

CHEMICAL COMPOSITIONS OF ANTARCTIC METEORITES I

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Abstract: Sixty-four chondrites (14 H, 25 L, 17 LL and 8 C), 32 achondrites and 2 rare stony-iron meteorites from Antarctica were analyzed by standard wet chemical analysis method. In the present paper the analyses of the chondrites and the stony-iron meteorites are reported. Many Antarctic meteorites are more or less weathered or oxidized. Analyses of fresh and weathered parts of three chondrites indicate that abundances of most major elements are essentially the same between the two parts except for the proportions of Fe, FeO and Fe₂O₃. The analyses of the chondrites show that H chondrites and L and LL chondrites are distinct in several components (*e.g.*, Na₂O is separated at 0.85 wt %). When iron and FeS are subtracted, however, all the ordinary chondrites have essentially the same compositions, although H chondrites are slightly higher in Mg and lower in Si than L and LL chondrites. The compositions of the eight carbonaceous chondrites indicate that they comprise both C2 and C3 types in equal number. The analyzed carbonaceous chondrites are distinctly lower in SiO₂, Na₂O and K₂O and higher in MgO, Al₂O₃ and CaO than the ordinary chondrites. The stony-iron meteorites analyzed are similar to lodranite; however, one differs from lodranite in SiO₂, Al₂O₃ and CaO, and the other differs in SiO₂ and Fe/Mg ratio.

1. Introduction

During the past 14 years the Japanese Antarctic Research Expeditions have collected nearly 5000 pieces of meteorites from Antarctica, mostly from the Yamato Mountains. For the purpose of determining the chemical characteristics of these abundant meteorites as well as providing basic compositional data to other researchers, we began a long-term project to determine the major element compositions of as many these meteorites as possible. This work started in 1981, and 98 meteorites (64 chondrites, 32 achondrites, 2 stony-iron meteorites) have been analyzed by the senior author (H. H.). Analyses of a great number of meteorites by a single analyst using the same method eliminate interlaboratory biases and enable us to compare their compositions in detail, as was already pointed out by WILK (1956). The present paper reports the analyses of all the analyzed chondrites and two rare stony-iron meteorites. The analyses of achondrites will be published elsewhere.

Selection of meteorites for analysis is affected by their size and degree of alteration. The Antarctic meteorites are variable in size and degree of alteration. We have

selected relatively fresh samples (mostly weathering type A and some type B of LIPSCHUTZ, 1982) with weight greater than 100 g. However, interesting samples weighing less than 100 g were also analyzed.

2. Analytical Method

All analyses were made with standard wet chemical analysis method. Samples ranging in weight from 1 to 10 g were first ground to less than 250 mesh, except for metal grains. The fine-grained powder was separated by a hand magnet into magnetic and non-magnetic fractions. The former consists of metal and some silicates, whereas the latter consists essentially of silicates. The magnetic fraction was divided into three portions. Two portions were used for determination of S and P, respectively. The third portion was dissolved in a mixed acid (3 parts HNO_3 and 1 part HCl). Ten elements (Fe, Ni, Ti, Al, Ca, Mg, Mn, Cr, Na and K) were determined in the acid-soluble. The acid-insoluble which consists of silicates was analyzed for Si, Al, Ni and Mg. The non-magnetic fraction was analyzed for 13 elements and water with the same method as that for analyzing terrestrial rocks. In this fraction, however, very fine-grained metal grains are included, resulting in a slight overestimation of Fe and Ni. The amount of such fine-grained metal is estimated to be less than 0.5 wt % and does not seriously affect the iron content of this fraction. Figure 1 shows the elements analyzed for each fraction. The above analytical method was checked by analyzing an artificial mixture of powdered peridotite and metallic iron with known compositions and was found to be satisfactory. One problem is that some Antarctic meteorites contain ferric iron and part of it may be reduced by S during analysis. Ferric iron in the sample (if any) may, therefore, be underestimated. This effect was checked by analyzing mixtures of magnetite + pyrrhotite and basalt + pyrrhotite. The amount of ferric iron reduced was about 3% of the total ferric iron present, and does not affect the analyses of the meteorites which contain less than 3 wt % Fe_2O_3 .

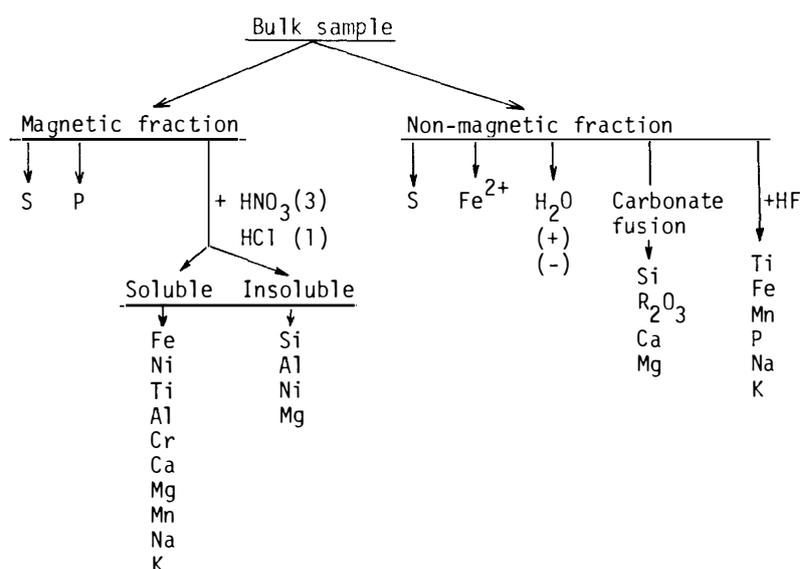


Fig. 1. Analytical procedures and elements analyzed in respective fractions.

