

Petrochemistry of the Late Cretaceous-Paleogene igneous rocks in the Ikuno-Akenobe mines area, Southwest Japan

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Abstract: The Ikuno and Akenobe vein deposits are known to be typical subvolcanic type being hosted in the Late Cretaceous volcanic rocks in the Ikuno mine area and in Paleozoic-Mesozoic igneous and metamorphic rocks in the Akenobe mine area. The ore veins have mostly N-S, partly NW strikes and steep dips in the Ikuno mine, and are rich in silver and base metals historically. Tin was found in later years. The ore veins as a whole show a concentric zoning of the central Sn-Cu subzone, surrounded by Sn-Cu-Zn subzone, Zn subzone, Pb-Zn subzone, Au-Ag subzone and barren subzone. The Akenobe veins have generally NW strike swinging to NE in the western part and steep dips. The ores are polymetallic but shown by two different stages of the early Pb-Zn-Cu substage and the later W-Sn-Cu substage.

Late Cretaceous volcanic formation of the Ikuno Group is composed of andesitic, dacitic and rhyolitic lavas and pyroclastic rocks. By the measurement of the magnetic susceptibility and microscopic observations, these volcanic rocks are found to belong generally to the I-type magnetite-series. These rocks are plotted K-rich calc-alkaline rocks in the variation diagram. Rich ores tend to occur associated with basaltic and rhyolitic dikes in the Ikuno mine. Cu- and Sn-rich ore fluids may be originated in the basaltic and rhyolitic magmas, respectively. Abundant dikes, mostly post-ore though, in the Akenobe mine indicate that the I-type magnetite-series magmatism with wide range of compositions prevailed in this mine area and supplied the ore fluids to the early stage base metal mineralizations. But the second stage of Sn-rich ore fluids may be derived from an I-type ilmenite-series granitic body still hidden.

Keywords: Late Cretaceous, volcano-plutonic complex, polymetallic veins, Ikuno mine, Akenobe mine

1. Introduction

Late Cretaceous volcanic and granitic rocks distributed in the Inner Zone of Southwest Japan are considered as volcano-plutonic complex, accompanying coeval metallic ore deposits of different types (Ishihara *et al.*, 1988). Yet chemical and chronological comparisons of the volcanic and plutonic rocks and ore deposits have been rarely done, because of difficulty to obtain fresh samples from volcanic rocks. Related dikes have not been studied for the chemistry but for analyzing regional stress effect in the southern part of the Chugoku-Shikoku District in the Inner Zone of Southwest Japan (Yokoyama, 1984).

In the central part of Hyogo Prefecture, there occur intense tin-bearing base-metal mineralizations of the Late Cretaceous age at the Ikuno and Akenobe mines, which are classic examples of “xenothermal” type (Park

and MacDiarmid, 1964; Imai *et al.*, 1975), and are rich in a rare element of indium (Ishihara *et al.*, 2006). These base metal deposits have a long history of mining for silver especially at the Ikuno mine (Maruyama, 1957), and tin-bearing base metal mineralizations were discovered in rather recent years both at the Ikuno and Akenobe deposits, which are somehow similar to the development history of the Potosi mine, Bolivia. Thus, they have been well studied polymetallic view points (Imai, 1970, 1978; Kojima and Asada, 1973; Sato *et al.*, 1977; Sato and Akiyama, 1980; Ishihara *et al.*, 1981a, b).

A new In-bearing mineral, sakuraiite (Cu,Zn,Fe)₃(In,Sn)S₄ was discovered in the Ikuno mine in the 1960s (Kato, 1965), and roquesite was commonly observed in the Ikuno and Akenobe deposits (Kato and Shinohara, 1968; Shimizu and Kato, 1991; Murao and Furuno, 1991). Sphalerite-rich ores contain up to 4,240

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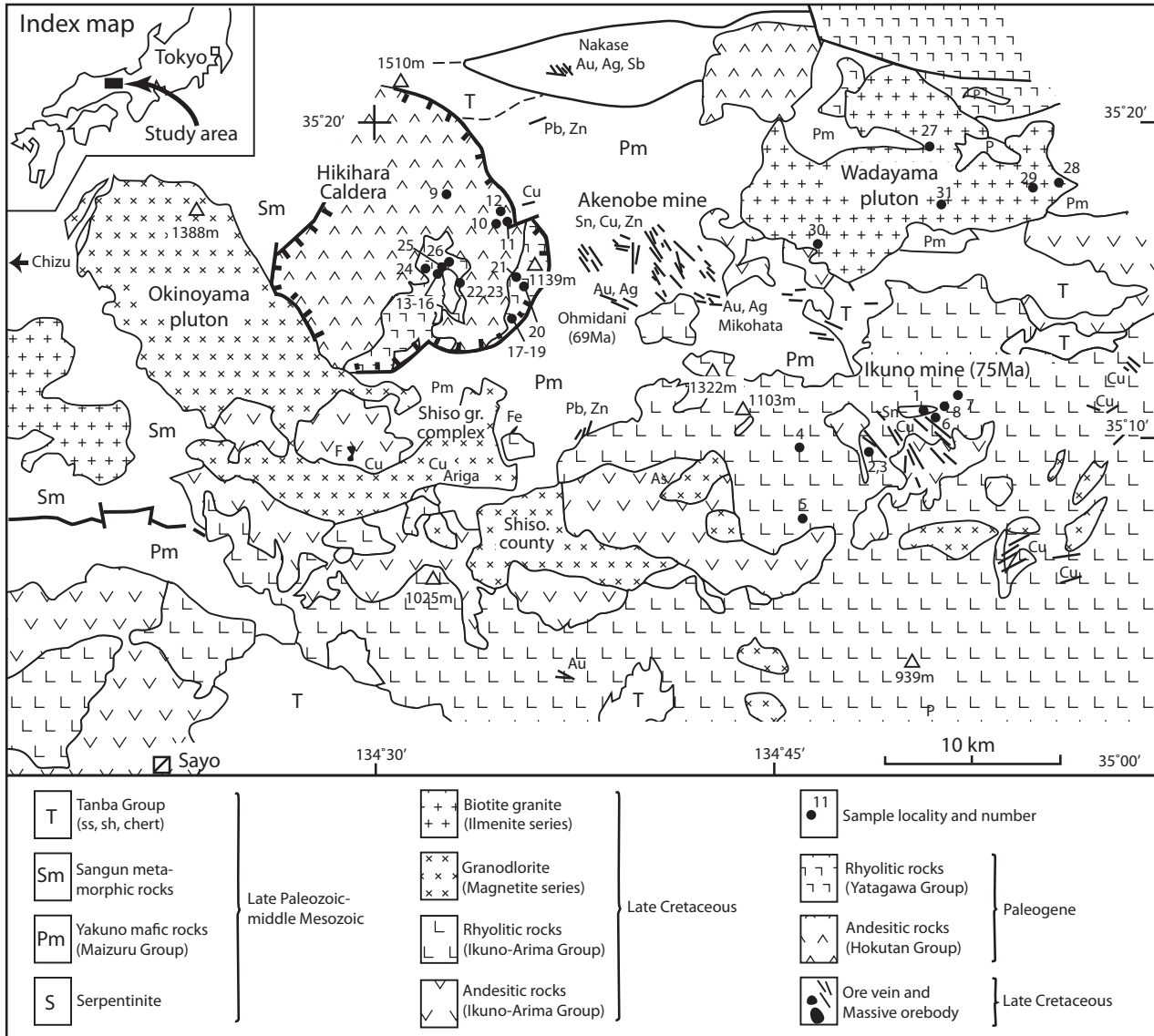


Fig. 1 Simplified geological map of the Ikuno-Akenobe mines region (from Ishihara *et al.*, 1981a).

ppm In in these polymetallic quartz vein deposits (Ishihara *et al.*, 2006). Recently, Potosi deposits of Bolivia were reevaluated from a view point of high indium contents in black sphalerite, which was never recovered from the Potosi deposits (Ishihara *et al.*, 2011). The mineralizations at the Ikuno-Akenobe mines are similar to those of the Potosi mine and nearby Porco mine, in terms of the ore mineralogy and related subvolcanic activities.

In this paper, we review the metal production of the Ikuno-Akenobe mines, and report new petrochemical data of volcanic, subvolcanic and plutonic rocks of the Ikuno-Akenobe region, then types of the igneous activities responsible for the polymetallic mineralizations are discussed. The chemical results are compared with those of the similar igneous rocks in the Potosi and Porco mines area in Bolivia.

2. Produced metals

The Ikuno mine was historically silver mine and tin-polymetallic ores were discovered in recent years, which is similar to the development history of the Toyoha mine in Hokkaido, but in much older in age. Therefore, it is difficult to figure out the whole production of silver from the Ikuno mine, but Fujiwara (1988) was able to estimate the silver production of 1,723 tons Ag, based upon the production record of the past 420 years and also calculating length of the drift-tunnel before the 420 years. Much smaller silver-rich precious metal veins occur around the southern margin of the Akenobe vein system as Ohmidani (422 kg Au and 83,349 kg Ag in 1937-43 and 1961-83) and Mikohata (306 kg Au and 137,314 kg Ag in 1945-1983, MMPIJ, 1994) deposits, which are very rich in silver. Further to the north, silver-rich Sb veins are seen at the Nakase

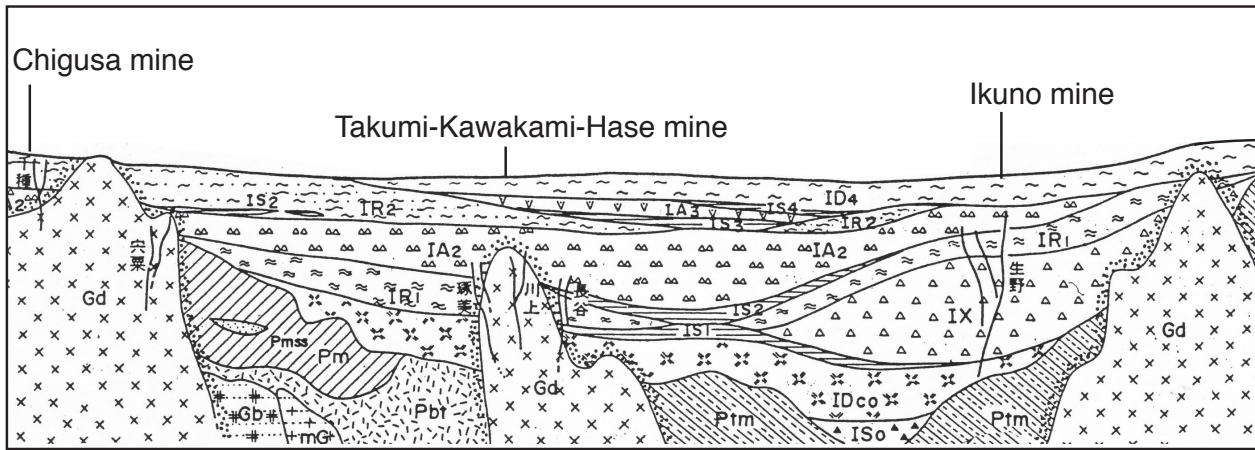


Fig. 2 East-west profile of volcanic and plutonic rocks of the Ikuno-Takumi mines transect modified after MITI (1988). Basement metamorphic and plutonic rocks are shown as Gb, mG, Pm, Pmss, Pbt, and Ptm. Volcanic rocks of the Ikuno Group from the bottom to the top as ISo (black shale with breccias), IDco (dacitic pyroclastics), IS1, (black shale, sandstone, tuff), IX (rhyolitic-andesitic pyroclastics, partly lava), IR1 (rhyolitic welded tuff), IS2 (tuff/shale), IA2 (andesite and its tuff), IR2 (rhyolitic welded tuff), IS3 (tuff/shale), IA3 (andesite & its tuff), IS4 (tuff/shale), and ID4 (dellenite welded tuff). Gd: Shiso granitoids.

mine (Figs. 1 and 2), which has the production record (1941-1969) of 6,245 kg Au; 36.0 tons Ag, and 2,501 tons Sb (MMPIJ, 1994). Mineralization age of this deposit occurring in fractures of a volcanic vent, could well be younger, Miocene, age than the late Cretaceous age of the Ikuno-Akenobe deposits.

Production records of the polymetallic ores from the large two mines are only available in rather recent years as follows: Akenobe mine, 1921-1987 (Mitsubishi Metal Corp. in Nakamura and Sakiyama, 1995): Produced ores 17,254, 000 tons with the ore grades of 1.03 % Cu, 1.69 % Zn and 0.40 % Sn. The metal contents are 178×10^3 tons Cu, 292×10^3 tons Zn, 69×10^3 tons Sn. The Ikuno deposits in 1956-73 production are higher in lead-zinc and lower in tin contents than those of the Akenobe mine, as 1.19 % Cu, 2.06 % Zn, 0.43 % Pb and 0.16 % Sn for the produced ores of $3,803 \times 10^3$ tons, which is assumed to be 33 % of the total production in the history (Mitsubishi Metal Corp. in Aoki and Yoshikawa, 2005). The recorded and assumed productions are calculated to be as follows: 45,256/137,139 tons Cu, 16,353/49,555 tons Pb, 38,342/237,399 tons Zn, and 6,085/18,439 tons Sn. Thus, the two deposits are roughly equal in size, although the Akenobe deposits are richer in tin as cassiterite, and tungsten as ferberite and scheelite (not recovered), while the Ikuno deposits are much richer in silver, mainly argentite, and lead as galena.

3. Geological background

All the ore deposits mentioned above occur associated with Late Cretaceous to Paleogene volcanic and subvolcanic (dike) rocks of the Ikuno Group, which could belong to both magnetite- and ilmenite-series

(Appendix I), although we still need detailed studies. The host rocks of the two mines are quite contrasting: the Ikuno veins are hosted in the Late Cretaceous volcanic and subvolcanic rocks of the Ikuno Group; while the Akenobe veins are hosted in the late Paleozoic to the earliest Mesozoic metamorphic rocks intruded by many Late Cretaceous to Paleogene dikes (Figs. 1 and 2). Maruyama (1957) pointed out that pre-ore N-S and NW-SE basaltic dikes and sheets controlled sizes of the ore veins in the Ikuno deposits and a bonanza was formed in E-W-trending rhyolite dike in the southern part. In the Akenobe mine, on the other hand, most of the ore veins follow in NW-SE and partly E-W tensional fractures (Saigusa, 1958), and most of the dikes, which are generally post-ore, occur mostly in NE-SW fractures (Sato and Akiyama, 1980).

