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THE RATIO OF DEPRESSION AND MOUND VOLUMES: A PROMISING CRITERION FOR THE IDENTIFICATION OF SMALL METEORITE CRATERS

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Abstract. Apart from other morphometric characteristics, the approximate correspondence of the volumes of the excavation depression and ring mound is one of the important parameters for the identification of small meteorite craters. This parameter is particularly significant in the case of the craters with a diameter of 20—100 m, as usually the coarse clastic meteoritic material is already disintegrated during impact and the features of impact metamorphism are not sufficiently developed yet.

The Estonian experience of the study of Holocene meteorite craters has shown that the ratio of these volumes is relatively constant (0.6—1.4), not much affected by indirect factors, except for later human activity. The correspondence of the above volumes allows us to distinguish real meteorite craters from doubtful hollows of different genesis.

Key words: small meteorite craters, diagnostics of meteorite craters, Estonia.

INTRODUCTION

Small meteorite craters, with a diameter of less than 100 m, exist on the earth's surface only for a short period, as they usually get fixed in loose well-denudated Quaternary sediments without leaving permanent traces in solid bedrock. Therefore such craters have received less attention compared to the larger ones.

Anyway, small craters as well deserve to be registered and studied, as only in this way we can get a trustworthy picture about the frequency of medium-sized meteoritic bodies falling to the earth, also about the whole statistics of meteorite showers. The finds of small craters become more often from year to year, therefore their registration in recent or past-time sediments remains topical, and the crater diagnostics needs to be improved also in the future.

This concerns particularly the craters with a diameter of over 50 m. The shock energy of a cosmic body on the earth's surface is then big enough to cause complete dispersal of meteoritic material and its ejection from the crater depression. So, there is not much possibility left for the identification of the origin of the crater on the basis of direct finds of meteoritic matter. Such a regularity is well observed in the case of the Sikhote Alin meteorite shower of 1947 (Кринов, 1959). Unbroken meteoritic bodies occur here only in the funnels of up to 3.5 m in diameter, split pieces are found also in the depressions ranging up to 9 m in diameter. Greater depressions yield only dispersed pieces occurring on the crater slopes, in the mound material or already outside the crater. The same pattern holds generally also for the relatively well studied Kaali crater field of Estonia. Here meteorite pieces are most abundant in smaller craters (diameter 15—25 m), less numerous in larger ones and as yet not found in the main crater with a diameter of 100—105 m (Tiirmaa, 1994).

As the experience of Sikhote Alin has shown, the diameter 9—10 m is an essential parameter for classifying small meteorite craters into funnels and craters also in energetic sense. The forms, with a diameter exceeding that limit, are usually negative cone-shaped depressions in ground, having a regular concentric centre, i. e. they are real craters, the morphology of which does not show any more the bilateral or even asymmetric component, caused by the direction of the meteorite fall or inclination of the target slope. Shock energy is here already high enough for creating a spherical zone of influence.

Thus, proceeding from the aforesaid, we may state that it is very difficult to prove the meteoritic origin of the crater depressions with a diameter of a few tens of metres, as searching for meteoritic matter has here little perspective (considering also the decomposition of its dispersed variety in the course of time), but traces of impact metamorphism or melting of rocks, usually characterizing more powerful explosions, are missing here. Moreover, these craters are notably influenced by a high variability of the physical consistency of target rock, which causes great changes also in their morphological characters and outward nature, thus lessening the unifiability of the diagnostics of small meteorite craters.

