

*The Morven meteorite, an aerolite from South  
Canterbury, New Zealand.*

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THE meteoric stone to be described was found in 1925 by Mr. William Stewart while ploughing on his farm four-and-a-half miles south of the Morven railway station ( $44^{\circ} 49' S.$ ,  $171^{\circ} 8' E.$ ) in South Canterbury, about one hundred miles north-east of Dunedin, New Zealand. It must have weighed originally about 7100 grams, but when presented to the Otago University Museum it weighed 14 lb. 14 oz. (6753 grams), the remainder having been broken off by the finder. There is no local record of the fall, and the nature of the weathered crust suggests that it may have been in the soil for a long time.

The stone (fig. 1) is roughly pyramidal, measuring approximately  $22.5 \times 17.5 \times 15.0$  cm. It was covered with a thin, soft ochreous crust occasionally as much as 2-3 mm. thick. Two of the faces are decidedly 'knobby', but the whole surface is pitted by deep 'thumb-marks'. Except for the absence of stream-marks and of flattish patches on the faces, the general appearance is that of the Mangwendi meteorite described by Lightfoot, Macgregor, and Golding.<sup>1</sup> Noteworthy is the presence of shearing surfaces which are exposed on breaking the meteorite. These are strongly slickensided and show generally a glossy black colour, except where a film of oxides occurs.

A polished surface displays many irregular steely bright grains of nickel-iron alloy, and small, occasionally encircling masses of bronze-coloured troilite, both set in a dark green to brownish-green silicate matrix, in which small chondrules may be seen. This matrix is stained to a varying degree by limonite films.

<sup>1</sup> B. Lightfoot, A. M. Macgregor, and E. Golding, The meteoric stone seen to fall in the Mangwendi native reserve, Southern Rhodesia, on March 7, 1934. *Min. Mag.*, 1935, vol. 24, pp. 1-12.

*Petrographical description.*

A petrographic study shows that the meteorite may be termed a crystalline chondrite.

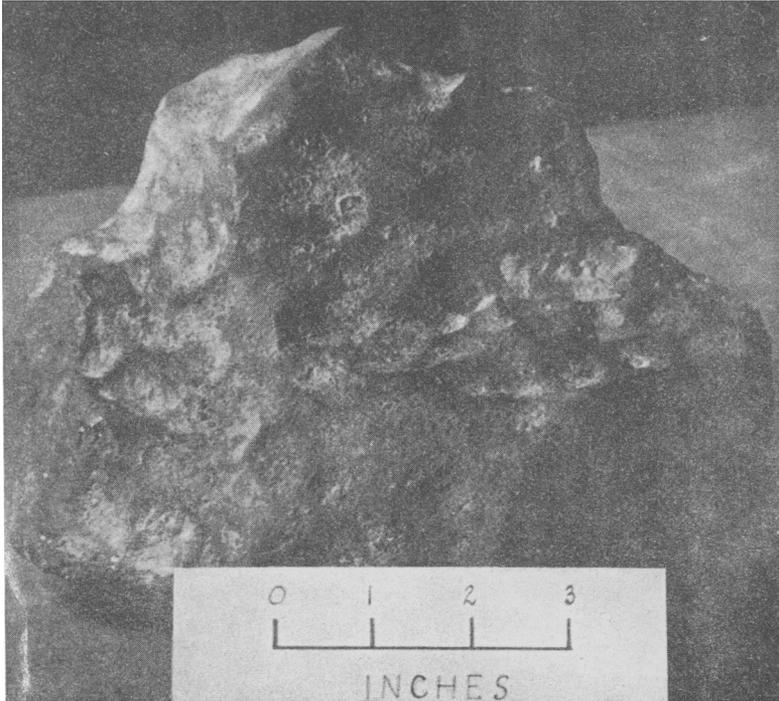


FIG. 1. The Morven meteorite.

