3 September 1965, Volume 149, Number 3688 SCIENCE

CURRENT PROBLEMS IN RESEARCH

Meteorites and Craters of Campo del Cielo, Argentina

Field studies have thrown new light on a unique prehistoric encounter of a cosmic body with the earth.

William A. Cassidy, Luisa M. Villar, Theodore E. Bunch, Truman P. Kohman, Daniel J. Milton

The earliest Spanish explorers to enter the region that now is northern Argentina heard marvelous stories from the Indians of a large block of iron that had supposedly fallen from the sky. The place where it lay was called Piguem Nonraltá, or, in Spanish, Campo del Cielo (Field of the Sky or Heaven). In 1576 an expedition under Captain Hernán Mexía de Miraval visited the site, returning with a few small pieces of a very large mass, which came to be known as the Mesón de Fierro (Large Table of Iron). Suspecting a silver deposit rivaling those of Peru, Bartolomé Francisco de Maguna led expeditions to the site in 1774 and 1776. He estimated the Mesón de Fierro to weigh about 500 quintales (23 metric tons) and brought back samples, which were found to be iron of extraordinary quality. To determine the workability of the deposit, expeditions were sent to the site in 1779 under Sergeant Major Francisco de Ibarra, and in 1783 under Royal Navy Lieutenant Miguel Rubín de Celis. In addition to securing a sample and measuring the mass, Rubín de Celis reported that there was no evidence for a subsurface extension. He turned the iron body over, using levers, and exploded gunpowder in shot holes in order to examine the soil in its bed. He may have had to dig a hole next to the object to be able to shift such a large mass. Apparently he effectively lowered every part of it below the earth's surface, because the Mesón de Fierro has been lost ever since. However, drawings of the object made by Rubín de Celis and by Cerviño are extant (*1*), and Rubín de Celis's estimate of the weight of the body as over 300 quintales (14 metric tons) has been recorded (*2*).

Another iron mass, weighing about 80 arrobas (900 kg), was found in the region in 1803 by an expedition of Lieutenant Colonel Diego del Rueda. This was eventually recognized as a meteorite and its main mass sent to the British Museum (*3, 4*), where it is cataloged as the "Otumpa" meteorite (*5*). Gradually many small and several large meteorites were found in the region, the largest, El Toba, weighing 4210 kilograms. Table 1 lists known specimens weighing 100 kilograms or more. All that have been examined have been classified as nickel-poor ataxites (*6*) or as hexahedrites (*7*), with nickel content ranging from 5.11 to 5.87 percent (*5*).

About 15 kilometers south of Gancedo, Chaco Province, in the same general region in which these meteorites occur, three shallow depressions were discovered in 1913 by Manuel Santillán Suárez. These, and a fourth at an unspecified location, were investigated by Nágera in 1923 (*8*). Nágera believed the depressions to have been dug by Indians, and meteorites found in one to have been hidden there by them. Spencer, however, concluded in 1933 that the depressions were meteorite impact craters (*9*).

Argentine-American Expedition

In July 1961, as a result of inquiries from Lamont Geological Observatory, one of us (Villar) went to Gancedo and inspected the craters. This brief reconnaissance supported the idea that these depressions were caused by the impact of meteorites, and the information obtained about local field conditions made possible detailed planning of an expedition to study the craters and the associated meteorites.

In 1962 the National Science Foundation awarded a grant to Lamont Geological Observatory of Columbia University to conduct a study of the area. Scientists from several other institutions in the United States were invited to participate, and arrangements were made for a formal association between Lamont and the Dirección Nacional de Geología y Minería to cooperate in the field work. The authors of this article formed a combined Argentine–U.S. field party that visited Campo del Cielo from 17 August to 17 October 1962.

A second combined field party, headed by Cassidy and Villar, visited the site again from 23 August to 23 October 1963, also under NSF sponsorship.

The field parties studied possible meteorite craters, made a reconnaissance map of the crater field and detailed surveys of some of the craters, searched for meteorites with mine detectors and a portable magnetometer, studied depth distribution of meteorites

W. A. Cassidy is a research scientist at Lamont Geological Observatory, Columbia University, Palisades, New York. L. M. Villar is a geologist with the Dirección Nacional de Geología y Minería, Buenos Aires, Argentina. T. E. Bunch is a research assistant in the Department of Earth and Planetary Sciences, University of Pittsburgh. T. P. Kohman is professor of chemistry, Carnegie Institute of Technology, Pittsburgh, Pennsylvania. D. J. Milton is a geologist with the U.S. Geological Survey, Menlo Park, California.

Table 1. Large meteorites found in the Campo del Cielo region of Argentina.

Meteorite*	Individual name (if any)	Mass (kg)	Year found	Place of find † S. lat.	Place of find † W. long.	Present location
A	El Mesón de Fierro	~15,000	Before 1576	Unknown ‡		*In situ*
B	El Toba	4,210	1923	27°39.5′	61°46.5′	Museo Bernardino Rivadavia, Buenos Aires
C	El Taco	3,090	1962	27°40′	61°47.5′	U.S. National Museum, Washington (on loan)
D	El Mataco	990	1937	27°40′	61°44.5′	Parque Independencia, Rosario, Santa Fé Province
E	Otumpa	~900	1803	Unknown §		British Museum (Natural History), London (634 kg)
F	El Tonocoté	850	1931	Unknown		Dirección Nacional de Geología y Minería, Buenos Aires
G	El Mocoví	732	1925	~27°35′	~61°35′	Museo Bernardino Rivadavia
H	El Abipón	460	1936	Unknown		Museo Bernardino Rivadavia
I	El Patio	~350	Before 1960	27°39′	61°43.5′	Estancia El Taco, Gancedo, Chaco Province
J		132	Before 1960	27°39′	61°42′	Museo Municipal, Rafaela, Santa Fé Province
K		~100	Before 1960	27°37′	61°36′	Estancia Los Guanacos, Gancedo

* These designations, in order of decreasing mass, are for identification in Fig 2. † Absolute locations are uncertain by about 1′, but relative locations should be accurate to about 0.5′. ‡ The latitude given by Rubín de Celis, 27°28′S, is intersected by the strewnfield–crater-field axis at about 61°25′W longitude; this might be near the actual location of the mass. § Supposedly at a place called Runa Pocito, some 20 leagues from the Mesón de Fierro (see *18*).

