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The Dar al Gani meteorite field (Libyan Sahara): Geological setting, pairing of meteorites, and recovery density

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Abstract–As of July 2001, 1238 Libyan meteorites have been reported. Most were found in two areas called Dar al Gani and Hamadah al Hamra. Dar al Gani is located on a plateau of marine carbonate rocks with marly components. Eight-hundred and sixty-nine meteorites between 6 g and 95 kg totalling 687 kg have been found here but the calculated mean recovery density is comparatively low with one meteorite on 6.5 km^2.

Dar al Gani is a perfect site for the recognition and preservation of meteorites. The existence of meteorites is the result of a combination of specific geological and geomorphological conditions: there is a bright-colored, old limestone plateau (<2 Ma), under arid weather conditions over long periods of time, with rapid elimination of surface water if present and low erosion rates. The preservation of meteorites is guaranteed through the absence of quartz sand on the plateau, strongly reducing wind erosion and a basic environment emerging from the carbonate ground retards rusting of metallic meteorite components. A supposed soil cover during pluvial times has probably protected older meteorites and led to a concentration of meteorites of different periods.

An evaluation of Dar al Gani meteorites suggests the existence of at least 26 strewnfields and 26 meteorite pairs reducing the number of falls to, at most, 534. Shock and weathering grades as a tool for the recognition of pairings turned out to be problematic, as several strewnfields showed paired meteorites which had been classified to different shock and weathering grades.

INTRODUCTION

During the last decade many new meteorites have been recovered from hot deserts. Suitable surfaces like the Nullarbor Plain in West and South Australia, the desert high plains of the USA as well as the Arabian Peninsula and parts of the Sahara contain relatively high meteorite concentrations. Two of these areas are located in Libya, meteorites found there are called Dar al Gani (DaG) and Hamadah al Hamra (HaH) (Fig. 1). Some earlier finds from the latter location are known under the name Daraj. The 1985 *Catalogue of Meteorites* of the British Museum (Graham *et al.*, 1985) lists only two finds from Libya; the 2000 edition, however, reports 853 specimens (Grady, 2000). Areas with relatively high meteorite abundance must satisfy two specific conditions: in visual surveys the *recognition* of meteorites must be easy and the *preservation* of meteorites must be guaranteed over relatively long time periods. Surface conditions, recent geological history of the area, climate and related weathering processes are thus important.

In this report we present geological and geomorphological information about the Dar al Gani meteorite field. It is combined with a statistical analysis of its meteorites based on data compiled by MetBase 5.0 (Koblitz, 2000), and recent information from the *Meteoritical Bulletin* (Grossman and Zipfel, 2001).

THE LIBYAN METEORITE FIELDS

The two main meteorite fields in Libya are located in the Central Sahara south of Tripoli (Hamadah al Hamra; approximately 28.4–30° N and 11–13.5° E) and on a plateau in the eastern Sarir al Qattusah (Dar al Gani; approximately 26.7–28° N and 15.5–17° E). Figure 1 shows a map with indicated meteorite finds.

As of the summer of 2001, in the Hamadah al Hamra region, 360 meteorites have been found since 1986, on the Dar al Gani field, 869 meteorites have been found since 1996. These meteorites were mainly discovered by private collectors and/or mineral dealers. The find locations of most reported meteorites are properly documented and adequate type

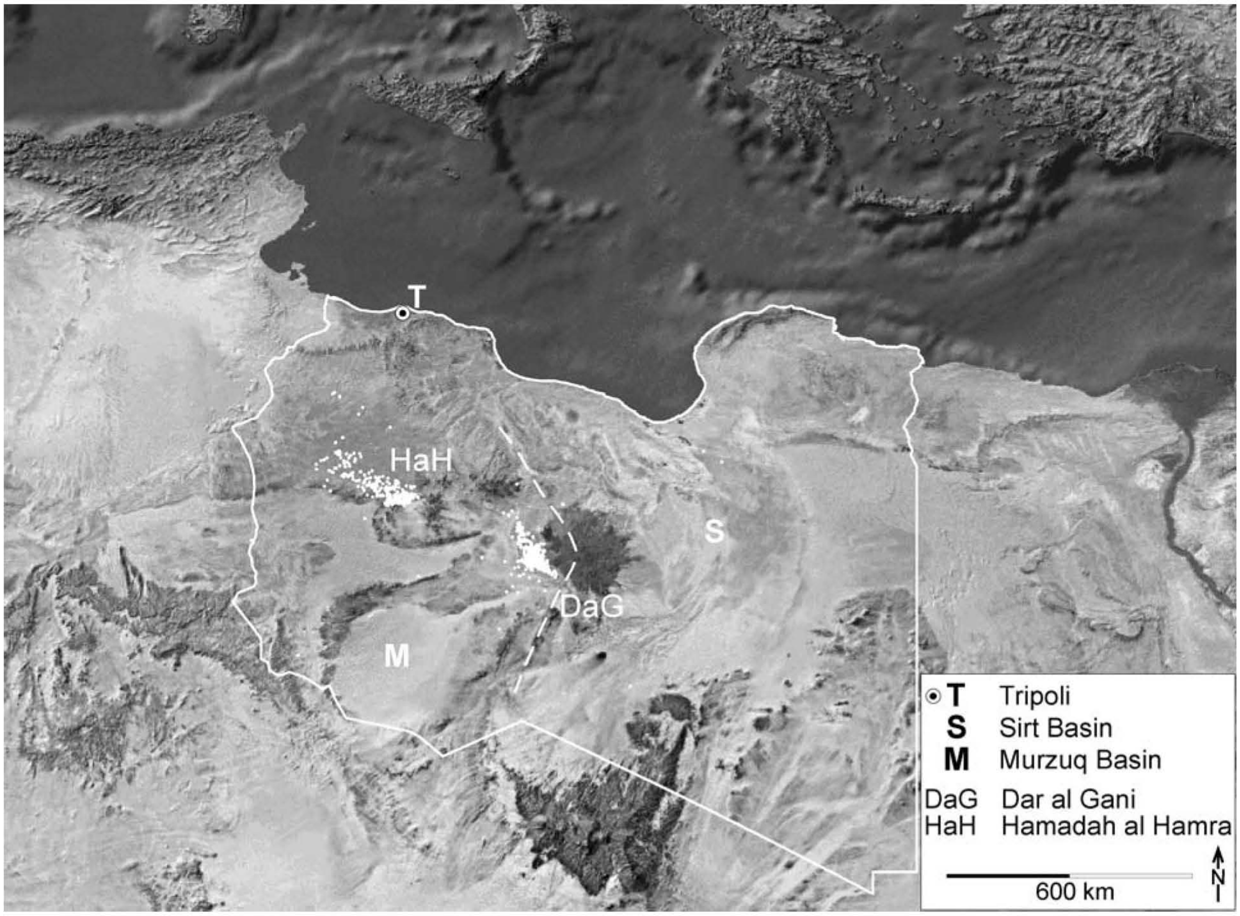

FIG. 1. Meteorites (white dots) of Libya. The dashed white line indicates the main watershed between Sirt and Murzuq Basins.

specimens are deposited in collections of museums or research institutions. The find mass as well as classification of these meteorites are available, but detailed investigations have been carried out mostly on specific samples only (*e.g.*, shergottite–nakhlite–chassignite group (SNC) or lunar meteorites). Geological information on the find regions is sparse.

