

# Chemical, Petrographical, Mineralogical and Noble Gas Studies on the Chondrite Higashi-Koen

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## Abstract

In order to examine whether or not the chondrite Higashi-Koen is the same fall as the chondrite Nio, which fell 3 days before and only 120 km away, detailed chemical analyses, petrographical and mineralogical examination of the former and determination of noble gases of both chondrites have been performed.

Chemical data indicate that Higashi-Koen is a typical H-group chondrite, that is,  $Fe_{total}/SiO_2$ ,  $Fe_{metal}/Fe_{total}$ , and  $SiO_2/MgO$  are 0.754, 0.685 and 1.591 by weight respectively and fayalite ratio is 17.5 (norm) and 17.9 (EPMA) mole percent. Except for phosphorus behavior against various reagents used for stepwise fractional dissolution, no remarkable differences between Higashi-Koen and Nio were observed.

From the petrographical and mineralogical data, it was confirmed that Higashi-Koen belongs to petrologic type 5 presented by Van Schmus and Wood. In the matrix of the Higashi-Koen, a non-chondritic, basaltic fragment up to 1.5 mm in size, was observed. This was completely different from their host minerals except in olivine composition and cobalt contents in kamacite. It seems to have experienced different thermal processes during their histories.

Higashi-Koen is enriched in spallogenic and radiogenic noble gases like other ordinary chondrites while Nio contains a large amount of trapped gases. Such data indicate that both chondrites came from completely different parent bodies in space.

## 1. Introduction

The chondrite Higashi-Koen was said to fall in the park called Higashi-Koen, in Fukuoka-shi, Kyushu, approximately  $33^{\circ}36'N$ ,  $130^{\circ}26'E$ , on August 11, 1897 (Jimbo,

1906; Wakimizu, 1911). They described testimony by M. Fujimori, that it weighed originally about 200 momme (750 g), but had been distributed in fragments to several collectors. They regretted to have no opportunity to study, even to observe it.

According to the Catalogue of Meteorites (Prior and Hey, 1953), British Museum (Natural History) preserved 29.5 g of Higashi-Koen.

The chondrite Higashi-Koen was classified as grey olivine-bronzite chondrite in the Catalogue of Meteorites and as H 5 chondrite by Van Schmus and Wood (1967) but no detailed report on chemical composition, petrography, mineralogy and so on has been published to date.

Further, if the above description of date and place of fall of Higashi-Koen is true, it is only 3 days after and only 120 km from the site of the fall of the chondrite Nio which fell in Ikaida, Nio-mura, Yoshiki-gun, Yamaguchi-ken, 34°12'N., 131°34'E., on August 8, 1897 (short note "Iseki-Inraku" 1897; Jimbo, 1906; Wakimizu, 1911). The latter has not only several eye-witnesses as well as records and description, but also two of the three stones recovered have been preserved in the National Science Museum, Tokyo, and the Yamaguchi Museum in Yamaguchi-ken, respectively.

Based on the recent report on the frequency of meteorite falls on the earth by Halliday *et al.* (1984), only 39 falls of 100 g of meteorites per year in an area of  $10^6$  km<sup>2</sup> are estimated. Compared with the above estimate, if area and masses of Higashi-Koen and Nio falls are assumed to be 120 km<sup>2</sup> and 750 g respectively, the frequency is about  $2 \times 10^5$  times higher.

Muraoka (1963) collected stories on meteorite-Nio-fall from several newspapers in the period August 10 to 13, 1897, for the purpose of calculating the orbiting path in and from space. When analysed the stories seemed to mix up two falls and it is doubtful that both would be the same fall or the same shower (Murayama, 1960).

On the other hand, the chondrite Nio is described as spherical olivine-bronzite chondrite in the Catalogue of Meteorites (1953) and as H-group chondrite by Miyashiro and Murayama (1967). From our observations, it belongs rather, say, to H 4 (Shima *et al.*, 1984).

It should be confirmed whether Nio and Higashi-Koen are the same fall or not. For this reason, we have studied the chondrite Higashi-Koen in detail using the small chip recently provided us by Dr. Hatchison, British Museum (Natural History).