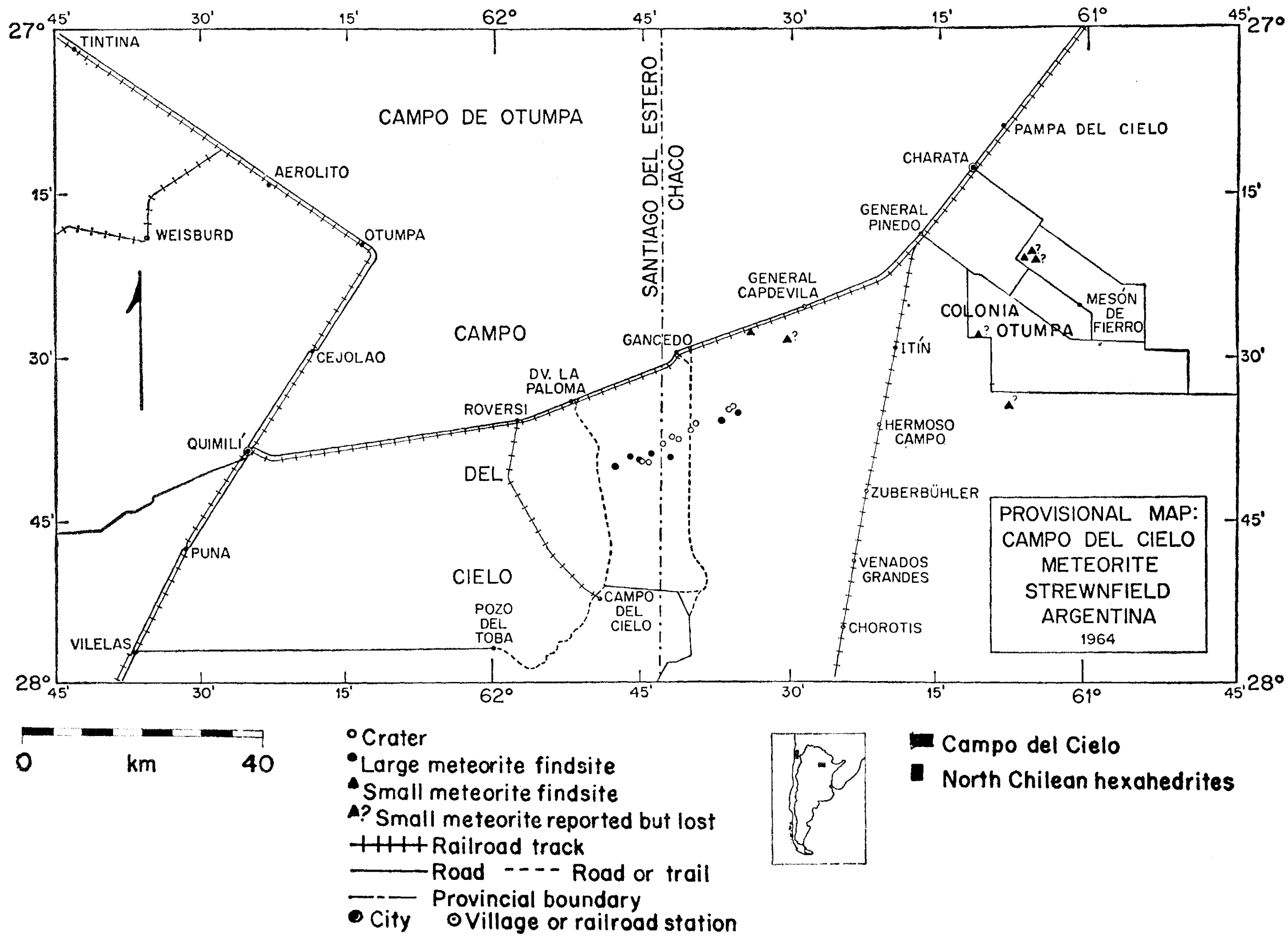


Fig. 1. Map of the Campo del Cielo region of Argentina, showing the meteorite strewnfield and crater field in relation to towns and other geographic features. Based on *Carta Provisional de la República Argentina*, Scale 1 : 500,000, 1957, Sheets 2763 ("Santiago del Estero") and 2760 ("Corrientes"). Note the influence the tradition of native iron and meteorites has had on place names in the region, such as "Aerolito" and "Mesón de Fierro."

in the ground by trenching within the crater field, trenched the rim of one crater, and took serial soil samples with a core drill in and around the same crater. In addition, members of the parties inspected the crater field from the air.

Crater Field

At least nine meteorite impact craters exist in the area. This number includes the four described by Nágera and five not previously described. Identification of the nine craters as meteorite-impact craters rests chiefly on our finding of meteoritic iron or oxidized fragments ("iron shale") associated with them, but also on the fact that the depth-to-diameter ratios of the craters are greater than those of ordinary *represas* (shallow depressions) of the region, and, in most cases, on the presence of low but distinct raised rims.

Figures 1 and 2 show the locations of the identified impact craters, as well as of the known findsites of large meteorites. The most striking facts about the crater field as it is now known are: (i) It is markedly linear in configuration, all of the craters lying close to a line bearing N60°E. (ii) Its linear extent is great, the extreme craters being 17.5 kilometers apart. In both shape and extent it is unique among known terrestrial crater fields—for example, the maximum distance between craters in the Sikhote-Alin group in Siberia is about 1.2 km (*10*); in the Kaalijarv group in Estonia, 1.0 km (*11*); and in the Henbury group in Australia, 0.7 km (*12*).

Dimensions and approximate locations of the meteorite craters are listed in Table 2. Craters 1, 2, and 3 are Nágera's "Hoyo de la Cañada" (Fig. 3), "Hoyo Rubín de Celis" (Fig. 3), and "Laguna Negra" (Fig. 4). Nágera's unmapped "Hoyo aislado" may be the one we designate No. 4. Some apparent pairing occurs: craters 3 and 8 are 1 km apart; craters 5 and 7 (Fig. 5) are 0.6 km apart; craters 1 and 2 are only 200 m from center to center (Fig. 3); and 6a and 6b are overlapping craters consisting of two adjacent depressions with a low rim between them. Beyond the *cañada* (gully) breaching the rim of crater 1 is an extension of the depressed area (Fig. 3), which might be the remnant of one or more smaller craters.

After it became apparent that all of these craters lay close to a straight line, a special effort was made to locate meteorite craters not on this line, without success. In certain areas depressions were very common, but meteoritic materials were not associated with any of these, and all of them could be related to the regional drainage pattern. Because differences in elevation in this area are very slight, it was rather difficult to discern the drainage trends