*Chondrules.*—The most abundant mineral, olivine, occurs as various forms of chondrules. Some are perfectly rounded up to 0.75 mm. in diameter and are composed of tiny grains of olivine with a little iron-ore. The largest aggregate of this structure is oval in cross-section and 1.3 mm. long. Less often the constituent grains are coarse and set in a dusty greyish microcrystalline material, a transition to the porphyritic type of chondrule. Rarely the chondrules are composed of matted lath-like crystallites, 0.5 mm. long (fig. 2 D). Some chondrules are monosomatic, that is, consisting of a single grain, the largest being 0.4 mm. in diameter. The grains are clear and unbroken but occasionally show features approaching those of

the barred type<sup>1</sup> of chondrule. Enstatite chondrules are rather less abundant, but more varied in character and reach 1.0 mm. in diameter. Some are little more than ovoid aggregates of minute grains (fig. 2 A),

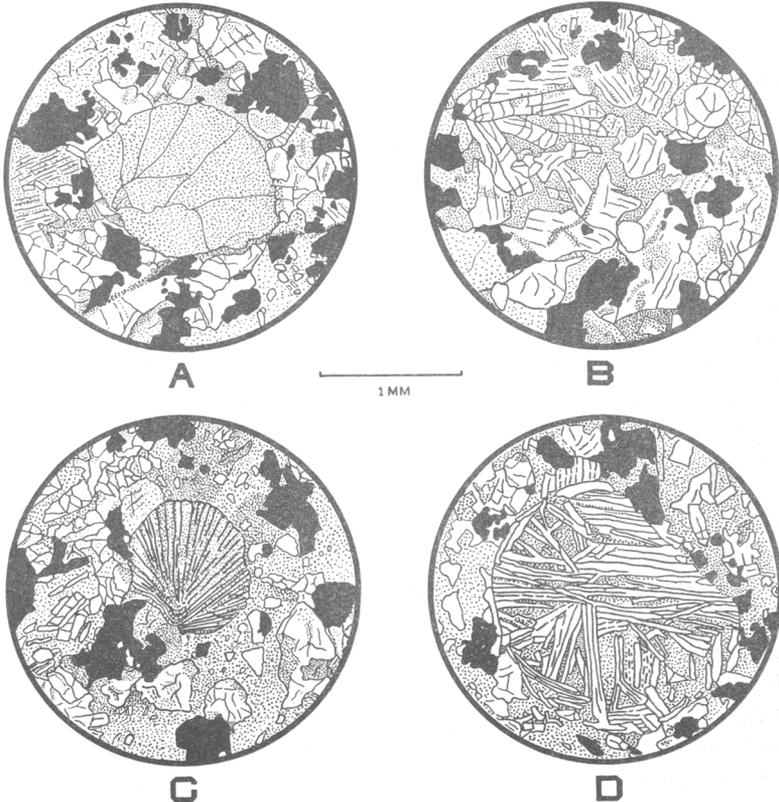


FIG. 2. Micro-sections of the Morven meteorite.

A. A chondrule of minutely fibrous enstatite surrounded by olivine, enstatite, troilite, and nickel-iron alloy.

B. An irregular chondrule composed of laths of enstatite embedded in a grey dusty matrix and surrounded by a granular mass of olivine, with troilite and iron-ore.

C. A radiating enstatite chondrule similarly surrounded.

D. A chondrule of prismatic crystals of olivine, with grey dusty matrix, surrounded by olivine, iron-ores, and a little enstatite.

<sup>1</sup> For example of this type of chondrule see R. E. S. Heineman, *Petrography of the Roy, Harding County, New Mexico, meteorite*. *Amer. Min.*, 1935, vol. 20, p. 439, fig. 3. [M.A. 6-104.]

perhaps deformed by shearing. In others, equally irregular, the grain size is less minute (fig. 2 B). Others again show a fibrous or prismatic radiating structure, which is often eccentric. More often there are seen merely sectors of a chondrule, seldom more than hemispherical. In one of these the radiating fibres of one side are bent around the central point and are continued into the radial fibres of the opposite side (fig. 2 c). In one section a well-rounded grain of diopside, 1.0 mm. in diameter, occurs; it is well cleaved, with extinction  $c:\gamma$  of  $37^\circ$  and optically positive. The largest grain of enstatite was of irregular form, 2.6 mm. in length, with wavy cleavage lines and undulose extinction. It is granulated along fracture lines. This cannot, however, be considered part of a chondrule.

