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THE KAALIJÄRV METEOR CRATERS (ESTONIA)

SUPPLEMENTARY RESEARCH OF 1937; DISCOVERY OF METEORIC IRON

BY

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supplementary research of 1937; discovery of meteoric iron.

by I. A. Reinvald, mining engineer, inspector of mines.

(Tallinn, Estonia).

Acknowledgements.

I consider it my pleasant duty to express my deep appreciation to the Commander-in-Chief general J. Laidoner, for having enabled me to illustrate this paper with photographs of the region from an aeroplane, and also to Captain M. Sukk who succesfully took them.

Abstract.

In the article are described the conditions under which, during the exploration of the fragmentary masses filling craters Nr. 2 and Nr. 5 in the summer of 1937, meteoric iron was discovered in the Kaalijärv group (Saaremaa = Ösel, Estonia).

In the beginning of the article a classification of meteor craters discovered up to the present on the earth's surface according to geological conditions on the spot of their formation is proposed and the position of the Kaalijärv group among them is ascertained.

For the convenience of the exposition the results of the author's previous explorations in 1927 and 1929 are stated in brief.

Preface.

The fall of meteorites being a common cause for the formation of meteor craters, the craters themselves differ from one another according to the difference of geological conditions on the spot. From this point of view the meteor craters (fig. 1) so far discovered on the earth's surface may be divided into the following groups *).

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*) Dr. L. J. Spencer. "Meteorite Craters as Topographical Features on the Earth's Surface" (The Geographical Journal, vol. LXXXI no. 3, March 1933).

Fletcher Watson JR. "Meteor Craters" (Popular Astronomy, vol. XLIV, no 1, January 1936).

A. Craters the meteoric origin of which is considered to unproved:

1. The crater near Gwarkuh (Persian Baluchistan) (d = 36—45 m.), formed in the loose (alluvial?) deposits, has been little explored and has completely lost its original form,

2. The Ashanti crater (Bosumtvi Lake, N. W. Africa) (d = 6½ miles) formed in the Pre-Cambrian phyllites and

3. Carolina Bays (South Carolina U. S. A.) — an interesting group of craters of an elliptical and round form with diameters ranging from a few metres to 2,5 kilometres, excavated in the Waccamaw formation of the Pliocene age.

B. Craters the meteoric origin of which proved.

I. Formed in desert sands:

4. The Wabar group (Rub'al Khali, Arabia) (d = 40—100 m); country rock, lying under the sands, has not been established by exploration.

II. Formed in swamps lying on permanently frozenclay:

5. The Siberian group of craters (Podkamennaja Tunguska), formed by the fall of a swarm of meteorites on the 30th June 1908; the largest of the discovered craters has a diameter of 50 m.

III. Formed in sandy loess.

6. A group of craters (los hoyos) Campo del Cielo (Argentina); the diameter of the largest crater is 65—78 m.

IV. Formed in the soil (?)

7. Crater of an elliptical form (17 m. × 10,7 m.) near Haviland (Kansas, U. S. A.).

V. Formed in horizontally lying sedi.m.e,n,-tary rocks.

8. The "Meteor Crater" of Arizona (d = 1200 m.) formed in limestone and sandstone.

9. The Odessa Crater (Texas; d = 160 m.), formed also in limestone and sandstone.

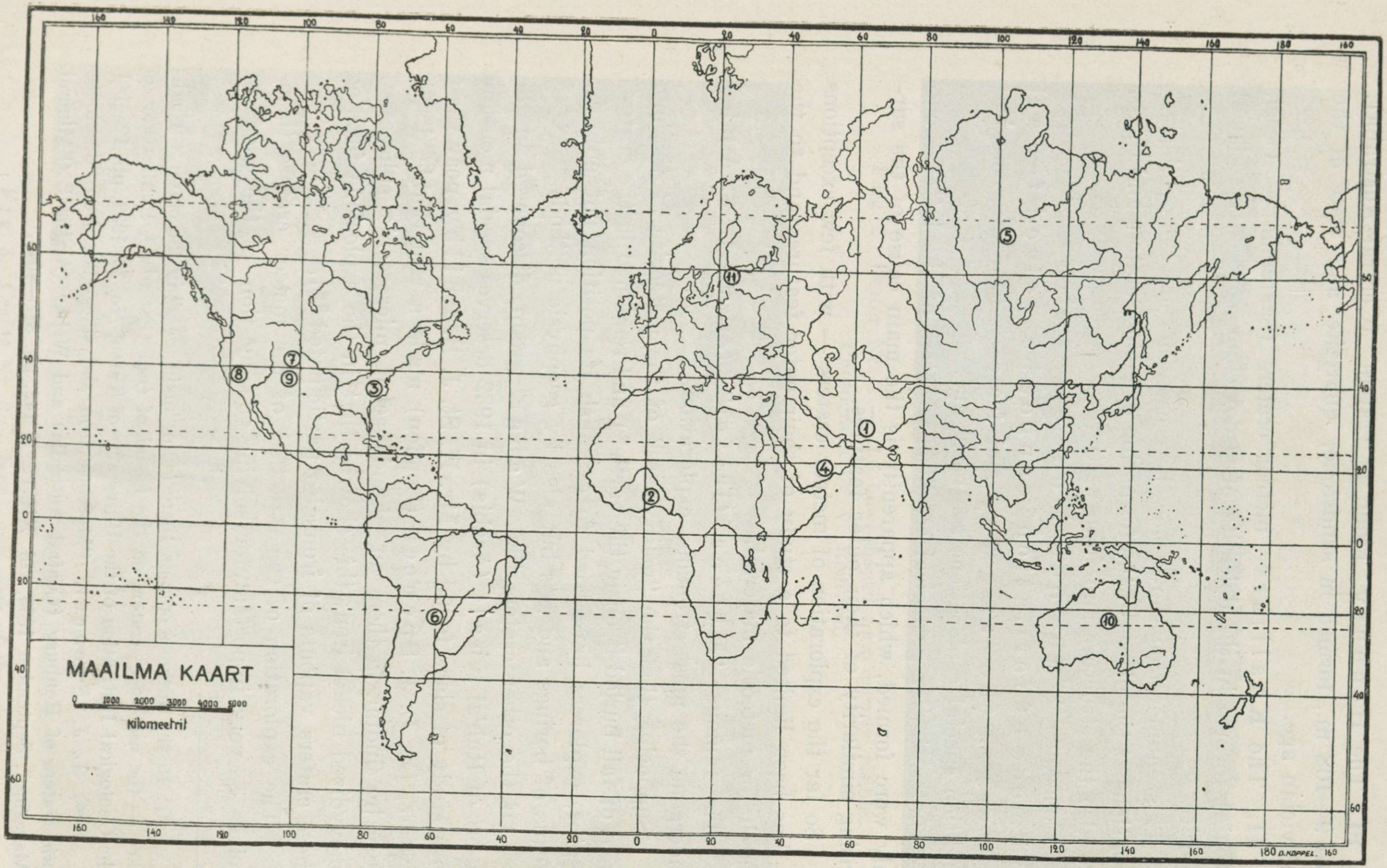

Fig. 1. Distribution of the meteor craters on the earth's surface: 1. Gwarkuh, 2. Bosumtwi Lake, 3, Carolina Bays, 4, Wabar, 5. Podkamennaja Tunguska, 6. Campo del Cielo, 7. Haviland, 8. Arizona, 9. Odessa (Texas), 10. Henbury, 11. Kaalijärv.

10. The Henbury group of craters (Central Australia), d = 9—108 m., formed in sandstone, quartzite and slate of the Ordovician age.

11. The Kaalijärv meteor craters (Saaremaa = Oesel, Estonia) formed in the dolomite of Ordovicium, covered by glacial deposits.

This enumeration shows how heterogeneous are the geological conditions at the places of the formation of meteor craters and therefore also the structure and form of the craters themselves.

Consequently the question of their structure and mode of formation cannot be solved for all craters in the same way and for each type of geological condition special explorations are necessary.

Under similar geological conditions craters of the latter group only were formed, which apparently is the main cause of the surprising similarity of their outer features.

So far the exploration of meteor craters — with few exceptions — has been limited to a study of their outer features and to the search for meteoric material.

The famous "Meteor Crater" (Arizona U. S. A.) has undergone the most strenuous exploration.