3. Analytical Results and Discussion

The results of the analyses of H, L, LL and C chondrites are given in Tables 1–4. Classification of these chondrites was made on the basis of their compositions, particularly by plotting the analyses in a UREY and CRAIG (1953) diagram. The analyses plot in four distinctly different regions corresponding to those of H, L, LL and C chondrites of UREY and CRAIG (1953) and MASON (1962) (Fig. 2). The compositions

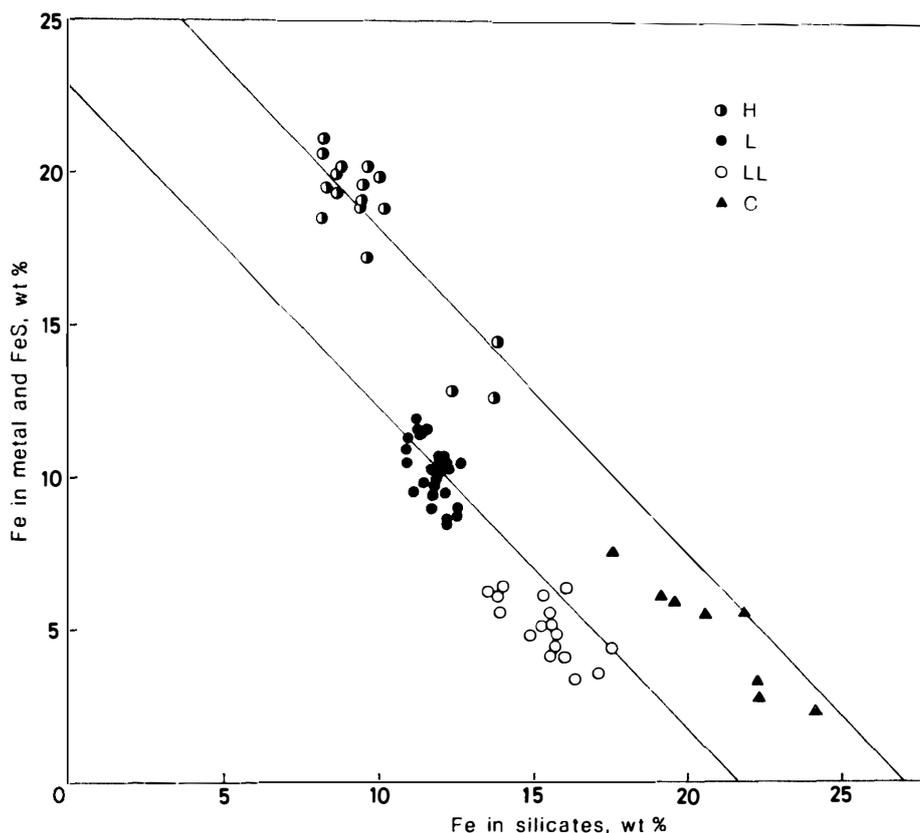


Fig. 2. Analyses of chondrites plotted in the Urey-Craig diagram.

of the carbonaceous chondrites, which contain up to 15 wt % volatiles, were recalculated to 100% and plotted assuming that all S is present as FeS. They plot close to the region for carbonaceous chondrites of WILK (1956) and MASON (1962). Carbonaceous chondrites can also be distinguished from ordinary chondrites by the presence of appreciable amounts of carbon which we estimated semi-quantitatively during our analytical procedures. Some ordinary chondrites also contain carbon, but the abundances are distinctly lower than those of carbonaceous chondrites.

Three H chondrites plot in an area of low metallic iron contents. These samples are significantly weathered, but many other Antarctic meteorites are also weathered or oxidized. The effect of weathering or oxidation on the major element abundances other than FeO and Fe₂O₃ was, therefore, examined. Both the oxidized and the relatively fresh parts of three chondrites were analyzed (Nos. 5 and 16, and 10 and 17 in Table 1; Nos. 3 and 4 in Table 3). The chondrite ALH-768 (Nos. 10 and 17 in Table

Table 1. Chemical compositions of H chondrites*.

	1	2	3	4	5	5-A	6	6-A	7	8	8-A
SiO ₂	34.07	35.62	35.70	36.62	35.41	35.72	36.42	36.58	35.70	34.27	34.68
TiO ₂	0.07	0.11	0.12	0.17	0.09	0.09	0.13	0.13	0.09	0.11	0.11
Al ₂ O ₃	1.31	2.87	2.08	2.19	1.88	1.90	1.50	1.51	2.52	2.24	2.27
Fe ₂ O ₃	0	0	0	0	0.49	0	1.59	0	0	0.28	0
FeO	12.14	12.12	11.35	11.13	11.99	12.09	10.78	10.92	12.08	12.78	12.93
MnO	0.23	0.31	0.27	0.33	0.27	0.27	0.30	0.30	0.31	0.26	0.26
MgO	23.67	23.77	24.03	24.38	23.53	23.72	23.84	23.95	23.48	23.35	23.62
CaO	3.42	1.66	1.52	1.66	1.63	1.64	1.80	1.81	1.63	1.51	1.53
Na ₂ O	0.71	0.78	0.74	0.86	0.85	0.85	0.74	0.74	0.71	0.43	0.43
K ₂ O	0.07	0.07	0.09	0.09	0.14	0.14	0.08	0.08	0.08	0.05	0.05
H ₂ O(+)	0.3	0.8	0.1	0.0	0.43	0	0.4	0	0.3	1.1	0
H ₂ O(-)	0.06	0.21	0.05	0.00	0.00	0	0.13	0	0.18	0.27	0
P ₂ O ₅	0.20	0.23	0.27	0.26	0.22	0.22	0.24	0.24	0.20	0.24	0.24
Cr ₂ O ₃	0.42	0.53	0.47	0.55	0.47	0.47	0.49	0.49	0.41	0.46	0.46
FeS	5.46	5.32	5.21	4.87	5.32	5.36	5.63	5.66	5.30	5.53	5.59
Fe	16.01	13.60	15.93	15.45	15.29	15.76	14.66	15.84	15.61	15.91	16.30
Ni	1.66	1.68	1.69	1.75	1.70	1.71	1.68	1.69	1.90	1.45	1.47
Co	0.076	0.028	0.070	0.039	0.060	0.060	0.066	0.066	0.084	0.067	0.068
Total	99.87	99.70	99.69	100.34	99.77	100.00	100.47	100.00	100.58	100.30	100.00
	9	10	11	12	12-A	13	14	15	16	17	17-A
SiO ₂	35.89	35.20	35.83	36.12	36.13	35.44	33.69	36.62	37.85	34.67	36.72
TiO ₂	0.07	0.08	0.06	0.06	0.06	0.07	0.06	0.16	0.10	0.12	0.13
Al ₂ O ₃	1.73	1.81	2.04	1.74	1.74	1.61	2.50	2.14	2.10	2.32	2.46
Fe ₂ O ₃	0	0	0	0.16	0	0	0	0	0	10.17	0
FeO	11.19	13.04	11.09	10.47	10.47	10.16	17.26	17.43	15.58	9.96	10.55
MnO	0.24	0.30	0.25	0.25	0.25	0.25	0.30	0.30	0.31	0.29	0.31
MgO	23.22	23.56	23.69	23.61	23.62	22.94	22.54	23.92	25.05	23.21	24.58
CaO	1.43	1.75	1.62	1.49	1.49	1.49	1.43	1.72	1.74	1.70	1.80
Na ₂ O	0.69	0.80	0.71	0.75	0.75	0.72	0.81	0.85	0.94	0.78	0.83
K ₂ O	0.08	0.09	0.08	0.09	0.09	0.08	0.06	0.10	0.12	0.08	0.08
H ₂ O(+)	0.7	0.3	0.2	0.1	0	0.2	2.3	0.4	0.0	1.9	0
H ₂ O(-)	0.1	0.17	0.22	0.09	0	0.03	0.31	0.13	0.00	0.58	0
P ₂ O ₅	0.23	0.27	0.23	0.20	0.20	0.28	0.27	0.37	0.10	0.23	0.24
Cr ₂ O ₃	0.46	0.48	0.45	0.44	0.44	0.43	0.49	0.57	0.52	0.50	0.53
FeS	5.83	5.33	5.58	5.90	5.90	6.21	5.11	3.02	3.91	4.58	4.85
Fe	16.18	15.45	16.60	16.70	16.82	18.53	10.74	10.80	10.26	7.44	15.41
Ni	1.66	1.64	1.54	1.98	1.98	1.69	1.38	1.54	1.36	1.41	1.49
Co	0.043	0.048	0.058	0.060	0.060	0.078	0.078	0.034	0.046	0.021	0.022
Total	99.74	100.31	100.24	100.21	100.00	100.20	99.32	100.10	99.98	99.96	100.00