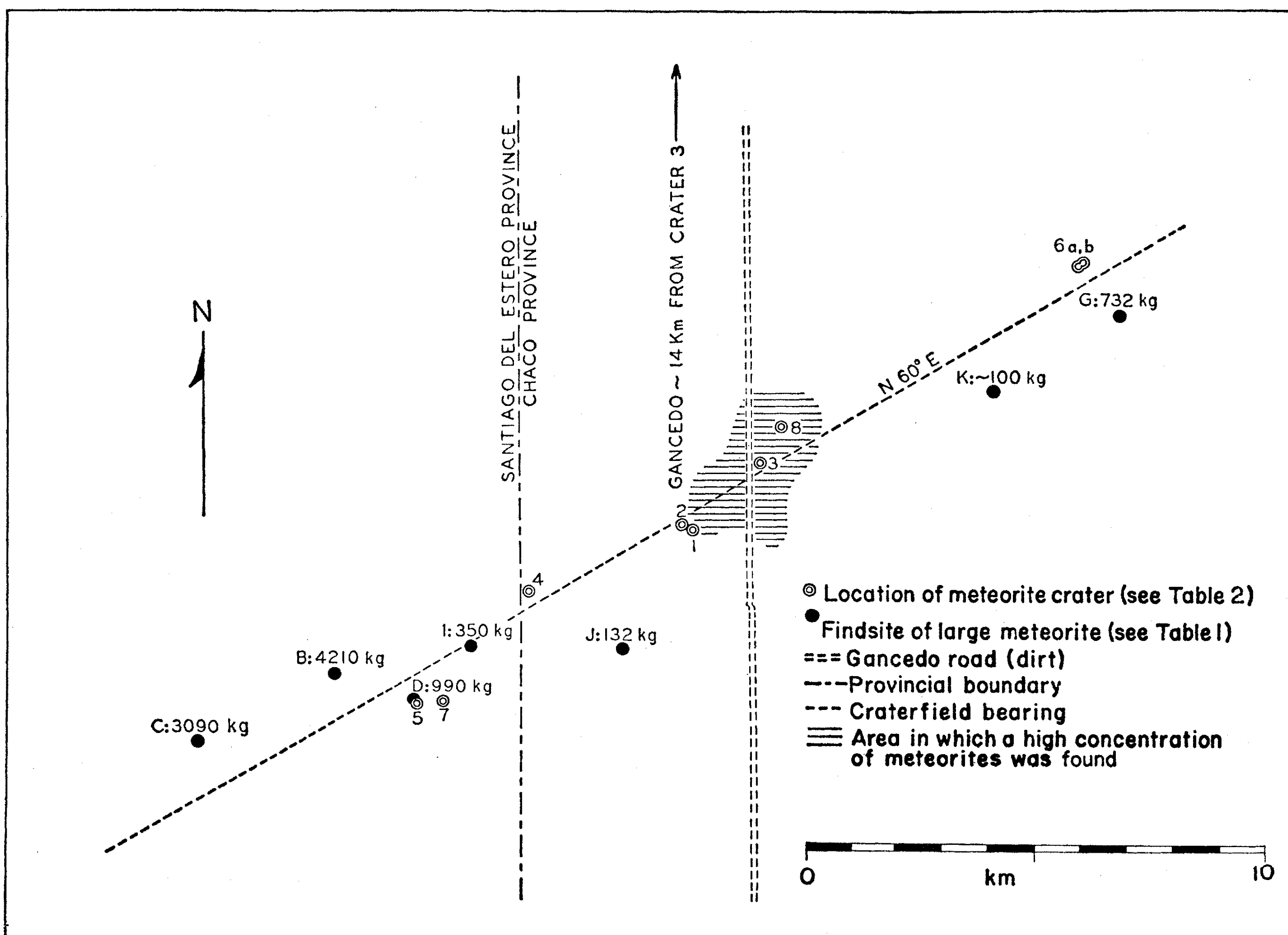
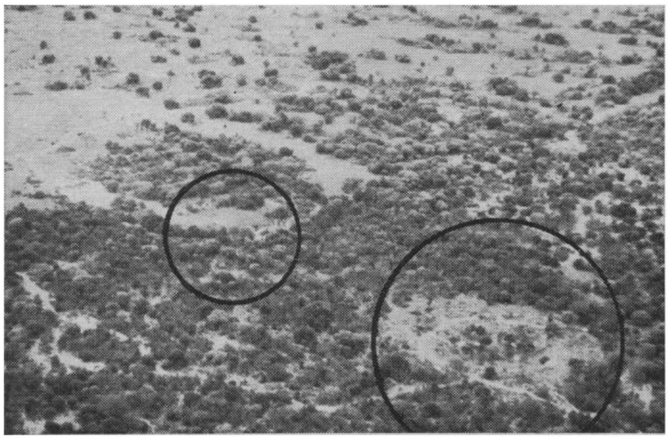


Fig. 2. Provisional map of the Campo del Cielo crater field, showing locations of identified craters, sites where large meteorites were found, and approximate extent of the dense meteorite strewnfield where it has been determined by mine-detector surveys. Meteorites are lettered as in Table 1. Craters are numbered as in Table 2.



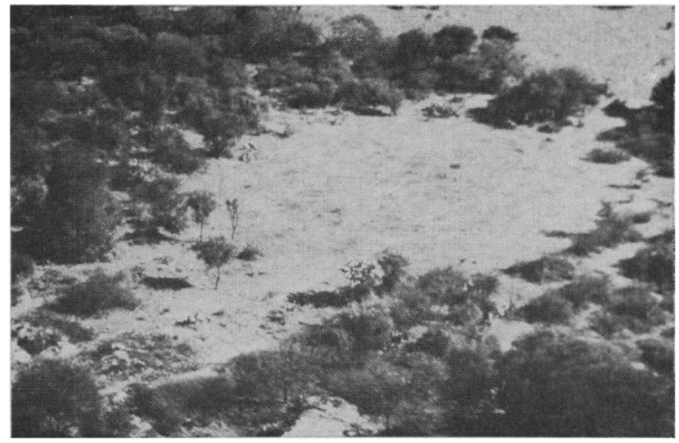


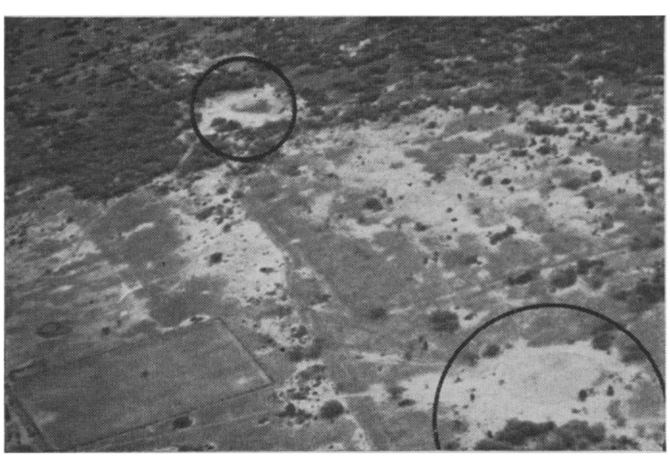
Fig. 3 (left). Aerial view of crater 1 (left) and crater 2 (right), from the northwest and north-northwest, respectively. These are two of the three "Hoyos Agrupados" of Nágera, being only about 200 m apart. Fig. 4 (right). Aerial view of crater 3, "Laguna Negra," from the north. The crater has been filled nearly to ground level by lake sediments and in-wash from the rim.

until a series of green bands was noted from the air. Evidently a series of "lowlands" crosses the area from north to south, with swales several kilometers in width leading into a very broad east-west drainage system passing 20 to 30 km to the south of the crater area. The north-south lowlands are characterized by strings of large salt pans or dry lakes. The areas between these salt pans contain numbers of small shallow depressions. While all those depressions with no traces of meteoritic material could be related to the drainage pattern, the meteorite craters could not.

Crater Investigations

The terrain, typical of much of the Chaco Austral, is semiarid, generally hot, and extremely flat, with an altitude of about 100 m. About equal areas are covered by dense thorn forest and scrub (*monte*) and by grassy savanna, now used for grazing and to some extent for cotton growing. The land is underlain by a thick layer of unconsolidated sediments of the Andean pediment series (*13*). The upper portion is an unbedded clayey loess consisting in part of wind-blown sand and volcanic ash (*8*). The soil is composed of fine sand, clay, caliche, and some humus. The high permeability of the soil is reflected by the absence of permanent surface waters and of any erosional features. There are no nearby rock outcroppings and, except for the meteorites, virtually no mineral fragments larger than sand grains.