Supposing that the "main mass" of the meteorite at the moment of fall buried itself in the earth *) and remained in the crater's depths, explorers have tried to establish its position not only by means of borings and pits but also by geophysic methods.

Of the other craters the Wabar group, discovered in the desert of Rub'al Khali (Arabia) in 1932 deserves special mention. In a study of slags found by Mr. H. St. J. B. Philby near these craters, Dr. L. J. Spencer (London) made a remarkable discovery by finding in them an abundance of microscopic spheres of unoxydized nickel iron; this showed that in the explosions forming these craters vapours of iron also participated **).

The exploration of the structure of the meteor craters themselves — very important for solving the question of the mode of

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*) In the author's opinion there is no "main mass" in the crater ("Kaalijärv — the meteorite craters on the island of Ösel (Estonia)". Publications of the Geological Institution of the University of Tartu, No. 30. 1933, pp. 12—14).

**) L. J. Spencer, "Meteoric iron and silica-glass from the meteoric craters of Henbury (Central Australia) and Wabar (Arabia)" ("Mineral. Magazine", September 1933, vol. XXIII, N 142, pp. 387—404).

Fig. 2. Crater Nr. 3 — the bowl-shaped form clearly visible.
Photograph by V. Reinvald.

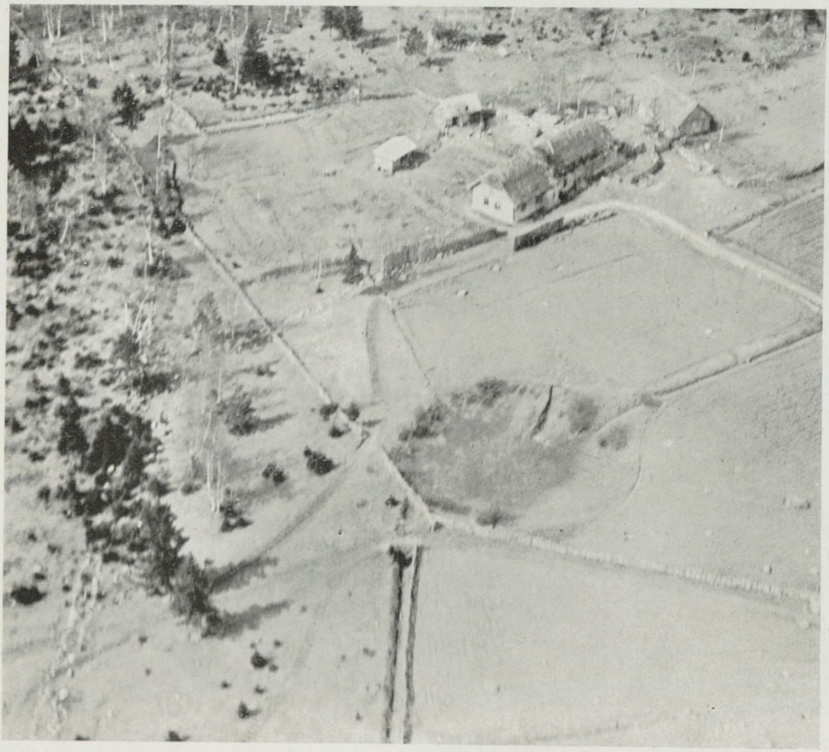

Fig. 3. Crater Nr. 3 — bird's eye view of the crater.
Photograph by Estonian Air Defence.

F i g. 4. View of K a a l i j ä r v group from an aeroplane (1500 m.); K.j. — the main crater; 1—6 — small craters.
Photograph by Estonian Air Defence.

their origin — by means of corresponding excavations so far have been made at two points only: 1) by the author at the Kaali-järv group on the island of Saaremaa (= Oesel, Estonia) in 1927 and 2) by Dr. H. H. Nininger at the Haviland Crater (Kiowa County, Kansas U. S. A.) in 1933. It is very important to note that both the structure of the craters and the disposition of the meteoric material proved to be different in both craters: the form of the original bottom of the craters of the Kaalijärv group is round and bowl-shaped (explosion craters) (fig. 2, 3), while the bottom of the Haviland crater is elliptical and has a conical form (impact crater) *); fragments of the meteoric iron in the Kaalijärv craters are sporadically distributed in the loose mass filling the craters, but in the Haviland crater they lie in a thin layer on the original bottom of the crater and are covered by layers of soil washed in later.

A comparatively larger possibility of comparison opens for craters Nos 8—11, i. e. for the craters of Arizona, Odessa (Texas), Henbury and Kaalijärv; this latter owing to its accessibility, small dimensions and excellent preservation occupies among them quite an exceptional position and is very convenient for establishing the conditions of formation. Exploration work in this group was carried out by the author in 1927, 1929 and 1937. —

Summary of explorations made before.

The craters of the Kaalijärv group (fig. 4) lie 20 kilometres to the North—East of Kuressaare (Arensburg) on the Island of Saaremaa (= Oesel, Estonia) and are situated amidst tilled fields on an area of approximately ¾ klm. The question of the formation of this group has been discussed in scientific literature

*) H. H. Nininger and J. D. Figgins "The Excavation of a Meteorite Crater near Haviland, Kiowa County, Kansas". (Proceedings of the Colorado Museum of Natural History. Vol. XII; no. 3, Nov. 1933). Based on facts established by the authors one may admit that the Haviland Crater was formed owing to the impact of a meteorite not followed by an explosion. The meteorite (pallacite) shattered at the impact and its fragments flew in the direction of the conical surface of the bottom. Fragments which obtained a lesser velocity remained at the bottom of the crater, whereas the fragments which had obtained a greater velocity flew out of the crater limits and fell on the surface around the crater where they were found. Later the crater was filled with material chiefly washed into it by atmospheric waters.

since 1827 but its meteoric origin was not established until 1927 *). During this investigation not only the formerly known outer peculiarities of the craters were studied but by excavation the dolomite bed of the craters was laid open and studied as well.

This exploration showed that the craters of the group are round bowl-shaped hollows formed in the horizontally lying layers of dolomite, covered by approximately 1 m. of clay-sandy glacial deposits.

In the upper part of the interior slopes of the explored craters broken edges of the dolomite strata dipping away from the centre at different angles are observed. The rim of the main crater (lake Kaalijärv) (fig. 5) rises 6—7 m. above the neighbouring country. Under the huge fragments in the middle of the inner slope lies a belt of crushed dolomite; in the main crater it looks like a powder containing fragments of burned soft dolomite; in other craters it was found that the smaller the crater the coarser the crushing.

The dolomite bottom of the crater has a step form (Main Crater, Nr. 1, Nr. 4). On the lower platform of the bottom — near its western rim — a small (d. = 0,5 m. at a diameter of the crater (Nr. 4) = 20 m.) blind oval funnel-shaped hollow was discovered; the bottom of the crater around this hollow is smashed and burned.

The craters are filled with fragments of dolomite mixed with the material of glacial deposits.

These facts gave ground for presuming that the craters were formed by explosions accompanying the fall with great velocity of comparatively small meteorites.

At the moment of impact there were released corresponding amounts of heat causing the heating of dolomites and an unavoidable instantaneous turning into steam of the water contained therein (moisture of the dolomite, ground water); explosions followed forming craters. At this moment not only fragments of dolomite and glacial deposits were thrown out but the very meteorites obviously shattered into more or less small fragments under the influence of the simultaneous action of the impact and the explosion. After the explosion the masses thrown out fell back partly into the crater partly on to the surrounding surface.

In 1929 the author had the opportunity of spending two days in the supplementary exploration of the shattered and burned bot-

*) J. Reinvald, „Bericht über geologische Untersuchungen am Kaalijärv (Krater von Sall) auf Oesel“, mit Beiträgen von A. Luha. Publications of the Geological Institution of the University of Tartu Nr. 11, 1928.