1. Y-74142,71 (H3) 2. Y-74192,77 (H5) 3. Y-74371,77 (H5)
4. Y-74647,96 (H5) 5. Y-790746,83 (H6) 5-A. No. 5 on H₂O and Fe₂O₃-free basis.
6. Y-791143,71 (H4) 6-A. No. 6 on H₂O and Fe₂O₃-free basis.
7. Y-791312,72 (H4) 8. Y-791315,73 (H4) 8-A. No. 8 on H₂O and Fe₂O₃-free basis.
9. Y-792764,61 (H5) 10. ALH-768,59 (H6) 11. Y-791406,62 (H4)
12. Y-791427,71 (H4) 12-A. No. 12 on H₂O and Fe₂O₃-free basis.
13. Y-74155,52 (H4) 14. Y-74640,87 (H6)^L 15. Y-75028 (H3)
16. Y-790746,63 (H6) 17. ALH-768,72 (H6) 17-A. No. 17 on H₂O and Fe₂O₃-free basis.

* Nos. 1-13 are relatively fresh and Nos. 14-17 are oxidized.

1) shows the strongest effect of oxidation near the surface (type C of LIPSCHUTZ, 1982). The core of this sample is free of Fe_2O_3 , whereas the marginal part contains 10.17 wt % Fe_2O_3 and much less Fe. Judging from the analyses, Fe_2O_3 would have been formed essentially by oxidation of metallic iron. There is no clear evidence for oxidation of mafic silicate minerals to give Fe_2O_3 even in such extensive weathering. Both $\text{H}_2\text{O}(+)$ and $(-)$ are also higher in the oxidized parts. However, most of other major elements are nearly the same for both the parts. Alumina, however, is higher in the oxidized part than in the core. It is not certain whether this is due to weathering or not, because Al_2O_3 is variable even in a single relatively fresh chondrite. The analyses of Fe_2O_3 -bearing chondrites were converted to Fe_2O_3 -free composition on the assumption that all Fe_2O_3 has been formed by oxidation of metal. The recalculated analyses are given in the next column (A) of each of the uncorrected analyses containing Fe_2O_3 . Oxidation of metal would also produce FeO in some chondrites. This is clearly shown by Y-790746 and Y-74646 chondrites (Nos. 5 and 16 in Table 1, and Nos. 3 and 4 in Table 3, respectively); Nos. 5 and 3 show higher Fe and lower FeO contents than Nos. 16 and 4, respectively. Other chondrites such as Nos. 14, 15 and 16 in Table 1 also show such oxidation. The analyses of these oxidized samples are shown in separate columns (Nos. 14–17) in Table 1.

Heterogeneity of the sample other than due to oxidation was also examined for two different parts of sample ALH-761 (Nos. 21 and 22 in Table 2). The two analyses are very similar except for SiO_2 , MgO and Fe which show differences of about 1 absolute wt %. All the analyses given in the tables are expected to have similar variations within the respective samples.

The Na_2O and K_2O contents of all the analyzed chondrites are shown in Fig. 3. K_2O in the chondrites, though its abundance is low, appears to be positively correlated with Na_2O . The $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios range from 0.07 to 0.14 with a mean value of about 0.10. There are no systematic variations in $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio with petrologic type of the chondrites. The $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios of the "superior analyses" selected by UREY and CRAIG (1953) range from 0.02 to 0.48 wt % and scatter considerably. WIJK's (1956) analyses show a much smaller scatter and the average is close to ours. Twenty-three analyses of chondrites by JAROSEWICH (1966, 1967) and JAROSEWICH and MASON (1969) show very coherent values of Na_2O and K_2O . Analyses of Orgueil and Ivuna (C1) by WIJK (1956) have $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios of 0.95 and 0.93 respectively. These analytical results indicate that K and Na were not significantly fractionated during the formation of chondrites.

The Na_2O contents of L and LL chondrites analyzed are higher than those of H chondrites; the former has >0.85 wt % Na_2O , and the latter $<0.85\%$, except for two (Figs. 3 and 4). Figure 4 shows that the CaO contents of H chondrites are also slightly lower than those of L and LL chondrites. The same results are obtained from the analyses by JAROSEWICH (1966, 1967). However, when metal and FeS are subtracted and the compositions of the silicate portions are recalculated to 100%, the CaO and Na_2O contents of most of the chondrites analyzed plot in the narrow area and they become indistinguishable (Na_2O ; 1.01 ± 0.11 wt % and CaO, 2.00 ± 0.30 wt %) as shown in Fig. 5. These results indicate that the silicate fractions of ordinary chondrites have relatively uniform CaO, Na_2O and K_2O abundances and suggest that these elements

Table 2. Chemical compositions of L chondrites.