EXPERIENCE OF THE STUDY OF SMALL METEORITE CRATERS IN ESTONIA

A relatively large number of meteorite craters, with the dimensions corresponding to the group considered, and their good study in Estonia (Fig. 1), may be of considerable help in improving the criteria for the identification of small craters. Continuing A. Aaloe's investigations in this direction (Аалоэ, 1972, 1979), we have repeatedly stressed the necessity of a complex morphometric analysis, which is successfully applied in the case of doubtful objects (Pirrus & Tiirmaa, 1984, 1988, 1990, 1991, 1994; Пиррус & Тийрмаа, 1985). At that the most essential parameters are the shape of the crater depression, the presence of the ring mound and its composition, the occurrence of horizontal deformations at the mound base, the location of meteoritic matter, approximate correspondence of the mound and depression volumes. The last one, the comparison of the total volume of mound material with that of the depression, has received too little attention in the practical investigation of terrestrial craters, although it is known as the so-called Schroeter's rule and has been applied by the study of the moon craters (Pike, 1967; Ударные . . ., 1983). In the earth craters these volumes should also be in approximate correspondence or shift systematically in one certain direction. Deviation of this parameter from the norm makes the meteoritic origin of a depression questionable.

In fact, the ratio of the volumes of the excavated depression and the surrounding ring mound is affected by a number of geological factors, which should be kept in view and the variability of which should be known when investigating meteorite craters of a definite origin. The experience obtained through the study of Estonian small craters helps to solve this problem.

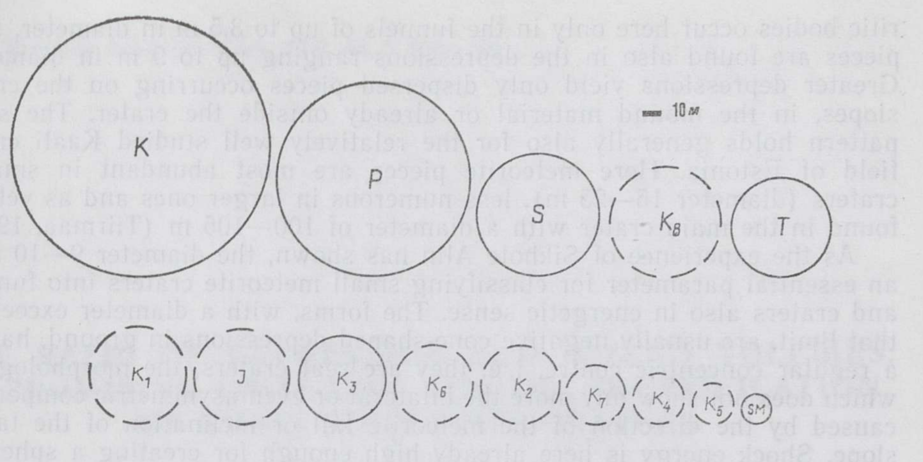

Fig. 1. Small meteorite craters of Estonia with a diameter of 9—100 m. Continuous line marks morphologically well preserved, dashed line strongly damaged craters. *K*, Kaali main crater; K_{1-8}, Kaali small craters; *P*, Ilumetsa Põrguhaud; *S*, Ilumetsa Sügavhaud; *J*, Ilumetsa Kuradihaud; *T*, Tsöörikmägi; *SM*, Simuna.

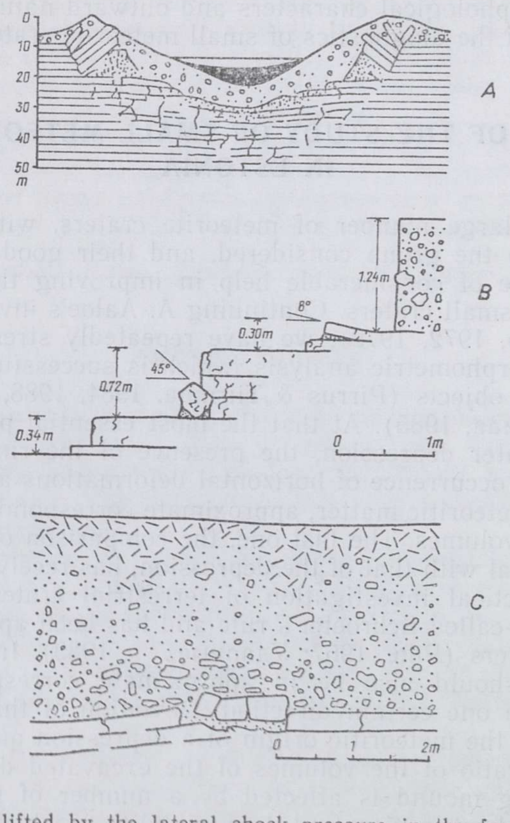

Fig. 2. The bedrock lifted by the lateral shock pressure in the foundation part of the mound: as notable uplifts in a larger crater (*A*, Kaali main crater, diam. 100 m); rare small blocks in satellite craters (*B*, Kaali crater No. 5, diam. 15 m; *C*, Kaali crater No. 7, diam. 22 m). After A. Aaloe's drawings.

