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Vaca Muerta mesosiderite strewnfield

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Abstract—A field investigation is presented of the strewnfield of the mesosiderite Vaca Muerta, originally found in 1861. The area, 11.5 km long, 2.1 km wide, is located about 60 km southeast of Taltal, Chile, in the Atacama Desert. It has yielded 80 meteorites with a total mass exceeding 3782 kg. Most fragments were found in an undisturbed state, but some had been broken by prospectors. The present studies, in connection with historical records, indicate that the original mass of Vaca Muerta exceeded 6 metric tons. One impact feature, somewhat modified by man, consists of a 10.5-m diameter, 1.7-m deep hole, without an uplifted rim. Small masses were scattered up to 85 m from the hole.

INTRODUCTION

The mesosiderite class of stony-iron meteorites comprises at least 26 finds and 6 falls (Graham *et al.*, 1985), and the total mass is given as 1632 kg (Buchwald, 1975). Vaca Muerta is one of the earliest and best known finds, dating from 1861; about 45 kg is in museums worldwide.

Material from Vaca Muerta has been subjected to many studies, including recent analysis of the meteorite's diverse silicate inclusions (Rubin and Jerde, 1987; 1988). Begemann and Vilcsek (1969) measured the activity of ^{36}Cl and deduced the surprisingly high terrestrial age of 240,000 a which, however, was considered very uncertain. Recently, A. J. T. Jull (pers. comm., 1990) measured a ^{14}C age of 3500 a.

In the present article, we describe the historical evidence, the results of recent field work, and give a comparison with the old reports. Appendix A contains a discussion of the synonyms used for the historic material and Appendix B contains a description of the artifacts left by prospectors. A list of the material's distribution into collections has been deposited with the editor of the Meteoritical Bulletin, together with further details of the field work.

HISTORICAL EVIDENCE

The first masses, ranging in size from a few g to more than 20 kg, were reported in 1861 (Domeyko, 1862). Shortly thereafter, Domeyko (1864a,b) stated that at least two "quintals" (one Spanish quintal ~46 kg) were in the hands of collectors, and it was estimated that 20 quintals (920 kg) could easily be collected.

The first specimens which came into Domeyko's possession were received from his old pupil, Leonidas Garcia, at Copiapo (or Coquimbo) who also wrote two letters with information on the find (Domeyko, 1864a). The first letter dated August 17, 1861, states (in Spanish) that: "The meteorite is found in great abundance 10 leagues (one Chilean league = 4.5 km, but see later) southeast of the silver mine Isla, close to Taltal. The terrain on which it is found, is level, a vast plain, and there are some hills nearby, but it can in no way be supposed that these stones have rolled down.... The pieces are found largely embedded, and one can see, next to each stone, and at some distance from it, a depression, as if the stone had fallen there before arriving to the place where it is now found. These depressions are located to the east of the stones.... I owe the previous data to don José Diaz Gana (in his time a well-known mining entrepreneur) who, before giving me them had read what Dr. Philippi (*i.e.*, Philippi, 1860, 121–123) says referring to the iron meteorite from Imilac." Domeyko (1864b, in French), states: "... a large number of meteoritical masses are dispersed, without any order or definite direction" and it is only the largest masses which are "slightly depressed in the terrain" and have an "empty concavity" on the eastern side.

In his second letter, Garcia stated an allegedly more precise find-location "enormously in front of sierra del Chaco." This was accepted by Domeyko until, some years later, he became convinced that the meteorites originated from a different place, called *Quebrada* (dry riverbed) *Vaca Muerta* (Domeyko, 1875) by prospectors. This was stated to be approximately 12 leagues from a small bay named Guanillo. The latter is a non-unique place-name, and Fletcher (1889), in his thorough discussion of the location of Vaca Muerta, has described how this incidentally correct information caused confusion, since Domeyko assumed it to be one near Paposo which is further north.

At an unknown time, possibly towards the end of 1882 or 1883, Domeyko obtained three samples of rock, claimed to be "iron mineral"; at least two were recognized to be from Vaca Muerta. They were sent from Chañaral by Domingo Alarcon (Domeyko, 1897, 312), who stated that they were found at "a location 5 kilometers northeast of the plant at Carrizalillo and approximately 54 kilometers (12 leagues, *sic*!) from the coast, to the left entering the country by the cart-track which runs from the port of Pan de Azucar and which passes by the refuge or watering place Quinchigüe, Las Vegas and Carrizalillo," and he assured Domeyko that they originated "from a vein 97 centimetres wide, and next to it there are something like 60 to 70 quintals (*i.e.*, 2760 to 3220 kg) taken out from various small holes dug along the run of the vein."

At about the same time, on November 23, 1883 (or 1884), the fall area was visited by the Norwegian geologist Lorenzo Sundt (1909, 17–18). Sundt was doing mineralogical studies of the Atacama Desert, on behalf of a Chilean government commission. During a one-day excursion from the recently discovered nearby silver mine Esmeralda (alias Vaca Muerta, see Appendix A), he came upon (was guided to?) the meteorites and recognized them to be those described in Domeyko's "Mineralojia." In apparent reference to Alarcon's account he denied that they came from a vein. Sundt reported the work by miners

