Observations on the spatial distribution of Dhajala meteorite fragments in the strewnfield

D LAL and J R TRIVEDI
Physical Research Laboratory, Ahmedabad 380 009

MS received 15 April 1977; revised 22 August 1977

Abstract. The Dhajala meteorite fragments were found scattered over an elliptical area of approx. 50 sqkm. More than 500 fragments weighing over 60 kg have been collected and their geographical coordinates have been documented. The observed number-mass distribution of fragments indicates that the overall collection efficiency is probably better than 60%. The laboratory observations of meteorite fragments and the field observations of their distribution indicate that:
(a) more than 95% of the stones had well developed crust on their surfaces. A few fragments shattered on impact but most retained crust on at least 70% of their surface area,
(b) the differential number mass distribution follows a single power law relation with a slope of 1.53±0.12 for fragments of mass between (10-10,000)g,
(c) the mass of fragments, geometric as well as arithmetic, increases exponentially as a function of projected distance along the major axis of the strewnfield, in the direction of flight, with a scale length of 2.2 km. The observations on the spatial distribution strongly support Frost's hypothesis of sorting proposed on the basis of a few other meteorite showers.

Keywords. Meteorite; fossil tracks; ablation; fragmentation dynamics.

1. Introduction

A meteoritic body entered the earth's atmosphere in the north-eastern skies of Gujarat, India, on 28 January, 1976 at about 20:40 hrs. I.S.T. Its interaction with the atmosphere led to brilliant light flashes accompanied with detonations. The apparent magnitude of the fireball was brighter than -20. A large number of fragments survived the fireball phenomena. We present in this paper results of systematic search made over a period of one year to collect the fragments of this meteorite which has been named as Dhajala, the village where a large number of fragments were found within a few hours of the fall. From an analysis of the meteorite recovery data, we believe that fragments of mass (10-10,000)g have been collected from the strewnfield with an efficiency better than 60%. We cannot exclude, however, the possibility that one or two single large fragments have escaped detection.

In view of the relatively high efficiency of collection for the Dhajala fragments, probably higher than for any of the meteorite showers reported earlier, we have made a detailed analysis of the number and mass distribution of meteorite fragments as well as their location in the strewnfield. A brief description was presented earlier along with a preliminary results of physical, chemical and mineralogical analysis (Bhandari et al 1976). The cosmic ray exposure age of Dhajala has been determined as 7 m.y. (Gopalan et al 1977). Observations of the meteor trail have been described
by Bhandari et al (1976) and Ballabh et al (1976). The latter authors have also computed the probable orbit of Dhajala meteorite from eye-witness reports of the meteor trail.

It may be mentioned here that the meteorite belongs to H-group of chondrites and according to Bhandari et al (1976) and Jarosewich et al (1976) probably falls in the petrological type 3 of Van Schmus and Wood (1976). H3 chondrites are rare; only 6 of the 114-H-group meteorites are type 3 (Wasson 1974). The Dhajala fragments have also been extensively studied for cosmic ray track densities (Bagolia et al 1977). These investigations have provided data on (i) the positions of individual fragments in the preatmospheric body and (ii) the magnitude of ablation as a function of radial distance in the meteorite.

2. The Dhajala meteorite shower

The meteorite fragments were found to be strewn in a nearly elliptical area around Dhajala in Gujarat as shown in figure 1. The directions of the meteor trail and of the major axis of the strewnfield are also indicated in this figure. The meteor trail observations have been discussed in more detail by Ballabh et al (1976). According to

Figure 1. The Dhajala meteorite strewnfield. Latitude and longitude of Dhajala are 22°22'40" N and 71°25'38" E respectively. The arrows show the direction of the meteorite trail and the major axis of the elliptical strewnfield; the area of the strewnfield is about 50 km².
Figure 2. A meteorite brigade in action. The boys and girls moved as a front separated by distance of 5-15 feet depending on their own size. This photograph was taken near the Gram Vidyalaya Lokshala School at Dhajala.
them the high altitude winds above 9.6 km were (60-100) knots westerly and south-westerly and are adequate to account for the estimated difference of 15° between the directions of the meteor trail and the axis of the strewnfield. The smaller fragments which fell in the first few kilometers of the strewnfield were deflected towards east because of these winds.

