	1.1
K_2O	0.03	0.03	0.03	<0.01	0.03	0.06	0.00	0.6	0.05
P_2O_5	0.23	0.23	0.23	0.31	0.25	0.11	0.00	n.d.	0.0
$H_2O(+)$	<0.1	<0.1	<0.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
$H_2O(-)$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	n.d.	n.d.
C	0.29	0.29	0.29	0.37	0.36	0.00	0.06	0.02	n.d.
Cl	n.d.[2]	n.d.	—	n.d.	n.d.	n.d.	n.d.	2.0[3]	n.d.
FeS[1]	3.98	4.08	4.03	1.95	5.49	1.78	0.00	n.d.	n.d.
NiS[1]	1.64	1.56	1.60	2.26	1.05	0.87	0.00	n.d.	n.d.
CoS[1]	0.08	0.08	0.08	0.06	0.09	0.03	n.d.	n.d.	n.d.
Fe	0.15	0.19	0.17	n.d.	0.40	n.d.	n.d.	n.d.	n.d.
Ni[1]	0.32	0.40	0.36	n.d.	0.85	n.d.	0.03	0.05	0.06
Co[1]	0.01	0.01	0.01	n.d.	0.02	n.d.	n.d.	n.d.	n.d.
Total	99.95	100.02	99.98	100.61	99.83	99.82	100.62	100.6[3]	99.9
$D(g/cm^3)$			3.65	n.d.	n.d.	n.d.	3.25	2.80	3.18
Total Fe	23.85	23.84	23.85	25.71	26.56	8.47	0.29	6.82	1.76
$\frac{100\ FeO}{FeO + MgO}$ (mole)			38	42	44	13	2	25	9

n.d. = not determined

[1] Calculated on basis of microprobe data for metallic phase: 68% Ni, 31% Fe and 1.6% Co. Metallic Fe was determined chemically and metallic Ni and Co assigned on basis of analysis given above. Remainder of Ni and Co were calculated as sulfides. The remaining S was calculated as FeS.

[2] M. Quijano-Rico, Max-Planck-Institut, Mainz, determined Cl by neutron activation, obtaining 224 ppm in bulk sample and 1.5% in chondrule type *c*. The difference between the 1.5 and 2.0% value is undoubtedly due to our use of a gravimetric method with a very small sample (33 mg).

[3] Total of 100.99 corrected by 0.45, the Cl = 0.

[4] 1.5 g sample weight.

[5] 0.31 g sample weight.

[6] Gast et al. (1970) reported the following results on a similar inclusion (all in ppm): K 96.4, Rb 3.5, Sr 180, Ba 47.3, La 4.63, Ce 11.5, Nd 8.40, Sm 2.82, Eu 1.30, Gd 3.87, Dy 4.90, Er 3.44, Yb 3.96.

to that of the Efremovka meteorite (Jarosewich and Mason, 1969), except that Efremovka has about 7 percent nickel-iron and correspondingly less iron combined in the silicates.

The analysis of the dark inclusion was performed on a 1.3 g sample. As pointed out above, it is closely comparable with that of the bulk material of Allende, and it is very similar to the analysis of Mokoia (Wiik, 1956), which is another Type III carbonaceous chondrite.

The analyzed material of the matrix, and the chondrule concentrate, were prepared by carefully crushing and sieving a number of fragments of the meteorite. Gentle crushing releases a large amount of the matrix in the form of fine dust which passes through a 325-mesh screen, and a sample of this was used for the analysis (2.9 g). The chondrules were concentrated in the -10 $+30$ mesh fraction (approximately 0.6–2.0 mm diameter), a 1.5 g sample being obtained. The analyzed chondrules were not entirely free from matrix; the $FeO/FeO+MgO$ molecular percentage in the analysis is 13, so the average for the chondrules themselves will be considerably less.

The composition of the matrix is not markedly different from that of the bulk meteorite, which is reasonable, since matrix forms about 60 percent by volume of the meteorite and somewhat more by weight. The matrix clearly contains most of the metal and sulfide phases. The $FeO/FeO+MgO$ molecular percentage of 44 is consistent with the average fayalite percentage (50) in matrix olivine, since the matrix fraction contains other minerals (calcium aluminum silicates and spinel) with low $FeO/FeO+MgO$ ratios.