THE FACTORS AFFECTING THE DEPRESSION AND MOUND VOLUMES

Instant transformation of the meteorite shock energy on the earth's surface or, mainly, at a certain depth, actually represents a process having typical impact parameters. The forces released momentarily proceed radially in all directions from the impact centre. When directed downwards, they cause the compression of rock mostly by nearing its components on the account of the pore capacity. However, considering the momentariness of the deformation and elasticity of the solid matter, the resulting increase of the depression volume cannot be more than 5—10% of the volume of the depression made by excavation. Keeping in view the opposite, crater base lifting action caused by the rarefaction following the shock, the distortion mentioned may be left unconsidered or treated as negative.

The ratio of the volumes is greatly distorted by lateral pressure, particularly by the force vectors directed slopewise to the earth's surface from the shock centre. Undispersed material, not ejected from the depression, is lifted into the foundation part of the mound in the form of blocks. The fracture caverns formed loosen the target rock and in this way the mound obtains extra volume compared to the excavation depression. The analysis of Estonian craters has shown that the foundation part (composed of rock blocks) is not typically present in small craters. Judging from the horizontal buried soil layer, the Simuna small crater (diameter 9 m) lacks completely the uplifted basal part. Also in Kaali small craters (No. 4, 5, 7, etc.), extending into dolomites, this deformation is expressed in the uplift of only some blocks under an angle of a few degrees on the inner slope or at the mound base (Fig. 2). To sum up, these processes do not increase notably the mound volume. In loose Devonian sandstones, as well as in the overlying Quaternary sediments, the uplifted part of the mound is not very well observed even in relatively large craters (Tsõõrikmäe — 40 m, Põrguhaud — 80 m), although plastic and rupture deformations referring to strong lateral pressure clearly exist here. The uplifted basal part of the mound is noteworthy only in the case of the Kaali main crater with a diameter of 100—105 m, where the elevated and exteriorly tilted large dolomitic blocks are well known (Аалоэ, 1963). However, we should bear in mind that the lifted blocks originate from the crater margin areas, therefore, above all, only the loosening factor accompanying the explosion must be taken into account. When assessing the maximum relative increase in the mound volume of the Kaali main crater on the account of the lifted and loosened basal part to be 20%, and considering the above-mentioned observations of the Simuna small crater as a zero level, we could compile an approximate theoretical correction chart for estimating this deviation by different crater sizes (Fig. 3). Thus, this deformation factor should first of all be considered by the investigation of larger craters and mainly in the circumstances when target rock is represented by the bedrock yielding large solid blocks.

So, the ratio of the depression and mound volumes is still predominantly determined by the force vector directed upwards. The destruction of rocks and the scattering of destruction products into the air column shape the most significant features, the excavation depression itself and the surrounding strewing mound. Undoubtedly, the surface of the target rock becomes loosened and this should bring about considerable increase in the mound volume, although part of the material ejected into the air falls back into the crater depression, in this way somewhat smoothing the contrast in mound and depression volumes. The loosened structure of the ejecta mound was observed also during the digging performed at the Tsõõrikmäe crater. The mound could hardly be visually distinguished from the target rock, represented by till, and from unsorted deposit formed of it, but the boundary between them was well felt under the spade. Unfortunately, at that time the volume weights and porosity of these rocks were not directly measured, which could have permitted to assess the phenomenon also quantitatively.