3. Collection of Dhajala fragments from the strewnfield

It became apparent within 48 hrs of the fireball that a large number of fragments had been showered over a linear distance of more than 10 km. Search parties were sent out by the Physical Research Laboratory to the area of fall to determine the approximate boundaries of the strewnfield. The scientific importance of collecting each and every fragment was brought to the notice of villagers. Simultaneously, thanks to the cooperation of daily newspapers and All India Radio, the public was made aware of the scientific importance of meteorites. In addition, meteorite brigades (MB) were formed to search the meteorite fragments. More than 200 school children of age group 5-15 volunteered to join the MB. They undertook systematic combing of the strewnfield under the guidance of one of us (JRT) who happens to be a native of Gujarat. Students walked as a front, separated by a distance of 5-20 feet depending on their own size (figure 2). The MB made ten marches between February 3-6 and 17-19, 1976. These tracks are shown in figure 3; areas not covered in these tracks were combed by smaller groups.

Each fragment found or given to us by villagers was coded and documented with
Figure 4. Dispersion ellipse for Dhajala fragments. Number of fragments found in each grid of 1 x 1 km are given. The unbracketted number refers to completely crusted fragments. The number of incomplete fragments is given within brackets.

Figure 5. Location of Dhajala fragments in the strewnfield. The dot size approximately corresponds to the size of the fragment.
Figure 6. Biggest Dhajala fragment consisting of three parts. The crusted regions are dark black in contrast to the grey coloured texture. Few chondrules (dark colour) are encircled.
Figure 7. Comparison between visual appearances of terrestrial besalt (left size) and Dhajala fragments.
Dhajala meteorite fragments

respect to its position in the field. The position of the fragments could be ascertained conveniently in the 1×1 km grid map with respect to local landmarks (figure 4). (It is believed that except possibly for a few fragments which might have been withheld, the natives have handed over almost all the samples).

To date a total of nominally 500 fragments weighing about 60 kg have been found. The largest fragment weighed 11.6 kg and was found accidentally on 29th January by a shepherd while tending his field, near the southern tip of the strewnfield (figure 5). Including this, the total number of fragments found prior to 31st January 1976 was 106 and total mass 25 kg. Of the remaining 436 fragments (total mass 36 kg) 140 fragments (18 kg) were found in the ten MB operations (figure 3) between 3-19 February 1976. Many of the MB students continued their search in small groups. Adults also joined in this venture. These searches led to a recovery of about 50% of the total weight found subsequent to the organised marches. The total number of fragments handed over after the last walk of MB on 19 February was 296, totalling 18 kg. About 25% of these fragments were recovered from the fields while harvesting and ploughing.

At the time of fall, wheat crops were thriving in about 5% of the area of the strewnfield and cotton crop in about 10% of the area; 60% of the land is uncultivated and barren. The villagers made conscious efforts to look for meteorites in fields where crops were growing at the time of the fall.

The meteorite brigade pick-up efficiency is estimated to be 30% only for fragments of mass greater than 10-20 gm based on recoveries from the scanned areas. An important reason for the low efficiency is the similar appearance of the crusted Dhajala stones and the dark coloured Deccan Trap basaltic fragments found extensively in the strewn field. In figure 6, a photograph of the biggest Dhajala stone (11.6 kg) is shown and in figure 7, six Dhajala fragments are shown alongside basalt pieces to contrast their similarity in appearance. The villagers, however, quickly learnt to distinguish meteorite pieces from native rock fragments.

Figures 4 and 5 show the distribution of meteorites in the strewnfield. The number of stones found in grids of 1×1 km is given in figure 4. Figure 5 is a schematic drawing showing the approximate size of the fragments found at different locations in the strewnfield.

The impact of the stones produced only shallow craters. The largest crater was 40 cm deep, 35×25 cm across. The size of the individual craters varied approximately as the size of the stone producing it. At a few places, where the ground was hard, the stones broke on impact. Sample T-11 shattered to small pieces which were found dispersed over a zone of 5×6 m.

Most fragments were found to have a well developed crust. 245 of the 542 fragments are completely crusted, 58 are partly crusted and 239 fragments have crusts only on a small fraction of the surface area. Most fragments of the latter type, i.e. those with incomplete crust resulted due to curiosity of natives who broke them in several pieces.

A great variety is seen in the crust. In several fragments which fell in the first half of the ellipse (figure 4), marked flow patterns and striations are visible. About 10 fragments have one or two faces with thin underdeveloped brownish crust indicating late fragmentation in the atmosphere.
4. Discussion of results

The number-mass distribution of completely crusted Dhajala fragments is shown in figure 8 at four different stages as the search continued. The overall slope of the number \(N\) mass \(m\) distribution did not change as the collection progressed but the fit of the distribution improved with a single power law over 3 orders of magnitude in mass (figure 8):

\[ dN = km^{-s} \, dm \]

with \(s = 1.53 \pm 0.12\); \(k\) is a constant.

