GENERAL ATOMIC

DIVISION OF GENERAL DYNAMICS

GA-7223

ABUNDANCES OF TRACE ELEMENTS Na, Sc, Cr, Mn, Fe, Co, AND Cu IN CHONDRULES AND METEORITES; In IN METEORITES AND TERRESTRIAL MATTER; AND U IN TYPE I CARBONACEOUS CHONDRITES

QUARTERLY PROGRESS REPORT

FOR THE PERIOD ENDING JUNE 15, 1966

Contract NASw-843

National Aeronautics and Space Administration

July 15, 1966

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PREVIOUS REPORTS IN THIS SERIES

GA-5594—September 1, 1963, through August 31, 1964
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CONTENTS

This progress report covers the contract period from March 1, 1966, through June 15, 1966, under Contract NASw-843.

During this quarter a revised manuscript entitled "Chainpur-like Chondrites, Possible Primitive Precursors of Ordinary Chondrites," by R. A. Schmitt, G. G. Goles, and R. H. Smith, was accepted for publication by Science.

A manuscript entitled "Rare-earth Distributions," by L. A. Haskin (University of Wisconsin) and R. A. Schmitt, has been completed as a chapter in the forthcoming Researches in Geochemistry, Vol. 2 (P. H. Abelson, Editor).

ABUNDANCES OF Na -Cu

Abundances of seven elements--Na, Sc, Cr, Mn, Fe, Co, and Cu--were determined by instrumental neutron activation analysis (INAA) in 20 individual chondrules separated from the unequilibrated chondrite Weston (see Table 1) and in 20 individual chondrules from Tennasilm (see Table 2), another unequilibrated chondrite. Both of these chondrites have been identified as unequilibrated chondrites by Dodd and Van Schmus.[1] Collation and interpretation of the presently determined chondrule abundances with previously established values for other chondrules[2] will be included in a future paper on chondrule abundances.

A few observations on Weston and Tennasilm abundances are noted below. The extremely high Fe contents (53% to 81% in chondrules 1, 2, 5, 8, and 9) in five magnetic Tennasilm chondrules (see Table 2) compare favorably with the high Fe concentrations (76% to 94% in chondrules 1, 2, 4, 5, 11, and 12) observed [3] in a few magnetic chondrules separated from the Type II carbonaceous chondrite, Renazzo. However, the high Co contents ranging from 3450 to 5320 ppm and the high Cu contents of 220 to 400 ppm in the high Fe Tennasilm chondrules exceed by approximately a factor of two the high Co and Cu contents in the Renazzo chondrules, which have correspondingly high Fe concentrations. The high Cu abundances that are correlated with the high Co contents seem consistent with the postulate that both Co and Cu reside in the metallic phase. The element gold observed by INAA in Tennasilm chondrules 8 and 9 (see Table 2), was identified via decay of the 0.41-MeV γ-ray of 65-hour Au^{198}.

Since chondrules from Tennasilm and Renazzo have similar abundance properties as cited above, Tennasilm minerals should be subjected to intensive electron microprobe mineralogical studies similar to Renazzo investigations.[4]

Table 1

ABUNDANCES OF Na, Sc, Cr, Mn, Fe, Co, AND Cu IN WESTON CHONDRULES (UNEQUILIBRATED CHONDRITE) DETERMINED BY NEUTRON ACTIVATION ANALYSIS

Chondrule	Mass (mg)	Na (ppm)	Sc (ppm)	Cr (ppm)	Mn (ppm)	Fe (%)	Co (ppm)	Cu (ppm)[a]
1	0.099	7430±150	0.0	3090±60	1880±60	3.1±3.1	26±75	5±25
2	.296	6620±130	9.4±0.9	1890±40	1900±40	4.1±1.0	85±30	37±12
3	.382	5240±100	8.9±1.1	2990±60	2020±40	5.7±1.1	89±35	38±11
4	.463	6400±130	7.0±0.7	3430±70	1980±40	7.4±0.4	0	55±11
5	.513	5800±120	19.5±0.8	970±20	480±20*	3.6±1.0	290±20	81±12
6	.552	3750±70	7.0±0.5	2660±60	1830±40	2.1±0.8	6±18	14±7
7	.610	5580±110	6.9±0.5	2780±60	2640±50	2.6±0.7	15±15	36±9
8	.807	17,100±340(out)	15.0±0.6	1840±40	650±20*	5.9±0.7	250±20	102±11
9	.849	4730±100	10.1±0.5	1100±30	1970±40	13.1±0.6	8±12	21±7
10	.855	12,000±240	5.4±0.4	2370±60	1690±30	4.8±0.6	49±12	52±9
Average		6400±1550	8.9±3.7	2310±690	1700±460 (1990±170)[b]	5.2±2.2	82±77	44±23
11	.900	2620±60	2.5±0.4	3120±60	3610±70*	7.2±0.9	16±10	10±6
12	.948	7000±140	2.9±0.4	1950±40	1930±40	6.4±0.7	31±10	28±8
13	.950	6890±140	6.2±0.4	3420±70	2830±60*	5.1±0.6	6±10	46±8
14	1.19	4500±90	14.3±0.5	1400±40	1780±40	4.2±0.5	5±8	26±5
15	1.51	7270±150	9.1±0.5	1850±40	1820±40	6.1±0.4	15±8	24±5
16	1.67	5630±110	6.9±0.4	4460±90	1960±40	7.2±0.4	18±7	27±5
17	2.47	4030±80	6.1±0.3	2880±60	2130±40	7.3±0.3	48±6	37±4
18	2.81	5350±110	9.4±0.3	2250±50	2040±40	6.1±0.2	11±5	26±4
19	7.24	6200±120	7.9±0.3	2280±50	1720±40	8.3±0.2	36±3	31±3
20	11.92	5420±110	6.3±0.2	2330±60	1950±40	6.6±0.2	10±2	5±5
Average		5490±1110	7.2±2.4	2590±700	2180±420 (1920±110)[b]	6.5±0.8	20±11	26±8
Grand Average		5920±1310	8.0±3.1	2450±680	1940±370 (1950±140)[b]	5.8±1.7	50±50	35±17

[a] Via coincidence counting of annihilation radiation of 12.8-hr Cu^{64}.

[b] Average value if starred values are excluded. Differences between starred values and average values are more than four times the mean deviation.

Table 2

ABUNDANCES OF Na, Sc, Cr, Mn, Fe, Co AND Cu IN TENNASILM CHONDRULES (UNEQUILIBRATED CHONDRITE) DETERMINED BY NEUTRON ACTIVATION ANALYSIS

Chondrule	Mass (mg)	Na (ppm)	Sc (ppm)	Cr (ppm)	Mn (ppm)	Fe (%)	Co (ppm)	Cu[a] (ppm)	Au[b] (half-life)
1 (m)[c]	0.271 H.D.[d]	440±20	0	1880±80	198±10	77±2	5320±100	350±40(D)[e]	
2 (m)	0.433 H.D.	3950±80	0	2920±60	1180±30	53±2	3450±70	220±20(D)	
3 (m)	0.590	10,600±200	9.6±0.6	4700±100	2770±60	13.4±0.6	63±15	35±10(D)	
4 (m)	0.632	7780±150	9.0±0.6	4110±80	2750±60	12.7±0.7	280±20	44±9 (D)	
5 (m)	0.706 H.D.	540±20	0	1100±40	235±10	71±2	5250±100	350±30(D)	45±4 hr
6 (m)	1.145	5460±100	5.2±0.4	3640±70	3140±60	10.4±0.5	110±10	32±6 (D)	
7 (m)	1.21	6820±130	7.1±0.4	3520±70	3120±60	8.9±0.5	140±10	31±7 (D)	
8 (m)	3.125 H.D.	290±10	0	250±20	100±5	81±2	4980±100	400±20(D)	66±5 hr
9 (m)	3.44 H.D.	500±20	0	580±30	130±5	78±2	4870±100	380±20(D)	57±5 hr
10 (m)	3.91	7190±140	10.5±0.6	3580±70	2160±40	29±1	1320±30	85±6 (D)	
Average		4360±3210	4±4	2620±1310	1580±1210	43±29	2580±2200	190±150	
11	0.163	10,150±200	11.4±1.4	4930±100	3160±90	4.0±2.0	52±50	10±20	
12	.631	9050±180	11.9±0.6	4270±80	2940±80	10.3±0.7	87±18	55±12	
13	.651	8300±160	9.6±1.9	2950±60	2960±60	7.8±1.0	45±15	21±10	
14	.670	7490±150	10.4±0.4	4090±80	3030±60	8.4±0.7	25±12	16±10	
15	.697	5040±100	11.3±0.5	3690±70	3170±60	8.6±0.6	28±14	5±8	
16	.724	6290±120	6.7±0.4	3370±60	3140±60	9.8±0.6	57±17	41±10	
17	3.01	7530±140	7.8±0.3	4940±100	4080±80	10.1±0.3	39±4	26±5	
18	5.75	8840±170	9.4±0.2	3240±60	2700±60	10.9±0.2	63±3	22±4 (D)	
19	6.47	10,200±200	9.3±0.2	4240±80	3780±80	5.0±0.2	14±2	15±4 (D)	
20	12.6	9770±200	10.5±0.2	3360±70	2610±50	11.5±0.2	12±2	6±4	
Average		8270±1340	9.8±1.3	3910±590	3160±310	8.6±1.9	42±19	22±12	
Grand Average		6320±2790	7±4	3260±1000	2370±1010	26±23	1310±1730	100±100	

[a] Via coincidence counting of annihilation radiation of 12.8-hr Cu^{64}.