From the abovesaid we may conclude that the loosening caused by the redeposition of the material should always result in certain predominance of the mound volume over the depression volume. In Estonia, this is observed in several well-preserved small craters (Table). The phenomenon is quantitatively characterized by the ratios 1.00—1.45, which, as a rule,

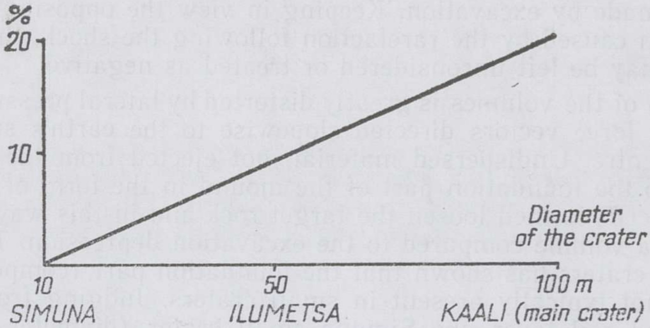

Fig. 3. Supposed increase of the mound volume on the account of the lifted basal part depending on the diameter of the crater (in per cent with respect to the volume of the crater depression).

Relation of the depression and mound volumes in small meteorite craters of Estonia and some similar to them glacigenous structures

Crater	Age, yr	Depression volume, m³	Mound volume, m³	Ratio of the mound and depression volumes	Dimensions of the crater: Diameter (d), m	Dimensions of the crater: Depth (h), m	Index h : d
Kaali	3500						
Main crater		22520	13780	0.61	100	22	1:4.5
No. 1	„	1156	314	0.37	38.5	3.3	1:11.6
No. 2/8		1893	1875	0.99	55.7	4.6	1:12.1
No. 3		1263	215	0.17	40.5	3.6	1:11.2
No. 7		99	20	0.20	22	1.8	1:12.2
Ilumetsa	6000						
Põrguhaud		6523	6613	1.01	76	9	1:8.5
Sügavhaud		1483	2011	1.36	47.2	5.5	1:8.8
Tsõõrikmäe	9500	2100	3050	1.45	40	5.8	1:6.8
Simuna	55	18.2	13.5	0.74	8.9	1.9	1:4.7
		Glacigenous structures					
Sapi		12000	26000	2.2	100	9	1:10
Ronga		8700	48000	5.6	115	11.3	1:10

seem not to depend on the age or size of the crater or on the target rock. Still, in a number of cases the mound volume is somewhat smaller than that of the depression but close to it anyway (Kaali main crater, Simuna — 0.6—0.7).

Such a correspondence of volumes with theoretical considerations even in old craters definitely refers to relatively small importance of the opposite factor: partial transportation of ejecta away from the crater field at the moment of the explosion or by later erosion. The total amount of fine particles, carried away by wind during the explosion, seems to be too small to notably reduce the volume of the mound formed. Certain inhibiting effect is evidently exerted by low height of the dust column thrown into the air during the formation of small craters. Later erosion of the mound must certainly be taken into consideration, but this is also surprisingly modest, and moreover refers theoretically to the approaching of mound and depression volumes. Of certain importance seem to be here the rapid appearance of the erosion-checking plant cover in the temperate climate zone, as well as the methods used for the determination of the mound volume. If, like in our calculations, we take for the exterior boundary of the mound the last isohypse, closing concentrically around the crater (Fig. 4), we have to do already with the mound zone, partly levelled during more recent processes. Most of the denudation products are not transported out of this zone.

Considerable transport of the material out of the crater area is in Estonia observed only in the largest, Kaali main crater (100—105 m). Here the volume of the mound is much smaller compared to that of the depression, although the results expected should be contrary due to the uplifted and loosened basal part. The answer to this question can be obtained through the analysis of the surrounding topography close to the crater. According to the plan of detailed sounding compiled by Reinwaldt (1928), the main crater is situated on a NW—SE ridge, with a diameter of 200—500 m, which rises higher above the surrounding area for 1—1.5 m and may have formed on the account of the material ejected out of the crater. Keeping in view a higher impact energy during the formation of this crater, the dust column was very high here, and therefore became naturally dispersed over a wider area.