THE DAR AL GANI METEORITE FIELD

The designation Dar al Gani (DaG) was introduced by the nomenclature committee of the Meteoritical Society in spite of an earlier find named "Dor el Gani" (Mücke and Klitzsch, 1976). The name "Dar al Gani", used today by meteorite collectors and scientists, describes a plateau in the eastern Sarir al Qattusah in central Libya, ~200 km east of the town of Sebha. The name Dar al Gani does not exist in the National Atlas of Libya, although the northwestern benchland of the Sarir al Qattusah plateau is given as "Dur al Ghani" on the geological map of Libya (Woller, 1984). A "serir" or "sarir"—depending on the way of transcription from the Arabic language—is a gravel desert. In the Algerian Sahara this kind of desert is called a "reg".

The area where most of the DaG meteorites are found stretches over a distance of ~200 km reaching a maximum width of 60 km (Fig. 2a,b). It is situated on a platform of stratiform Tertiary marine sediments belonging to the Eocene Bishimah formation which includes clay-rich dolomites, dolomites, limestones and marls (Woller, 1984) (Figs. 3 and 4). These rocks are eroded to an even-grained limestone grit. Winds have removed the finest fractions at the surface leaving behind centimeter-sized rock fragments often arranged to a mosaic-like paved floor, forming a surface resistant to further erosion. The Khayir member of the Bishimah formation forms most of the present surface of the plateau. It carries no large dark components thus building a bright-coloured, perfect plain (Fig. 5). A black-coloured meteorite of fist size can be spotted from a distance of at least 150 m.

The large basaltic complex of the Haruj al Aswad is located to the east of Dar al Gani. Volcanic activities, between 6.0 and 0.4 Ma ago (Ade-Hall *et al.*, 1974), have poured out mainly basaltic lava flows onto the plateau (Fig. 6). Erratic black basaltic rocks from the Haruj are found on the Dar al Gani plateau in a zone near the basaltic outcrops. Because of the difficulty of recognizing meteorites among the dark basaltic

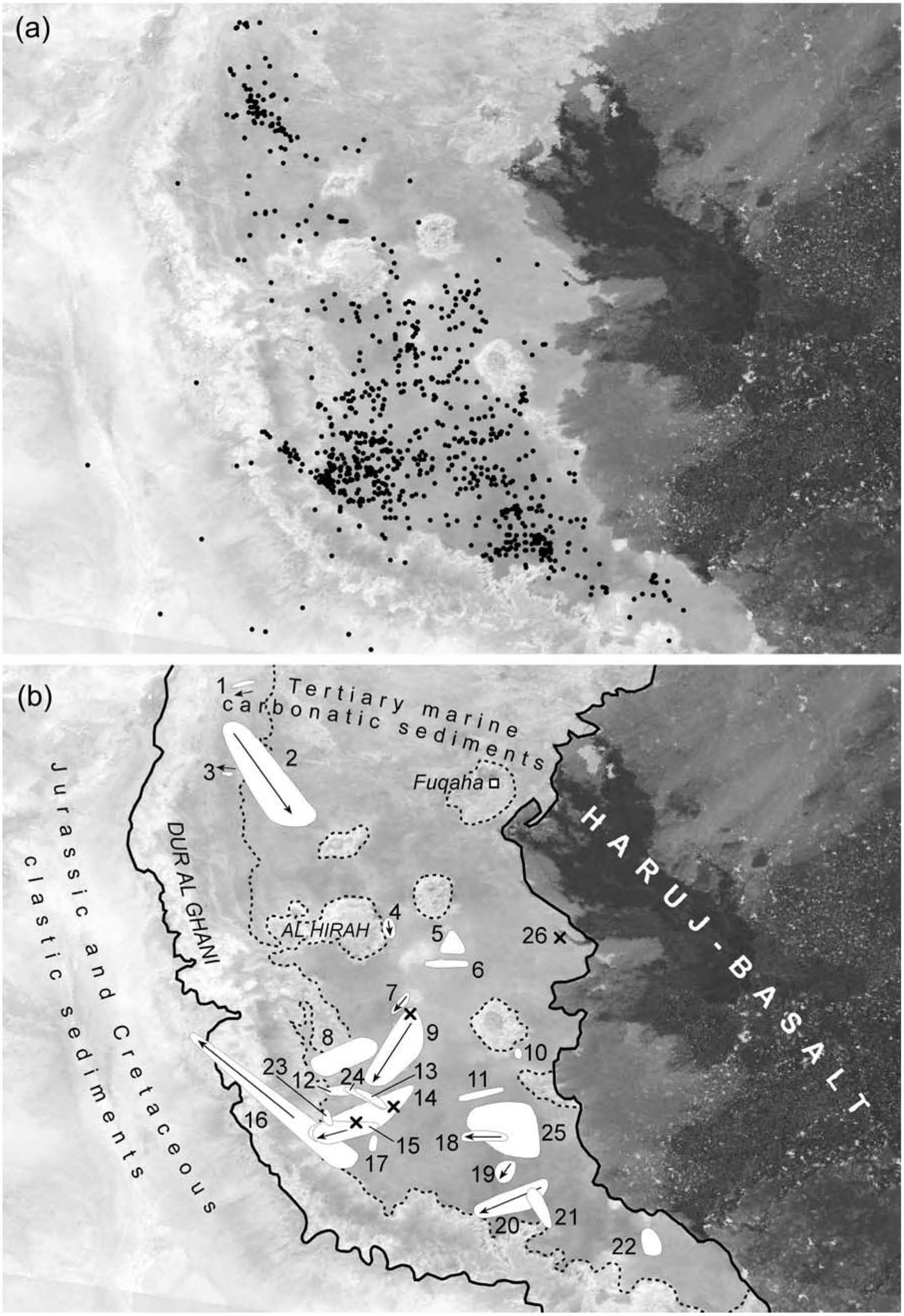

FIG. 2. (a) Satellite image (Landsat 7, USGS; width: 175 km) of the Dar al Gani area with meteorite finds (black dots) until summer of 2001. (b) Satellite image (Landsat 7, USGS; width: 175 km) with geological contour map (dotted circular structures = Qaràrats), Dar al Gani strewn fields (numbered areas), infall orientations (arrows) and position of shergottite finds (DaG 476, 489, 735, 876; no. 26; crosses).