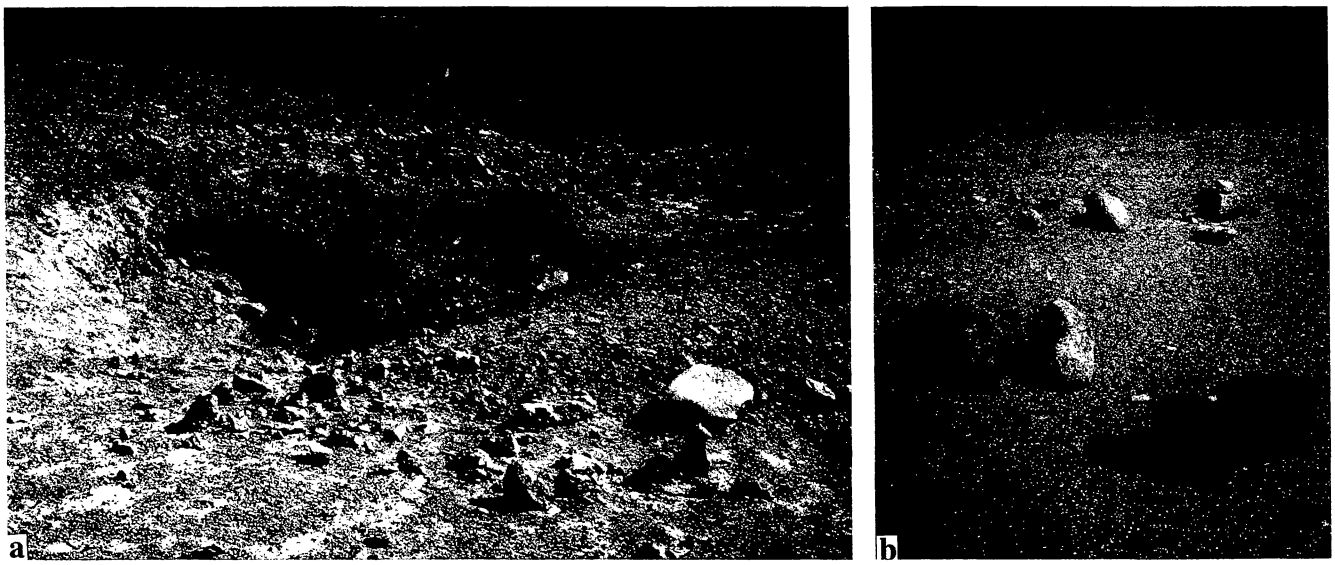

FIG. 1 a. Area near VM 6. This is probably the location seen by two travelers, Sundt and Alarcon, in the 1880s, while it still contained substantial amounts of meteoritic fragments. The volume of the hole is probably considerably larger than that of the excavated Vaca Muerta mass. An anvil stone is seen in the right foreground and has possibly been used for breaking the meteorite up. Underneath it was a cache of miner's tools: hammer and iron bars. Between the hole and the jeep but concealed from view is about 850 kg of chopped meteorite, size-sorted into three piles. b. A depot of meteorites weighing 17.40, 10.52, and 1.25 kg left behind by prospectors in the triple fall-area of VM 62, 64, 65. An anvil stone is seen a few meters behind the meteorites. A hammer stone is still on top, probably untouched for more than 100 years.

who had broken the meteorite into pieces and piled the material on sacks in the belief that it was silver or silver ore. He noted two such places, approximately north–south of each other and separated by ~4 cuadras (1 cuadra ~125 m). The southern heap (probably our location Vaca Muerta (VM) 6, and evidently the most impressive to Sundt) contained several hundred fragments and was found next to an excavation which was 1.5 by 3 m wide, 1.5 m deep. In the sides of that excavation, pieces of meteorite, some as long as 6 inches, could be seen, mixed with gravel, until a depth of 1 m, and Sundt presumed that much more meteoritic material could still be recovered. The northern heap (location VM 5) was estimated to contain 10 Spanish quintals (460 kg), and he was told that it had been there for at least 10 years. It was reported to Sundt that similar pieces had been found some leagues further north and that they also had been taken for silver. He used this apparent alignment to infer that the meteorites had been dropped by a fireball traveling along a north–south direction. For study by the commission he removed one sackful of fragments from each of the two piles.

RECENT FIELD STUDIES

During the hundred years following Sundt's investigation, no field studies are known, although some material has been collected, at least until 1891 (see later). In 1985, after a lengthy bibliographic study, the fall-area was rediscovered by E. Martinez (pers. comm., 1986; 1988; 1991). Martinez located five sites known to miners during the last century and one untouched specimen which weighed approximately 300 kg. We designate this new location VM 1. Information about its location was provided to the present authors, who independently located the five other sites and 74 more.

Among the 80 masses are the two locations described by Sundt (Fig. 1) and several others at which commercial exploitation had been attempted. However, most of the area is rarely visited by man, and we had the privilege to discover many specimens in their original fall locations.

The field work was carried out from 1987 to 1991. Approximately 100 man-days were spent in the area. The search was greatly facilitated by the meteorites' dark brown color, which contrasted sharply with the golden color of the vegetation-free desert. Many meteorites were first seen from a distance, in some instances using binoculars. We believe that practically all masses visible on the surface have been collected, with the possible exception of some having masses of 1 kg or less. The searched area included several km long strips beyond the documented ends of the strewnfield. No unrelated meteorites were found.

The landscape is characterized by low undulating mountains, alluvial fans, and open plains. The hills are covered by sand and gravel, and only in rare areas is naked rock (granite and andesitic volcanite) exposed. The open plains contain a lumpy porous layer of gypsum about 20–40 cm below the desert surface, which at places is compact and which partially encased VM 9 and 10. The alluvial fans merge into a broad dry riverbed (*Quebrada Buena Esperanza*). Some masses found adjacent to the braided channels of the quebrada have escaped burial by gravel moved during the rare floods. The most distant eastern mass was found on a saddle-point of a promontory reaching into this quebrada. Morning fog (*camanchaca*) is common and can form dew or rime frost. Accumulation of aeolian sand occurs only locally and has affected the visibility of just one out of 80 recognized meteorites. We infer that few meteorites remain hidden in sandy tracts.

Ancient tracks of oxcarts cross the western end of the strewnfield in a north–south direction, passing between VM 1 and 9. Sundt noted the same tracks in 1883. They are decorated with cans, sand-blasted bottles, and skeletons of mules. In this part