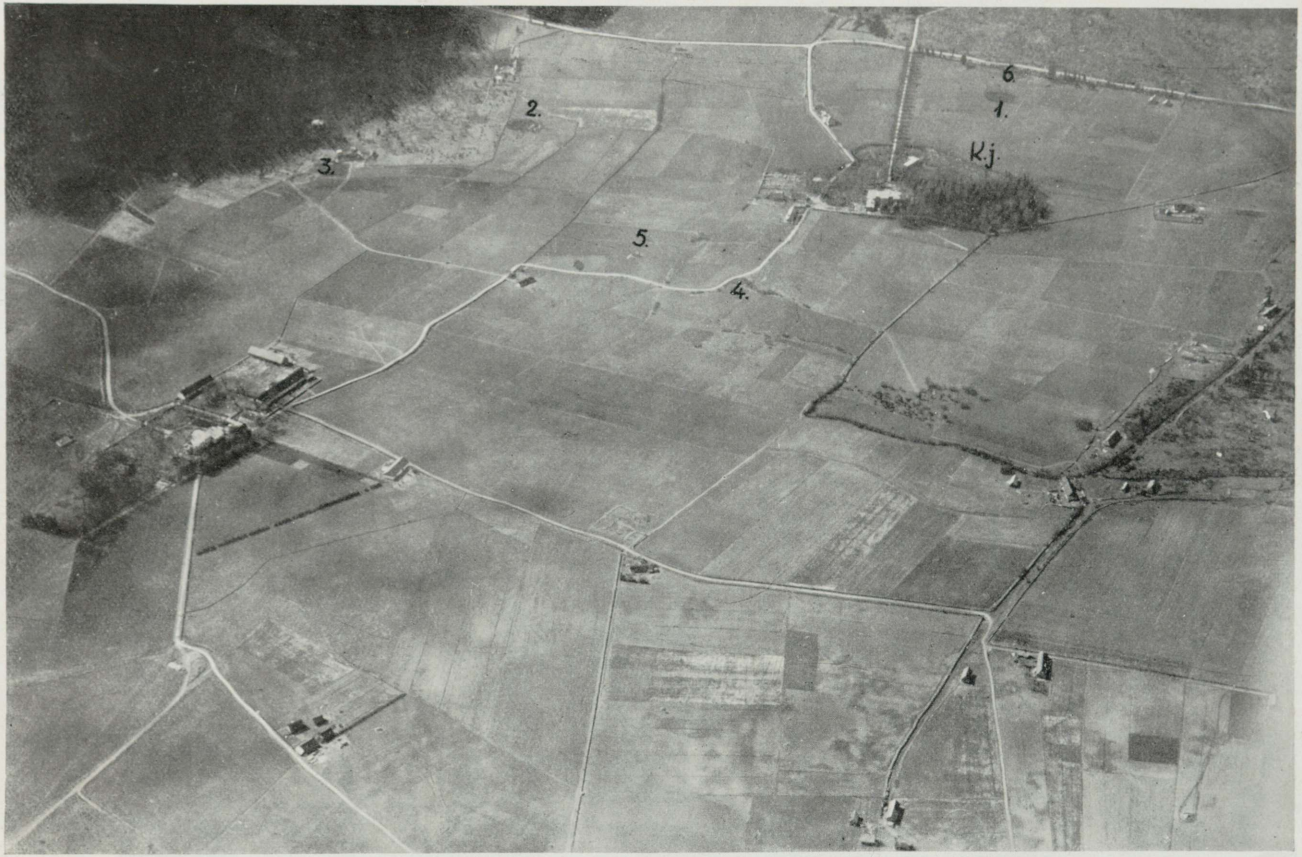

Fig. 4 — a. View Kaalijäry group from an aeroplane (1500 m.); K.j. — the main crater; 1—6 — small craters. Photograph by Estonian Air Defence.

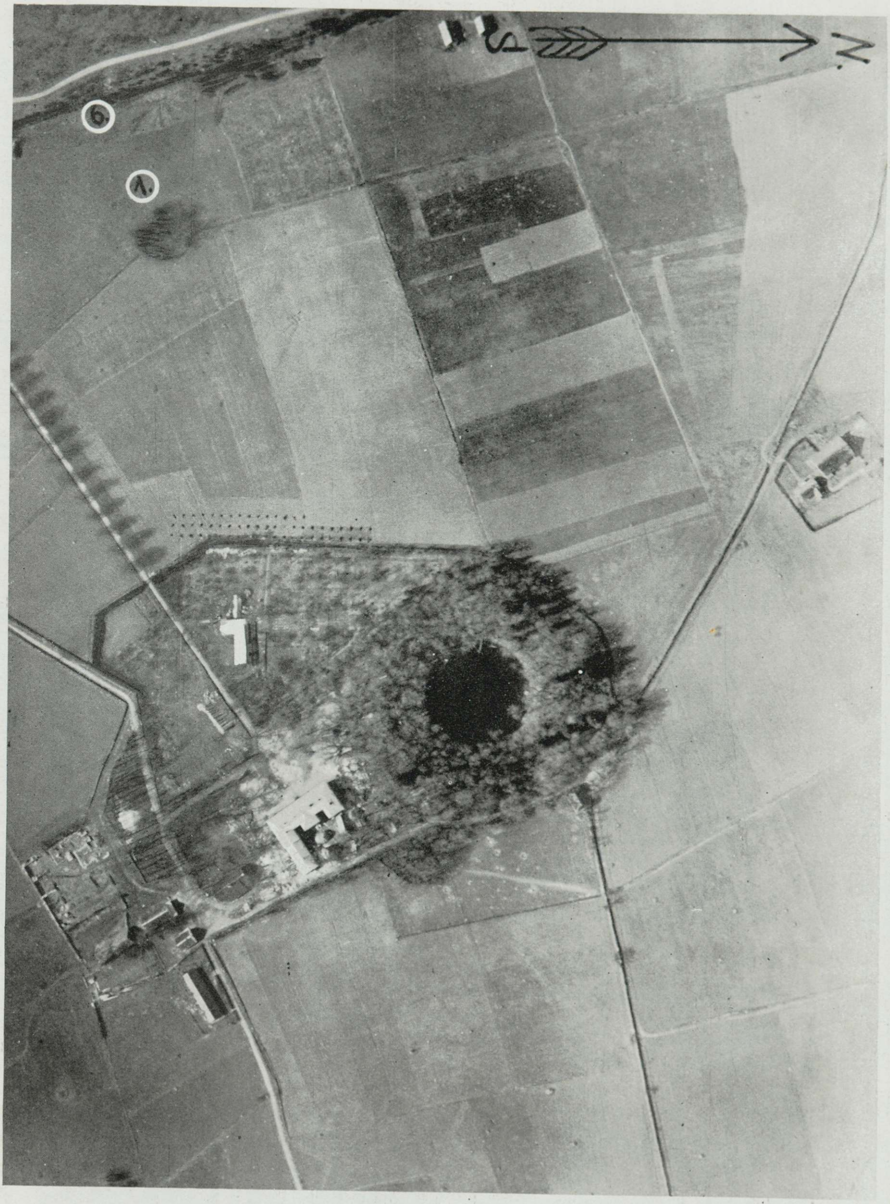

Fig. 5. The Kaalijärv meteor crater — from an aeroplane (1000 m) — craters Nr. 1 and Nr. 6 visible.

Photograph by Estonian Air Defence.

tom of crater Nr. 4 considerably damaged by climatic conditions and the curiosity of visitors.

During this exploration *) it was established that the crater was formed only on the surface of the dolomite massive; diamond boring showed that the dolomite was shattered and burned — totally or partly — to a depth of 4—5 m. and underneath lies the normal fresh rock.

In studying the considerably damaged hollow of impact it appeared that the thin layers of marl contained in the dolomite forming the lower — shattered and burned — platform of the bottom are sharply bent down in the hollow of the impact, i. e. this cavity is the result of mechanical action.

It is important to note that the dimensions of the body which made the impact, i. e. the meteorite (d — not exceeding 0,5 m) are considerably less than the dimensions of the crater itself (d = 20 m.).

The sharpness and clearness of the trace of the impact gave cause to presume that the meteorite was an iron one.

No remains of fallen meteorites were found here either in 1927 or in 1929.

Where to look for meteoric iron?

Although in the opinion of the author the characteristic peculiarities of the dolomite bed of the craters found during the above explorations appear to be quite sufficient not only as proof of the meteoric origin of the craters of the Kaalijärv group, but also for the establishment of the mode of their formation, it was nevertheless very interesting to find also remains of the meteorites and thus finally to clear up the whole matter.

The author did not obtain the possibility of taking up this work until 1937.

The abovementioned description of the process of the formation of the craters by an explosion makes it quite obvious that the remains of meteorites must lie amongst the fragmentary mass thrown out of the craters by the explosion and at present covering both the bottom of the craters and the surrounding country.