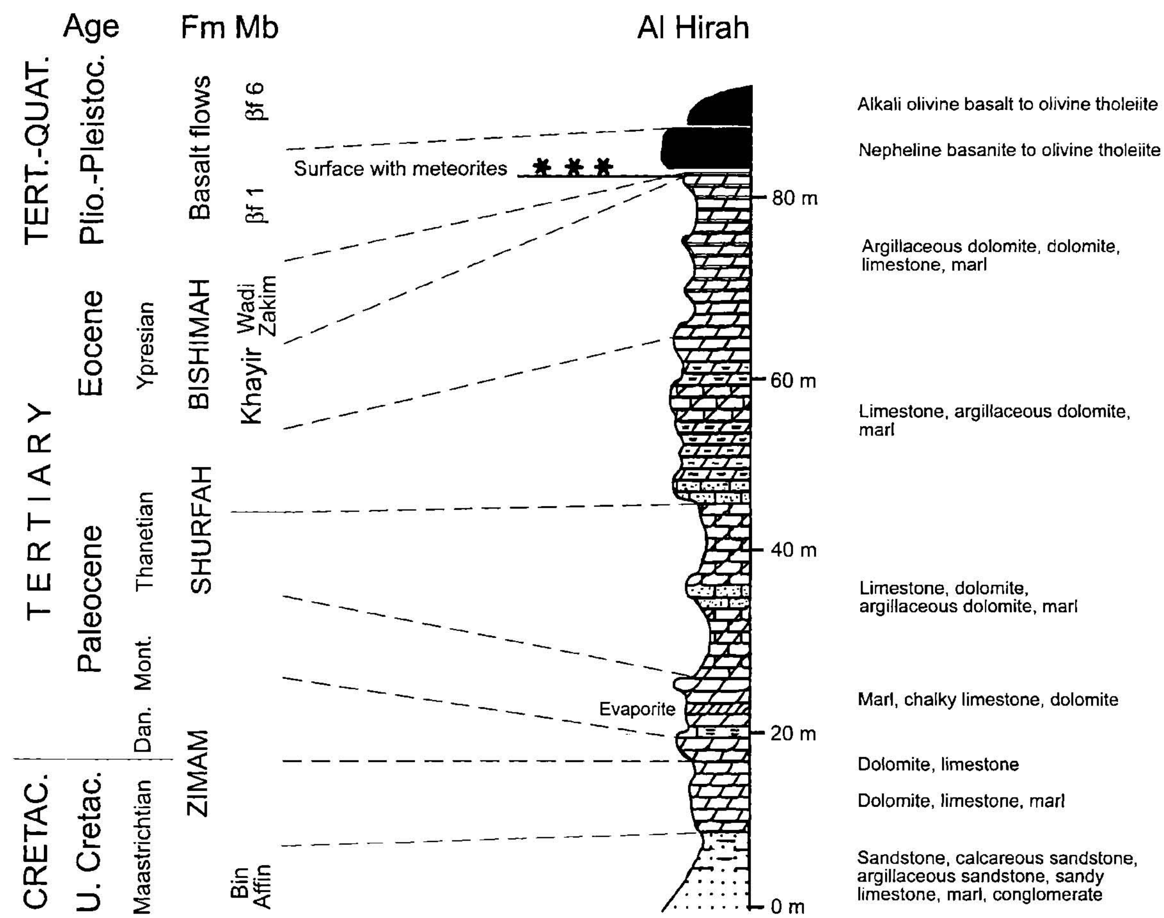

FIG. 3. Geological section of the Dar al Gani site at Qaràrat al Hirah.

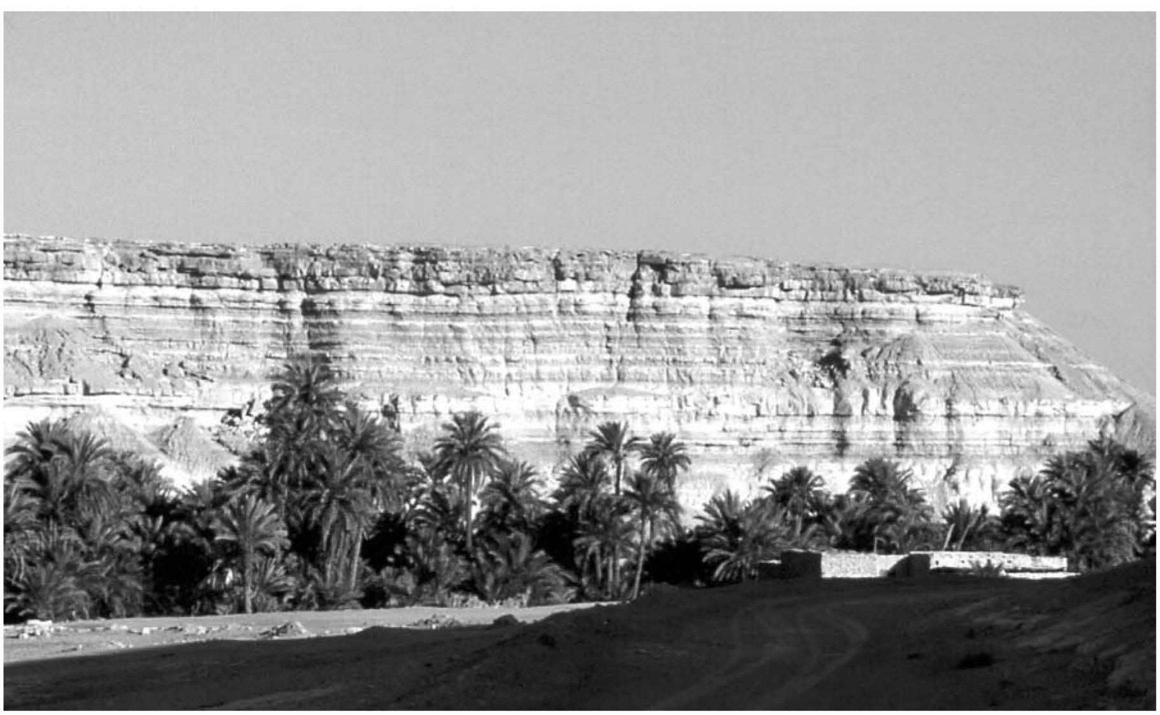

FIG. 4. Tertiary carbonate marine sediments of the Bishimah formation (Paleogene) exposed in the oasis of Qaràrat al Fuqaha.

FIG. 5. Meteorite find DaG 908 resting on a bright-coloured surface built up of Tertiary carbonate marine sediments.

rocks, only a few meteorites have been found in this zone. In the lee, west of the Haruj, areas exist with a soft layer of fine dust, and it is possible that meteorites are buried here.

In the southern part of the Dar al Gani region, the plateau locally shows coarser grained rocks or its surface is disturbed by occasional water, making the recognition of meteorites more difficult.

In the northern part of the Dar al Gani region, around the Al Fuqaha oasis, younger members of the Bishimah formation (Rawâghah and Wâdi Zâkim members) are exposed which, in contrast to the Khayir member, contain dark cherts and limonitic concretions. Due to their higher resistance to erosion, these dark components are concentrated on the surface complicating meteorite searches. In the west and south, the plateau ends in a cuesta landscape of older Tertiary strata (Paleogene Shurfah formation) stepping down towards the west, where Jurassic and Cretaceous sediments appear ~100 m below the plateau.

The Dar al Gani plateau contains several circular depressions, called Qarârats, up to ~100 m deep, and 4 to 14 km wide. The origin of Qarârats is due mainly to eolian deflation combined with tectonic, karstic and fluviatil processes (Klitzsch, 1974). The floors of these depressions are covered with young, fine-grained clastic material like clay and carbonate sand. No meteorites have been found here.

Reducing the ~12 000 km^2 large surface of the entire plateau by such unfavourable areas, ~7900 km^2 of the Bishimah formation favourable for the recognition of meteorites is left. In this area of the plateau 835 meteorites have been found, and only 34 meteorites on its Tertiary benchland, the surface of which is also built up by bright-coloured marine sediments, but with a coarser morphology (Fig. 2a). All these meteorites actually were spread over an area totalling 5500 km^2. With few exceptions all meteorites have been found situated directly on the present surface. The 869 DaG meteorites with masses between 6 g and 95 kg have a total weight of 687 kg.