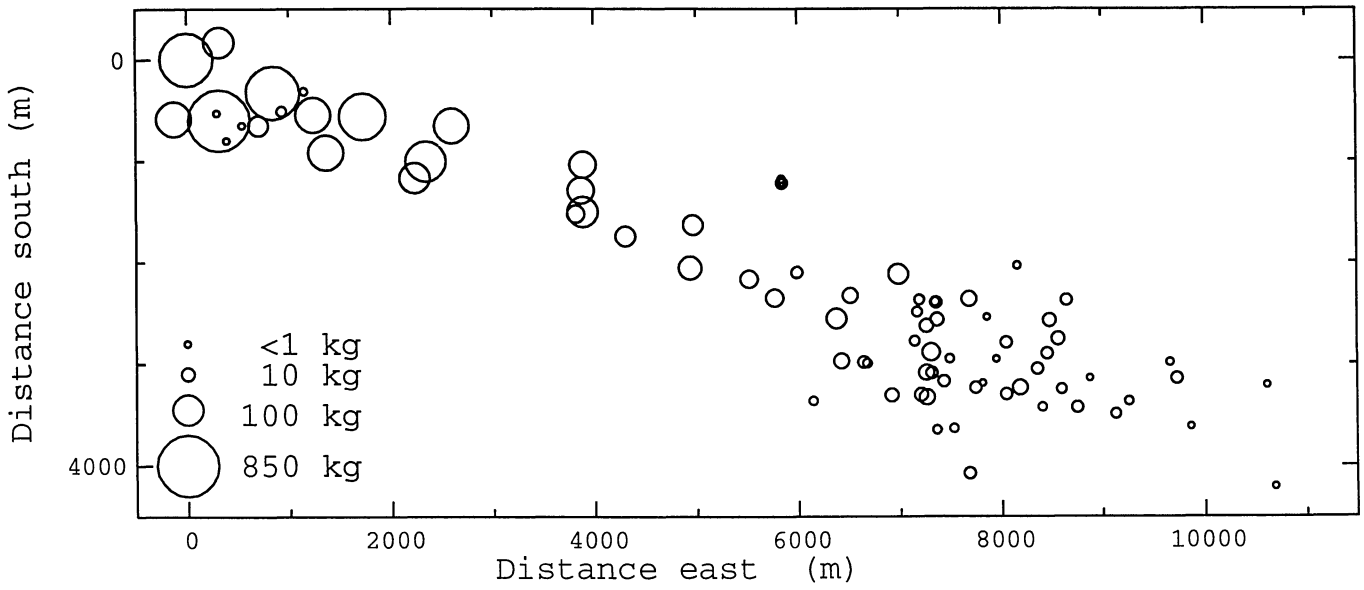

FIG. 2. The diagram shows geographic distribution of the 80 primary masses, ranging in size from 2 g–850 kg; the origin is fixed at the location of mass VM 5. The diameters of the circles are proportional to the logarithms of the masses, with a single size used for masses <1 kg.

of the strewnfield, the density of fall sites is so low that no meteorite is likely to have been discovered by the travelers.

The find-places are assigned Nos. VM 2 through 86, in chronological order of discovery. By mistake, three numbers (36, 47, 80) were never assigned and three others (63, 66, 78; see later) correspond to intact meteorites that had been moved prior to discovery by us. With one exception (VM 82), any small mass found <100 m from a much larger mass has been discussed in the context of the latter. The most important properties of the individual fragments are listed in Table 1. The masses range from 2 g to ~850 kg.

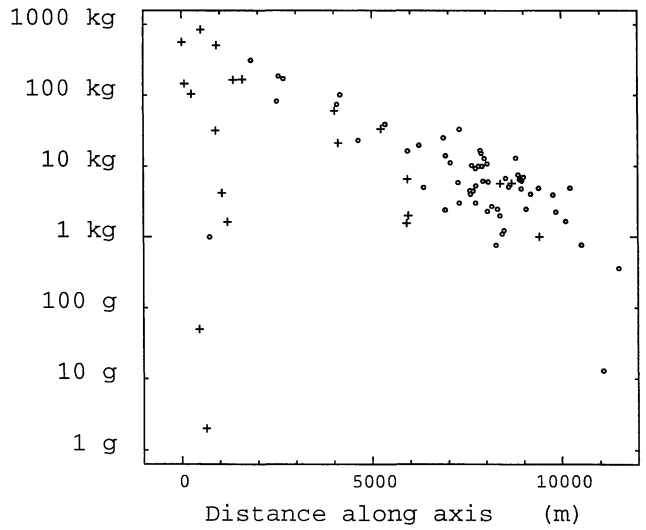

FIG. 3. The size-distribution along the axis of the strewnfield. Disturbed masses are marked with a cross (+). In general, small masses found <100 m from a large mass have been excluded from this diagram. One tiny undisturbed mass at ~700 m may be due to late atmospheric break-up or to impact scattering. Some disturbed masses in the large-mass end seem to have been rather effectively cleaned out; most were found near holes indicating a substantially larger initial size (50–3000 kg).

When 49 meteorites had been located, their (x, y, z)-positions were measured using a theodolite-mounted IR range-meter (Wild, DI 4). The theodolite was also used to determine astronomical north. Less accurate positions were determined for the subsequently discovered masses. In Table 1 and Fig. 2, we give the (x,y) coordinates of each mass relative to the most distant large mass, VM 5, which is at 25° 50′ S, 70° 23′ W. Using the method of least squares (minimizing orthogonal distance) and giving equal weight to each of the 80 masses, we have determined the azimuth of the strewnfield to be 109 degrees E of north (Fig. 3). The fall zone is 700–800 m above sea level.

The 80 masses were found in different states of preservation. Primarily, we distinguish between undisturbed masses, *i.e.*, masses which apparently have never been touched by humans, and disturbed masses. All available evidence point to 19th-century prospectors as the agents of this disturbance. The smallest separation between a disturbed and an undisturbed meteorite is 70 m, in the case of VM 11 and 12.

Undisturbed Masses

Sixty masses belong to this category. They range in size from 13 g–312 kg. Many larger masses are accompanied by a fan-shaped pattern of minute particles, up to 10 m long, probably transported by wind or rain (Fig. 4a). From their appearance in the field, we subdivide the undisturbed masses into: exposed masses (which can be either single, double, or multiple), and submerged masses (some transitional cases exist).

Exposed masses are solid, well preserved meteorites which lie nearly fully exposed on top of the surface of the land. Larger pieces have irregular, rounded and (with rare exceptions) convex shapes. The lower sides are rather flattened and more corroded than the tops which never show visible cracks. Most masses rest on small amounts of oxidized meteoritic shale. They have no fusion crust, and the appearance is dark brown and slightly

TABLE 1. Locations and masses of the Vaca Muerta specimens recognized during the past six years.