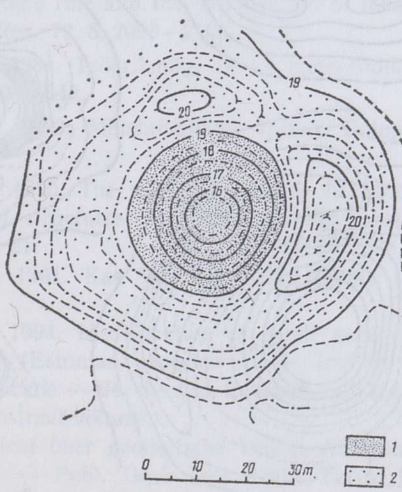

Fig. 4. Ilumetsa Süvahaud. An example of determining the mound volume basing on a detailed topographical plan. Close hatching shows the depression, sparse hatching marks the mound area. The boundary coincides with the last, 19 m isohypse, closing concentrically around the mound.

CONCLUSIONS

The correspondence of the depression and mound volumes (with certain deviation in favour of the mound) is a significant criterion for the identification of craters, above all those with a diameter of 20—100 m. In the case of smaller craters the measuring accuracy of volumes may serve as an inhibiting factor, by the identification of larger craters (over 100 m in diameter) additional parameters must be considered: the lifted basal part, dispersal character higher above the ejecta column, etc. Anyway, great variation of volumes needs to be specially studied. In Estonia, this has been successfully used by the investigation of several ring structures, which have later turned out glacigenous (Pirrus & Tiirmaa, 1988). The abovesaid permits us to make also a practical suggestion: by investigating

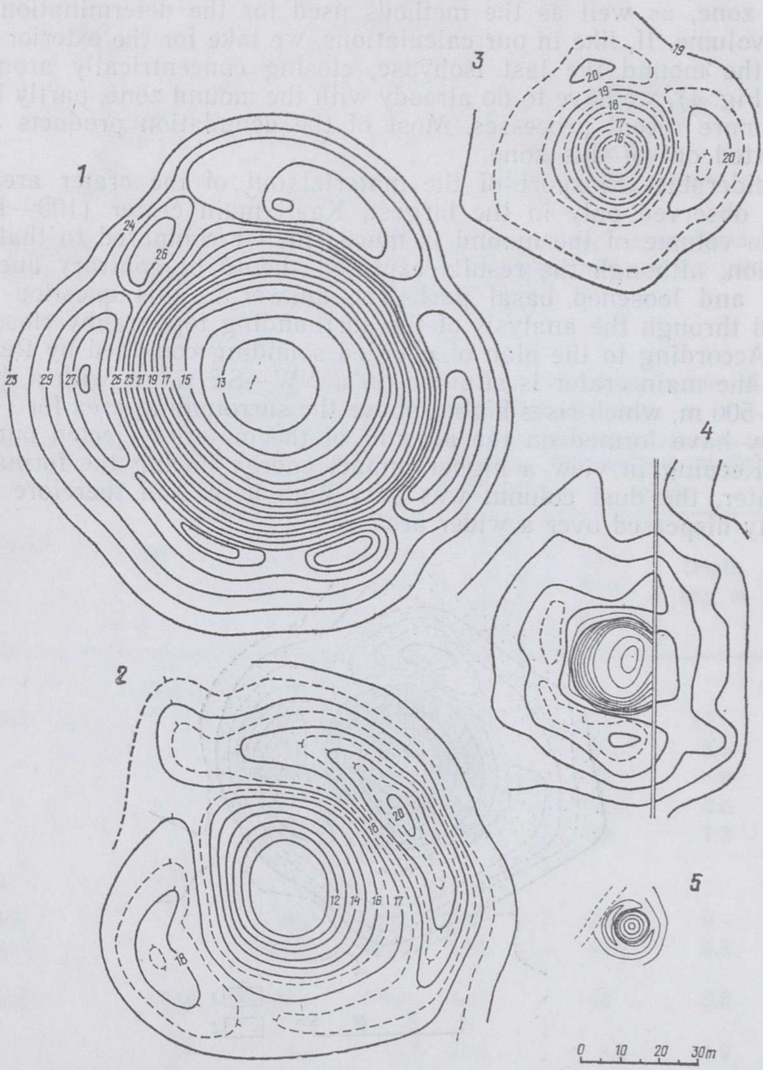

Fig. 5. Morphologically better preserved meteorite craters of Estonia (in comparable measure). *1*, Kaali main crater (100 m); *2*, Ilumetsa Põrguhaud (76 m); *3*, Ilumetsa Süvahaud (47 m); *4*, Tsõõrikmägi (40 m); *5*, Simuna (9 m).

