ON THE POSSIBLE NUMBER AND MASS OF FRAGMENTS FROM PUŁTUSK METEORITE SHOWER, 1868

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The earlier efforts to approximate the total number and mass of fragments from Pułtusk meteorite shower 1868 have been found unsatisfactory.
With the use of the field data of Samsonowicz and the sorting equation after Frost, differential expressions approximating the mass and number of fragments are derived. These expressions numerically integrated over the elliptical strewnfield area lead to the estimates $\sim 1.8 \times 10^5$ *and* $\sim 2 \times 10^6$ *g for the total number and mass of fragments respectively.*
The meaning of the obtained results is discussed.

Over a century of efforts devoted to an approximation of the possible number of fragments from Pułtusk meteorite shower 1868 did not lead to any satisfactory issue.

The majority of figures shown in Table 1 are semi-quantitative statements rather than reasonable estimates. Two of them only, those of Paneth and Samsonowicz, are based on adequate though highly oversimplified calculations. An attempt at a new approach, leading to some better approximation of the number and mass of fragments which fell on January 28, 1868, is presented in this paper.

Table 1

Author	Year	Number	Reference
G. vom Rath	1869	several hundred thousand	1
J. Galle	1870	"innumerable"	2
E. Wülfing	1897	100,000	3
M. Neumayr	1912	3,000	4
C. Olivier	1925	100,000	5
E. Stenz	1937	3,000	6
F. Paneth	1937	42,000	7
J. Spencer	1937	100,000	8
J. Samsonowicz	1952	68,870	9

In his calculation, F. Paneth has accounted for two data: (1) the number of fragments per 1 kg mass as reported by Krantz (a well-known meteorite dealer from Bonn and owner of many Pułtusk meteorite specimens) and (2) the total recorded mass of fragments. Paneth's calculation, accounting for fragment mass distribution, would be correct if the reported figure could be recognized as related to a representative statistical sample for the meteorite fragment population. J. Pokrzywnicki (1954), however, in his comprehensive review has given evidence that it is not the case.

Samsonowicz used for calculation, the data elaborated by himself during the field investigations of 1922 and 1929, when the memory of the event was yet relatively fresh and some eyewitnesses were alive. With these data he had been able to draw up the approximate borderline of the strewnfield and to determine zones for various fragment masses, as well as to estimate the most probable inter-fragmental distances inside various places of the strewnfield. The values of 18 and 9 kilometers were found by him for the axes of the strewnfield ellipse, Fig. 1, its total area being 127 km^2.

Having divided this area into three parts, each equal respectively to s_i ($i = 1, 2, 3$), Samsonowicz obtained partial fragment number N_i from the expression:

$$N_i = \frac{s_i}{\bar{d}_i^{\,2}}$$

where with $\bar{d}_i$ represents the respective average inter-fragmental distance. The results of Samsonowicz are summarized in Table 2.

Table 2

Part number i	Partial areas; (km^2)	Average inter-fragmental distance $\bar{d}_i$ km	Partial number N_i	N_i^*
1	30	0.370	220	169
2	62	0.070	12,650	9,760
3	35	0.025	56,000	43,200
Total	127		68,780	53,129

When the square fragment arrangement, assumed by Samsonowicz, is replaced by a hexagonal one, which seems to be more correct, this leads to lower values for fragment number, partial number N_i^* in Table 2.

An approach suggested recently by M. Frost (1969) enables a quantitative treatment of the fragment size and spatial distribution in meteorite shower. Attempting to approximate the number and mass of Pułtusk meteorite fragments, we derived from Frost's approach the following assumptions:

1. The fragmentation process is assumed homogeneous, i.e. subordinated to one, presumably stepwise, comminution mechanism of the meteoroid body.
2. The large number of fragments should favor the demonstration of the statistical characteristics of the population.
3. The variation of the spacial density of fragments along the strewnfield axis can be approximated by a monotonic function, resulting from joint fragmentation and sorting effects.
4. The transverse scattering is purely random.