	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	39.46	39.07	39.24	40.09	38.80	38.63	38.67	40.20	39.71	39.33	39.34
TiO ₂	0.09	0.14	0.10	0.24	0.09	0.14	0.09	0.08	0.21	0.07	0.06
Al ₂ O ₃	1.61	2.29	2.83	2.89	2.62	2.38	2.38	2.48	2.60	2.61	2.77
Fe ₂ O ₃	0	0	0	0	0	0	0	0	0	0	0
FeO	15.09	15.33	14.05	14.68	15.15	15.62	14.30	15.25	15.77	14.01	13.99
MnO	0.30	0.32	0.32	0.35	0.31	0.32	0.36	0.31	0.34	0.34	0.36
MgO	25.69	25.09	25.86	24.89	25.58	25.38	24.96	25.91	26.03	25.37	25.62
CaO	2.79	1.61	1.91	1.79	1.86	1.73	1.66	1.67	1.82	1.63	1.61
Na ₂ O	0.92	0.85	0.97	0.97	0.94	0.88	0.87	0.87	0.95	0.92	0.92
K ₂ O	0.10	0.06	0.12	0.13	0.12	0.2	0.07	0.07	0.08	0.07	0.08
H ₂ O(+)	0.2	0.4	0.1	1.13	0.2	0.1	0.1	0	0	0	0
H ₂ O(-)	0.04	0.07	0.00	0.05	0.1	0.00	0.08	0.00	0.02	0.03	0.00
P ₂ O ₅	0.23	0.14	0.25	0.20	0.24	0.25	0.11	0.23	0.26	0.32	0.28
Cr ₂ O ₃	0.49	0.50	0.51	0.72	0.57	0.43	0.52	0.39	0.58	0.53	0.61
FeS	7.84	6.30	6.13	5.01	6.11	6.03	6.77	4.14	5.94	6.12	6.11
Fe	4.44	6.49	6.55	5.66	6.04	6.65	7.53	7.11	4.88	7.39	7.09
Ni	0.97	1.24	1.11	0.85	1.16	1.08	1.26	1.13	1.19	1.12	1.05
Co	0.029	0.019	0.040	0.032	0.040	0.040	0.043	0.041	0.038	0.042	0.042
Total	100.28	99.91	100.09	99.68	99.93	99.86	99.77	99.90	100.41	99.90	99.93
	12	12-A	13	13-A	14	14-A	15	15-A	16	17	18
SiO ₂	39.77	40.10	40.51	40.62	37.60	38.46	39.29	39.37	39.38	39.90	39.42
TiO ₂	0.11	0.11	0.11	0.11	0.11	0.11	0.09	0.09	0.09	0.11	0.09
Al ₂ O ₃	1.77	1.78	1.93	1.94	3.35	3.43	1.92	1.92	1.88	2.72	1.99
Fe ₂ O ₃	0.17	0	0.69	0	2.94	0	1.03	0	0	0	0
FeO	16.05	16.13	14.64	14.68	15.20	15.54	15.39	15.41	15.52	15.76	15.77
MnO	0.33	0.33	0.36	0.36	0.23	0.23	0.33	0.33	0.37	0.32	0.34
MgO	26.01	26.14	25.99	26.06	25.56	26.14	25.38	25.42	25.06	25.97	24.76
CaO	1.96	1.97	1.65	1.65	1.58	1.62	1.90	1.90	1.89	1.73	1.64
Na ₂ O	0.95	0.95	0.94	0.94	0.89	0.91	0.94	0.94	0.90	0.95	0.87
K ₂ O	0.11	0.11	0.09	0.09	0.07	0.07	0.12	0.12	0.10	0.10	0.07
H ₂ O(+)	0.3	0	0.2	0	1.7	0	0.3	0	0.5	0.3	0.5
H ₂ O(-)	0.18	0	0.04	0	0.12	0	0.16	0	0.00	0.00	0.11
P ₂ O ₅	0.28	0.28	0.21	0.21	0.22	0.22	0.27	0.27	0.20	0.21	0.26
Cr ₂ O ₃	0.43	0.43	0.53	0.53	0.44	0.45	0.55	0.55	0.49	0.56	0.53
FeS	5.21	5.24	4.64	4.65	5.90	6.03	6.16	6.17	6.00	5.56	6.41
Fe	5.36	5.39	6.36	6.86	3.50	5.69	5.62	6.35	6.90	5.06	6.09
Ni	0.99	1.00	1.27	1.27	1.05	1.07	1.11	1.11	1.31	1.08	0.94
Co	0.040	0.040	0.030	0.030	0.033	0.035	0.052	0.052	0.040	0.044	0.031
Total	100.02	100.00	100.19	100.00	100.49	100.00	100.61	100.00	100.63	100.37	99.82
1.	Y-74024,72 (L3)		2.		Y-74164,71 (L6)		3.		Y-74190,77,78 (L6)		
4.	Y-74191,86 (L6)		5.		Y-74354,93,94 (L6)		6.		Y-74362,75,85 (L6)		
7.	Y-74417,83 (L3)		8.		Y-74455,73 (L6)		9.		Y-75097,73 (L4)		
10.	Y-75102,79 (L6)		11.		Y-75110,84 (L6)		12.		Y-790253,72 (L5)		
12-A.	No. 12 on H ₂ O and Fe ₂ O ₃ -free basis.					13.		Y-791008,71 (L6)			
13-A.	No. 13 on H ₂ O and Fe ₂ O ₃ -free basis.					14.		Y-791034,71 (L6)			
14-A.	No. 14 on H ₂ O and Fe ₂ O ₃ -free basis.					15.		Y-791080,71 (L6)			
15-A.	No. 15 on H ₂ O and Fe ₂ O ₃ -free basis.					16.		Y-791781,61 (L6)			
17.	Y-791828,61 (L3 or L4)		18.		Y-793235,81 (L6)						

Table 2. Continued.