The composition of the chondrule concentrate shows marked contrasts with that of the matrix, particularly in total Fe content, MgO content, and in $FeO/FeO+MgO$ molecular percentage. This of course reflects the fact that most of the chondrules are made up largely of forsteritic olivine, with minor amounts of clinoenstatite. The calcium-rich chondrules account for the somewhat higher CaO and Al_2O_3 contents. Sulfides are notably lower in the chondrule concentrate; they usually occur on the surfaces of the chondrules, but are sometimes enclosed within them. Metallic nickel-iron was observed both in matrix and in chondrules.

The aggregates and the calcium-rich chondrules present the most marked chemical contrasts to the rest of the meteorite. They contain up to ten times the amount of calcium and aluminum (and titanium) as in the meteorite as a whole. They are quite unlike any composition that has yet been recorded from stony meteorites. The composition is also quite unlike any terrestrial rocks, except for some rare calcsilicate hornfels, such as that described by Knopf and Lee (1957). The nearest analogy is to some blast-furnace slags. The composition given by the analysis of the type *a* chondrule corresponds to the low-melting region in the CaO-MgO-Al_2O_3-SiO_2 system, and the association anorthite–gehlenite–fassaite–spinel is consistent with crystallization of a melt of this composition. The origin of such a melt from meteoritic matter, however, presents certain problems. Both calcium and aluminum are minor elements in average chondritic matter, being present at about the 1 percent level. One procedure for enriching them is the removal of large amounts of magnesium as olivine and clinoenstatite; neither of these minerals incorporates appreciable amounts of calcium and aluminum. This can be seen from the composition of the glass in the magnesium-rich chondrules, quoted earlier, although this glass is somewhat richer in SiO_2 than the calcium-rich chondrules and aggregates. The composition of the single aggregate analyzed is rather similar to the type *a* chondrule, except for a much higher sodium content, expressed in its mineralogy by the presence of nepheline and sodalite. The type *c* chondrule has a very distinctive composition, marked by high sodium and potassium (about twenty times that in the bulk meteorite), and a remarkable chlorine content, more than fifty times that in the bulk meteorite. These extreme fractionations pose some intriguing questions regarding the processes involved in the formation of such chondrules, presuming the parent material was essentially undifferentiated. In this connection it is probably significant that anorthite, gehlenite, and spinel are among the first solids to condense from a gas of cosmic composition. Larimer and Anders (1970) have convincingly argued for chemical fractionations in meteorites by addition or removal of early formed phases. They find that under the probable conditions within the cooling solar nebula $MgAl_2O_4$ condenses first at 1470°K, followed by Ca, Ti, and Al minerals. At

1350°K Mg_2SiO_4 *begins to condense,* followed by $MgSiO_3$ and nickel-iron at 1300°K. The presence of spinel, anorthite, gehlenite, and fassaite as chondrules and aggregates in Allende and other Type III carbonaceous chondrites indicates that this class of meteorites owes some of its unique characteristics to the incorporation of this early formed condensate.

COMPARATIVE CHEMICAL DATA.—Additional chemical data on the Allende meteorite are given in Tables 4 and 5. Table 4 lists concentrations for a number of trace elements determined by spark source mass spectrometry. In Table 5 our chemical data are compared with the published data of King (1969); Emery et al. (1969), Morgan et al. (1969), and Wakita and Schmitt (1970). In general, agreement between workers and the various techniques represented is excellent. The work reported by Emery et al. contains several discrepancies, however, perhaps due either to unrepresentative sampling or inadequate methods. Table 5 also contains data on elements that we have not determined.

TABLE 4.—*Trace element data on the Allende meteorite* [1]

Values in parts per million					
B	1	Y	2	Nd	0.9
Sc	11	Zr	9	Sm	0.5
V	70	Nb	0.9	Eu	0.1
Cu	100	Mo	2	Gd	0.6
Zn	25	Sn	0.7	Tb	0.09
Ga	7	Sb	0.2	Dy	0.6
Ge	15	Ba	5	Ho	0.1
As	2	La	0.7	Er	0.3
Br	0.5	Ce	1	Yb	0.4
Rb	0.9	Pr	0.2	Pb	1
Sr	13				

Elements detected but not of suitable intensity for measurement, or suitable standards were lacking.