The other possible igneous rocks related to the mineralizations are granitic rocks exposed toward the eastern and western parts from the Akenobe deposits, which are called Wadayama and Hikihara Granites, respectively. The Wadayama Granite belongs to the ilmenite-series, rich in trace amounts of tin (Terashima and Ishihara, 1982), and is expected to occur below the Akenobe vein system (Kojima and Asada, 1973). This granite is most suitable igneous body for the tin mineralizations, while the Hikihara granite belongs to the magnetite-series, unsuitable type for the tin mineralizations. To the south and west of the Akenobe-Ikuno ore deposits, the Shiso granitic complex of I-type magnetite-series with intermediate compositions (Ishihara, 2002), which are similar to those of the Chilean copper belt (Ishihara and Chappell, 2010), occur together with coeval volcanic rocks in and around the Shiso County in an east-west direction (Fig. 1). No tin but many small copper and magnetite deposits are associated with

them. Disseminated chalcopyrite at Ariga (Fig. 1) was once considered as a porphyry copper type and drilled for the downward extension.

Except for the Shiso and Wadayama granitoids (Ishihara, 2002; Terashima and Ishihara, 1982), no petrochemical work has been done on the volcanic and subvolcanic rocks of this region. Therefore, the volcanic rocks were collected from the late Cretaceous Ikuno Group in the Ikuno mine area (8 samples), and Paleogene volcanic (21 samples) and subvolcanic (3 samples) rocks from the Hikihara caldera, just west of the Akenobe veins system (Fig. 1). These samples are listed in Appendix I and shown in Figure 1. From the underground tunnels of the Akenobe mine, the late Cretaceous to Paleogene subvolcanic rocks were also collected from the eastern part (18 samples) and western part (18 samples). They are listed in Appendix II.

4. Late Cretaceous volcanic, subvolcanic and plutonic rocks

4.1 Mode of occurrence and K-Ar age

The Ikuno-Akenobe mines area is underlain by the Late Paleozoic Sangun metamorphic rocks, the Yakuno mafic rocks (340 Ma, MITI, 1988) belonging to the Maizuru Group, which are associated with small amounts of serpentinite. These rocks are intruded and overlain unconformably by late Cretaceous to Paleogene volcanic rocks (Fig. 2), which are divided into the Late Cretaceous Ikuno-Arima Group in the south of the Sanyo Belt, and the Paleogene Yatagawa Group in the north of the Sanin Belt (Geological Society of Japan, 2009). In the studied area, the Ikuno Group occurs in the southern part (Fig. 1). This group is composed mainly of rhyolitic to dacitic lavas and pyroclastics, and locally of andesitic and basaltic rocks (Fig. 2). Similar volcanic rocks are exposed in the northwestern part of the Hikihara caldera, yet the formation age is still unknown.

About granitic rocks, ilmenite-series granitoids of the Wadayama pluton is considered as oldest, because similar ilmenite-series granitoids of the Mochigase and Chizu bodies give 80.9 and 78.2 Ma, respectively; while magnetite-series granitoids of the Shiso granitic complex are dated at 68.3 and 66.3 Ma; all on the biotite (Shibata, 1979). There is one K-Ar age of 64.2 Ma in the Wadayama pluton (K015), but the dating was done on the whole rock method (MITI, 1988) and further studies are necessary for the age of the Wadayama pluton.

These volcanic rocks of the Ikuno Group were only dated by a whole-rock K-Ar method, which showed 78.9 Ma to 57.7 Ma (MITI, 1988), in which the older ages appear to be close to the real ages. The volcano-plutonic complex at the Hikihara caldera, to the west of the Akenobe vein system (Fig. 1), is composed of andesitic and rhyolitic rocks, whose averaged whole rock K-Ar age is 55.7 Ma (n=3). These volcanic rocks

belong to the magnetite-series but may be younger than those of the Ikuno Group as Paleogene Formation.

K-Ar ages of adularia from the Ryokuju vein at 19L of the Ikuno vein system gives 74.2 Ma (MITI, 1988). The pre-ore rhyolitic host rock containing much sericite and chalcopyrite gives a whole-rock K-Ar age of 72.8 Ma (Ishihara and Shibata, 1972), which may represent the sericite age. Thus, the main base metal mineralization of the Ikuno mine is considered to have a Late Cretaceous age, though we still need U-Pb age determination on the contained zircon. Adularia from the marginal Au-Ag quartz veins at Ohmidani and Mikohata deposits may be much younger in age than the base metal mineralization, because adularia from the Ohmidani Au-Ag quartz vein was dated at 62.7 Ma (MITI, 1988). Similar age is known on K-feldspar of molybdenite-quartz vein deposit of the Shiso mine, located in the Shiso granitic complex to the south (Fig. 1).

No data are available on the ore veins of the Akenobe mine. The early stage of the veins are similar in the mineral assemblage to that of the Ikuno veins, and therefore the formation age may be similar to that of the Ikuno vein system. Subvolcanic rocks intrude into the host rocks and cut through the vein system in the underground of the Akenobe mine. These dikes have a wide range of composition, being more mafic than the volcanic rocks of the Ikuno Group.

Felsic dikes at two localities of the Ryusei vein -6 Level and Kanagidani -2 Level, may have intruded very close to the second Cu-Sn mineralization stage. Whole-rock K-Ar age of these dikes give 57.8 and 52.6 Ma (Ishihara and Shibata, 1972), which are much younger than the latest Cretaceous mineralization ages of the Ikuno ore deposits. These dated dikes have to be reexamined by U-Pb method on the contained zircon in future.

4.2 Magnetic susceptibility

Studied volcanic rocks of the Late Cretaceous Ikuno Group are mostly rhyolitic and dacitic lavas and pyroclastics, and some basaltic and andesitic rocks with the silica around 52 % SiO₂. Those of the Paleogene Hikihara caldera are also rhyodacitic rocks with some andesites. Magnetic susceptibility of these rocks was measured by a portable device of KT-5, and is plotted in the SI value vs. silica diagram (Fig. 3). These volcanic rocks are plotted in the general magnetite-series field, but widely scattered toward lower magnetic area than a typical magnetite-series granitoids of the Shiso granitic complex, because of hydrothermal alteration on these volcanic rocks.

The studied volcanic rocks are least altered in the mafic rocks containing unaltered clinopyroxene, and their CO₂ contents are low. The magnetic susceptibility was highest in these rocks, e.g., 84.0 x 10⁻³ SI unit on the 80082636 basaltic lava (No. 1, Appendix I), 90 x 10⁻³ SI unit on the 82032109 andesite sheet (No.18, Appendix I), and 92 x 10⁻³ SI unit on the 8308071135A

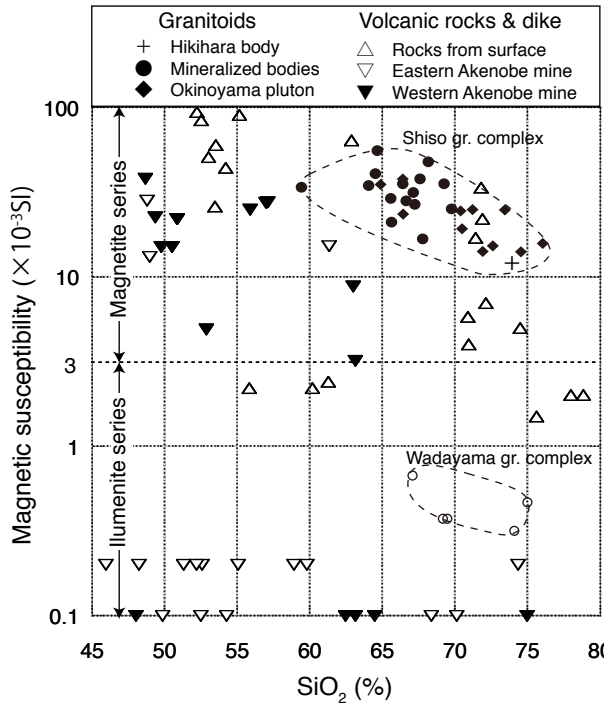


Fig. 3 Magnetic susceptibility vs. silica contents of the studied igneous rocks, Ikuno-Akenobe mines region.

andesite dike (No.22, Appendix I). Rhyolitic rocks have generally lower SI-values up to 22.0×10^{-3} SI, which exceeds easily the lower limit of 3.0×10^{-3} SI for the magnetite-series rocks. However, these volcanic rocks have lower SI-values (Fig. 3) locally by severe later hydrothermal alteration, due to breaking down of the original magnetite into hematite and others.

On the contrary, all the granitoids are relatively unaltered, composed of high magnetic susceptibilities, SI values higher than 10.0×10^{-3} in the Shiso granitic complex to the south (Ishihara, 2002). But those of the Wadayama granitic complex to the northeast are low, belonging to the ilmenite-series, which are shown in the lower part of Figure 3. Minor intrusion of the leucocratic granite in the Hikihara caldera, on the contrary, belongs to the magnetite-series (Fig. 3). The volcanic rocks exposed on surface show mostly magnetite-series values (Appendix I).

Subvolcanic dikes cutting these ore veins occur in the underground tunnels of the Akenobe mine. Selected rocks were studied in the eastern and western sides of the Akenobe N-S Fault and are listed in the Appendix II. The Eastern Group includes subvolcanic rocks cutting the ore veins of Nanei, Myoko, Siroiwa, Ryusei, Ginsei etc., and Western Group includes those cutting through the Shinhokusei, Hotei, Fujino, Eisei, Nansei, Chiemon veins, etc.. These studied rocks in the western part belong generally to magnetite-series (Fig. 3). Many of these rocks are low in the magnetic susceptibility in those from the eastern Akenobe mine tunnels, which contain much hydrothermal minerals. Loss of the

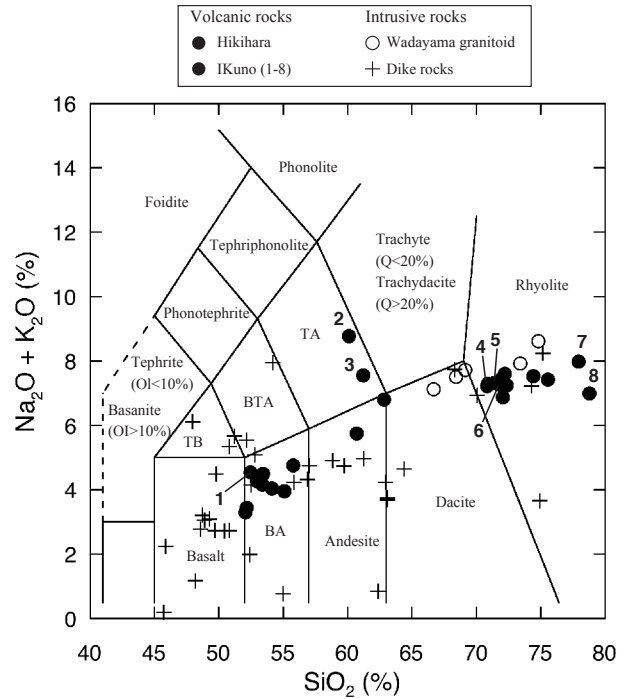


Fig. 4 Alkali-silica diagram of the studied plutonic and volcanic rocks. Nos. 1-8 correspond those in Fig. 1 and Table 1.

magnetic susceptibility was considered due to decomposition of the primary magnetite by the hydrothermal alteration.

5. Chemical characteristics

5.1 General remarks

Volcanic rocks (n=21) and dikes (n=3), and granitic rocks from the Wadayama (n=5) and Hikihara (n=2) plutons were collected from surface outcrops, which are shown in Figure 1 and described in the Appendix I, and are analyzed by the same XRF method described in Ishihara and Chappell (2007). The results are listed in Table 1. Subvolcanic dikes occurring in the whole underground of the Akenobe mine have also been examined in the eastern part (n=18) and the western part (n=19), whose localities are listed in the Appendix II. These analytical results are listed in Tables 2 and 3.

The analyzed volcanic and subvolcanic rocks from surface are weakly altered hydrothermally. Altered minerals are commonly epidote and calcite on calcic rocks like basalts and andesites. The epidote replaces typically phenocrystic amphibole crystals. Calcite occurs as veinlets and filling other crystals. The CO₂ contents are very high as 2.51-2.83 % on the 80082635 dacites, but are generally lower than 1.2 % . Chlorite is common altered mineral over mafic silicates, especially of biotite. Sericite occurs as fine subhedral crystals in feldspars. Plagioclase phenocrysts contain irregular forms of calcite and fine specks of sericite within the crystals. Phenocrystic K-feldspar has been also sericitized

Table 1 Chemical compositions of the volcanic (nos. 1-21), subvolcanic (nos. 22-24) and plutonic (nos. 27-31) rocks from the Ikuno, Hikihara and Wadayama areas.