*Metals and sulphides.*—The nickel-iron alloy occurs as highly irregular masses, averaging 0.3 mm. in diameter (rarely up to 1.0 mm.), which may enclose grains of olivine and enstatite. Troilite (or pyrrhotine) is often intergrown with, or encloses, this alloy. Troilite as rather abundant ragged grains, up to 0.4 mm. across, has a bronze colour in reflected light and, in addition to being scattered throughout the rock, forms veinlets or thin sheets along the shearing planes.

*The matrix.*—The matrix is holocrystalline, consisting of an aggregate of irregular grains of olivine and pyroxene with finely divided troilite and nickel-iron alloy. There are present also rare small, irregularly-shaped grains, not exceeding 0.3 mm. in diameter, composed of a substance like maskelynite. They are isotropic and transparent, with a low refractive index, and they would appear to have been among the latest minerals to crystallize. In addition to these, there also occur a few chondrule-like aggregates composed entirely of dusty-grey minute granules with weak refringence and birefringence. Similar grey material frequently occurs as small, irregularly-shaped grains, interstitial to the grains of ferromagnesian silicates.

As a result of weathering, the minerals are frequently stained by thin films of limonite.

#### *Chemical analysis.*

The general scheme of analysis was that used by the chemists of the United States National Museum in the analysis of the Florence stone<sup>1</sup> and later by E. Golding for the Mangwendi stone (loc. cit., p. 9). A chip of the meteorite was taken and ground up to pass

<sup>1</sup> G. P. Merrill, The composition and structure of meteorites. Bull. U.S. Nat. Mus., 1930, no. 149, p. 57. [M.A. 4-257.]

80-inch mesh. This powder was then spread out thinly on glazed paper and separated into magnetic and non-magnetic portions by means of a hand-magnet. The attracted portion was thoroughly re-worked in order to rid it of as much non-magnetic material as possible, while the non-magnetic portion was likewise re-treated. The chip taken weighed 39.5 grams, and after magnetic separation the following results were obtained:—

Attracted portion ... ..	9.3585 grams
Unattracted portion ... ..	30.0224
	<hr/> 39.3809

*Attracted portion.*—The whole of the magnetic portion was then digested with aqua regia, then later with  $\text{Na}_2\text{CO}_3$ , as recommended by Merrill (loc. cit., p. 58), with the following results:—

Dissolved ... ..	7.7027 grams (19.55 % of whole)
Undissolved ... ..	1.6558
	<hr/> 9.3585

The washings and filtrate from the two digestions were combined and made up to one litre at  $15^\circ\text{C}$ ., after the separation of silica. From this solution duplicate aliquot portions were taken for the various determinations and an average of the values obtained gives the following results:—

	Grams.	19.55 % of whole.
<i>Soluble silicate:</i>		
$\text{SiO}_2$ ... ..	0.5274	1.339 %
$\text{TiO}_2$ ... ..	trace	trace
$\text{Al}_2\text{O}_3$ ... ..	0.0010	0.002
$\text{FeO}$ ... ..	0.1923	0.488
$\text{MnO}$ ... ..	0.0040	0.010
$\text{MgO}$ ... ..	0.5756	1.462
$\text{CaO}$ ... ..	0.0409	0.103
	<hr/> 1.3412	
<i>Pyrrhotine (<math>\text{Fe}_7\text{S}_8</math>):</i>		
Fe ... ..	0.3702	0.939
S ... ..	0.2430	0.617
	<hr/> 0.6132	
<i>Metal:</i>		
Fe ... ..	5.0424	12.800
Ni ... ..	0.5418	1.376
Co ... ..	0.0422	0.107
Cu ... ..	nil	nil
P ... ..	0.0838	0.212
	<hr/> 5.7102	
	7.6646	19.455