Se, Ru, Rh, Pd, Ag, Cd, In, I, Te, Cs, Tm, Hf, W, Re, Os, Ir, Pt, Au, Tl, Bi, Th, U.

Hg was not detected.

Ta could not be confirmed because of possible contamination from spark stand.

Lu could not be determined because it was used as an internal standard.

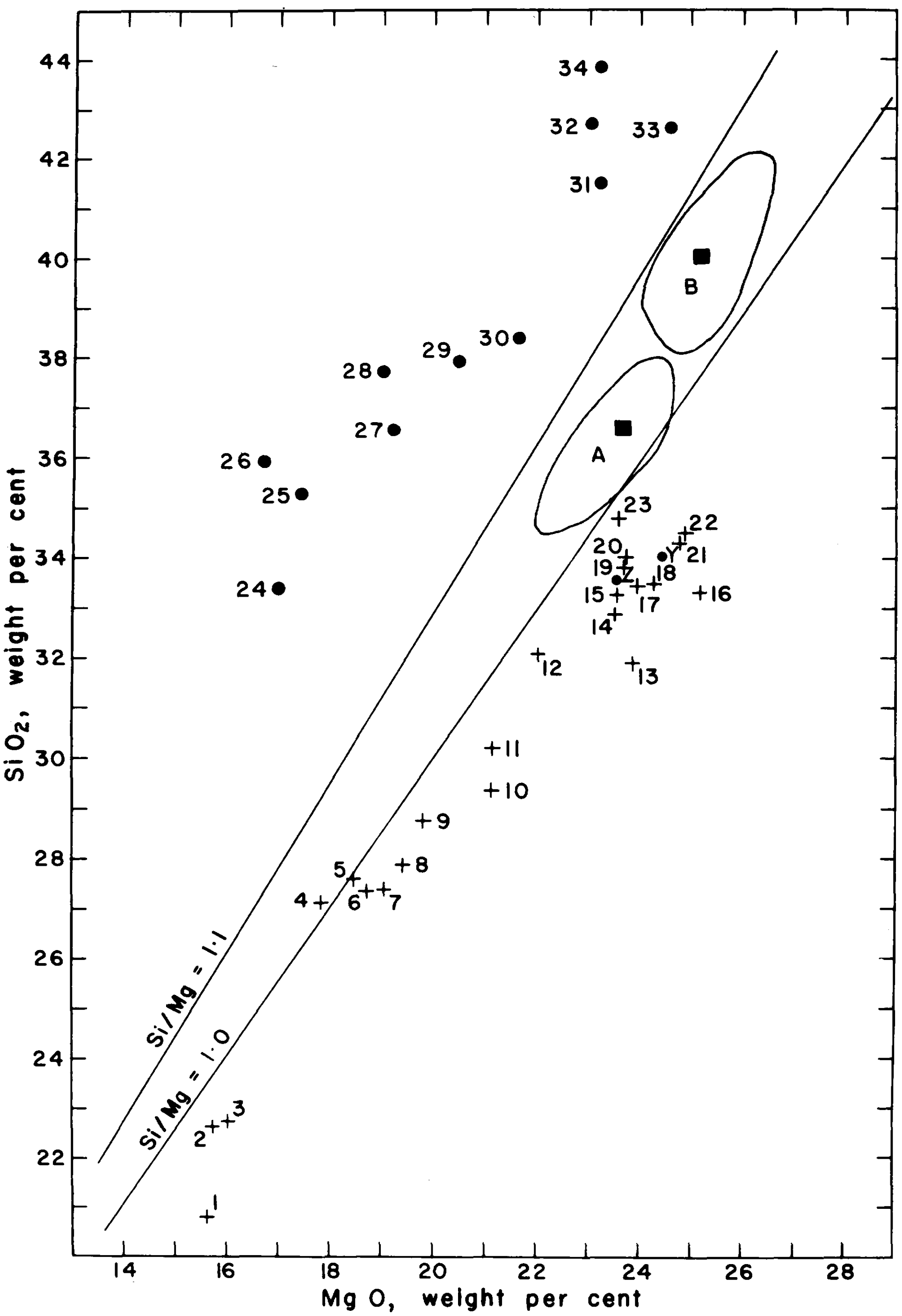
[1] B. Mason and A. L. Graham, analysts. Determinations made by spark-source mass spectrometer while B. Mason was a Visiting Research Fellow in the Department of Geochemistry, Australian National University, Canberra, 1969.