Area	Ikuno area								Hikihara area								Hikihara area	
	Fil. no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO ₂	52.51	60.17	61.26	71.41	71.88	72.12	77.99	78.84	53.45	53.51	54.19	75.61	53.02	62.87	71.80	72.40	55.83	55.15
TiO ₂	1.04	0.73	0.70	0.24	0.23	0.26	0.03	0.04	1.08	1.03	1.01	0.10	0.99	0.70	0.21	0.21	0.77	0.84
Al ₂ O ₃	17.22	15.89	15.30	13.71	13.33	13.69	10.86	10.69	18.44	17.44	16.98	12.78	17.10	15.18	13.78	13.02	15.61	17.52
Fe ₂ O ₃	7.87	4.62	4.35	3.03	2.88	2.80	0.98	1.04	8.03	7.54	8.95	1.50	8.38	5.14	2.60	2.61	7.13	8.02
MnO	0.14	0.09	0.07	0.08	0.08	0.06	0.03	0.03	0.14	0.14	0.15	0.04	0.14	0.10	0.03	0.07	0.12	0.15
MgO	5.61	0.92	1.29	0.55	0.63	0.42	0.04	0.17	3.30	4.53	4.12	0.20	4.19	1.69	0.68	0.52	5.81	2.19
CaO	8.12	3.61	3.54	2.13	2.02	0.36	0.52	0.16	8.40	6.83	7.27	0.19	7.44	3.55	1.57	1.72	5.26	7.09
Na ₂ O	2.97	2.94	2.96	3.90	3.51	3.37	3.72	0.79	2.89	3.49	2.73	3.48	2.65	3.86	3.34	3.15	3.77	2.84
K ₂ O	1.56	5.82	4.58	3.40	3.73	3.49	4.25	6.18	1.25	0.99	1.29	3.92	1.60	2.92	4.01	4.07	0.97	1.10
P ₂ O ₅	0.29	0.20	0.19	0.11	0.09	0.06	0.03	0.03	0.26	0.29	0.24	0.04	0.25	0.22	0.08	0.09	0.19	0.27
S	0.01	0.21	0.10	0.02	0.01	0.02	0.01	0.01	0.15	0.02	0.02	0.01	0.02	0.01	<0.01	0.02	0.02	0.01
H ₂ O+	1.99	2.34	2.61	1.02	1.08	2.43	0.93	1.50	2.32	3.71	2.81	1.59	3.06	2.29	1.47	1.38	3.96	2.83
H ₂ O-	0.74	0.28	0.49	0.21	0.28	0.78	0.31	0.47	0.47	0.46	0.44	0.50	0.50	0.41	0.31	0.29	0.46	1.81
CO ₂	0.20	2.51	2.83	0.14	0.22	0.15	0.14	0.12	0.31	0.25	0.18	0.11	1.06	1.17	0.30	0.63	0.34	0.51
O=S		-0.10	-0.05	-0.01		-0.01			-0.07	-0.01	-0.01		-0.01			-0.01	-0.01	
Total	100.27	100.23	100.22	99.94	99.97	100.00	99.84	100.07	100.42	100.22	100.37	100.07	100.39	100.11	100.18	100.17	100.23	100.33
Rb	40	248	203	113	137	145	164	302	26	21	25	143	35	72	152	142	22	21
Sr	480	274	299	232	179	119	68	38	512	930	443	94	475	380	190	181	356	514
Ba	486	640	590	860	500	610	233	171	349	760	407	610	390	670	560	580	289	331
Zr	156	202	197	142	119	225	68	66	138	169	156	97	156	261	123	122	100	120
Hf	3.0	5.2	5.8	5.9	5.4	7.2	6.0	6.5	3.5	7.6	4.5	4.7	3.1	7.4	5.8	5.8	3.2	3.7
Nb	7.5	11.5	12.9	48.4	12.2	12.1	17.0	10.8	10.0	16.8	62.6	12.7	7.5	11.3	13.9	40.8	12.8	11.0
Ta	<4	<3	4.3	3.3	2.2	2.2	3.3	2.3	<4	3.2	3.1	2.2	<3	<3	2.6	3.4	<4	1.7
Y	25	27	22	24	30	26	28	37	26	26	27	15	25	36	27	27	22	24
La	21	23	26	54	26	22	6	13	13	20	30	5	16	27	23	30	14	12
Ce	42	47	54	110	45	48	18	26	32	45	57	39	38	54	43	52	33	31
V	190	99	105	37	25	18	8	8	243	197	197	9	210	92	30	27	157	105
Cr	242	96	127	345	212	46	268	214	77	90	120	205	78	112	144	225	227	34
Co	21	<8	9	11	8	6	4	6	<10	12	14	5	15	7	5	9	11	<10
Ni	67	4	6	5	4	4	5	5	9	12	5	4	8	4	3	3	50	2
Cu	29	11	9	7	4	4	4	3	25	12	15	5	19	8	5	5	30	3
Zn	128	61	59	47	50	61	19	48	91	87	87	37	83	68	42	43	71	91
Pb	11	18	15	24	25	24	32	40	12	17	14	21	10	16	24	25	12	8
Ga	17.6	16.4	15.8	15.2	15.4	16.4	6.8	12.5	20.1	17.8	18.3	13.8	17.4	16.3	15.1	14.7	14.1	19.2
Ge	1.4	0.8	0.6	1.3	1.3	0.8	1.9	2.1	1.3	2.7	1.4	1.0	1.1	1.2	1.6	1.3	1.2	0.8
As	1.5	1.9	0.9	2.3	0.9	3.6	3.9	1.1	3.1	4.2	2.0	0.5	1.0	1.1	1.0	0.4	3.2	<0.4
Se	0.3	0.7	0.5	0.6	0.5	0.3	0.7	0.3	0.5	1.1	0.4	0.6	0.5	0.4	0.6	0.6	0.4	0.6
Br	0.3	0.2	0.3	0.3	0.2	0.2	0.2	0.1	0.2	1.0	0.4	0.1	0.2	0.2	0.3	0.4	0.2	0.3
Mo	0.6	4.5	1.1	4.8	4.0	0.7	4.5	0.3	5.3	6.8	4.5	4.6	3.7	4.1	5.5	7.3	3.4	4.8
W	1.8	<2	2.1	<1	0.9	10.1	4.8	2.2	<2	3.0	<2	0.7	<2	<2	2.1	1.9	1.4	<2
Sn	1.7	2.7	2.5	3.1	3.7	3.3	6.8	6.9	1.8	2.2	1.9	3.4	1.4	2.1	3.5	2.7	2.1	1.0
Sb	<0.5	<0.5	<0.5	<0.5	0.6	<0.5	3.5	1.1	<0.5	1.1	<0.5	0.6	<0.5	<0.5	<0.5	<0.5	0.3	<0.5
Cs	2.7	4.4	6.2	2.9	4.7	7.2	5.0	10.0	<1.5	3.1	<1.5	8.7	<1.5	<1.5	6.4	5.1	<1.5	<1.5
Tl	1.1	3.8	3.1	2.1	2.5	1.8	2.5	2.7	1.1	3.0	1.3	1.7	1.1	1.6	2.1	2.4	1.6	1.2
Bi	0.9	0.9	0.9	1.2	0.9	0.8	1.8	1.1	1.1	2.3	0.7	1.1	<0.4	0.9	1.0	1.3	1.4	1.0
Th	5.9	11.1	9.4	14.9	16.1	13.4	21.3	16.7	5.3	6.1	7.7	16.7	5.3	10.1	18.0	18.1	7.5	3.3
U	<0.5	9.5	2.3	7.9	5.9	2.3	9.9	5.0	5.3	4.8	7.5	6.4	2.8	4.2	9.2	6.9	4.7	4.4
Cl	100	52	89	69	58	66	40	42	76	100	47	66	69	67	71	75	60	110
A/CNK	0.81	0.90	0.94	0.98	0.99	1.37	0.93	1.29	0.86	0.91	0.89	1.24	0.87	0.95	1.09	1.02	0.93	0.93
NK/A	0.38	0.70	0.64	0.74	0.74	0.68	0.99	0.75	0.33	0.39	0.35	0.78	0.36	0.63	0.71	0.74	0.46	0.33
Rb/Sr	0.1	0.9	0.7	0.5	0.8	1.2	2.4	7.9	0.1	0.0	0.1	1.5	0.1	0.2	0.8	0.8	0.1	0.0
Th/U	11.8	1.2	4.1	1.9	2.7	5.8	2.2	3.3	1.0	1.3	1.0	2.6	1.9	2.4	2.0	2.6	1.6	0.8
ZrT°C	721	773	781	770	757	848	714	741	720	748	741	765	736	809	769	764	719	727

Analyzed by polarized XRF by B. W. Chappell. O=S meaning quoted as oxides, despite some occur as sulfides. The value of O=S is the S value multiplied by the ratio of atomic weights, or 15.9994/32.06.

Chemical compositions of the granitoids (Ishihara and Chappell)

Table 1 Continue.

Area				Dikes in Hikihara			Hikihara granite			Wadayama granite			
	Fil. no.	19	20	21	22	23	24	25	26	27	28	29	30
SiO ₂	70.88	70.94	74.48	52.22	52.12	60.74	72.27	73.47	66.72	68.48	69.19	72.03	74.86
TiO ₂	0.20	0.28	0.11	0.77	0.76	0.98	0.21	0.18	0.48	0.40	0.36	0.17	0.11
Al ₂ O ₃	13.39	13.75	12.77	18.10	17.99	15.67	14.02	13.42	15.24	14.73	14.58	12.78	13.05
Fe ₂ O ₃	2.51	2.95	1.87	8.14	8.00	6.26	2.28	1.80	4.44	3.39	3.31	2.10	1.47
MnO	0.05	0.07	0.05	0.10	0.10	0.10	0.03	0.05	0.08	0.05	0.05	0.05	0.02
MgO	0.47	0.76	0.22	3.21	3.42	1.99	0.46	0.32	1.34	0.92	0.82	0.36	0.17
CaO	1.77	1.89	0.96	7.81	7.82	5.04	1.15	1.38	3.19	2.51	1.93	1.71	0.73
Na ₂ O	3.24	3.42	4.74	2.67	2.58	3.25	4.47	4.77	3.92	3.88	3.81	3.43	3.67
K ₂ O	3.96	3.85	2.77	0.75	0.70	2.48	3.11	3.14	3.19	3.61	3.89	4.00	4.93
P ₂ O ₅	0.07	0.10	0.04	0.19	0.19	0.31	0.08	0.07	0.16	0.13	0.13	0.06	0.06
S	0.52	<0.01	0.01	0.02	0.14	0.01	0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01
H ₂ O ⁺	1.83	1.52	1.23	2.73	2.90	2.23	1.27	0.63	1.14	1.35	1.36	1.09	0.72
H ₂ O ⁻	0.25	0.29	0.15	2.76	2.86	0.34	0.47	0.35	0.06	0.14	0.05	0.13	0.02
CO ₂	1.67	0.34	0.73	0.90	0.91	0.79	0.12	0.33	0.10	0.40	0.73	2.03	0.07
O=S	-0.26			-0.10	-0.07								
Total	100.55	100.16	100.13	100.36	100.42	100.19	99.95	99.91	100.06	100.00	100.21	99.94	99.88
Rb	143	133	79	15.2	13.7	68	90	92	92	141	183	128	153
Sr	192	206	134	490	503	381	195	181	312	276	252	154	108
Ba	660	560	610	254	494	520	700	730	780	750	740	680	500
Zr	120	133	156	89	87	211	164	187	202	206	177	105	154
Hf	5.9	4.6	4.8	2.0	2.0	5.4	5.6	7.0	6.5	6.5	5.6	4.4	6.2
Nb	21.2	9.9	9.5	6.0	6.5	10.5	10.9	12.0	8.2	8.7	8.7	7.7	9.5
Ta	3.4	1.6	2.5	<3	<3	<3	1.6	<2	2.8	2.1	<3	2.6	1.6
Y	26	26	28	18	18	31	47	35	28	21	24	22	28
La	30	25	26	8	18	24	34	22	27	27	35	22	47
Ce	53	48	57	18	30	53	52	50	57	52	64	41	85
V	26	33	9	221	231	129	24	5	54	31	26	11	8
Cr	244	151	138	50	42	43	192	10	11	14	11	15	14
Co	8	5	4	<10	9	9	9	6	8	9	12	<5	6
Ni	5	5	3	3	2	1	4	2	2	2	3	2	1
Cu	4	5	4	20	14	6	5	2	5	4	10	3	3
Zn	43	48	43	74	89	80	50	28	56	35	38	32	36
Pb	26	22	15	8	8	15	11	14	13	15	18	10	20
Ga	14.6	14.5	11.9	19.8	18.9	18.4	16.1	15.0	17.3	16.4	16.2	13.7	16.4
Ge	1.3	1.3	0.9	1.1	1.3	1.2	1.3	1.1	1.5	1.3	1.2	1.0	1.3
As	2.3	1.9	2.0	1.8	1.3	2.7	1.7	<0.4	<0.4	<0.4	0.6	1.5	<0.5
Se	0.9	0.4	0.3	0.6	0.4	0.5	0.5	0.6	0.8	0.5	0.6	0.3	0.4
Br	0.6	0.3	0.1	0.2	0.5	0.2	0.2	0.3	0.5	0.3	0.4	0.2	0.4
Mo	2.6	2.7	2.4	4.5	3.8	3.7	4.6	3.8	1.7	2.3	1.6	1.9	0.3
W	2.8	0.6	1.2	<2	<2	<2	1.8	3.4	<2	1.1	78	1.0	1.4
Sn	3.2	2.9	2.0	1.2	1.1	2.4	2.5	3.1	3.3	6.7	6.5	2.1	1.5
Sb	<0.5	0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.5	<0.5
Cs	8.9	5.1	1.0	2.0	1.1	<1.5	<1.5	3.4	4.5	6.3	8.3	13.3	1.1
Tl	3.2	1.5	1.1	1.0	0.9	1.2	1.6	1.9	2.4	1.8	2.2	1.6	1.4
Bi	2.0	0.5	0.6	1.3	1.1	0.7	0.7	1.2	1.4	1.4	3.6	0.8	0.6
Th	13.9	14.5	12.2	2.3	2.4	8.2	9.0	9.2	10.1	12.3	14.7	11.9	33.1
U	3.7	4.1	2.0	3.1	3.9	3.0	5.0	4.9	1.5	2.8	3.0	2.7	4.1
Cl	57	68	54	150	180	62	98	60	240	220	190	32	89
A/CNK	1.04	1.04	1.02	0.93	0.94	0.91	1.09	0.98	0.97	0.99	1.04	0.98	1.03
NK/A	0.72	0.71	0.85	0.29	0.28	0.51	0.76	0.84	0.65	0.70	0.72	0.78	0.87
Rb/Sr	0.7	0.6	0.6	0.0	0.0	0.2	0.5	0.5	0.3	0.5	0.7	0.8	1.4
Th/U	3.8	3.5	6.1	0.7	0.6	2.7	1.8	1.9	6.7	4.4	4.9	4.4	8.1
ZrT/C	763	771	786	700	699	781	795	794	792	799	793	747	785

Table 2 Chemical compositions of the studied dikes from the Akenobe underground tunnels: Western vein group.

