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Cenozoic Island Arc Magmatism in Java Island (Sunda Arc, Indonesia): Clues on Relationships between Geodynamics of Volcanic Centers and Ore Mineralization

Lucas Donny SETIJADJI[1], Shigeo KAJINO, Akira IMAI and Koichiro WATANABE

Department of Earth Resources Engineering, Kyushu University, Fukuoka 812-8581, Japan [e-mail: lucas@mine.kyushu-u.ac.jp]

[1] *Also with position at Department of Geological Engineering, Gadjah Mada University, Yogyakarta 55281, Indonesia*

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Abstract: Java island, regarded as a classic example of island arcs, is built through multi events of Cenozoic arc magmatism produced by the subduction of Indian-Australian oceanic crusts along the southern margin of Eurasian plate. Regional crustal compositions, subducted slabs, and tectonics determined the spatial-geochemical evolution of arc magmatism and regional metallogeny. Tertiary geodynamics of island arc was dominated by backarc-ward migrations of volcanic centers. Only after the Miocene-Pliocene roll-back effects of retreating slab, slab detachment, and backarc magmatism took place in central Java. The source of arc magmas is mainly partial melting of mantle wedge, triggered by fluids released from dehydrated slabs. Increasing potassium contents of arc magmas towards the backarc-side and younger magmas is typical for all magmas, while alkali and incompatible trace elements ratios are characteristics for different settings of volcanic centers. The oceanic nature of crust and the likely presence of hot slab subducted beneath the eastern Java determine the occurrences of adakitic magmas. Backarc magmatism has a deeper mantle source with or without contributions from subduction-related materials.

The domination of magnetite-series magmatism determines the sulfide mineralization for the whole island. District geology, geodynamics, and magma compositions in turn control particular styles and scales of precious metals concentrations. Deep-seated crustal faults have focused the locations of overlapping volcanic centers and metalliferous fluids into few major gold districts. Porphyry deposits are mostly concentrated within Lower Tertiary (early stage) volcanic centers in eastern Java which are not covered by younger volcanic centers, and whose sulfides are derived from partial melting of basaltic parental materials. On the other hand, high-grade low-sulfidation epithermal gold deposits formed in later stages of arc development and are spatially located within younger volcanic centers (Upper Miocene-Pliocene) that overlap the older ones. Gold in low-sulfidation epithermal system is likely to be derived from crustal materials. The overall interacting factors resulting in the petrochemical systematics that are applicable for exploration: 1) early-stage volcanic centers with high Sr/Y and Na_2O/K_2O ratios are more prospective for porphyry mineralization, while 2) later-stage volcanic centers with high K_2O, total alkali, and K_2O/Na_2O ratios are more prospective for low-sulfidation epithermal mineralization.

Keywords: Arc magmatism, volcanic center, ore deposits, geodynamics, Java island

1. Introduction

Spatial relationships between volcanic arcs and metallic mineralization are recognized in many island arcs in the world. Some genetic relationships have also been proposed, such as relationships between magnetite-series magmatism with sulfide mineralization, ilmenite-series with cassiterite-wolframite deposits (Ishihara, 1981), and adakitic magma with porphyry Cu-Au deposits (Oyarzun et al., 2001; Imai, 2002). In tectonic-geodynamic contexts, Kerrich et al. (2000), Blundell (2002), and MacPherson and Hall (2002) suggested several determining factors such as volcanism, tectonic regime, and fluid transport system for locating mineralization. However, their works are best described as a generic model for regional context; there is no specific conclusion on what kind(s) of volcanism, structure, and trap system that have created different types of mineralization that can be applied as an exploration guide at district scale.

In this study, we conduct an evaluation on such determining factors for metallic mineralization in Java island (Sunda arc, Indonesia) during its Cenozoic island arc development. We put together most features studied by previous researchers (i.e., tectonics, geodynamics, and petrochemistry) to test either specific factors are influential in the case of Java island. The purpose is to better define the likely locations of mineral deposits by understanding the geodynamics of an island arc, mainly through observation of volcanic centers. One basic assumption is that volcanoes are direct products of island arc geodynamics that are most obvious and most accessible to human

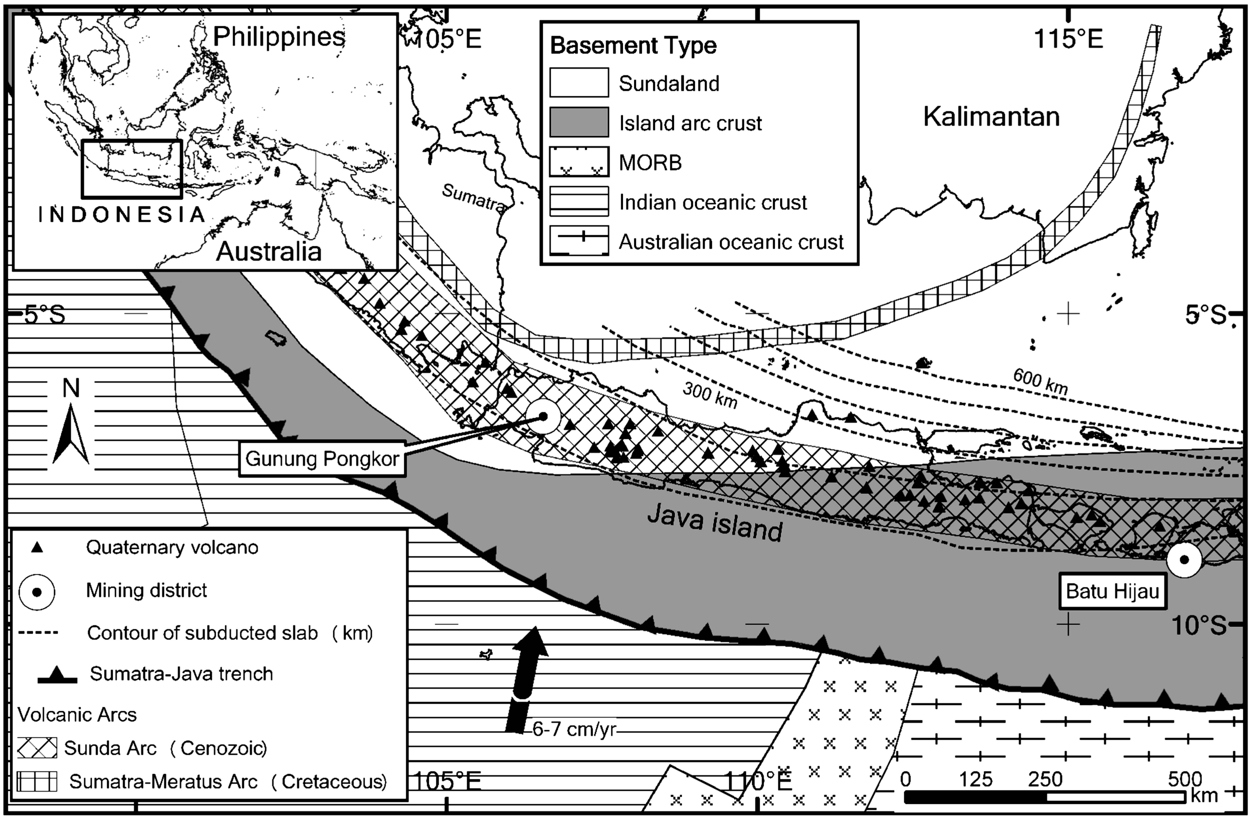


Fig. 1 Geologic framework of Java island, Indonesia. Note there are two different arcs (Cretaceous and Cenozoic) and this study concerns only on Cenozoic one, as part of the Sunda arc. There are two operating mines in this region, the Gunung Pongkor Au-Ag mine in western Java and Batu Hijau Cu-Au mine in Sumbawa island. Contour of subduction zone depth is from Hamilton (1979), while crustal geology is compiled from Hamilton (1979), Carlile and Mitchell (1994), and Hall (2002).

being (Gill, 1981; Tatsumi and Eggins, 1995). Therefore, spatial-temporal evolutions and geochemical variations of island arc volcanoes can be related with different tectonic settings and sources of partial melting (Green, 1980; Nicholls et al., 1980; Gill, 1981; Wheller et al., 1987; Peacock et al., 1994; Martin, 1999).

2. Geologic Background of Java Island

2.1. Tectonic framework of subduction zone

Java island is part of a volcanic arc whose length is about 3,700 km that extends from the northern tip of Sumatra island through Java to east of Damar island (Hamilton, 1979; Carlile and Mitchell, 1994). This long arc progressively developed from west to east since the Mesozoic, and is divided in three segments: the Sumatra arc comprising Sumatra island, the Sunda arc from Java to Flores islands, and the Banda arc for the islands east of Flores. The Java segment was built in the early Tertiary at a convergent tectonic margin between the Indian-Australian oceanic plates and the southeastern margin of Eurasian continental plate named the Sundaland (Katili, 1975; Hamilton, 1979; Carlile and Mitchell, 1994) (Fig. 1). The oceanic crusts are being subducted more or less perpendicular to the volcanic arc at a rate of about 6-7 cm/yr (Hamilton, 1979; Simandjuntak and Barber, 1996). The Wadati-Benioff seismic zone currently extends to depths of more than 600 km (Hamilton, 1979; Puspito and Shimazaki, 1995). Tomographic imaging suggests that the lithospheric slab penetrates to a depth of at least 1500 km (Widiyantoro and Van der Hilst, 1996).

While the present configuration of the Java sector has existed at least since the mid-Tertiary, some researchers (e.g., Katili, 1975; Hamilton, 1979; Carlile and Mitchell, 1994; Metchalfe, 1996) suggested that during Cretaceous an older trench existed from central Java to southeastern Kalimantan (Meratus Mountains). The Cretaceous arc stretched along Sumatra island, northwestern Java, to southeastern Kalimantan (Fig. 1). The timing and nature of transition from the Cretaceous Sumatra-Java-Kalimantan trench into the Cenozoic Sumatra-Java trench is largely unknown, as there is a Late Cretaceous to Eocene hiatus in volcanic activity (Packham, 1996).

2.2. Compositions of crust and subducted slabs

The crust underneath the arc thins eastward, from

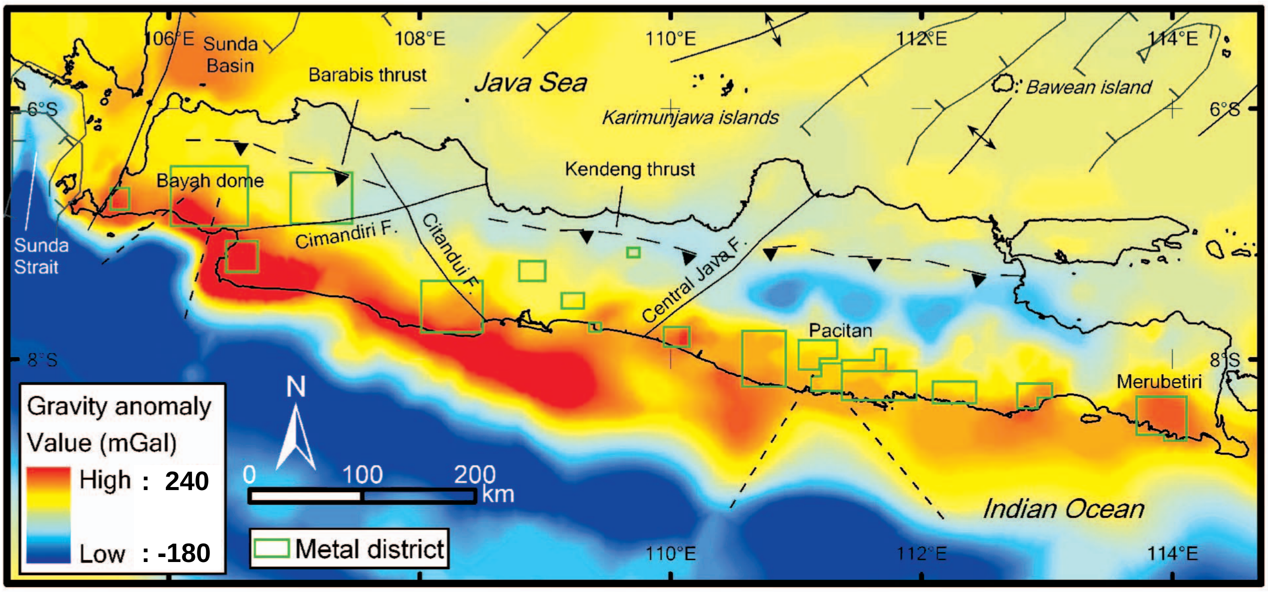


Fig. 2 Major geologic structures, locations of known metallic minerals districts, and regional gravity anomaly of Java. The most important mineral districts in Java (esp. Bayah dome and Pacitan) are sitting on narrow gravity highs bound by sharp gravity gradient representing major crustal structures. The gravity map is digitized and re-gridded from the map of Budiman et al. (2000). The geologic structures are taken from Simandjuntak and Barber (1996).

approximately 30 km beneath the Sumatra island to 15 km beneath the Flores Sea (Ben-Avraham and Emery, 1973). In Java the crust is about 20-25 km thick. The western segment (i.e., Sumatra, west Java, and perhaps central Java) is underlain by a continental basement of the Sundaland (Fig. 1). On the other hand, areas east of central Java are underlain by an island arc crust, starting from the Cretaceous accretionary complex in central Java (Miyazaki et al., 1998) to principally oceanic crust further east (Carlile and Mitchell, 1994; Simandjuntak and Barber, 1996).