a doubtful structure it is necessary to perform a thorough morphometric analysis, preferably basing on a detailed plan of levelling (Fig. 5). The last one is the most important link by the identification and documenting of small craters and it must necessarily be drawn before the excavations for searching for meteoritic material are started. Unfortunately, often the process of investigation is contrary. This lessens the information obtained for improving the structural-morphological diagnostics of namely small craters.

The analysis of volumes is surely affected by later human activity, which is well expressed at Kaali, particularly in small craters surrounding the main crater. 3500 years of agriculture have caused the levelling of mounds, filling of crater depressions with field rocks, thus making the corresponding analysis in several cases impossible. Undesirable human influence may essentially damage the crater morphology even during a few days after the formation of a recent crater, as has shown the experience of the Sterlitamak crater in Bashkiria (Petaev et al., 1991; Петаев et al., 1992). In unspoiled landscape, however, the corresponding parameter, the volumetric index, should always be pointed out. It serves as a convincing argument for the establishing of the impact origin of a structure.

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SÜVENDI JA VALLI MAHU SUHE KUI LISAPARAMEETER VÄIKESTE METEORIIDIKRAATRITE DIAGNOSTIKAS

Enn PIRRUS

Meteoriidikraatrite diagnostikas on teiste morfomeetriliste parameetrite kõrval kaalukaks argumendiks kraatrisüvendi ja ringvalli ruumala ligilähedane vastavus. Ruumalade võrdlemine on jäänud väikekraatrite identifitseerimisel põhjendamatult tagaplaanile. Eriti tähtis on see näitaja 20—100-meetrise läbimõõduga meteoriidikraatrite identifitseerimisel, sest meteoriidi väikese põrkeenergia tõttu puuduvad neis veel löögimetamorfismi tunnused, meteoriidiaine leidmine on aga juba väheperspektiivne.

Eestis uuritud sellise suurusjärgu kraatrite keskstüvendi ja ringvalli maht on heas vastavuses (0,6—1,4), mis näitab kõrvaltegurite suhteliselt väikest mõju selle suhte kujundamisel. Erandiks on vaid inimtegevus, mis kraatri morfoloogiat tugevasti moonutab.

Nimetatud suhtvahekord võimaldab meteoriidikraatreid edukalt eristada liustikutekkelistest lohkvormidest.

СООТНОШЕНИЕ ОБЪЕМОВ ЦЕНТРАЛЬНОГО УГЛУБЛЕНИЯ И ОКРУЖНОГО ВАЛА — ДОПОЛНИТЕЛЬНЫЙ ПАРАМЕТР В ДИАГНОСТИКЕ МАЛЫХ МЕТЕОРИТНЫХ КРАТЕРОВ

Энн ПИРРУС

При диагностике небольших метеоритных структур рекомендуется использовать наряду с другими морфометрическими параметрами соотношение объемов центрального углубления и окружного вала, что легко осуществимо при наличии детального топоплана кратера. Этот показатель особенно информативен для кратеров диаметром от 20 до 100 м, в которых шансов для нахождения сохранившегося метеоритного материала мало, а проявления ударного метаморфизма развиты еще слабо.

Опыт изучения метеоритных кратеров такой размерности в Эстонии демонстрирует устойчивость этого критерия, в частности при различении метеоритных кратеров от сходных структур гляциогенного происхождения. Другие явления, сопровождающие удар метеорита, мало влияют на рассматриваемое соответствие объемов. Наибольшие его искажения обусловливает деятельность человека.