[b] Half-lives of the 0.41 MeV γ-ray peaks were determined. 65-hr Au^{198} is expected product of Au activation.

[c] Denotes magnetic chondrules.

[d] H.D. denotes high-density chondrules.

[e] (D) denotes average of two determinations usually separated by 15 to 24 hours.

The large Mn dispersion of magnetic Tennasilm chondrules is entirely consistent with the highly unequilibrated state of Tennasilm olivine and pyroxene minerals, as evidenced by the broad Fe dispersion in these minerals, observed by Dodd and Van Schmus.[1] Note, however, that the Mn dispersion--another index of unequilibration suggested[2] previously--for the nonmagnetic Tennasilm chondrules at some ±10% mean deviation is slightly higher than the ±6% mean Mn dispersion observed in chondrules from ordinary and equilibrated H-, L-, and SB-group chondrites. Since both the magnetic and nonmagnetic Tennasilm chondrules extend over similar mass ranges and therefore have comparable dimensions and should have had similar diffusion lengths for similar chondrule sizes, it is conceivable that the magnetic and nonmagnetic chondrules could have formed according to the general Wood chondrule origin hypothesis in different parts of the solar nebula, with subsequent mixing. The Tennasilm chondrules high in Fe, Co, and Cu probably formed in a relatively high reducing atmosphere with little or no metamorphism of the chondrules in the overall chondritic matrix. Postulating little or a slight degree of metamorphism for Tennasilm would suggest that the environment for formation of the nearly equilibrated nonmagnetic Tennasilm chondrules must have been oxidizing with nearly sufficient time for complete Mn equilibrium distribution among the main chondrule and matrix minerals.

For Tennasilm chondrules, the abundances of the lithophilic elements Na, Sc, Cr, and Mn are inversely correlated with the high Fe, Co, and Cu contents, similar to Renazzo observations.[3] Assuming that the high Fe concentrations (53% to 81%) of the five Tennasilm chondrules are in the metallic phase, the concentrations of the element Na in the silicate phases of these chondrules are about two to five times less compared to the corresponding Na abundances in the nonmagnetic Tennasilm chondrules. This observation, also noted for high-Fe Renazzo chondrules,[3] indicates a low plagioclase content and possibly a higher temperature of chondrule formation in the solar nebula for these high-Fe chondrules.

Chondrules of Weston, a less unequilibrated chondrite than Tennasilm, according to the Fe-dispersion index of Dodd and Van Schmus, show a distinctly high Mn dispersion, consistent with high Mn dispersions in chondrules separated from similar chondrites.

According to the Dodd-Van Schmus Fe-dispersion index for unequilibration, minerals from the chondrite Chainpur rank higher in unequilibration than those from Tennasilm. Although high, none of the Co abundances in Chainpur chondrules approach those observed in Tennasilm or Renazzo chondrules. The absence of appreciable NiO in Chainpur minerals and the presence of appreciable NiO[5] in Renazzo minerals suggest that if the chondrules of Chainpur and Renazzo underwent a similar chemical and physical history in their formation, Chainpur probably experienced a slightly higher degree of metamorphism, which caused appreciable movement of Ni and Co across the chondrule-matrix interfaces but no significant change in the overall Fe dispersion in the olivine and pyroxene minerals. See Ref. 6 for a further discussion on this point. The general correspondence of Fe, Co, and Cu abundances in several magnetic chondrules from Renazzo and Tennasilm suggests that NiO would be found by microprobe analysis of Tennasilm troilite and silicate minerals.

In the preparation of an extensive manuscript(7) on elemental abundances, it became clear that elemental abundances which were first determined by INAA approximately 3 years ago should be redetermined with greater accuracy, and also that Cu should be redetermined in all ~150 meteorites by our fast γ-γ coincidence technique. In Table 3, the new and old data (the latter published in previous quarterly reports) have been listed. In Tables 4 through 8 we have compiled the best values which will be reported in the forthcoming manuscript.(7)

ABUNDANCES OF INDIUM

In the last progress report, indium abundances in some 15 meteorites and five terrestrial specimens were published. The In abundance study by radiochemical neutron activation analysis has essentially been completed. In Tables 9 and 10, all the In abundances including an additional 12 meteorites and 10 terrestrial specimens have been compiled. Table 11 lists the pertinent atomic abundances for comparison. Further solar abundance studies on In are required to check the high (by a factor of ~9) In solar value compared to carbonaceous chondrites.

In Table 12, In abundances have been compared with the other major elements in the third group of the periodic table. These data and those found in Table 13 will be included in a manuscript on this work.

ABUNDANCES OF U IN TYPE I CARBONACEOUS CHONDRITES

A problem of considerable importance, as set forth by Fowler and Hoyle,(27) has been the nucleosynthetic generation of heavy elements such as uranium and thorium in stars by the r- or rapid neutron capture process. Clayton(28) and Hoyle and Fowler(29) calculated that $\approx$0.034 $\pm$0.011 U atoms/10^6 Si atoms should be produced, which is equivalent to $\approx$0.030 ppm U in Type I carbonaceous chondrites, $\approx$0.044 ppm U in Type II carbonaceous chondrites, and $\approx$0.052 ppm U in ordinary chondrites. It has been established fairly well (Reed et al.(23) and Goles and Anders(30)) that the U abundance in ordinary chondrites is $\approx$0.013 ppm, a factor of four less than the theoretical.

Table 3

ABUNDANCES OF Na, Mn, AND Cu IN METEORITES DETERMINED BY INAA

Type of Meteorite	Mass (g)	Na (ppm)		Mn (ppm)		Cu[a] (ppm)	
		New	Old	New	Old	New	Old
Type I Carbonaceous							
Alais	.020	4760±100	5000±200	2180±40	2120±80	141±13 (D)	180±80
Ivuna-A	.394	5190±100	5560±120	1620±30	1760±30	149±7 (D)	111±8
Ivuna-B	.414	4990±100	5420±120	1740±40	1800±30	138±7 (D)	125±7
Orgueil	.175	4880±100	5180±100	1750±40	1830±110	115±7 (D)	119±13
Type II Carbonaceous							
Al Rais	.541	3380±70	3400±80	1630±30	1630±20	98±6	95±15
Boriskino-A	.596	4400±90	4380±80	1570±30	1610±30	124±18 (D)	130±9
Boriskino-B	.255	4190±80	3630±150	1590±30	1790±80	140±9	-
Boriskino-C	.815	4170±80	-	1540±30	-	131±8	-
Cold Bokkeveld	.388	2380±50	2410±50	1580±30	1630±20	134±8	144±11
Mighei-A	.521	3850±80	3840±80	1620±30	1650±30	137±10	122±3
Mighei-B	.053	4020±80	4360±200	1620±30	1570±80	124±12	-
Murray-A	.774	1510±30	1370±70	1550±30	1780±40	128±6 (D)	116±3
Murray-B	.187	1630±30	1690±80	1600±30	1880±90	131±12 (D)	-
Renazzo	.357	3420±70	3430±40	1650±30	1750±20	107±8	106±3
Santa Cruz-A	.215	4400±80	4200±300	1580±30	1760±30	138±8	119±18
Santa Cruz-B	.248	4500±90	4570±190	1620±30	1780±90	126±13	110±50