By projecting the d estimates of Samsonowicz for a set of places onto the symmetry line of the strewnfield taken as co-ordinate, Fig. 1, a set of x values has been obtained. These places, listed in Table 3, are situated near the symmetry axis of the strewnfield.

Table 3

Name of place	x km	d value km
Rzewnie, Boruty	0	0.450
Dąbrówka	3.34	0.200
Rowy, Gostkowo	7.8	0.070
Ciołkowo	12.9	0.013
Obryte	14.5	0.010

Plotting logarithms of d against corresponding x values leads in a rough approximation to a linear dependence, Fig. 2:

$$\log d \approx -0.12x - 0.32$$

$$d \approx \exp(-0.27x - 0.75)$$

The fragment number N can be expressed by following integral:

$$N = \int_{x_1}^{x_2} N'(x)\, k(x)\, dS(x)$$

where N' (x) denotes the variable fragment density, i.e. the variable number of fragments per unit area:

$$N'(x) = 0.77\, d^{-2}$$

$$N'(x) = 0.77 \exp(0.53x + 1.49)$$ (for assumed hexagonal fragment arrangement)

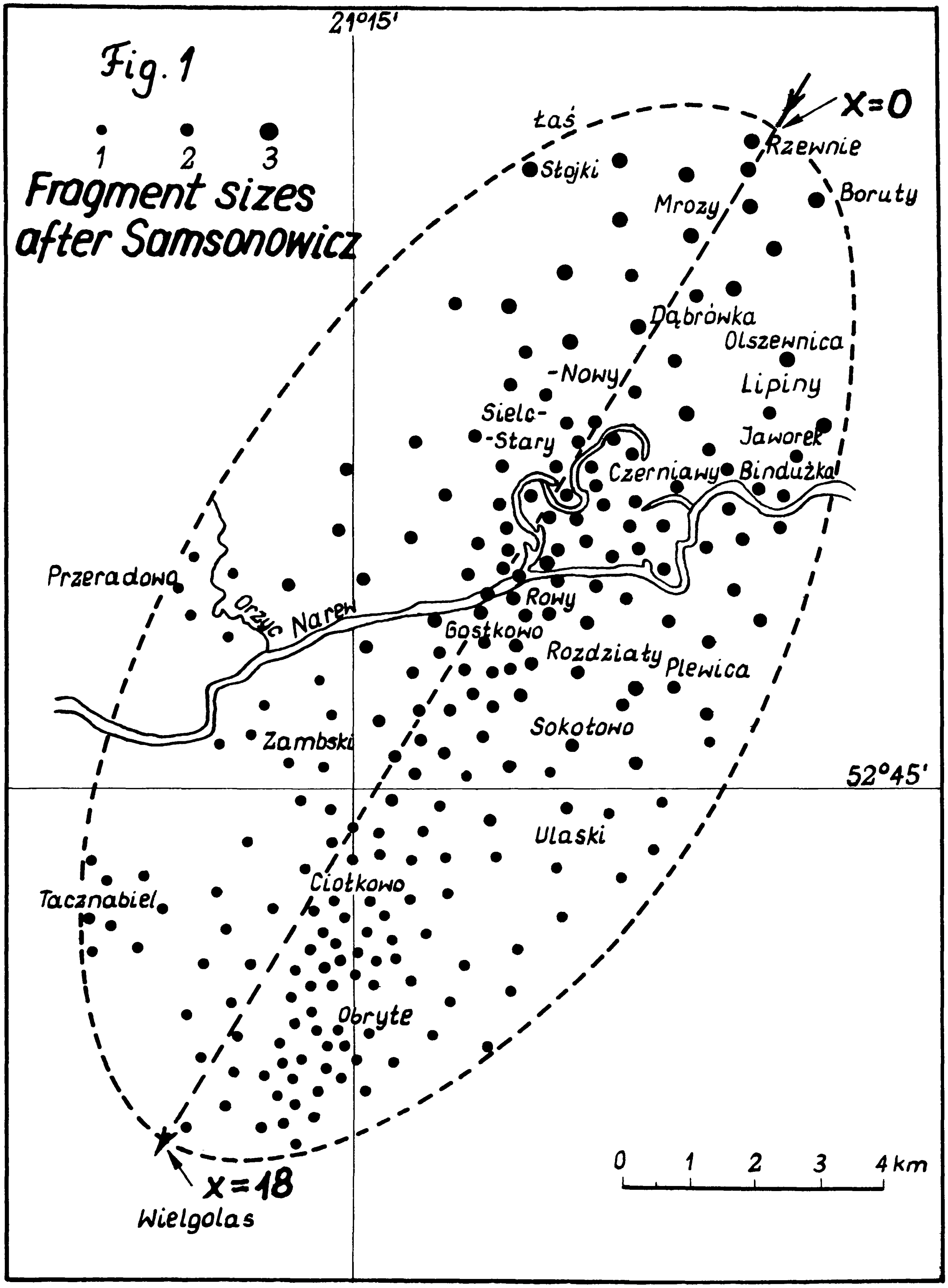

Fig. 1. The strewnfield of the Pułtusk meteorite shower 1868; The x-co-ordinate coincides with the main symmetry axis as indicating the direction of fall.