Gast et al. (1970) have reported on several trace elements in a calcium-rich inclusion in Allende. Their values are given in a footnote to our bulk analysis of one of these inclusions (Table 3).

Discussion

The classification of the Allende meteorite presents some interesting problems. Visual inspection immediately suggests that it is a carbonaceous chondrite, specifically a Type III as defined by Wiik (1956)—it is closely similar to others of this type such as Vigarano and Mokoia. Chemical and mineralogical examination confirms this similarity. It has the Si/Mg ratio characteristic of the carbonaceous chondrites, and it falls within the range of other Type III meteorites (Figure 36). The conjunction of iron-poor olivine in chondrules with iron-rich olivine in matrix is also distinctive for these meteorites. Yet the carbon content (0.3 percent) is low for a carbonaceous chondrite, lower in fact than in a number of chondrites whose Si/Mg ratio places them in the ordinary (bronzite and hypersthene) classes.

Recently Van Schmus and Wood (1967) have provided a revised classification for the chondrites, based on a two-dimension grid combining chemical composition and textural and mineralogical features. They divide the carbonaceous chondrites into four types, designated C1, C2, C3, and C4. Types C1, C2, C3 include the same meteorites as Wiik's Types I, II, III, except that Kaba and Mokoia are considered C2 rather than Type III. This produces some ambiguity in the classification of Allende, since it is very similar to Mokoia in chemical and mineralogical composition; however, separating Mokoia and Kaba from the other C3 chondrites seems poorly based, since both these meteorites belong with the other Type III carbonaceous chondrites in terms of bulk chemical composition. Their matrix consists largely of iron-rich olivine, whereas in Type II–C2 chondrites the matrix is hydrated magnesium-iron silicate (serpentine or chlorite). Wiik's classification appears more suited to the carbonaceous chondrites than that of Van Schmus and Wood. Whereas the latter classification seems well adapted for the other classes of chondrites, its application to the carbonaceous chondrites presents certain inconsistencies—probably because the sequence C1 to C4 for the carbonaceous chondrites reflects different conditions of genesis than the E3–E6, H3–H6, L3–L6, and LL3–LL6 sequences for the other classes of chondrites. Significantly, types 1 and 2 in the Van Schmus–Wood classification are known only in the carbonaceous chondrites; their absence in the other chondrite classes suggests a fundamental genetic difference.



Van Schmus (1969) has recognized two distinct subtypes of the C3 chondrites, provisionally called the Vigarano and the Ornans subtypes. He writes: "The most obvious distinction between the subtypes is textural. The chondrites belonging to the Vigarano subtype may be characterized as having large (1–2 mm diameter) 'spongy' chondrules embedded in an abundant, fine-grained, opaque matrix; 'spongy' chondrules contain numerous spheroidal droplets of nickel-iron or sulfide dispersed through the silicate chondrule. The chondrites belonging to the Ornans subtype may be characterized as a close-packed aggregate of small (0.2–0.5 mm diameter) metal-poor chondrules with fine-grained, opaque matrix packed between the chondrules."

The distinction is a useful one, and can usually be easily made by visual inspection. The Vigarano subtype (designated A in Table 6) has large prominent chondrules in a black or dark gray matrix, whereas the Ornans subtype (B) has an evenly granular texture of close-packed chondrules and a uniform light- or medium-gray color. The chemical analyses of the different meteorites show a close similarity for the major components, and for many of the minor and trace elements; carbon, however, is quite variable, as is H_2O+ (the H_2O+ reported in the chemical analyses is probably not combined water but H (and O) combined with carbon in an organic complex—unweathered meteorites of this type do not contain hydrated minerals, and H_2O+ is generally correlated with carbon content). The recorded densities show a considerable range for a group of meteorites of rather uniform composition. Some of this range can perhaps be ascribed to the difficulties of determining accurate densities of porous and fine-grained material; however, the higher densities are characteristic of subtype B meteorites, which generally have an appreciable content (up to 5 percent) of free nickel-iron, whereas subtype A meteorites usually have little or no free nickel-iron and a larger content of carbonaceous material.