VM	E (m)	N (m)	Mass* (kg)	Type†	Largest bodies‡ (kg)
1	1720	−560	312	s	
2	843	−328	510	d	
3	1237	−546	165	d	
4	320	171	95	d	
5	0	0	557	d	
6	315	−600	868	d	
7	1362	−916	168	d	
8	3889	−1036	59	d	
9	2339	−1002	186	s	
10	2594	−652	165	s	
11	3887	−1502	102	s	
12	3820	−1522	21	d	
13	3870	−1290	75	u	46
14	4304	−1744	23	s	
15	4967	−1632	33	d	
16	7678	−2366	10.8	u	7.8
17	7187	−2372	4.5	s	
18	6982	−2119	33	u	32.6
19	4937	−2056	39	s	
20	7166	−2492	4.0	u	4.0
21	7254	−3090	15	u	14.0
22	7306	−3094	6.1	s	
23	6676	−2998	3.0	s	
24	6643	−2987	5.9	s	
25	6145	−3367	2.4	s	
26	6914	−3311	10.2	s	
27	7260	−3333	12.9	s	
28	7202	−3308	10.0	u	8.6
29	7682	−4079	5.1	u	4.9
30	7525	−3636	2.5	m	1.6, 0.7
31	7740	−3240	5.7	d	
32	7425	−3175	6.0	u	6.0
33	8399	−3428	2.5	u	2.4
34	6424	−2975	11.1	m	2.8
35	7481	−2954	2.3	u	2.3
37	2229	−1165	83	s	
38	7301	−2889	17	s	
39	7809	−3194	1.1	s	
40	7357	−3652	2.8	u	2.7, 0.06
41	8590	−3252	4.0	u	3.6
42	10,686	−4207	0.36	m	
43	6377	−2559	25	s	2.5
44	8178	−3238	13.0	m	3.7, 3.1, 1.3, 0.8
45	6514	−2331	14.1	u	11.9
46	5519	−2166	16	s	0.5
48	7853	−2545	0.76	m	
49	7360	−2569	10.0	s	
50	7256	−2630	9.3	u	7.7
51	5989	−2101	5.0	s	
52	9129	−3493	3.9	u	3.8
53	8449	−2903	4.8	u	3.6
54	7142	−2779	4.5	s	
55	8043	−2795	6.8	s	0.3
56	8643	−2375	6.2	m	0.8, 0.3, 0.2
57	8473	−2575	7.3	m	1.2, 0.5, 0.3
58	8153	−2035	2.0	u	1.4
59	8750	−3431	4.9	u	2.2, 0.3, 0.2
60	9660	−2986	1.6	s	
61	8349	−3053	6.5	s	0.2
62	5849	−1211	1.7	d	
63	—	—	30.7	D	17.4, 10.5, 1.3
64	—	—	6.5	d	
65	—	—	1.8	d	
66	—	—	5.2	D	2.4, 2.8
67	9257	−3368	2.2	u	2.0
68	5771	−2351	20	u	13.1
69	9863	−3619	0.77	s	
70	8872	−3143	1.0	d	
71	9727	−3143	4.9	u	3.2
72	7942	−2958	1.2	u	1.1
73	8042	−3303	5.8	d	
74	10,607	−3213	0.01	u	0.01
75	1149	−314	1.6	d	
76	928	−511	4.2	d	
77	700	−653	9.2	d	
78	—	—	23	D	
79	539	−650	1.0	m	
81	390	−798	0.002	d	
82	294	−528	0.05	d	
83	−129	−586	146	d	
84	8557	−2755	7.0	m	0.4
85	7349	−2400	5.3	u	4.5
86	7342	−2393	3.0	u	1.0

* Including estimates of remaining material.

† The following abbreviations are used: u: an exposed, single mass; m: an exposed, double or multiple mass; s: a submerged mass; d: a disturbed mass; D: a depot.

‡ Only given for the surface-exposed material of undisturbed meteorites.

VM 1: Martinez' mass. The largest recovered piece weighed 39 kg. It was transferred to R. Haag. Other collectors have received approximately 7 kg. VM 3: Someone may have noted this meteorite as late as 1974. It was marked by a block of gypsum, underneath which we found a cigarette carton, in use from 1955 to 1974. Strings of coarsely spun, dark, natural fibers, probably alpaca or llama, were found in between the meteoritic material. VM 5: 460 kg, according to Sundt. VM 6: 3 tons, according to Alarcon. VM 7: Much of the crushed material is in the form of very small particles, 1–3 mm. VM 8: A large solid mass may have been removed from the site. The remaining material was grouped into four small piles. Two small amounts of minor fragments, each about 1 kg, VM 8a and 8b, were found southeast of VM 8, and distant from that by 9 and 10 m, respectively. A third, VM 8c, is seen 35 m to the northwest. VM 11: See Fig. 5. VM 12: This location is one from which material (probably a large exposed mass) has been removed. The distance to the undisturbed mass VM 11 is only 70 m. VM 13: A half submerged mass (Fig. 4a). One piece, which is on display at La Serena University, weighs 46 kg. VM 15: The mass was found scattered around a shallow sand-filled hole, with the largest concentration to the north. Big pieces (up to 10 cm) of silicates had been placed on the western side. From the size of the hole we estimate that the initial mass cannot have exceeded 200 kg. VM 15a, <1 kg, was found about 7 m from VM 15. VM 18: A solid mass lying fully exposed. The meteorite is now on exhibition at Tycho Brahe Planetarium, Copenhagen. VM 21: A rather flattened mass, 33 by 19 by 12 cm. VM 22: Material which has earlier been exposed to the air was found partially covered by drifting sand. As such, the specimen was unique. VM 34: An exceptional group of meteorites, consisting of about 12 large and many smaller solid masses, within a diameter of 1.2 m (Fig. 4b). VM 42: This is the second smallest of all primary impacts. It was found fragmented into pea-sized masses in between desert-floor pebbles. VM 52: Found on a slope inclining 10 degrees. VM 63, 66: These masses are not shown in Fig. 3. VM 74: The smallest of all undisturbed masses. The positional uncertainty is 200 m. VM 78: In Fig. 3 this mass has been added to that of VM 77.

FIG. 4 a. VM 13, the largest exposed meteorite, weighs 74.5 kg; of this, the largest piece weighs 46 kg. The notebook is 30 cm long. Photo by co-discoverer Jørgen Østgård Olsen. b. The exposed mass, VM 34, *in situ*. The meteorite probably fell as a single body and was later split into fragments by weathering. The total mass is 10.6 kg, of which 6.2 kg is contained in the 12 largest fragments. Much of the remainder is underground. The diameter of the compass is about 6 cm.

shiny. Opaquely scattering, slightly elevated black specks, typically 5–10 mm across, cover about one-tenth of the surface. These seem to be oxide-coated metal grains. Larger nodules of metal protrude here and there, and larger inclusions of metal-free silicates can also be seen as greenish or ocherous spots.

Some exposed masses consist of two or more fragments, separated by up to 1.2 m (Fig. 4b). Individual fragments have the characteristic appearance just mentioned for single masses. It is not clear if the separation is due to break up upon impact or to weathering, but the latter seems more likely. Whichever the process of fragmentation, the mass-loss due to weathering must be appreciable ($\gtrsim$20%), otherwise the multiple masses could not have achieved their rounded shapes. Many of the smaller specimens were rich in metal, the phase which has best resisted weathering.