	19	20	21	22	23	23-A	24	25	26
SiO ₂	39.93	39.43	38.91	37.87	38.52	40.15	39.08	38.83	38.41
TiO ₂	0.12	0.05	0.09	0.09	0.07	0.07	0.06	0.05	0.07
Al ₂ O ₃	2.30	2.31	2.66	2.50	2.61	2.72	2.18	1.88	2.60
Fe ₂ O ₃	0	0	0	0	2.09	0	0	0	0
FeO	15.03	14.42	16.12	16.27	14.65	15.26	14.76	14.96	14.51
MnO	0.35	0.31	0.36	0.35	0.33	0.34	0.32	0.33	0.33
MgO	25.21	25.65	25.76	24.67	25.28	26.35	24.95	25.63	25.33
CaO	1.69	1.82	2.39	2.40	1.84	1.92	1.72	1.84	1.86
Na ₂ O	0.94	0.10	0.96	0.98	0.81	0.84	0.93	1.09	0.95
K ₂ O	0.07	<0.02	0.11	0.11	0.09	0.09	0.08	0.10	0.09
H ₂ O(+)	0.2	0.2	0.2	0.4	2.2	0	0	0	0
H ₂ O(-)	0.06	0.00	0.12	0.13	0.90	0	0.03	0.00	0.00
P ₂ O ₅	0.23	0.27	0.24	0.22	0.26	0.27	0.23	0.33	0.29
Cr ₂ O ₃	0.52	0.48	0.49	0.50	0.48	0.50	0.46	0.49	0.52
FeS	6.29	5.93	5.27	5.89	7.53	7.84	6.07	6.75	6.45
Fe	6.21	7.55	5.64	6.77	1.39	2.94	7.74	7.19	7.43
Ni	0.90	1.21	1.21	1.29	0.65	0.68	1.26	1.08	1.14
Co	0.014	0.042	0.042	0.053	0.029	0.030	0.033	0.036	0.039
Total	100.06	99.79	100.57	100.49	99.72	100.00	99.90	100.58	100.01

19. Y-793464,71 (L6) 20. Y-793465,91 (L6) 21. ALH-761,60 (L6)
 22. ALH-761,67 (L6) 23. Y-74660,71 (L3) 23-A. No. 23 on H₂O and Fe₂O₃-free basis.
 24. Y-791440,72 (L6) 25. Y-791441,76 (L6) 26. Y-791442,72 (L6)

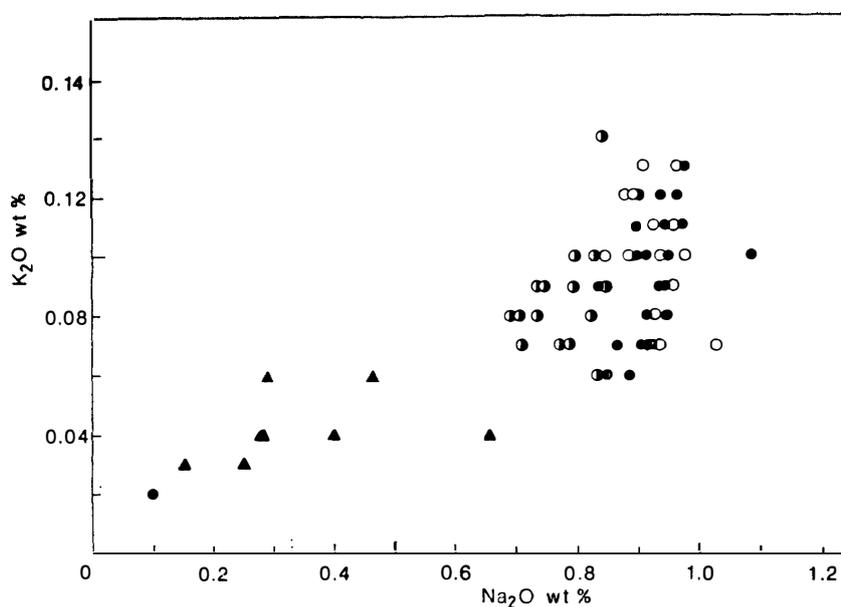


Fig. 3. K₂O–Na₂O relations of chondrites analyzed. Symbols are the same as those in Fig. 1.

were not fractionated significantly one from another during formation of these chondrites. The “superior analyses” selected by UREY and CRAIG (1953) show that the Na₂O contents of the H chondrites range from 0.41 to 2.07 wt % with an average of 0.91 wt %. The range of scatter overlaps that for the L chondrites (0.40–2.27 wt %).

Table 3. Chemical compositions of LL chondrites.

	1	2	3	4	5	6	7	8	9	9-A
SiO ₂	39.99	40.47	40.26	40.00	40.40	38.74	39.57	39.35	38.74	40.18
TiO ₂	0.06	0.23	0.15	0.15	0.06	0.18	0.14	0.23	0.15	0.16
Al ₂ O ₃	2.60	3.63	3.37	2.26	2.09	2.03	2.52	1.86	2.93	3.04
Fe ₂ O ₃	0	0	0	0	0	0	0	0	1.36	0
FeO	17.61	17.89	19.02	20.05	19.63	25.38	20.19	20.06	16.68	17.29
MnO	0.34	0.35	0.37	0.33	0.34	0.36	0.35	0.32	0.33	0.34
MgO	27.03	24.95	25.11	25.71	26.41	25.05	25.55	25.54	25.00	25.92
CaO	1.53	1.98	1.72	1.82	1.59	1.79	1.96	1.85	1.82	1.89
Na ₂ O	0.94	0.94	0.97	0.93	0.94	0.93	0.89	0.96	0.85	0.88
K ₂ O	0.07	0.23	0.13	0.11	0.07	0.08	0.10	0.09	0.12	0.12
H ₂ O(+)	0.0	0.58	0.64	0.2	0.0	0.2	0.1	0	2.63	0
H ₂ O(-)	0.05	0.00	0.00	0.05	0.00	0.00	0.24	0.10	0.73	0
P ₂ O ₅	0.31	0.22	0.25	0.24	0.26	0.34	0.23	0.28	0.21	0.22
Cr ₂ O ₃	0.52	0.82	0.78	0.56	0.52	0.57	0.55	0.59	0.56	0.58
FeS	4.35	4.84	4.59	5.51	4.77	3.75	5.04	6.77	5.87	6.09
Fe	3.29	2.48	1.96	0.90	2.03	0	1.65	1.24	1.33	2.36
Ni	0.88	0.99	1.01	0.96	0.99	0.97	0.80	1.05	0.90	0.93
Co	0.028	0.015	0.031	0.030	0.067	0.024	0.023	0.012		
Total	99.59	100.61	100.36	99.81	100.16	100.39	99.90	100.30	100.21	100.00
	10	11	12	13	14	15	15-A	16	17	
SiO ₂	39.16	39.55	38.57	40.09	39.57	40.07	40.44	40.33	36.26	
TiO ₂	0.15	0.16	0.13	0.09	0.11	0.11	0.11	0.09	0.13	
Al ₂ O ₃	2.13	2.29	2.31	2.00	2.81	1.71	1.72	2.25	3.95	
Fe ₂ O ₃	0	0	0	0	0	0.23	0	0	0	
FeO	20.72	19.85	19.70	20.78	19.85	20.38	20.55	17.97	21.07	
MnO	0.34	0.35	0.33	0.35	0.36	0.35	0.35	0.31	0.30	
MgO	25.41	25.92	25.52	26.54	26.15	25.72	25.94	25.80	24.29	
CaO	1.87	1.83	1.63	1.69	1.98	1.87	1.89	1.67	1.62	
Na ₂ O	0.89	0.89	1.03	0.88	0.96	0.93	0.94	0.98	0.88	
K ₂ O	0.12	0.11	0.07	0.11	0.11	0.10	0.10	0.10	0.12	
H ₂ O(+)	0	0.0	0.0	1.10	0.2	0.8	0	0.1	3.64	
H ₂ O(-)	0.00	0.0	0.10	0.33	0.05	0.07	0	0.00	0.70	
P ₂ O ₅	0.19	0.20	0.26	0.23	0.21	0.30	0.30	0.26	0.25	
Cr ₂ O ₃	0.57	0.60	0.60	0.46	0.57	0.54	0.54	0.55	0.53	
FeS	3.91	5.81	6.31	4.98	5.84	5.68	5.73	6.00	5.27	
Fe	3.86	1.40	2.02	0	0.37	0.25	0.41	2.58	0	
Ni	1.03	0.90	1.16	0.59	0.71	0.94	0.95	1.27	0.90	
Co	0.021	0.031	0.021	0.016	0.024	0.039	0.039	0.022	0.023	
Total	100.37	99.89	99.76	100.23	99.87	100.08	100.00	100.28	99.93	