Composition of metallic portion (14.50 % of whole meteorite):

Fe.	Ni.	Co.	P.	Pt metals.	Au.
88.31	9.49	0.74	1.47	trace	nil

In the estimation of Fe, FeO, Ni, Co, CaO, MgO, &c., analytical procedure was practically the same as that recommended by Merrill (loc. cit., p. 59), with certain exceptions. The precipitation of aluminium and ferric hydroxides was done most carefully, since Lundell and Knowles<sup>1</sup> have shown it is difficult to effect a complete separation of these hydroxides from cobalt. Following their recommendations a large amount of ammonium chloride and nitrate were present in the solution and the pH value was carefully adjusted. Four reprecipitations of these hydroxides were made. The nickel was then estimated in the filtrate by precipitation with dimethylglyoxime; the bulky red precipitate after filtering through a Gooch crucible, and washing, was treated with 5 c.c. of alcohol followed by ether, then dried for a short time *in vacuo*.<sup>2</sup> The estimations of Co, CaO, and MgO were then carried out as recommended by Merrill (loc. cit., p. 59). As a check on the estimation of cobalt, 50 c.c. of the original solution<sup>3</sup> were taken, precipitated four times with ammonia, the precipitate each time being dissolved in 4*N* sulphuric acid. To the solution then freed from aluminium and iron, 10 grams of ammonium sulphate and a moderate excess of strong ammonia were added. This solution was electrolyzed using a rotating cathode and a current of 0.75 amps., until a spot-test showed that no trace of nickel remained in the liquid. The cathode was then weighed, the increase in weight being due to the nickel and cobalt deposited.<sup>4</sup> These two metals were then dissolved off the cathode with 1:1 nitric acid, and the nickel in that solution determined gravimetrically as nickel dimethylglyoxime. The value obtained for nickel by this method was almost identical with that obtained previously (0.5418 and 0.5420 gram respectively), but the amount of electrolytic cobalt (0.0422 gram) was slightly higher than that determined before (0.0400 gram).

<sup>1</sup> G. E. F. Lundell and H. B. Knowles, The separation of iron and aluminium from manganese and certain other elements. Journ. Amer. Chem. Soc., 1923, vol. 45, pp. 676-681.

<sup>2</sup> C. A. Mitchell, Recent advances in analytical chemistry, London, 1931, vol. 2, p. 272.

<sup>3</sup> This solution was evaporated to dryness several times with concentrated hydrochloric acid, in order to free from nitrates, before precipitation with ammonia.

<sup>4</sup> Copper, if present, would have been precipitated under the same conditions.

*Soluble silicate in the unattracted portion.*—For the analysis of the soluble silicate portion, triplicate portions of two grams (2·0000) of the unattracted powder were taken and treated with aqua regia and later with  $\text{Na}_2\text{CO}_3$  as was the case with the magnetic fraction. The average result was:—

Dissolved	...	...	1·0787 grams
Undissolved	...	...	0·9213
			2·0000

The average composition of the dissolved portion was:—

$\text{SiO}_2$	...	...	0·3339 grams	...	30·96 %
$\text{TiO}_2$	...	...	trace	...	trace
$\text{Al}_2\text{O}_3$	...	...	0·0340	...	3·15
$\text{FeO}$	...	...	0·2260	...	20·96
$\text{NiO}$	...	...	0·0151	...	1·40
$\text{CoO}$	...	...	nil	...	nil
$\text{MnO}$	...	...	0·0040	...	0·37
$\text{MgO}$	...	...	0·3285	...	30·47
$\text{CaO}$	...	...	0·0143	...	1·33
$\text{P}_2\text{O}_5$	...	...	0·0085	...	0·79
$\text{Fe}$	...	...	0·0684	...	6·35
$\text{S}$	...	...	0·0393	...	3·64
			1·0720		99·42