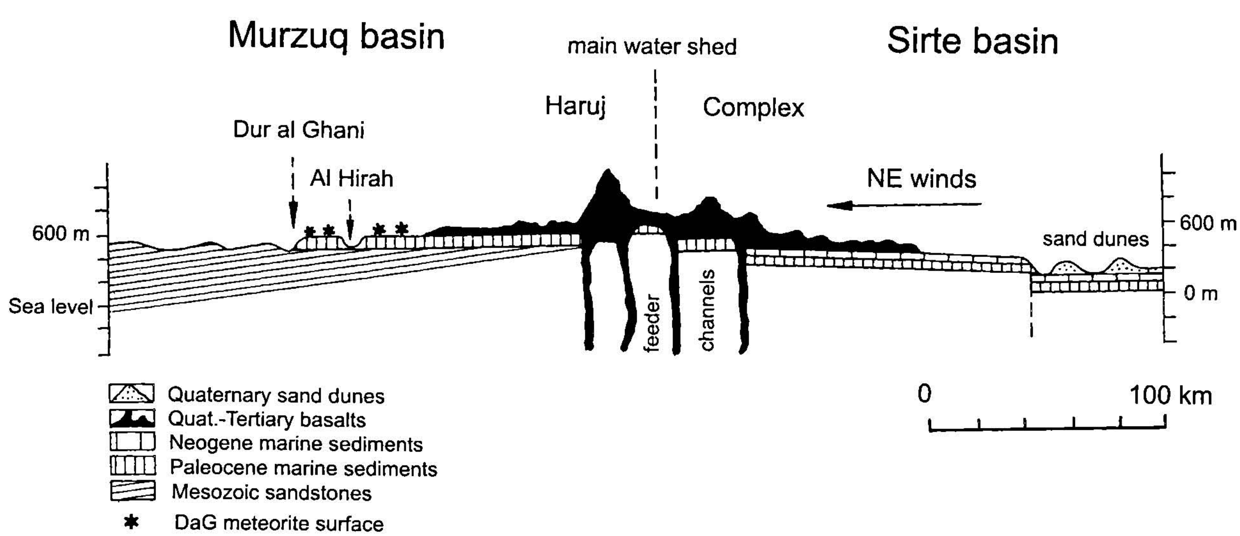

FIG. 6. Schematic geological east-west cross-section at 27° 30' N of the Dar al Gani meteorite field (scale exaggerated).

During this investigation we learned from private collectors and mineral dealers that they still retain a significant number of meteorites from the Dar al Gani region, mostly ordinary chondrites, which have not been classified yet. Furthermore, in 2001 at mineral shows like Tucson or Munich and also local markets around the Sahara, predominantly Moroccan dealers sold many unclassified meteorites without giving find locations or other information. Most of those meteorites have been later catalogued as Northwest Africa (NWA) meteorites. It can not be ruled out that these meteorites may have come from Algeria and Libya as well. There are also indications that several rare meteorites named Sahara xxx may originate from the Dar al Gani region.

This is a rather disappointing situation from the standpoint of meteorite research because much important information is not available, and the calculation of reliable infall rates, terrestrial age distributions and weathering rates are hampered.

Most of the DaG meteorite masses are between 50 and 100 g. The differences in the distribution of masses between Antarctic, Nullarbor and DaG meteorites are explained by differences of surface features and collecting methods. In the Nullarbor region, Australia, where most finds have masses of 10 to 50 g, collecting on foot is practiced and thus smaller meteorites are also found (Bevan *et al.*, 1998).

The main masses of Saharan meteorites—from Algeria and the Hamadah al Hamra region—(Bischoff and Geiger, 1995) were between 100 and 150 g. The discovery of lunar and martian meteorites in the Dar al Gani region in the later years led to a more detailed search in the Dar al Gani region resulting in the find of more smaller meteorites, shifting the mean value towards a smaller mass.

GEOLOGY

Essential for the Dar al Gani area as a meteorite collecting site is the geological signature of its underlying rocks. Many areas of the Sahara offer promising conditions for meteorite recoveries with old and flat deflation areas. However, many of these areas contain bedrocks with dark or black colours, or they have bright-coloured rocks with dark components. Or they simply have been turned black by eolian, lateritic or geochemical processes. For instance, areas west of the Dar al Gani plateau, where bright-coloured sandstones of Jurassic or Cretaceous age occur, cannot serve as collecting sites because their exposed rocks are covered by black desert varnish, making the search for meteorites very difficult. The Dar al Gani area instead exhibits more or less bright-colored carbonate rocks, which lack desert varnish. Consequently, meteorites show up perfectly because of their dark appearance.

Desert varnish is a dark patina that forms on rock surfaces over hundreds to thousands of years. It consists of a blackish mixture dominated by clay minerals—mostly illite and montmorillonite—with manganese and iron oxides. Several explanations for the development of desert varnish are given in the literature. According to Dorn and Oberlander (1981) the development of desert varnish is attributed to microbial activity. Special bacterial cells absorb onto large clay particles, where they can oxidize and concentrate manganese and iron. The components of the desert varnish are derived from airborne dust and other sources not connected to the underlying rock (Potter and Rossman, 1977). Favourable conditions for the action of the bacteria are near-neutral pH values. This could explain why the Dar al Gani region, with its more or less basic limestone or dolomite plains, has not developed desert varnish.

However, meteorites on the Dar al Gani plateau are always dark even if their fusion crust is lost by weathering processes. One reason for this could be besides simple iron staining the development of thin coatings of dark desert varnish because of their different "local" geochemical environment.

The geochemical signature of the Dar al Gani surface rocks has possibly also a strong influence on the preservation of meteorites. Its basic environment can essentially retard the dynamics of rusting of metallic meteorite components.

Another special feature of the Dar al Gani meteorite field is its topographical and geological position. The plateau is situated at the northeastern fringe of the Murzuq basin, close to the watershed of the neighbouring geological basin to the east, the Sirte basin. Only a small catchment area delivers water onto the Dar al Gani plain.

Furthermore, in case of occasional heavy rainfall—today the average annual rainfall reaches 10 to 20 mm—or during pluvial phases the rainwater is quickly drawn off by an underground karst system. This is shown close to the village of Al Fuqaha, which is situated in one of the Qaràrats, where several karst springs discharge freshwater. The water of these springs is fed mainly by rainfall in the central areas of the Jabal Haruj. Due to a very low gradient (~0.2%) of the plateau towards its western edge, running water has no erosional strength, so that valleys and gullies on the Dar al Gani plateau are only developed near the Qaràrats and in the western and southern benchlands where the relief is much higher. Because of the subdued relief on the plateau the run-off is highly reduced. Furthermore, strong evaporation due to low humidity and high temperatures dries the surface very efficiently.

Another geological feature on the Dar al Gani plateau is responsible for the higher preservation of meteorites than in other deserts: the lack of quartz sand. In the Tertiary marine sediments of the Bishimah formation quartz is nearly absent. Younger quartz-containing rocks were never deposited on this strata, as indicated by the younger basaltic flows of the Haruj, which lie directly on rocks of the Eocene Bishimah formation. Large sand dunes only occur in the far distance, west and south of the Dar al Gani site, and ~100 m below its elevation.

The main wind direction in this part of the Sahara is from the northeast towards the southwest. The wind transports quartz sand from sand dunes north and east of the Haruj towards Dar al Gani (Fig. 6), but here the large ~50 000 km² rough surface of the Haruj complex acts as a sand filter. For these reasons, there are no sand dunes on the Dar al Gani plateau and wind-shaped pebbles do not exist. Consequently, the DaG meteorites are not exposed to sand blast, as are rocks and meteorites in other regions of the Sahara (Fig. 7).