## 2. Chemical Composition

The chemical composition of Higashi-Koen was determined by recommended methods in the papers by one of the authors (Shima, 1974; 1980). Table 1 shows elemental abundances of main components and results of stepwise chemical fractional dissolution. The results calculated from above data and the data from a modified Bernas's decomposition method (Bernas, 1968) are tabulated in Table 2 with conventional format. The amount of iron in the sulphide phase was calculated as an equimolar ratio of the total sulphur, and metallic iron was calculated from the results

of the stepwise fractional dissolution experiment (Table 1). The normative abundances calculated on the basis of the analytical data are also listed in Table 2.

Table 1. Relative elemental abundances in separated phases of the chondrite Higashi-Koen

Element	Whole meteorite (%)	Fraction (%)			
		CuCl <sub>2</sub> -KCl	EDTA	Br <sub>2</sub> -aqua regia	Residue
Si	17.476				
Mg	14.172	0.62	0.29	57.63	41.46
Fe	28.190	67.26	1.24	24.81	6.69
Al	1.121	<0.3	<0.2	3.31	96.69
Ca	1.073	2.61	12.42	14.96	70.01
Na	0.728				
K	0.088				
Cr	0.363	~0	~0	1.3	98.7
Mn	0.254	1.75	0.75	48.73	48.77
Ti	0.054	~0	~0	20.7	79.3
P	0.149	~0	57.6	41.8	0.6
Ni	1.967	86.56	2.12	11.16	0.16
Co	0.107	93.08	1.01	3.51	2.40
S	1.734				
Cu	0.0116				

Table 2. Chemical composition and CIPW norm of the chondrite Higashi-Koen

Species	Weight percent	Species	Weight percent
SiO <sub>2</sub>	37.387	Olivine	— Fo 22.06
MgO	23.501		— Fa 6.78
FeO	7.539	Hypersthene	— En 25.74
Al <sub>2</sub> O <sub>3</sub>	2.119		— Fs 4.82
CaO	1.501		— En 1.31
Na <sub>2</sub> O	0.981	Diopside	— Fs 0.25
K <sub>2</sub> O	0.106		— Wo 1.73
Cr <sub>2</sub> O <sub>3</sub>	0.530		— Or 0.63
MnO	0.328	Plagioclase	— Ab 8.30
TiO <sub>2</sub>	0.091		— An 1.07
P <sub>2</sub> O <sub>5</sub>	0.342	Apatite	0.79
Metal	19.310	Chromite	0.78
— Fe	1.967	Ilmenite	0.17
— Ni	0.107	Nickel-Iron	21.38
— Co	0.107	Troilite	4.75
FeS	4.754		
Sum	100.563		100.56

### 3. Petrography and Mineralogy

Thin sections for both microscopic and electron microprobe studies were prepared from a chip of the specimen. The microprobe analysis of minerals was performed using an automated Shimadzu EMX-SM7 electron probe microanalyser, operated at 15 kV accelerating voltage and about 20 nA sample current. The standard materials are well-analyzed synthetic and natural crystals. The analytical data were corrected by the procedure of Bence and Albee (1968).

Higashi-Koen meteorite is an ordinary chondrite consisting of major olivine and orthopyroxene, subordinate plagioclase, clinopyroxene, nickel-iron and troilite and accessory chromite, apatite and native copper.

Chondrules range from 0.1 to 0.8 mm in size. Chondrules and their fragments are buried in the granulated matrix containing considerable amounts of metal and sulfide grains. The outline of most chondrules is poorly distinguished from the surrounding matrix (Fig. 1), but the internal textures characteristic of chondrules, microporphyritic aggregate of olivine and pyroxene phenocrysts and radiating or layered arrangement of elongated olivine and pyroxene crystals, are clearly observed in thin sections. In most microporphyritic chondrules and in a few layered ones, phenocrysts are surrounded with dark-brown fine-grained mesostasis composed of micron-sized granular or very fine acicular silicate crystals, but in several olivine chondrules,