*Insoluble silicate portions.*—The insoluble residues that remain after the digestion of the attracted and unattracted portions were thoroughly mixed. Of this approximately one gram (0·9533 gram) was taken, fused with alkali carbonates, and analysed by standard methods, the chromite being decomposed by the addition of a little potassium nitrate to the fusion mixture. The analysis of the insoluble silicate gave the following results:—

$\text{SiO}_2$	...	...	0·5358 grams	...	56·21 %
$\text{TiO}_2$	...	...	0·0025	...	0·26
$\text{Al}_2\text{O}_3$	...	...	0·0570	...	5·98
$\text{Cr}_2\text{O}_3$	...	...	0·0018	...	0·19
$\text{FeO}$	...	...	0·0797	...	8·36
$\text{NiO}$	...	...	nil	...	nil
$\text{CoO}$	...	...	nil	...	nil
$\text{MnO}$	...	...	0·0030	...	0·31
$\text{MgO}$	...	...	0·2184	...	22·92
$\text{CaO}$	...	...	0·0325	...	3·41
$\text{Na}_2\text{O}$	...	...	0·0220	...	2·30
$\text{K}_2\text{O}$	...	...	0·0036	...	0·38
$\text{P}_2\text{O}_5$	...	...	nil	...	nil
			0·9563		100·30

From these various analyses the bulk chemical composition of the meteorite may be calculated as follows:—

	Attracted %.		Unattracted %.		Bulk	
	Grams.	Per cent.	Grams.	Per cent.	Grams.	Per cent.
SiO <sub>2</sub> ...	6.85	...	43.58	...	14.2404	36.160
TiO <sub>2</sub> ...	trace	...	0.13	...	0.0402	0.102
Al <sub>2</sub> O <sub>3</sub> ...	0.01	...	4.56	...	1.4371	3.649
Cr <sub>2</sub> O <sub>3</sub> ...	nil	...	0.09	...	0.0294	0.075
FeO ...	2.50	...	14.66	...	4.8793	12.390
NiO ...	nil	...	0.70	...	0.2268	0.576
CoO ...	nil	...	nil	...	nil	nil
MnO ...	0.05	...	0.34	...	0.1020	0.259
MgO ...	7.47	...	26.69	...	9.0556	22.990
CaO ...	0.53	...	2.37	...	0.7833	1.989
Na <sub>2</sub> O ...	nil	...	1.15	...	0.3559	0.904
K <sub>2</sub> O ...	nil	...	0.19	...	0.0588	0.149
P <sub>2</sub> O <sub>5</sub> ...	nil	...	0.39	...	0.1276	0.324
P ...	1.09	...	nil	...	0.0838	0.213
Fe ...	70.28	...	3.17	...	6.4396	16.350
Ni ...	7.03	...	nil	...	0.5418	1.376
Co ...	0.55	...	nil	...	0.0422	0.107
Cu ...	nil	...	nil	...	nil	nil
S ...	3.16	...	1.82	...	0.8330	2.114
Pt ...	trace	...	—	...	trace	trace
Totals	99.52	...	99.84	...	39.2768	99.727
SrO ...	—	...	—	...	—	nil
H <sub>2</sub> O > 105° ...	—	...	—	...	—	nil
H <sub>2</sub> O < 105° ...	—	...	—	...	—	0.230
V <sub>2</sub> O <sub>3</sub> ...	—	...	—	...	—	trace?
SO <sub>3</sub> ...	—	...	—	...	—	trace
Cl ...	—	...	—	...	—	nil
Grand total						99.957

Specific gravity of four chips (not chips analysed): 3.54, 3.55, 3.59, 3.62.