Geological observations also offer some information on the age of the Dar al Gani meteorite field. The Haruj volcanic complex is of Pliocene age and its oldest eruptions have been dated at 6 Ma. Most of the flows, especially those which directly lie on the Wâdi Zâkim and Khayir members of the Bishimah formation, are dated at between 0.41 and 2.2 Ma (Ade-Hall *et al.*, 1974). Lava flows closest to the meteorite recovery area tend towards 2 Ma. This indicates that the meteorite-carrying Dar al Gani plateau could have an age of up to 2 Ma.

The terrestrial ages of meteorites from the world's hot deserts are mainly up to 40 000 years (Bland *et al.*, 2000). For the Dar al Gani no terrestrial ages of ordinary chondrites have been published yet, but martian meteorites DaG 476/489/670/735 (Nishiizumi *et al.*, 2001) and the lunar meteorite DaG 262 (Nishiizumi *et al.*, 1998) show terrestrial ages of 60 ± 20 ka and 17.3 ± 1.4 ka, respectively.

The geological setting allows the estimation of erosion rates for the Dar al Gani plateau. At a southeasterly contact between Haruj basalts and Dar al Gani surface, the basaltic flows rest on a small relic of the Wâdi Zâkim member, proving that the underlying Khayir member—the "meteorite-ground"—at this location is completely preserved (Fig. 3). The Khayir member with a thickness of 14 to 18 m is present on the entire meteorite recovery area. This implies that since the basaltic eruption this plateau could not have been eroded more than 18 m, otherwise older member of the Shurfah formation should be exposed on the Dar al Gani surface. The geological situation on the Dar al Gani plateau implies that erosion was dominated by aeolian activities. Such wind erosion without sand drift could affect small components, forming the observed mosaic-like floor and leaving behind larger rocks like the erratic basalts found on the plateau—or meteorites. If we accept a minimum age of 1 Ma for the Dar al Gani plateau and suppose a maximum erosion between 10 and 20 m, in a model of continuous erosion we come up with an erosion rate of only 1 to 2 cm in a millennium. This does not exclude higher erosion rates at certain times, but it indicates an overall low erosion rate.

The favourable conditions for meteorites on the Dar al Gani plateau can thus be summarized: (1) an old deflation plateau; (2) relatively low surface erosion rates; (3) arid weather conditions over long periods of time; (4) rapid elimination of surface waters if present; (5) no wind abrasion through quartz sand blast; and (6) a basic chemical environment, which reduces the dynamics of rusting.

Recent field trips to other Libyan desert areas, like the Djabal Zaltan plateau or limestone plains south of the Haruj, met with very similar conditions, but no meteorites were found. So the high concentration of meteorites on the Dar al Gani plateau requires the influence of additional conditions.

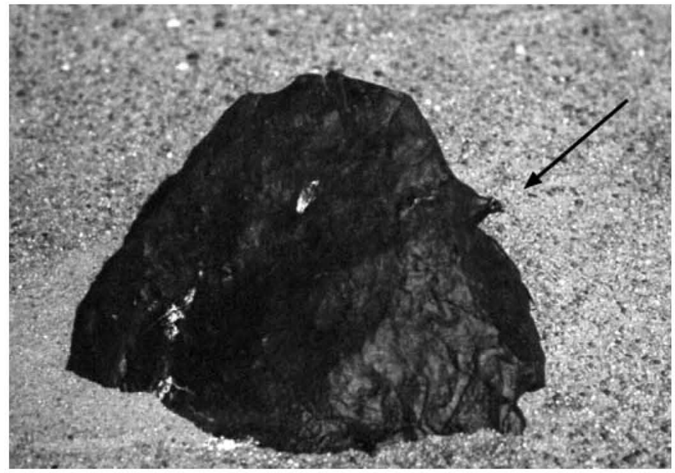

FIG. 7. The 27 kg meteorite Tiffa 001, Niger, with its terrestrial age of 5.7 ± 1.6 ka (Schultz *et al.*, 1998) shows strong wind corrosion. A 3 cm long "nose" (arrow) due to a large nickel-iron grain on its tip has been developed by quartz sand blasting.

The position of the Dar al Gani meteorite field—in the lee of the Haruj complex—leads to the assumption that this geomorphological feature might have been responsible for its meteorite concentrations. As already described above, areas on the Dar al Gani plateau close to the Harudj are covered with a layer of fine dust, which has settled in the lee of the Harudj. This could indicate that during the last wet period in this region a soil cover could have developed on the Dar al Gani plateau. Modern isolated clay-dominated tamariske hills in the Sahara show that just a bit of moisture like dew and some roots can easily lead to an agglomeration of soil components. Neolithic artifacts like tools and especially millstones for the processing of grain as well as engravings and rock paintings showing antelopes and human hands (Klitzsch, 1974) and—in the Murzuq basin—hippos and crocodiles prove that a wet period with grass and bush vegetation sufficient to allow human settlements occurred. This wet period, with short dry intervals, is supposed to have occurred between about 11 000 and 3000 years ago.

Meteorites that had accumulated during earlier arid periods on the Dar al Gani plateau could have been covered by soil and thus protected during the wet period. Further accumulation of meteorites and a complete removal of this soil by deflation during the current arid period could leave behind a concentration of meteorites on the bedrock. The high terrestrial age of the DaG shergottites of 60 ± 20 ka seem to support this model.

The determination of terrestrial ages of ordinary chondrites from the Dar al Gani region is currently under way.

STREWN FIELDS

The spindel-shaped area (Fig. 2a) where most (845 meteorites) of the 869 officially approved DaG meteorites (including three Sarir Qattusah meteorites and the Dor el Gani iron meteorite) are concentrated covers ~5500 km^2. With a total mass of 649 kg for all DaG meteorites, this leads to 118 g of meteorite mass on 1 km^2 of the Dar al Gani field or to only one meteorite on 6.5 km^2. By considering only the southeastern part of the Dar al Gani field with its highest concentration of meteorites—2900 km^2 and 699 official meteorites—we find a recovery density of one meteorite on 4.2 km^2 (Table 1).

As in all meteorite concentration areas, many of the specimens belong to meteorite shower and are thus paired. A prominent large strewn field of CO3 chondrites is already described (Pelisson and Pelisson, 2000, unpubl. data). It is a 43 km long ellipse trending southeast–northwest with 60 individual finds (only 46 of these finds are approved by the Meteoritical Society) with a total mass of 180 kg (Fig. 2b, no. 16).

Another remarkable strewn field consists of the already mentioned five shergottites (DaG 476, 489, 670, 735, 876), which are distributed along a southwest–northeast trend over a distance of at least 58 km (Fig. 2b, no. 26; crosses).

To detect pairings of DaG meteorites we combined the geographical distribution of meteorite class and type, including detailed mineral chemistry, as well as shock and weathering grade.

Most easily discernible are pairings of rare meteorite classes with close spatial distribution, or similar analytical data (*e.g.*, similar exposure ages or terrestrial ages). For a suspected strewn field the mass distribution of the meteorites can furthermore indicate its existence.

Meteorite classes like L6, H5 or H6, especially with shock grades of 2 or 3, are very common. The recognition of such paired meteorites is difficult unless their spatial distribution suggests a common fall. A strewn field like that of the shergottites can obviously not be detected by these methods, so the presence of further undetected pairings of this kind is very likely. Using these criteria so far we have identified 26 strewn fields with more than two members (Fig. 2b and Table A1). Twenty six other meteorite pairs (two members) are suggested (Table A2). Taking into account the mass distribution within the strewn fields it has also been possible to determine the fall direction of some of the meteoroids that produced the meteorite shower (Fig. 2b; arrows).