Submerged masses are recognized as spots of minor fragments of meteorite and shale, confined to a diameter <1 m. Some are elevated by up to 8 cm above the surface, while the main mass is submerged in the desert. Excavation shows that they have inevitably weathered into many pieces, often with sharp edges (Fig. 5). In some specimens, the cracks reach 3–5 mm wide, and are filled by rust-colored terrestrial sand. Individual pieces are

FIG. 5. VM 11. At this stage of excavation, about one third of the 102-kg meteorite had been removed. The fragmented nature of the body can be appreciated. The pencil length is 17 cm.

generally compact with abundant preserved metal in their interiors. Beautifully green-colored "Nickel-mold" is seen on some of the interior fragments. In several cases, in particular >15 cm below ground, it is possible to identify the original surface. It shows depressions, regmalypts, which are typically 15 mm wide and 3 mm deep. Corrosion has caused this surface to be bounded to a single layer of rusty sand.

Disturbed Masses and Depots

Masses disturbed by humans constitute the remaining 20 sites. They range in size from 2 g to ~850 kg. Some locations, in particular VM 12, 62, 65, 70, and 73, are sites from which large masses have been earlier removed, leaving shale and minor fragments behind. In other cases, in particular VM 2 through 7 and 15, the disturbance was one of chopping and sorting according to size. Nuggets of (nearly) pure metal occur only rarely. From two samples of VM 6, totalling 6 kg, we have measured the specific density 3.5–4.0 g cm^{-3} while the expected average for mesosiderites is 4.5–5.0 g cm^{-3}. The care with which the chopped meteorite was stored (the heaps at VM 5 and 6 were placed on burlap) indicates that it was intended to be picked up at a later time.

Most of the disturbed masses were very clearly visible, giving us confidence that we can have missed few of the sites known to last century's prospectors. Two man-made excavations near the strewnfield's western end appear totally void of meteoritic material and are inferred to represent sites from which all recognizable meteoritic material has been recovered (it seems unlikely that they can be unrelated mineral exploration holes). We also found three depots of solid masses, VM 63, 66 and 78, extracted from unidentified, but probably nearby, locations.

Artifacts found near some of the disturbed masses are discussed in Appendix B.

Recovery

Apart from the well-preserved exposed masses, the process of recovery was technically difficult. The aureole of small particles, which surrounded many masses, was picked up using permanent magnets. We also used a sieve with 1.5-mm holes to separate larger particles from desert sand. Thereby tiny particles of meteoritic silicates and oxidized metal were lost; in

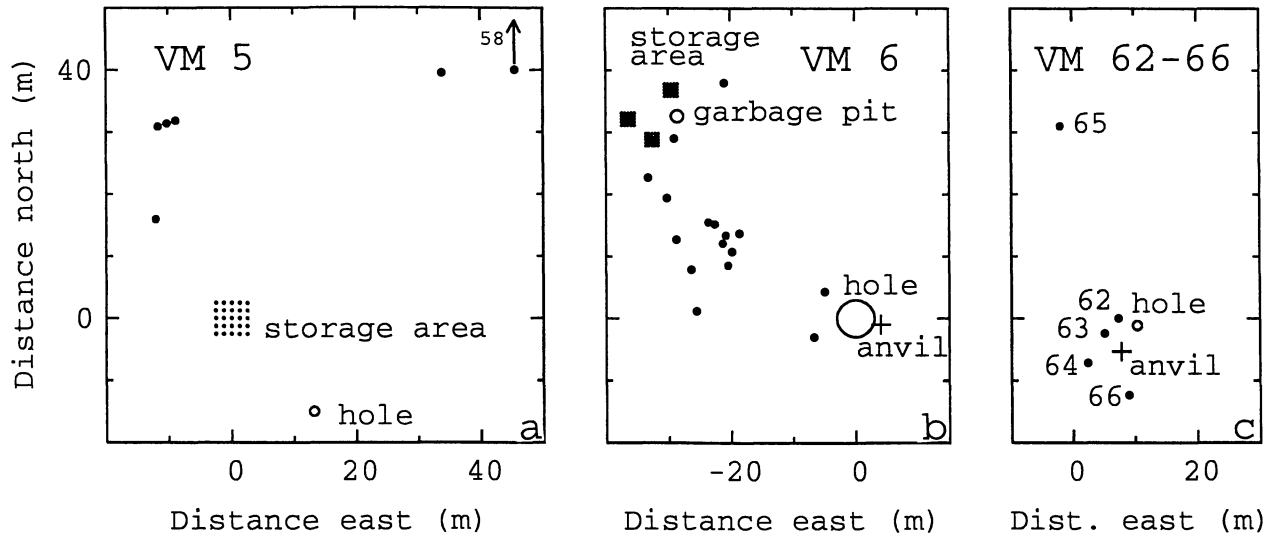

FIG. 6 a. Area near VM 5. The storage area is indicated. Dots denote minor concentrations of meteoritic fragments. b. Area near VM 6. The storage areas are indicated. Dots denote excavations and some minor concentrations of meteoritic fragments. The long axis of the excavation aligns with the direction of the strewnfield. c. Area of VM 62–66, showing location of anvil and the two depots (VM 63 and 66).

some cases the loss is estimated to reach 3–5 percent of the meteorite's total mass. For VM 10, the loss was much larger, perhaps 20 percent. Material from below surface was excavated with much care, but it could not be avoided that the excavation process itself led to more fragmentation. A detailed description of the location of each larger fragment was carried through only in case of the submerged masses VM 9 and 10, the biggest undisturbed masses found by us.

The disturbed meteorites were recovered using mechanical methods. The largest pieces were handpicked, but for most of the material we used shovels and sieves. The finest sieve was mostly one of 2.5-mm openings. The retained material includes some terrestrial material. The mass fraction of magnetic (*i.e.*, almost exclusively meteoritic) material, typically 0.9, has later been determined from representative samples.

Particles which passed the sieves constitute the bulk of unrecovered meteorite, and are estimated to be 300 kg.

The Major Masses

VM 1: Details of the recovery of VM 1 are not available to us.

VM 2: The disturbed material covers an irregular 2-m diameter spot. The particles are small, mostly <2 cm. A few pieces reach 7 cm; these are silicate inclusions which were of no interest to miners. A shallow man-made hole is located 25 m to the east. Although superficially it did not appear related, a closer inspection revealed that this is indeed an impact location, partially excavated. From this hole, 135 kg of meteorite was extracted, most of which (including a 1.1 kg silicate body) was *in situ*. The meteorite reached solid rock 60 cm below surface. Some of the lowest fragments were infiltrated by plant roots (and are unique in this respect).

VM 3: The crushed material has a fresher appearance than at other places and may have been disturbed as late as 1974 (ref. notes to Table 1). The size of the metal-containing fragments is larger than typical for disturbed masses, up to 10 cm. During recovery, it was noted that the lowest part of the meteorite was *in situ* reaching 37 cm below ground surface.