In order to determine the modal composition of the Morven meteorite, the author follows the writers on the South Rhodesian meteorite (*loc. cit.*, p. 8) in treating the three analyses separately. It must be stressed, however, that certain compounds such as triplite and schreibersite, assumed for purpose of calculation, have not been identified in thin section, but the various molecules constituting these compounds may be divided between yet other modal compounds.

In the soluble magnetic portion, sulphur was reckoned as pyrrhotine, while the phosphorus was divided between the metallic phosphide, schreibersite, and the manganese and iron phosphate, triplite.

The lime was calculated as monticellite and included in the olivine, as lime has been reported in some analyses of olivines in meteorites.<sup>1</sup> The silica, magnesia, and some iron were combined to form olivine.

*Modal Composition.*

	Magnetic portion.	Insoluble silicates.	Soluble silicates.	Bulk.
<b>Felspars:</b>				
Orthoclase ...	—	0.76	—	0.76
Albite ...	—	7.66	—	7.66
Anorthite ...	—	1.92	—	1.92
<b>Pyroxenes:</b>				
Diopside ...	—	3.68	—	3.68
Bronzite ...	—	20.93	—	20.93
<b>Olivine:</b>				
Olivine ...	3.37	4.16	33.21	40.74
<b>Spinellids:</b>				
Chromite ...	—	0.11	—	0.11
Hercynite ...	—	—	2.21	2.21
<b>Sulphides:</b>				
Troilite ...	—	—	4.11	4.11
Pyrrhotine ...	1.56	—	—	1.56
<b>Phosphorus compounds:</b>				
Triplite ...	0.05	—	0.82	0.87
Schreibersite ...	1.30	—	—	1.30
<b>Iron-ore:</b>				
Ilmenite ...	—	0.20	—	0.20
<b>Oxides:</b>				
Nickel oxide ...	—	—	0.57	0.57
<b>Metals:</b>				
Iron ...	11.70	—	—	11.70
Nickel ...	1.38	—	—	1.38
Cobalt ...	0.11	—	—	0.11
<b>Totals ...</b>	<b>19.47</b>	<b>39.42</b>	<b>40.92</b>	<b>99.81</b>

The procedure in the case of the soluble silicate portion was similar, except that the sulphur was calculated as troilite and the alumina as hercynite. There remains, however, 1.4 % of nickel oxide which may represent nickel from the incompletely separated attracted portion or may quite possibly include also some nickel from the olivine. In view of this uncertainty it has been left as the uncombined oxide.

For the insoluble silicate portion, all the alkalis, alumina, and some lime were combined to form felspars, while the remainder of the lime was reckoned as diopside. The chromium and titanium

<sup>1</sup> C. Doelter, *Handbuch der Mineralchemie*, 1914, vol. 2, pt. 1, pp. 292, 301.

were calculated as chromite and ilmenite respectively, while the remainder of the bases were calculated as pyroxene together with a little olivine, the manganese being included in the pyroxene.<sup>1</sup>

The modal composition is shown on the previous page.

For the purposes of comparison with other meteorites the following data are given:—

- |  |     |     |     |     |     |       |
|--|-----|-----|-----|-----|-----|-------|
| (1) percentage of metal (' <i>f</i> ')                       | ... | ... | ... | ... | ... | 13.19 |
| (2) ratio of iron + cobalt to nickel in metal (' <i>n</i> ') | ... | ... | ... | ... | ... | 9.58  |
| (3) ratio of MgO to FeO in silicate by weight                | ... | ... | ... | ... | ... | 2.45  |
| "    "    "    by molecular proportion (' <i>m</i> ')        |     |     |     |     |     | 4.36  |
| (4) dominant felspar—basic oligoclase.                       |     |     |     |     |     |       |

*Classification.*—The above data indicate that the Morven meteorite belongs naturally to group 2 of class 3 of Prior's classification,<sup>2</sup> that is, one of the Cronstad type. Following Prior (loc. cit., p. 61) then, the Morven meteorite is termed a veined brecciated grey bronzite-olivine-chondrite. Petrographically it is rather similar to the Roy, Mangwendi, and Makarewa stones, but differs chemically from the two latter by reason of their lower iron content. Chemically the Morven meteorite bears a close resemblance to the following stones as shown in the table below:<sup>3</sup>