[a] All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 3 (Continued)

ABUNDANCES OF Na, Mn, AND Cu IN METEORITES DETERMINED BY INAA

Type of Meteorite	Mass (g)	Na (ppm)		Mn (ppm)		Cu[a] (ppm)	
		New	Old	New	Old	New	Old
Type III-A							
Felix-A	.283	4010±80	-	1570±30	-	150±10	-
Felix-B	.158	4120±80	4600±200	1460±30	1650±80	128±8	-
Groznaja-A	.770	3260±60	3180±60	1570±30	1600±30	108±7	105±8
Groznaja-B	.260	2980±60	2700±130	1550±30	1900±90	122±9	-
Groznaja-C	.846	3380±70	-	1500±30	-	120±6	-
Kaba	.184	3500±70	3620±80	1480±40	1590±40	107±5 (D)	128±6
Karoonda-A	.072	2760±60	2830±120	1320±40	1480±80	110±8 (D)	80±30
Karoonda-B	.788	2700±90	2980±60	1240±30	1360±30	97±6	107±4
Karoonda-C	.376	4430±250	-	1290±30	-	92±8	-
Lancé-A	.845	3700±80	3600±180	1470±40	1630±30	140±6 (D)	118±3
Lancé-B	.692	3630±70	3490±170	1460±30	1610±30	127±7	127±5
Mokoia-A	.871	3290±60	3430±100	1280±30	1360±40	106±6	106±11
Mokoia-B	.235	3540±70	2970±150	1370±30	1720±80	103±9	-
Ornans	.286	3910±80	3940±80	1620±30	1680±40	132±11	140±7
Vigarano	.416	1730±40	1840±40	1280±30	1280±40	105±9	108±14
Warrenton-A	.166	4000±80	4390±90	1440±40	1690±80	147±6 (D)	140±30
Warrenton-B	.733	3780±80	3920±80	1480±30	1580±30	141±8	137±9

[a] All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 3 (Continued)

ABUNDANCES OF Na, Mn, AND Cu IN METEORITES DETERMINED BY INAA

Type of Meteorite	Mass (g)	Na (ppm)		Mn (ppm)		Cu[a] (ppm)	
		New	Old	New	Old	New	Old
Type III-B							
Tieschitz	.533	6260±120	6390±90	2200±40	2290±20	101±8	94±3
Bishunpur	.082	7700±150	8070±160	2440±70	2580±50	83±6	40±30
Chainpur-A	.279	7080±140	7470±150	2660±50	2880±180	83±10 (D)	40±20
Chainpur-B	.810	5680±150	-	2050±40	-	91±8 (D)	-
Chainpur-C	1.232	6520±130	6610±70	2450±70	2670±30	87±5 (D)	100±2
Khohar	.157	6970±140	7200±150	2360±60	2700±300	105±6	60±40
Mezö-Madaras	.597	6780±140	-	2220±40	-	97±5 (D)	-
Tennasilm	.549	6260±120	-	2360±50	-	91±7	-
Prairie Dog Creek	.652	5300±100	-	2160±40	-	97±7	-
Bremervorde-A	.258	5940±240	6700±150	2440±40	2380±90	122±17	50±20
Bremervorde-B	.604	6340±120	—	2230±40	—	104±8	—
Ngawi	.479	6360±120	6740±120	2370±50	2460±30	106±10 (D)	90±20
(no mafic glass) Castalia	.354	5480±220	6500±130	2270±40	2250±90	89±14	46±18
Lua	.594	6630±130	-	2400±50	-	88±7	-
Weston	.535	5470±110	-	2030±40	-	101±7	-
Ranchapur	.494	5270±100	-	2030±40	-	117±8	-

[a] All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 3 (Continued)

ABUNDANCES OF Na, Mn, AND Cu IN METEORITES DETERMINED BY INAA

Type of Meteorite	Mass (g)	Na (ppm)		Mn (ppm)		Cu[a] (ppm)	
		New	Old	New	Old	Mew	Old
<u>Enstatites</u>							
<u>Type A</u>							
Abee	.727	7900 ± 160	9200 ± 300	3650 ± 100	3790 ± 80	206 ± 15 (D)	164 ± 9
Indarch-A	.096	6680 ± 140	6700 ± 150	1920 ± 60	2790 ± 150	187 ± 8 (D)	-
Indarch-B	.161	7440 ± 140	8030 ± 160	2030 ± 60	2390 ± 190	209 ± 6 (D)	130 ± 70
<u>Type B</u>							
Atlanta	.744	4370 ± 80	-	1770 ± 40	-	94 ± 8 (D)	-
Hvittis	.531	5000 ± 100	-	1480 ± 30	-	96 ± 7	-
Khairpur	.171	5600 ± 110	6200 ± 120	2200 ± 60	2760 ± 100	106 ± 5 (D)	60 ± 40
St. Marks	.333	5630 ± 110	5530 ± 120	1570 ± 50	2100 ± 120	220 ± 18 (D)	-

[a] All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 3 (Continued)

ABUNDANCES OF Na, Mn, AND Cu IN METEORITES DETERMINED BY INAA

Type of Meteorite	Mass (g)	Na (ppm)		Mn (ppm)		Cu[a] (ppm)	
		New	Old	New	Old	New	Old
High-Fe Group							
Agen	.180	5950±120	6430±120	2180±60	2320±90	91±5	60±20
Alessandria	.220	4610±180	5890±100	2100±40	2120±80	132±26	50±20
Allegan-A	.621	5690±120	6020±120	2190±60	2220±60	104±8	70±30
Allegan-B	.452	4990±100	5350±110	2000±60	2430±150	52±15	101±17
Allegan-C	.613	5800±120	5830±120	2140±60	2500±150	149±7 (D)	102±16
Ambapur Nagla	.099	5650±130	6100±200	2060±60	2190±110	111±7	70±20
Archie	.285	5330±200	6110±120	2280±40	2200±40	63±19	49±17
Barbotan	.147	6030±120	6280±120	2060±60	2190±90	115±6	50±20
Beardsley-A	.233	5310±100	5770±120	2900±90	2530±120	106±13	≤120
Beardsley-B	.329	5260±100	5000±300	2200±70	2350±120	111±12	-
Beaver Creek	.358	5030±200	5980±120	2170±40	2130±90	148±15	66±17
Bielokrynitschie	.053	6120±120	6710±140	2350±40	2140±110	92±15	50±13
Colby (Kans.)	.072	4990±100	5440±120	2080±60	2150±80	91±7	80±20
Cortez	.059	6690±130	7000±300	2670±70	2800±200	88±11	90±60
Ehole	.429	5310±200	6150±120	2240±40	2490±140	60±17	59±18
Fayetteville	.103	4070±80	4530±90	1490±40	1720±80	146±7 (D)	110±50
Forest City	.669	5750±120	-	2110±40	-	99±7	-
Kilbourn	.440	5350±210	6230±120	2210±40	2180±90	95±12	67±17
Miller-A	.115	5470±100	5300±300	2290±60	3190±160	107±7	-
Miller-B	.580	5200±100	-	2000±40	-	101±7	-
Monroe(Flows)	.026	5930±120	6200±120	2150±40	2290±70	80±20	100±30
Ochansk-A	.285	6050±120	6190±120	1860±60	2400±120	83±11	50±40
Ochansk-B	.358	5830±240	-	2300±40	-	71±15	-
Pantar (II-dark)A	.399	5180±200	6250±120	2120±40	2550±150	95±12	70±20

[a] All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 3 (Continued)