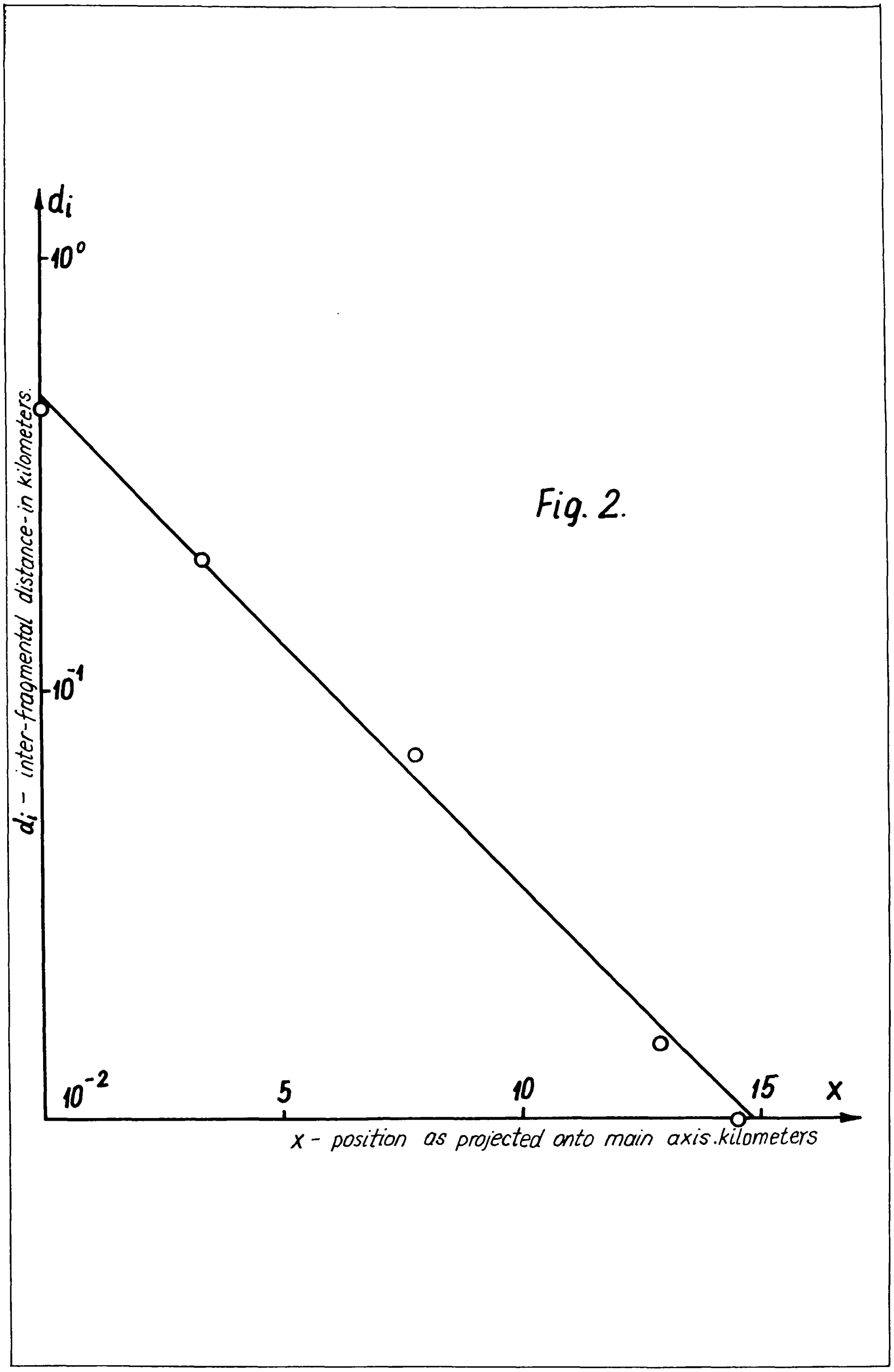

Fig. 2 Dependence of the inter-fragmental distances upon position of fragments as projected onto the main axis of the strewnfield.

dS(x) denotes the differential of the strewnfield surface, while the coefficient k(x) accounts for the transverse non-uniform fragment spacial density. This non-uniformity can be concluded from d values for Plewica, Przeradowo, and Tocznabiel, 0.10, 0.13 and 0.03 respectively, which are situated relatively far from central line when compared with the figures for places situated near the axis and showing a higher fragment spacial density, cf. Fig. 1. It seems reasonable to assume a constant normal transverse fragment distribution, leading to a coefficient $k(x) = \text{const} \approx 0.402$.

By integrating over the variability limits for the argument x one obtains the approximate value for N:

$$N = \int_{x_1}^{x_2} 0.77 \exp(0.53x + 1.49) \times 0.402 \times 2\frac{9}{2} \sqrt{1 - \left(\frac{x - \frac{18}{2}}{\frac{18}{2}}\right)^2}\, dx$$

$$\approx 12.18 \Big[I_{x,N} \Big]_{x_1}^{x_2}$$

where $I_{x,N}$ denotes the variable part of the integral.

Putting $x_1 = 0$ and $x_2 = 1, 2, \ldots, 18$ for integration limits, with the aid of GIER computer a set of values has been obtained. They are given in Table 4 and shown in Fig. 3.

In a similar way the total fragment mass can be approximated.

Assuming the validity of the sorting equation (Frost, 1969):

$$x = a - b \log M(x)$$

where a and b are constant for a given meteorite shower, while M(x), the mass of sorted single fragments, using the data of Samsonowicz and Pokrzywnicki, we have found for a and b the values of 18.0 and 4.55 respectively.

M(x) is equal

$$M(x) = \exp(9.12 - 0.51x)$$

The total fragment mass can be approximated by an integral

$$M = \int_{x_1}^{x_2} N'(x)\, k(x)\, M(x)\, dS(x) \approx 1.13 \times 10^5 \Big[I_{x,M} \Big]_{x_1}^{x_2}$$

where $I_{x,M}$ denotes the variable part. The values for $I_{x,M}$ and M have been tabulated in columns 5 and 6 of Table 4.

Our results, as compared with those of Samsonowicz, indicate a much higher value for the total fragment number N, equalling 18.0×10^4 vs. 5.31×10^4. The difference is due mostly to the large number of the smallest