If we reduce the meteorites of the 26 strewn fields and the 26 possible meteorite pairs to one individual meteorite each, we are left with a total of only 534 meteorites. This leads to significant changes in the class distribution (Table 2) and results in a mean meteorite density of one meteorite in 10.8 km^2 for the Dar al Gani recovery site. With a total of 420 meteorites corrected for pairing in the southern most populated zone we come up with a ratio of one meteorite per 6.9 km^2.

Such low rates for a meteorite recovery area like the Dar al Gani with its perfect conditions for recognition and preservation could have been caused by several factors: (1) an incomplete collection or the absence of smaller meteorites; (2) a significant number of meteorites found on the Dar al Gani plateau not officially registered, or even known under another name like Sahara xxx; (3) weathering effects which reduce the number of meteorites originally present (Bland *et al.*, 1998).

At a first glance it is not surprising that the number of small DaG meteorites is rather low compared to those from the Nullarbor plain, which is searched on foot. However, the conditions at the Dar al Gani field are such that meteorites smaller than 50 g should also be recognized, which is the case for samples that are split in small pieces on impact or by later weathering processes. It is unlikely that small specimens are removed by strong winds like Antarctic meteorites on blue ice; also the destruction by weathering should not be dependent on the original mass. This is shown by the mass distribution of the more weathered Roosevelt County meteorites (see Fig. 8), which have longer terrestrial ages but also smaller masses.

From field observations we believe that small meteorites (<50 g), expected in high numbers, are only occasionally present on the Dar al Gani field. At the present time we cannot give an explanation for the "missing" small meteorites.

Table 2 shows that the correction for pairing strongly reduces the numbers of CO chondrites and ureilites because their apparent overabundance results from two distinct strewn fields. Furthermore, the total number of ordinary chondrites is reduced essentially by pairing, with a more intense reduction for L chondrites (–45.5%) opposite to the H chondrites (–26.4%) shifting the H/L ration towards higher values.

With only two iron meteorites found on the Dar al Gani field, the stone/iron ratio is very low in comparison with modern falls and finds in other regions of the world. This might be explained by an anthropogenic influence; neolithic settlements were found by Klitzsch (1974) in the Qaràrat al Hirah.

The H/L ratio of DaG meteorites after correction for pairing is very high in contrast to modern falls, world finds and the Nullarbor (Table 3). Surprisingly, the Dar al Gani ratio is identical with that of Antarctica and other Saharan areas (Bevan *et al.*, 1998). It seems unlikely that regional differences in the fall ratio of H and L chondrites occur, and there are no hints that L chondrites have a higher weathering rate than H chondrites. Because of the similarity in the H/L ratio with Antarctica it is unlikely that unclassified meteorites are dominantly L chondrites. Therefore, it is possible that among the high numbers of

TABLE 1. Meteorite recovery per km^2 ratios for DaG meteorites.

	All DaG meteorites	DaG meteorites corrected for pairing
DaG recovery site	1:6.5 km^2	1:10.8 km^2
Southern most populated part of the Dar al Gani field	1:4.2 km^2	1:6.9 km^2

Antarctic and Sahara finds many H-chondrite pairings simply have not been recognized.

THE VALUE OF SHOCK AND WEATHERING GRADES AS INDICATORS OF PAIRING

A problem that arises for the recognition of pairings using shock and weathering grades is shown for the strewn field in the northwest corner of the Dar al Gani field (Fig. 2b, no. 2). Here an isolated ellipse of 45 L6 chondrites is discernible, whose mass distribution indicates a fall direction of the meteoroid from the northwest. The classification of these meteorites was carried out in different laboratories. While the classification L6 was unambiguous, the shock grades varied between S3 (17 meteorites), S3/4 (6), S4 (15) and S6 (7) (Fig. 9). Weathering grades are given between W1 (36) and W2 (9).

TABLE 2. Dar al Gani meteorite statistics.

Class	Koblitz (2000) and Grossman and Zipfel (2001)		Koblitz (2000) and Grossman and Zipfel (2001)*	
CV	5		3	
CR	1		1	
CO	48		3	
CM	1		1	
CK	4		3	
Cungrouped	4		1	
EL	1		1	
H	383		282	
L	319		174	
LL	59		40	
R	2		2	
URE	17		6	
HED	16		12	
Lunar	2		2	
SNC	5		1	
Stony-iron	0		0	
Iron	2		2	
Total	869		534	
	n	%	*n*	%
Not differentiated	827	95.17	515	95.69
Differentiated	42	4.83	23	4.31
Chondrites, ordinary	761	87.57	496	92.88
E and R	3	0.35	3	0.56
Chondrites, carbonaceous	63	7.25	12	2.25
Achondrites	40	4.60	21	3.93
Stony-irons	0	0	0	0
Irons	2	0.23	2	0.38
Total	869	100	534	100
H/L	1.20		1.62	

*Meteorite counts corrected for pairing.
Abbreviations: HED = howardite–eucrite–diogenite group ; SNC = shergottite–nakhlite–chassignite group; URE = ureilites.