Compositions of the subducted crusts along the Java trench are traditionally considered to be cold Indian oceanic crust with ages increasing eastwards at approximately 80-140 Ma (Whitford, 1975; Cloetingh and Wortel, 1986; Packham, 1996). However, regional geodynamic reconstruction by Hall (1996, 2002) suggested that the oceanic floor south of Java in Early Tertiary was composed of the western Mesozoic Indian plate, the eastern Jurassic Australian plate, and Late Cretaceous-Early Tertiary mid-oceanic ridges basalts (MORB) in between. The Indian and Australian plates started to separate since the Cretaceous leading to the opening of Indian Ocean and closing of the Tethyan Ocean. The Indian and Australian plates were supposed to be two different plates during Early Eocene (50-40 Ma), bound by a N-S spreading center that continued to the north. This hot MORB was then being subducted somewhere along the Java trench (Hall, 2002). After the period of about 45 Ma the rate of northward motion of Indian Plate reduced significantly and Indian and Australian Plates became a single plate. The Australian plate started to be separated from the Antarctica in Late Cretaceous and started moving northward relatively rapidly.

2.3. Major tectonic events and structures

The Cenozoic tectonic history of Java, based largely on petroleum backarc basins records, is divided into two main phases: 1) the Paleogene extensional and subsidence-dominated tectonics, and 2) the Neogene compressional and thrusting-folding events (e.g., Simandjuntak and Barber, 1996; Hall, 2002). Stratigraphic unconformities suggest two orogenic events during the Neogene, i.e., in Upper Miocene and Plio-Pleistocene. These compressive events created a major backthrust (the Barabis-Kendeng thrust) which can be traced from the Sunda Strait eastwards across Java (Simandjuntak and Barber, 1996).

The main structural features of Java are shown on Figure 2 and are summarized as follows. Besides the backarc thrust of Barabis-Kendeng fault, there are three main strike-slip faults found in Java. In western Java, the still active NE-SW Cimandiri fault crosscuts the whole of west Java. Another strike-slip fault, namely the Citandui fault, occurs in western Java and trends NW-SE. This old and inactive fault was interpreted from gravity data (Untung and Sato, 1978). The third system occurs in central Java, namely the Central Java fault as a NE-SW left-lateral strike-slip fault which crosscuts the whole island (Simandjuntak and Barber, 1996). The 27

May 2006 earthquake that devastated Yogyakarta region and killed almost 5,000 people is likely to be associated with this fault system. On the Java Sea part, there are many petroleum sub basins and basement highs controlled by NE structures. Meanwhile, the Sunda Strait has been experiencing crustal opening since 2 Ma and related volcanic activity since 1 Ma (Nishimura et al., 1986).

2.4. Mining districts

Within Sunda arc there are currently only two (but major) active mining districts. The first is the Pongkor Au-Ag mine in the Bayah dome district, west Java (Basuki et al., 1994; Milesi et al., 1999), where a total reserve of about 100 tons of gold has been discovered. The other is the world-class Batu Hijau porphyry Cu-Au mine in Sumbawa island (Garwin, 2002; Arif and Baker, 2004; Imai and Ohno, 2005) with a reserve of 914 mt @ 0.53 % Cu, 0.40 g/t Au). As two major gold districts (with different styles) are found at the two ends of the 1,500 km long Sunda arc section, the question is to determine the mineral potential in areas between.

3. Methods of Study

This study started with data compilation and building a database from geoscience datasets for the entire Java island. Datasets were managed within a relational database using a specially designed database schema. The data model and its implementation strategy were already described in Setijadji and Watanabe (2005). The relational databases are then linked to a geographic information system (GIS), in which visualization, query, spatial analysis, and map production were conducted using the ArcMap and ArcScene of ESRI's ArcGIS. Many analytical charts (e.g., alkalinity, total alkali, alkali ratio, adakite vs normal arc volcanics) have been created as GIS base maps, so that all analysis works were done visually using GIS. Major analytical tasks consisted of the reconstruction of Cenozoic volcanic centers, studying petrochemical systematics of arc volcanics, and evaluation on spatial-genetic relationships among mineralization, geodynamics, and arc magmatism.

Studying Cenozoic evolution of the volcanic arcs was done firstly by a reconstruction of all volcanic centers since early Tertiary to Recent. In this case, observation on Quaternary volcanoes was used as a base for studying the Tertiary counterparts. Locations of Tertiary volcanic centers were reconstructed based on combining evidence criteria, i.e., occurrences of intrusive complexes (volcanic necks), significant exposure of volcanic rocks surrounding an intrusive complex, radiometric ages of igneous rocks, and geomorphology criteria (e.g., circular features of caldera remnants). Evidence was either collected during fieldwork or by GIS-based computer manipulations on digital geologic maps 1:100,000, digital elevation model, and satellite images. On defined volcanic centers, a buffer zone of 20-km radii was applied from the center of intrusive complex as a representative size of a volcano. For each assigned volcanic center we gave a name and the likely geologic age based on available radiometric data and/or relative ages from surrounding lithostratigraphy units. We defined geologic epochs into the Paleocene-Eocene (66.4-37.5 Ma), Oligocene (37.5-22.5 Ma), Lower Miocene (22.5-15.0 Ma), Upper Miocene (15.0-5.3 Ma), Pliocene (5.3-1.8 Ma), and Quaternary (<1.8 Ma).

The reconstructed Cenozoic volcanic centers became a starting point for further analyses. First, it was used for analysis on spatial evolution of volcanic arcs. Second, it was used as base for studying geochemical evolution of arc magmas by assigning geologic epochs for all compiled petrochemical data. Third, it was used for studying relationships between volcanic centers and metallic mineralization. For metallic mineral deposits, as many deposits still lack of quantitative analytical data, for standardization we classified metallic mineral deposits using the classification by Corbett and Leach (1998) that allows field-based observations as a primary base for classification. Mineral deposits are classified as follows. First is a porphyry-related system hosted within or subjacent to intrusions at depths of typically greater than 1 km from surface. This class includes the porphyry Cu-Au, skarn Fe, and skarn Zn-Cu-Pb deposits. Second is the high sulfidation Au-Cu that forms when magmatic volatiles and brines are discharged rapidly upward with minimal rock reaction or mixing with circulating meteoric fluids. Third is the low sulfidation system that forms when magmatic fluids are reduced by rock reaction and dilution by circulating meteoric waters. This system is divided into a continuum to progressively shallow crustal levels and away from the intrusion source as follows: quartz-sulfide Au-Cu (polymetallic vein), carbonate-base metal Au, and epithermal Au-Ag (or adularia-sericite epithermal Au-Ag).

4. Datasets

Among various and large amounts of geoscientific datasets involved in this study, following are some of the more important ones. A mineral deposits database was compiled from both secondary and primary data. Primary data came from central to eastern Java, where we conducted field visits and direct observations. Geochronology data were compiled from many published papers and unpublished agency reports, such as JICA-JOGMEC (2004), Soeria-Atmadja et al. (1994), Marcoux and Milesi (1994), Saefudin (1994), Sunardi and Kimura (1998), Lemigas (2001), Harijoko et al. (2004), and McInnes et al. (2004). The majority of geochronology techniques used the whole-rock K-Ar dating method. Few primary K-Ar

Table 1 Representative petrochemical data of Cenozoic volcanic centers in Java island.

Volcanic center	Ceremai	Galunggung	Bayah (east)	Bayah (north)	Cineam	Bayah (South)	Bayah (South)	Tasikmalaya
Location	West Java	West Java	West Java	West Java	West Java	West Java	West Java	West Java
Epoch	Holocene	Holocene	Pliocene	Upper Miocene	Upper Miocene	Lower Miocene	Oligocene	Oligocene
Sample Name	041218-09C	13346	L600HR07A	G.Limbung1	041217-08	JM-49	JM-34B	041217-01B
SiO_2 (%)	54.43	49.01	55.93	63.63	58.06	60.35	53.00	47.94
TiO_2	1.01	0.70	0.79	0.54	0.68	0.50	0.62	1.00
Al_2O_3	17.68	15.09	15.57	16.64	17.99	16.40	16.85	19.78
Fe_2O_3*	7.72	9.53	7.94	5.19	6.58	5.95	8.30	9.03
MnO	0.16	0.16	0.15	0.32	0.16	0.12	0.18	0.23
MgO	4.57	12.52	4.98	1.94	2.96	2.85	5.42	4.72
CaO	8.93	11.59	6.76	4.29	7.96	5.80	9.65	11.13
Na_2O	3.35	1.94	2.31	3.39	3.28	3.15	2.71	2.95
K_2O	1.35	0.29	3.30	3.74	1.32	1.67	0.41	0.16
P_2O_5	0.22	0.07	0.19	0.18	0.12	0.11	0.16	0.13
LOI	0.44	-0.77	1.93	0.00	0.74	2.37	2.33	2.81
Total	99.86	100.13	99.85	99.86	99.85	99.27	99.63	99.88
Cr (ppm)	31	711	16		7	23	164	31
Ni	13	193	7	23	3	7	72	3
Zr	107	39	216		83	62	80	53
Rb	42	6	129		49	36	12	2
Y	20	14	33	20	17	18	23	20
Sr	350	197	309	402	257	311	240	385
Ba	256	40	238	525	231	400	102	52
Sr/Y	17.50	14.10	9.40	20.10	15.10	17.30	10.40	19.30
K_2O+Na_2O (%)	4.70	2.23	5.61	7.13	4.60	4.82	3.12	3.11
K_2O/Na_2O	0.40	0.15	1.43	1.10	0.40	0.53	0.15	0.05
Data source	This study	Bronto, 1990	Syafrizal, pers comm.	Alderton et al., 1994	This study	Soeria-Atmadja et al., 1994	Soeria-Atmadja et al., 1994	This study

* toatal Fe reported as Fe_2O_3.