VM 4: Practically all of the crushed material is in the form of very small pieces (typically 1–5 mm). The impact site may correspond to a small excavation (partially of human origin) 25 m east. The desert floor continues into the eastern side of the hole indicating a great age.

VM 5: The crushed material is spread over a rather large area (about 5 m diameter) and is sorted according to size. Much is lying on top of burlap sacks. Several additional small amounts of meteoritic material, each less than 1 kg, were found up to 70 m away from the heap (Fig. 6a). A nearby hole (2–3 m diameter, 30 cm deep) may be the impact site, but it contains no meteoritic material.

VM 6: The fall-location probably corresponds to a hole (Fig. 6b) on a hill-side. It is now 1.2 m deep and partly filled in by sand. Its diameter is 6 m, with steep sides surrounding the central 2.5 by 4 m cavity. This central hole is evidently of human origin and has probably been excavated between 1871 and 1880 (Appendix B). Initially, we took it for a small copper mine, but minerals are absent in the sedimentary bedrock. Metal detector searches did not reveal any meteoritic material remaining inside the hole, but small amounts are mixed with the excavated material. Many years ago, portions of the crushed meteorite, at least 850 kg, were sorted into three groups according to size, and placed on top of burlap sacks about 45 m northwest. The largest heap was placed in a shallow excavation. The two other amounts were placed on the open terrain and consist of somewhat smaller particles, mostly 1–10 mm. In between the excavation and the storage area we noted several minor concentrations of meteoritic fragments and, using a metal detector, we located three submerged masses, 0.5, 0.6, and 0.8 kg, apparently *in situ*. Their surface texture was markedly different from all other material, being angular but without sharp edges.

In the same area, within 45 m from the excavation, we noted 11 shallow holes, 30–100 cm diameter, most of which are ev-

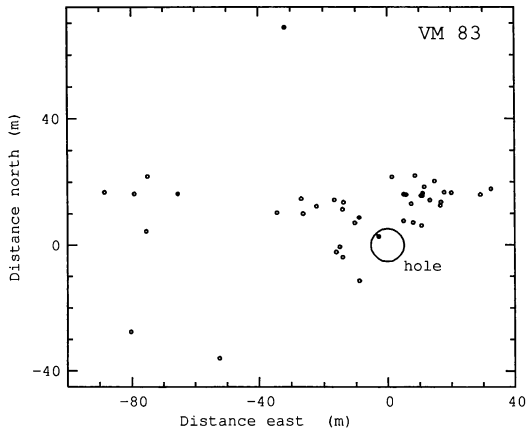

FIG. 7. The meteorite broke up on impact and scattered minor masses up to 85 m away.

idently due to ancient human activity. Near these, and where not covered by the excavated soil, the desert surface is littered with numerous small meteorite particles (very few reaching 20 g), having the typical appearance of weathered material scattered around undisturbed masses. We infer that meteoritic masses in the 10–100 kg class have been removed from these places. We presume that they were produced by impact scattering. Alternatively, they can be due to very late atmospheric break-up, but it is then surprising that the smaller masses in general traveled further west than the main mass. Another small amount, 0.255 kg, was found 120 m southwest of VM 6. It is possibly an independent fragment but was not assigned a separate number.

VM 9: Initially this submerged mass was seen as a dark spot, approximately 50 cm across, rising from 5 cm above the surrounding desert sand. Upon excavation in April 1987, the body was found to be of roughly spherical shape. From top to bottom the extent was 54 cm, and the largest horizontal cross-section was 47 cm. The meteorite was very fragmented, in particular its upper half. The lower part was embedded in compact gypsum which must have formed following the impact. It was collected into 109 lots, each labeled according to depth and position in a 10 by 10 cm grid. Single pieces up to 4 kg were recovered, while other lots consist of particles down to 1.5-mm size.

VM 10: This submerged mass showed no appreciable elevation above the desert sand. It was excavated in January 1990 by J. T. Wasson and two of the authors. The body was 102 cm long, 65 cm wide. The thickness was typically 23 cm and in no place greater than 30 cm. An attempt was made to recover the mass as a whole by using a cast. However, this operation failed due to the heavily fragmented nature of the body. Instead, the location of each large piece (up to 4 kg) was recorded. Although reconstitution may not be possible, detailed studies of isotopic and chemical composition within the mass are planned.

VM 62, 64, 65, 66: Three disturbed meteorites, VM 62, 64, 65, were found within 40 m of each other (Fig. 6c). Two of them, VM 62 and 65, had obviously been single exposed masses; during the excavation we observed the imprint in the topsoil from which the masses had later been lifted out. In between the three falls was a depot of three solid masses, 17.4, 10.52, and 1.25 kg, on top of 0.5 kg of shale (see Fig. 1b). That shale was free of silt and evidently much younger than similar material at other locations. A further depot (or independent fall?) was nearly covered by sand. It consisted of two well-preserved solid masses, 2.4 and 2.8 kg, in contact. For convenience, these depots are given the location numbers VM 63 and 66, respectively.

VM 77: This was noticed as a 1.3 by 1.9 m wide, 1 m deep man-made hole, surrounded by blocks of bedrock. Apparently, miners had tried to trace a vein here. About 9 kg of meteorites were found in the immediate vicinity of the excavation. A second smaller hole is located about 14 m east. Concealed underneath the material excavated from that, we found an old burlap sack containing 23 kg of meteorite. The pieces are rather large and have not been crushed. Undoubtedly, the material in this depot (VM 78) has been taken out of VM 77.

VM 83: A 10.5-m diameter, 1.9-m deep hole is now filled in with 20 cm sand. Part of the southwestern upper flank was covered to about one third by a layer of meteoritic particles, typically 10–30 mm across. These fragments have a different appearance from material crushed by miners. Using a metal detector, a fragmented but complete 9.3 kg body was located *in situ* under the hole's northwestern slope. It extended from 15–30 cm below the surface.

Within 40 m from the hole about 20 ancient excavations were found, similar to those mentioned for VM 6. Other masses, some ~2 kg, had escaped the miner's attention since they were fully submerged. Some small, undisturbed masses were seen up to 85 m away (Fig. 7).

Some of the loose gravel from the crater's inner slope has been artificially relocated, whereby part of the circumference shows a slightly elevated rim.