File no.	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Sam. no.	20202	20203	20304	20405	20406	20407	20608	20609	20610	20611	20612	20613	20715	20816	20817	20818	20919
SiO ₂	54.26	61.32	74.34	52.56	58.91	55.05	52.20	48.95	51.29	70.11	48.79	59.78	45.94	48.23	68.37	52.48	49.84
TiO ₂	0.85	0.58	0.10	0.98	0.60	1.05	0.89	0.83	0.99	0.11	0.86	0.60	1.02	0.95	0.12	1.03	0.89
Al ₂ O ₃	17.93	16.37	12.66	16.17	15.70	14.24	18.38	18.35	17.54	12.63	16.30	15.90	19.89	16.07	12.70	14.31	18.79
Fe ₂ O ₃	7.68	5.53	1.89	8.25	6.57	8.96	7.97	7.95	8.48	1.13	9.13	7.76	13.04	18.14	1.58	8.47	10.20
MnO	0.76	0.13	0.09	0.56	0.15	0.49	0.20	0.12	0.29	0.06	0.07	0.26	1.24	0.71	0.06	1.56	0.81
MgO	4.23	1.45	0.29	5.64	1.16	6.46	4.29	3.02	5.96	0.71	2.66	2.05	8.62	6.51	0.62	7.36	4.29
CaO	1.25	4.98	0.33	3.19	3.51	5.44	5.71	8.40	6.56	0.91	6.88	4.27	1.54	0.37	0.88	3.65	5.56
Na ₂ O	0.21	3.86	3.29	0.19	3.64	0.13	1.48	2.24	0.18	3.11	2.49	3.48	<0.05	0.06	5.29	<0.05	0.16
K ₂ O	7.72	1.08	3.91	3.94	1.24	0.62	4.03	0.79	5.47	3.81	0.69	1.24	2.18	1.09	2.43	1.94	4.30
P ₂ O ₅	0.21	0.30	0.04	0.31	0.30	0.27	0.21	0.21	0.23	0.06	0.21	0.31	0.24	0.22	0.04	0.27	0.22
S	0.02	<0.01	0.03	0.20	0.01	0.22	0.01	0.15	0.01	0.03	<0.01	0.01	1.39	0.02	0.02	1.32	0.02
H ₂ O+	4.37	2.15	1.22	5.55	2.52	5.62	3.73	4.29	0.74	6.00	5.04	1.47	2.45	2.68	7.64	7.33	4.88
H ₂ O-	0.49	1.07	0.24	0.77	1.80	0.66	0.43	1.71	0.52	0.32	2.98	1.61	0.68	0.31	0.20	0.33	0.38
CO ₂	0.53	1.26	1.43	2.16	4.33	1.15	0.82	3.73	2.14	1.08	4.57	1.66	2.61	5.86	0.12	0.13	0.39
O=S	-0.01		-0.01	-0.10		-0.11		-0.07		-0.01			-0.69	-0.01	-0.01	-0.66	-0.01
Total	100.50	100.08	99.85	100.37	100.44	100.25	100.35	100.67	100.40	100.06	100.67	100.40	100.15	101.21	100.06	99.52	100.72
Rb	329	22	116	220	25	37	165	25	197	146	13.2	28	141	64	65	146	140
Sr	245	400	80	95	331	210	435	473	264	117	577	315	59	11.7	109	133	274
Ba	1680	410	690	479	473	56	650	295	960	950	294	436	198	259	500	83	800
Zr	102	111	131	155	138	120	89	76	94	136	85	139	115	97	172	134	96
Hf	4.1	3.2	5.4	4.2	4.3	2.8	2.6	1.2	<2	6.2	1.1	3.2	3.3	3.2	7.0	6.3	2.4
Nb	7.3	9.3	10.3	9.4	8.6	8.8	3.7	4.3	4.2	8.1	4.7	7.8	7.6	8.8	10.8	11.5	5.4
Ta	<3	<2	<2	<3	<2	<4	<3	<3	<3	1.5	<3	<3	<5	<4	1.5	<15	<4
Y	20	24	26	25	24	19	19	18	23	24	17	21	16	22	27	19	23
La	4	14	37	16	13	18	7	6	5	30	8	15	8	9	35	18	9
Ce	12	31	71	38	36	38	24	20	21	61	20	35	24	25	63	39	25
V	222	23	<3	186	23	216	197	185	168	<4	164	25	233	218	5	212	207
Cr	36	10	28	231	10	470	33	15	113	35	7	8	21	54	13	460	<2
Co	9	<8	7	23	<8	23	9	<10	<10	7	21	<10	<15	<15	8	21	<10
Ni	40	34	29	105	33	82	41	41	45	35	38	34	14	<3	5	54	4
Cu	4	3	4	<1	3	18	9	4	5	6	2	3	<1	<1	2	362	17
Zn	224	91	54	1080	98	739	99	100	169	44	89	112	7230	1060	42	5850	156
Pb	56	13	30	570	21	1070	12	10	14	41	6	33	3820	38	44	4980	32
Ga	15.8	17.9	13.0	12.1	18.9	11.2	16.8	19.0	13.1	13.3	18.0	17.9	n.d.	16.2	13.1	n.d.	17.9
Ge	1.1	1.5	0.8	0.4	1.4	1.4	1.7	1.4	1.1	0.4	1.3	1.5	<1.0	0.9	<0.3	<0.9	1.9
As	8.7	0.7	2.8	<2.7	2.4	10.1	3.8	0.6	1.3	1.9	14.8	<0.6	<8.3	1.9	0.9	24	17.5
Se	0.9	0.5	0.5	<0.3	0.4	<0.3	0.5	0.4	0.6	0.6	0.3	0.4	<0.6	0.7	0.6	<0.7	0.4
Br	0.2	0.4	0.2	<0.1	0.3	<0.2	0.2	0.3	<0.1	0.2	0.2	0.2	1.5	<0.2	0.1	1.3	0.2
Mo	6.5	7.4	5.5	5.9	3.8	4.6	4.1	2.7	2.2	3.0	3.2	3.3	6.2	9.9	5.8	5.6	4.5
W	4.0	7.8	43	<5	5.8	<4	3.7	2.5	<2	49	2.2	<2	<12	<6	47	<12	3.2
Sn	1.7	1.2	2.3	1.7	1.7	4.8	1.3	1.1	1.0	4.8	1.1	3.3	44	34	2.4	16.4	9.9
Cd	0.6	0.2	<0.2	3.9	0.3	4.7	<0.2	<0.2	<0.2	<0.2	<0.2	0.4	30.5	0.3	<0.2	29	<0.2
Sb	6.6	<0.5	<0.5	1.1	0.7	8.5	1.4	<0.5	1.7	2.3	<0.5	<0.5	1.4	<0.5	0.3	254	19.9
Cs	15.2	3.1	8.0	18.4	11.5	11.9	7.2	40	28	12.5	9.4	15.5	4.5	<1.5	1.6	1.6	17.6
Tl	8.7	1.2	2.1	4.5	1.2	1.8	3.8	1.3	4.6	2.3	0.9	1.0	9.2	2.0	2.1	8.5	3.2
Bi	<0.5	1.5	0.8	<1.1	1.1	<1.5	0.4	0.8	0.7	0.7	0.4	0.7	<3.4	<0.7	1.2	<3.5	0.4
Th	5.4	3.5	14.3	<0.5	3.7	<0.5	2.9	1.9	1.7	12.3	1.6	3.3	<0.5	5.4	14.1	<0.5	4.6
U	9.1	5.0	7.7	7.9	3.1	4.2	<0.5	1.0	1.5	3.6	1.2	0.6	9.1	6.3	6.3	9.7	8.1
F	300	<100	<100	600	<100	800	200	<100	300	<100	<100	<100	2400	100	<100	8400	400
Cl	60	140	38	43	81	54	32	130	47	77	89	98	90	48	28	93	25
A/CNK	1.63	0.99	1.24	1.56	1.15	1.32	1.07	0.93	0.97	1.16	0.94	1.07	3.79	8.24	0.98	1.62	1.25
NK/A	0.49	0.46	0.76	0.28	0.47	0.06	0.37	0.25	0.35	0.73	0.30	0.44	0.12	0.08	0.89	0.15	0.26
Rb/Sr	1.3	0.1	1.5	2.3	0.1	0.2	0.4	0.1	0.7	1.2	0.0	0.1	2.4	5.5	0.6	1.1	0.5
Th/U	0.6	0.7	1.9	0.1	1.2	0.1	5.8	1.9	1.1	3.4	1.3	5.5	0.1	0.9	2.2	0.1	0.6
ZrT(°C)	777	738	790	812	774	779	718	683	710	786	699	767	830	835	787	805	741

n.d.: not determined

Analyzed by polarized XRF. O=S implying quoted as oxides, despite some occurring as sulfides. The value of O=S is the S value multiplied by the ratio of atomic weights, or 15.9994/32.06.

Chemical compositions of the granitoids (Ishihara and Chappell)

Table 3 Chemical compositions of the studied dikes from the Akenobe underground tunnels: Eastern vein group.

Fil.no.	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66
Sam.n	40801	40802	40803	41004	41005	41006	41007	41208	41209	41210	41312	50801	51203	51204	51206	51207	51208	51409
SiO ₂	48.66	49.34	50.87	50.51	63.14	49.76	62.98	57.08	50.86	56.97	74.97	55.89	52.86	64.45	48.01	45.78	62.44	63.14
TiO ₂	0.80	0.72	0.87	0.66	0.16	0.68	0.37	0.57	0.63	0.56	0.10	0.71	0.77	0.16	0.84	0.78	0.29	0.36
Al ₂ O ₃	17.97	16.51	16.68	13.98	15.26	14.88	15.70	17.99	13.52	18.01	13.64	15.62	16.45	15.27	15.10	13.41	14.06	14.73
Fe ₂ O ₃	8.79	6.80	7.74	8.54	3.86	7.11	4.82	7.02	7.40	6.97	1.48	7.17	7.82	4.23	8.48	28.06	3.22	4.58
MnO	0.17	0.13	0.15	0.28	0.09	0.26	0.13	0.16	0.10	0.17	0.04	0.15	0.12	0.09	0.23	0.51	0.13	0.13
MgO	4.93	2.34	4.73	9.49	0.40	5.75	1.17	2.13	10.09	2.12	0.65	6.17	5.85	0.66	5.05	2.40	1.12	1.11
CaO	8.57	7.88	5.96	4.97	4.92	8.92	4.60	6.16	7.65	6.35	0.85	7.13	5.63	3.80	6.95	0.42	5.69	4.52
Na ₂ O	2.20	2.37	3.63	2.20	2.39	2.45	3.73	3.76	1.64	3.48	0.34	2.53	3.12	2.86	3.58	0.13	0.27	2.77
K ₂ O	0.56	0.69	1.69	0.50	1.34	0.26	0.47	0.97	1.07	0.81	3.30	1.67	1.94	1.76	2.51	0.05	0.56	0.90
P ₂ O ₅	0.15	0.18	0.35	0.19	0.13	0.18	0.21	0.24	0.18	0.24	0.05	0.18	0.18	0.15	0.16	0.21	0.15	0.19
S	0.12	0.02	0.13	1.15	<0.01	0.76	0.03	<0.01	0.06	0.01	0.03	0.03	0.26	<0.01	0.38	0.22	0.02	0.02
H ₂ O ⁺	2.67	3.48	4.32	5.96	4.05	4.41	3.61	2.16	3.71	2.00	3.18	2.41	3.69	3.41	4.12	7.20	5.38	3.45
H ₂ O ⁻	2.96	2.26	0.69	1.13	0.47	0.44	2.27	1.78	3.24	1.61	0.16	0.59	0.71	0.67	0.54	0.60	0.68	1.03
CO ₂	2.21	7.82	2.86	2.23	4.00	5.33	0.20	0.28	0.31	0.96	1.18	0.18	1.38	2.74	5.02	2.29	6.29	3.18
O=S	-0.06	-0.01	-0.06	-0.57		-0.38	-0.01		-0.03		-0.01	-0.01	-0.13		-0.19	-0.11	-0.01	-0.01
Total	100.70	100.53	100.61	101.22	100.21	100.81	100.28	100.30	100.43	100.26	99.96	100.42	100.65	100.25	100.78	101.95	100.29	100.10
Rb	11.8	17.6	54	13.4	47	12.6	23	23	20	18	147	40	73	58	101	4.0	25	26
Sr	524	441	561	336	274	538	837	599	582	590	34	607	620	241	293	12.2	282	254
Ba	176	291	630	265	221	880	550	355	348	361	120	337	373	323	510	23	100	273
Zr	59	82	176	107	181	97	127	92	105	93	88	129	124	184	74	96	136	119
Hf	1.6	1.6	3.3	2.5	4.2	4.3	4.4	3.8	2.2	3.7	4.3	3.9	4.8	5.0	2.9	<10	4.8	3.7
Nb	4.6	4.9	6.9	5.9	9.0	7.1	8.1	6.0	5.5	9.0	10.5	9.6	8.8	10.5	5.0	7.9	8.5	7.1
Ta	<3	<3	<3	<4	1.4	<4	2.0	<2	<5	2.0	2.1	4.0	3.1	1.2	<4	<20	<2	1.2
Y	16	16	24	20	7	18	23	19	17	19	18	21	22	7	21	18	17	19
La	4	6	23	16	21	7	13	9	14	10	32	17	15	20	7	10	16	12
Ce	13	19	51	36	43	23	28	23	34	26	51	34	34	43	21	26	34	27
V	221	214	186	170	<4	170	<5	63	162	47	9	161	176	<4	243	161	<4	<5
Cr	34	7	55	800	<1	232	<1	<2	850	<2	8	183	117	<1	322	32	7	<1
Co	<10	8	<10	38	<6	26	<8	<8	30	<10	4	16	17	<8	19	<20	<6	<8
Ni	5	7	25	240	3	72	1	4	265	3	4	71	39	2	54	9	3	4
Cu	8	21	18	26	2	31	5	3	34	2	2	48	23	2	29	406	2	2
Zn	69	85	87	284	72	141	105	75	69	72	30	101	82	73	129	461	72	118
Pb	7	28	25	13	15	51	23	9	12	7	17	31	17	15	22	62	18	19
Ga	18.8	18.4	16.5	15.9	16.7	16.7	16.8	19.6	14.9	18.7	14.9	16.9	16.4	18.3	13.8	15.1	14.6	16.1
Ge	1.1	1.5	1.1	1.6	1.1	0.6	0.9	1.2	0.7	0.9	1.2	1.1	1.1	0.9	0.6	0.6	1.8	1.4
As	4.6	6.5	6.2	6.6	<0.4	7.6	3.0	<0.4	0.9	<0.4	1.0	1.3	1.4	<0.4	12.9	3.2	2.2	2.0
Se	0.5	0.3	0.4	0.7	0.5	1.0	0.8	0.5	0.5	0.8	0.7	0.6	0.7	0.5	0.6	0.4	0.6	0.5
Br	0.1	0.1	0.3	0.1	0.2	0.8	1.0	0.4	0.4	0.5	0.1	0.7	0.5	0.3	0.2	<0.2	0.4	0.3
Mo	3.3	2.9	4.0	3.7	3.9	5.7	4.8	3.2	3.6	6.4	5.7	8.2	6.1	3.9	3.5	6.4	3.5	3.5
W	12.9	2.1	9.0	<3	8.6	11.3	9.4	13.2	11.7	13.9	29	21	4.7	5.0	4.0	<5	6.3	1.7
Sn	0.8	1.4	1.7	21	1.5	3.1	2.3	1.3	1.5	1.9	2.6	3.1	2.8	1.0	1.9	22	1.8	1.5
Sb	<0.5	<0.5	0.6	1.3	<0.5	1.7	0.6	<0.5	<0.5	<0.5	5.0	0.9	<0.5	<0.5	0.5	<0.5	1.3	0.4
Cs	<1.5	14.1	12.3	5.5	9.1	19.0	63	3.4	4.2	4.9	15.4	8.6	19.5	11.8	3.3	1.0	7.4	8.9
Tl	1.2	0.9	1.3	0.5	1.0	3.0	2.7	2.0	1.9	2.4	2.8	2.0	2.3	1.6	2.7	<1	1.7	1.6
Bi	1.0	1.0	0.5	1.1	0.6	2.9	1.7	1.9	2.0	1.9	1.3	1.1	4.0	1.2	0.7	<1.0	1.3	1.4
Th	1.4	2.2	5.9	5.1	5.2	4.8	3.9	2.6	5.0	3.3	14.9	7.5	5.8	5.6	3.7	5.2	3.9	3.1
U	3.0	4.1	4.6	3.6	4.5	3.1	4.8	4.7	4.5	3.2	9.8	5.4	5.0	4.1	6.8	3.1	3.5	4.3
F	<100	<100	200	500	<100	600	<100	<100	<100	<100	300	100	<100	<100	<100	100	<100	<100
Cl	130	60	76	120	490	39	420	68	440	100	55	93	120	450	69	67	320	n.d.
A/CNI	0.91	0.9	0.90	1.06	1.07	0.72	1.05	0.98	0.76	0.99	2.40	0.83	0.94	1.13	0.71	13.00	1.23	1.07
NK/A	0.24	0.28	0.47	0.30	0.35	0.29	0.42	0.40	0.29	0.37	0.30	0.38	0.44	0.43	0.57	0.02	0.07	0.38
Rb/Sr	0.02	0.04	0.10	0.04	0.17	0.02	0.03	0.04	0.03	0.03	4.32	0.07	0.12	0.24	0.34	0.33	0.09	0.10
Th/U	0.5	1.9	1.3	1.4	1.2	1.5	0.8	0.6	1.1	1.0	1.5	1.4	1.2	1.4	0.5	1.7	1.1	0.7
ZrI(°C)	663	685	749	742	792	672	759	714	694	717	797	720	732	802	647	840	787	759

n.d.: not determined.