Volcanic center	Merapi	Ungaran	Muria	Petungkriyono	Borobudur	Kulon Progo	Kulon Progo	Iyang-Argopuro
Location	Central Java	Central Java	Central Java	Central Java	Central Java	Central Java	Central Java	East Java
Epoch	Holocene	Pleistocene	Pleistocene	Pliocene	Upper Miocene	Lower Miocene	Oligocene	Holocene
Sample Name	Mp050830-08	UGR04-06	72-940	041221-02	040822-04B	041215-01	WP-51	040815-11
SiO_2 (%)	56.59	59.59	54.50	57.91	60.78	58.96	61.70	50.58
TiO_2	0.94	0.62	0.29	0.78	0.44	0.72	0.42	0.67
Al_2O_3	17.77	16.70	22.80	16.25	15.88	17.20	16.19	13.01
Fe_2O_3*	8.00	6.60	3.76	7.30	5.17	6.70	4.56	12.36
MnO	0.18	0.16	0.12	0.14	0.14	0.18	0.11	0.23
MgO	2.74	2.42	0.79	2.22	3.07	2.64	2.65	8.54
CaO	8.42	6.11	4.60	6.64	7.10	7.15	6.02	12.39
Na_2O	3.65	3.59	5.48	3.09	3.53	3.52	3.49	1.95
K_2O	1.82	2.90	8.00	2.18	1.52	1.65	1.23	0.85
P_2O_5	0.24	0.26	0.12	0.15	0.12	0.23	0.10	0.11
LOI	0.26	0.87	2.44	1.08	2.13	0.88	2.45	0.37
Total	99.81	99.82	100.46	97.01	99.89	99.83	99.72	99.82
Cr (ppm)	1	15	3	2	23	10	45	201
Ni	3	5	6.30	2	7	2	14	53
Zr	113	150	367	143	91	147		41
Rb	41	99	215	65	34	46	35	16
Y	22	23	34	27	16	26		43
Sr	546	464	1690	301	500	327		374
Ba	480	513	920	431	302	233	633	343
Sr/Y	24.80	20.20	49.70	11.10	31.30	12.60		8.70
K_2O+Na_2O (%)	5.47	6.49	13.48	5.27	5.05	5.17	4.72	2.80
K_2O/Na_2O	0.50	0.81	1.46	0.71	0.43	0.47	0.35	0.44
Data source	Kohno et al., 2005	Kohno et al., 2005	Nicholls and Whitford, 1983	This study	This study	This study	Soeria-Atmadja et al., 1994	This study

Table 1 (continued)

Volcanic center	Lawu	Wilis (Ngebel)	Ringgit	Merubetiri	Selogiri	Merubetiri	Bayat	Bawean
Location	East Java	East Java	East Java	East Java	Eastt Java	East Java	East Java	Java Sea
Epoch	Holocene	Holocene	Pleistocene	Upper Miocene	Upper Miocene	Lower Miocene	Oligocene	Pleistocene
Sample Name	040828-07	040829-10A	040815-06	040812-01	040821-07	040814-02A	BYT-09	BW-45
SiO_2 (%)	62.43	65.57	50.13	72.70	64.22	55.95	48.54	48.45
TiO_2	0.54	0.36	0.93	0.17	0.47	0.46	2.04	0.92
Al_2O_3	15.68	15.25	18.64	13.64	14.61	17.27	15.10	16.24
Fe_2O_3*	5.65	4.24	9.70	1.62	5.03	6.32	13.29	7.24
MnO	0.14	0.12	0.17	0.04	0.09	0.07	0.17	0.17
MgO	1.97	1.69	2.92	1.07	2.31	3.75	6.36	5.23
CaO	6.21	5.58	9.15	1.53	6.68	6.76	8.19	9.39
Na_2O	3.63	3.33	3.34	2.89	3.43	4.25	3.96	3.98
K_2O	2.32	1.47	2.40	4.01	1.43	0.52	0.28	4.50
P_2O_5	0.14	0.12	0.39	0.04	0.15	0.12	0.18	0.45
LOI	1.08	2.07	1.98	2.14	1.40	4.08	1.73	1.82
Total	99.89	99.80	99.76	99.86	99.83	99.89	99.84	99.22
Cr (ppm)	9	10	33	3	19	17	75	158
Ni	3	3	11	4	6	5	22	39
Zr	143	91	109	88	87	64	133	
Rb	61	33	58	103	29	7	4	280
Y	22	13	25	15	13	12	40	
Sr	448	516	627	171	525	480	155	866
Ba	623	617	822	772	731	62	60	1086
Sr/Y	20.40	39.70	25.10	11.40	40.40	40.00	3.90	
K_2O+Na_2O (%)	5.95	4.80	5.74	6.90	4.86	4.77	4.24	8.48
K_2O/Na_2O	0.64	0.44	0.72	1.39	0.42	0.12	0.07	1.13
Data source	This study	This study	This study	This study	This study	This study	This study	Bellon et al., 1989

data on mineral separates were collected in this study, and were reported in Setijadji et al. (2005) and Kohno et al. (2005). A total of 309 radiometric data was used, and after data quality consideration, we used 286 data.

Petrochemical data were collected from various publications and primary data. Secondary petrochemical data from Quaternary volcanoes were compiled from Whitford (1975), Nicholls et al. (1980), Nicholls and Whitford (1983), Wheller et al. (1987), Soeria-Atmadja et al. (1985, 1991), Bellon et al. (1989), Bronto (1990), Leterrier et al. (1990), Sitorus (1990), Vukadinovic and Sutawidjaja (1995), Bogie and MacKenzie (1998), Sunardi and Kimura (1998), Camus et al. (2000), Carn and Pyle (2001), and Gertisser and Keller (2003). Petrochemical data from Tertiary volcanoes were collected from, among others, Alderton et al. (1994), Soeria-Atmadja et al. (1991, 1994), Sukarna (1998), Sunardi and Kimura (1998), Alves et al. (1999), and JICA-JOGMEC (2004). Primary petrochemical data were mainly collected from central and eastern Java, and only few come from the Pongkor and Cibaliung mineral districts in western Java on donated rock samples. Primary data consist of 241 rock analysis on major and trace elements using X-ray fluorescence spectrometer (XRF), while in total we have 705 petrochemical records. After data selection based on quality criteria (known locations, geologic ages, and LOI <5 %), only 668 samples were used for analysis. Representative data from selected volcanic centers are shown in Table 1.

5. Reconstruction of Cenozoic Volcanic Centers

5.1. Quaternary volcanoes

Our database on the Quaternary arc contains of fifty (50) Quaternary Java volcanoes that occupy the median line of Java island (Fig. 3). Different types of volcanoes are currently present, from single volcanic chain, double volcanic chain (containing volcanic front, trench-side, and backarc-side volcanoes), and backarc magmatism. At westernmost Java, a single volcanic arc chain develops in the submarine Krakatau volcano in Sunda Strait, the Danau Complex, and the Salak volcanic groups. The eastern part of west Java contains a double volcanic chain arc with a high clustering of volcanoes at the trench-side, such as the Papandayan, Galunggung, and Malabar. Associated backarc-side volcanoes are Tangkuban Prahu and Ceremai. Going eastwards, the isolated Slamet volcano is located in the western central Java, and is distinctively different from highly populated double volcanic chain in eastern central Java that consists of the Merapi and Sumbing as volcanic fronts, and Dieng and Ungaran volcanoes as backarc-side ones. A backarc volcanic center is present at Muria (1.1-0.4 Ma; Bellon et al., 1989). In east Java, the short single volcanic chain of Lawu is followed by a continuous double volcanic chain to further east. Volcanic front and trench-side volcanoes consist of,

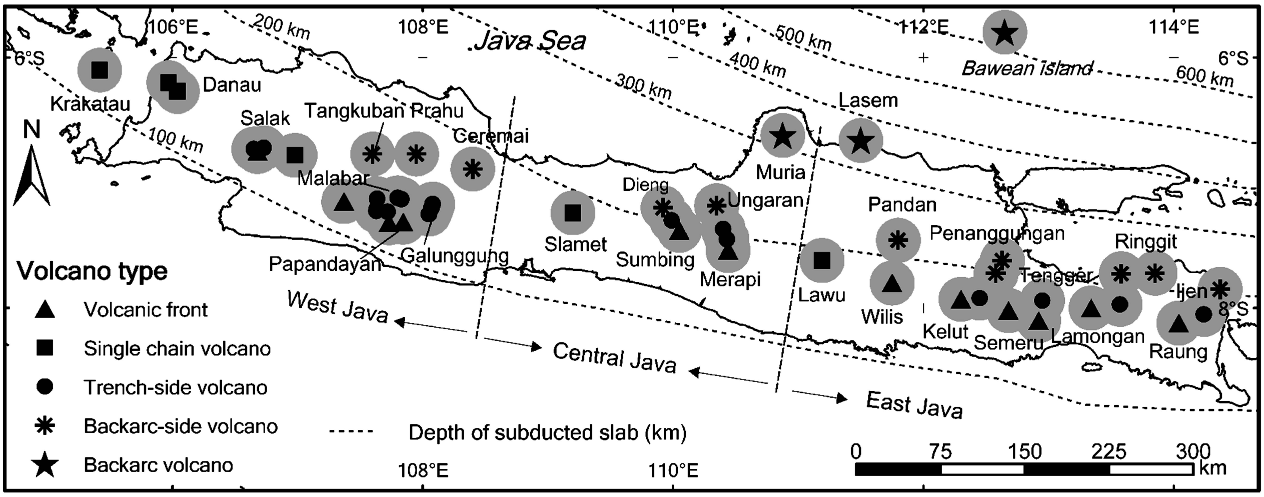


Fig. 3 Distribution of Quaternary volcanoes in Java, consisting of fifty volcanoes distributed either as single, double-chain volcanoes, or backarc volcanoes (onland and offshore). Volcano classification follows Tatsumi and Eggins (1995). Geographic division of west, central, and east Java is shown for location reference during the discussion.

among others, the Wilis, Kelut, Semeru, Tengger, Lamongan, Raung, and Ijen volcanoes. Backarc-side volcanoes are Pandan, Penanggungan, and Ringgit. The Lasem volcano (1.6-1.1 Ma) and the basalt field of Bawean island (0.8-0.3 Ma) represent the backarc volcanoes in eastern Java (Bellon et al., 1989).

5.2. Tertiary volcanic centers

While Quaternary volcanoes are clearly observable, Tertiary volcanic centers have to be reconstructed using criteria described earlier. Earliest Tertiary (Paleocene-Eocene) igneous rocks very few of which are recognized in Java. They are most likely present at Bayah dome (Cikotok Formation) and Jatibarang Volcanic Formation (JVF) in west Java (Fig. 4). The JVF has been dated as Late Eocene to Early Oligocene (e.g., Hutchison, 1982), although its reliability is questionable. The JVF is only encountered at the subsurface and it becomes a host rock of hydrocarbon reservoir at northwest Java island. The submarine volcanic breccia of Cikotok Formation was reported to be Late Eocene-Late Oligocene in age (Sujatmiko and Santoso, 1992). Other locations are scattered and less convincing, but some radiometric data suggest this age; these include the volcaniclastic tuff and gabbro in Ciletuh, west Java (50.1-50.9 Ma; Pertamina-ITB, 2002), dioritic dike in Karangsambung, central Java (37.6 Ma; Soeria-Atmadja et al., 1994), and basaltic pillow lava (42.7 Ma; Soeria-Atmadja et al., 1994) and andesite intrusion (38.7 Ma; JICA-JOGMEC, 2004) in the Pacitan area (east Java).

While the Paleocene-Eocene volcanic centers are ambiguous, the Oligocene ones are more certain and represent the earliest recognizable Cenozoic volcanic belt in Java. In west Java, Oligocene volcanics are represented by the Cikotok and Jampang Formations, and the Cihara granodiorite. Radiometric data include a tuff sample (33.9±2.0 Ma or Lower Oligocene; Pertamina-ITB, 2002), a dacite intrusion (32.3±0.3 Ma; Pertamina, 1989), a basalt dike (28.1±6.2 Ma; Soeria-Atmadja et al., 1994) and a volcanic breccia (33.6±3.8 Ma; Lemigas, 2001). In central Java, Oligocene volcanics are mapped as the Totogan Formation, from which a dioritic dike was dated 26.5±1.9 Ma (Soeria-Atmadja et al., 1994). Surrounding the Yogyakarta region, central Java, volcanic rocks are mapped as the Kebo-Butak Formation, and radiometric dating at the Kulon Progo dome complex gives consistent ages of Upper Oligocene (25.4-29.6 Ma; Soeria-Atmadja et al., 1994). At Bayat region a diorite was dated 33.2±1.0 Ma (Lower Oligocene), while a basalt sill 24.3±0.6 Ma or Upper Oligocene (Soeria-Atmadja et al., 1994). At Parangtritis beach, an andesite intrusive was dated 26.4 and 26.55 Ma or Upper Oligocene (Soeria-Atmadja et al., 1994). In eastern Java, the Oligocene volcanic units are mapped as the Arjosari, Mandalika, Panggang, and Watupatok Formations. At Pacitan, pillow lavas of Mandalika Formation (33.6 Ma, Lower Oligocene) are intruded by a 28±1.5 Ma (Upper Oligocene) basaltic dike (Soeria-Atmadja et al., 1994). A hornblende dacite intrusion was also dated as 30.8±2.9 Ma (Saefudin, 1994). At Trenggalek, an andesite lava has been dated 29.4±4.5 Ma and at Lumajang an andesite intrusive has been dated 23.7±3.5 Ma (JICA-JOGMEC, 2004). At easternmost Java, the Merubetiri Formation (Sapei et al., 1992) represents the whole Oligocene-Middle Miocene volcanic breccia within the Merubetiri plutonic-volcanic complex. No radiometric data is available from this area. In overall, we divided the known Oligocene volcanic units of Java into following volcanic centers (from west to east): the Bayah (south), Ciletuh-Ciemas, Jampang, Pangandaran, Tasikmalaya, Karangsambung, Kulon Progo, Parangtritis,