If we assume that the power law behaviour holds down to fragments of mass 1 g we estimate that about 1.6 kg of small fragments of (1-10) g mass have not been recovered. The blank area under the power law lines in figure 8 between 4 and 10 kg corresponds to a mass of about 30 kg; if this gap is considered statistically significant, a couple of fragments in this mass range may have escaped detection or have been collected by villagers but not handed over to us. To search for any large fragment lying in the strewnfield or around it, particularly towards Ninama, (figure 4) the area

![Figure 8. Differential number-mass distribution of complete fragments (having crust on more than 70% of their surface) collected up to different epochs of time during the search: (a) Total weight of 28.5 kg represented by 140 fragments. (b) Additional 1.9 kg. (37 fragments). (c) Additional 1.1 kg. (66 fragments). (d) Additional 8.5 kg. (64 fragments).](image-url)
was scanned with a low flying helicopter. No stone was found. However, we have no idea of the efficiency of the aerial search carried out.

As seen from figure 5, the size of the fragments progressively increases as one goes south-west along the direction of flight of the meteorite. This feature can be very clearly seen in figures 9 and 10 where arithmetic mean ($\bar{m}_a$) and geometric mean ($\bar{m}_g$) masses of crusted fragments are plotted as a function of projected distance, $d$, along the major axis of the strewnfield. The group mass-distance relationship are well represented by the exponential fits:

$$\bar{m}_a = \text{const. exp.} \left( d/b_a \right)$$

$$\bar{m}_g = \text{const. exp.} \left( d/b_g \right)$$

where $b_a$ and $b_g$ are the scale lengths in the two distributions. The scale lengths for the arithmetic mean mass is determined from figure 9 to be slightly higher than that for the mean geometric mass (figure 10); $b_a = 2.28$ km; $b_g = 2.06$ km.

Several attempts have been made earlier to study the spatial distributions of fragment masses in the strewnfield. Frost (1969) was the first to consider spatial sorting of fragments in meteorite showers. He examined Barwell, Johnstown, Krymka

![Figure 9. Arithmetic mean mass of fragments as a function of projected distance along the major axis of the strewnfield. The error bars represent 1 standard deviation value. Only fragments which had more than 70% of their area crusted were included in this study.](image)

![Figure 10. Geometric mean mass of fragments as a function of projected distance along the major axis of the strewnfield. Only crusted (wholly or partially) fragments were included in this study. Note that the five points for distances exceeding 11 km are based on one or two fragments.](image)
Kunashak, Leedey, Plainview and Shikote-Alin showers and observed an approximate relationship of the type:

\[ d = a - b \log \bar{m}. \] (4)

The scale length \( b \) in eq. (4) is the same as that in eqs (2) or (3). A fit with experimental data of eq. 3 was attempted in the case of Allende (Kowalski and Lang 1972), Lowicz (Lang 1972) and Shikote-Alin (Lang and Kowalski 1973) showers. In all

Figure 11. Total number of crusted fragments in strips of width 1.4 km, along the major axis of the strewnfield.

Figure 12. Total mass of fragments in strips of width 1.4 km, along the major axis of the strewnfield. All fragments, whether crusted or not are included in this study.

Figure 13. Cumulative mass of fragments as a function of distance along the major axis of the strewnfield. All fragments are included in this study.
these cases the experimental distribution is found to be only a crude approximation to eq. (4) described as Frost's rule (Kowalski and Lang 1972). The departures have been partly attributed to incomplete recovery from the strewnfield and partly to complex fragmentation dynamics. In Allende, the mass vs distance scatter diagram could be thought of as representing two sub-populations, each following eq. (4) with a different scale length $b$.

In the case of Dhajala, the close fit (figures 9 and 10) of experimental data with the exponential $(d-m)$ relationship, indicates a simple ablation-fragmentation history for Dhajala as well as high efficiency of collection from the strewnfield in the entire mass range 10 gm-10 kg.

Of course, it should be noted here that it is not useful to compare the value of $b$ for different showers because this parameter depends on the angle of entry of the meteorite, its velocity, physical properties of the meteorite, etc.

In figure 11 we have plotted the total number of fragments found in strips of 1.4 km width, perpendicular to the main axis of the strewnfield, as a function of projected distance. A similar plot for the total mass of all fragments is given in figure 12. The corresponding cumulative mass is shown in figure 13. The data in these figures differ from those in figures 9 and 10 in as much as we have now included fragments having partial crusts which might have broken either on impact or by the natives.

The cumulative mass-distance curve in figure 13 is a divergent function as would be expected from the number-mass distribution relationship for Dhajala fragments.

