# *The Kaalijärv meteorite from the Estonian craters.*

(With Plate III.)

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KAALIJÄRV is a crater-lake on the estate Kaali (järv = lake in the Estonian language) at 58° 24′ N., 22° 40′ E. Known in German as Sall, this locality is 20 km. NE. of Arensburg (= Kuresaare) on the Baltic island of Oesel (= Saaremaa). On the level agricultural country a thickly wooded knoll 6–7 metres high is seen. Inside there is a crater 15½ m. in depth, the circular rim of which measures 92–110 m. across. The lake at the bottom is about 60 m. across. The rock of the district is horizontally bedded Silurian dolomite with a covering of glacial deposits. The rim of the crater consists of fragmentary materials, and the steeper inner slopes show the beds of dolomite dipping outwards as a dome at angles of 30–40°. Near by, on an area of ¾ sq. km., are five other smaller craters similar in character, and at least three other depressions that have been filled with stones collected from the tilled fields.

These craters present many points of resemblance to the famous Meteor Crater in Arizona and the Henbury craters in Central Australia, but they were known much earlier. They have often been described, first by J. von Luce in 1827, and many suggestions have been made as to their mode of origin. They have been thought to be earthworks made by man, and they have been compared with the volcanic crater-lakes of the Eifel and the Campi Flegrei. Other modes of origin that have been suggested are: (1) gas explosions, (2) oozing out of a bed of clay, (3) karst weathering of the dolomite, (4) solution of rock-salt from salt domes, (5) expansion of anhydrite by hydration. Eruptions of natural gas are known in Estonia from bituminous beds of the *Dictyograptus* (*Dictyonema*) shales of Cambrian age and the Kuckers beds of Ordovician age; and as these beds underlie the Silurian dolomite of the island of Oesel, the formation of the craters by gas explosions seemed not improbable.[1] I was myself inclined to this view until the recent finding

[1] O. von Linstow, Der Krater von Sall auf Oesel. Centr. Min., 1919, pp. 326–339.

of meteoritic material. At a later date (J. Kalkun,[1] 1922) the craters were compared with the Meteor Crater in Arizona.

A detailed survey of the craters with excavations and borings was undertaken in 1927 by Mr. Ivan Reinvald, Inspector of Mines in Estonia. He found tilted, shattered, powdered, and 'burnt' dolomite, and in his paper[2] he makes out a strong case for the meteoritic origin of the craters, although no trace of meteoritic material could be found. He concluded that they are explosion craters, attributing the explosion to the generation of steam from ground-water when the meteorites struck the earth. He returned to the work again in 1929,[3] but still no meteoritic material was found. Under his guidance the locality was visited by A. Wegener[4] in 1927, A. R. Hinks[5] in 1933, and Dr. Clyde Fisher[6] in 1936, each of whom was convinced of the meteoritic origin of the craters. A later discussion by W. Kranz,[7] based on Reinvald's papers, supports the same view. A review was given by me in 1933.[8] The lack of meteoritic iron at this locality is explained by Mr. Reinvald by the fact that the land here has been tilled from time immemorial, and any masses of metal would have been already gathered for use as implements.[9]

With remarkable persistence Mr. Reinvald again returned to the work of excavation in July, 1937, when he was at last rewarded by finding

[1] J. Kalkun [= J. Kaljuvee], [Üdine geoloogia. Tallinn, 1922, p. 101] quoted by I. Reinwaldt, loc. cit., 1928; J. Kaljuvee, Die Grossprobleme der Geologie. Tallinn, 1933, pp. 102–108. [M.A. 5–410.]

[2] I. Reinwaldt, Bericht über geologische Untersuchungen am Kaalijärv (Krater von Sall) auf Ösel. Mit Beiträgen von A. Luha. Sitzungsber. Naturfors. Gesell. Univ. Tartu, 1928, vol. 35, pp. 30–70, 8 pls.; separate as Publ. Geol. Inst. Univ. Tartu, 1928, no. 11, 42 pp., 8 pls. [M.A. 5–17.]

[3] J. A. Reinvaldt, Kaali järv—the meteorite craters on the island of Ösel (Estonia). Ibid., 1933, vol. 39 (for 1932), pp. 1–20, 3 pls.; separate, ibid., 1933, no. 30, 20 pp., 3 pls. [M.A. 5–301.]

[4] E. Kraus, R. Meyer, and A. Wegener, Untersuchungen über den Krater von Sall auf Ösel. Gerlands Beitr. Geophysik, 1928, vol. 20, pp. 312–378, 1 pl., 10 text-figs., pp. 428–429. [M.A. 5–17.]