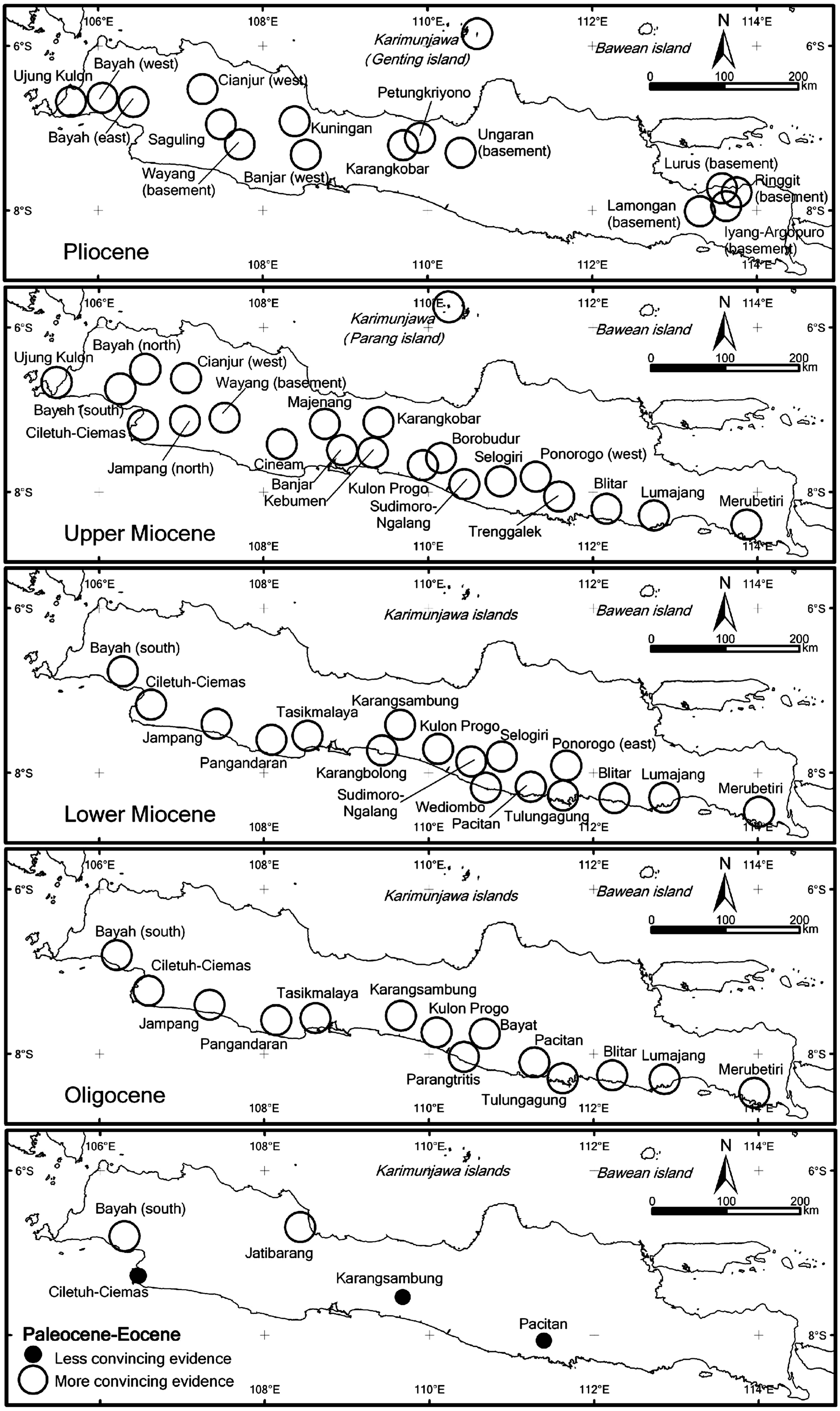


Fig. 4 Reconstructed Tertiary volcanic centers.

Bayat, Pacitan, Tulungagung, Blitar, Lumajang, and Merubetiri (Fig. 4). Most volcanic centers formed within a single-chain volcanic arc, and only the Parangtritis and Bayat volcanoes in central Java show a double volcanic chain phenomenon.

Volcanic rocks of Lower Miocene are scattered nearby the Oligocene units and are mainly products of subaerial volcanism. In west Java, volcanic units are represented by the Cimapag and Citarete Formations, and the Cihara granodiorite (22.4±0.4 Ma; Wikarno et al., 1993). Andesitic lavas at Cirotan are dated at 15.3±0.7 Ma (Marcoux and Milesi, 1994). To the east the breccia of the Jampang Formation are exposed at Ciletuh-Ciemas and Pangandaran area, from where a quartz andesite was dated 22.4±1.5 Ma (Pertamina-ITB, 2002). In addition a quartz diorite porphyry has an age of 17.8 and 16.8 Ma (McInnes et al., 2004), with lava flows at 17.6±0.6 and 17.9±0.9 Ma (Soeria-Atmadja et al., 1994). In central Java, volcanic units are named as the Waturanda and the Gabon Formations. Members of Gabon Formation were dated as 19.1 ±1.1 Ma on a breccia and 17.2±1 Ma based on an andesite intrusion (Lemigas, 2001). In the Yogyakarta region (e.g., Kulon Progo, Selogiri, and Wonosari) the Lower Miocene volcanic rocks consist of the upper part of Kebo-Butak and the Semilir Formations which are dominated by submarine lapilli tuff (Rahardjo et al., 1995). At Kulon Progo dome area, systematic dating on different tuff layers gave results of 17.0±2.0 to 16.0±2.2 Ma (Wikarno et al., 1993). Meanwhile, at Selogiri a microdiorite intrusion within an extinct caldera was dated 21.7±1.9 Ma (JICA-JOGMEC, 2004). A small andesite intrusion at Wonosari, also near Selogiri, was dated 19.7±0.9 Ma (JICA-JOGMEC, 2004). In east Java, volcanic rocks consist of members of Besole Formation that spread out from Pacitan to Tempursari (Lumajang) area. At Pacitan, many andesitic to basaltic intrusions are part of a cluster of exposed volcanic necks with ages of 17.3±2.0 and 19.5±1.8 Ma (Saefudin, 1994), 18.2±1.7, 20.9±0.7, and 17.3±1.5 Ma (JICA-JOGMEC, 2004). East of Pacitan at Trenggalek and Ponorogo regions, two radiometric data from an intrusion-volcanic complex gave results of 17.1±0.8 and 21.0±2.6 Ma (JICA-JOGMEC, 2004). The volcanic unit continues further east, and three radiometric dates from an intrusion-volcanic complex west of Lumajang give ages of 19.6±1.3, 17.8±2.5, and 18.2±1.5 Ma (JICA-JOGMEC, 2004). At the easternmost part of Java, the Merubetiri subvolcanic complex may also contain volcanic units of Lower Miocene age, although there is no radiometric data available to confirm this. The reconstructed volcanic centers in western Java are very similar in location when compared to the Oligocene ones. In central Java, a double chain volcanic arc formed at Karangbolong (trench-side) and Karangsambung (backarc-side) volcanoes. At east Java volcanism was very active during the Early Miocene time, and double chain volcanoes are recognized at Wediombo-Ngalang-Selogiri and Tulungagung-Ponorogo. The volcanic center locations at easternmost Java are virtually the same as the Oligocene ones. In Merubetiri district, there are scattered stocks and sub batholithic bodies with granodioritic compositions considered to be middle Miocene in age (Sapei et al., 1992). These represent the largest exposures of granitoid intrusions in Java and were referred as the Ngrawan Granite by Van Bemellen (1949).

Upper Miocene volcanic rocks are abundant throughout the island. In westernmost Java the Honje Formation was dated 11.4±0.8 Ma (Harijoko et al., 2004). In the Bayah dome area, Marcoux and Milesi (1994) reported several radiometric dates of Upper Miocene from Ciawitali (andesitic pyroclastics, 5.7±0.4 Ma) and Cirotan (rhyolite ignimbrite, 9.6±0.3 Ma). Soeria-Atmadja et al. (1994) reported an age of 13.7±1.8 Ma for basaltic lava south of Bayah dome near the beach. At Ciletuh-Ciemas, McInnes et al. (2004) reported an age of 7.2 Ma for a quartz diorite intrusion. At Cianjur there are many exposures of andesitic intrusions, some of which have an Upper Miocene age (e.g., 6.0±0.7 Ma; Lemigas, 2001). Soeria-Atmadja et al. (1991) reported 12.1 Ma for andesite lava from the base of Wayang volcano. At Cineam in west Java, Widi and Matsueda (1998) reported ages from 13.5 to 8 Ma for hydrothermal activities related with volcanism and epithermal mineralization in this area. In central Java, stocks at Karangkobar district were dated 7.9±1.0 and 8.9±0.8 Ma (Soeria-Atmadja et al., 1994). Consistent ages were reported from Kulon Progo to Borobudur region, such as the age of an andesite intrusion (13.0±1.0 Ma; Lemigas, 2001), tuff (12±1.1 Ma; Wikarno et al., 1993), and a hornblende dacite intrusion (12.4±0.7 Ma; Setijadji et al., 2005). This study also reveals the continuity of Upper Miocene volcanic centers towards the east by reporting the ages of 12.5±0.9 Ma for an andesite intrusion at Wonosari area, 11.9±0.7 Ma for a hornblende tuff at Selogiri area, and 9.6±0.3 Ma for a hornblende dacite intrusion complex at Ponorogo area. In east Java the Upper Miocene volcanic units are represented by Wuni Formation which is widespread at Blitar and Lumajang areas. There is only one radiometric date for the Wuni Formation, i.e. 10.1±0.5 Ma for a dacite intrusion (JICA-JOGMEC, 2004). At easternmost Java, the Mandiku Formation and parts of the Ngrawan Granite intrusive complex at Merubetiri area are also considered Upper Miocene in age (Sapei et al., 1992). A new phenomenon in Upper Miocene that is not observed in earlier ages is the presence of volcanic rocks (lavas) in the backarc basin (Java Sea), i.e., at Karimunjawa islands (Parang island) which are reported to be 5.6±0.3 and 6.5±0.3 Ma (Soeria-Atmadja et al., 1985). Our reconstruction suggests that during Upper Miocene, volcanism was also very active especially in western and central Java, and many new volcanic centers existed such as the Ujung Kulon and Cianjur in west Java, and Majenang, Karangkobar, and Borobudur in central Java. Several older volcanic centers such as the Bayah, Ciletuh-Ciemas, and Jampang still existed but the new volcanic centers had moved northward from the older ones. Double volcanic chains developed at Bayah, Ciemas-Cianjur (western Java), and Kebumen-Majenang-Karangkobar (central Java). In eastern Java the volcanic arc developed as a single volcanic chain and occupied the site of backarc-side volcanic chain of Oligocene time (i.e., Selogiri and Ponorogo). The Upper Miocene volcanic centers in eastern Java did not seem to shift far from their Oligocene sites. Backarc magmatism started to develop in the Java Sea, especially at Parang island of Karimunjawa.