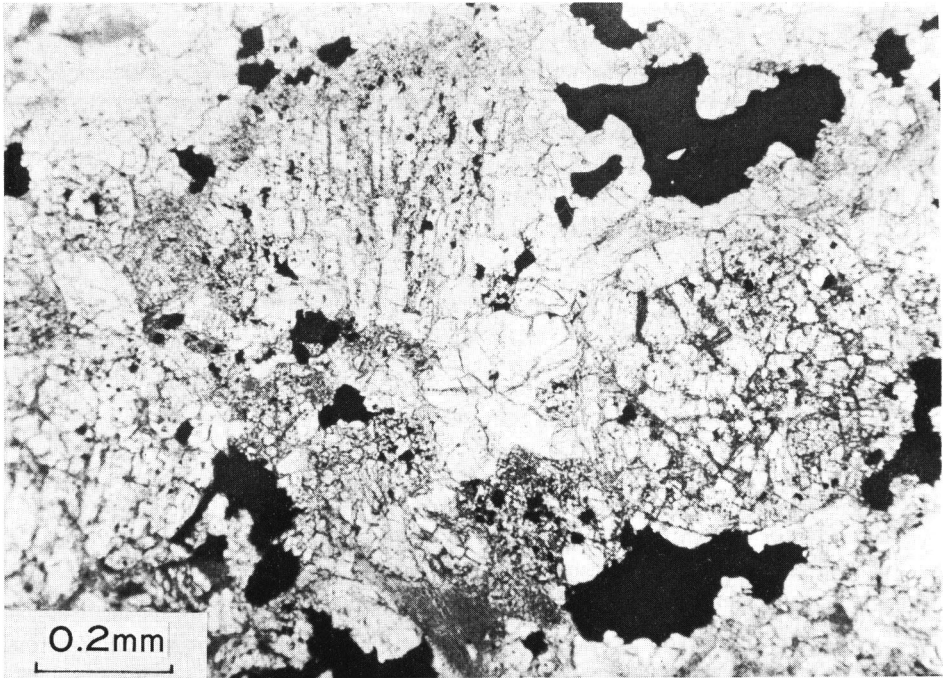


Fig. 1. A thin section of the chondrite Higashi-Koen.

Table 3. Modal composition of the chondrite Higashi-Koen

Species	Weight percent
Olivine	31
Orthopyroxene	30
Clinopyroxene	2
Plagioclase	9
Apatite	0.5
Chromite	1
Nickel-iron	22
Troilite	5
Sum	100

clear plagioclase is present in the interstitial area.

The matrix surrounding chondrules consists of granular aggregate of silicate grains, varying in size, and xenomorphic opaque grains.

Evidence of light to moderate shock deformation is observed in every silicate grain under cross polars, *i.e.*, distinctly wavy extinction and mosaic extinction in olivines and pyroxenes, bent pyroxene crystals by plastic deformation and kinking in a few olivine grains. The shock effect is also indicated by the presence of Neumann bands in nital-etched kamacite grains.

Higashi-Koen contains a non-chondritic and basalt-like fragment, ranging up to 1.5 mm in size. The modal composition of minerals as measured by the microscopic observation of whole thin sections except the area of basaltic fragment is shown in Table 3. In the host area, electron probe microanalysis of four elements (Si, Ca, Mg and Fe) shows that the average composition and PMD of 44 olivines are Fa: 17.9 mole percent and 5.2, and that those of 53 low-Ca pyroxenes are Fs: 16.5 mole percent and 6.3 (Fig. 2). Low-Ca pyroxene is dominantly orthopyroxene (bronzite), but minor clinobrozoite is present both in chondrules and in the matrix. As is shown in Table 4, the chemical composition of each silicate species, chromite and kamacite coincides with that of H-group chondrites (Keil and Fredriksson, 1964; Van Schmus and Ribbe, 1968; Bunch *et al.*, 1967; Afiattalab and Wasson, 1980).

The basaltic fragment included within Higashi-Koen (Fig. 3) is quite different from the host in mineral abundance, texture and chemical composition. Dominant plagioclase laths, up to 0.2 mm long, are separated by thin crystals of clinopyroxene and by very fine-grained aggregates of clinopyroxene-like grains in the interstitial area. Large diopsidic clinopyroxene crystals, up to 0.15 mm long, possess submicron exsolution lamellae of clinopyroxene in parallel to (001) plane. Table 5 shows the chemical composition of the basaltic fragment as determined by the broad electron probe microanalysis and CIPW norm. Because of the significant amount of plagioclase and calcic pyroxene, the fragment is Al-, Ca- and Na- rich. The olivines in the fragment contain more CaO, 0.12 weight percent on average, compared with those in the host in Table 4, in which CaO content is less than the detection limit by electron