[5] A. R. Hinks, Geogr. Journ. London, 1933, vol. 82, p. 375.

[6] C. Fisher, The meteor craters in Estonia. Nat. Hist., Amer. Mus. Nat. Hist., 1936, vol. 38, pp. 292–299, 10 figs. [M.A. 7–73.]

[7] W. Kranz, "Krater von Sall" auf Ösel, wahrscheinlich "Meteorkrater". Gerlands Beitr. Geophysik, 1937, vol. 51, pp. 50–55. [M.A. 7–73.]

[8] L. J. Spencer, Meteorite craters as topographical features on the earth's surface. Geogr. Journ. London, 1933, vol. 81, p. 233; reprinted in Ann. Rep. Smithsonian Inst. Washington for 1933, 1935, p. 315. [M.A. 5–301, 6–208.]

[9] A similar explanation is given for the absence of meteoritic iron in India (as contrasted with America and Australia). Of the 111 recorded Indian meteorites only one is a found iron.

small rusted fragments of meteoritic iron, and so definitely proving that he had correctly interpreted his previous work.[1] During fourteen days with six workmen and carefully sorting the loose material dug out from the inside of the craters, thirty fragments were found. Two of these were found in crater no. 5, which has a diameter of 10–13 m., and the remainder in the smaller part of the oval (double) crater no. 2, which measures 53×36 m. The fragments range from 24 to 0·1 grams, and the total weight amounted to only about 100 grams.

A selection of this precious material has been very kindly submitted to me by Mr. Reinvald for description, and he has very generously presented three pieces for the British Museum collection of meteorites.[2] The ten fragments sent for examination range in weight from 18·6 to 0·8 grams. They have the appearance of bits of iron-shale, but the heaviness of some pieces suggests that some metal is present inside. This iron-shale or rust is flaky and rather friable on the surface, but inside it is hard and takes a good polish. The surface is often in part encrusted with pale yellowish calcite which is minutely botryoidal, and clearly a secondary deposit formed during the period that the fragments were buried in the ground in association with the dolomite-rock.[3]

Three of the heavier and more suitably shaped pieces were ground down until a surface of metal appeared, which was then polished and etched for study. Curiously, each of them showed a different type of structure, due perhaps to the small size of the areas. All of them came from crater no. 2.

*Section no.* 1 (pl. III).—This is the largest piece and had already been ground down and very well etched by Mr. Reinvald; it then weighed 18·6 grams. Fig. 1 reproduces a photograph (4 diameters natural size) of the etched surface as received; and fig. 2 the same surface after it had been repolished and re-etched with dilute nitric acid (and photographed in a different inclination of the light). The fragment measures $3\times2\frac{1}{2}$ cm., and the irregular area of metal on the polished surface about $2\frac{1}{2}\times1\frac{1}{4}$ cm.

[1] Brief mention of this discovery has been made by I. A. Reinwald, Der Krater von Sall (Kaali järv)—ein Meteorkrater-Feld in Estland. Natur und Volk, Ber. Senckenb. Naturfor. Gesell., Frankfurt am Main, 1938, vol. 68, pp. 16–24, 7 figs. [M.A. 7–73.]

[2] Rock specimens from the craters were presented to the British Museum by Mr. Reinvald in 1932.

[3] A similar secondary deposit of calcium carbonate is seen on the iron-shale of the Hoba (South-West Africa) meteorite which had lain in surface limestone (L. J. Spencer, Min. Mag., 1932, vol. 23, p. 7). It is clearly not the result of the welding of cosmic and telluric material at the time the meteorite fell, as suggested by P. Range and R. Schreiter (1931). [M.A. 5–11.]

with a surrounding area of iron-shale. Conspicuous are irregular areas or blebs of bright tin-white schreibersite (dark in fig. 1, and light in fig. 2). This abundance of schreibersite recalls the La Primitiva (Angela) meteoritic iron from Chile.[1] Prominent also are three areas traversed by a fine system of parallel bars, which in a certain inclination with respect to the light shine up with a bright tin-white colour. These are at first suggestive of bars of taenite in plessite areas. Other irregular bars and lines and numerous bright specks (fig. 2) are scattered through the groundmass. These bright bars, lines, and specks all appear to be schreibersite. They have the same colour and lustre as the larger blebs of schreibersite, and they are anisotropic in reflected polarized light. Further, they are not attacked by copper ammonium chloride solution. Partly enveloping and penetrating blebs of schreibersite are small patches and strings of graphite. No troilite was detected. The groundmass is very fine grained under the highest power of the microscope, suggesting an ataxite, but there is no oriented sheen in reflected light.