Table 4

x_2	S(x) (km^2)	$I_{x,N}$	N	$I_{x,M}$	M (g)
1	2	3	4	5	6
1	2.7	0.429	5.45	0.31	3.54×10^4
2	7.7	1.685	20.7	0.89	1.00×10^5
3	13.9	4.36	53.5	1.63	1.84×10^5
4	21.1	9.57	117.4	2.51	2.82×10^5
5	28.8	1.93×10	237	3.49	3.93×10^5
6	37.1	3.69×10	453	4.57	5.15×10^5
7	45.7	8.82×10	836	5.73	6.45×10^5
8	54.6	1.23×10^2	1.57×10^3	6.96	7.83×10^5
9	63.5	2.18×10^2	2.68×10^3	8.23	9.27×10^5
10	72.5	3.79×10^2	4.65×10^3	9.55	1.08×10^6
11	81.4	6.51×10^2	7.99×10^3	10.98	1.23×10^6
12	90.0	1.10×10^3	1.55×10^4	12.22	1.38×10^6
13	98.3	1.84×10^3	2.26×10^4	13.54	1.53×10^6
14	106.1	3.02×10^3	3.71×10^4	14.82	1.67×10^6
15	113.1	4.86×10^3	5.97×10^4	16.03	1.81×10^6
16	119.2	7.59×10^3	9.3×10^4	17.11	1.93×10^6
17	124.4	1.13×10^4	1.38×10^5	17.99	2.03×10^6
18	127.3	1.47×10^5	1.80×10^5	18.51	2.08×10^6

fragments, which our method is giving for the end area of 14.2 km^2 (cf. Table 4), 68 percent of the total number being related to this partial area.

The above fragments were probably too small to be observed with the same precision like the larger ones; therefore, a majority of them could be overlooked. One can imagine, too, that minor attention had been given to these fragments when they were reported many years after the event. On the other hand, despite the difference in approach, the value for the area of 30 km^2, covered by the heaviest fragments, is in better agreement (~ 240 vs. ~ 170).

Another probability, however, cannot be excluded: a part of the originally smallest fragments did not reach the strewnfield at all, being earlier converted into particles of a dust. This could happen to the fragments with an initial shape – immediately after respective fragmentation step of the meteoriod body – sharply contrasting with the one leading to a spherical shape. The spherically shaped well-known "Pułtusk peas," recovered from Obryte, situated closely to the area, covered by the smallest fragments, seem to argue for such probability. If so, our value for N would be biased by a large