1. Y-74080,79 (LL6)*

2. Y-74442,95 (LL4)

3. Y-74646,88 (LL6)

4. Y-74646,95 (LL6)

5. Y-74663,81 (LL6)

6. Y-75258,92 (LL6)

7. Y-790256,75 (LL6)

8. Y-790345,61 (LL shocked)

9. Y-790448,71 (LL3)

9-A. No. 9 on H₂O and Fe₂O₃-free basis.

10. Y-790519,41 (LL shocked)

11. Y-790519,80 (LL shocked) 12. Y-790574,91 (LL shocked) 13. Y-790728,81 (LL shocked)

14. Y-790964,71 (LL shocked) 15. Y-791067,74 (LL6)

15-A. No. 15 on H₂O and Fe₂O₃-free basis.

16. Y-792772,51 (LL4 or L4)

17. ALH-77015,62**

* No. 1 has been classified as L6 by MASON and YANAI (1983). It is possible that metal in these samples is oxidized, and their compositions plot in the region for LL-group of U-C diagram.

** This has been classified as L3 by MARVIN and MASON (1980). It is possible that metal in this sample is oxidized and it plots in the region for LL-group of U-C diagram.

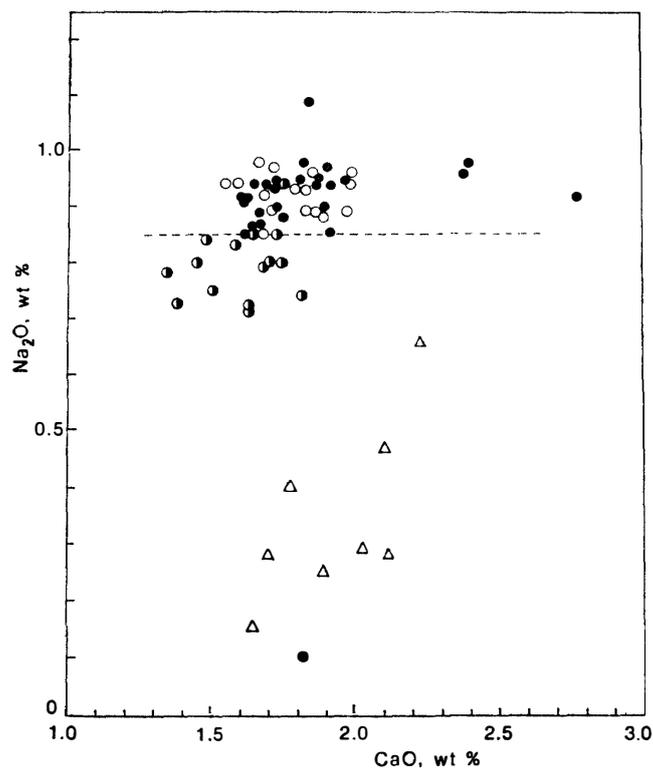


Fig. 4. Na_2O -CaO relations of bulk compositions of chondrites analyzed. Symbols are the same as those in Fig. 1. Dashed line denotes 0.85 wt % Na_2O by which H chondrites and L and LL chondrites are separated with two exceptions.

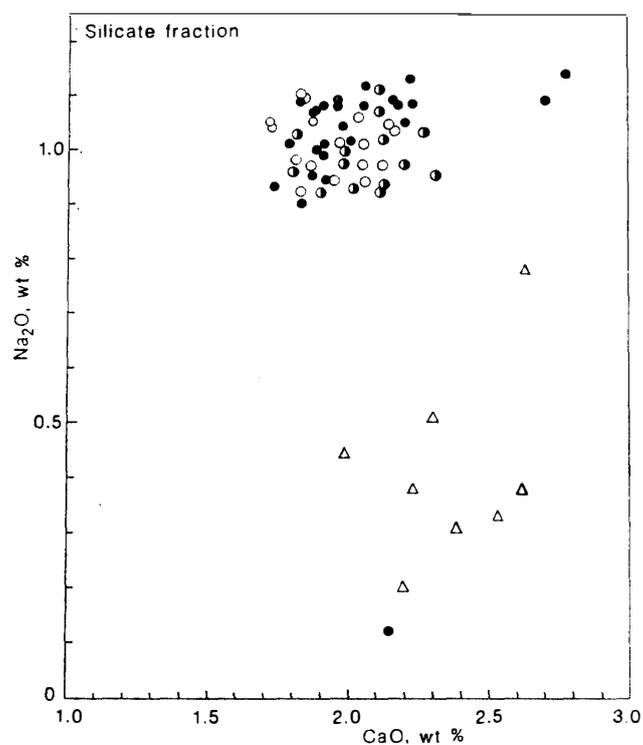


Fig. 5. Na_2O -CaO relations of the silicate fractions of chondrites analyzed. Symbols are the same as those in Fig. 1.