*Section no.* 2.—This fragment weighed 5·6 grams as received. After grinding down and polishing it weighed 4·9 grams. The metal area on the polished surface measures $1\frac{1}{2}\times\frac{1}{2}$ cm. It shows curved lines of taenite 1–2 mm. apart with dull granulated kamacite between, and the structure much resembles that of the distorted fragments from the Henbury meteorite craters in Central Australia.[2] In copper ammonium chloride solution copper is deposited over the whole surface, but this is readily wiped off except on the thin lines of taenite. The taenite is then shown prominently by the copper colour, and a small plessite area with bars of taenite also becomes evident.

*Section no.* 3.—This fragment weighed 2·7 grams and after grinding and polishing 2·0 grams. The polished metal area, $1\times\frac{1}{2}$ cm., shows no obvious structure and no oriented sheen in reflected light. It may be described as an ataxite. No schreibersite was seen. Material for analysis was taken from this specimen.

Of these three sections, nos. 1 and 3 suggest an ataxite, the former rich in schreibersite; while no. 2 suggests a medium octahedrite, but much distorted, and showing the effects of heating, which probably happened at the time the meteorite fell and exploded.

A preliminary chemical analysis was made by Mr. A. Väärismaa of the Tallinn Technical University, using a fragment weighing 0·4 gram from crater no. 2. His results are Fe 84·04, Ni 6·45, insoluble 0·53 = 91·02.

[1] G. T. Prior, Min. Mag., 1914, vol. 17, p. 131, pl. VI, figs. 2 and 3.

[2] L. J. Spencer, Min. Mag., 1933, vol. 23, p. 230, pl. XIV, fig. 8.

This gives a ratio Fe : Ni = 13; but it is evident from the deficiency in the total that the material analysed included iron rust, and this is no doubt less rich in nickel than the metal from which it was derived.

A micro-chemical analysis was made by Dr. M. H. Hey in the Mineral Department of the British Museum on 6·6 mg. of metal removed with a dental drill from the surface of section no. 3. His results are Fe 91·50, Ni 8·32 = 99·82. The 'Fe' includes any cobalt and copper, but these can be present in only small amount. Phosphorus was tested for but not found. Sulphur was not determined. The ratio Fe : Ni is here 11. The following is Dr. Hey's note on the method of analysis:

The metal was dissolved in dilute hydrochloric acid, evaporated, and oxidized with nitric acid, and the solution filtered. There was no insoluble residue. After addition of tartaric acid, the solution was made ammoniacal and the nickel precipitated with dimethylglyoxime, filtered off, dissolved and reprecipitated, dried, and weighed as $Ni(C_4H_7O_2H_2)_2$. In the evaporated filtrates, acidified with acetic acid, iron, cobalt, and copper were precipitated with 8-hydroxyquinoline, and the combined precipitate filtered off, dried, and weighed; neglecting its cobalt and copper content, the precipitate was taken to be $Fe(C_9H_6ON)_3$ and its iron content calculated.

Three meteorites have been previously recorded from Estonia (= Eesti):

*Oesel.* A shower of stones fell on May 11, 1855, on the Kaanda estate and some in the sea in the Taga laht (laht = gulf), on the NW. coast of the island of Oesel (= Saaremaa), 58° 30′ N., 22° 2′ E. Only fragments weighing 6 kg. were recovered.

*Pillisfer.* A shower of stones fell on August 8, 1863, at several places near Pillisfer (= Pilisvere), 58° 40′ N., 25° 44′ E. Stones weighing about 14, 7½, 1½, and ¼ kg. were recovered.

*Tennasilm.* A stone weighing 28½ kg. fell on June 28, 1872, on the Sikkensaare farm near the village of Tennasilm (= Tänasilma), 58° 44′ N., 24° 54′ E.