Analyzed by polarized XRF. O=S implying quoted as oxides, despite some occurring as sulfides. The value of O=S is the S value multiplied by the ratio of atomic weights, or 15.9994/32.06.

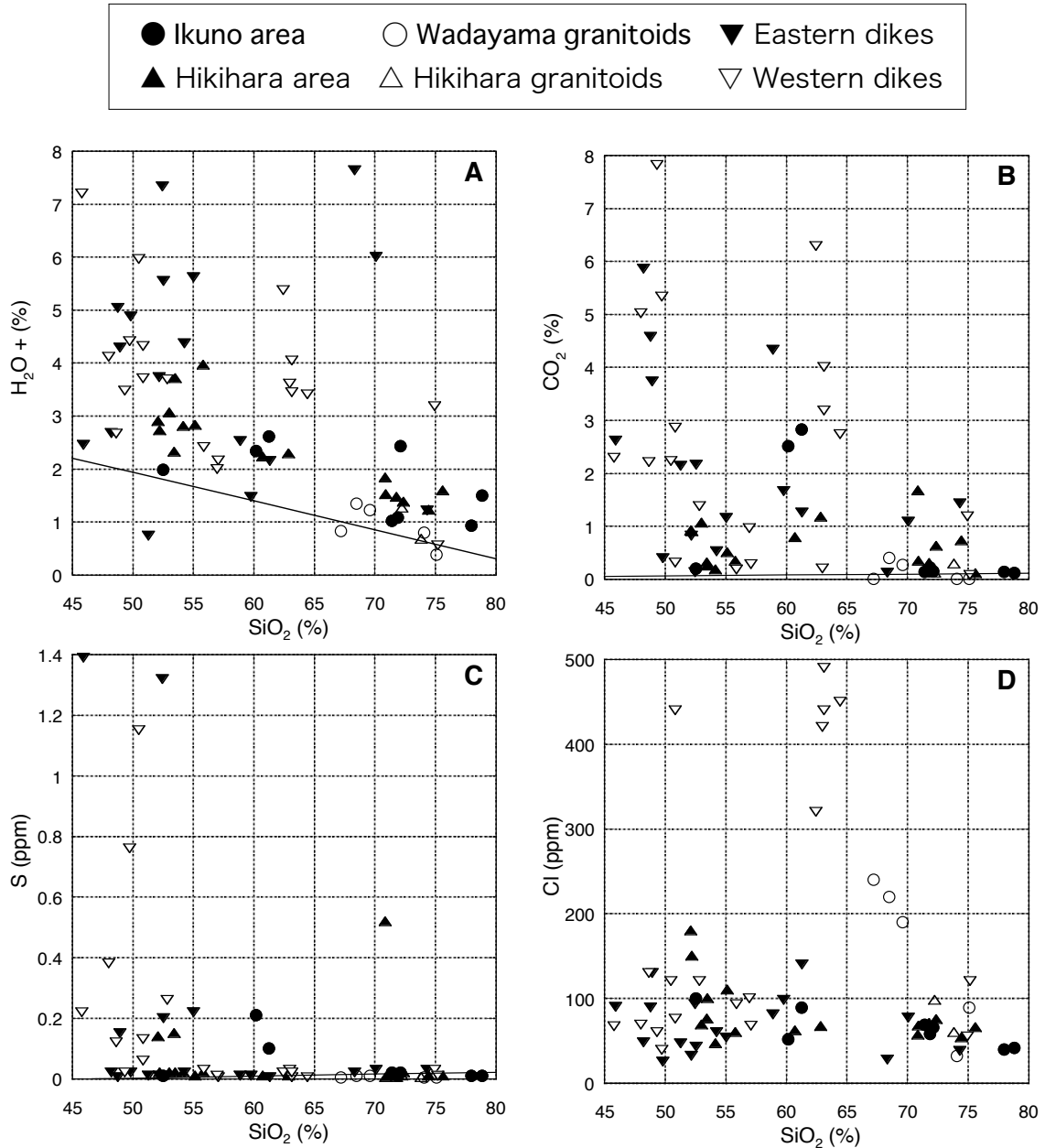


Fig. 5 Variation diagrams of the studied volcanic and plutonic rocks: H₂O⁺, CO₂, S and Cl. Straight line is the average line of the Shiso granitic complex of the west-central Hyogo Prefecture reported in Ishihara (2002).

The analyzed rocks are plotted in the Na₂O+K₂O vs. SiO₂ diagram in order to identify their rock types. Most of the studied volcanic rocks are plotted in the upper area of so-called calc-alkaline basalt-andesite-dacite-rhyolite field (Fig. 4), and those of the Late Cretaceous Ikuno Group and the Paleogene Udagawa Group are plotted in the same trend, at a lower level than that of the Wadayama granitoids. Two plots (Nos. 2 and 3, Fig. 4) higher in the alkali components for the silica contents, are strongly altered rocks containing 5.13-5.93 % H₂O+CO₂. They are not alkaline rocks, but the high alkali contents represented by 4.58 and 5.82 % K₂O for 61.3 and 60.2 % SiO₂ derived from hydrothermal sericite. Both the granitic and volcanic rocks studied are

considered to belong to calc-alkaline series. Subvolcanic dikes show very wide variation on this diagram, because of severe alteration, but about half of the dikes follow the trend of those of the Ikuno Group and Hikihara caldera, indicating that all the volcanic and subvolcanic rocks belong to the same group.

The subvolcanic rocks have been most commonly altered to chlorite, epidote, carbonates, sericite and kaolinite. The volcanic rocks exposed on surface contain the total alteration components of S, H₂O(+), H₂O(-) and CO₂ from 1.39 to 6.03 % , while the subvolcanic dikes have higher values between 3.37 and 6.41 % . The underground dikes are much more severely altered, especially on those of the eastern Akenobe mine than

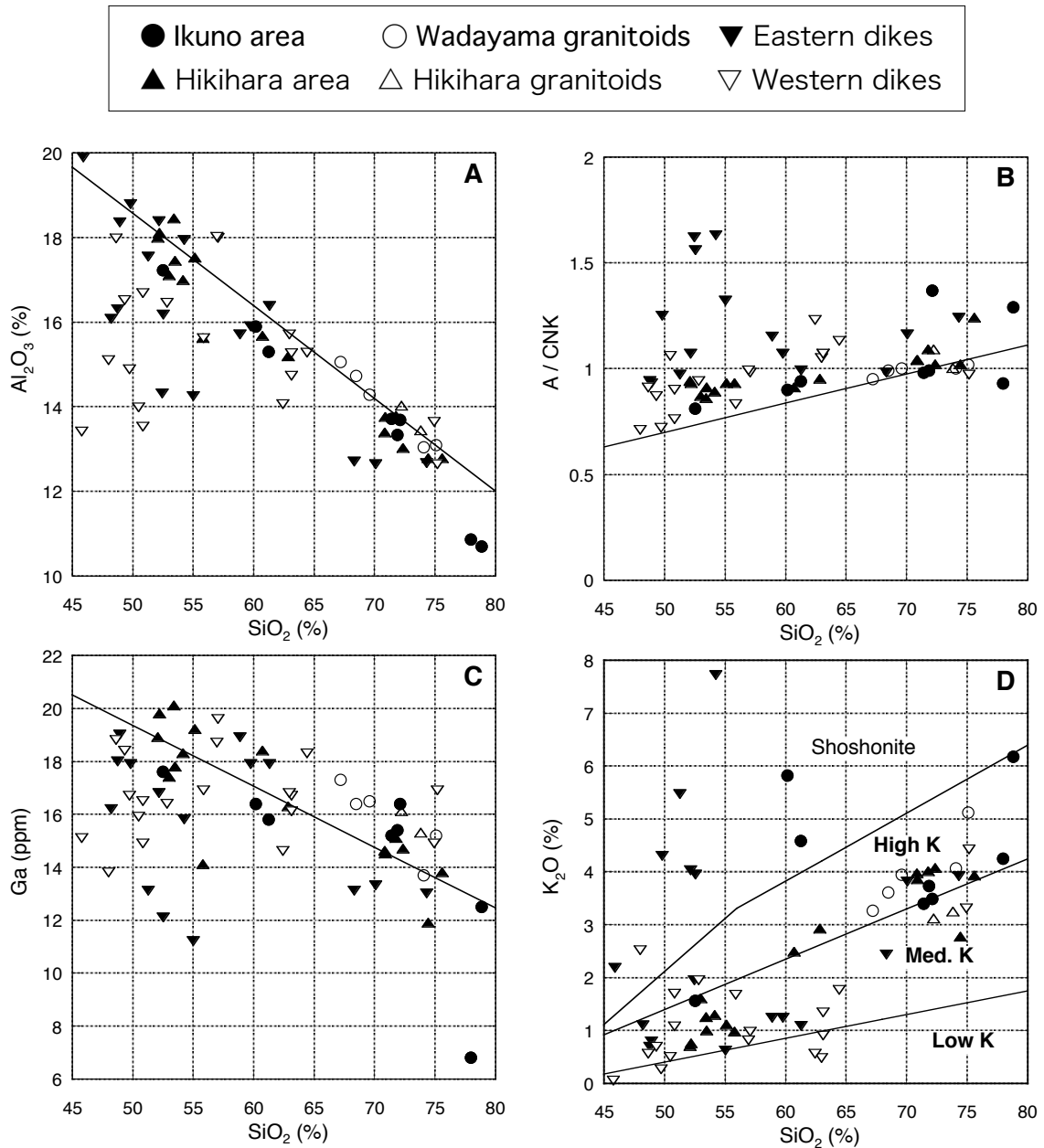


Fig. 6 Variation diagrams of the studied volcanic and plutonic rocks: Al_2O_3 , A/CNK, Ga and K_2O . The straight line is the same as that of Fig. 5.

of the western part. Alteration also effects on magnetic susceptibility, because of hematitization over magnetite.

5.2 Variation diagrams

The volcanic rocks vary from basalt to rhyolite having silica range of 52.5 to 78.0 % , and their average is 65.3 % (n=21). If volatile components such as $\text{H}_2\text{O}(+)$, $\text{H}_2\text{O}(-)$, CO_2 and S were excluded, these values increase from 54.0 to 80.5 % and the average is 67.3 % . An anhydrous average silica content of the Wadayama granitic pluton (71.6 %) is higher than the average of the volcanic rocks, but that of the Shiso granitic complex is averaged as 68.6 % SiO_2 , which is similar to the average of the volcanic rocks.

Among the volatile components, both $\text{H}_2\text{O}(+)$ and CO_2 contents are generally abundant in the low to intermediate silica rocks (Fig. 5 A, B), because of highly calcic and mafic nature. S-contents which are contained in fine-grained pyrite are relatively low for the intensive hydrothermal alterations. It exceeds 1 % S in only three samples of the dike rocks (Fig. 5C). Cl is very low in the volcanic rocks, but high locally in the intermediate composition, 60-65 % SiO_2 , of some dikes and Wadayama granitoids.

Al_2O_3 contents are negatively correlated with the silica contents, but two high silica rocks (Nos. 7 and 8, Fig. 6A) and many of the dike rocks in mafic compositions (Fig. 6A) have low Al_2O_3 contents, which

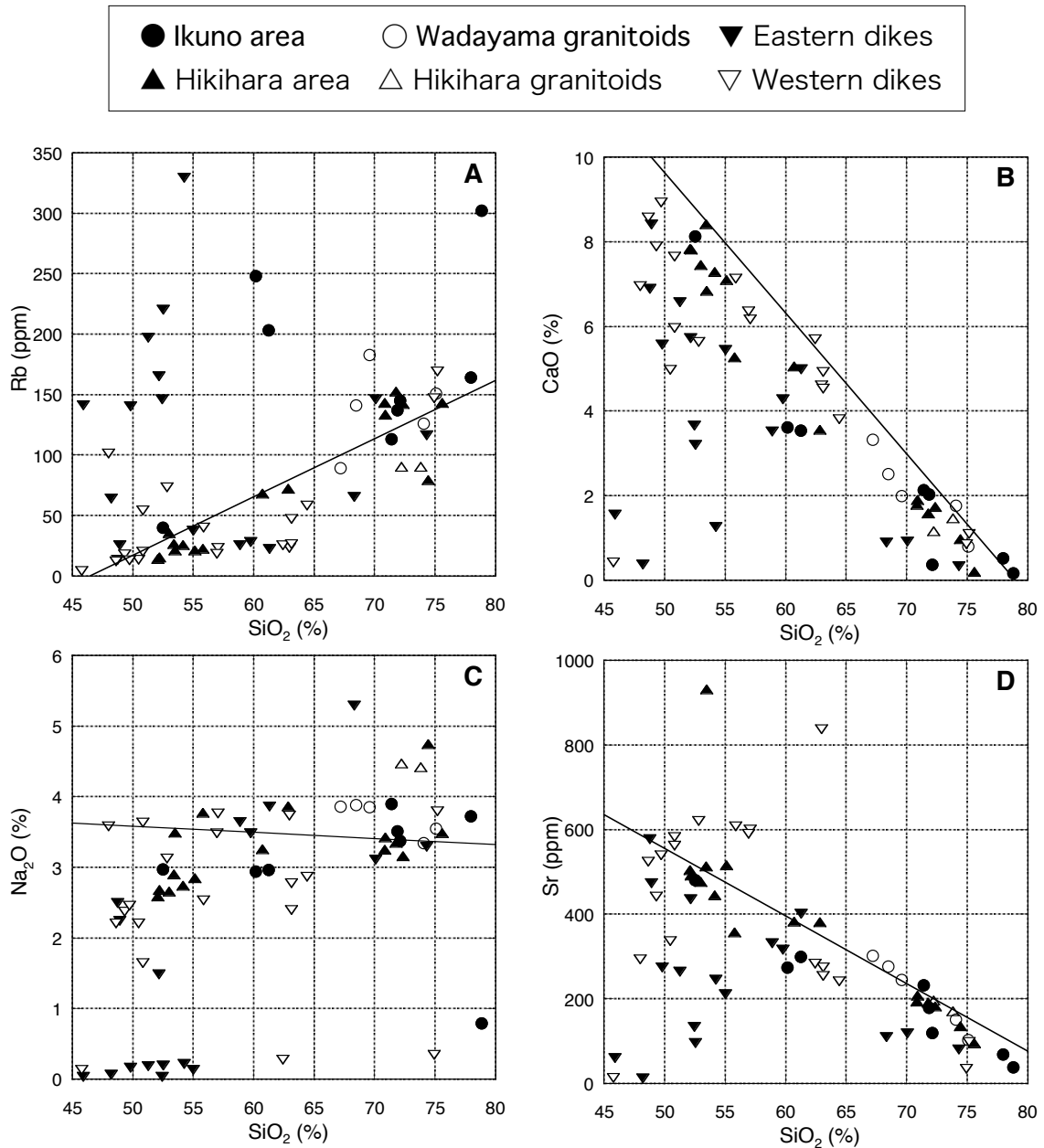


Fig. 7 Variation diagrams of the studied volcanic and plutonic rocks: Rb, CaO, Na₂O and Sr. The straight line is the same as that of Fig. 5.

are due to later hydrothermal alteration of plagioclase as shown by decreasing of CaO, Na₂O and Sr, and increasing of CO₂. The alteration is somehow effective to A/CNK index (Fig. 6B), and the studied rocks are generally higher than the average line of the Shiso granitic complex. Two high silica rocks (Nos. 7 and 8, Table 1) and many mafic dikes higher than 1.1, are considered resulted from break-down of plagioclase by later hydrothermal alterations. Ga contents are low, below 20 ppm, and therefore no indication of A-type character. Ga substitutes generally Al-position in feldspars, so that its distribution is very similar to that of alumina (Fig. 6C).