This is probably due to compilation of analyses of various qualities. The averages of the Na₂O contents in the silicate fractions of H and L chondrites selected by UREY and CRAIG (1953) are 1.22 and 1.21 wt %, respectively. Although these absolute values are 0.2% higher than the present analytical values, the conclusion that the Na₂O contents in the silicate fractions of both H and L (including LL) chondrites are the same is also obtained. Average CaO contents in the silicate fractions in the UREY and CRAIG's averages, however, are significantly different between H and L chondrites; they are 2.28 and 2.62 wt % for L and H chondrites, respectively.

The carbonaceous chondrites analyzed comprise four C2 chondrites and four C3 chondrites (Table 4). Total iron contents in these carbonaceous chondrites range from 24.98 to 26.37 wt % (volatile-free basis) with an average of 25.52 wt %. No systematic differences were found between the C2 and C3 chondrites, although the analyses of WILK (1956) show that the average total iron in C2 chondrites (26.38 wt %) is slightly higher than that of C3 chondrites (25.67 wt %). The SiO₂/MgO ratio (wt), which is useful for distinguishing E, C and ordinary chondrites (AHRENS, 1964, 1965), shows a slight difference between the C2 and C3 chondrites analyzed; the average ratio is 1.45 for C2 and 1.36 for C3. However, this difference is not systematic in other carbonaceous chondrites (DODD, 1981) and may not be generalized.

The average compositions of the four different chondrite types are given in Table 5. The average composition of H chondrites is different in FeO and Fe from that given by UREY and CRAIG (1953); even the "fresh" chondrites analyzed in the present study contain 2.5 wt % more FeO and 2% less Fe than the average by UREY and CRAIG (1953). Because the total iron contents are essentially the same, the higher FeO contents in the Antarctic chondrites may be due to oxidation. Other oxide components

Table 4. Chemical compositions of carbonaceous chondrites.

	1	2	3	4	5	6	7	8
SiO ₂	28.53	29.18	26.43	31.87	31.24	28.41	33.28	31.49
TiO ₂	0.24	0.22	0.13	0.11	0.18	0.12	0.20	0.16
Al ₂ O ₃	3.58	2.38	2.44	1.86	4.05	2.62	2.74	3.30
Fe ₂ O ₃	4.26	0	17.51	6.88	3.26	12.67	1.98	0
FeO	18.28	22.53	5.30	23.48	24.57	9.24	26.26	21.91
MnO	0.25	0.22	0.26	0.25	0.16	0.27	0.25	0.25
MgO	19.24	19.29	19.74	23.17	23.93	19.52	23.38	23.71
CaO	2.03	1.70	1.89	2.11	1.79	1.65	2.10	2.22
Na ₂ O	0.29	0.28	0.25	0.28	0.40	0.15	0.47	0.66
K ₂ O	0.06	0.04	0.03	0.04	0.04	0.03	0.06	0.04
H ₂ O(+)	11.83	13.26	11.52	3.8	2.6	12.81	1.18	2.1
H ₂ O(-)	1.54	1.56	4.69	1.00	1.42	2.85	0.75	0.50
P ₂ O ₅	0.25	0.23	0.43	0.16	0.22	0.26	0.28	0.37
Cr ₂ O ₃	0.51	0.52	0.44	0.52	0.52	0.42	0.50	0.50
FeS	7.60	7.38	7.68	3.23	4.12	8.03	5.08	11.45
NiO	1.37	0.85	1.17	1.39	1.30	0.92	1.22	1.21
Co	0.036	0.059	0.054	0.046	0.048	0.045	0.045	0.028
Total	99.89	99.69	99.96	100.19	99.84	100.01	99.77	99.89

1. Y-74642 (C2)

2. Y-74662 (C2)

3. Y-790032,92,93 (C2)

4. Y-790112,80 (C3)

5. Y-790992,66 (C3)

6. Y-791198,71,82 (C2)

7. Y-791717,61 (C3)

8. B-7904,93,97,98 (C3)

Table 5. Average chemical compositions of Antarctic chondrites.

	H ¹⁾ (12)	L (26)	LL (17)	C2 (4)	C3 (4)
SiO ₂	35.64	39.32	39.58	28.14	31.97
TiO ₂	0.10	0.10	0.14	0.18	0.16
Al ₂ O ₃	2.00	2.39	2.52	2.76	2.99
Fe ₂ O ₃	—	—	—	8.61	3.03
FeO	11.71	15.13	19.86	13.84	24.06
MnO	0.28	0.33	0.34	0.25	0.23
MgO	23.73	25.52	25.70	19.45	23.55
CaO	1.76	1.85	1.78	1.82	2.06
Na ₂ O	0.73	0.90	0.87	0.24	0.45
K ₂ O	0.08	0.09	0.11	0.04	0.05
H ₂ O(+)	0.22	0.17	0.39	12.36	2.42
H ₂ O(-)	0.07	0.10	0.10	2.66	0.92
P ₂ O ₅	0.23	0.24	0.25	0.29	0.26
Cr ₂ O ₃	0.46	0.52	0.58	0.47	0.51
FeS	5.45	6.04	5.27	7.68	5.97
Fe	15.80	6.10	1.33	—	—
Ni	1.70	1.10	0.95	0.85	1.28
Co	0.058	0.036	0.025	0.049	0.042
Total	100.01	99.93	99.79	99.68	99.95
Total Fe	27.91	21.70	20.35		
	27.52 ²⁾	21.82 ²⁾	20.87 ²⁾		
	27.81 ³⁾	21.64 ³⁾			

1) Excluding oxidized H chondrites.

2) Average values given by KEIL and FREDRIKSSON (1964).

3) Average values given by DODD (1981).

Numbers in parentheses are those of analyses averaged.

are much less different. The total iron contents in the ordinary chondrites of three different types are very close to those given by KEIL and FREDRIKSSON (1964) (Table 5).

The average compositions of the analyzed chondrites of the four different types recalculated on an iron-free basis are very close to one another. The average of H chondrites is slightly higher in MgO and lower in SiO₂, and has about 2 wt % more forsterite and 1–2% less enstatite than those of L and LL chondrites. The average of iron-free C chondrites is distinctly higher in TiO₂, Al₂O₃, MgO and CaO, and lower in SiO₂, Na₂O and K₂O.