The craters, with one exception, are quite shallow in relation to their diameters, having been largely filled with organic lake sediments and material washed in from the walls and rims. In most cases, the rims are low but distinct, and were undoubtedly much higher when the craters were formed. Crater 2 (Hoyo Rubín de Celis), though not the largest in area, is by far the deepest and at present has the greatest volume (Fig. 6). Crater 3 (Laguna Negra, Fig. 4) has the largest area but has a very flat and shallow floor. Many of the craters have an elliptical or subrounded outline (see Table 2) whose major axis lies generally northeast-southwest. This tendency toward a parallel elongation in many of the craters suggests original asymmetric shapes. The present outline of crater 8 is an exception, being somewhat irregular but definitely elongated in the north-south direction; according to local residents, it was a more pronounced feature with higher rims before the field in which it lies had been cleared and cultivated.



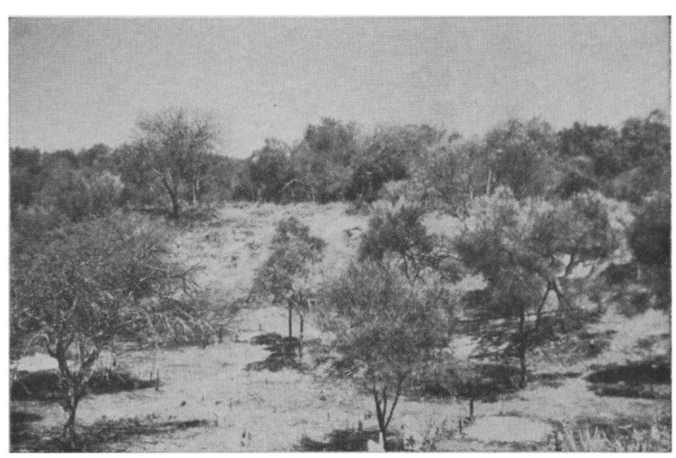


Fig. 5 (left). Aerial view of crater 7 (lower right) and crater 5 (upper left), from the southeast and east-southeast, respectively. The two craters are 0.6 km apart on an east-west line. Apparent "satellite craters" adjacent to these craters are probably of artificial origin, according to local residents. The craters contain water during part of the year. Cattle tracks form the apparent "ray pattern" around crater 7. Fig. 6 (right). View across crater 2, "Hoyo Rubín de Celis," looking southwest from the north rim, after clearing of brush.

Crater 2 was selected for detailed study because it was the least altered. It was thickly overgrown by thorn forest, however, which had to be cleared away before even the general shape could be seen. Figures 7 and 8 show the topography of the present surface.

A radial trench was dug through the northwest rim of the crater. Near the crest, a vertical succession of four zones is well marked (Fig. 9). A modern soil (zone *a*) and subsoil (zone *b*) have developed in the throwout material which forms the raised rim. Below these two members an ancient (pre-impact) soil (zone *c*) and subsoil (zone *d*) can be seen. The throwout material has a lumpy texture which probably reflects its fragmental character, whereas the pre-impact soil and subsoil are more compact and smooth-textured. Farther than about 25 meters from the crest the modern subsoil and the ancient soil can no longer be differentiated (zone *b'*).

The contours of the upper surfaces of the ancient soil and subsoil indicate that the pre-impact surface was raised by about 50 centimeters near the rim of the crater. In addition, the pre-impact soil horizon apparently becomes thicker near the rim, suggesting that it includes some ejected soil deposited directly upon undisturbed soil; inversion of stratigraphy, so that the pre-impact unit that was nearest to the surface lies at the base of the throwout, is characteristic of impact craters.

Trenches in the bottom of the crater revealed a light-tan, clayey zone (zone *e*) of relatively recent wash from the crater walls, grading down into a darker zone (zone *f*), richer in organic matter, which apparently reflects an earlier, slower accumulation of sediments that allowed more extensive soil formation. The indicated recent accelerated mass-wasting is believed to be due to the introduction of livestock into the area several decades ago. Below the organic-rich zone is a reddish zone (zone *g*); the soil is progressively more clayey as depth increases and has an obscurely fragmental texture that is believed to reflect faster deposition due to the originally steeper and higher walls of the crater.

Examination of undisturbed core samples suggests the crater contains a "clay breccia" to a depth of at least 14.8 m below the present crater floor in the center. Red clay clasts in a red-brown matrix predominate near the top, but angular green clay fragments and veinlike green clay inclusions are also noteworthy components. The proportion of the green component increases with depth; green clay is very common at 6.7 m, predominates at 7.0 m, and then decreases. Powder patterns obtained by x-ray diffraction of the red and green clay were identical. Whether there is any relation between this color difference and the probable meteoritic origin of the crater is unknown.

Probably we had not reached the original floor of the crater, because the apparent clay breccia was still present at our greatest sampling depth, 14.8 m. Meteorite fragments and "iron shale" were recovered at depths between 4.0 and 9.3 m in the center. A second hole 10 m S60°W from the center and near the edge of the present crater floor yielded very similar soil samples, with traces of meteoritic material at depths from 3.1 to 6.6 m. The inferred lenslike zone of meteoritic material suggests that the crater was originally deeper, the floor being at least 9.3 m lower than at present, or 13.8 m below present ground surface.

The rim is now only about 1 m higher than ground level, but the amount of infilling indicates that the original rim was one or two meters higher than at present.

Just below the presumed pre-impact surface in the rim flank, a sizable carbonized stump was found still in upright position in the side of the trench. Another pocket of charcoal was encountered about 7 m outside the crest of the rim, at a depth of about 1.3 m, near the contact of the ancient soil and its subsoil; the curvature of the growth rings indicated that this charcoal consisted of separate fragments of fairly sizable pieces of wood lying roughly horizontally. The carbon-14 age of this charcoal (reference No. L-746 for sample dated at Lamont) was determined as 5800 ± 200 years. It is extremely unlikely that charcoal could have been buried in this position after the formation of the crater. It is possible that the charcoal is older and was already buried by about the thickness of the ancient soil at the time of impact. It is far more probable, however, that both this charcoal and the stump were