The meteoric origin of other craters of the same type discovered in localities untouched by civilisation was established by the

*) I. A. Reinvald "Kaalijärv — the meteorite craters on the island of Oesel (Estonia)" (Geological Instution of the University of Tartu Nr. 30, 1933).

finding of fragments of meteoric iron on the surface of fragmentary masses lying around the craters. Undoubtedly this evidence was at hand in the Kaalijärv group immediately after its formation, but from the time this district began to be tilled the upper part of the fragmentary masses was turned into a cultivated layer and the remains of the meteorites lying on the surface disappeared.

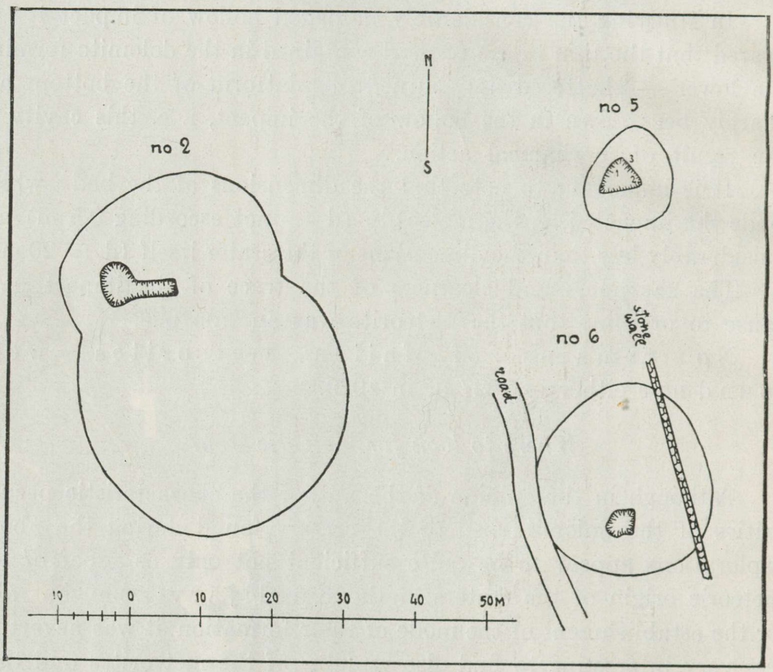

Fig. 6. Contours of the craters excavated in 1937.

Naturally the remains of meteorites must still exist in the untouched part of these masses. From the moment of the formation of the craters only that part of the fragmentary masses lying in the craters remained quite untouched, and it was therefore decided to undertake its exploration.

The two smallest craters were chosen for the study: the smaller part of the double crater Nr. 2 (d = 30—32 m.) and the smallest crater Nr. 5 (d. = 12—15 m.). During excavation work the survey of the contours of both the craters and the boundary of the excavated area was made by means of a geologist's compass and pocket steel tape (fig. 6).

Fig. 7. Crater Nr. 2 overgrown by trees (July 1936).
Photograph by dr. Clyde Fisher (New York).

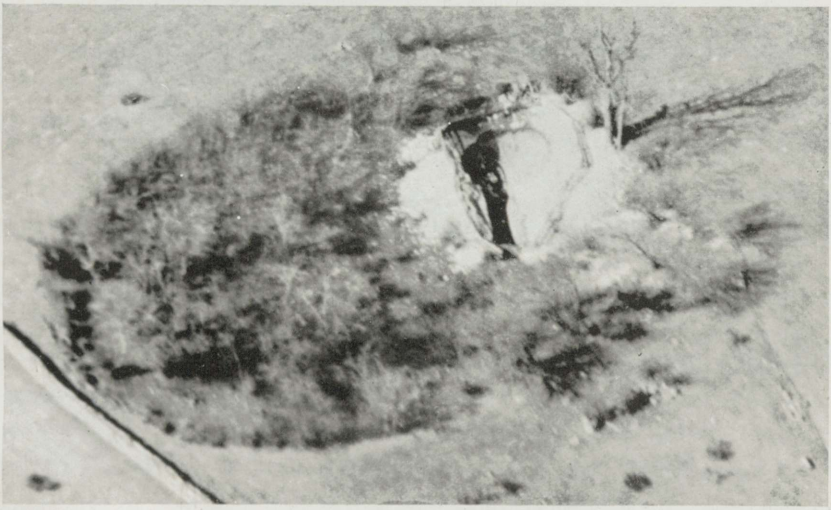

Fig. 8. Crater Nr. 2; view from an aeroplane (April 1938; a tall tree seen at left on fig. 7 — to the right of the spot of excavation).
Photograph by Estonian Air Defence.

Fig. 9. Section of the fragmentary mass filling crater Nr. 2.
Photograph by V. Reinvald.

Results of excavations.

The excavations gave following results.

Crater Nr 2 (double, fig. 7).

Place of excavation. The excavation was commenced from the centre of the lesser part of the crater towards the west in the form of a test-pit (2 m. × 10 m.) which was then enlarged mainly toward the North (fig. 6, 7, 8).

The excavation was made up to the dolomite bottom of the crater which is here at a depth of 2 metres.

Thus approximately 80 cub. m. were excavated.

Fragmentary mass filling the crater. On the surface of the loose mass filling the crater there has formed a layer of soil 10—15 cm. thick. Under it lies a compact brownish mixture consisting on the average of small fragments of dolomite (up to powder incl.) and clay-sandy glacial deposits. The entire mass — due to an admixture of clay and moisture — is slightly bound and during the digging was thrown out in lumps which easily broke up under the knock of the shovel.

On the whole the mass consisted of small pieces (Fig. 9) but there were also large fragments of dolomite and glacial boulders of eruptive and metamorphic rocks.

From top to bottom the described mass appears to be quite uniform in character and lies untouched since the formation of the crater.

Meteoric iron. In order to discover the remains of the meteorite, lumps of the excavated mass were shattered and thoroughly inspected.

In the upper half of the fragmentary mass no traces of meteoric iron were found, but at a depth of about 1 m. the exploration was crowned with success: a fragment of meteoric iron covered with a thick crust of iron-shale weighing 24 gramms was found. During further deepening there appeared from time to time small fragments of meteoric iron sporadically distributed in the fragmentary mass.

In the 80 m^3 of the excavated mass there were found in all 28 fragments of meteoric iron with a total weight of 102,4 gr. (fig. 10). The weight of separate fragments ranges between 0,1 & 24,0 gr.

Coal, shells, markasite. On carefully inspecting the excavated mass other admixtures were found which are very interesting for the ascertaining of the general characteristics of crater formation.

First of all one has to note small pieces of coal occurring in the entire thickness of the fragmentary mass; these coals represent small fragments of branches of needle-trees, oaks etc. having a diameter of 1—3 cm. and rarely 5—6 cms. There were found scores of pieces sporadically distributed in the explored mass.

Also sporadically distributed in the fragmentary mass were found a few score shells of land snails — from small fragments to well preserved shells. All the shells found belong to species at present living in the locality *).

Besides the objects mentioned above markasite is often found in a fresh condition in the shape of small fragments, spheroid concretions etc., or changed into limonite in the shape of lumps or powder.

The presence of markasite in the fragmentary mass is easily explained by the fact that it occurs very often as insertions in the local dolomites: at the explosion the markasite released from the shattered dolomite fell together with the entire fragmentary mass into the craters separately or bound with pieces of dolomite.

Crater Nr. 5.

Place of excavation (fig. 6, 12). The original shape of this crater is now deformed owing to the fact that from the adjoining field on to its rim there were heaped stones now overgrown with grass and masking the true shape of the crater. At present the rim of the crater has irregular oval contours, but the hollow (depth = 0,9 m.) has preserved its characteristic bowl-shaped form. Like most of the other craters it is covered with hazel bushes (fig. 11).

For the study of the fragmentary mass filling it a test-pit of triangular form was excavated on the west side of the crater; the dolomite bottom was reached here at the depth of 1,9 m.

The fragmentary mass. On the whole about 40 m.^{3} were excavated. On the surface of the fragmentary mass there has formed

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*) Dr. K. Krausp a well known expert on the Gastropoda of Estonia having obligingly inspected at the author's request the collected material classified the shells found as belonging mainly to the species of *Cepaea hortensis* Müller and *Fruticola fruticum* Müller; much more rarely was found *Succinea putris* L.