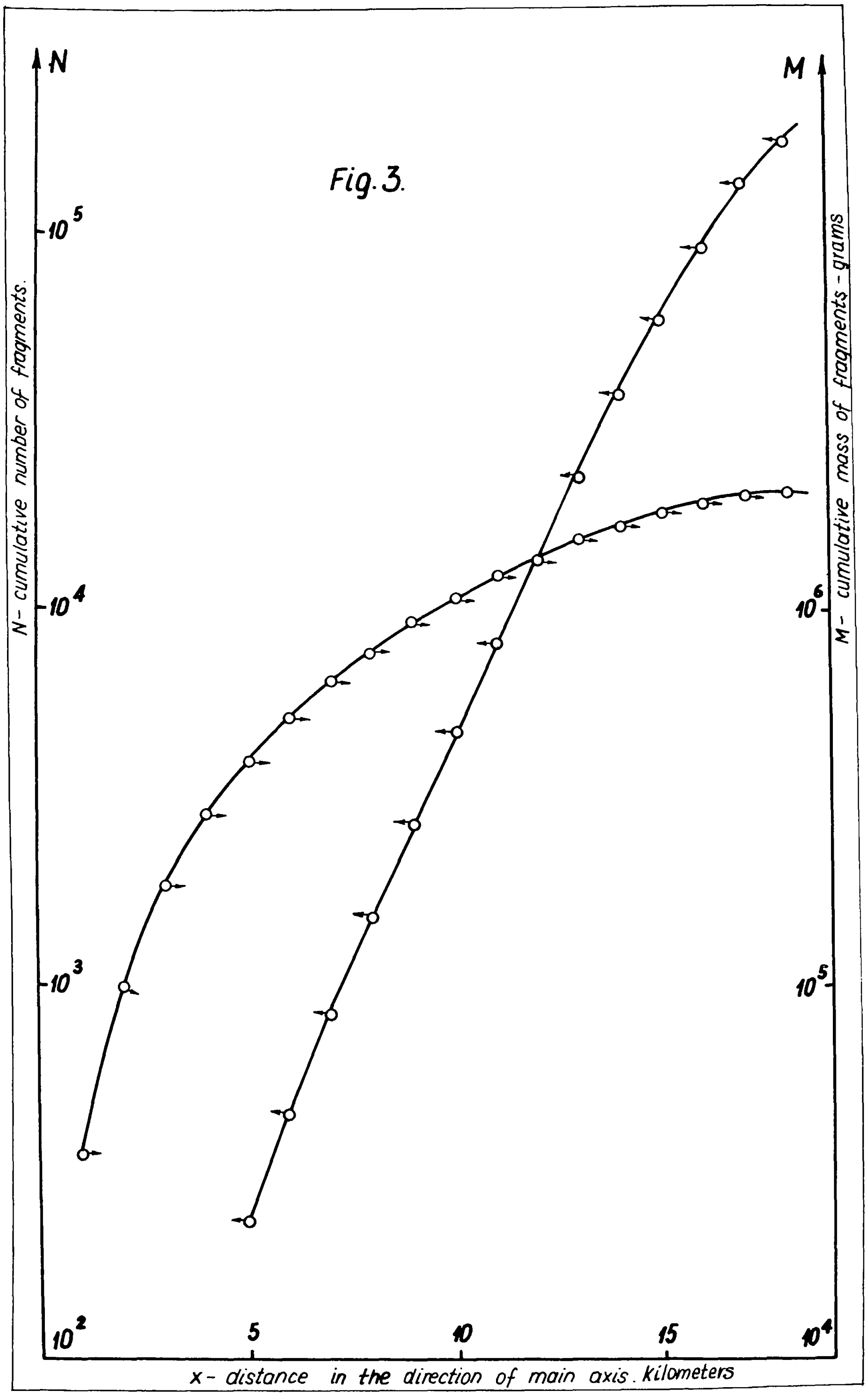

Fig. 3 The cumulative number N and the cumulative mass M (grams) of fragments from Pułtusk meteorite shower 1868 as dependent upon the upper limit of integration.

number of never fallen fragments. In such a case the elliptical shape of the strewnfield would remain unchanged.

As to the mass of fragments, our estimate of ~ 2 metric tons seems to be a satisfactory approximation low sensitive to the number of the smallest fragments, which do not exceed 13.5 percent of the total mass.

The averaging procedure adopted by Samsonowicz is responsible for both the exaggerated values and the considerable discrepancy from our estimate (8.65 vs 2.08 metric tons).

It seems to be an intriguing question to prove, what particle size distribution would be compatible with the pronounced elliptical shape of the Pułtusk meteorite strewnfield.

With the logarithm of fragment mass with minus sign for particle size being taken (Frost, 1969), a normal distribution against such random variables seems to be relevant while fitting the fragment spacial distribution by number and mass and accounting for both the sorting equation and the elliptical strewnfield shape. The normal distribution with logarithmic argument had been introduced by A. Kolmogoroff (1941), then applied to breakage of solids by B. Epstein (1948), and discussed by B. Beke (1964).