	1.	2.	3.	4.	5.	6.	7.	8.	9.
<i>f</i> ...	13.19	18.5	11	17	15	10.5	17	14	15.5
<i>n</i> ...	9.58	11	8	11	8	9	10	10.5	10.5
<i>m</i> ...	4.36	5	4	4	4	3.5	5	4.75	5

1, Morven stone, South Canterbury, New Zealand. 2, Cronstad stone, Orange Free State, South Africa. 3, Homestead stone, Iowa, U.S.A. 4, Salt Lake City stone, Utah, U.S.A. 5, Lixna stone, Dvinsk, Latvia. 6, Marion stone, Linn County, Iowa, U.S.A. 7, Ogi stone, Hizen, Kyushu, Japan. 8, Cobija stone, Pampa of Santa Barbara, Antofagasta, Chile. 9, Queens Mercy stone, Matatiel, Griqualand East, Cape Province, South Africa.

The Morven stone is the fourth meteorite to be recorded from New Zealand. Those previously known are:

*Wairarapa* Valley, Wellington, North Island. A stone of about 30 lb. found in 1864 at Tohirua, near Masterton (40° 57' S., 170° 40' E.). Jurors' Report, N.Z. Exhibition, 1865, Dunedin, 1866, p. 410;

<sup>1</sup> For presence of manganese in orthorhombic pyroxenes see O. C. Farrington, *Meteorites*. Chicago, 1915, p. 173.

<sup>2</sup> G. T. Prior, *The classification of meteorites*. *M. n. Mag.*, 1920, vol. 19, pp. 51-63.

<sup>3</sup> Data obtained from the British Museum Catalogue of Meteorites (1923) and appendix (1927) by G. T. Prior; the symbols employed are those used in the museum catalogue.

W. Flight, *Geol. Mag. London*, 1875, p. 556. and *History of Meteorites*, 1887, p. 140; G. R. Marriner, *Trans. N.Z. Inst.*, 1910, vol. 42 (for 1909), p. 177.

*Makarewa*, Invercargill, Southland. A stone of 4 or 5 lb. found in 1879 when constructing the railway (46° 20' S., 168° 20' E.). G. H. F. Ulrich, *Proc. Roy. Soc. London*, 1893, vol. 53, p. 54; L. Fletcher, *Min. Mag.*, 1894, vol. 10, p. 287; G. R. Marriner, *loc. cit.*, p. 178. The place-name is incorrectly spelt *Makariwa* in the papers of Ulrich and Fletcher.

*Mokoia*, Taranaki, North Island (39° 38' S., 174° 22' E.). A shower of stones fell at 12.30 p.m. on November 26, 1908; two of about 5 lb. each were recovered. G. R. Marriner, *loc. cit.*, p. 180.

In conclusion, it might be of interest to include here an abstract from Elsdon Best's *Dominion Museum Monograph* (1922, no. 3, p. 57) on 'The astronomical knowledge of the Maori'.

Meteors are termed by the Maori *Tumatakohiri*, and other names derived therefrom. To some they were merely stars at their gambols, stars that have wandered out of their places and have been struck by their elders, the sun and the moon. The appearance of a meteor was often considered an evil omen, betokening, for example, the death of a chief. On the other hand, if a meteor seems to approach one it is a good sign. Yet again they have other prophetic significance. 'Another ancestor is *Tumatakohiri*, who is seen at night. His appearance is that of a star flying through space. His task, as he so flies, is to foretell the aspect and conditions of the heavenly bodies, of winds, and of seasons. If he swoops downwards the following season will be a windy one. If he just flies through space, a fruitful season follows, a season of plenty lies before the people. That ancestor is a supernatural being, though really a star flying through space.'

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