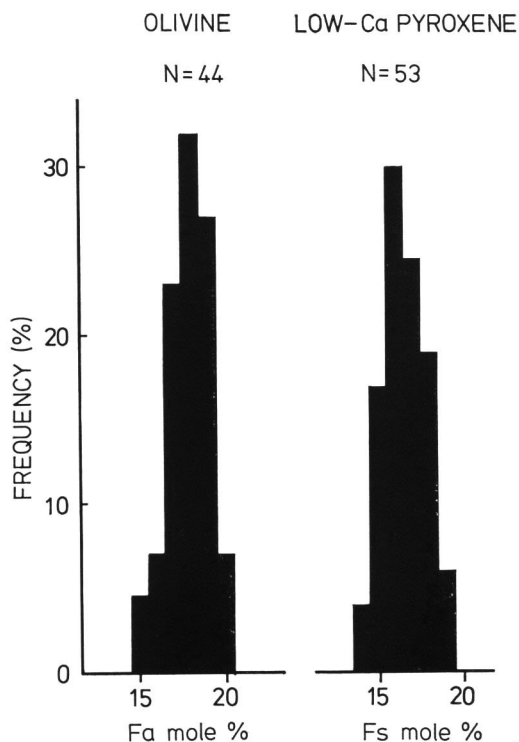


Fig. 2. Histogram of olivine and low-Ca pyroxene composition.

microprobe analysis, indicating that the two olivines experienced different thermal processes (Dodd, 1969).

#### 4. Noble gases

The noble gases were extracted from 0.05374 g and 0.163 g of chip samples of Higashi-Koen and Nio respectively and isotopic abundances of He, Ne, Ar,  $^{84}\text{Kr}$  and  $^{132}\text{Xe}$  were determined by a method similar to that described by one of authors (Takaoka, 1976; Nagao and Takaoka, 1979). The results are presented in Table 6. Higashi-Koen contains both radiogenic and spallogenic noble gases in an amount typical for an H-group chondrite (Schultz *et al.*, 1983), while Nio contains tremendous amount of trapped gases, masking the level of spallogenic gases present. The latter is apparently so-called gas-rich chondrite.

Cosmic-ray-exposure ages and gas-retention ages calculated from data are also shown in Table 6. Since Th and U contents in both meteorites are not available yet for calculation of  $^4\text{He}$  ages, they were assumed to be  $\text{U}=12$  ppb and  $\text{Th}/\text{U}=3.6$ .

Table 4. Electron probe microanalysis of minerals in Higashi-Koen (weight percent)

	olivine		low-Ca Pyroxene host	clino- pyroxene frag.	feldspar host	chromite host	kamacite	
	host	frag.					host	frag.
No. of grains	9	13	8	4	5	12	13	2
SiO <sub>2</sub>	39.7	39.8	56.9	50.7	68.6	—	—	—
TiO <sub>2</sub>	—	—	0.17	1.20	—	2.01	—	—
Al <sub>2</sub> O <sub>3</sub>	0.03	—	0.18	4.23	19.7	6.69	—	—
Cr <sub>2</sub> O <sub>3</sub>	0.03	—	0.13	2.15	—	58.0	—	—
FeO	16.7	15.8	10.3	3.10	—	28.9	—	—
MnO	0.44	0.46	0.45	0.20	—	0.92	—	—
MgO	42.8	43.8	30.6	14.8	—	3.10	—	—
CaO	0.02	0.12	0.57	22.0	2.16	—	—	—
Na <sub>2</sub> O	—	—	0.04	0.88	8.58	—	—	—
K <sub>2</sub> O	—	—	—	—	0.79	—	—	—
Fe	—	—	—	—	—	—	94.3	94.5
Ni	—	—	—	—	—	—	6.03	4.81
Co	—	—	—	—	—	—	0.40	0.48
sum	99.7	100.0	99.3	99.3	99.8	99.6	100.7	99.8
	Fo: 82	Fo: 83	Wo: 1	Wo: 49	Or: 5			
	Fa: 18	Fa: 17	En: 83	En: 46	Ab: 83			
			Fs: 16	Fs: 5	An: 12			