Exposures of Pliocene volcanic rocks are very limited, and western Java contains more significant exposures of Pliocene volcanics than the rest of island. Perhaps the most important Pliocene units are those that are located in the Bayah dome region. These host the majority of gold mineralization (Marcoux and Milesi, 1994). Other Pliocene volcanics in west Java are concentrated around the Bandung Basin. A lava dome in the Cianjur area was dated at 2 Ma (Soeria-Atmadja et al., 1994). Near the Saguling dam and Kromong mountain, several dacitic intrusions and andesitic lava were dated at 3.07 to 4.08 Ma (Sunardi and Kimura, 1998). To the southeast of Bandung Basin, Pliocene volcanic rocks are concealed beneath the Quaternary volcanic units of Malabar-Papandayan group of volcanoes. These were intercepted during drilling of geothermal project. Soeria-Atmadja et al. (1991) reported K-Ar ages of 3.9 to 2.7 Ma for andesite lava within Papandayan-Galunggung volcanic complex. We also suggest that Pliocene volcanism may also occur at Kuningan area, where remnants of crater are observed just south of the Quaternary Ceremai volcano. In central Java, dated Pliocene volcanics are found at Banjar (5.1±0.4 Ma) and Karangkobar (3.0±0.3 and 3.0±0.2 Ma). These are related to andesitic intrusions (Soeria-Atmadja et al., 1994). Andesite lava flows as the substratum of Dieng geothermal field are also reported to be Pliocene (3.6, 2.6, and 1.8 Ma; Soeria-Atmadja et al., 1991), and are considered to be part of the Petungkriyono volcanic center. At the basement of the Quaternary Ungaran volcano, there is an intrusive complex thought to be Mio-Pliocene (Thanden et al., 1996). In east Java, the only data concerning Pliocene volcanism is the reported radiometric ages of the basement of the Lamongan, Iyang Argopuro, Ringgit, and Beser volcanoes (1.8-2.1 Ma; Soeria-Atmadja et al., 1991). In general, the Pliocene volcanic centers show significant northward shift from those of Upper Miocene. Double volcanic chains occurred at Papandayan-Malabar-Cianjur, Banjar-Kuningan, and perhaps the Lumajang-Ringgit-Beser. In the backarc basin of Java, backarc magmatism took place at Genting island of Karimunjawa islands, where basalt is dated 2.5±0.1 to 1.8±0.3 Ma (Soeria-Atmadja et al., 1985).

5.3. *Spatial evolution of volcanic centers during Cenozoic*

While we still do not fully understand the first volcanic arc formed during the initiation of Java trench in Paleocene-Eocene, the spatial evolution of volcanic arcs since Oligocene can be reconstructed. During the Tertiary (Oligocene to Pliocene), the volcanic centers have dominantly shifted northward (towards the backarc-side). The shifting distances increase relatively eastwards, and such spatial movement may be better defined as a counter-clockwise rotation of volcanic arcs, with westernmost Java (around Bayah dome) as the rotational pole. The Lower Tertiary volcanic arcs occupied the southern coast of the island, and perhaps also southern offshore as indicated by high gravity anomaly (Fig. 2). In Upper Miocene significant northward migration of volcanic centers was noteworthy in eastern part of west Java and central Java, but not in east Java. Again during the Pliocene, volcanic centers shifted northward. The backarc-ward volcanic shift ended after Pliocene, and the trench-ward volcanic shift started in Quaternary. The trench-ward shift is demonstrated by the ‘invasion’ of Upper Tertiary volcanic centers by Quaternary volcanoes in west and central Java, and the ‘missing’ Pliocene volcanoes in most of east Java. This may be due to a complete coverage by Quaternary volcanoes. Radiometric data from the Quaternary across-arc volcanic chain of Merapi-Merbabu-Telomoyo-Ungaran also suggest that the Quaternary volcanism gradually moved trench-ward (Kohno et al., 2005). An exception occurs at the westernmost Java, where Quaternary volcanism (Krakatau and Danau) migrated backarc-ward due to the Sunda Strait opening (Nishimura et al., 1986).

Backarc magmatism only took place since the uppermost Miocene to Quaternary. With recent physiography as reference, there are two main locations of backarc magmatism, i.e., onland Java where the current depth of subducted slab is around 320-350 km (Quaternary Muria and Lasem volcanoes) and offshore Java where the current depth of subducted slab is around 600 km (Quaternary Bawean island). Analogous to volcanic arc trench-ward shift after Pliocene, the locations of backarc magmatism seem also to shift trench-ward from the Karimunjawa islands to the Muria-Lasem volcanoes.

6. Magnetic Susceptibility

Magnetic susceptibility measurements were done on fifty (50) igneous rock samples collected in different areas and from different ages. The result demonstrates that most igneous rocks have magnetic susceptibility values much exceeding 10^{-4} emu/g, a threshold value for separating

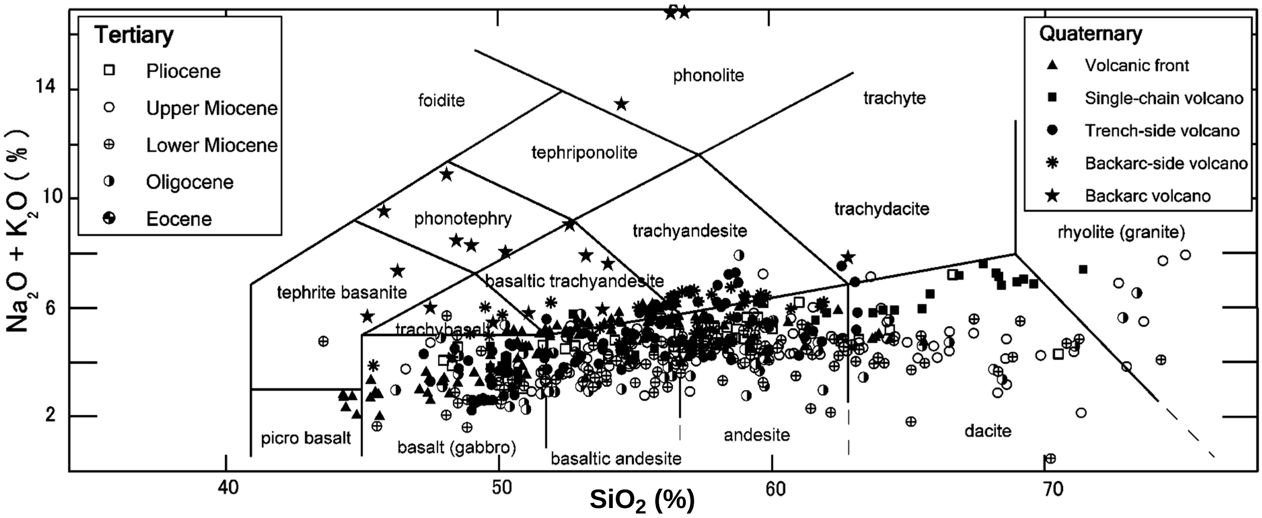


Fig. 5 Variation diagram of SiO_2 versus total alkali (TAS) for all Cenozoic igneous rocks in Java (LeBas et al., 1986).

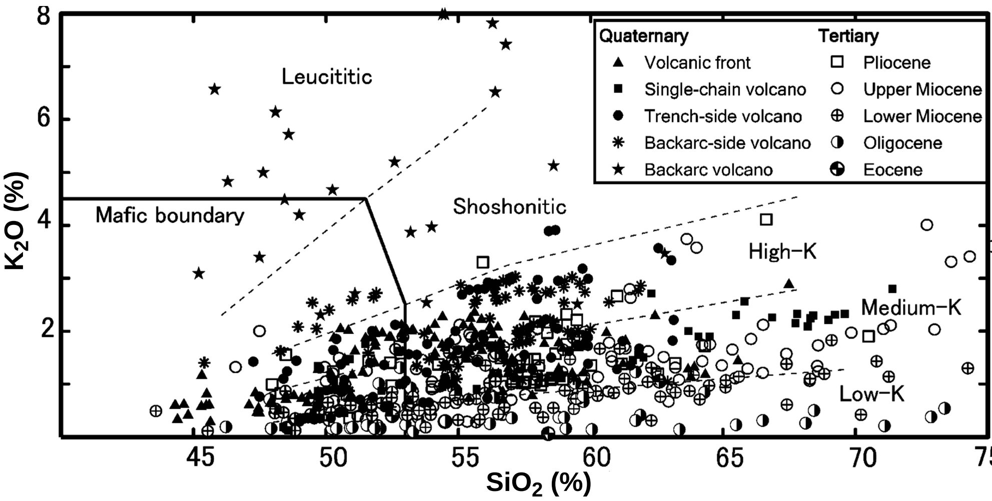


Fig. 6 Variation diagram of SiO_2 versus K_2O for all Cenozoic igneous rocks in Java. There is a strong trend of increasing K_2O contents at the same SiO_2 levels towards younger ages. The classification is from Peccerillo and Taylor (1976), while boundaries of mafic volcanics and shoshonitic-leucititic are from Wheller et al. (1987).

magnetite vs. ilmenite granitoid series (Ishihara, 1981). It means that the majority of Cenozoic igneous rocks in Java are members of magnetite-series. In our data, there are only two records with values below 10^{-4} emu/g. First is an Oligocene (?) dacite from Karangsambung district in central Java (0.0092×10^{-4} emu/g) and second is a Miocene granitic rock from Merubetiri district, eastern Java (0.94×10^{-4} emu/g). The first case is very much lower than the threshold value so that it is definitely a member of the ilmenite-series. However, this unit is not significant in spatial distribution and may represent a small amount of felsic melting products of an ophiolite complex which becomes a basement in this region (Miyazaki et al., 1998). The second case is also not convincing as its value is relatively close to the threshold 10^{-4} emu/g and there is only one measurement data on this unit. However, as this value comes from the only exposed granitic intrusions in Java (the Ngrawan Granite of Van Bemellen, 1949) it is interesting to follow up this result in the future to find out whether an ilmenite-series granitoid is really present or not in Java. At this time, we simplify the matter by concluding that virtually all Cenozoic magmatism events in Java are magnetite-series.

7. Petrochemistry

7.1. Major elements

Java rocks are characterized by widespread silica contents, typical of island arc settings (Gill, 1981). The classification of Java igneous rocks based on total alkali versus silica contents (TAS) classification (LeBas et al., 1986) demonstrates that almost all Tertiary rocks fall in the fields of basalt-andesite-dacite (Fig. 5). Quaternary rocks in general have higher total alkali contents than Tertiary rocks and, although they are still dominated by basalt-andesite-dacite series, there are many rocks come which plot within the trachybasalt-trachyandesite fields, and even into the alkaline series such as phonothepry and phonolite. Quaternary rocks tend to have lesser silica contents than Tertiary ones. A few Quaternary rocks have dacitic composition and only one has rhyolitic composition (i.e., from the Krakatau caldera). On con-

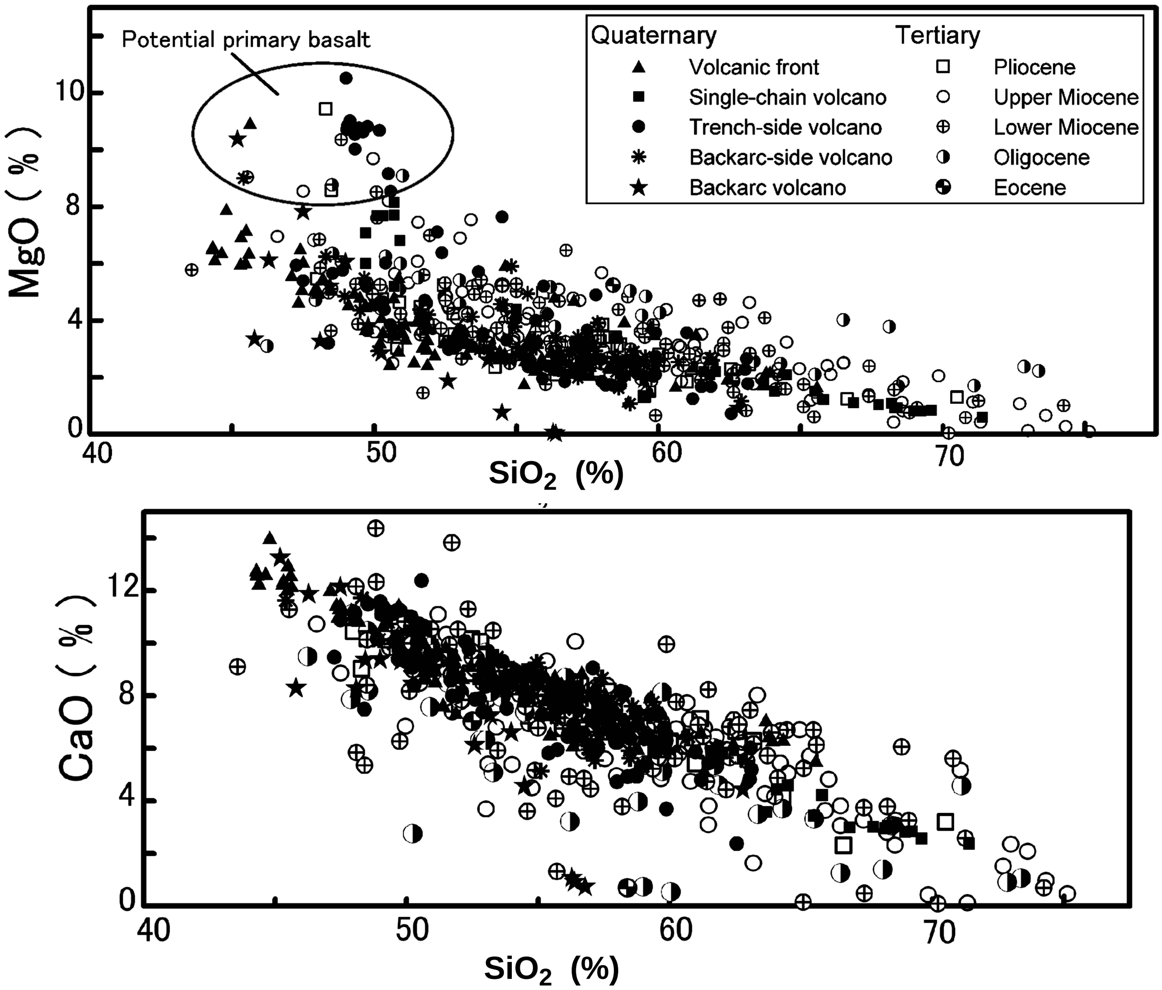


Fig. 7 Variation diagrams of silica contents versus major elements as oxides of MgO and CaO. Only few rocks still have primary basalts composition (indicated by circle) and most rocks experience fractional crystallization before reaching earth surface.