FIGURE 36.—SiO_2 plotted against MgO (weight percentages) for chemical analyses of chondrites; the diagonal lines are for Si/Mg atomic ratios of 1.0 and 1.1. A is the field for 36 analyses of bronzite chondrites, B the field for 68 analyses of hypersthene chondrites, the black squares being the means for each group. The analyses of carbonaceous chondrites (+) and enstatite chondrites (●) are plotted individually, as follows:

Type I

1. Alais
2. Orgueil
3. Ivuna

Type II

4. Nawapali
5. Boriskino
6. Cold Bokkeveld
7. Erakot
8. Mighei
9. Murray
10. Santa Cruz
11. Al Rais

Type III

12. Grosnaja
13. Kaba
14. Vigarano
15. Lancé
16. Karoonda
17. Mokoia
18. Ornans
19. Renazzo
20. Felix
21. Efremovka
22. Coolidge
23. Warrenton

Y. Allende (bulk analysis)
Z. Allende (black inclusion)

Enstatite Chondrites

24. St. Sauveur
25. Indarch
26. Adhi Kot
27. St. Marks
28. Abee
29. Atlanta
30. Daniel's Kuil
31. Hvittis
32. Khairpur
33. Blithfield
34. Jajh deh Kot Lalu

TABLE 5.—*Comparison of chemical data on the Allende meteorite. (Values in percent unless noted, ppm = parts per million, ppb = parts per billion)*

Element	*King*[1]	*Emery et al.*[2]	*Morgan et al.*[3]	*Wakita and Schmitt*[4]	*This Work*
O		34.7	35.9±0.7		[36.6]*
Si	15.9	15.9	15.81±0.35		16.00
Ti	0.11				0.09
Al	1.75	1.35		1.71±0.05	1.73
Cr	0.42	0.42	0.39±0.1	3680±100 ppm	0.36
Mn	0.13	0.17		1450±40 ppm	0.14
Mg	14.5	13.1			14.85
Ca	1.8	1.88		2.0±0.2	1.87
Na	0.30		0.33±0.01	3370±100 ppm	0.33
K	0.025	0.18±0.12			0.02
C	0.27				0.29
Ni	1.41	1.15	1.43±0.09		1.39
Co	0.070	0.06	684±17 ppm 612±54 ppm	640±20 ppm	0.06
Fe	23.6	27.8	24.4±0.4	21.9±0.4	23.85
B	0.010				1 ppm
Sc		10 ppm	12.2±0.2 ppm	11.0±0.5 ppm	11 ppm
V	0.017			130±10 ppm	70 ppm
Rb				1.3±0.1 ppm	0.9 ppm
Zr	0.006		12.0±0.7 ppm		9 ppm
Cd				0.19±0.01 ppm	
In				0.027±0.001 ppm	
Cs				0.06±0.01 ppm[5]	
Ba	0.001				5 ppm
Hf		≤0.7 ppm	0.16±0.02 ppm		
W			0.15±0.02 ppm		
Ir			0.71±0.03 ppm		
Pt			1.8±0.2 ppm		
Au			0.26±0.01 ppm		
U		19 ppb			
La				0.44±0.02 ppm	0.7 ppm
Ce				1.25±0.06 ppm	1 ppm
Pr				0.20±0.01 ppm	0.2 ppm
Nd				0.91±0.05 ppm	0.9 ppm
Sm				0.29±0.01 ppm	0.5 ppm
Eu				0.107±0.005 ppm	0.1 ppm
Gd				0.43±0.02 ppm	0.6 ppm
Tb				0.074±0.005 ppm	0.09 ppm
Dy				0.42±0.02 ppm	0.6 ppm
Ho				0.12±0.01 ppm	0.1 ppm
Er				0.31±0.02 ppm	0.3 ppm
Tm				0.049±0.001 ppm	
Yb				0.32±0.02 ppm	0.4 ppm
Lu				0.058±0.002 ppm	
Y				3.0±0.1 ppm	2 ppm

*Oxygen by difference.
[1] King (1969).
[2] Emery et al. (1969).
[3] Morgan et al. (1969).
[4] Wakita and Schmitt (1970).
[5] Changed from published values, Schmitt, personal communication (1970).