In K₂O-SiO₂ diagram (Fig. 6D), a majority of the

studied rocks are plotted in the fields of medium-K and high-K series. There seems to be no low-K series in the volcanic rocks. The Wadayama granitoids are plotted in similar region to that of the volcanic rocks, but the Hikihara granitoids are slightly depleted in K₂O. There are three volcanic rocks (Nos. 2, 3 and 8) and seven dike rocks plotted in the shoshonite field (Fig. 6D), which contain abundant hydrothermal sericite under microscope. Distribution pattern of Rb is similar to that of K₂O (Fig. 7A), excluding three high values above 200 ppm. Potassium and Rb seem to move together during the hydrothermal alteration. In detail, the Wadayama granitoids have higher content of Rb than the Hikihara granite.

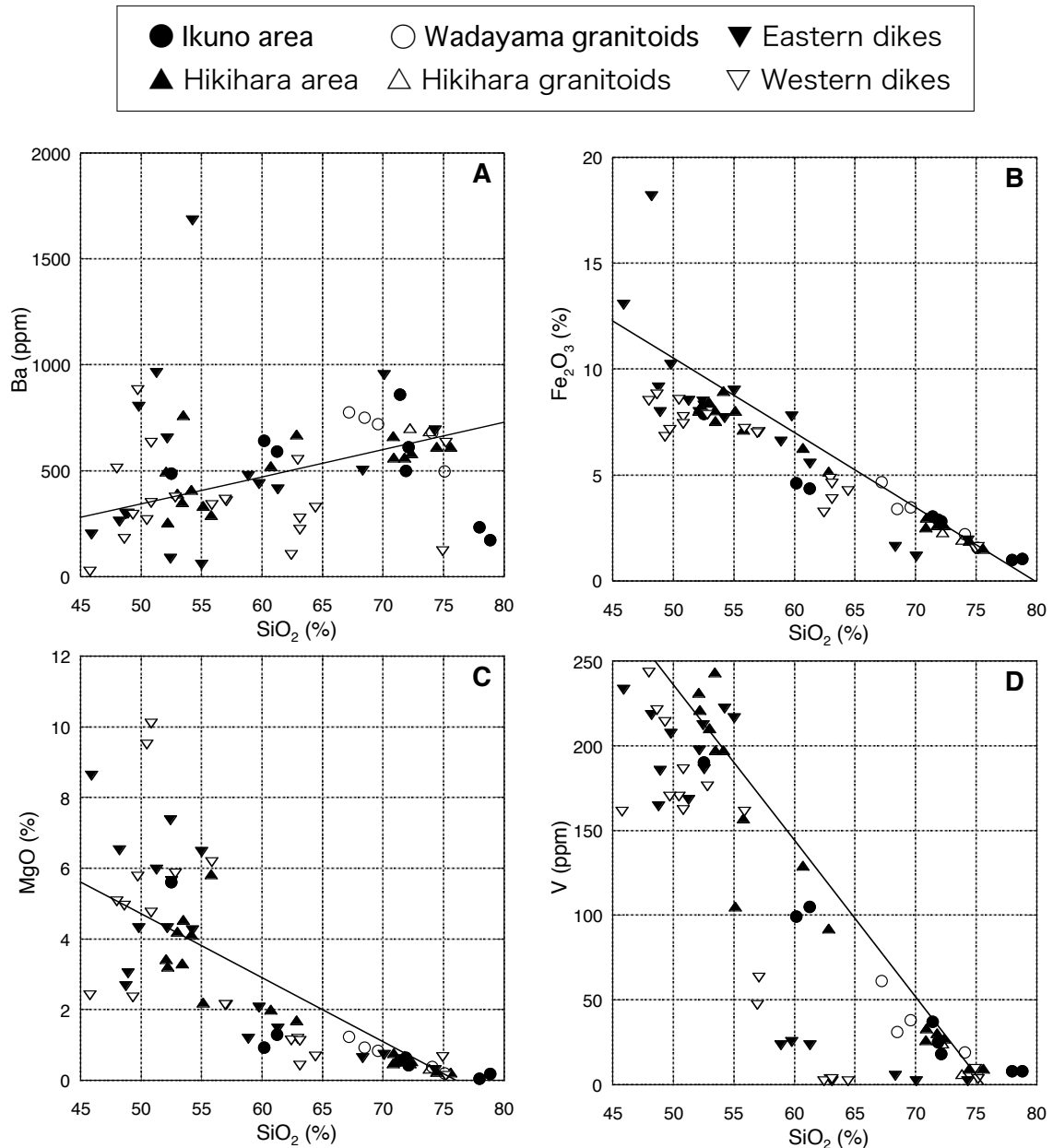


Fig. 8 Variation diagrams of the studied volcanic and plutonic rocks: Ba, Fe_2O_3 , MgO and V. The straight line is the same as that of Fig. 5.

CaO contents are lower than the average value of the Shiso granitic complex (Fig. 7B). Even unaltered granitoids show a less calcic nature, which is characteristic of the Wadayama granitoids. Low values of the volcanic rocks and dikes are due to the hydrothermal alteration.

Na_2O contents of the volcanic rocks and granitic rocks are positively correlated with SiO_2 contents (Fig. 7C), except for one (No. 8), which is strongly altered. The positive correlation may be theoretically valid, but Na_2O contents of the Shiso granitic complex has no change with the silica contents, which is commonly seen in the magnetite-series granitoids (e.g., Shirakawa granitoids: Ishihara and Tani, 2004). Many of the un-

derground dikes are very much depleted in Na_2O , indicating sodium was leached out after decomposition of the plagioclase. Yet, Sr content decreases with decreasing of silica, and follows the CaO trend. Ba contents are positively correlated with those of SiO_2 contents, except for Nos. 7 and 8, and some altered dikes that are high or low in the contents (Fig. 8A).

Among mafic components, the total iron contents as Fe_2O_3 are negatively correlated with SiO_2 contents, and plotted below the average line of the Shiso granitic complex, except for the high silica rocks (Fig. 8B). MgO contents are lower than the average of the Shiso granitic complex, but low silica volcanic rocks and dikes are high in the content, which may be due to

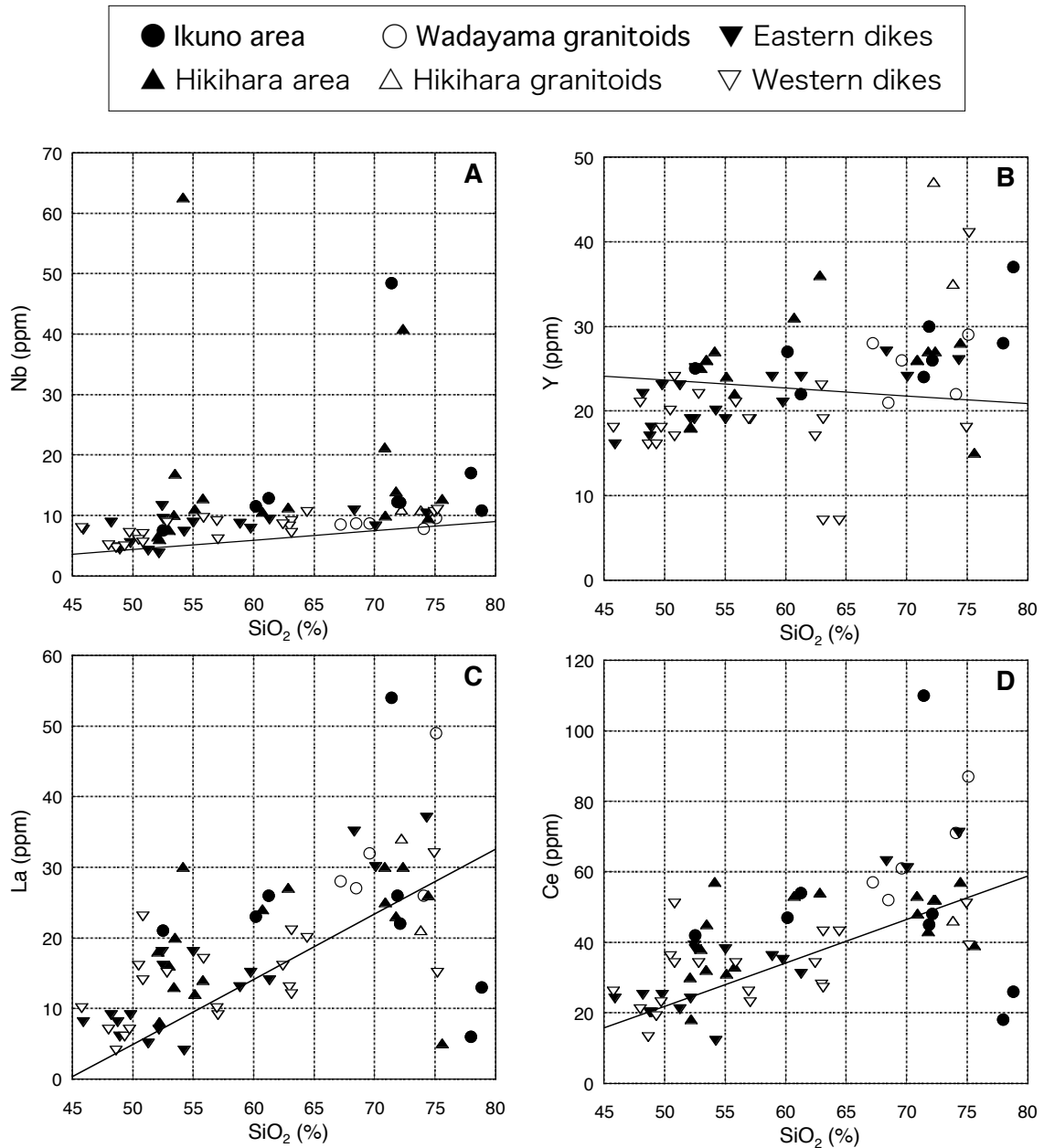


Fig. 9 Variation diagrams of the studied volcanic and plutonic rocks: Nb, Y, La and Ce. The straight line is the same as that of Fig. 5.

hydrothermal alteration. Vanadium, which may be contained in the rock-forming magnetite, is generally lower than the average of the Shiso granitic complex. The content is very low in many of the altered dikes. Unaltered Wadayama granitoids are also low in the content, because they are free of magnetite.

Nb contents of the studied rocks are generally higher than the average Nb contents of the Shiso granitic complex (Fig. 9A). The contents are extremely high in the three altered volcanic rocks of Nos. 11 (63 ppm), 4 (48 ppm) and 16 (41 ppm). Some Nb-bearing accessory minerals could be expected in these altered rocks. Y contents are generally higher than 15 ppm, and increase with increasing of SiO₂ contents. Variation of the con-

tents in the altered rocks seems to be small relative to other trace elements (Fig. 9B). No rocks show high Sr/Y ratio equivalent to the values of adakite in porphyry copper mineralized regions (Ishihara and Chappell, 2010). La and Ce contents also increase with increasing SiO₂ contents, and the contents are generally higher than the average content of the Shiso granitic complex (Figs. 9C, 9D). Some altered volcanic rocks are extremely high (No. 4) and low (Nos. 7, 8, 12) in these components.