ABUNDANCES OF Na, Mn, AND Cu IN METEORITES DETERMINED BY INAA

Type of Meteorite	Mass (g)	Na (ppm)		Mn (ppm)		Cu[a] (ppm)	
		New	Old	New	Old	New	Old
High-Fe Group Cont.							
Pantar (II-dark)-B	.411	6040±120	6180±120	2300±70	2760±180	57±11	65±19
Pantar (II-lt)-A	.265	6180±240	6460±120	2340±50	2530±150	94±21	50±20
Pantar (II-lt)-A	.368	5490±100	6090±120	2220±70	2740±140	73±14	99±8
Pultusk	.304	5720±120	6180±120	2350±70	2470±180	81±22	61±19
Richardton	.585	5320±110	-	1980±40	-	105±7	-
Stalldalen	.172	6000±120	6670±120	2070±60	2430±120	111±6	60±50
Sindhri	.559	5500±110	-	2060±40	-	99±7	-
Low-Fe Group							
Alfianello	.091	8260±160	8000±300	2380±70	2460±90	100±7	50±30
Atarra	.120	6800±140	7380±140	2420±80	2500±100	93±7	70±30
Atemajac	.086	5970±120	7050±140	2420±70	2530±100	95±7	70±30
Ausson	.311	6400±240	6900±150	2570±50	2420±50	91±18	50±20
Aztec	.092	7700±150	7830±160	2460±70	2230±110	103±8	50±30
Barratta	.385	6400±120	6600±120	2510±70	2530±170	56±9	60±30
Bath Furnace	.426	6040±240	6640±130	2490±50	2310±90	82±12	30±20
Baxter	.330	6950±280	7600±150	2530±50	2590±50	76±16	40±20
Bjurböle	.217	6150±120	6980±150	2260±70	2860±140	112±14	100±40
Bori	.103	7000±140	7000±300	2280±60	2320±110	127±8	80±20
Bruderheim-A	.200	7140±140	6520±150	2320±60	2800±50	95±6	-
Bruderheim-C	.562	6380±120	-	2440±50	-	93±8	-
Bruderheim-D	.260	6730±140	-	2500±50	-	94±12	-
Farmington	.304	4840±50	5460±110	2210±70	2250±90	92±10	60±50

[a] All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 3 (Continued)

ABUNDANCES OF Na, Mn, AND Cu IN METEORITES DETERMINED BY INAA

Type of Meteorite	Mass (g)	Na (ppm)		Mn (ppm)		Cu[a] (ppm)	
		New	Old	New	Old	New	Old
Low-Fe Group (Cont.)							
Harleton	.301	7000±280	7350±150	2520±50	3000±300	70±14	60±20
Holbrook	.302	6730±140	5970±120	2580±80	2870±150	80±13	-
Homestead	.029	7080±140	7560±160	2540±50	2500±300	114±20	110±70
Kyushu	.100	7430±150	6520±150	2470±70	2900±200	89±7	-
Leedey	.291	6650±130	5790±120	2440±70	2730±150	118±11	-
McKinney	.256	5840±120	5420±120	2300±70	2850±150	134±12	-
Mocs	.417	5550±220	6110±120	2270±40	2150±120	136±14	63±18
Modoc	.131	6240±120	5700±120	2380±60	2690±150	92±6	-
Paragould	.419	6650±240	7300±140	2550±50	2880±140	113±11	60±20
Peace River	.276	6340±120	7050±140	2490±70	2760±160	99±25	51±7
Perpeti	.131	6630±130	7070±140	2280±60	2390±120	108±7	70±50
Saratov	.682	6000±120	-	2180±40	-	116±7	-
St. Michel	.219	7110±150	7500±300	2520±70	2640±130	87±11	≤130
Tenham	.164	6240±120	6850±130	2350±70	2590±130	86±6	≤140
Walters-A	.336	6480±260	6560±130	2580±50	2540±120	108±12	50±20
Walters-B	.191	6900±140	7100±300	2330±60	2450±80	144±6	140±20
Wickenburg	.532	6750±130	6760±130	2380±60	2740±140	115±8	120±40

[a] All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 3 (Continued)

ABUNDANCES OF Na, Mn, AND Cu IN METEORITES DETERMINED BY INAA

Type of Meteorite	Mass (g)	Na (ppm)		Mn (ppm)		Cu[a] (ppm)	
		New	Old	New	Old	New	Old
Soko-Banjites							
Albareto	.337	6260±120	7050±140	2510±70	2880±80	88±11	40±20
Appley Bridge	.825	6880±140	6940±70	2510±70	2560±30	73±7	120±30
Arcadia	.149	6130±120	6440±120	2440±80	2810±150	69±6	80±40
Benton	.037	4390±90	5660±110	2220±60	2640±100	260±20(D)	210±20
Cherookee Springs	.505	6330±120	-	2410±50	-	79±6	-
Ensisheim	.218	5380±210	6200±200	2230±40	2440±130	117±19	70±40
Jelica	.273	6340±240	7000±300	2590±50	2470±40	67±17	35±19
Lake Labyrinth-A	.401	6530±260	7140±140	2640±50	2880±150	65±12	≤110
Lake Labyrinth-B	.850	6170±120	-	2420±50	-	90±7	-
Manbhoom	.172	6770±140	6200±300	2390±60	2970±150	73±5	-
Mangwendi	.809	6310±120	6300±400	2360±70	2540±30	95±7 (D)	140±30
Nås	.159	6930±140	7000±300	2510±80	2530±30	98±6	90±6
Olivenza	.890	6640±130	6810±30	2380±70	2540±30	101±7	146±18
Ottawa	1.045	6740±140	6990±70	2470±70	2540±60	97±7	149±3
Soko-Banja	.889	6640±130	6820±50	2420±70	2530±30	107±8	137±13
Vavilovka	.311	6920±140	6100±300	2490±70	3010±150	64±11	-

[a] All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 3 (Continued)

ABUNDANCES OF Na, Mn, AND Cu IN METEORITES DETERMINED BY INAA

Type of Meteorite	Mass (g)	Na (ppm)		Mn (ppm)		Cu[a] (ppm)	
		New	Old	New	Old	New	Old
Achondrites							
Ca-rich(Eucrites)							
Haraiya	1.510	2800±60	2870±150	3660±120	4110±80	5±3	6±6
Juvinas	.252	2800±60	2520±130	3970±120	4600±200	8±6	-
Moore County	.226	3070±60	3020±150	3450±100	3230±150	7±9	-
Nobleborough	.503	3130±60	3500±150	4100±120	4140±80	1±2	8±2
Nuevo Laredo	.172	3430±70	3900±200	4070±120	4300±200	7±2	-
Pasamonte	1.398	2990±60	2990±150	3860±120	4110±80	4±3	6±6
Sioux County	.927	2860±60	3630±120	3890±120	4110±80	3±3	10±10
Stannern	.444	3780±80	3380±160	3970±120	4300±200	20±5	-
Kapoeta (Howardites)	.235	1620±50	1720±80	3910±120	2840±140	6±5	-
Petersburg "	.241	2840±90	3000±150	3790±110	3590±160	6±6	-
Nakhlites							
Nakhla	.742	3040±60	-	3520±70	-	14±2 (D)	-
Ca-poor (Aubrites)							
Bishopville-A	.424	6440±260	6560±120	2420±50	2550±100	11±6	< 35
Bishopville-B	.460	9950±400	9900±200	870±20	800±30	7± 8	< 10
Cumberland Falls-A	.228	280±10	220±20	870±20	860±30	1±6	6±2
Cumberland Falls-B	.837	920±20	1120±50	1410±40	1470±30	24±4	28±11
Norton County	.172	380±10	450±20	1600±50	1710±100	14±2	-
Pena Blanca Springs	.167	1470±30	1240±60	1220±40	1090±50	9±2	-
Pesyanoe	.484	2610±50	3410±60	1020±30	1040±30	12±4	15±5

[a]All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 3 (Continued)

ABUNDANCES OF Na, Mn, AND Cu IN METEORITES DETERMINED BY INAA

	Type of Meteorite	Mass (g)	Na (ppm) New	Na (ppm) Old	Mn (ppm) New	Mn (ppm) Old	Cu[a] (ppm) New	Cu[a] (ppm) Old
	Ca-poor (Diogenites)							
	Johnstown	.776	124±6	-	3300±60	-	10±2 (D)	-
	Ureilites							
	Novo Urei -A	.333	300±20	520±30	2860±90	3050±60	12±4	9±1
	Novo Urei -B	.384	360±10	-	2750±60	-	11±2	-
	Goalpara	.275	200±10	-	2770±50	-	11±2	-
	Pallasites (Olivines)							
Selected Olivines	Admire	.396	-	73±4	1880±40	1950±40	5±2	22±1
Selected Olivines	Eagle Station	.248	-	69±4	1380±30	1340±30	4±2	38±1
Selected Olivines	Imilac	.478	-	69±4	2130±40	2210±40	5±2	29±1
Selected Olivines	Ahumada	.579	68±2	71±4	1910±60	1990±20	1±1	33±1
Selected Olivines	Marjalati	.492	58±14	-	2160±40	-	8±2	-
Selected Olivines	Salta	.263	52±19	-	2120±40	-	6±2	-
Selected Olivines	Springwater	.278	-	65±4	2380±40	2350±40	6±2	43±1
	Brenham-A	.788	73±3	79±5	1340±40	-	24±2 (D)	-
	Brenham-B	1.058	32±2	-	1100±30	-	28±3	-
	Phillips County	.162	400±10	-	1340±130	-	60±4	-
	Brenham	.146	75±4	-	1430±40	-	1±1	-
	Mesosiderites							
	Estherville	.388	1630±40	-	3460±120	-	43±12	-
	Vaca Muerta	.558	1190±30	-	1990±60	-	127±7 (D)	-
	Special							
	Pine River (Silicates)	.414	5510±110	-	1320±50	-	81±8	-