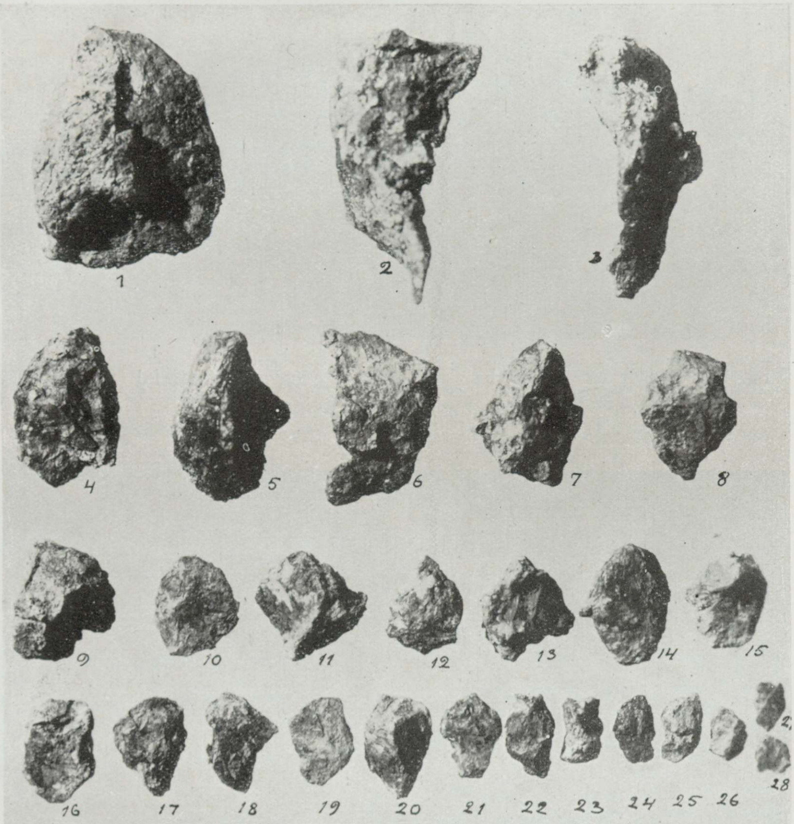

Fig. 10. Fragments of meteoric iron found in crater Nr. 2; nat. size.
Photograph by author.

Fig. 11. Crater Nr. 5; on the right heap of excavated material (july of 1937). Photograph by V. Reinvald.

Fig. 12. Crater Nr. 5 — view from aeroplane (150. m.; April 1938); in the middle place of excavation; near the crater — excavated material. Photograph by Estonian Air Defence.

a layer of soil 0,10—0,20 m. The mass itself consists approximately of one half of big fragments of dolomite (fig. 13); the remaining part represents a mixture of crushed dolomite with clay-sandy glacial deposits giving the entire mass a brownish colour. On the whole the mass lies loose and amongst the large fragments often occur hollows half filled with fine stuff.

Meteoric iron. In 1937 in the excavated part of the mass only 2 pieces of meteoric iron were found covered by a thick crust of oxydized iron and weighing 4,18 and 3,44 gr. (fig. 14, no. 1 and 3).

At an additional inspection of the excavated mass one more fragment was found in 1938, weighing 9,1 gr., and having a very characteristic twisted form (fig. 14, no. 2). As in crater Nr. 2 these fragments were found in the lower part of the excavated mass.

Shells, coal. As in Nr. 2 here were sporadically distributed at all depths the shells of land snails of the abovementioned species. There were found also pieces of coal (burnt branches) but more rarely than in Nr. 2.

Traces of previous excavations. It is very interesting to note, that in the described crater during the digging there were discovered traces of previous excavations, apparently quite ancient, as there remained no outer trace of them, and it was impossible to obtain any information about them from the local inhabitants. On the whole traces of three pits were found filled with the same fragmentary material but mixed with black soil. On fig. 4 their situation is shown by figures 1, 2 and 3. Pit Nr. 1 was deepened only to 1 m., Nr. 2 — slightly deeper, but did not reach the dolomite bottom, and Nr. 3 was excavated to the dolomite bottom of the crater.

In this latter amongst the fragments filling it was found a narrow bronze strip (91 × 4 × 1 mm) with sharpened ends, ornamented at the edges by incisions made by hand (fig. 15). The strip is covered on the surface by the characteristic green ("aerugo nobilis"). In local archeological investigations object of this kind have not been found, and therefore the establishment — if only approximately — of the date of this strip appears to be difficult, the more so as ornaments of this kind were made by rustic amateurs in the last century too.

Properties of meteoric iron.

Nickel-iron. All the pieces found appear as small fragments of nickel iron either covered by a relatively thick crust of oxide or, sometimes, appareitly oxydized throughout.

The preliminary polishing and etching of the biggest sample (fig. 10 nr. 1, original weight 24 g) brought forth signs of crystalline structure in the iron core of the piece (fig. 16). The preliminary chemical analysis of the small fragment nr. 21, weighing 0,4 gm., was kindly made in the laboratory of the Tallinn Technical University by Mr. A. Väärismaa. It showed Fe — 84,04 and Ni — 6,45, i. e. the ratio Fe:Ni = 13.

These results may be looked upon as only approximate, the fragment chosen for analysis being too small to be cleaned thoroughly not only from oxyde but also from other mineral admixtures in the fissures. Nevertheless, the preliminary examination has ascertained that the iron in question is really the remnants of a meteorite.

A more detailed examination of the iron found was, on request by the author, kindly undertaken by Dr. L. J. Spencer (London, Formerly Keeper of Minerals in the British Museum), a prominent expert in meteoric iron and author of many valuable investigations in this branch of science*).

There were sent for examination 10 pieces of the iron found (fig. 10. nr. 1, 5, 7, 11, 14, 16, 17, 18, 19, 20). In pieces nr. 1 and nr. 7 Dr. Spencer by polishing and etching established signs of crystalline structure in the nickel-iron mass and the presence in it of iron-nickel combinations (taenite, kamacite, plessite) characteristic of meteorites. In nr. 1 was established a fair quantity of schreibersite [$(Fe, Ni, Co)_3 P$] which occurs in meteorites only.

The polishing and etching of the third piece (nr. 11) did not reveal any structure. The micro-chemical analysis kindly made by Dr. M. H. Hey (British Museum Laboratory) showed the iron of this small piece contained Fe 91.50 and Ni 9.32, i. e. the ratio Fe:Ni = 11.

It may be of interest to state that the crystalline structure of both the samples examined showed signs of corrugation, which in the opinion of Dr. Spencer is due to the influence of the very

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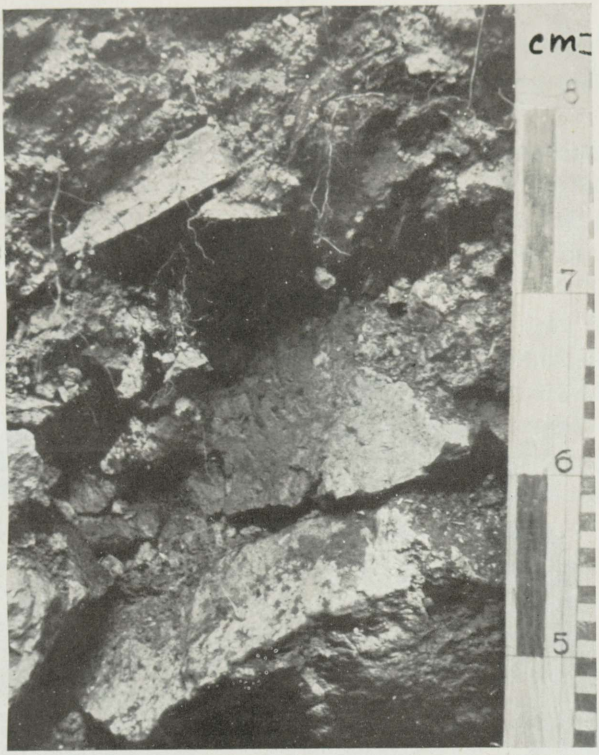
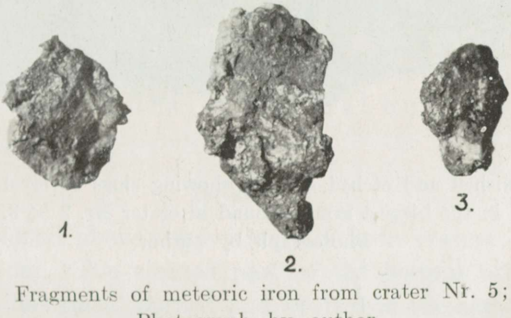
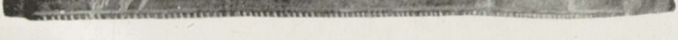
*) "The Kaalijärv meteorite from the Estonian craters" by L. J. Spencer, C. B. E., M. A., Sc. D., F. R. S., formerly Keeper of Minerals in the British Museum. "Min. Mag.", London, June, 1938, vol. XXV, no. 161.