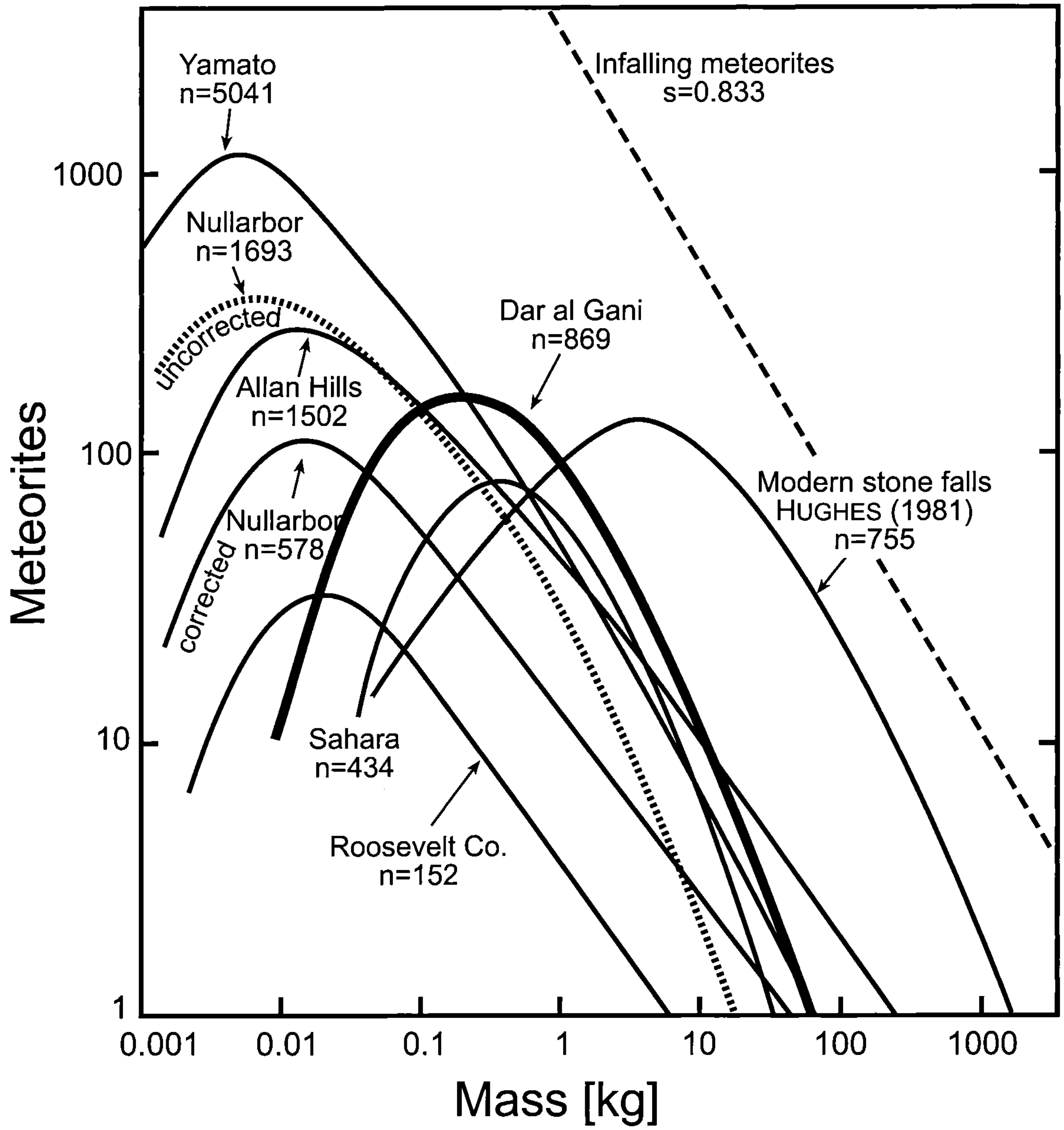

FIG. 8. Mass distribution of DaG meteorites after Huss (1990, 1991) and Bevan *et al.* (1998). Sahara curve (Bischoff and Geiger, 1995) derived from Algerian and Libyan (HaH) finds until 1993. Infalling meteorites are arbitrarily marked on the diagram.

This demonstrates that in some cases the shock grade is not a good criteria for the detection of paired samples. This is in agreement with Bischoff and Geiger (1995), who stated that "meteorites containing ringwoodite were classified as S6 chondrites. However, it must be pointed out that the presence of ringwoodite is restricted to local regions in or near melt zones of the chondrites. The host rock has experienced a lower-shock metamorphism (S4 or S5)."

To make sure that the L6 chondrites of this suite with different shock grades belong to the same fall we have measured the noble gases in DaG 328 (S3), 458 (S4) and 457 (S6). Included is also a measurement of shock vein material of DaG 457. Concentrations of the stable isotopes of He, Ne and Ar were determined using techniques and methods recently described by Scherer and Schultz (2000). The results are given in Table 4.

The shielding sensitive parameter $(^{22}Ne/^{21}Ne)_{cos}$ of the meteorites is very low at ~1.07. This indicates that the measured samples come from locations with high shielding. The meteoroid of this L6 shower was thus relatively large ($r > 40$ cm). The given cosmic-ray exposure ages are calculated from the cosmogenic nuclide ^{21}Ne using procedures and production rate of Eugster (1988). The value of ~38 Ma is a lower limit because the production rate with high shielding is possibly smaller. The

TABLE 3. Meteorite falls and finds.

	Modern falls* (%)	All finds* (%)	DaG (this study) (%)	DaG (corrected for pairing) (%)	Antarctica† (%)	Nullarbor† (%)	Sahara† (%)
C chondrites	3.6	2.5	7.25	2.25	3.9	4.6	4.2
O chondrites	73.5	62.3	87.57	92.88	87.3	87.3	91.0
E chondrites	1.4	0.9	0.12	0.19	0.7	0.8	0.7
R chondrites	0.1	0.1	0.23	0.37	?	?	?
Others	0.1	<0.01	–	–	?	?	?
Total chondrites	78.7	65.8	95.17	95.69	91.9	92.7	95.9
H/L	0.9	1.0	1.20	1.62	1.6	1.0	1.6
Achondrites	7.7	2.5	4.6	3.93	6.3	5.4	1.5
Unclassified stones	7.2	27.3	–	–	?	?	?
Total stones	93.5	95.6	99.77	99.62	98.2	98.1	97.4
Total iron meteorites	4.8	3.9	0.23	0.38	1.3	1.5	1.9
Total stony-iron meteorites	1.2	0.5	0	0	0.5	0.4	0.7
Unknown types	0.5	0.03	–	–	?	?	?
Total meteorites	1003	21150	869	534	3930	260	456

*Bischoff (2001) and references cited therein.
†Bevan *et al.* (1998) and references cited therein.

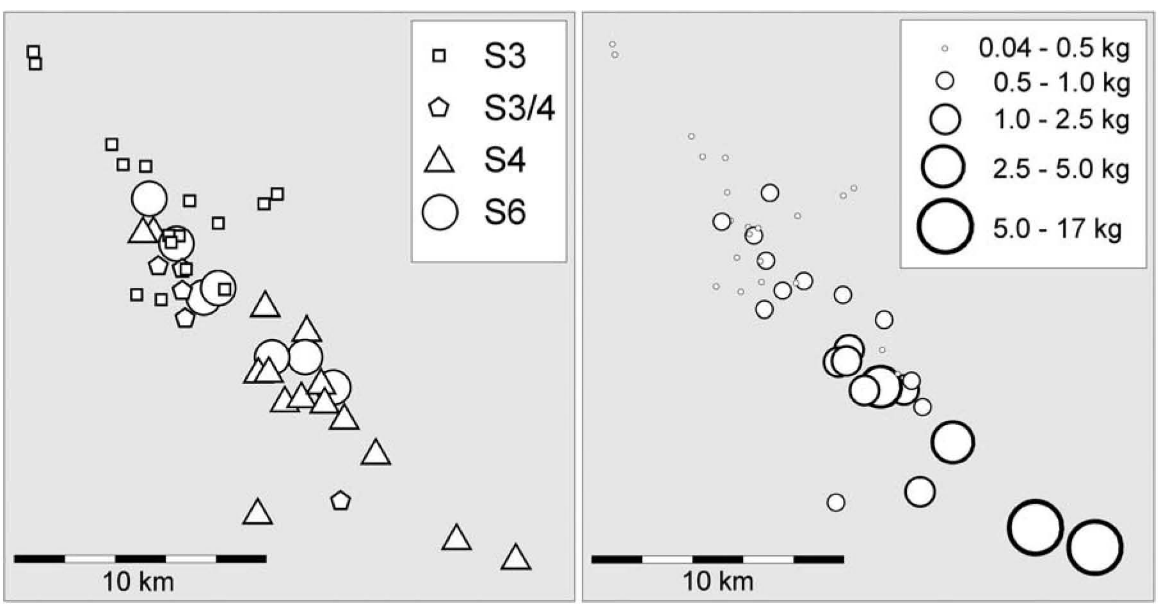

FIG. 9. Shock grades and mass distribution of Dar al Gani strewn field no. 2 with 45 L6 meteorites.

TABLE 4. Noble gas concentrations (in 10^{-8} cm^3 STP/g), the cosmogenic $^{22}Ne/^{21}Ne$ ratio, as well as the cosmic-ray exposure age of specimen of the L6 shower with different shock grades.