## *Postscript.*

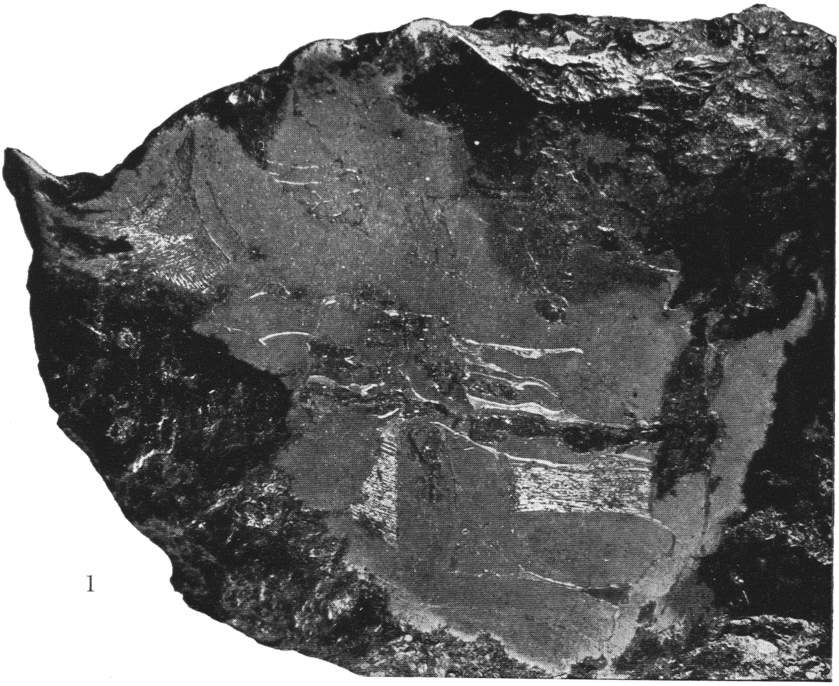
In December, 1937, Mr. I. Reinvald received a mass of iron weighing 2·4 kg. that had been found at a distance of ¾ km. from the main crater of Kaalijärv. It had been dug up from a depth of 50–60 cm. on the neighbouring estate of Köljala by students of the agricultural school when repairing foundations in the courtyard. Naturally Mr. Reinvald had hopes that this was meteoritic iron and that it might have some connexion with the meteorite craters, but a preliminary analysis showed the absence of nickel (Fe 91·90, P 0·85 %), and he was puzzled by the curious structure shown on a polished surface. He therefore very kindly sent the whole specimen for further examination.

The mass has an irregular rounded shape, about 11 cm. across, but with none of the concavities and pittings often to be seen on meteoritic irons. There is a thick crust of dark brown iron oxide, which is very hard and compact, and in part shows a minutely mamillated surface. It is strongly magnetic, and has an indistinct laminated structure, being very like the iron-shale found around weathered meteoritic iron. The polished (unetched) surface of the metal shows from numerous centres stellate groups (about 1 mm. across) of curved threads, the whole surface being covered with an intricate network of minute curved lines. These are cross-sections of flakes of graphite, which on a highly polished surface are worn down below the general level. Minute bright flakes of graphite are seen on fractured surfaces of the iron and also in the iron-shale. A fragment of the iron dissolved in hydrochloric acid left a residue of about 5 % consisting mainly of flakes of graphite. No nickel was detected. This pseudo-meteorite is therefore a block of grey cast iron.

## Explanation of Plate III.

The Kaalijärv meteorite from crater no. 2, Oesel, Estonia.

Photographs by D. L. Williams, Mineral Dept., British Museum, with different inclination of the light in the two figures. × 4. The light areas in fig. 2 are schreibersite in a grey ataxite groundmass, and the surrounding dark portion is iron-shale.



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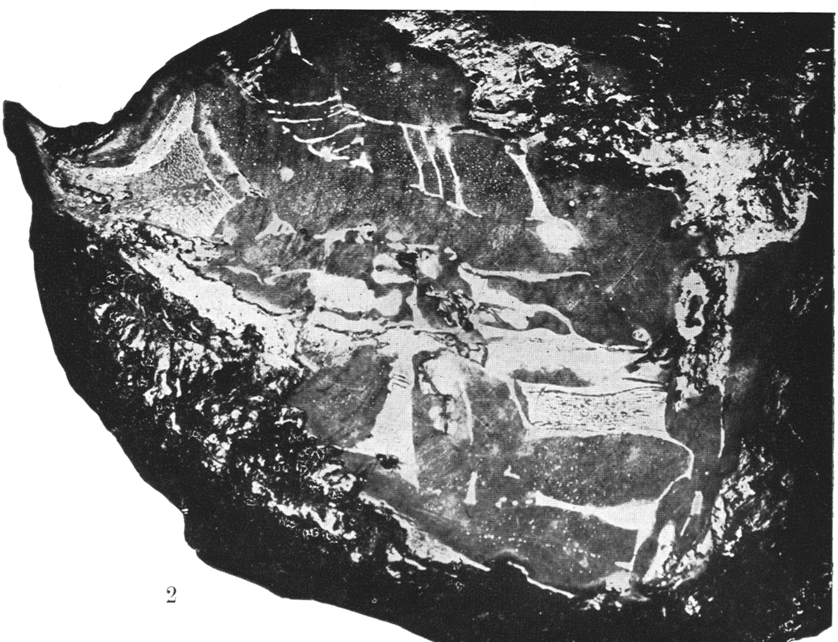

2

L. J. SPENCER: KAALIJARV METEORITE