Integration of eq. (1) gives the total number, $N$ or mass, $M$ of fragments contributed by fragments of mass lying between $m_1$ and $m_2$:

$$
N (m_1-m_2) = \int_{m_1}^{m_2} dN = \frac{k}{1-s} \left[ \frac{m^{1-s}}{m_1} \right]^{m_2} \tag{5}
$$

$$
M (m_1-m_2) = \int_{m_1}^{m_2} mdN = \frac{k}{2-s} \left[ \frac{m^{2-s}}{m_1} \right]^{m_2} \tag{6}
$$

Since the value of the slope, $s$ is determined to be $1.53 \pm 0.12$, the number of fragments converges as mass increases but this is not the case for the total mass. For example, if the shower had fragments of mass between 12-50 kg, the total mass contributed by these would approximately equal that below 12 kg.

We may compare the mass distribution data for Dhajala with that reported for other showers of stony meteorites. Although some basic data on this aspect have been reported for several showers, the collection and documentation of these samples have not been made as systematically as in the present case. We think that the best documented case for large showers of stony meteorites is that of Norton County (LaPaz 1965). The results for 1500 fragments of this shower have been analysed by Lang and Liszewska (1973). The data when plotted as in figure 8 yield a slope of $2.3 \pm 0.2$ (figure 14) which is considerably steeper than that for Dhajala and is outside the experimental uncertainties. It may be thought that this may be due to the difference in the atmospheric velocity of the two meteorites. However, as shown from laboratory experiments on fragmentation of these meteorites, the differences are
primarily due to their texture and tensile strength (Lal and Trivedi 1977). That the slope in the size distribution depends only weakly on the energy available for fragmentation seems to be well established (Charles 1956; Harris 1968; Lang and Liszewska 1973; Kutter and Fairhurst 1971). Higher energy results only in production of larger amount of fines but without any appreciable change in the slope.

5. Conclusions

More than 500 fragments of Dhajala meteorite weighing about 60 kg have been recovered from the strewnfield of 50 km² area. The yield of fragments collected within one year of the fall is estimated to be better than 60%. Information about their position in the strewnfield is available in the case of practically all the fragments. Each fragment has been coded and information on the crusting of the surfaces has been documented.

In this paper we have presented results of analyses of number-mass relationship for the fragments as also on the spatial sorting of fragments. The number-mass relationship is well described by a single power law for fragments of mass (10-10,000) g. The slope is 1.53±0.12 and hence most of the mass is contained in larger fragments. The group average mass of fragments increases exponentially with a mean distance of 2.2 km in the strewnfield and lends support to the sorting hypothesis put forward by Frost (1969).

The preatmospheric size of the meteorite has been determined to be 38±2 cms by Bagolia et al (1977) based on cosmic ray track density. The distribution of fragments described here enable us to draw some conclusions on the fragmentation dynamics which will be discussed elsewhere (Lal and Trivedi 1977).

Acknowledgements

We thank the school teachers and students of Dhajala, Nanamatra and neighbouring villages for their participation and assistance in the collection of meteorite fragments.
The help provided by the State Government officials and Geological Survey of India in the operations is gratefully acknowledged. Special appreciation is due to Aruna Lal, A Bhatnagar and K Gopalan for their active participation in the recovery. We thank N Bhandari and S K Gupta for discussions.

We record our appreciation to the Indian Air Force for help in the helicopter survey for the large crater/fragments. Our thanks are due to the R N Pandey for his careful low altitude survey of the strewnfield. Finally, we are extremely grateful to S Dhawan and M G K Menon for their encouragement in the present investigations.

References

Bagolia C, Doshi N, Gupta S K, Kumar S, Lal D and Trivedi J R 1977 Nucl. Track detection 1 83
Bhandari N, Lal D, Trivedi J R and Bhatnagar A 1976 Meteoritics 11 137
Frost M 1969 Meteoritics 4 217
Jarosewich E, Noonan A and Fredriksson K 1976 Private Communication
Lal D and Trivedi J R 1977 On the fragmentation dynamics of Dhajala meteorite shower (in preparation)
Lang B 1972 Earth Planet. Sci. Lett. 14 245
Lang B and Lisezewska K 1973 Meteoritics 8 277
LaPaz L 1965 Cat. Collection of the Institute of Meteoritics (University of New Mexico: Albuquerque)

Note added in proof

Our attention has recently been drawn by Prof. Klaus Keil to the fact that the data used by Lang and Lisezewska (1973) on the number-mass distribution of the Norton County fragments includes samples which broke on impact. A steeper slope for the Norton County fragments, compared to Dhajala, may therefore be due to inclusion of 'secondary' fragments.