F i g. 13. Section of the fragmentary mass filling crater N. 5.
Photograph by V. Reinvald.



F i g. 14. Fragments of meteoric iron from crater Nr. 5; nat. size.
Photograph by author.



F i g. 15. The bronze strip discovered at the excavation of crater Nr. 5; nat. size.
Photograph by prof. A. Öpik. (Tartu).

Fig. 16. Polished and etched surface, showing sings of crystalline structure in the biggest sample found in crater Nr. 2 × 3.
Photograph by author.

great heat developed at the time of the fall of the meteorite. Evidently, owing to the same circumstance crystalline structure disappeared in sample nr. 11.

This supposition agrees wholly with the conditions of the burnt bottom in crater nr. 4 at the impact funnel and the adjacent shattered part of the dolomite massif and appears to be new and very convincing evidence of the development of enormous heat at the moment of impact.

I r o n - s h a l e. All the fragments of meteoric iron found are covered with a relatively thick crust of so called "iron-shale" which consists of dark brown — nearly black — iron oxyde attracted by a magnet. The outer layer of the crust has a flaky structure, easily cracks and crumbles when dried up, whereas the inner, adjacent to the iron, layer is very hard and presents difficulties in the cutting and grinding down of the sample.

On the surface of the crust and in the fissures there occur small stains of light brown rust which is obviously the result of oxydation while lying in the humid fragmentary mass.

The dark brown oxyde of the principal part of the crust was probably formed at the time of the formation of the crater when the iron fragments were thrown out and their surface, semi-melted by heat, came into contact with atmospheric oxygen.

S h a p e o f f r a g m e n t s. The greater part of the pieces found are characteristic fragments of angular or laminated shape (fig. 10, 14). Pieces 2, 3 (fig. 10) and 2 (fig. 14) are characteristically twisted and bent as the obvious result of their tearing off from the body of the meteorite; similar pieces were found in great quantities near the meteor-craters of the H e n b u r y group (Central Australia) *).

Solid bed.

As mentioned above excavations in both craters reached the dolomite bottom. The cleaned part of the bottom proved in both craters to be deformed, burned and swelled in the same way as the bottom of crater Nr. 4 explored in 1927.

It is very interesting to note that both the burned and the fresh

*) "The Henbury (Central Australia) Meteoric Iron" by A. R. Alderman, M. Sc., F. G. S., "Records of the South Australian Museum". Adelaide, Vol. IV. nr. 4, 1932.

part of the dolomite bottom of both craters (as in crater Nr. 4) do not show any signs of weathering.

It would be highly interesting to study more completely the bottom of the craters laid open and to establish in what shape the traces of the impact of the meteorite have been preserved, but, considering the sad fate of the bottom of crater Nr. 4, reduced since 1927 to an almost unrecognizable state by outer influences and vegetation, the author could not decide to clean the bottom with the accuracy necessary for such a study.

The complete exploration of the bottom of both craters was postponed until the time the author obtains the possibility, following the necessary cleaning of the dolomite bottom, of protecting it by suitable buildings from the destructive influences of outer conditions.

The wall surrounding the main crater.

Besides the excavations mentioned which represented the main part of the proposed exploration an excavation was also made on the outside slope of the wall surrounding K a a l i j ä r v, opposite the school house.

The excavation showed that the outer part of the wall consists of a fragmentary mass in which the crushed (from powder to large fragments) dolomite is mixed with glacial clay-sandy deposits and boulders. As in craters Nos. 2 & 5 amongst this mass were found fragments of coal and the shells of land snails.

No meteoric iron was found.

Crater Nr. 6.

Simultaneously with the main explorations a shallow round hollow situated at a few score metres to the west of crater Nr. 1 near the road running there was inspected (fig. 6).

This hollow had been observed here by some of the explorers (Prof. O. L i n s t o v, prof. A. W e g e n e r, prof. R. M e y e r and others) who considered it to be a meteor crater also but, as it differs from other craters of the group in its comparatively small depth, the author refrained from including it in the group of certain meteor craters in describing the crater field in 1927 and 1933.

A small test-pit made in this hollow showed that it is filled with dolomite fragments mixed with glacial deposits containing coal and shells, which show its similar origin to other craters.

The crater (d = 25 — 26 m., depth = 0,65 m.) has a round shape (fig. 6); through its western edge runs a road, and on the other side the crater is cut by a stone wall parallel to the road.

No meteoric iron was found.

Summary.

The fact of finding fragments of meteoric iron as well as the composition and character of the bedding of fragmentary masses described above gives one the possibility to clear us more fully than hitherto the conditions of the formation of the craters under discussion.

The discovery of meteoric iron in the explored craters proves that the Kaalijärv Crater Group was formed — as was supposed by the author in 1927 and 1933 — by the falling of iron (not stone) meteorites.

No whole meteorite body (so called "main mass") was found in the explored craters. The discovery of but small fragments of meteoric iron proves that the meteorites at the moment of the fall under the combined influence of impact and explosion were shattered and thrown out by the explosion together with fragments of dolomite and glacial deposits.

At present the remains of the shattered meteorites lie not only in the craters themselves but also around them in the fragmentary mass thrown out under the cultivated layer of now tilled fields. By the exploration of all these masses it is undoubtedly possible to discover some more fragments of meteoric iron amongst which may be found also comparatively large pieces, as was observed near similar craters in other parts of the world.

At the moment of the formation of the craters the locality was a continent overgrown by young forest (oak, needle-trees, shrubs): this is proved by the finding of coals and the shells of land molluscs in the fragmentary masses filling the craters.

The vegetation of the locality was apparently burned before the moment of explosion under the action of streams of compressed heated air parting before the falling meteorites (a so called "head wave"; cf. the semi-burned forest at a radius of 50 klm. from the spot of the fall of the meteorites in the Podkamennaja Tunguska — Siberia). The high temperature created at the point of impact in the depth of the crater could not burn up surface vegetation, as it was protected from its influence by the intermediate rock.

The creation of a high temperature at the point of impact as the cause of the explosion is also confirmed by the condition of the fragments of meteoric iron found. The deformation of the crystalline structure on the surface of the fragments examined occurred apparently under the influence of the sharp instantaneous heating at the moment of the impact: until the moment of the impact when the meteorite was shattered all these fragments were components of its internal part and obviously had the normal crystalline structure.

The mixed composition of the fragmentary mass filling the crater, the presence at all depths of coals and shells, sporadically distributed fragments of meteoric iron, uniform character of mixture from top to bottom — all these peculiarites are the natural result of the falling back into the crater of the rocks, broken, mixed and thrown out by the explosion.

The entire absence of indications of weathering on the rock bottom of the craters shows that the protecting fragmentary mass covered it immediately after the formation of the crater.

In conclusion it is important to note that the thickness of the loose masses proved to be approximately equal in craters Nr. 2 (2,0 m.), Nr. 4 (2,0 m.) and Nr. 5 (1,9 m.) regardless of the considerable difference of their diameters: 30—32 m. in Nr. 2, 20 m. in Nr. 4 and 12—15 m. in Nr. 5. This circumstance shows that among the craters there is no complete similarity.

Pseudo-meteorites. The establishing of the meteoric origin of Kaalijärv and the adjoining small craters furthered among the population a heightened interest in the search for sundry metal-like objects found in the locality.

Most attention is drawn by the markasite appearing in local dolomites in the shape of concretions of different forms, sometimes of very regular spherical.

Rarer concretions of pyrite are to be found. In July, 1937 during a visit to Kaalijärv by the Commander-in-Chief General J. Laidoner together with the cavaliers of the order of the Cross of Liberty after the speech made by him about the scientific significance of this group of craters the local workmen handed over to him two large pieces of pyrite found at the excavation work for foundation of the new schoolhouse then being built. These samples were obligingly contributed by the general to the author's collection.