TABLE 6.—*The Type III carbonaceous chondrites*

Name	Date of fall	Weight recovered, kg	$D(g/cm^3)$	%C
	Subtype A or Vigarano subtype			
Allende (Mexico)	8/2/1969	>2000	3.65	0.29
Bali (Cameroon)	22/12/1907	3?	3.58	0.56
Coolidge (Kansas)	find	4.5	3.53	0.19
Efremovka (U.S.S.R.)	find	21	3.53	0.76
Grosnaja (U.S.S.R.)	28/6/1861	3.5	3.49	0.56
Kaba (Hungary)	15/4/1857	3	3.40	1.99
Leoville (Kansas)	find	8.1	3.48	0.77
Mokoia (New Zealand)	26/11/1908	5	3.55	0.75
Vigarano (Italy)	22/1/1910	16	3.42	1.15
	Subtype B or Ornans subtype			
Felix (Alabama)	15/5/1900	3	3.78	0.64
Kainsaz (U.S.S.R.)	13/9/1937	>200	3.76	0.61
Karoonda (Australia)	25/11/1930	42	3.57	0.10
Lancé (France)	23/7/1872	52	3.64	0.58
Ornans (France)	11/7/1868	6	3.61	0.35
Warrenton (Missouri)	3/1/1877	50?	3.64	0.30

The Si/Mg ratio is slightly lower in the Type III carbonaceous chondrites than in the ordinary chondrites, and the FeO content is considerably higher. This has far-reaching consequences, since the bulk composition is now very undersaturated with respect to SiO_2, so much so that feldspathoids appear in place of feldspar. Specifically, sodium in the common chondrites is present as sodic feldspar ($NaAlSi_3O_8$, with about 10 percent of the $CaAl_2Si_2O_8$ component), whereas in Allende (and probably in other chondrites of this group) sodium is present as the $NaAlSiO_4$ component (nepheline), and the feldspar is calcic, being almost pure $CaAl_2Si_2O_8$. It has always been something of a puzzle why feldspar composition in stony meteorites is remarkably quantized, being sodic plagioclase in the common chondrites and calcic plagioclase in most achondrites, intermediate compositions (common in terrestrial rocks) being essentially unknown in meteorites. Possibly this segregation of sodium and calcium into distinct phases in the Allende meteorite is a clue to the solution of this puzzle.

The Allende meteorite is noteworthy as being the largest of the carbonaceous chondrites yet recovered. As such, it offers an unequaled opportunity for a thorough investigation. Our work has emphasized the significance of the contrasts between matrix, chondrules, and aggregates. These peculiar aggregates are certainly the most intriguing feature. The larger ones (those readily visible to the naked eye) are not uniformly distributed through the meteorite, being certainly more prominent in some specimens than others. Similar aggregates have been noted in other Type III carbonaceous chondrites. Sztrókay et al. (1961) noted them in the Kaba meteorite, but because of scarcity of material they were not closely investigated. Michel-Lévy (1968, 1969) has described mineralogically similar aggregates from the Vigarano and Lancé meteorites. We have observed them in the Bali meteorite. The meteorite which resembles Allende most closely, however, is Leoville. Only a brief abstract describing this meteorite has so far appeared (Keil et al., 1969), but conversations with Professor Keil and inspection of specimens of Leoville confirm the remarkable similarity. Especially significant is the presence of numerous white aggregates in Leoville, essentially similar in chemical and mineralogical composition to those in Allende.

Literature Cited

Barcena, M.
1876. On Certain Mexican Meteorites. *Proceedings of the Academy of Natural Sciences of Philadelphia,* 28: 122–126.