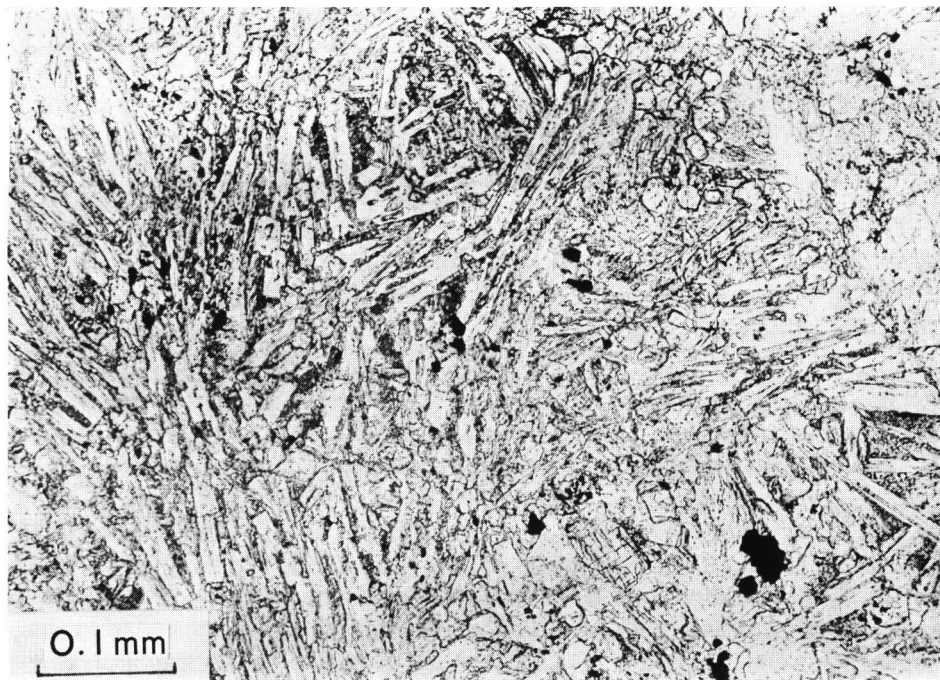


Fig. 3. A basaltic lithic fragment in the chondrite Higashi-Koen.

Table 5. Chemical composition and CIPW norm of the Higashi-Koen lithic fragment

Species	Weight percent	Species	Weight percent
SiO <sub>2</sub>	54.9	Olivine	— Fo 9.49
TiO <sub>2</sub>	0.36		— Fa 2.43
Al <sub>2</sub> O <sub>3</sub>	16.3		— En 5.83
Cr <sub>2</sub> O <sub>3</sub>	0.30	Diopside	— Fs 1.36
FeO	2.82		— Wo 7.94
MnO	0.10		— Or 2.19
MgO	7.78	Feldspar	— Ab 47.47
CaO	7.35		— An 17.44
Na <sub>2</sub> O	5.78	Nepheline	0.78
K <sub>2</sub> O	0.37	Chromite	0.44
		Ilmenite	0.68
Sum	96.1		96.05

Table 6. Concentration of noble gases and cosmic-ray-exposure and gas-retention ages of chondrites Higashi-Koen and Nio (10<sup>-8</sup> ccSTP/g)

Chondrite	<sup>3</sup> He	<sup>4</sup> He	<sup>20</sup> Ne	<sup>21</sup> Ne	<sup>22</sup> Ne
Higashi-Koen	11.9	1695	2.46	2.69	2.88
Nio	48.2	13,700	59.0	12.4	18.1

Chondrite	<sup>36</sup> Ar	<sup>38</sup> Ar	<sup>40</sup> Ar	<sup>84</sup> Kr	<sup>132</sup> Xe
Higashi-Koen	1.28	0.502	5880	0.0159	0.0161
Nio	6.67	3.21	7490	0.0237	0.0359

Chondrite	cosmic-ray-exposure ages*			gas retention ages**	
	<sup>3</sup> He	10 <sup>6</sup> years <sup>21</sup> Ne	<sup>38</sup> Ar	10 <sup>6</sup> years <sup>4</sup> He	<sup>40</sup> Ar
Higashi-Koen	4.72	5.16	3.48	4.0	4.25
Nio	(18)	(28)	(31)	—	4.51

\* Production rates given by Cressy and Bogard (1976) were used. For Nio, (<sup>20</sup>Ne/<sup>22</sup>Ne)<sub>c</sub>=0.85, (<sup>21</sup>Ne/<sup>22</sup>Ne)<sub>c</sub>=0.88, (<sup>20</sup>Ne/<sup>22</sup>Ne)<sub>t</sub>=12.5, (<sup>38</sup>Ar/<sup>36</sup>Ar)<sub>c</sub>=1.55 and (<sup>38</sup>Ar/<sup>36</sup>Ar)<sub>t</sub>=0.187 were used for estimation of cosmogenic <sup>21</sup>Ne and <sup>38</sup>Ar.