[a] All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 4

RESULTS OF RECENT DETERMINATIONS OF Na, Mn, AND Cu ABUNDANCES IN TYPES I AND II CARBONACEOUS CHONDRITES[a,b]

Type I Carbonaceous	Mass (g)	Na(ppm)	Mn(ppm)	Cu(ppm)[c]
Alais	.020	4880 ± 120	2150 ± 30	141 ± 13 (D)
Ivuna-A	.394	5370 ± 180	1690 ± 70	149 ± 7 (D)
Ivuna-B	.414	5210 ± 210	1770 ± 30	138 ± 7 (D)
Orgueil	.175	5030 ± 150	1790 ± 40	115 ± 7 (D)
Avg (weighted) and Std. Dev. (weighted)		5250 ± 130	1750 ± 70	138 ± 12
Type II Carbonaceous				
Al Rais	.541	3390 ± 10	1630 ± 10	98 ± 6
Boriskino A	.596	4390 ± 10	1590 ± 20	124 ± 18 (D)
Boriskino B	.255	4190 ± 80	1590 ± 30	140 ± 9
Boriskino C	.815	4170 ± 80	1540 ± 30	131 ± 8
Cold Bokkeveld	.388	2400 ± 20	1600 ± 30	134 ± 8
Mighei-A	.521	3840 ± 10	1640 ± 20	137 ± 10
Mighei-B	.053	4020 ± 80	1620 ± 30	124 ± 12
Murray-A	.774	1440 ± 70 (out)	1670 ± 120	128 ± 6 (D)
Murray-B	.187	1630 ± 30 (out)	1600 ± 30	131 ± 12 (D)
Renazzo	.357	3420 ± 10	1700 ± 50	107 ± 8
Santa Cruz-A	.215	4300 ± 100	1670 ± 90	138 ± 8
Santa Cruz-B	.048	4530 ± 40	1620 ± 30	126 ± 13
		3820 ± 590	1620 ± 50	125 ± 13

[a]Weighted average have their population standard deviation; i.e. $\text{avg}^{\overline{H}} = \frac{\Sigma m_i H_i}{\Sigma m_i}$.

Weighted dispersion index $\equiv \left(\frac{\Sigma m_i (Hi-\overline{H})^2}{\Sigma m_i}\right)^{1/2}$.

[b]Value (±) after each abundance is either the standard dev. of two determinations on same specimen (both abundances determined by peak area method) or is the standard deviation of a single determination.

[c]All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 5

RESULTS OF RECENT DETERMINATIONS OF Na, Mn, AND Cu ABUNDANCES IN TYPE III-A CARBONACEOUS CHONDRITES[a,b]

Type III-A	Mass (g)	Na (ppm)	Mn (ppm)	Cu (ppm)[c]
Felix-A	0.283	4010±80	1570±30	150±10
Felix-B	.158	4120±80	1460±30	128± 8
Groznaja-A	.770	3220±40	1580±20	108± 7
Groznaja-B	.260	2980±60	1550±30	122± 9
Groznaja-C	.846	3380±70	1500±30	120± 6
Kaba	.184	3560±50	1540±60	107± 5 (D)
Karoonda-A	.072	2800±40	1400±80	110± 8 (D)
Karoonda-B	.788	2840±140	1300±60	97± 6
Karoonda-C	.376	4430±250	1290±30	92± 8
Lancé-A	.845	3650±50	1550±80	140±6 (D)
Lancé-B	.692	3560±70	1540±80	127±7
Mokoia-A	.871	3360±70	1320±40	106±6
Mokoia-B	.235	3540±70	1370±30	103±9
Ornans	.286	3920±20	1650±30	132±11
Vigarano	.416	1790±60 (out)	1280±10	105±9
Warrenton-A	.166	4200±200	1570±130	147±6 (D)
Warrenton-B	.733	3850±70	1530±50	141± 8
		3520±400	1460±120	119±17

[a]Weighted average have their population standard deviation; i.e. avg $\overline{H} = \frac{\Sigma m_i H_i}{\Sigma m_i}$.

Weighted dispersion index $\equiv \left(\frac{\Sigma m_i (H_i-\overline{H})^2}{\Sigma m_i}\right)^{1/2}$.

[b]Value (±) after each abundance is either the standard dev. of two determinations on same specimen (both abundances determined by peak area method) or is the standard deviation of a single determination.

[c]All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 6

RESULTS OF RECENT DETERMINATIONS OF Na, Mn, AND Cu ABUNDANCES IN TYPE III-B CARBONACEOUS CHONDRITES[a,b]

Type III-B	Mass (g)	Na (ppm)	Mn (ppm)	Cu[c] (ppm)
Tieschitz	.533	6320±70	2240±40	101±8
Bishunpur	.082	7890±190	2510±70	83±6
Chainpur-A	.279	7280±200	2770±110	83±10 (D)
Chainpur-B	.810	5680±150	2050±40	91±8 (D)
Chainpur-C	1.232	6570±50	2560±110	87±5 (D)
Khohar	.157	7090±120	2530±170	105±6
Mező-Madaras	.597	6780±140	2220±40	97±5 (D)
Tennasilm	.549	6260±120	2360±50	91±7
Prairie Dog Creek	.652	5300±100	2160±40	97±7
Bremervorde-A	.258	6320±380	2410±30	122±17
Bremervorde-B	.604	6340±120	2230±40	104±8
Ngawi (glass?)	.479	6550±190	2420±50	106±10 (D)
(wt'd avg and wt'd std. dev.)		6320±550	2450±230	96±9
(No mafic glass)				
Castalia	.354	5990±510	2260±10	89±14
Lua	.594	6630±130	2400±50	88±7
Weston	.535	5470±110	2030±40	101±7
Ranchapur	.494	5270±100	2030±40	117±8

[a] Weighted average have their population standard deviation; i.e. $\text{avg}^{\bar{H}} = \frac{\Sigma m_i H_i}{\Sigma m_i}$.

Weighted dispersion index $\equiv \left(\frac{\Sigma m_i (Hi - \bar{H})^2}{\Sigma m_i} \right)^{1/2}$.

[b] Value (±) after each abundance is either the standard dev. of two determinations on same specimen (both abundances determined by peak area method) or is the standard deviation of a single determination.

[c] All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 7

RESULTS OF RECENT DETERMINATIONS OF Na, Mn, AND Cu ABUNDANCES IN ENSTATITES[a,b]

Enstatites	Mass (g)	Na (ppm)	Mn (ppm)	Cu [c] (ppm)
Type A				
Abee	.727	8600±700	3720±70	206± 15 (D)
Indarch-A	.096	6680±140	1920±60	187± 8 (D)
Indarch-B	.161	7740±300	2030±60	209± 6 (D)
		8270±610	3270±760	205± 6
Type B				
Atlanta	.744	4370±80	1770±40	94±8 (D)
Hvittis	.531	5000±100	1480±30	96±7
Khairpur	.171	5900±300	2490±290	106±5 (D)
St. Marks	.333	5630±110	1570±50	220±18 (D)
		4940±560	1720±280	119±48

[a]Weighted average have their population standard deviation; i.e. $\text{avg}^{\bar{H}} = \frac{\Sigma m_i H_i}{\Sigma m_i}$.

Weighted dispersion index $\equiv \left(\frac{\Sigma m_i (Hi - \bar{H})^2}{\Sigma m_i}\right)^{1/2}$.

[b]Value (±) after each abundance is either the standard dev. of two determinations on same specimen (both abundances determined by peak area method) or is the standard deviation of a single determination.