Zircon is generally known to be stable mineral during hydrothermal alteration. The Zr contents vary widely from 66-68 ppm (Nos. 8 and 7) to 261 ppm (No. 14, Fig. 10A) in the volcanic rocks, which have a

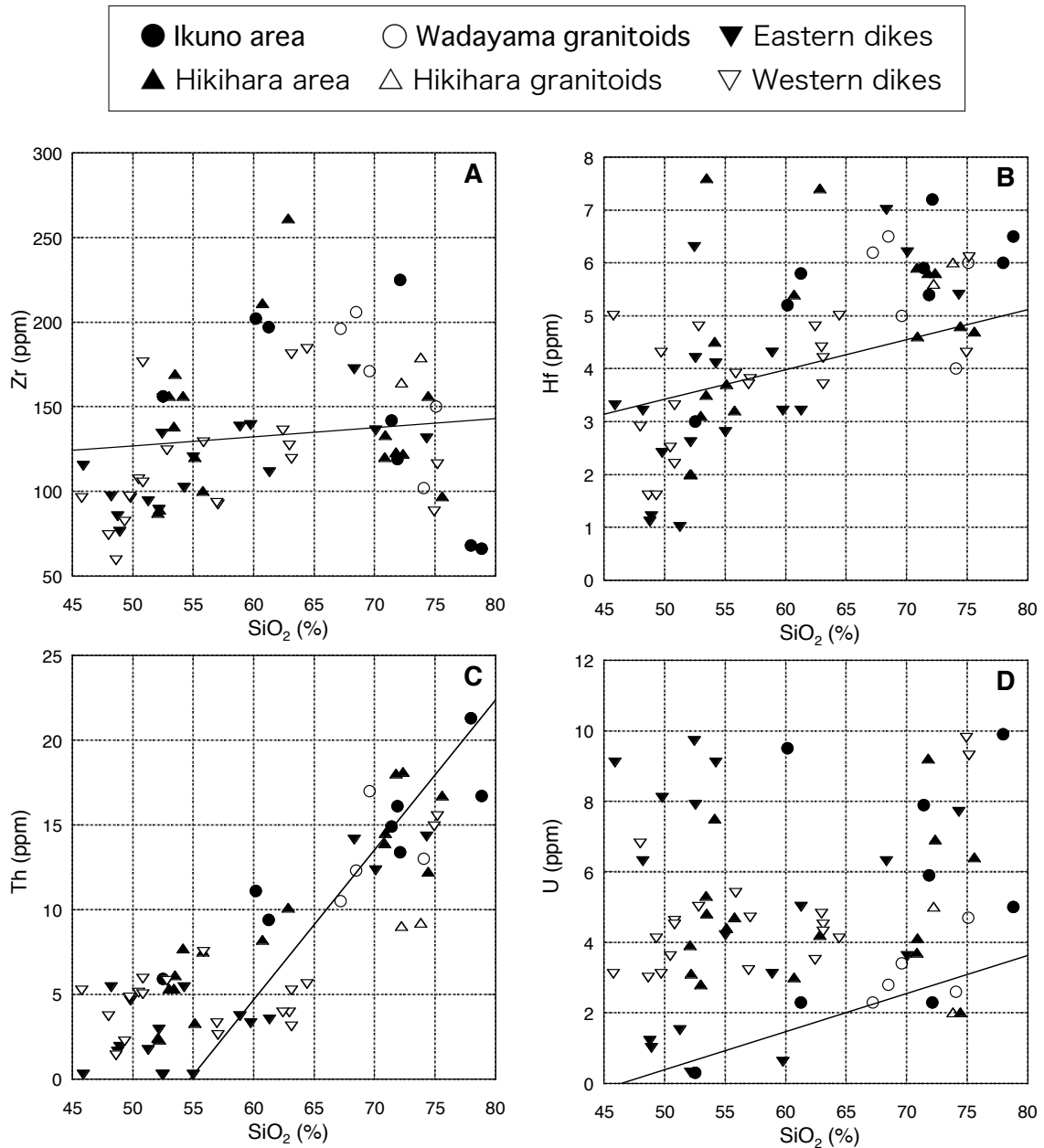


Fig. 10 Variation diagrams of the studied volcanic and plutonic rocks: Zr, Hf, Th, U, Sn and W. The straight line is the same as that of Fig. 5.

peak at 65 % SiO₂ (Fig. 10A). This pattern was considered typical in the high temperature I-type granitoids (Chappell *et al.*, 2004). Hf contents are low in the low SiO₂ rocks, and high in the high SiO₂ rocks (Fig. 10B), resulting a wide range of Zr/Hf ratio compared with that of unaltered granitoids. Unaltered Wadayama and Hikihara granitoids have Zr/Hf ratio of 24-32, but the studied volcanic rocks have Zr/Hf ratio of 20-52, and the underground dikes have 21-77 in the eastern group and 19-53 in the western group. Thus, the alteration gives rise to higher Zr/Hf ratio.

Th contents are positively correlated with silica contents. Even altered dikes follow this general trend, implying the elements were contained in accessory miner-

als, which are resistant to the hydrothermal alteration. Uranium, on the other hand, is scattered widely, implying that the element is contained in both accessory oxides and common mafic silicates, and is easily mobile during the alterations.

Zinc in igneous rocks is generally correlated with mafic major components. Unaltered granitoids and volcanic rocks are plotted around the line of the Shiso granitic complex in Figure 11A. Three samples of this figure and five high values up to 7,230 ppm listed in the Table 3 are, of course, altered equivalents. Lead replaces generally potassium position of K-feldspar in igneous rocks, and the Pb contents of the volcanic rocks are slightly higher than those of the Shiso granitic com-

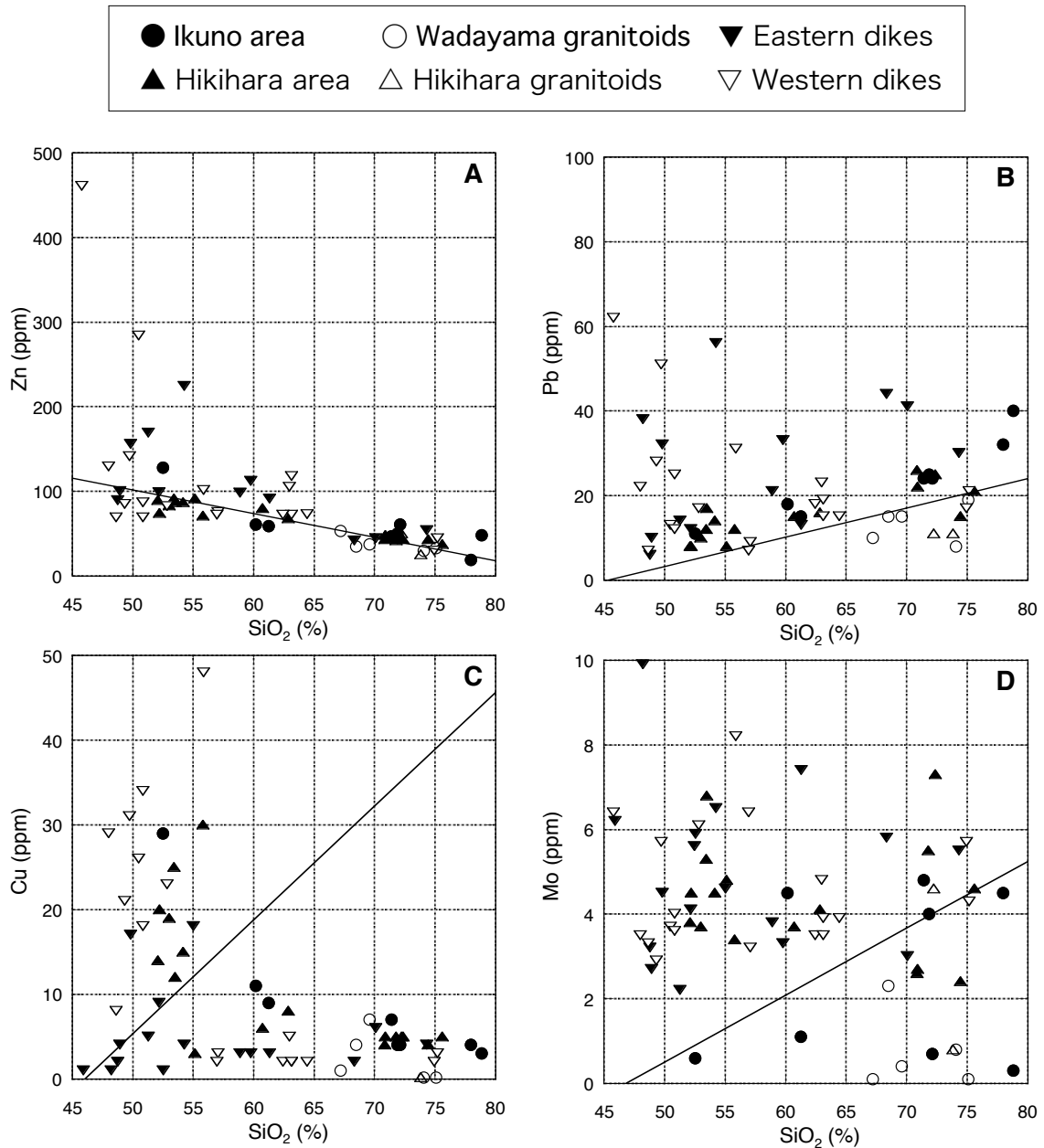


Fig. 11 Variation diagrams of the studied volcanic and plutonic rocks: Zn, Pb, Cu and Mo. The straight line is the same as that of Fig. 5.

plex (Fig. 11 B). The Pb contents vary greatly in the altered dikes up to 4,980 ppm. The Pb anomalies are positively correlated with the Zn anomalies in general, implying these elements moved around together during the alterations.

Copper is predominant in mafic rocks in general, especially in basaltic dikes, indicating therefore the capital L-shaped plot in Fig. 11C. The volcanic rocks are generally higher in Cu contents than dike rocks. Two altered dikes have very high values as 406 and 362 ppm Cu (see Table 3). Molybdenum content increases generally in high SiO₂ rocks of the Shiso granitic complex, but the studied rocks show higher and erratic distributions (Fig. 11D). The Mo contents of the

Wadayama pluton are lower than those of the Shiso granitic complex.

Trace amounts of tin in unaltered ilmenite-series granitoids increase generally with increasing silica contents (Ishihara and Terashima, 1977a, b). In the studied rocks, most of the volcanic and subvolcanic rocks are plotted in the 2-8 ppm range, very close to the average content of the Shiso granitic complex (Fig. 12A), and only six altered dikes showed high values of 10-44 ppm Sn (Tables 2 and 3). On the contrary, tungsten contents vary widely and many of the western dikes are high in W contents up to 29 ppm W (Table 3). The eastern dikes are also higher than the average of the Shiso granitic complex (Fig. 12B).

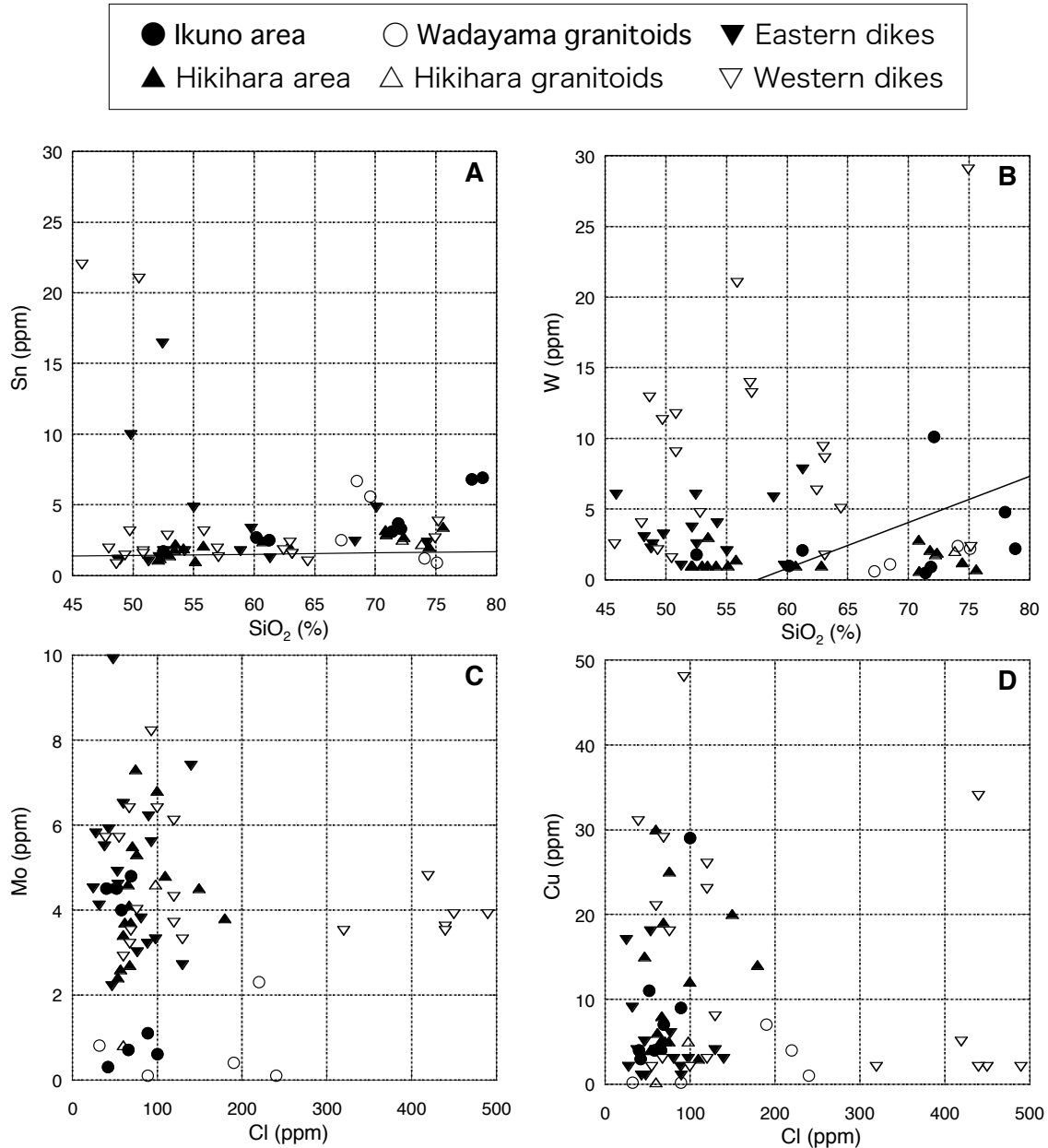


Fig. 12 Variation diagrams of the studied volcanic and plutonic rocks for Sn, W and Mo, and Cu-Cl diagram. The straight line is the same as that of Fig. 5.

Chlorine, which is an important carrier of chalcophile metals during hydrothermal mineralizations, shows no clear correlation with the Mo contents (Fig. 12C). In the case of Cu, the correlation is rather negative (Fig. 12D). About the bulk contents, granodiorite of the Wadayama pluton contains 240-190 ppm Cl, but the granite phase contains only 89-32 ppm Cl. Fluorine could be a good transporter for tin. The fluorine contents of the Wadayama granitoids are as low as 100 ppm F.

6. Cause of polymetallic character

In the vein and skarn-type deposits of the Japanese Island, magnetite and sulfide-forming ore metals tend to

occur associated with the magnetite-series magmatism, but tin and tungsten oxides are concentrated with the ilmenite-series magmatism (Ishihara, 1981). In the veins of the Ikuno mine, there occur many metals occurring as sulfide and sulphosalts, indicating that the related magma must be the magnetite-series. In those of the Akenobe mine, the early stage vein contain abundant magnetite and sulfide-sulphosalt commodities, which seem to be formed by the ore fluids separated from the magnetite-series subvolcanic intrusion of mafic to intermediate compositions.

On the other hand, Sn-W veins of the later stage are poor in magnetite and sulfide-sulphosalt minerals, which seem to be generated in the ilmenite-series

granitic magma. In the case of the Japanese plutonic rocks, trace amounts of tin tend to be high in those of tin-bearing ilmenite-series granitic rocks (Ishihara and Terashima, 1977a). Here in the studied area, the Wadayama granite contains 1.0 to 6.4 ppm Sn with an average of 3.8 ppm (n=6), while the Shiso tin-free magnetite-series granitic rocks contain only 0.8 to 1.6 ppm Sn with the average of 1.3 ppm Sn (n=11) (Terashima and Ishihara, 1982).