Meteorite	DaG 328	DaG 458	DaG 457	DaG 457
Shock grade	S3	S4	S6	S6 shock vein
^{3}He	66.4	72.3	63.9	66.4
^{4}He	630	660	870	620
^{20}Ne	13.9	15.1	13.9	13.6
^{21}Ne	15.5	16.7	15.4	15.1
^{22}Ne	16.4	17.8	16.4	16.5
^{36}Ar	2.38	2.83	4.43	2.52
^{38}Ar	2.30	2.38	2.23	2.17
^{40}Ar	1640	1610	1870	2060
$(^{22}Ne/^{21}Ne)_{cos}$	1.056	1.067	1.064	1.091
^{21}Ne exposure age (Ma)	35.4	40.3	36.6	41.7

Uncertainties of individual measurements are estimated to be <5%, those of exposure ages are <15%.

higher contents of trapped Ar in DaG 457 is explained by contamination with gases from the terrestrial atmosphere (Scherer *et al.*, 1994).

The noble gas record of these meteorites is very similar and indicates that the samples come from the same meteoroid. This clearly shows that the DaG chondrites of shower no. 2 in spite of different shock grades belong to the same fall.

Additionally, the weathering classifications proved to be not very useful for a such a comparison. Differing weathering grades are observed in most of the strewn fields or meteorite pairs, which might be partly the result of individual interpretations of the common classification scheme (Wlotzka, 1993). Furthermore, weathering within a given meteorite might also be variable. Bischoff and Geiger (1995) note "the degree of weathering can be variable on a centimeter-scale. Based on the thin section study, it is quite obvious that the effects of weathering decrease from the outside to the centre of the meteorite. The outer millimeter of a rock can be heavily weathered (W4), while in ~1 cm depth the degree of weathering can be moderate (W2)." Usually the classification of meteorites is carried out on specimens of some grams only. It cannot be excluded that this material is not typical for the whole meteorite.

These observations reveal that data for shock and weathering grades alone should be taken with caution for the determination of pairings.

SUMMARY AND CONCLUSIONS

Reasons for the high abundance of meteorite specimens on the surface of the Dar al Gani region in Libya are investigated. There are a number of geological and geomorphological conditions, which allows the easy detection of black meteorites in this area. This includes the presence of bright-coloured carbonate rocks and almost no desert varnish. Furthermore, Dar al Gani is an old deflation plateau with low erosion rate. In addition, the degree of weathering of meteorites is also low because of arid weather conditions over long time periods, the fast elimination of possible surface water, the geochemical environment and the lack of mechanical abrasion by wind-borne quartz grains.

Possible pairings among these meteorite finds are evaluated using the find locations and classification characteristics. For this purpose the shock and weathering grades are not very helpful because within one meteorite different grades can occur. This has been demonstrated also by noble gas measurements of individual specimens of one specific group of paired L6 chondrites. In total, 26 meteorite strewn fields are suggested in addition to 26 individual pairings.

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APPENDIX A

The appendix appears on the following pages.

TABLE A1. Supposed strewnfields and its members.

Strewn field	Class	Probable members
1	L6 (S4)	461, 462, 463, 464, 465, 466, 467
2	L6 (S3 + S3/4 + S4 + S6)	326, 328, 352, 357, 359, 360, 361, 362, 363, 364, 365, 367, 368, 372, 374, 375, 376, 377, 379, 396, 397, 401, 402, 403, 404, 420, 421, 422, 439, 453, 455, 456, 457, 458, 459, 460, 470, 477, 478, 753, 754, 755, 756, 757, 758
3	H6 (S2 + S3)	370, 371, 398
4	L6 (S4)	307, 309, 805
5	L6 (S4 + S6)	414, 440, 441, 619, 620?
6	LL5–6 (S3)	061, 062, 222, 498
7	AEUC and AEUC-P(S2) (see also Sipiera *et al.*, 2001)	276, 391, 411, 480, 844
8	L6 (S5 + S4 (+ S6))	047, 092, 168, 488, 502, 505, 506, 507, 551, 553, 554, 555, 569, 649, 650, 657, 725, 726
9	L5 (S3 + (S2))	048, 050, 058, 059, 287, 345, 349, 352, 387, 479, 501, 549, 866
10	C3 ungrouped (S2 + S1)	055, 056, 429, 430
11	L6 (S5)	495, 530, 531, 532, 534, 537, 538, 539, 540
12	H4 (S2)	075, 240, 348?, 545
13	H6 (S3)	029, 133, 134, 153, 154, 245
14	LL6 (S3)	001, 026, 046, 177, 185, 247, 492?, 585?, 744?
15	H6 (S3)	002, 003, 024, 072, 073, 076, 077, 079, 080, 087, 099, 100, 101, 102, 104, 105, 106, 107, 121, 122, 123, 124, 125, 156?, 157, 172?, 193, 201, 202, 213, 214, 215, 217, 582, 614?, 651?, 747?, 905
16	CO3 (S2)	005, 006, 023, 025, 027, 032, 067, 078, 081, 082, 083, 136, 137, 171, 173, 186, 188, 189, 190, 191, 192, 194, 203, 204, 226, 227, 228, 229, 230, 231, 289, 291, 331, 332, 601, 667, 668, 749, 845, 846, 847, 848, 852, 853, 854, 858
17	L6 (S3)	033, 086, 258, 293, 341, 906
18	LL6 (S2)	036, 037, 038, 039, 252, 254, 265, 266
19	AURE (S3 + (S2, S2/3, S5))	084?, 164, 165, 485, 660, 661, 680, 681, 787, 801, 830, 857
20	L6 (S4 + S5 (+ S6))	529?, 652, 656, 674?, 676, 690, 694, 700, 701, 702, 703?, 704, 707?, 708?, 709, 713, 714, 715, 760, 762, 781, 789, 790, 803, 808, 809, 810, 823, 836, 840, 865
21	H5 (S3 (+ S2))	302, 598, 641, 774, 776, 780, 782, 788, 794, 795, 798, 804, 811, 812, 813, 815, 816, 822, 824, 825, 827, 831, 833, 835, 838, 839
22	H5 (S2 + S3)	600, 603, 606, 635, 646
23	H5 (S3 + S2)	088, 089, 090, 119, 155
24	H5 (S3)	113, 114, 115, 151, 166, 244?, 273, 497, 739?
25	L6 (S4)	040, 130, 131, 181, 182, 183, 251, 253, 711
26	ASHE	476, 489, 670, 735, 876

TABLE A2. Supposed meteorite pairs.

Class	Probable meteorite pair
H5/6/S2/W3 + W4	031/336
H5/S3/W3 + W4	035/586
H5/S3/W4	041/042
L6/S2/W1 + W2	057/837
H5/S2/W3	063/279
H5/S3/W3 + W4	132/139
H5/6/S2/W4	143/144
H5/S3/W2	147/148
H5–6/S3/W1 + W0-1 (?)	207/208
L6/S3/W3 + W4	209/210
H-AN	241/242
L5/S3/W2	255/267
LL5–6/S3/W3	256/257
H6/S2 + S3/W3	259/260
H6/S2/W3 + W4	268/269
CK5, CK4–5/S2/W3 + W4 (?)	275/412
L6/S2 + S3/W2 + W3 (?)	281/282
L5/S2 + S3/W3	292/330
H6/S2/W3	407/817
H4/5/S1/W3	499/500
CV3/S1 (?)	521/731
L6/S5 + S6/W2 + W4 (?)	527/528
CV3/S1	533/535
L6/S5	541/542
L6/S4/W2	624/867
L6/S4/W1 + W2 (?)	770/842