trary, dacite and rhyolite (granite) are more common in Tertiary rocks. Most rhyolites are volcanic rocks (tuff) or shallow intrusions (dikes) with porphyritic texture, but there are also hypabyssal batholitic granitic intrusions in easternmost Java.

A more regular and consistent trend for evaluating arc magmas in Java is better demonstrated by the variation of SiO_2 and K_2O contents (Fig. 6). Using the rock affinity classifications by Peccerillo and Taylor (1976) which is modified by Wheller et al. (1987), the igneous rocks from Java fall into very wide distributions, i.e., low-K, medium-K, high-K, shoshonitic, and leucitic. During discussion, informal terminology of tholeiitic (low-K) and calc-alkaline (medium- and high-K) will also be used. There is a general trend of increasing K_2O contents towards younger rocks. Lower Tertiary rocks have a dominant low-K tholeiitic affinity and only few data show medium-K calc-alkaline. After Upper Miocene, the igneous rocks were distributed from low-K to high-K, with a dominance of medium-K calc-alkaline. Finally during the Pliocene and Quaternary rocks are dominated by calc-alkaline and high-K calc-alkaline. Quaternary rocks have the widest range of compositions compared to older rocks. With a detailed classification on the volcanic types, it is shown that K_2O contents of Quaternary volcanoes increase from the trench-side towards the backarc-side. Backarc volcanism generally shows lower silica but higher K_2O contents compared to volcanic front magmas.

As K_2O contents are inherited from primary magma composition rather than crystallization history, the SiO_2 versus K_2O classification therefore represents different types of magma compositions (Tatsumi and Eggins, 1995; Vukadinovic and Sutawidjaja, 1995). Volcanic arc volcanoes (i.e., volcanic front, trench-side and backarc-side) whose genetic relationship with subduction is robust show a range primary magma from low-K to shoshonitic series, and there seems a continuous or gradational spectrum between them. On the other hand, the backarc volcanoes, whose genetic relationship with subduction is debatable, show a spectrum from high-K to leucititic magma series, with a domination of shoshonitic primary magma.

Most other major elements (i.e., MgO, CaO, Fe_2O_3, Al_2O_3, and TiO_2) show a negative relationship with silica contents. Some features suggest that the most important primary magma source in Java is partial melting of mantle wedge that produce a basaltic magma. For example, the SiO_2 versus MgO distribution diagram (Fig. 7) shows that some basaltic rocks have high MgO contents (>5 %) that resemble potential primary basalt produced by partial melting of mantle peridotite (Tatsumi and Eggins, 1995). The most important petrogenetic aspect after the formation of primary basaltic magma is fractional crystallization, as seen from a negative correlation between MgO and CaO versus silica (Fig. 7) which indicates these elements behave compatibly throughout the entire series. The decreasing MgO and CaO contents are related to removal of olivine and clinopyroxene, respectively.

The alkali ratio is applicable for another differentiation purpose. Figure 8 demonstrates that backarc volcanoes are especially characterized by higher K_2O/Na_2O ratios compared to the volcanic arc magmas at the same SiO_2 level. The boundary between arc magmas versus backarc ones approximates the boundary between calc-alkaline and shoshonitic series. However, backarc volcanoes such as Karimunjawa (Mio-Pliocene), Bawean, and Lasem (Quaternary) show a transitional trend. However, some arc volcanics fall within shoshonitic series, and it is interesting to find that one sample from Pongkor gold mining district plots within this field. Also Lower Tertiary volcanics have lower K_2O/Na_2O ratios, and the field of high Sr/Y rocks (discussed later) is closely associated with the lowest K_2O/Na_2O ratios, i.e., about 0.5.

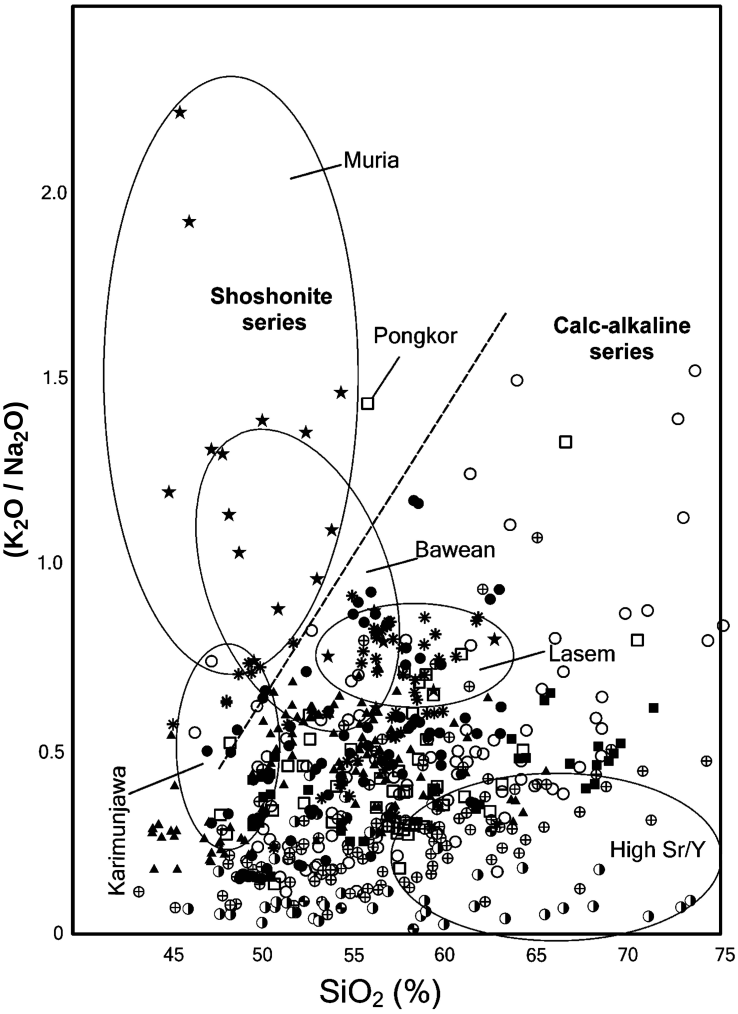


Fig. 8 Variations of silica contents versus alkali ratio of Cenozoic igneous rocks in Java. The backarc magmas fall mainly within the shoshonite series, but some volcanoes overlap on the calc-alkaline series (the domain of volcanic arc). Older magmas are dominated by lower K_2O/Na_2O ratio, and the high Sr/Y field is located at the lowest K_2O/Na_2O ratios (<0.45) at intermediate to high silica contents. Note that one sample from Pongkor gold mine is part of the shoshonite series. The boundary of calc-alkaline and shoshonite series is after Ishihara and Murakami (2004).

7.2. Trace elements

7.2.1. Ni and Cr: The abundance of Ni and Cr in volcanic rocks is important to interpret the sources of magma, as these elements are very compatible that their contents within the melt phase are depleted rapidly during the early stage of fractional crystallization. Volcanic rocks with a Ni content greater than 200 ppm and a Cr content greater than 400 ppm are candidates for primary magma produced by partial melting of mantle peridotite (Green, 1980; Nicholls et al., 1980; Tatsumi and Eggins, 1995). The contents of Ni and Cr in Java volcanics are relatively low. Most rocks have contents of Ni less than 40 ppm and Cr less than 100 ppm. This indicates that the original composition of primary magma has been largely modified into more evolved compositions before eruption. However, notably two Quaternary volcano complexes have a combination of high Ni and Cr contents, i.e., the Galunggung (Bronto, 1990) and Muria (Nicholls and Whitford, 1983; Letterrier et al., 1990).

7.2.2. Rb/K: As Rb and K are incompatible elements that have similar partition coefficients during melting of upper mantle peridotite, their element ratios are expected to change very little as a function of degree of partial melting. Such differences in Rb/K ratios reflect variation in their magma sources (Gill, 1981; Tatsumi and Eggins, 1995). In the case of Java rocks, there is no observable increase in Rb/K across the volcanic arc (from the trench-side to backarc-side volcanic chains). There is also no significant difference between Tertiary and Quaternary

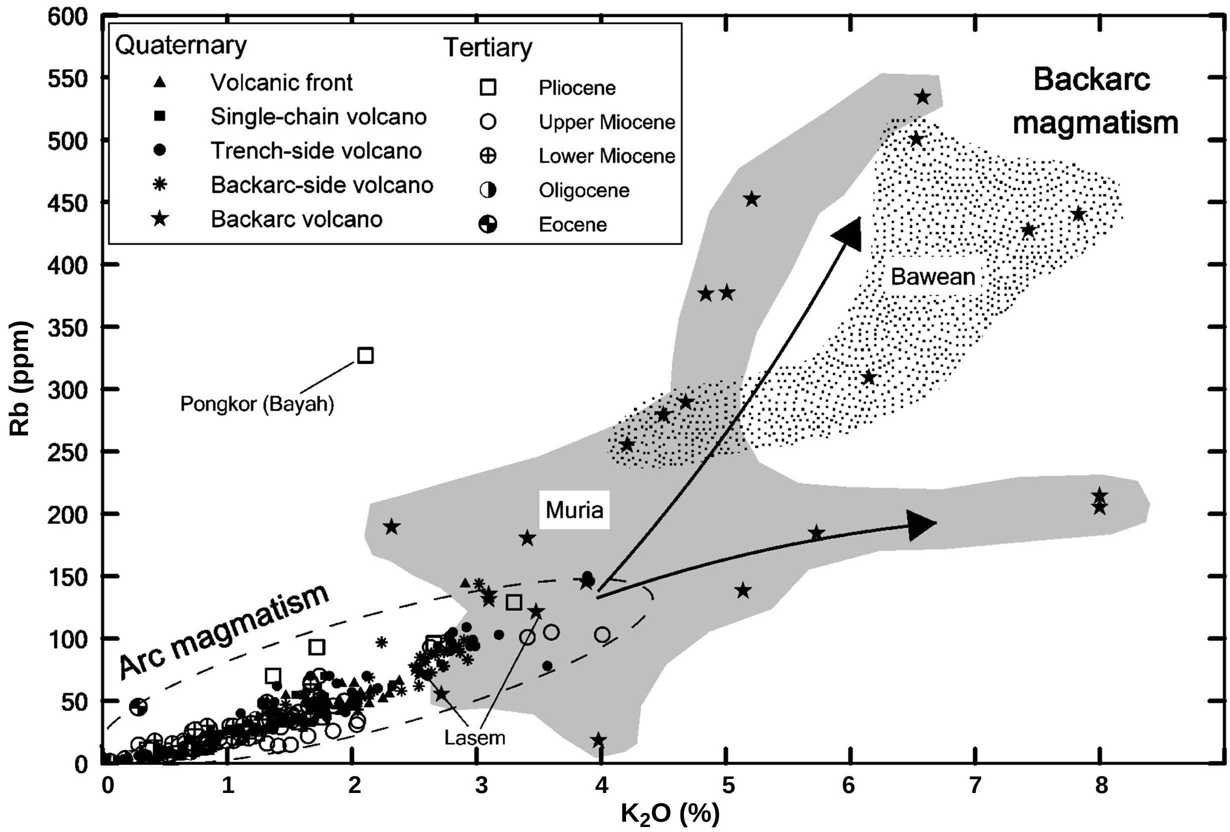


Fig. 9 Distribution of Rb/K ratios for Cenozoic volcanic rocks in Java. With an exception from Pongkor sample, all magmas associated with subduction-arc magmatism fall within a narrow Rb/K zone regardless the ages. On the other hand, backarc magmatism demonstrates a mixture trend between arc-related (Lasem and part of Muria volcanoes) and non-arc environment (Bawean and part of Muria volcano).