In the case of the Pułtusk meteorite shower the particle size, given by the sorting equation for the strewnfield ellipse midpoint, coincides with that one for the maximum of the probability density function as found with the use of normal probability paper.

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REFERENCES

Beke, B., 1964. Principles of Comminution. Akademiai Kiado, Budapest.
Epstein, B., 1948. *Ind. Eng. Chem.* **40**, 2289.
Frost, M., 1969. *Meteoritics* **4**, 217.
Galle, J., 1870. *Breslauer Ztg.* **8**, 7.
Kolmogoroff, A., 1941. *Dokl. Akad. Nauk SSSR* **31**, 99.
Neumayr, M., 1912. History of Earth. Warsaw. (Translation into Polish).
Olivier, C. P., 1925. Meteors. Waverly Press, Baltimore.
Paneth, F., 1937. *Nature* **140**, 504.
Pokrzywnicki, J., 1954. *Stud. Geolog. Polonica* **15**, 77.

Samsonowicz, J., 1952. *Wiad. Muz. Ziemi* **6**, 57.
Spencer, L. J., 1937. *Nature* **140**, 113.
Stenz, E., 1937. *Nature* **140**, 113.
vom Rath, G., 1869. *Neves Jahrb. Mineralogie* **80.**
Wülfing, E., 1897. Die Meteorite in Sammlungen und ihre Literatur, Tübingen.