A sizable amount of gunpowder was found about 450 m away (just south of VM 6), and the question arises whether this hole could have been produced by prospectors who mistakenly thought they had found a mass comparable to VM 6. Disruption by a gunpowder blast might explain some of the difference in the nature of the broken fragments relative to VM 6, and a much smaller initial mass could explain why no pile of chopped fragments was found nearby. However, the explosion should have scattered recognizable terrestrial debris nearby, and none was observed.

COMPARISON WITH DOMEYKO'S AND SUNDT'S REPORTS

In partial agreement with the description by Diaz, we have observed (mostly shallow) excavations close to several meteorites (VM 2, 4, 5, 6, 62, 78), at distances of 3–25 m and invariably on the eastern side. Five out of six are located in the strewnfield's hilly region, contrary to the claim that the meteorites were found on a vast plain. No depressions were found near the 60 undisturbed meteorites.

VM 5 and 6 are almost certainly the places visited by Sundt. Their separation agrees with his description, and part of the chopped meteorite is indeed piled upon sacks. The direction is off by 27 degrees from the stated approximate north–south. At VM 6 there may have been some later activity. The excavation is now wider than seen by Sundt and devoid of meteoritic material. However, a coin found in the top of the excavated material seems to date the last earthworks at 1881 or before. It is conceivable that the southern site is VM 83 which is more directly south of VM 5, but there is no evidence that a pile of specimens was ever present at VM 83.

VM 6 is probably the site seen by Alarcon, although this implies that the distance and direction from Carrizalillo is grossly in error. His statement that the iron had been recovered from a vein can be understood if he interpreted the smaller nearby masses as further outcrops. Most of them align rather well with the main mass (Fig. 6b). The 97-cm width of the "vein" most likely corresponds to the diameter (or a minor axis) of the main-body. Together with the 1-m depth value by Sundt, the inferred volume is consistent with Alarcon's mass estimate of 3 tons (which does not include "ore" previously removed). Only ~850 kg is accounted for in the present work.

The direction of the strewnfield is inconsistent with the note by Sundt that other similar masses had been found several leagues further north. Unfortunately, this cannot be taken as strong evidence for an undiscovered part of the strewnfield. Sundt was aware that meteorites, following atmospheric break-up, would fall along a line, and since the two piles were located along an approximate north–south line, he may have "improved" vague positional information to fit his hypothesis. The distant finds may be those at VM 62, 64, 65. Although only 6 km from VM 5 and 6, one should consider the difficulty of distance estimates in the desert; according to Bertrand (1885, 248) the effective size of the league is often less than 4000 m when traveled distances are quoted by muleteers and guides.

Domeyko (1864a,b) came into possession of "complete" pieces, looking like individual meteorites (his type *A*, our surface exposed material) and "fragments" or "broken pieces" (his type *B*). The largest one studied by him, one of >20 kg, was of the first type, yet he speculates that it was broken off from a much larger piece. He was unable to determine if the state of type *B* material was due to terrestrial corrosion or to the action of miners.

DISCUSSION

The first site location stated by Diaz is reasonably correct; the largest masses were found about 25 km south southeast of the ancient mine *Isla*. None of the other indications, such as synonyms (Appendix A), the mark on Arnes' map (Appendix A), or Sundt's distant masses, give reason to suspect a fall-area distant from the one described here. Diaz' shallow holes on the eastern side of larger meteorites remain enigmatic.

The amount of material recovered since 1985 is 3782 kg. To estimate the total size, we can add the two quintals (92 kg) known to be in collections already in 1864, the approximately 45 kg which currently is in collections (partially identical to the previous), and the two sacks of material removed by Sundt (and later lost).

Old Vaca Muerta material in Chilean collections include a 78-g piece labeled "Las Bombas" (Santiago, Museo Nacional de Historia Natural). Records kept there indicate that it was collected in 1891 and that it arrived via Carrizalillo. An 826-g piece of unknown history is in La Serena University. Neither has apparently been listed in generally available compilations.

The provable mass of Vaca Muerta is thus 3828 kg, but plausible evidence suggests that the amount that entered the atmosphere was much larger: >6.0 tons. The difference is explained by the known but unrecovered material (about 300 kg, finely fragmented) and the large mass seen by Alarcon.

Already in the early 1860s, part of the chopped meteorite was brought to the mining town of Copiapo (Domeyko, 1864a) and some further on towards Argentina. The enterprise continued during the 1870s, and artifacts left at VM 6 indicate that a minimum of several man-days have been spent at the site. The work appears to have been done by fairly wealthy gold miners, who must have considered the find an important one; that they removed the high-density material suggests that they thought the metal was silver. Unfortunately, the available evidence does not allow for their identification nor to trace the fate of the removed material.

Two values are known for Vaca Muerta's terrestrial age: Begemann and Vilcsek (1969) found 240,000 a, based on ^{36}Cl and the absence of measurable quantities of ^{36}Ar. This value apparently has a large uncertainty. Recently, A. J. T. Jull (pers. comm., 1990) determined a ^{14}C age of 3500 a ± 1300 a, based on the assumption that the meteoroid was a reasonably small object, ≤50 cm. As the pre-atmospheric cross-section of Vaca Muerta must have exceeded 110 cm, the true terrestrial age may well be lower than calculated by Jull.

Shaly scraps formed during the last 120 a at depot VM 63 indicate that the shaling rate is about 4 $\mu m\ a^{-1}$, or 1.4 cm over 3500 a.

The materials studied by Rubin and Jerde (1987, 1988) were derived from locations VM 2 through 6 (E. Martinez, pers. comm., 1991).

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APPENDIX A: SYNONYMS

As often happened with meteorite finds from the last century, the material was assigned a variety of names. In the case of Vaca Muerta, this is particularly understandable, since the meteorites were collected over a long interval of time and from a sparsely populated area. Some of the material passed through several hands, during which specific provenance information was lost. Nevertheless, the synonyms listed for Vaca Muerta (Graham *et al.,* 1985) offer a source of information on the location and size of the strewnfield. The most interesting are probably those discussed below. Others are too vague to be of value (Chañaral, Taltal, Chile) or even misleading (Sierra de Chaco, Mejillones, San Pedro, San Pedro de Atacama, Harvard University).