Buchwald, V. F.
1968. A Reclassification of Mexico's Iron Meteorites. *Program of the Annual Meeting of the Geological Society of America, Mexico City,* (Abstract), pages 40–41.

Carr, M. H.
1970. Atmospheric Collection of Debris from the Revelstoke and Allende Fireballs. *Geochimica et Cosmochimia Acta.* 34:689–700.

Durrani, S. A., and C. Christodoulides
1969. Allende Meteorite: Age Determination by Thermoluminescence. *Nature,* 223:1219–1221.

Emery, J. F., J. E. Strain, G. D. O'Kelley, and W. S. Lyon
1969. Non-Destructive Neutron Activation Analysis of the Allende Meteorite. *Radiochemical Radioanalytical Letters,* 1:137–141.

Farrington, O. C.
1915. Catalogue of the Meteorites of North America to January 1, 1909. *National Academy of Sciences Memoir,* 13:513 pages, 36 plates.

Fireman, E. L.
1969. Freshly Fallen Meteorites from Portugal and Mexico. *Sky and Telescope,* 37(5): 1–4.

Fireman, E. L., J. De Felice, and E. Norton.
1970. Ages of the Allende Meteorite. *Geochimica et Cosmochimica Acta,* 34:873–881.

Fletcher, L.
1890. On the Mexican Meteorites, with Especial Regard to the Supposed Occurrence of Wide-Spread Meteoritic Showers. *Mineralogical Magazine,* 42:91–175.

Fuchs, L. H.
1969. Occurrence of Cordierite and Aluminous Orthoenstatite in the Allende Meteorite. *American Mineralogist,* 54:1645–1653.

Gast, P. W., N. J. Hubbard, and H. Weismann
1970. Chemical Composition and Petrogenesis of Basalts from Tranquillity Base. *Geochimica et Cosmochimica Acta, Supplement I, Proceedings of the Apollo 11 Lunar Science Conference, Houston, Texas January 5–8, 1970,* 2:1143–1163.

Han, J., B. R. Simoneit, A. L. Burlingame, and M. Calvin
1969. Organic Analysis on the Pueblito de Allende Meteorite. *Nature,* 222:364–365.

Hey, M. H.
1966. *Catalogue of Meteorites.* The British Museum (Natural History), London. Printed in Great Britain by The Alden Press (Oxford) Limited.

Hindley, K. B., and H. G. Miles
1970. Fireball and Meteorite of April 25, 1969. *Nature,* 225:255–257.

Jarosewich, E.
1966. Chemical Analyses of Ten Stony Meteorites. *Geochimica et Cosmochimica Acta.* 30:1261–1265.

Jarosewich, E., and B. Mason
1969. Chemical Analyses with Notes on One Mesosiderite and Seven Chondrites. *Geochimica et Cosmochimica Acta,* 33:411–414.

Keil, K., G. I. Huss, and H. B. Wiik
1969. The Leoville, Kansas, Meteorite: A Polymict Breccia of Carbonaceous Chondrites and Achondrite. In *Meteorite Research* (editor P. M. Millman). D. Reidel Publishing Company, Dordrecht, Holland. Page 217. (Abstract.)

King, E. A., Jr.
1969. Petrography and Chemistry of the Pueblito de Allende Meteorite. *EOS Transactions, American Geophysical Union,* 50: 459.

King, E. A., Jr., E. Schonfeld, K. A. Richardson, and J. S. Eldridge
1969. Meteorite Fall at Pueblito de Allende, Chihuahua, Mexico: Preliminary Information. *Science,* 163:928–929.

Knopf, A., and D. E. Lee
1957. Fassaite from near Helena, Montana. *American Mineralogist,* 42:73–77.

Kulik, L. A.
1922. Report on Meteorite Expedition Conducted Between May 19, 1921 and November 1922. *Academiia nauk S.S.S.R., Leningrad.* Bulletin, series 6, 16:391–410.

Kullerud, G., and A. El Goresy
1969. Sulfide Assemblages in the Odessa Meteorite. *Carnegie Institution Year Book,* 67:187–189.

Larimer, J. W., and E. Anders
1970. Chemical Fractionations in Meteorites—III. Major Element Fractionations in Chondrites. *Geochimica et Cosmochimica Acta,* 34:367–387.