\*\* Decay constants for <sup>4</sup>He and <sup>40</sup>Ar are given by Steiger and Jäger. Concentration of U and ratio of U/Th were assumed as 12 ppb and 3.6, respectively.

## 5. Discussion

The chemical composition of major elements in Table 1 and 2 as well as ratios by weight of Fe<sub>total</sub> to SiO<sub>2</sub>, Fe<sub>metal</sub> to Fe<sub>total</sub> and MgO to SiO<sub>2</sub>, and molar percent of fayalite in olivine in Table 7 indicate that the Higashi-Koen is a typical H-group chondrite. From petrographical and mineralogical examination, its petrological type



Table 7. Comparison of chemical and mineralogical data between Higashi-Koen and ordinary chondrites\*

	Higashi-Koen	H	L	LL
Fe <sub>total</sub> /SiO <sub>2</sub>	0.754	0.77±0.07	0.55±0.05	0.49±0.30
Fe <sub>metal</sub> /Fe <sub>total</sub>	0.685	0.63±0.07	0.33±0.07	0.08±0.07
SiO <sub>2</sub> /MgO	1.591	1.55±0.05	1.59±0.05	1.58±0.05
Fa**	17.5 (norm) 17.9 (EPMA)	18±2	24±2	29±2

\* Classification, after Van Schmus and Wood (1967).

\*\* Mole percent fayalite in olivine.

Table 8. Phosphorus and calcium appeared in EDTA fraction in various H-group chondrites

Chondrite	Class	Element	Dissolved in EDTA (%) to total P or Ca	Atomic ratio
Ogi <sup>1)</sup>	H 6	—P	45.80	1
		—Ca	3.37	0.74
Xinyang <sup>2)</sup>	H 5-6	—P	30.17	1
		—Ca	0.81	0.17
Higashi-Koen	H 5	—P	57.6	1
		—Ca	12.42	1.2 = 2.4
Nio <sup>3)</sup>	H 4	—P	17.0	1
		—Ca	4.6	1.7 = 3/5

1) Yabuki *et al.*, (1981).2) Shima *et al.*, (1983).3) Shima *et al.*, (1984).

is ascribed to be 5 as was tabulated by Van Schmus and Wood (1967). The CIPW norm in Table 2 and the modal composition in Table 3 agree very well. This is also confirmed by petrological type with homogeneity of the Higashi-Koen.

At a glance, the chemical form of phosphorus in H-group chondrite is puzzling. In the course of stepwise fractional dissolution, calcium phosphate minerals such as apatite, merrillite and whitlockite should be dissolved in ammoniacal EDTA solution, because of the very strong affinity of calcium and EDTA in higher pH, whereas phosphide minerals such as schreibersite should be decomposed by Br<sub>2</sub>-aqua regia. As is shown in Table 2 and Table 8, 57.6 percent of phosphorus in Higashi-Koen are in the EDTA- and the rest are in the Br<sub>2</sub>-aqua regia fractions. This means in Higashi-Koen more than half of phosphorus would be in the form of phosphate. Compared with it, in the Nio, only 17.0 percent of phosphorus is in the high oxidation state. Further, molar ratio of phosphorus to calcium dissolved in EDTA from Higashi-Koen and Nio are also different, that is, in the former, it is 1 to 1.2, close to whitlockite, 2 to 2.5, and in the latter 1 to 1.7, close to apatite, 3 to 5. Two other examples in Table