The most interesting find was handed over to the author by Mr. H a i d e s k, the headmaster of the agricultural school in Kõljala (about 3/4 klm. distant from Kaalijärv). This was a fragment of iron rounded on one side and weighing 2,4 kg. which was found by the students of the school at a small depth when digging during repairs to the foundation of the garden fence. Its outer form, a thick (about 20 mm. at the rounded part of the surface) and hard lamellar crust of oxydized iron similar to the iron shale of the meteorites made it possible to accept this find as the fragment of a meteorite.

In an analysis, obligingly made by Mr. A. V ä ä r i s m a a, it was found that this iron does not contain nickel, and at its polishing and etching no signs of crystalline structure were found.

Nevertheless, the outer peculiarities of this piece made the author ask for the opinion of Dr. L. J. S p e n c e r, who obligingly studied it. The analysis made in London discovered 5% graphite and a complete absence of nickel. The sample was determined by Dr. S p e n c e r, to be ordinary cast iron.

During a visit to Kaalijärv in the beginning of April 1938 the author had opportunity to acquaint himself with the finding place of this piece: the hole where it was discovered had been dug near the ruined stone garden fence in a layer of black soil intermixed with refuse.

How this piece of cast iron came to be there and how its peculiar shape is to be explained remains a mystery.

Questions to be solved.

Although the cause and mode of the formation of the Kaalijärv crater may be considered as finally cleared up, the exploration of this interesting group cannot be regarded as closed. Apart from the abovementioned incomplete exploration of the dolomite bottom of craters Nos. 2 and 5 laid open the following questions remain open:

1. The actual number of the craters has not been established.

Near Kaalijärv there are many hollows of unknown origin, and a thorough investigation some of them may prove them to be meteoric craters, and the general picture of our crater field, though it has suffered from agricultural activity, may be restored more fully.

2. In the crater field besides typical craters there are some small pits of unknown origin, but obviously not dug by human hands.

These pits are filled to the top with stones and are partly overgrown. These pits were already noticed in 1919 by prof. Linstov and marked during the author's exploration in 1927, when he could not undertake their examination. It is possible that the formation of these pits is also connected with the falling of meteorites.

3. Up to the present that part of material thrown out from the craters which lies around them has not been examined. It would be interesting to fix their thickness and limits of distribution; during this examination a find of meteoric iron is of course also possible.

4. The masses of silt forming the middle part of the bottom of the main crater were not examined; this silt gradually settled on the bottom of the crater, and its deeper layer is more or less contemporaneous with the formation of the crater. An examination of the pollen of plants therein contained might give material for approximately fixing the time of the formation of the craters.

The clearing up of these questions would give new interesting material, not only to clear up questions connected with the origin of the group in question but also to throw some light on the origin of craters of the same type as Kaalijärv.

Conclusion.

Kaalijärv with its peculiarities has long ago drawn the attention of lovers of nature and is visited every year not only by scientists but also by a large number of tourists.

Up to the present visitors must regrettably be content with viewing the lake only and go away in complete ignorance of the fact that they have visited the only field in Europe of excellently preserved meteor craters.

In the first report on the exploration of Kaalijärv in 1928 the author pointed out the necessity of making these craters the property of the State, putting the excavations made into order, protecting them from outside influences and thus giving the tourists a chance thoroughly acquaint themselves with this unique natural phenomenon.

A decision of the Government to take the Kaalijärv group under the control of the State was made in the summer of 1938, but no measures for the actual protection of the craters laid open have so far been taken yet.

However, up to the present the exposed bottom of Kaalijärv meteorite crater Nr. 4 with all its characteristic peculiarities continues to be **t h e o n l y o n e i n t h e w o r l d** yet studied and described.

Unfortunately during the last 11 years this natural wonder severely suffered from our climate and from other outside influences and lost some valuable peculiarities, though preserving up to the present many properties valuable to science.

Besides crater Nr. 4 protection is needed also for craters Nos. 2 and 5 laid open in 1937 as they have bottoms quite similar to bottom Nr. 4 and are so far in a fresh condition.

The easy access to this interesting group situated in a cultivated locality, the beautiful preservation of the craters and their small dimensions make it easily possible to establish on the island of Oesel an "Open air Meteor Crater Museum". For this purpose it is necessary to put into order and to prepare for inspection the excavations made by the author, and to protect them from outside influences by pavillions convenient for demonstration and acceptable in the aesthetic sense.

At the suggestion of the Director of the "Management of Public Parks" (at present "Institute of Nature Protection and Touring") Mr. P. P ä t s, the author submitted in August 1937 a plan for arranging such a museum. *)

It would be necessary to protect the open craters from ruin as soon as possible, for every year brings about irreparable damage.

Any delay in taking measures of protection would lead to an inexcusable decay, in the cultural sense, of an object valuable not only to Estonia, but offering — on account of its singularity — general scientific interest.

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*) Suggested:

1. To protect by pavilions craters: Nr. 4 excavated to one half, Nr. 5 (excavated in toto) and Nr. 2 (excavated to ¼ of the area of the lesser part of this double crater).

2. To lay open by a narrow trench to the raised dolomite fragments the wall surrounding the main crater from the outside and the inside and protect them by a covered gallery.

3. To arrange a museum in one of the rooms of the local school for a preliminary introduction to visitors of the disposition of the craters, fragments of meteoric iron, photographs, descriptions etc. and

4. to interconnect the craters by convenient paths equipped with indication signs for the convenient finding of the craters.

to be the only ones in the world to get studied and described. For the lapse of time passed since 1927 the material would be severely suffered from our climate and from other outside influences and lost some valuable peculiarities, though preserving up to the present many properties valuable to science.

Besides crater No. 1 protection is recommended also for craters Nos 2 and 5 laid open in 1927 as they have bottoms quite similar to bottom No. 1 and are [illegible] in a fresh condition.

The easy access to this interesting group situated in a cultivated locality, the beautiful preservation of the craters and their small dimensions make it really possible to establish on the island of Oesel an "Open-air Meteor Crater Museum". For this purpose it is necessary to put up a fence and to prepare for display the excavations made by the author and to protect them from outside influence by pavilions covering up [illegible] or hitherto acceptable in the scientific sense.

At the suggestion of the Directorate of the Management of Public Parks" (at present "Institute of Nature Protection and Touring") Mr. P. Pits, the author submitted in August 1927 a plan for arranging such a museum.*)

It would be necessary to protect the open craters from rain as soon as possible, for every year brings about irreparable damage.

Any delay in taking measures of protection would lead to an increasable decay in the cultural sense of an object valuable not only to Estonia, but offering — on account of its singularity — general scientific interest.

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*) 1. To protect by walls or roofs craters No. 1 (recommended in [illegible]) and No. 2 (amounting to ¾ of the area of the lesser part of the south crater).

2. To lay down a narrow branch to the [illegible] surrounding the main crater A on the outside and the inside and put them by a covered gallery.

3. To arrange a museum in one of the rooms of the local school for preliminary introduction to visitors of the phenomenon of the crater, fragments of meteoric iron, photographs, drawings etc. etc.

4. To reconstruct the crater for convenient paths equipped with [illegible] dition and be [illegible] understanding of the crater.

Tartu Ülikooli Geoloogia-Instituudi Toimetused.
Publications of the Geological Institution of the University of Tartu.

№ 1*. H. Bekker, Ph. D., D. I. C., Mõned uued andmed Kukruse lademe stratigraafiast ja faunast. — Stratigraphical and Paleontological Supplements on the Kukruse Stage of the Ordovician Rocks of Eesti (Estonia). With 2 plates, 1 map and 6 fig. in text. — Märts 1924.

№ 2*. — Devon Irboska ümbruses, stratigraafia, fauna ja paleogeograafia. — The Devonian Rocks of the Irboska District (S. E. Estonia) with the Description of a new Cemented Brachiopod. With 1 map, 6 plates and 15 fig. in text.— Okt. 1924.

№ 3. A. Öpik, Beitrag zur Stratigraphie und Fauna des estnischen Unter-Kambriums (Eophyton-Sandstein). Mit 10 Textfig. und 3 Taf. — Veebr. 1925.

№ 4*. A. Luha, Professor Hendrik Bekker, Ph. D. Sc. Nekroloog, pildiga. With English Summary.
A. Öpik, Beiträge zur Kenntnis der Kukruse-(C_2-)Stufe in Eesti. I. — Über die Kalksandsteinfacies des Vaginatenkalkes auf der Halbinsel Baltischport und über ein *Acidaspis*-Pygidium aus denselben Schichten. — Dets. 1925.