Rb/K ratios (Fig. 9). On the other hand, rocks from the backarc volcanoes (i.e., Muria, Lasem, and Bawean) behave at least in two different ways. First is the same (extended) trend as those of the volcanic arc and the second trend has higher Rb/K ratios than those of the volcanic arc magmas. The rocks from the Lasem volcano fall at the same trend as the arc magma. The Muria volcano, on the other hand, has been divided into two different trends. Rocks from Bawean island have exclusively Rb/K ratios higher than those of arc magmas. As a conclusion, backarc magmatism seems to be influenced by two different magma sources, i.e., subduction-related and magma which is not related with subduction.

Note that again one sample from the Pongkor gold district area (Bayah dome, west Java) shows anomalously a high Rb/K ratio that far exceeds the common field for arc magmatism volcanics.

7.2.3. Sr/Y: High Sr/Y magmas or adakites are considered as convincing geochemical evidence for the partial melting of subducted slab (e.g., Kay, 1978; Defant and Drummond, 1990; Peacock et al., 1994; Martin, 1999), although some adakites magmas may have formed by partial melting of other mafic source of underplated basalts (Peacock et al., 1994; Garrison and Davidson, 2003). Modern adakites are found in many parts along the circum-Pacific margins (Martin, 1999), as results of subduction of young, typically 50 Ma or younger, consequently warm, lithosphere (Scaillet and Prouteau, 2001; Garrison and Davidson, 2003). Systematically most adakites are intermediate to felsic volcanic rocks, despite plutonic and basaltic members are not excluded (Martin, 1999).

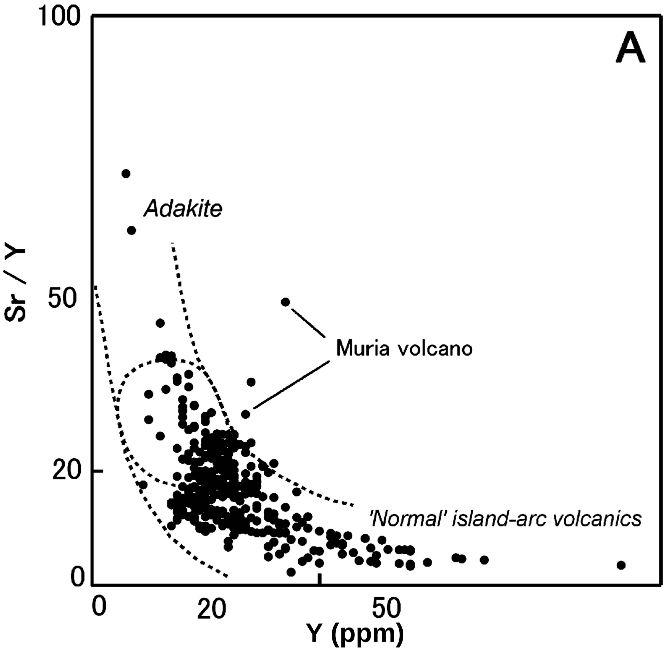
Several Java rocks fall into the adakite field as defined by Defant and Drummond (1990), although most rocks do show 'normal' island arc character (Fig. 10A). So far this is the first report of adakitic rocks in Java and the whole Sunda arc. All adakitic rocks come from volcanic arc region; other high Sr/Y rocks from the Muria backarc volcano deviate from neither the adakite nor 'normal' island arc magma (Fig. 10A). Spatial distribution of adakitic rocks in Java is shown on Figure 10B using following criteria: Sr/Y >20, Y <19 ppm, and Sr >400 ppm (Garrison and Davidson, 2003). Then another threshold of Sr/Y >40 (Defant and Drummond, 1990) is used as the ultimate definition of adakite, while rocks with values 20< Sr/Y <40 are considered as the high Sr/Y class (or probable adakites). Using these criteria, the adakitic rocks in Java are clearly concentrated only in the eastern half of the Java island (Fig. 10B). Adakitic rocks come from stock-like intrusions, lavas, and pyroclastic rocks ranging in age from Oligocene to Quaternary. The highest Sr/Y ratio recorded is 126.6 from a dacitic intrusion from the Karangsambung district, central Java. Other adakitic volcanic centers include the Upper Miocene Selogiri caldera (maximum Sr/Y = 40.4), Lower Miocene Wediombo volcanic center (Sr/Y = 46), Miocene Tulungagung volcanic center (Sr/Y = 40.3), and Quaternary Ngebel caldera lake of Wilis volcanic complex (Sr/Y = 39.7). The high Sr/Y values are supported by other characteristic petrochemical evidence, such as high Al_2O_3 and low K_2O/Na_2O values, and moderate Ni and Cr contents (Defant and Drummond, 1990; Tatsumi and Eggins, 1995; Martin, 1999; Scaillet and Prouteau, 2001).

8. Metallic Deposits

Mineral deposits in Java are dominated by the whole range of Cu-Au mineralization deposit type typical of the western Pacific (Corbett and Leach, 1998), and closely associated with magnetite-series granitoid (Ishihara, 1981). Many of these are associated with subaerial island-arc volcanic centers (Cooke and Simmons, 2000). Some districts have porphyry-related and epithermal gold deposits in the same areas (e.g., Bayah dome and Pacitan) suggesting these deposits were formed in a similar tectonomagmatic setting (Hedenquist et al., 1996, 2000; Cooke and Simmons, 2000; Kerrich et al., 2000). However, the fact that each region is dominated by a specific mineralization type, and only few deposits reach economic status, there are considerable differences among mineral districts. Brief descriptions on all mineral occurrences in Java are outlined below.

8.1. West Java

Metallic deposits in westernmost Java are so far the most economical and well-studied compared other districts. In the Ujung Kulon district, several gold deposits collectively named the Cibaliung (Sunarya, 1997; Angeles et al., 2002; Harijoko et al., 2004) were recently discovered. Mineralization is typical of an adularia Au-Ag low sulfidation epithermal system, and the current reserve is approximately 15.3 t Au and 89.4 t Ag. The age of mineralization is 11.14±0.06 to 11.1±0.09 Ma or Upper Miocene, coincident with the age of volcanism event of 11.4±0.8 (Harijoko et al., 2004). Just to the east, the Bayah dome represents the most productive gold districts in Java. There are many gold deposits in this region, but currently the only operating mine is Gunung Pongkor (98 t Au and 1,026 t Ag), with additional reserves at Cikidang (2.7 t Au and 15.1 t Ag) and smaller resources at Cirotan (Cikotok). Marcoux and Milesi (1994) divided gold mineralization into two main classes: 1) Cirotan type: cockade breccia veins containing rhodochrosite, rhodonite, electrum, abundant polymetallic sulfides, and some cassiterite and wolframite; and 2) Pongkor type: crustiform banding containing electrum, rare sulfides minerals and manganese oxides.



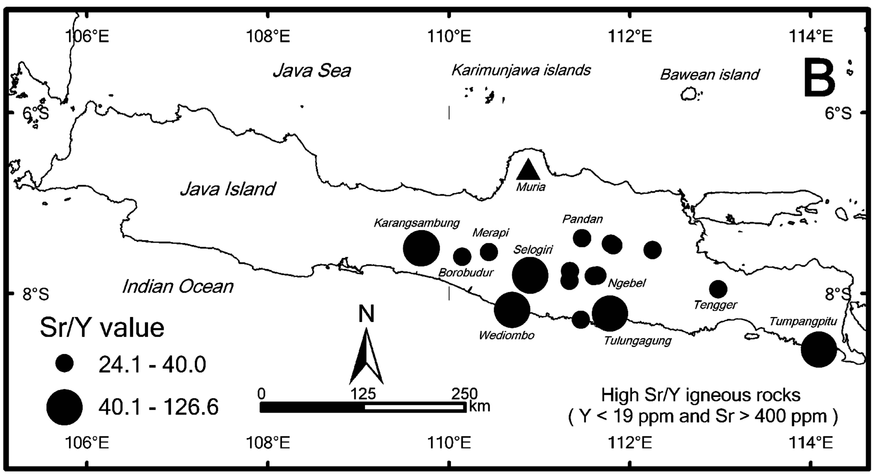


Fig. 10 Distribution of Java rocks within: A. The diagram of Y versus Sr/Y of Defant and Drummond (1990), and B. Spatial distributions of high Sr/Y rocks in Java, defined by Sr/Y >20, Y <19 ppm, and Sr >400 ppm. Note that high Sr/Y (adakitic) rocks are consistently present only in the eastern half of Java. Backarc volcanoes such as Muria are neither adakite nor normal island-arc volcanics.

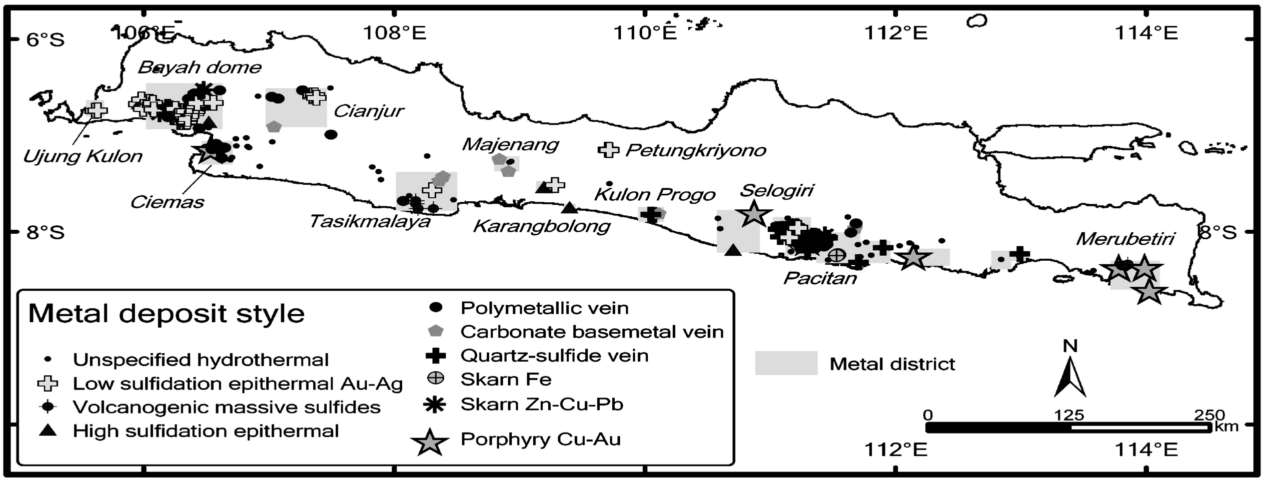


Fig. 11 Distribution and style of metallic deposits in Java

The Gunung Pongkor deposit (Basuki et al., 1994; Marcoux and Milesi, 1994; Milesi et al., 1999; Warmada et al., 2003; Syafrizal et al., 2005) and Cikidang (Rosana and Matsueda, 2002) show typical low-sulfidation Au-Ag epithermal system, such as low sulfide and base metals contents and low salinity. Gunung Limbung (Alderton et al., 1994), Cirotan, Cipanglesseran, Sopal, Cimari, Lembak Sembada, Cimari, Ciusul, Ciawitali, and Cikotok (Marcoux and Milesi, 1994) are of Cirotan type. Sunarya (1997) also reported high sulfidation system at Kadukalahang and Gunung Batu, and a skarn deposit associated with the Gunung Malang quartz diorite. Radiometric dating on these deposits shows Pliocene ages: Gunung Pongkor (2.05 Ma; Milesi et al., 1999), Cikidang (2.4±0.1 Ma; Rosana and Matsueda, 2002), Cipanglesseran (2.1±0.6 Ma; Marcoux and Milesi, 1994), and Cirotan (1.7±0.1; Marcoux and Milesi, 1994). The skarn deposit at Gunung Malang is most likely Lower Miocene in age. The Bayah dome complex has been a volcanic center since the early Eocene period. The volcanism gradually shifted to the north, and the Pliocene volcanic center may have been located within the proximity of Gunung Pongkor-Cikidang district (Milesi et al., 1999). The known mineral deposits formed since the Upper Miocene, but most gold deposition took place in the late Pliocene.