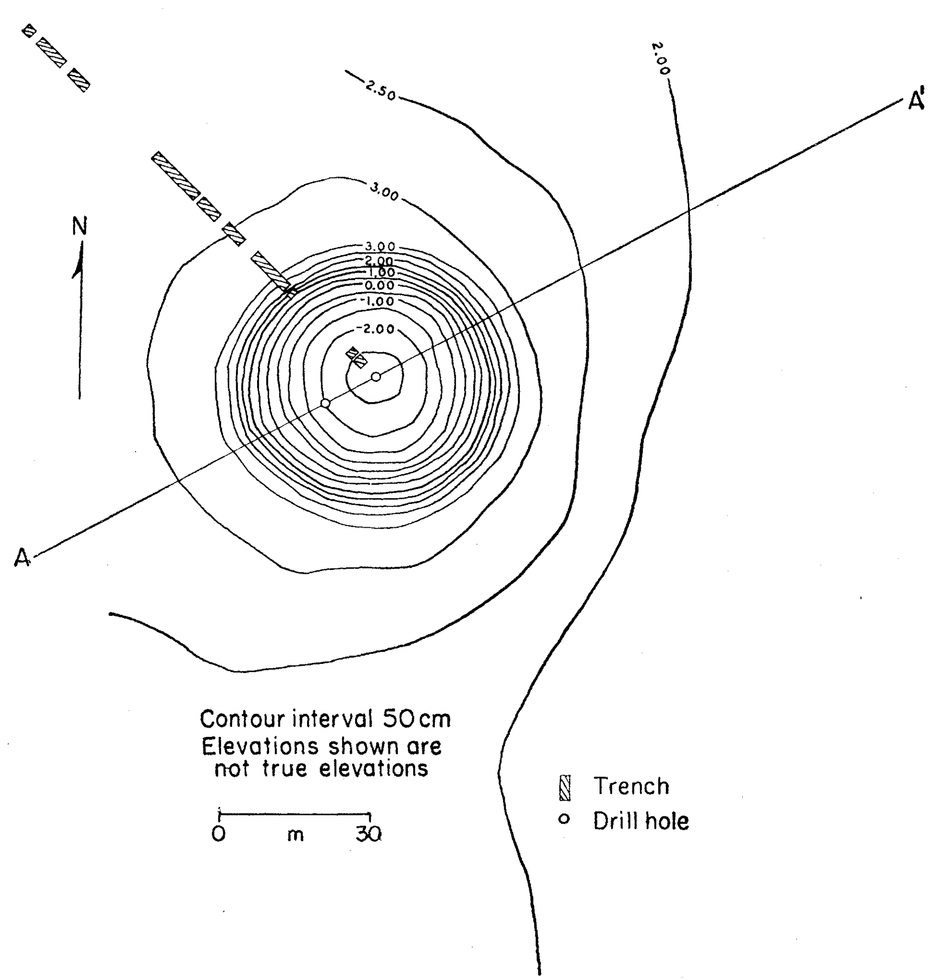


Fig. 7. Contour map of crater 2, "Hoyo Rubín de Celis."

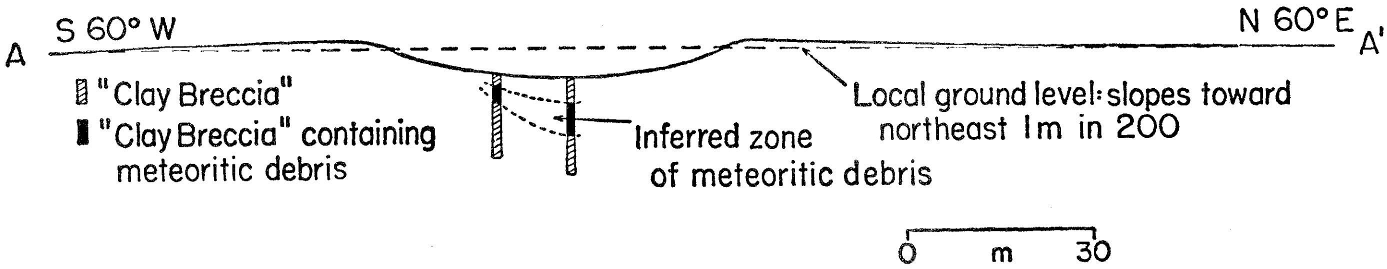


Fig. 8. Cross-section of crater 2 along A–A′ (see Fig. 7).

wood that was buried beneath loose throwout and burned in a forest fire caused by the meteorite fall, under conditions approximating those of commercial charcoal production, in which wood piles are covered with earth before burning in order to limit the access of oxygen. This date, therefore, is a maximum age for the crater and probably the actual age.

Nágera (*8*) reported finding in the bottom of this crater a decimeter-sized agglomerate of volcanic ash containing angular, curved, and striated particles of transparent glass, fragments of plagioclase, grains of amphibole, quartz, pyroxene, and iron oxide, and flakes of biotite. Spencer (*9*) surmised from the absence of local volcanism that the glass could not be volcanic, but would probably prove to be silica-glass of impact origin. We made an intensive search for glass in the craters, particularly in the trench in crater 2, but no loose fragments were found. However, on the interior surface of crater 2, a few centimeter-sized fragments of coherent rock-like material were found, which on laboratory examination were found to contain glass and the other minerals described by Nágera. The fine-grained minerals had been compacted and partially fused together. It cannot be stated unequivocally whether the rock is a product of volcanism, ground fire, human activity, or meteorite impact, but it is believed not to be volcanic because known centers of volcanism are too far away.

Meteorite Strewnfield

As a result of the great local interest attending our work, a farmer, Lázaro Melovich, was inspired to investigate an object buried in his cotton field, on which his plow had been catching during past planting seasons. It proved to be a 3090-kilogram meteorite (Fig. 10, Table 1), which we propose calling "El Taco" after the estancia on which it was found, 5 km southwest of crater 5. We were able to locate the exact places where five other large meteorites had been found by talking to longtime residents who had been present at their removal. These sites are plotted in Fig. 2 and help define the strewnfield. All of the six are close to the line of craters.

The locus of dispersion of meteorite fragments (meteorite strewnfield) at Campo del Cielo is even larger than the crater field; we interviewed farmers who had found meteorites on an extension of the line of craters as far as 55 km northeast of craters 6a and 6b (Fig. 1). We located the northeasternmost specimen in the hands of a collector and obtained a small slice of it. On the basis of metallographic examination, we believe this specimen was part of the same fall. Two other metallic meteorites had been found in adjoining fields. The strewnfield is thus at least 75 km long.

Searches for meteorites with U.S. Army surplus AN/PRS-3 mine detectors were very fruitful. Several field areas 60 by 60 m were covered thoroughly, and several kilometers of traverses about 2 m wide were made. These enabled the approximate extent of the meteorite strewnfield to be determined in the central region, as shown on Fig. 2. By far the greatest concentrations of fragments were found in the area around craters 1, 2, 3, and 8, and in some parts of this area it is impossible to search with a mine detector for more than a few seconds without finding a new meteorite. A sampling of much less than 1 percent of this central area yielded more than 500 specimens. The exact field locations of these meteorites were recorded, and about half of the meteorites were marked to show their orientation in the ground for studies of remanent magnetization. Masses range from 50 grams to 35.7 kilograms. Depths of occurrence cluster tightly between 15 and 25 centimeters.

Trenching in zones that had been searched earlier with mine detectors

Table 2. Meteorite craters in the Campo del Cielo region of Argentina.

Crater (our No. *)	Nágera's name (*8*)	Location †		Dimensions (m)			Maximum depth (m)	
		S. lat.	W. long.	Present authors (NE–SW × NW–SE)		Nágera (E–W × N–S)	Present authors	Nágera
				Rim ‡	Floor			
1	Hoyo de la Cañada	27°37.5′	61°41′	105 × 65	50 × 40	52 × 54.5	2	2.2
2	Hoyo Rubín de Celis	27°37.5′	61°41′	72 × 69	28 × 31	54.5 × 65	5.5	>5
3	Laguna Negra	27°37′	61°39.5′	115 × 91	74 × 46	78 × 65	2.5	~2
4	Hoyo aislado (?)	27°38′	61°43′	89 × 88	44 × 47	42 × 44	1.5	2
5		27°40′	61°44.5′	Indefinite	47 × 42		1	
6a		27°34.5′	61°36′	35 §	15 §		2.5	
6b		27°34.5′	61°36′	20 §	8 §		2.	
7		27°40′	61°44′	96 × 74	45 × 45		0.5	
8		27°36.5′	61°39′	28 × 46¶	Indefinite		0.5	

* These designations, in chronological order of entry in our field records, are the same used in Fig. 2. † Absolute locations are uncertain by about 1′, but relative locations should be accurate to about 0.5′. ‡ Measurements from highest points on opposite rims, and thus most are larger than the diameters reported by Nágera (*8*), made at unspecified high levels on the inside walls. § NE–SW dimensions obscured by overlap. ¶ E–W × N–S.

supported this apparent depth distribution. From a comparison of the numbers and sizes of fragments recovered by mine detector and by trenching, we concluded that the mine detectors were finding only about half the total number of fragments in any searched area, but about 90 percent of the total mass of meteoritic material present.