Levy, R. L., C. J. Wolf, M. A. Grayson, J. Gilbert, E. Gelpi, W. S. Updegrove, A. Zlatkis, and J. Oró.
1970. Organic Analysis of the Pueblito de Allende Meteorite. *Nature,* 227:148–150.

Marvin, U. B., J. A. Wood, and J. S. Dickey, Jr.
1970. Ca-Al Rich Phases in the Allende Meteorite. *Earth and Planetary Science Letters,* 7:346–350.

McCrosky, R. E., A. Posen, G. Schwartz, and C. A. Tougas
1969. Preliminary Comments on the Trajectory, Orbit and Initial Mass of the Allende Meteorite. *EOS Transactions, American Geophysical Union,* 50:458 (Abstract).

Meighan, I. G., and P. S. Doughty
1969. Recent Fall of the Bovedy Meteorite, Northern Ireland. *Nature,* 223:24–29.

Michel-Lévy, C.
1968. Un chondre exceptionnel dans la météorite de Vigarano. *Bulletin de la Société francaise de Minéralogie et de Cristallographie,* 91:212–214.
1969. Etude mineralogique de la chondrite C III de Lancé. In *Meteorite Research* (editor P. M. Millman). D. Reidel Publishing Company, Dordrecht, Holland. Pages 492–499.

Morgan, J. W., T. V. Rebagay, D. L. Showalter, R. A. Nadkarni, D. E. Gillum, D. M. McKown, and W. D. Ehmann

1969. Allende Meteorite: Some Major and Trace Element Abundances by Neutron Activation Analysis. *Nature,* 224:789–791.

Nininger, H. H.
1936. The Pasamonte, New Mexico, Meteorite. *Popular Astronomy,* 54(6):1–7.

Oró, J., and E. Gelpi
1969. Organic Analysis of the Pueblito de Allende Meteorite. *Meteoritics,* 4:287 (Abstract).

Ponnamperuma, C., K. Kvenvolden, S. Chang, R. Johnson, G. Pollock, D. Philpott, I. Kaplan, J. Smith, J. W. Schopf, C. Gehrke, G. Hodgson, I. A. Breger, B. Halpern, A. Duffield, K. Krauskopf, E. Barghoorn, H. Holland, and K. Keil
1970. Search for Organic Compounds in the Lunar Dust from the Sea of Tranquillity. *Science,* 167:760–762.

Prince, A. T.
1954. Liquidus Relationships on 10 Percent MgO Plane of the System Lime–Magnesia–Alumina–Silica. *American Ceramic Society Journal,* 37:402–408.

Rancitelli, L. A., R. W. Perkins, J. A. Cooper, J. H. Kaye, and N. A. Wogman
1969. Radionuclide Composition of the Allende Meteorite from Nondestructive Gamma-Ray Spectrometric Analysis. *Science,* 166:1269–1272.

Sztrókay, K. I., V. Tolnay, and M. Földvári-Vogl
1961. Mineralogical and Chemical Properties of the Carbonaceous Meteorite from Kaba, Hungary. *Acta Geologica,* 7:57–103.

Van Schmus, W. R.
1969. Mineralogy, Petrology, and Classification of Types 3 and 4 Carbonaceous Chondrites. In *Meteorite Research* (editor P. M. Millman). D. Reidel Publishing Company, Dordrecht, Holland. Pages 480–491.

Van Schmus, W. R., and J. A. Wood
1967. A Chemical-Petrologic Classification for the Chondritic Meteorites. *Geochimica et Cosmochimica Acta,* 31:747–765.

Wakita, H., and R. A. Schmitt
1970. Rare-Earth and other Elemental Abundances in the Allende Meteorites. *Nature,* 227:478–479.

Wiik, H. B.
1956. The Chemical Composition of Some Stony Meteorites. *Geochimica et Cosmochimica Acta,* 9:279–289.

Yoder, H. S.
1954. Garnets and Staurolite. *Carnegie Institution Year Book,* 53:120–121.

Yoder, H. S., and T. Sahama
1957. Olivine X-ray Determinative Curve. *American Mineralogist,* 42:475–491.

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