[c]All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 8

RESULTS OF RECENT DETERMINATIONS OF Na, Mn, AND Cu ABUNDANCES IN Ca-RICH ACHONDRITES[a,b]

Ca-rich Achondrites	Mass (g)	Na (ppm)	Mn (ppm)	Cu [c] (ppm)
Eucrites				
Haraiya	1.510	2830 ± 40	3890 ± 230	5 ± 3
Juvinas	.252	2800 ± 60	3970 ± 120	8 ± 6
Moore County	.226	3070 ± 60	3450 ± 100	7 ± 9
Nobleborough	.503	3300 ± 200	4120 ± 20	1 ± 2
Nuevo Laredo	.172	3430 ± 70	4070 ± 120	7 ± 2
Pasamonte	1.398	2990 ± 10	3980 ± 120	4 ± 3
Sioux County	.927	3240 ± 380	4000 ± 110	3 ± 3
Stannern	.444	3780 ± 80	3970 ± 120	20 ± 5
Howardites				
Kapoeta	.235	1620 ± 50	3910 ± 120	6 ± 5
Petersburg	.241	2840 ± 90	3790 ± 110	6 ± 6
(wt'd avg and wt'd std. dev.)		3020 ± 390	3940 ± 130	6 ± 5

[a]Weighted average have their population standard deviation; i.e. avg $\overline{H} = \frac{\Sigma m_i H_i}{\Sigma m_i}$.

Weighted dispersion index $\equiv \left(\frac{\Sigma m_i (Hi-\overline{H})^2}{\Sigma m_i}\right)^{1/2}$.

[b]Value (±) after each abundance is either the standard dev. of two determinations on same specimen (both abundances determined by peak area method) or is the standard deviation of a single determination.

[c]All are GA γ-γ coincidence work. (D) denotes average of two determinations usually separated by 15 to 24 hours.

Table 9

INDIUM ABUNDANCES IN METEORITIC MATTER
(10^{-9}g In/g of Meteorite)

Class	Specimen	In (ppb)	In atoms/10^6 Si atoms	Average In/10^6 Si
Carbonaceous Chondrites				
Type I	Orgueil-A	64±6	0.17	0.17±0.02
	Orgueil-B	80±8		
	Ivuna	80±8	0.18	
Type II	Mighei	64±6	0.12	0.10±0.02
	Murray	47±4	0.085	
Type III-A	Felix	23±2	0.035	
	Lancé	25±3	0.039	0.041±0.008
	Mokoia	32±3	0.050	
Type III-B	Chainpur	74±7	0.10	
	Khohar	14±1	0.020	0.05±0.04
	Mezö-Madaras	13±1	0.018	
Enstatite Chondrites				
Type A	Abee-A	130±10	0.13	0.13±0.05
	Abee-B	56±6		
	Indarch	90±9	0.13	
Type B	Atlanta	0.22±0.04	0.00027	
	Hvittis	2.9±0.3	0.0037	0.0014±0.0019
	Khairpur	0.24±0.07	0.00030	
Ordinary Chondrites				
L-Group	Holbrook	0.6±0.1		
	Leedey	0.3±0.1		
	Modoc	0.3±0.1	0.0004	0.0004±0.0002
H-Group	Allegan	0.1±0.3	±0.0002	
	Richardton	0.2±0.5		
	Beardsley	2.1±0.2		
Achondrites				
Ca-rich	Juvinas	1.6±0.2	0.0017	0.001±0.001
	Stannern	0.24±0.02	0.00026	
Ca-poor	Johnstown	0.34±0.03	0.00036	0.00036±0.00003
	Norton County	0.40±0.04	0.00037	

Table 10

INDIUM ABUNDANCES IN TERRESTRIAL MATTER
(10^{-9} In/g Matter)

Type	Sample	In (ppb)		In (Average) (ppb)
Ultramafic [a]	Dunite (alpine-type, Canwell Glacier, Alaska)	5.6±0.6		
	Garnet pyroxenite (Kakanui, New Zealand)	14±2		
	Peridotite (Gulkana Glacier, Alaska)	33±4		13±9
	Peridotite (slightly serpentinized, Tinaquillo, Venezuela)	5.0±0.5		
	Peridotite (serpentinized, Mayaguez, Puerto Rico)	6.2±0.6		
Basalts [b]	D3 (Tholeiitic East Pacific Rise)	94±9	80±15	
	D4 (Tholeiitic East Pacific Rise)	65±6	avg.	
	Gu-57 (more alkalic, Guadalupe Island)	67±7	73±7	73±4
	Gu-77 (more alkalic, Guadalupe Island)	80±8	avg.	
	Composite	67±6		
Granites [c]	Composite of 85, <60% SiO_2	83±8		
	Composite of 191, 60-70% SiO_2	67±6		69±9
	Composite of 213, >70% SiO_2	57±6		
Sediments [d]	Composite of 36 European paleozoic shales	48±5		59±11
	Composite of 40 North American shales	70±7		

[a] Ultramafic specimens obtained from G. G. Goles; ultimate sources were Dunite and Gulkana peridotite, J. Hawkins; garnet pyroxenite, B. Mason; Tinaquillo and Mayaguez peridotites, H. Hess.

[b] D3, D4, Gu-57, and Gu-77 basalts obtained from A. E. J. Engel; composite basalts from L. Haskin and P. W. Gast.

[c] Granitic composites obtained from L. Haskin and P. W. Gast.

[d] European shale composites obtained from A. G. Hermann; North American from L. Haskin and P. W. Gast.

Table 11

ATOMIC ABUNDANCES OF In ATOMS/10^6 Si ATOMS

Source	In/10^6 Si
Suess and Urey[8] (1956)	0.11
Cameron[9] (1959)	0.11
Clayton et al[10] (1961)	0.071
Aller[11] (1965)	0.89 (solar value)
Akaiwa[12] (1966)	0.094 (Type II carbonaceous chondrites)
This paper	0.10 ±0.02 (Type II carbonaceous chondrites)
This paper	0.0004 ±0.0002 (ordinary chondrites)

Table 12

COMPARISON OF AVERAGE ABUNDANCES OF GROUP III ELEMENTS IN METEORITIC AND TERRESTRIAL MATTER

Type of Matter	Element: Al[a] (%)	Ga[b] (ppm)	In[c] (ppm)	Tl[d] (ppm)
Meteorites				
Type II Carbonaceous Chondrites	1.2	10	0.055 ±0.008	0.10
Ordinary Chondrites	1.3	5	0.0003 ±0.00017	0.0006
Terrestrial Rocks				
Ultramafic	2.9	1.5	0.013 ±0.009	0.06
Basalts	8.7	17	0.073 ±0.004	0.12
	(8.1 in W-1)[e]	(16 in W-1)	(0.080 in W-1)	(0.13 in W-1)
Granites	8.8	17	0.069 ±0.009	3.2
	(7.6 in G-1)	(18 in G-1)	(0.030 in G-1)	(1.3 in G-1)
Sediments	8.2 (shales) 2.5 (sandstones)	19 (shales)	0.059 (shales) ±0.011	0.7 (shales) 0.8 (sandstones)

[a] Abundances in sequence (for carbonaceous, ordinary chondrites, ultramafic, basalts, granites, and sediments) taken from Mason,(13) Fisher, (14) Eskola,(15) and Nockolds(16) for an average of 23 peridotites; Engel and Engel(17) for Pacific and Atlantic tholeiitic basalts; Eskola(15) and Nockolds(16) for an average of 48 alkalic granites; and Clarke(18) for averages in composites of 78 shales and 253 sandstones.

[b] Abundances in sequence taken from Greenland;(19) Greenland,(19) and Onishi and Sandell;(20) Sandell;(21) Sandell;(21) Sandell;(21) and Shaw.(22)

[c] This paper.