Most of the craters yielded no, or very few, meteorite fragments. However, a mine-detector survey of the relatively small crater 8 yielded 24 meteorite fragments within the depression and one outside, with a total mass of 50 to 60 kg.

In addition to the mine-detector and trenching investigations, a Varian M49A portable proton-precession magnetometer was used to search for deeply buried meteorites. Theoretical calculations made by the Magnetics Section at Lamont Geological Observatory indicated that an iron sphere of 30-cm radius (mass about 900 kg) would be detectable with this instrument in the magnetic environment of Campo del Cielo (field strength, 0.248 gauss; inclination of the earth's magnetic field to the horizontal, 22°) at a depth of up to 4 m. Test grids run over the 3090-kg "El Taco" meteorite indicated that this somewhat tabular mass could have been detected at a depth of 7 m. Since the response of the magnetometer is much slower than that of the mine detectors, we used the magnetometer only in crater investigations. The northwest quadrant of the floor, wall, rim, and flank of crater 2 was magnetically mapped on a 1-m grid with the sensing head 60 cm above the ground. An 18.3-kg meteorite was found at a depth of 20 cm in the crater rim, but no large masses were noted.

In summary, it can be said that the strewnfield is very long, but not as narrow as the crater field. The major axes coincide, however, and the strewnfield appears to extend beyond the crater field in all directions (Fig. 1).

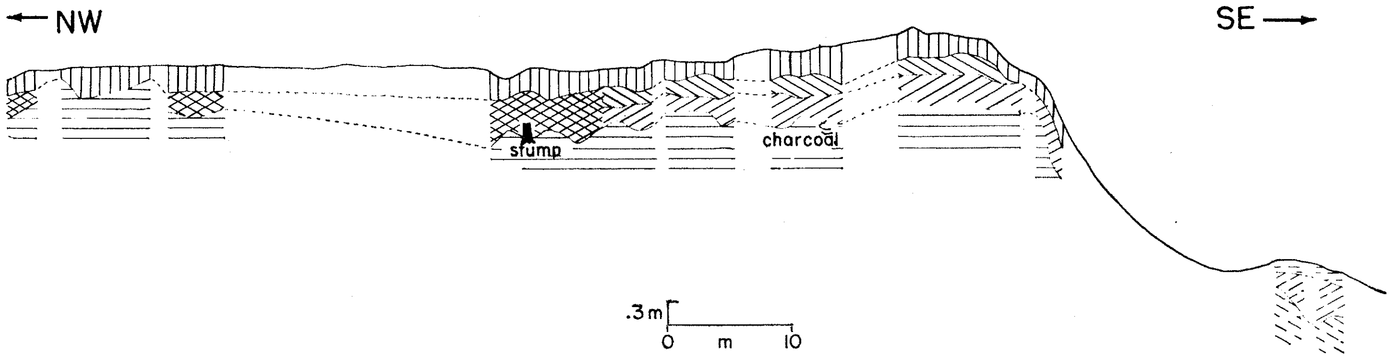
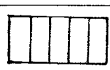
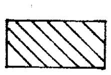
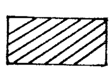
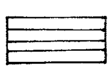
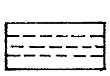
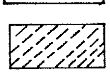


Fig. 9. Sectional diagram of trench along northwest radius, crater 2.

Symbol	Zone	Description	Interpretation
	a	Soft dark-colored soil with much vegetable matter Lumpy texture Gradational boundary	Modern soil developed in throwout material
	b	Light-tan, clayey material, in part cemented by caliche Lumpy texture Sharply defined boundary	Modern subsoil developed in throwout material
	c	Compact, dark-colored, organic-rich zone Gradational boundary	Pre-impact soil
	d	Compact, tan-colored, clayey material	Pre-impact subsoil
	*b′*	Darker, less clayey material than *b*, with material suggesting zone c occasionally near its base.	Transitional zone between *b* and c found at distances greater than 25 m from the crest, where the sharply defined boundary between *b* and c disappears
	e	Light-tan, clayey material Gradational boundary	Recent wash from crater walls
	*f*	Dark, organic-rich zone, becoming redder and containing decreasing amounts of organic material with greater depth Gradational boundary	Older wash from crater walls that accumulated relatively slowly and allowed some degree of soil formation
	*g*	Apparent "clay conglomerate" or "clay breccia" or both, consisting of dark brown or red clay containing apparent clasts of darker and harder clay fragments and variable amounts of caliche and veinlike and patchy green clay. Small meteorite fragments, oxide flakes, and rust spots also noted within a lenslike zone at depth (Fig. 8)	Older wash from crater walls that accumulated fast enough that soil formation did not occur. May grade downward into fallback material and autochthonous breccia

Metallography of the Meteorites

Villar has examined the slice taken from the specimen found at the northeastern end of the strewnfield, and found that it is a hexahedrite. A number of the meteorites recovered from other parts of the strewnfield have been sectioned and examined by Bunch, and all are hexahedrites. From the appearance of polished faces, they may be classified more specifically as grained hexahedrites. The polygonal grains seen in Fig. 11 are kamacite (α-iron) and are typically 0.3 by 1.0 cm in cross section.

Accessory minerals are taenite (γ-iron) lamellae, present as remnant plates following the Widmanstätten-oriented growth of the kamacite; and schreibersite [$(Fe,Ni)_3P$] as the rhabdite form in the kamacite, as the massive form in veins, and associated with massive trolite (FeS) in isolated patches. Silicate inclusions have been noted in minor amounts, the largest encountered measuring 2 by 1 by 1 cm. Forsterite, chrome-diopside, enstatite, and oligoclase, in order of decreasing abundance, are also present. Schreibersite, troilite, kamacite, graphite, chromite, and secondary iron oxides are randomly distributed throughout the silicate assemblage (*14*).

Neumann lines are common and occur in all parts of the kamacite. Broad deformation bands cut and offset Neumann bands (Fig. 12), indicating that the deformation bands were probably formed later than the Neumann bands and that the metal was severely stressed at some late stage in the history of the meteorites, possibly on impact with the earth. This is also indicated by the stretched and twisted appearance of the iron in many sections (Fig. 11).

Mode of Arrival

The distribution of craters and larger meteorites along a straight line suggests that the parent meteoroid entered the earth's atmosphere in a very flat trajectory and fragmented at great altitude in one or more violent disruptions. The fragments, according to this interpretation, were separated from one another with relatively small lateral and vertical velocity components. Vertical velocity differences were amplified by differential atmospheric drag into large horizontal differences in the points of arrival at the earth's surface, where the larger fragments produced craters. Small fragments may have had larger separation velocities, with the result that some came to earth beyond the crater-producing masses and some fell short.