№ 5. K. Jaansoon-Orviku, Beiträge zur Kenntnis der Aseri- und der Tallinna-Stufe in Eesti. I. — Veebr. 1927.

№ 6*. A. Öpik, Über den estländischen Blauen Ton. — Juuli 1926.

№ 7*. K. Jaansoon-Orviku, Rändpangaseid Eestis (Über die Glazialschollen in Eesti). Mit deutschem Referat. — Juuli 1926.

№ 8. K. Orviku, Die Rautenvariationen bei *Echinosphaerites aurantium* Gyll und ihre stratigraphische Verbreitung im estnischen Ordovizium. — Märts 1927

№ 9. A. Öpik, Die Inseln Odensholm und Rogö. Ein Beitrag zur Geologie von NW-Estland. — Sept. 1927.

№ 10. A. Öpik, Beiträge zur Kenntnis der Kukruse-(C_2-)Stufe in Eesti II. — Sept. 1927.

№ 11*. J. A. Reinvaldt, Bericht über geologische Untersuchungen am Kaalijärv (Krater von Sall) auf Ösel. Mit Beiträgen von A. Luha. — Sept. 1928.

№ 12. A. Öpik, Beiträge zur Kenntnis der Kukruse-(C_2-C_3-)Stufe in Eesti.— Okt. 1928.

№ 13. A. Öpik, Über Trockenrisse und Regenspuren im Monograptus-Schiefer von Hodkovičky (Böhmen), und über die Entstehung der Graptolithenschiefer überhaupt. — Märts 1929.

№ 14. K. Orviku, Uhaku. Kirde-Eesti karstiala stratigraafiast ja geomorfoloogiast. Deutsches Referat: Uhaku. Zur Stratigraphie und Geomorphologie des NO-estnischen Karstgebietes. — Mai 1929.

№ 15. A. Öpik, Studien über das estnische Unterkambrium (Estonium). I—IV — Juuli 1929.

№ 16. A. Öpik, Über Muskelhaftstellen der Glabella von *Pseudasaphus tecticaudatus* Steinh. *(Crust., Trilobita)* und über die Funktion der Fazialsutur. — Juuli 1929.

№ 17. A. Audova, Aussterben der mesozoischen Reptilien. I. — Aug. 1929.

№ 18*. A. Öpik, Der estländische Obolenphosphorit. — Aug. 1929.

№ 19. P. W. Thomson, Die regionale Entwicklungsgeschichte der Wälder Estlands. — Detsember 1929.

№ 20. A. Öpik, Brachiopoda Protremata der estländischen Kukruse-Stufe. — Jaanuar 1930.

№ 21. K. Orviku, Keskdevoni põhikihid Eestis. Deutsches Referat: Die untersten Schichten des Mitteldevons in Eesti. — Veebr. 1930.

№ 22. A. Luha, Über Ergebnisse stratigraphischer Untersuchungen im Gebiete der Saaremaa-(Ösel-)Schichten in Eesti. (Unterösel und Eurypterusschichten). — Jaanuar 1930.

№ 23. A. Heintz, Eine neue Rekonstruktion von *Heterostius* Asm. — K. Orviku, Die Glazialschollen von Kunda-Lammasmägi und Narva-Kalmistu (Eesti). — K. Orviku, Der Asaphiden-Kalkstein (Ordovizium) im Bohrloch von Lagedi (Eesti). — Juuli 1930.

№ 24. A. Öpik, Beiträge zur Kenntnis der Kukruse-(C_2-C_3-)Stufe in Eesti IV. — November 1930.

№ 25. A. Öpik, Über einige Karbonatgesteine im Glazialgeschiebe NW-Estlands — Mai 1931.
№ 26. Th. Heinrichson, Über *Porambonites wahli* n. sp., aus der ordovizischen Jõhvi-Stufe D_1 Estlands. — Sept. 1932.
№ 27. Johan Kiær †, Edited by A. Heintz. New Coelolepids from the Upper Silurian on Oesel (Esthonia). — Sept. 1932.
№ 28. A. Öpik, Über die Plectellinen. — Nov. 1932.
№ 29. A. Öpik, Über Scolithus aus Estland. — Jaan. 1933.
№ 30*. J. A. Reinvaldt, Kaali järv — the Meteorite Craters on the Island of Ösel (Estonia). — Jaan. 1933.
№ 31. A. Öpik, Über Plectamboniten. — Mai 1933.
№ 32. A. Öpik, Über einige Dalmanellacea aus Estland. — Mai 1933.
№ 33. A. Öpik und N. Thamm, Über ein anstehendes Eruptivgestein aus Estland. — Detsember 1933.
№ 34. N. Thamm, Über eine Gneisbrekzie im Glazialgeschiebe der Insel Osmussaar (Odensholm). — Detsember 1933.
№ 35. N. Thamm, Der Vorgang des muscheligen Bruchs. — Detsember 1933.
№ 36. A. Öpik und P. W. Thomson, Über Konzeptakeln von *Solenopora*. — Detsember 1933.
№ 37. L. Störmer, A New Eurypterid from the Saaremaa- (Oesel-) beds in Estonia. — Jaanuar 1934.
№ 38. A. Heintz, Revision of the Estonian Arthrodira. Part I. Family *Homostiidae* Jaekel. — Veebr. 1934.
№ 39. A. Öpik, Über Klitamboniten. — Juuni 1934.
№ 40. A. Öpik, Ristnacrinus, a New Ordovician Crinoid from Estonia. — Juuli 1934.
№ 41. A. Öpik, *Amphipora ramosa* (Phill.) in the Marine Devonian of Estonia. — Aprill 1935.
№ 42. Th. Heinrichson, Über *Endoceras glauconiticum* n. sp. aus dem Glaukonitkalk B_{II} Estlands. — Aprill 1935.
№ 43. A. Öpik, *Hoplocrinus* — eine stiellose Seelilie aus dem Ordovizium Estlands. — Juuli 1935.
№ 44. A. Öpik, Ostracoda from the Lower Ordovician *Megalaspis*-limestone of Estonia and Russia. — Juuli 1935.
№ 45. A. Öpik, Ostracoda from the Old Red Sandstone of Tartu, Estonia. — Juuli 1935.
№ 46. K. Orviku, Quartärgeologische Karte der Halbinsel Sõrve (Saaremaa, Estland). — August 1935.
№ 47. K. Orviku, Viljandimaa aluspõhi ja pinnakate. — Geologische Übersicht des Bezirks Viljandimaa. — Oktoober 1935.
№ 48. H. Barkla, The Drumlins of Türi (Estonia). — November 1935.
№ 49. P. Siegfried, Über das Pandersche Organ bei den Asaphiden des Ostbaltischen Ordoviciums. — Juuli 1936.
№ 50. A. Öpik, Ostracoda from the Ordovician Uhaku and Kukruse Formations of Estonia. — Märts 1937.
№ 51. A. Öpik ja A. Laasi, Läänemaa geoloogia — Geologie von Läänemaa — August 1938.
№ 52. A. Öpik, Trilobiten aus Estland. — Juuli 1937.
№ 53. A. Öpik, Ühest rändkivist Läänemaalt — An Erratic Block in the District of Läänemaa. — K. Orviku, Lubjanukud Raadi vanast kruusaaugust — Finds of Limedolls in the Fluvio-glacial Sands of the Raadi Gravel-Pit. — A. Öpik Porkuni—Tamsalu ümbruse geoloogiast — The Geology of the Environment of Porkuni—Tamsalu. — A. Laasi, Põhja-Pärnumaa otsmoreenist — The Terminal Moraine of Northern Pärnumaa. — A. Öpik, Settesoontest Aluvere murrus — The Sedimentary Dykes in the Aluvere Quarry. — Ev. Mels, Esku rannamoodustused — Shore Formations at Esku. — P. W. Thomson, Narva diatomiit — The Diatomite Deposit of Narva. — B. Stein, Vohilaiu geoloogiast — On the Geology of Vohilaid. Oktoober 1938
№ 54. P. Siegfried, Zur Kenntnis estländischer Trilobiten. Mit einem Zusatz: A. Öpik, Über Antennula-Zapfen und das Hypostom. — Dets. 1938.
№ 55. I. A. Reinvald, The Kaalijärv meteor craters (Estonia) supplementary research of 1937; discovery of meteoric iron. — Aug. 1939.

* out of print.

K. Mattieseni trükikoda o./ü., Tartu, 1939.