The analyses of two rare stony-iron meteorites are given in Table 6. One of them (Y-791493) is similar in mineral assemblage to the Lodran stony-iron meteorite (lodranite) first described by TSCHERMAK (1870), and the other (Y-75274) is also similar in mineral assemblage to the lodranite and the Y-791493 stony-iron meteorite, but is more magnesian than these two. Brief descriptions of these meteorites are given by YANAI and KOJIMA (1982) and MATSUMOTO *et al.* (1983).

The analyses of the silicate parts of both the Y-791493 and Y-75274 stony-iron meteorites contain considerable amounts of Fe₂O₃. Both the samples are weathered and show oxidation of metal under the microscope. The FeO contents of the silicate parts

Table 6. Chemical compositions of stony-iron meteorites.

	1	1S	A	2	2S
SiO ₂	34.90	45.91	50.5	24.06	44.19
TiO ₂	0.05	0.06	—	0.02	0.03
Al ₂ O ₃	0.90	1.18	0.31	0.18	0.33
Fe ₂ O ₃	6.02	—	—	2.82	—
FeO	6.12	9.44	10.0	2.36	3.59
MnO	0.42	0.55	—	0.21	0.38
MgO	29.53	38.83	39.0	27.02	49.65
CaO	1.54	2.02	0.62	0.45	0.83
Na ₂ O	0.21	0.28	—	0.14	0.25
K ₂ O	<0.02	0.02	—	<0.02	0.03
H ₂ O(+)	1.1	—	—	0.5	—
H ₂ O(-)	0.04	—	—	0.0	—
P ₂ O ₅	0.49	0.64	—	0.27	0.50
Cr ₂ O ₃	0.81	1.07	—	0.12	0.22
FeS	2.10	—	—	1.14	—
Fe	14.28	—	—	39.39	—
Ni	1.13	—	—	1.84	—
Co	0.067	—	—	0.136	—
Total	99.72	100.00	100.43	100.67	100.00

1. Stony-iron meteorites Y-791493,80 and 82.
- 1S. Silicate part recalculated to 100%. FeO is adjusted by the compositions of olivine (Fo 11.6) and orthopyroxene (Fs 12.2) given by YANAI and KOJIMA (1982).
- A. Composition of silicate part of Lodran stony-iron meteorite given by BILD and WASSON (1976).
2. Stony-iron meteorite Y-75274,51.
- 2S. Silicate part recalculated to 100%. FeO is adjusted by the compositions of olivine (Fo 3.9) and orthopyroxene (Fs 3.9) given by MATSUMOTO *et al* (1983).

of these samples were calculated using their compositions of olivine and pyroxene given by YANAI and KOJIMA (1982) for Y-791493 and MATSUMOTO *et al.* (1983) for Y-75274. The recalculated silicate compositions are compared with that of lodranite given by BILD and WASSON (1976). The Yamato stony-iron meteorite Y-791493 is close to the lodranite in Fe/Mg ratio, but Y-791493 is lower in SiO₂ and higher in Al₂O₃ and CaO. The other Yamato stony-iron meteorite Y-75274 has a lower Fe/Mg ratio than the above two, but Al₂O₃ and CaO contents are close to those of the lodranite.

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References

- AHRENS, L. H. (1964): Si-Mg fractionation in chondrites. *Geochim. Cosmochim. Acta*, **28**, 411–423.
 AHRENS, L. H. (1965): Observations on the Fe-Si-Mg relationship in chondrites. *Geochim. Cosmochim. Acta*, **29**, 801–806.
 BILD, R. W. and WASSON, J. T. (1976): The Lodran meteorite and its relationship to the ureilites.

- Mineral. Mag., **40**, 721–735.
- DODD, R. T. (1981): *Meteorites; A Petrologic-Chemical Synthesis*. Cambridge, Cambridge Univ. Press, 21.
- JAROSEWICH, E. (1966): Chemical analyses of ten stony meteorites. *Geochim. Cosmochim. Acta*, **30**, 1261–1265.
- JAROSEWICH, E. (1967): Chemical analyses of seven stony meteorites and one iron with silicate inclusions. *Geochim. Cosmochim. Acta*, **31**, 1103–1106.
- JAROSEWICH, E. and MASON, B. (1969): Chemical analyses with notes on one mesosiderite and seven chondrites. *Geochim. Cosmochim. Acta*, **33**, 411–416.
- KEIL, K. and FREDRIKSSON, K. (1964): The iron, magnesium, and calcium distribution in coexisting olivines and rhombic pyroxenes of chondrites. *J. Geophys. Res.*, **69**, 3487–3515.
- LIPSCHUTZ, M. E. (1982): Weathering effects in Antarctic meteorites. *Catalog of meteorites from Victoria Land, Antarctica, 1978–1980*. *Smithson. Contrib. Earth Sci.*, **24**, 67–69.
- MARVIN, U. and MASON, B. (1980): *Catalog of Antarctic meteorite, 1977–1978*. *Smithson. Contrib. Earth Sci.*, **23**, 50 p.
- MASON, B. (1962): The classification of chondritic meteorites. *Am. Mus. Novit.*, **2085**, 1–20.
- MASON, B. and YANAI, K. (1983): A review of the Yamato-74 meteorite collection. *Papers presented to the Eighth Symposium on Antarctic Meteorites, 17–19 February 1983*. Tokyo, Natl Inst. Polar Res., 2–4.
- MATSUMOTO, Y., YANAI, K. and KOJIMA, H. (1983): A stony-iron meteorite: Yamato-75274. *Papers presented to the Eighth Symposium on Antarctic Meteorites, 17–19 February 1983*. Tokyo, Natl Inst. Polar Res., 6.
- TSCHERMAK, G. (1870): *Der Meteorit von Lodran*. *Sitzungsber. Akad. Wiss. Wien, Math.-Naturwiss. Kl., Abt. 2*, **61**, 465–475.
- UREY, H. and CRAIG, H. (1953): The composition of the stone meteorites and the origin of the meteorites. *Geochim. Cosmochim. Acta*, **4**, 36–82.
- WIJK, H. B. (1956): The chemical composition of some stony meteorites. *Geochim. Cosmochim. Acta*, **9**, 279–289.
- YANAI, K. and KOJIMA, H. (1982): A lodranite in the Yamato collections (abstract). *Meteoritics*, **17**, 300.

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