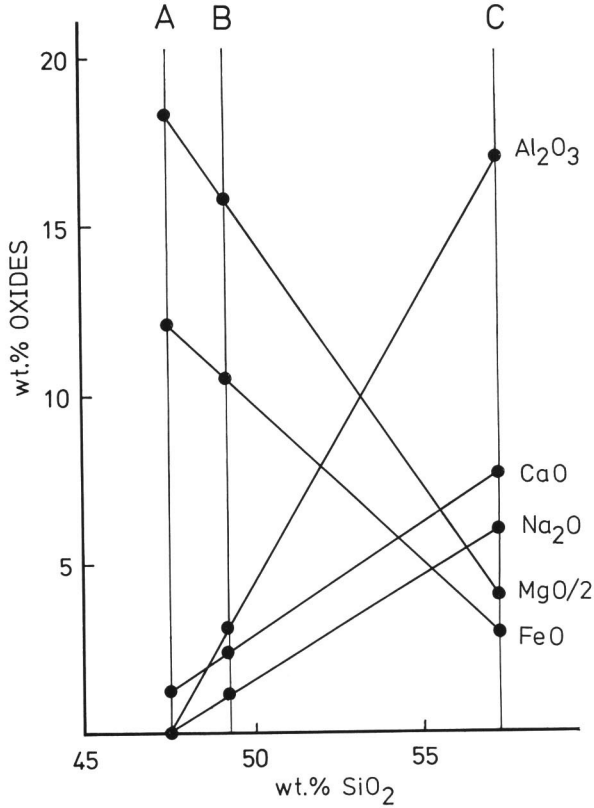


Fig. 4. SiO<sub>2</sub> variation diagram of oxide composition. A: a portion that is supposed to have been removed from H-chondrite composition. B: basaltic fragment of Higashi-Koen. C: H-chondrite (the average data are from Mason (1965)). The total of all oxide compositions was normalized to 100 weight percent, and minor components, less than 0.5 weight percent, were excluded in this figure.

8, Ogi, H 6 and Xinyang, H 5-6, show again different ratios, *i.e.*, greatly lacking in calcium against phosphorus to expect any calcium phosphate minerals. May we say that calcium moves from phosphate minerals to silicate minerals during metamorphic processes? Of course, there are still too few examples to conclude anything, however, at least we may say that, H-group chondrites with petrologic type in higher number, in other words, H-group chondrites well metamorphosed contain phosphorus in the form of phosphate in rather high ratio, and primitive ones have phosphorus in the definite chemical form with two extreme opposite oxidation states. This may suggest that phosphorus could be used for the indicator of metamorphism after H-group chondrites formed.

The basaltic fragment of Higashi-Koen could be igneous in origin from its texture.

It is different from such lithic materials as have been found in ordinary chondrites, *e.g.*, impact-melt-rock clasts consisting of olvine- and olvine-pyroxene-microphyrtes (Rubin *et al.*, 1983) and Ca-Al-rich chondrules and inclusions in ordinary chondrites, especially type 3 and 4, and in chondrite regolith breccia (Bischoff and Keil, 1983). The chemical composition as determined by broad beam electron microprobe analysis indicates the lithic fragment formed from SiO<sub>2</sub>-unsaturated silicate melt: a small amount of normative nepheline appears in the CIPW norm. The fragment could be related to H-chondritic material, because the fayalite composition of olvine, Co content of kamacite grains are similar to those of H group chondrite. The normative plagioclase, An<sub>25</sub>, of the fragment is close to that, An<sub>21</sub> on average, of H-group chondrites (Mason, 1965). The fractionation process causing almost complete removal of metal and sulfide and partial removal of mafic silicates from the melt of H-chondritic material might produce a (Ca, Na)-Al-rich silicate melt that forms such a lithic material as is present in Higashi-Koen. SiO<sub>2</sub> variation diagram in Fig. 4 suggests that partial removal of mafic silicates (normative olvine and hypersthene) from the silicate composition of H-group chondrite could produce that of Higashi-Koen lithic fragment. If the above model is correct, the melt that produced the basaltic material could have formed by the igneous process at depth in the parent body. As is shown by the melting experiment of basaltic rock, SiO<sub>2</sub>-unsaturated basaltic melt is formed at high pressure (Green and Ringwood, 1967). After the rock formed, it was excavated and disrupted by impact, and was reconsolidated with fragmented materials. The reconsolidation may have occurred after the maximum metamorphic temperature for type 5 ordinary chondrites, 700–800°C (Dodd, 1969), had been attained, because CaO content of olivines was not homogenized between the host and the basaltic fragment.

Based on the noble gas data, it is apparent that Higashi-Koen and Nio are from completely different falls and have different original bodies and history in space as was described in the section on noble gases. This was confirmed by phosphorus behavior in the course of stepwise fractional dissolution as is shown in Table 8.

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