As mentioned previously, the Ikuno and Akenobe vein deposits are characterized by polymetallic nature, containing base metal, tin, tungsten, silver and gold. Lead and silver are predominant in the Ikuno deposits, while tin and tungsten prevail in the Akenobe deposits. A rare metal of indium is rich in base metal ores of both the mines (Ishihara *et al.*, 2006). The announced metal grades of the produced ores of the recent years as follows:

(1) Ikuno mine in 1956-73: 1.19 % Cu, 2.06 % Zn, 0.43 % Pb, 0.16 % Sn and recoverable amounts of Ag and Au.

(2) Akenobe mine in 1921-1987: 1.03 % Cu, 1.69 % Zn, 0.40 % Sn and recoverable amounts of W.

These ore metals show both horizontal and vertical zoning in the Ikuno deposits. Maruyama (1957) recognized horizontal zoning of Zn-Sn-Cu zone surrounded by Zn zone, Pb-Ag zones and Au-Ag-quartz zone. Vertically, Sn zone occurs at the bottom together with Zn zone, and Ag-Au zone tends to occur in marginal to the main tin-base metal ores. He seemed to believe that a mono-ascendant ore solution formed such zoning by decreasing of temperatures and pressures. However, polyascendant model, like the case we see in the Akenobe deposits, can also be possible for the varieties of the ore metals and subvolcanic activities.

In the Ikuno ore deposits, the main mineralization is strongly controlled by fractures related to basaltic sheet and dike. The champion vein system of the Kanagase group including the Senju-honpi, Senju-maehi, Kaniyahi, Kinsei-hi, Keiju-hi, etc., tend to occur along cracks formed by cooling of the hot basalt and faulting along the wall rocks within or at margin of the basaltic dikes. Dikes have a variety of composition from basalt and andesite to dacite and rhyolite. E-W trending rhyolite dikes tend to contain Sn-rich ores within these intrusions (Maruyama, 1959).

Magnetite and base metal mineralizations of the Ikuno and Akenobe deposits may well be associated with magnetite-series subvolcanic activities of mafic to intermediate compositions, but tin and tungsten concentration must have occurred with felsic ilmenite-series intrusion. At the Akenobe deposits, relatively low temperature Ag-Pb-Zn-Cu-magnetite veins are cut by higher temperature Cu-Sn-W veins, which are best seen in the Chiemon Vein -10L (Sato *et al.*, 1977; Akiyama *et al.*, 1980). Therefore, the polymetallic nature of the Akenobe mine is resulted from poly-ascendant introduction of the hydrothermal ore solution, which

had a different magmatic/meteoritic water ratios (Murao and Urabe, 1993), and the earlier base metal veins were originated in subvolcanic activity, but later tin-base metal mineralization was derived from hidden granite (Imai *et al.*, 1975), similar but more fractionated one we see in the Wadayama granitic pluton.

7. Conclusions

Historical productions of the ores from the Ikuno and Akenobe mines were reevaluated. They were polymetallic in composition, being rich in chalcophile components in the Ikuno ores and the first-stage ores of the Akenobe ores, but tin and tungsten predominating in the second stage of the Akenobe ores. The Ikuno ores were formed by ore fluids liberated from magnetite-series subvolcanic rocks of basaltic to rhyolitic compositions. The Akenobe ores of the first-stage base metal-rich one were also formed by magnetite-series subvolcanic rocks of basaltic to dacitic compositions, but the second-stage of tin-tungsten-rich ores would have been formed by the ore fluids liberated from an ilmenite-series granite hidden below the ore veins.

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兵庫県明延—生野地域の鉍化作用と後期白亜紀火成岩類の化学的性質

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要 旨

生野—明延鉍床は日本を代表する多金属石英脈鉍床である。鉍脈は、明延鉍床においては古生代末期—中生代初期の苦鉄質岩類と変成岩類とを母岩とし、生野鉍床では後期白亜紀火山岩類と岩脈類を母岩とする。生野鉍床の鉍脈は、主力の金香瀬鉍脈群がN-S系、東に急傾斜し、一部、NW-SE系である。その他の太盛・青草地区では、主にNW-SE系とN-S系走向で、急傾斜を持つ。鉍脈は多金属性で、ベースメタルの他、金銀に富み、かつ錫を含むが、タングステンに乏しい。これらの鉍石鉍物は、鉍床の中心から外方へ、Sn-Cu帯、Sn-Cu-Zn帯、Zn帯、Pb-Zn帯、Au-Ag帯、不毛帯のゾーニングを持つ。インジウム鉍物も多産する。明延鉍床は母岩が苦鉄質岩類と変成岩類である点は生野鉍床とは異なるが、一般にはNW-SE系、西部でNE-SW系に彎曲する急傾斜鉍脈である。鉍脈はここでも多金属的であるが、生野鉍床に較べて、金銀・鉛に乏しく、スズとタングステンに富む。またその多金属性は鉍化ステージが違う複合鉍脈として見られ、早期Pb-Zn-Cu脈に、後期W-Sn-Cu脈が重複し、複合鉍脈を構成する。

後期白亜紀の生野層群は下部から上部へ、含角礫黑色頁岩 (ISo)、デイサイト質火砕岩 (IDco)、黑色頁岩 / 砂岩凝灰岩 (IS1)、流紋岩 > 安山岩質火砕岩 (IX)、流紋岩質溶結凝灰岩 (IR1)、凝灰岩 / 頁岩 (IS2)、安山岩と同質凝灰岩 (IA2)、流紋岩質溶結凝灰岩 (IR2)、凝灰岩 / 頁岩 (IS3)、安山岩と同質凝灰岩 (IA3)、凝灰岩 / 頁岩 (IS4)、デレナイト溶結凝灰岩 (ID4) に分類される。これらの火山岩類は帯磁率測定と顕微鏡観察により、磁鉄鉍系に属するものと判断される。二成分変化図上ではややカリウムに富むもの一般のカルクアルカリ岩系の領域を占める。銀とベースメタルに富む生野鉍床の富鉍部は玄武岩岩脈と流紋岩岩脈と空間的に密接であり、ベースメタルは前者とスズは後者に由来した熱水鉍液から沈殿した可能性が大きい。明延鉍山内の岩脈類も磁鉄鉍系に属する玄武岩から流紋岩に至るシリカ含有量を持ち、一部でショノナイトと高カリウム岩にプロットされるものもあるが、多くは中程度のカリウムを持つ一般のカルクアルカリ岩である。早期のベースメタル鉍化はこのような火山岩類に由来した鉍液に関係し、後期のスズに富む鉍化は潜在する珪長質岩体からもたらされた鉍液から沈殿した可能性が考えられる。地表に露出する和田山花崗岩は、鉍化関係花崗岩としては微量成分としてのスズには富むが、フッ素に乏しい難点がある。

Appendix I Locality and sample nos. with the rock types and magnetic susceptibility (SI unit) of the analyzed volcanic and granitic rocks from the Ikuno-Hikihara dam area.

Nos., Sample nos.	Rock types & magnetic susceptibility (SI unit $\times 10^{-3}$)	Locality
Ikuno Area		
1, 80082636:	Aphyric basalt, SI=48.0-84.0;	Ikuno dam (朝来市生野ダム東方直1.5 km)
2, 80082635A:	Porphyritic dacite, SI=2.2;	Ikuno, Taisei quarry (朝来市古城山大盛採石場)
3, 80082635B:	Fine diorite-looking dacite, SI=2.4;	Taisei quarry (同上)
4, 82031901:	Rhyolitic welded tuff, SI=17.0;	Ikuno Country Club (生野高原ゴルフ場の上)
5, 80082634:	Fine, rhyolitic tuff, SI=22.0;	Ogouchi-cho, Fuchi (大河内町淵東北500m)
6, 80082637:	Rhyolitic tuff, SI=7.0;	Ikuno dam east (朝来市生野ダム東方直2.2km)
7, 80082639:	Red porphyritic rhyolite, SI=2.0;	Ikuno dam ENE (同上、東北東直3.5 km)
8, 80082638A:	Banded rhyolite, SI=2.0;	ditto (同上、東北東直2.7 km)
Hikihara dam area		
9, 8308071101:	Aphyric andesite, SI=16.0-26.0;	Haga-cho, Hori (宍粟市波賀町堀)
10, 82032102:	Porphyritic andesite, SI=60.0;	Wakasugi-pass west (宍粟市若杉峠西)
11, 82032101:	Purple andesite, SI=44.0;	Wakasugi pass west (宍粟市若杉峠西)
12, 8308071002:	Rhyolitic tuff, SI=1.5;	Wakasugi pass west (宍粟市若杉峠西)
13, 8308071208:	Aphyric andesite, SI=44.0-51.0;	Shikafuse west (宍粟市鹿伏西方)
14, 8308071216:	Aphyric andesite, SI=58.0-64.0;	Shikafuse west (宍粟市鹿伏西方)
15, 82032105:	Purple andesitic tuff, SI=33.6;	Shikafuse west (宍粟市鹿伏西方)
16, 82032104:	Green andesitic tuff, SI=5.0;	Shikafuse west (宍粟市鹿伏西方)
17, 82032110:	Dacitic lava, SI=2.2;	Nishikumon, Mizotani (宍粟市西公文、溝谷)
18, 82032109:	Andesite sheet (1.5 m wide), SI=90.0;	ditto (宍粟市西公文、溝谷)
19, 82032108:	Rhyolitic tuff, SI=5.8;	ditto (宍粟市西公文、溝谷)
20, 8308071535:	Rhyolitic tuff, SI=3.0-4.0;	Obara NNW (宍粟市小原北北西方)
21, 8308071550:	Rhyolitic lava, SI=5.0;	Obara NNW (宍粟市小原北北西方)
Dike rocks		
22, 8308071135A:	Andesite in granite, 2 m wide, SI=92.0;	Shikafuse (宍粟市鹿伏北)
23, 8308071135B:	Andesite in granite, 1 m wide;	Shikafuse (宍粟市鹿伏北)
24, 8308071220:	Dacitic dike in granite; ditto	(宍粟市鹿伏西方林道)
Hikihara Granites		
25, 8308071147:	Porphyritic granite; ditto	(宍粟市鹿伏南、林道入り口)
26, 82749A:	Biotite granite; Haga-cho, Ishigame south	(宍粟市波賀町石亀)
Wadayama granitoids		
27, 71TO227:	Hb-bt granodiorite; Wadayama-cho, Makita	(和田山町牧田)
28, 71TO228:	Hb-bt granodiorite; Santo-cho, Tozaka pass	(山東町遠阪峠)
29, 82632:	Hb-bt granite; Asago, Santo-cho, Itsubou	(朝来郡山東町一品)
30, 71TO226:	Leucogranite; Yabu, Yashiro pass	(養父町八代峠)
31, 82633:	Leucogranite; Asago, Santo-cho, Hazama	(朝来郡山東町迫間)

Appendix II Locality and sample nos. with the rock types and magnetic susceptibility (SI unit) of the analyzed dikes from the underground Akenobe mine.

Sample No.: Rock type & magnetic susceptibility (SI unit $\times 10^{-3}$)	Locality
Eastern part	
32, 020202: Altered andesite, SI<0.2; -2L Nanei cross cut (南栄脈立入)	
33, 020203: Dacite, SI>15.2; -2L Meikou vein (明光脈) TP474	
34, 020304: Altered felsite, SI<0.2; -3L Sennari cross cut (千成脈立入)	
35, 020405: Altered basalt, SI<0.2; -4L Shaft-related cross cut (立坑切替立入)	
36, 020406: Altered dacite, SI<0.2; -4L Meikou cross cut (明光脈立入)	
37, 020407: Altered andesite, SI<0.2; -4L Meikou vein (明光脈) TF142	
38, 020608: Basalt, SI<0.2; -6L Kouzou Tunnel (構造坑道) 45m	
39, 020609: Altered basalt, SI=13.1; -6L Shiroyiwa vein (白岩脈) S30	
40, 020610: Basalt, SI=0.2; -6L, Shirogane cross cut (白金脈立入)	
41, 020611 Altered felsite, SI<0.2; -6L Sennari vein (千成脈) S40	
42, 020612: Altered basalt, SI=28.2; -6L Nanei vein North (南栄脈北部) E2	
43, 020613: Dacite, SI=0.2; -6L Meikou vein (明光脈) W13	
44, 020715: Altered basalt, SI=0.2; -7L Ryusei vein (竜盛脈) S49	
45, 020816: Altered basalt, SI=0.2; -8L Ryusei vein (竜盛脈) TB3	
46, 020817: Altered dacite, SI<0.2; -8L Ryusei vein (竜盛脈) TB4	
47, 020818: Altered andesite, SI<0.2; -8L Ryusei vein (竜盛脈) TF143	
48, 020919: Basalt, SI<0.2; -9L Ginsei vein south (銀星脈南部) S46	
Western part	
49, 040801: Basalt, SI=38.0; -8L 7 th vein (七脈) N28	
50, 040802: Basalt, SI=22.5; -8L Sinhokusei cross cut (新北星脈立入)	
51, 040803: Basalt, SI=22.0; -8L ditto(新北星脈立入)	
52, 041004: Basalt, SI=15.0; -10L Hotei cross cut (布袋脈立入)	
53, 041005: Garnet andesite, SI<0.2; -10L Hotei cross cut (布袋脈立入)	
54, 041006: Hornblende basalt, SI=15.0; -10L ditto (布袋脈立入)	
55, 041007: Dacitic felsite, SI=8.8; -10L Fujino cross cut (富士野脈立入)	
56, 041208: Hornblende andesite, SI=27.6; -12L Eisei cross cut (永世脈立入)	
57, 041209: Altered basalt, SI=22.0; -12L Nansei Kirikae (南星脈切替)	
58, 041210: Hornblende andesite, SI=27.5; -12L Chiemon cross cut (知恵門脈立入)	
59, 041312: Felsite, SI<0.2; -13L Eisei vein (永世脈) SS	
60, 050801: Hornblende andesite, SI=25.0; -8L Chiemon 5 th vein (知恵門5号脈) W8	
61, 051203: Altered andesite, SI=4.9; -12L Chiemon 7 th vein (知恵門7号脈) W6	
62, 051204: Garnet andesite, SI<0.2; -12L Chiemon 7 th vein (知恵門7号脈) W6	
63, 051206: Hornblende basalt, SI<0.2; -12L Chiemon 4 th vein (知恵門4号脈) W7	
64, 051207: Pre-ore basalt, SI=0.2; -12L Chiemon 3 rd vein (知恵門3号脈) W8	
65, 051208: Hornblende andesite, SI<0.2; -12L Chiemon 4 th vein (知恵門4号脈) E2	
66, 051409: Dacitic andesite, SI=3.2; -14 L Chiemon 7 th vein (知恵門7号脈) W9	