[d] Abundances in sequence taken from Reed <u>et al</u> (23) Reed <u>et al</u> (23) Shaw,(24) Shaw,(24) Shaw,(24) and Shaw.(24)

[e] Abundances in G-1 and W-1 standard granite and diabase taken from Fleischer.(25)

Table 13

INDIUM AND OTHER TRACE ELEMENTAL ABUNDANCES IN THE SAME ULTRAMAFIC ROCKS DETERMINED BY NEUTRON ACTIVATION AND ISOTOPIC DILUTION METHODS

Element	Dunite (Canwell Glacier)	Peridotite (slightly serp., Tinaquillo, Ven.)	Peridotite (serp., Mayaguez, P.R.)	Garnet Pyroxemite (Kakanui, New Zealand)	Peridotite (Gulkana Glacier, Alaska)
In (ppb) [a]	5.6±0.6	5.0±0.5	6.2±0.6	14±2	33±4
Na(ppm) [a]	107±6	144±7	233±10	3090±60	1540±40
Na(ppm) [b]	117±6	1200±60	405±15	3050±90	4170±100
K(ppm) [b]	19	26	---	940	---
Rb(ppm) [b]	0.072	0.093	---	1.7	---
Sr(ppm) [b]	2.3	3.9	---	33	---
Sc(ppm) [a]	5.0±0.3	11.4±0.3	7.5±0.3	18±0.4	51±1
Sc(ppm) [b]	5.9±0.2	14±0.3	9.2±0.3	15±0.3	15±0.4
Cr(ppm) [a]	5310±100	2400±50	1720±40	2540±50	175±6
Cr(ppm) [b]	3740±80	2290±50	1490±45	3020±60	4200±130
Mn(ppm) [a]	1090±20	870±20	800±20	880±20	1820±40
Mn(ppm) [b]	1240±40	950±20	820±15	1000±30	1110±25
Co(ppm) [a]	161±5	112±3	102±3	77±3	119±4
Co(ppm) [b]	195±8	134±7	93±8	105±6	78±15
Cu(ppm) [a, c]	44±4	45±4	9±3	12±3	270±20

[a] This work.

[b] Values by A. M. Stueber.[26]

[c] This work; Cu abundances obtained by counting the annihilation radiation (0.51-MeV gamma rays) of 12.8-hr Cu^{64} by a fast nanosecond coincidence circuit coupled to two 2 in. by 2 in. NaI solid crystals and two single-channel analyzers with windows set at 0.46 to 0.56 MeV. Abundances are averages of two determinations separated by about a 24-hr interval.

In 1960, Reed et al [23] determined by radiochemical neutron activation the U abundance in the Type I carbonaceous chondrite Orgueil at 0.008 ppm, or four times less than the Hoyle-Fowler theoretical value. It has been assumed by some cosmoscientific groups that Type I carbonaceous chondrites represent the most primitive matter available. However, from our recent work[6] it becomes highly probable that Type I carbonaceous chondrites may actually be collateral primitive matter compared to the other carbonaceous chondrites.

Two years ago Lovering and Morgan[31] published a U abundance of 0.024 ±0.004 ppm in the Type I carbonaceous chondrite Orgueil. Their result was also determined by radiochemical activation analysis, and their U result overlapped the predicted Hoyle-Fowler theoretical value. Since the expected ratio of U abundances in Type I to Type II carbonaceous chondrites as determined by Reed et al[23] agreed with the ratio of the rare-earth abundances observed by us in these two corresponding groups of chondrites, we were immediately suspicious of the Australian results[31] and decided to check the U abundance in two different Type I carbonaceous chondrites, Orgueil and Ivuna.

Experimental Details

Three carefully crushed specimens of Orgueil (0.250 g obtained from Dr. B. Nagy and 0.328 g from Dr. G. G. Goles) and Ivuna (0.738 g from Dr. B. Mason) were individually wrapped in two layers of 0.0005-in.-thick pure aluminum foil. The foil was weighed (≈0.130 g each), and its purpose was to retain any short-lived precursor xenon fission gases within the foil and also to absorb primary fission fragments. The 5.27-μg U standard was prepared by evaporating onto an aluminum cup (0.0005 in. thick) 0.053 cc from a U standard solution, containing 99.5 μg U/ml in 0.15N HNO_3. The heat source was a heat lamp. After the solution was evaporated, the aluminum cup was folded over into a flat disk and enclosed in a second aluminum foil to retain all fission gases and fission products. An aluminum blank foil weighing 0.133 g was also folded and enclosed for irradiation. All aluminum foils that contained the three chondritic specimens, the U standards, and the aluminum blank foil were approximately of equal weight; moreover, all of the five disks described above were finally wrapped in two more layers of 0.0005-in.-thick aluminum foils, which were discarded after irradiation.

The five samples were placed next to each other inside an aluminum capsule that was then irradiated for six hours at a thermal neutron flux of 7×10^{13} cm^{-2} sec^{-1} in position 6 of the hydraulic shuttle in the General Electric Test Reactor (Vallecitos, California). Since the centerline of the capsule was located about 6 cm from the centerline of the nearest fuel element, about 5.3×10^{12} fast neutrons (0.18 MeV to 10 MeV) cm^{-2} sec^{-1}

were present in the capsule. This total integrated fast neutron flux is approximately 10% of the total thermal neutron flux.

Pure iron wires of uniform thickness were placed at opposite ends of the five samples. The specific activities of the induced 45-day Fe^{59} monitors indicated a maximum thermal neutron flux difference of only 4% among the five samples and an average of 2% among the U standard and the three chondritic specimens. As will be evident below, this correction to the final data becomes negligible.

About three weeks after the irradiation, exhaustive radiochemistry was performed on the five samples to isolate the fission product 12.8-day Ba^{140}. Assuming [32] a common ratio for U^{235}/U^{238} in meteoritic and terrestrial U, isolation and counting of Ba^{140}, which is generated principally as a neutron fission product of U^{235}, will serve as an indicator of U abundances in the samples. In the radiochemical procedure, the meteorites and the U standard, each with its two inner aluminum wrappers, and the aluminum blank were individually placed in beakers containing about 19 mg of Ba carrier and HCl to dissolve the aluminum. The acids H_2SO_4, $HClO_4$, and fuming HNO_3 were used to destroy the organic matter. SiO_2 was removed by HNO_3 and HF fumings in teflon beakers with a final fuming by $HClO_4$. After H_3BO_3 and HNO_3 complexed any fluoride that remained, H_2SO_4 was added and digested to precipitate $BaSO_4$. After the centrifugation, the $BaSO_4$ was washed once with water and then metathesized by heating with 1M Na_2CO_3. The $BaCO_3$ was then dissolved in dilute HNO_3.

Final decontamination steps included (1) a $Ba(NO_3)_2$ precipitation from fuming HNO_3, (2) another $Ba(NO_3)_2$ and $Sr(NO_3)_2$ reprecipitation in the presence of 3 mg Sr carrier and fuming HNO_3, (3) a $Fe(OH)_3$ scavenge, (4) a $BaCrO_4$ precipitation, (5) two $BaCl_2$-H_2O precipitations from HCl-ether reagent, and (6) a final $BaSO_4$ precipitate that was mounted onto a thick aluminum disk and covered with 0.5-mil Mylar film. Chemical recovery yields ranged from 0.66 to 0.81.

Radioactivities of the purified Ba precipitates were followed by both beta and gamma-ray scintillation counting. A Sharp Lowbeta counter with a background of 0.3 counts/min and a geometry of ≈ 0.45 was used; for gamma-ray counting, the $BaSO_4$ specimens were placed directly on a 3-in. by 3-in. NaI solid crystal coupled to a 256-channel pulse height analyzer.

Results of Beta-Counting

All five $BaSO_4$ precipitates, corresponding to the Al background foil, the three chondritic specimens, and the U standard, were counted through an 80 mg/cm^2 Al absorber. This thickness of Al absorber will depress considerably the internally converted electrons arising from decay of

11.6-day Ba^{131} formed by the thermal neutron irradiation of Ba present in the chondrites, Al wrappers, Al background monitor foils, and U standard. Moreover, such an absorber will enhance the growth of the Ba^{140} daughter, 40-hour La^{140}, since Ba^{140} and La^{140} betas are transmitted by factors of 0.20 and 0.33, respectively, through ≈80 mg/cm^2 Al. Growth of La^{140} was carefully followed throughout the critical five to six day period after the last Ba^{140} -La^{140} separation. Beyond the growth peak of the decay curve, the decay followed a half-life of ≈12.8 days within experimental error.

A good test for purity of Ba^{140} -La^{140} betas in the counter response and the complete absorption in the 80 mg/cm^2 Al absorber of the Ba^{131} internally converted electrons involves a check of the ratios of the observed beta activity at the peak of the La^{140} growth curve to the beta activity at the time of last Ba^{140} -La^{140} separation time. For the Ba activities from the U standard, Al background foils, and Ivuna, Orgueil-N (Nagy), and Orgueil-G (Goles) samples, we observed ratios of 2.7 ±0.1, 2.7 ±0.5, 1.8 ±0.2, 2.0 ±0.2, and 1.8 ±0.2, respectively. These results indicate that the natural Ba concentration in the Al monitor was negligible relative to the U standard, while appreciable amounts of Ba^{131} electrons were transmitted in the chondritic specimens. This is not too surprising since the expected ratio of Ba^{131} to Ba^{140} activities in the carbonaceous chondrites is ≈26, assuming 3 ppm Ba and 0.008 ppm U. A large fraction of Ba^{131} decay occurs via a 0.494-MeV γ-ray which is partially internally converted. Since 80 mg/cm^2 of Al absorber corresponds to a range for 0.30-MeV electrons, internally converted electrons of energy 0.494 MeV minus the 0.037-MeV K-electron binding energy, or 0.457 MeV, will transmit the absorber.