It is uncertain whether the fragmentation producing the innumerable small meteorites strewn about occurred in the atmosphere or upon impact of the larger masses with the ground. The violent shearing evinced by many of these small fragments tends to support the latter supposition, whereas the inferred small radius of the throwout zone around crater 2 tends to support the former. Future field work on the distribution of these fragments may provide an answer to this question.

A nearly horizontal entry trajectory might result either from a grazing approach to the earth from a solar orbit or from decay of a closed terrestrial orbit into which the meteoroid had been captured earlier by lunar perturbation or atmospheric retardation. Dynamical considerations indicate that low entry angles are most likely to be associated with low geocentric velocities prior to arrival (*15*), and the worldwide distribution of hexahedrites (*16*) suggests that this class of meteorites may generally possess such orbital characteristics (*15*). Breakup before substantial atmospheric penetration occurred may have been induced by tidal stresses. In any case, any fragments escaping this passage with velocities between 7.8 km/sec (circular) and 11.0 km/sec (parabolic) would orbit the earth in ellipses and reenter the atmosphere at about the same latitude, or somewhat before.

In decaying near-circular orbits a revolution would take about 88 minutes, during which the earth would have rotated about 22 degrees eastwards. We note that some 1000 km to the northwest of Campo del Cielo there occurs another strewnfield of this rather rare type of meteorite, and we suggest that the two strewnfields may be related. At least a dozen hexahedrites have been found in northern Chile along a narrow coastal strip about 400 km from north to south (*17*). Their nickel contents range from 5.32 to 5.77 percent, essentially the same as those of the Campo del Cielo meteorites (*18*). The dispositions of the two strewnfields correspond remarkably well to the hypothesis that a meteoritic mass initially approached from the northeast of Campo del Cielo in a near-minimum orbit of about 40° inclination, with reentry on the next revolution somewhat to the north. A line drawn through a point 22 degrees due west of Campo del Cielo with a direction N60°E passes through the continental North Chilean strewnfield. Differences in orbital periods among fragments produced during the previous perigee pass would result in the considerably greater extent of the second strewnfield; this field may lie mostly in the Pacific Ocean off the Chilean coast. Detailed studies of physical properties and chemical composition of the meteorites, precise delineation of the strewnfields, and determinations of fall times and cosmic-radiation-expo-

Fig. 10. "El Taco" meteorite, mass 3090 kilograms. Considerable "iron shale" was found in the hole from which it was pulled.

sure histories might show whether or not the two occurrences were associated.

The name "Campo del Cielo" was applied by early Spanish explorers to the region containing large iron masses which are undoubtedly parts of the meteorite group we have been investigating. Cohen in 1905 designated the meteorites by "Campo del Cielo" (*6*), and Nágera in 1923 called the craters "los hoyos del Campo del Cielo" (*8*). On the basis of these precedents, we propose that this group of hexahedrites be called the "Campo del Cielo Meteorites" and the associated craters the "Campo del Cielo Craters" (*19*). Because of its meaning (Field of the Sky), this name is most appropriate and descriptive.

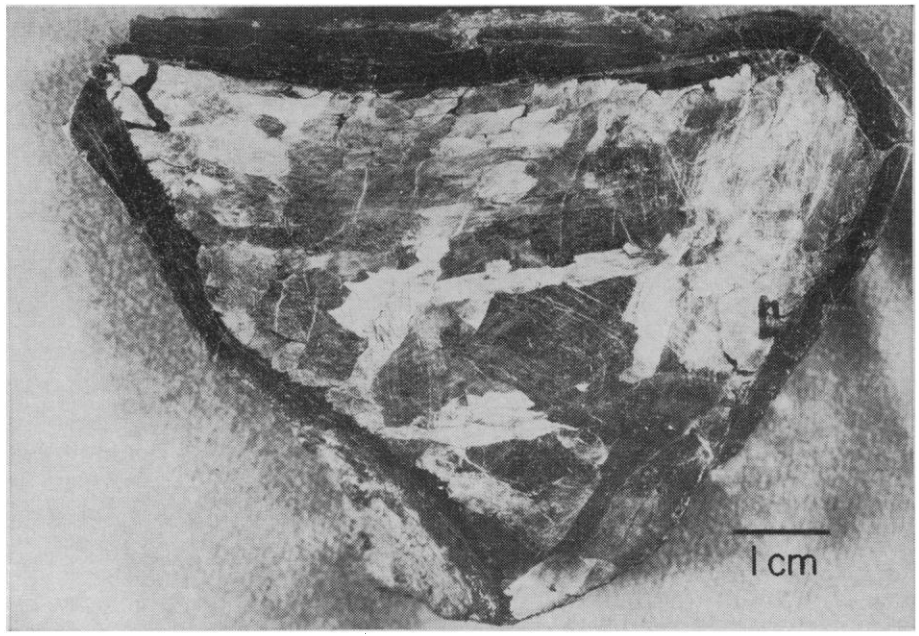


Fig. 11. Etched surface of a Campo del Cielo meteorite, showing deformed polygonal kamacite grains.

Another frequently used place name of this region is "Otumpa," derived from the Indian *hatumpampa* (high plain) (see Fig. 1). "Otumpa" has been used for the Mesón de Fierro (*2, 3*), for the object displayed in the British Museum (*4, 20*), and as a general name for the hexahedrites of the region (*5*). We feel that to continue usage of "Otumpa" as a group name would be misleading because localities now identifiable as Otumpa are not obviously connected with the strewnfield and the craterfield (see Fig. 1).

We suggest that the traditional names for individual large members of this group (Table 2) be retained and used (perhaps in parentheses after the group name) to designate specific meteorites, as: "Campo del Cielo (Otumpa)" for the meteorite in the British Museum.

Hundreds of Campo del Cielo specimens will be found in the future. We are numbering serially those we find. These numbers will be used in tables and location maps so that specific specimens can be requested for research by interested investigators. The fact that the craters and meteorite strewnfield were virtually untouched prior to our investigations adds to the value of our field observations. We intend to make recovered materials readily available for scientific studies, and we hope that this will become one of the world's best known and most thoroughly studied meteorite-impact events.

Summary

Field studies in 1962 and 1963 at Campo del Cielo, Argentina, by joint Argentine-American teams have indicated the presence of an iron meteorite strewnfield and crater field that is much larger than previously thought and unique in many respects. Nine depressions with craterlike morphology have been identified as of impact origin. They range in mean diameter from 20 to 100 m, and in maximum depth from 0.5 to 5.5 m. The rims have all been lowered by weathering and the bottoms considerably filled in. A maximum and probable age of about 5800 years is given by the radiocarbon dating of charcoal found under a crater rim.

Besides the lost Mesón de Fierro, estimated as weighing at least 14 tons, and the approximately 900-kg Otumpa meteorite found in 1803, at least eight irons with masses from 100 to 4210 kg had been discovered. A 3090-kg mass was uncovered by farmers during our 1962 field season. We found and dug

Fig. 12. Photomicrograph by reflected light of a polished and etched surface of a Campo del Cielo meteorite, showing many Neumann bands (fine structure) and broad deformation bands (trending from upper left to lower right). (× 110)

out more than 500 meteorites weighing from 50 g to 35.7 kg and aggregating about 600 kg. The total recovered mass is at least 12,400 kg, and this is probably only a small fraction of the metal remaining.