Vaca Muerta (*i.e.,* Dead Cow), *Quebrada de Vaca Muerta:* This name is first used by Domeyko (1875). As a geographical location, it appears in print only rarely. On a map studied by Fletcher (1889) and on one published by Espinoza (1897), *Llano de (la) Vaca Muerta,* is a plain, south or south-east of Taltal. In 1883 a number of rich silver mines were discovered in the coastal mountains of that area. One of them was initially known as Vaca Muerta (Vicuña Mackenna, 1883; Fletcher, 1889; Domeyko, 1897), but soon it received the "glorious name Esmeralda" (San Ramon, 1911). Finally, six named meteorites are marked on a map of mines in the province of Antofagasta, hand-drawn by Emilio Arnes, in 1934. Vaca Muerta is plotted as a position about 30 km north of the place where we found the largest masses. Sundt (1909) says that he saw the meteorites near a hill called Burro Muerto (Dead Donkey).

Carrizalillo: This is an important copper and gold mine about 15 km south of the presently determined strewnfield. The lode was discovered in 1855. *Corrizalillo* and *Carrisalillo* are simple misspellings. A fragment of the iron meteorite, Pan de Azucar, was found in this area (Buchwald, 1975).

Bomba, Cerro La Bomba: Las Bombas was the ore concentration plant of Carrizalillo, to which it was connected by a railroad. The ownership record from last century is unknown.

Vegas: According to Sundt (1909, 13) Las Bombas and Las Vegas denote the same location. The synonym *Vegas y Carrizalillo* (and its derivatives) is nicely explained in terms of the functional relation between the mine and its refinery.

Huanilla (Huanillos, Guanillos): These alternative spellings of a common name are associated with a bay, a *quebrada,* a watering place, a mountain close to the coast, and a mine in the Esmeralda complex.

Cachinal or *Cachinal de la Costa:* A location, close to the coast, on the ox cart route north of Pan de Azucar (Fletcher, 1889; Philippi, 1856, plate 3). *Quebrada de la Cachina* is a riverbed to the north and west of the strewnfield. According to Sundt (1909, 15), Q. Cachina and Q. Esmeralda are identical. Since the mines Esmeralda and Vaca Muerta are also synonymous, one would expect Q. Cachina = Q. Vaca Muerta. Q. Buena Esperanza, which overlaps the fall zone, is a tributary to Q. Cachina.

Janacera Pass: This synonym refers to a mass of 1784 g which was first mentioned in 1864. As surmised by Fletcher (1889), the correct spelling is undoubtedly Jorquera or Jarquera. This is an ancient borderpost in an Andean pass southeast of Copiapo, albeit well inside Chile (Sundt, 1909, 78). The pass is about 160–170 km off the strewnfield centerline. The discovery of a Vaca Muerta fragment at this location must, therefore, be due to human transport as already concluded by Fletcher.

Doña Inez, Llano del Inca (Inca): In 1889 material obtained by Prof. Ward in Santiago was said to have been found the previous year near Cerro Doña Inez (a 5065-m volcano) and at Llano del Inca. The latter was reported to be a location 35 leagues (135 km) southeast of Taltal. Both finds are attributed to a Chilean and Bolivian Boundary Survey Commission (Howell, 1890). We consider it likely that the material originally has been derived from the presently determined strewnfield, and that the locations of these sites near an extrapolation of the axis of the strewnfield is fortuitous.

Sierra de Chaco: Fletcher (1889) has discussed how this (initial) name might have caught the attention of Domeyko, while it was perhaps only meant as a descriptive term "sierra del chaco," *i.e.,* the "desert mountain range." Sierra del Carmen, peaking at 1429 m above sea-level, is immediately to the southeast of the strewnfield. It may be the one alluded to, although this is by no means evident.

APPENDIX B: ARTIFACTS

Clear signs of human activity were found near some of the disturbed meteorites. Minor amounts of artifacts were found at VM 5 (a spent cartridge marked V.M.C. .32 S & W), VM 76 (an iron bit), VM 77 (a can), VM 83 (several bottles, a nail, coal, a fireplace). A little used anvil stone at VM 62, 64, 65 was surrounded by pieces of scattered meteorite. Surprisingly, a hammer stone was still on the anvil's top (Fig. 1b). Within a distance of a few meters, we found two simple hand-made bottles, several nails, and five small pieces of broken flint. A tilted stone slab has provided lee for a fireplace.

Spread on top of the surface near VM 6 were a number of items which appeared to have been exposed to the air for a long time. We noted several bottles, several flat and round cans of food preserves, faience shards, two shirt buttons, a coat button of glass, a wooden reel of sewing thread, parts of boot soles, several hoops from small wooden barrels, coal and two small pieces of broken flint. Using a metal detector, we found, in the topsoil, three caps from cognac bottles, some metallic cork wire, and several caps from bottles of beer. The beer was produced in Liverpool after 1870 and in Stratford-on-Avon, most likely after 1873.

Another much used anvil stone made out of non-local granite is near the edge of the "crater" at VM 6. Hidden underneath it was a cache of miner's tools: a hammer and four iron bars with chiselpoints. The crater waste contained a Chilean coin from 1871 (the type remained in circulation until about 1880). We also located an old spade with a broken handle of crooked wood. It covered a latrine.

Near the storage area, we found a small garbage dump which originally was a fire pit. It contained a lump of transported gold-bearing mineral (andesite), minor amounts of coal and charcoal, several bones of a young goat or sheep, an integral hollowed calabas, barrel-wood, bottle cork, a broken horse-shoe, a horse-shoe-nail, ~100 common nails (ten as long as 75 mm), and two unused iron chisels (37 by 25 by 6 mm). A tiny plumb with fine chains may be from an oil-lamp regulator. Part of a fork or spoon carry the stamped letters JOHN YATES and, in stamped script VR, *i.e.,* Victoria Regiae. It has probably been produced at the John Yates and Son's factory for electroplated tableware in Birmingham which operated as early as 1864. A metallic label originated on a rather expensive can of cervelat sausage, manufactured in Lübeck, 1883 ± 10 a.

About 120 m south of VM 6 (at coordinates E 308 m, N −718 m), we found another cache that was concealed under excavated gravel from a possible location of a large meteorite fall. It contained various mining tools (including 1.3 kg of graphitized gun-powder with fuses), foodstuffs (flour, herbs), and cooking utensils (pan, mug and cast iron pot with soup residues). The whole set was covered by two sacks, sewn together to form a sleeping support.

Artifacts common to two or more places are thus nails, pieces of flint, and mining tools. The nails may have been intended for the manufacture of transport boxes. The flint can have served in a tinderbox (an indigenous origin is possible but supported by no other evidence). The mining tools are of a kind still used for rock perforation, in preparation of explosions, yet there is no evidence that they have been applied in that way at Vaca Muerta. As to the stony anvils, small 19th-century Chilean mines were often equipped with an implement of that kind. It was used to select the best mineral and to prepare it for mule or rucksack transport.