Choosing the activity values on the equilibrium portions of the Ba^{140}-La^{140}-Ba^{131} decay curve, we calculated the upper limits of U present in the five specimens. For the third column of Table 14, below, the calculations assume that U impurity is homogeneously distributed in the Al wrappers. Note that the U content of 0.080 ppm in the Al wrapper monitors is close to the U abundance of 0.060 ppm determined by neutron activation analysis in zone-refined Al by Jervis and Mackintosh.(33) The results place an average upper limit of 0.018 ppm of U in Type I carbonaceous chondrites by calculation of the equilibrium decay data.

A more precise calculation of U abundance involves only the beta growth of the 40-hour La^{140}, daughter of 12.8-day Ba^{140}. As stated above, the total beta activity of Ba^{140} -La^{140} -Ba^{131} was followed through 80 mg/cm^2 Al absorber. During the first few hours of beta counting after the last "zero-time" of Ba^{140} -La^{140} radiochemical separation, 40-hour La^{140} grows in linearly. By extrapolating each growth curve of the Ba samples from the U standard, the three chondritic specimens, and the Al blank, the zero-time activity of Ba^{140} + Ba^{131} was obtained for each. Subtraction of zero-time activity of the Al blank from each of the zero-time activities of the U standard and the three chondritic specimens yielded the zero-time activities of the $Ba^{140} + Ba^{131}$ for the chondritic and U standard specimens. Furthermore, subtraction of the total beta activity (say a day after zero-time) of the Al blank from the total beta activities (also the same time after zero-time) of the four other samples yielded the total $Ba^{140} + Ba^{131} + La^{140}$ activities for the four samples. The subtractions above merely account for any U and Ba impurities that are present in the Al wrappers. After the zero-time activities of $Ba^{140} + Ba^{131}$ have been corrected for decay (assuming a half-life of 12.2 days, the mean of 12.8-day Ba^{140} and 11.6-day Ba^{131}), the residual La^{140} beta activity is obtained by subtracting the $Ba^{140} + Ba^{131}$ activities (corrected for decay) from the total $Ba^{140} + La^{140} + Ba^{131}$.

Table 14

UPPER LIMITS TO U ABUNDANCES IN TYPE I CARBONACEOUS CHONDRITES DETERMINED BY Ba^{140}-La^{140}-Ba^{131} EQUILIBRIUM DECAY DATA

Sample	U Abundance (ppm) (No Correction for U in Al Wrapper)	U Abundance (ppm) (Corrected for U in Al Wrapper)
Al monitor	0.080 ±0.003	---
Ivuna	0.031 ±0.002	0.016 ±0.001
Orgueil (N)	0.062 ±0.003	0.020 ±0.003
Orgueil (G)	0.049 ±0.002	0.017 ±0.003

In Table 15 below, we have tabulated these results. Again, it must be emphasized that it is assumed that the U and Ba impurity levels that are present in the Al wrappers are homogeneously distributed, at least in 0.13 g Al pieces. (All Al foils used in these experiments were cut from the same Al sheet).

Table 15

U ABUNDANCES IN TYPE I CARBONACEOUS CHONDRITES DETERMINED BY La^{140} GROWTH ACTIVITY ONE DAY AFTER Ba^{140}-La^{140} SEPARATION

Sample	U Abundance (ppm) (No Correction for U in Al Wrapper)	U Abundance (ppm) (Corrected for U in Al Wrapper)
Al monitor	0.068 ±0.018	---
Ivuna	0.023 ±0.005	0.009 ±0.006
Orgueil (N)	0.042 ±0.007	0.003 ±0.009
Orgueil (G)	0.032 ±0.005	0.001 ±0.014

All errors attached to the above values indicate one standard deviation due to counting statistics. The U abundances in column two of the above table calculated by the La^{140} betas agree within the 95% confidence levels for the U abundances in column two of the preceding table. However, in all cases, the upper limit values for U are higher due to the contribution of 11.6-day Ba^{131}.

The average abundance of U in three Type I carbonaceous chondritic specimens of 0.004 ppm (column three of the above table) is a factor of two less than the value of 0.008 ppm in Orgueil reported by Reed et al.[23] Recently, Reed[34] has redetermined U in two specimens of Ivuna and one of Orgueil and reports 0.008, 0.007, and >0.006 ppm, respectively. The technique used was neutron activation of U in the well-thermalized neutron flux (isotope tray) at the Argonne Reactor followed by radiochemical separation of iodine fission products.

U abundances may also be calculated by the La^{140} activity in equilibrium with its parent Ba^{140}. Calculations similar to those described above (which yielded Table 15 results) were made for determination of the results listed in Table 16.

Table 16

U ABUNDANCES IN TYPE I CARBONACEOUS CHONDRITES DETERMINED BY La^{140} BETA ACTIVITY IN EQUILIBRIUM WITH Ba^{140} ACTIVITY

Sample	U Abundance (ppm) (No Correction for U in Al Wrapper)	U Abundance (ppm) (Corrected for U in Al Wrapper)
Al monitor	0.077 ±0.008	---
Ivuna	0.026 ±0.003	0.012 ±0.003
Orgueil (N)	0.052 ±0.005	0.013 ±0.007
Orgueil (G)	0.043 ±0.004	0.010 ±0.006

The average value for U abundances in Type I carbonaceous chondrites via La^{140} activity in equilibrium with its parent Ba^{140} is 0.012 ppm, which is 50% higher than the Reed[23] values.

Results of Gamma-Ray Counting

A more precise and unambiguous counting method consists of following the growth and decay of the 12.8-day Ba^{140} daughter, 40-hour La^{140} (see Table 17). Since the 1.60-Mev gamma-ray activity of La^{140} was very low, the $BaSO_4$ samples were generally counted for 800-minute counting periods. No 1.60-Mev gamma-ray peak was observed in the 800-minute background taken for the Cu-clad NaI integral crystal, housed in a 4-in.-thick lead brick cave.

Table 17

U ABUNDANCES IN TYPE I CARBONACEOUS CHONDRITES DETERMINED BY SCINTILLATION COUNTING OF THE 1.60-MeV γ-Ray of La^{140}

Sample	U Abundance (ppm) (No Correction for U in Al Wrapper)	U Abundance (ppm) (Corrected for U in Al Wrapper)
Al monitor	0.051 ±0.007	---
Ivuna	0.014 ±0.002	0.005 ±0.003
Orgueil (N)	0.030 ±0.005	0.003 ±0.005
Orgueil (G)	0.030 ±0.003	0.005 ±0.004

The average value for U in Type I carbonaceous chondrites determined by γ-ray counting is 0.004 ppm, which is a factor of two less than the Reed et al[23] values. However, the large standard deviations attached to the values in the last column of Table 17 certainly overlap the Reed et al[23,34] U abundance.

To determine U more precisely in carbonaceous chondrites, future specimens should be more massive and should be wrapped in pure Cu foils in order to reduce the large U contribution in the wrapper foils. Neutron irradiations will be lengthened and the interval from the end of the irradiation to the initiation of radiochemical procedures will be shortened. Also, the U impurity levels should be ascertained in many sections of the Cu wrapping foils in order to check on the assumed homogeneity of U impurity in the wrappers. Incorporation of these factors in future U determinations should permit error limits of ±10% to be achieved.

The amount of U standard evaporated to dryness in the above experiments was purposely kept at a low level of 5.27 μg in order to prevent appreciable neutron self-shadowing effects. Since the U abundance in the chondrites was $\sim 10^3$ times less compared to the irradiated U standard, errors (if any) due to self-shadowing in the U standard will be more serious than those in the chondritic specimens. Some self-shadowing effects might be expected from the large resonance neutron flux present in the General Electric Test Reactor shuttle tube. However, any such effects, if present, would result in a lower U standard activation compared to U activation in the chondritic specimens and, therefore, the true U abundances in the chondritic specimens should be lowered proportionately.

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