The craters all fall within 1 or 2 km of a line 17.5 km long, bearing N60°E. The largest meteorites and the densest parts of the strewnfield all occur within a few kilometers of the line defined by the craters, but the extreme findsites are at least 75 km apart. The newly found meteorites so far examined are hexahedrites, like those of the region previously classified. They have a granular texture showing considerable distortion, and displaced Neumann bands.

The great extent and extreme narrowness of both the crater field and the meteorite strewnfield make this a unique occurrence. A high-altitude breakup of a meteoroid in a very flat trajectory is indicated. It is speculated that this meteorite may have been a natural satellite of the earth in a decaying orbit, and that the North Chilean hexahedrites may be fragments of the same body which made one more revolution before coming to ground.

References and Notes

1. A. Alvarez, *El Meteorito del Chaco* (Peuser, Buenos Aires, 1926). Except where noted otherwise, this monograph supplied the material given in the introductory paragraphs.
2. M. Rubín de Celis, *Phil. Trans. Roy. Soc. London* **78**, 37; transl. 183 (1788).
3. W. Parish, *Phil. Mag.* **124**, 53 (1834).
4. ———, *Buenos Ayres and the Provinces of the Rio de la Plata* (Murray, London, ed. 2, 1852), pp. 288–96.
5. G. T. Prior and M. H. Hey, *Catalogue of Meteorites* (British Museum, London, ed. 2, 1953), pp. 281–2. The coordinates given under "Otumpa," 27°28′S; 60°35′W, are questionable.
6. E. Cohen, *Meteoritenkunde, Heft 3* (Schweizerbart, Stuttgart, 1905), pp. 35–44.
7. S. H. Perry, *U.S. Nat. Mus. Bull.* **184**, 17 (1944).
8. J. J. Nágera, "Los Hoyos del Campo del Cielo y el Meteorito," *Direc. Gen. Minas Geol. Hidrol., Buenos Aires, Publ. 19* (1926).
9. L. J. Spencer, *Geogr. J.* **81**, 227 (1933).
10. E. L. Krinov, *Principles of Meteoritics* (Pergamon, London, 1960), p. 143.
11. ———, *Am. J. Sci.* **259**, 430 (1961).
12. A. R. Alderman, *Mineral. Mag.* **23**, 19 (1932).
13. H. J. Harrington, "Handbook of South American Geology," W. F. Jenks, Ed., *Geol. Soc. Am. Mem.* **65**, 153 (1956).
14. F. Park, T. E. Bunch, A. M. Reid, T. B. Massalski, A. J. Cohen, abstract, *Trans. Am. Geophys. Union* **44**, 86 (1963).
15. E. Vilcsek and H. Wänke, "Cosmic-Ray Exposure Ages and Terrestrial Ages of Stone and Iron Meteorites Derived from Cl^{36} and Ar^{39} Measurements," *Radioactive Dating* (International Atomic Energy Agency, Vienna, 1963), p. 381.
16. E. P. Henderson, "Hexahedrites," *Smithsonian Inst. Misc. Collections* **148**, No. 5 (1965).
17. ———, *Am. Min.* **26**, 546 (1941).
18. G. T. Prior and M. H. Hey, *Catalogue of Meteorites* (British Museum, London, ed. 2, 1953), pp. xii–xiii, and alphabetical listings.
19. This suggestion has the approval of Dr. Edward P. Henderson of the U.S. National Museum and of Dr. Max H. Hey of the British Museum (personal communications).
20. M. M. Radice, *Rev. Museo de la Plata, Secc. Geol.* **5**, 29 (1959). The location given for the Otumpa findsite, 27°46′S, 62°33′W, is questionable.

21. We thank NSF for grants G-24481 and GP-1213, which financed most of this work; the Argentine Servicio de Hidrografía Naval and Dirección Nacional de Geología y Minería del Ministerio de Economía de la Nación for invaluable assistance with customs formalities and logistics; Dr. R. V. Tezon, Director Nacional de Geología y Minería, Capitán L. R. A. Capurro and Capitán N. Granelli, Servicio de Hidrografía Naval, and Dr. E. Methol, Dirección Nacional de Geología y Minería for a variety of aids and favors; F. Ramon, Universidad de Buenos Aires, for collaboration during part of the 1962 field season; S. Elia, Estancia Los Guanacos, Gancedo, and H. Favaron, Charata, for use of their private planes; E. Llorens, H. Favaron, and Capitán de Corbeta J. C. Moreno, Armada Nacional for piloting for aerial photography; L. O. Giacomelli, Buenos Aires, for information on large meteorites from Campo del Cielo; D. A. H. Christensen and other members of the family of the late Juan Christensen for making available notes, maps, and unpublished documents on the Mesón de Fierro; M. A. Severin, J. R. Báscolo, and B. Stoffel for giving us an important specimen and for help in interviewing local people; Prof. W. S. Broecker, Lamont, for radiocarbon age determination; Dr. J. R. Hiertzler, Lamont, for theoretical calculations of magnetic anomalies, and F. R. Park, Mellon Institute, for the photographs used for Figs. 11 and 12. T. E. Bunch thanks the Mellon Institute, his employer during his participation in the field and preliminary laboratory work, and NASA for support (grant NsG-57-60, Suppl. 62). T. P. Kohman thanks the Trustees of Carnegie Institute of Technology for a research leave-of-absence. This is Lamont Geological Observatory Contribution No. 837.

Chemical Communication in the Social Insects

Insect societies are organized principally by complex systems of chemical signals.

Edward O. Wilson

In his famous lyric work, *The Life of the Bee*, published in 1901, Maurice Maeterlinck imagined the existence of an intangible social force that directs the activity of the colony. "Where is this 'spirit of the hive' . . ." he asked, "where does it reside? . . . It disposes pitilessly of the wealth and the happiness, the liberty and life, of all this winged people; and yet with discretion, as though governed itself by some great duty." Perhaps entomologists never accepted this *élan social*, yet until quite recently their attempts to explain the organization of insect societies in mechanistic terms have gone slowly. The reason is that much of the "spirit of the hive" is actually invisible—a complex of chemical signals whose identities we have only now begun to reveal by the combination of chemical analyses and detailed studies of exocrine glands. Today this subject invites closer attention, because, in the first place, as I will argue shortly, most communication in social insects appears to be chemical, while, in the second place, pheromone systems have evidently reached their highest evolutionary development in these insects.

A chemical signal used in communication among members of the same species is called a *pheromone*, a term coined in 1959 as a substitute for the older, self-contradictory *ectohormone* (*1*). Pheromones may be classified as olfactory or oral according to the site of their reception. Also, their various actions can be distinguished as releaser effects, comprising the classical stimulus-response mediated wholly by the nervous system (the stimulus being thus by definition a chemical "releaser" in ethological terminology), or primer effects, in which endocrine and reproductive systems are altered physiologically (*2*). In the latter case,

The author is professor of zoology at the Biological Laboratories, Harvard University, Cambridge, Massachusetts.