In the Ciemas district, a sub-economic porphyry deposit is reported to occur associated with a Lower to Upper Miocene age intrusion (McInnes et al., 2004). Other geologic information is currently not available. Sunarya (1997) described occurrences of low sulfidation epithermal and base metals veins in the Cianjur district. Unfortunately other geologic information is also not available. At Tasikmalaya, many small-scale mining activities have taken place at epithermal gold deposits. The most active one being the Cineam deposit which is a small epithermal gold-silver-telluride deposit (Widi and Matsueda, 1998). K-Ar radiometric dating on altered rocks results the age of 13.5 to 8.0 Ma or Upper Miocene (Widi and Matsueda, 1998). In southern Tasikmalaya, some occurrences of volcanogenic massive sulfide (VMS) deposits formed within the submarine facies of Jampang Formation (JICA-MMAJ, 1996; Sunarya, 1997). There is no dating so far, but the likely age is Lower Miocene based on the volcanic assemblages.

8.2. Central Java

Mineral occurrences in central Java are the least known among other areas in Java. However, our field visits to several exploration projects and small-scale mining activities on gold deposits indicated that metallic deposits are scattered in several districts (Fig. 11). At Kulon Progo dome there are many small occurrences of quartz-carbonate-base metals veins found within the southern rim of the Kulon Progo dome intrusive-volcanic complex. Noteworthy are the Sermo and Kokap at southeastern rim, Plampang and Sangon at central-southern rim, and Curug at southwestern rim of the dome. Mineralization is dominated by narrow (5-20 cm) quartz-carbonate-barite-base metals of sphalerite-chalcopyrite-galena. The presence of active small-scale mines demonstrates that these deposits contain some extractable gold. The age of mineralization may range from (Late) Oligocene to Lower Miocene based on volcanic association.

At the western rim of the Lower Miocene Karangbolong intrusive complex, we found a zone of intensive clay alteration associated with narrow quartz veins. Sumantri and Hartono (1998) included this alteration zone as part of a high sulfidation epithermal system. To the north of Karangbolong, Prihatmoko et al. (2002) reported an epithermal mineralization zone associated with a diatreme breccia at Kebasen village. An interpretation based on the associated volcanic center suggests that the age of mineralization is Upper Miocene. At Majenang district, Prihatmoko et al. (2002) also reported several locations of quartz-calcite-base metals mineralization hosted by the Mid-Upper Miocene volcanics of Halang Formation. Many alluvial gold mines, firstly discovered in 1996, occur surrounding to these locations.

Our visit to the Petungkriyono (northern central Java) suggests the presence of epithermal mineralization within a depression caldera, perhaps of Pliocene age. The close proximity to the Dieng geothermal field suggests that Petungkriyono is perhaps an extinct geothermal system from Late Neogene (Pliocene?) period. Styles of mineralization are dominated by narrow quart veins with crustiform-colloform texture and vugs-filling quartz on argillic-altered hydrothermal breccia. Sulfide minerals are dominated by pyrite with few base metals. The mineralization can be classified as low sulfidation epithermal related with extinct geothermal system.

In general, types of mineralization in central Java are dominated by carbonate-base metals veins and high-sulfidation system in southern parts (associated with Lower Tertiary volcanic centers), and low-sulfidation Au-Ag in northern part (associated with Upper Tertiary volcanic centers).

8.3. East Java

There are many occurrences of mineral deposits in the so-called the Southern Mountains of eastern Java, although none are being mined at industrial scale. A few deposits in the western part (Pacitan district) have historical mining operations during the Dutch (pre-WW II) and Japanese (during WW II) era. Styles of mineralization vary from low-sulfidation epithermal Au-Ag, Au-base metals veins, high-sulfidation epithermal, skarn Fe, skarn Cu-Zn-Pb, and porphyry Cu-Au. Several mineral districts contain different styles of mineralization.

The Miocene Selogiri caldera and intrusive complex host many quartz-gold-base metals vein deposits, which have been exploited as small-scale mines since 1990s. Our field observations concluded that there is porphyry-style Cu-Au mineralization hosted by andesite to microdiorite stocks at Gunung Tumbu. Preliminary fluid inclusion results showed a wide range of homogenization temperatures (<200°C to >500°C) suggesting overlapping porphyry and epithermal systems (Shinomiya, 2005). At Wediombo beach, southern part of Selogiri district, high sulfidation mineralization is identified by the presence of vuggy silica float and a zone of kaolinite-alunite-illite-pyrite alteration. Mineralization seems to be associated with a Lower Miocene (?) hornblende dacite stock.

In the Pacitan district, there are also many mineral occurrences where several deposits are being worked by small-scale operations. These deposits are dominated by base metal veins, skarn deposits, and also low sulfidation epithermal Au-Ag veins at Gunung Gembes. Skarn and quartz-base metals deposits are found at Kasihan village, where a semi-detail exploration was done in year 1991-1993 (KMPC, 1993). Our observations suggest that clusters of ore bodies are located in a radius area of about 5 km. All mineralization sites are spatially (and most likely genetically) related with dacitic dikes intruding volcaniclastic unit of Oligo-Miocene age. The main alteration zone occurs in Kalitengah village (Gunung Pegat) where an area of about 1 km radius is completely altered into kaolinitic clay. Considering the wide extent of mineral occurrences, a potential for a porphyry-type mineralization is high. These mineral deposits are considered to be associated with a volcanic center of perhaps Lower Miocene. Another porphyry-related manifestation was noted by JICA-JOGMEC (2004) at Seweden and Tempursari (eastern part of Pacitan district).

The Merubetiri district in easternmost Java contains several occurrences of porphyry-related quartz-base metal veins (Soeharto and Hilman, 1997) associated with granodioritic to dioritic stocks of Upper Miocene age. Our fieldwork at Tumpangpitu beach (southern Merubetiri area) found widespread silica-clay (phyllic) alteration along the beach and at an exposed diorite stock near the beach (Merah island) where stockwork narrow quartz-pyrite-copper oxides veinlets are well developed. Hypogene potassic alteration has been replaced by phyllic alteration. At our best knowledge, this is the best outcrop of porphyry-style mineralization in Java and is associated with a volcanic center of probably Lower Miocene age.

9. Discussions

9.1. The causes of spatial evolution of volcanic arcs

Compared to typical spatial evolution of island arc in other parts in the world, Java island shows an opposite evolution trend, in which the Cenozoic evolution of island arc was dominated by a backarc-ward migration of volcanic centers and major compressive events. Normally, younger volcanic arcs move trench-ward relative to older arcs due to the roll-back effect of the cooling slab. The initiation of Java trench between 50 and 40 Ma by the northward drift of the Australian plate section has created and rotated the volcanic arcs in Java, from a more NW-SE trend of the Sumatra section into the E-W trend (Hall, 2002). The next major volcanic arc shift to the backarc-side occurred in the Upper Miocene (central and west Java) and Pliocene (entire Java). This can be related with compressive tectonics that produced large-scale thrust faults along the backarc-side of volcanic arc (Simandjuntak and Barber, 1996). The Central Java Fault (Fig. 2) might have controlled such differences in lateral displacements between western and eastern Java. Up to the Late Tertiary the compressive horizontal force of the northward drift of the Indian-Australian plates has somehow overcome the vertical force of the cooling subducted

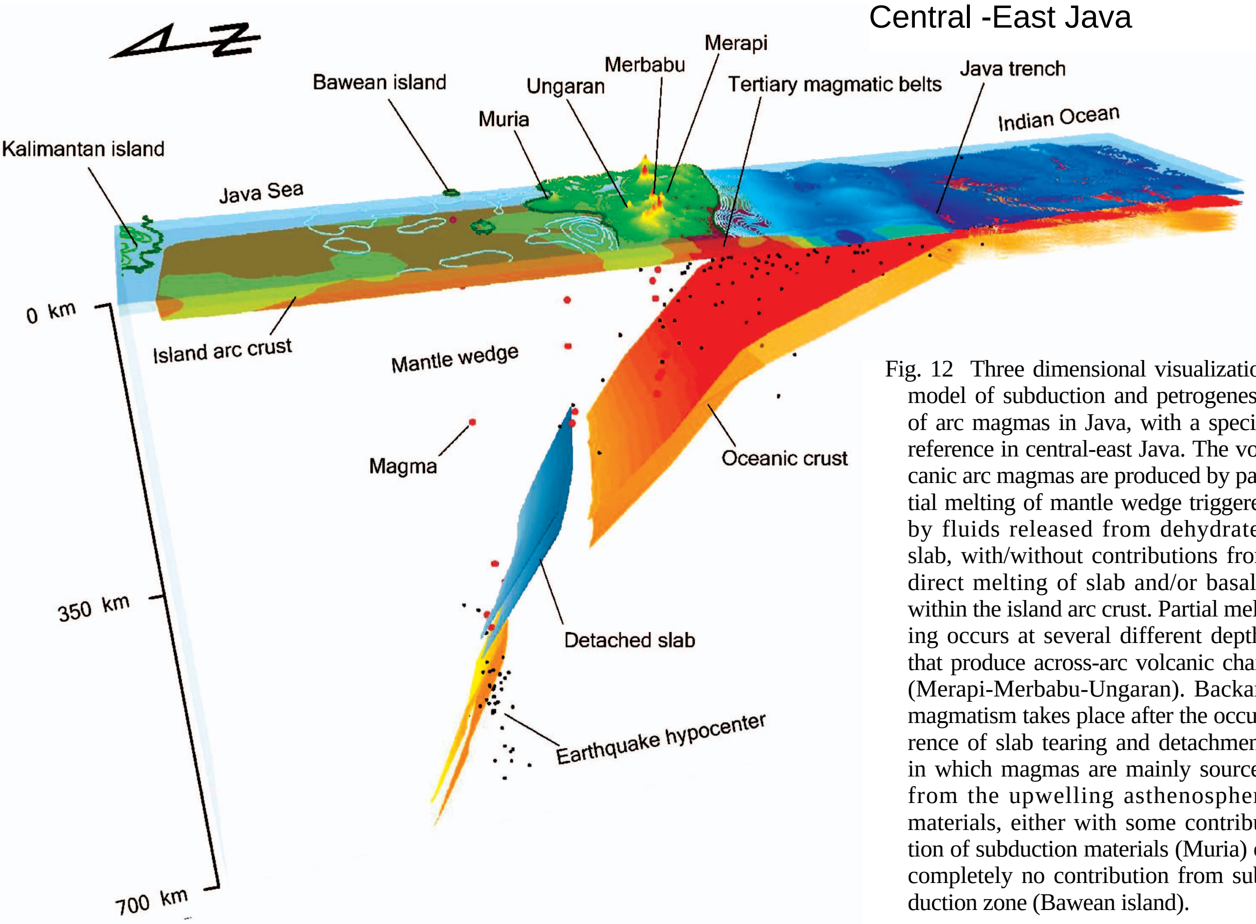


Fig. 12 Three dimensional visualization model of subduction and petrogenesis of arc magmas in Java, with a special reference in central-east Java. The volcanic arc magmas are produced by partial melting of mantle wedge triggered by fluids released from dehydrated slab, with/without contributions from direct melting of slab and/or basalts within the island arc crust. Partial melting occurs at several different depths that produce across-arc volcanic chain (Merapi-Merbabu-Ungaran). Backarc magmatism takes place after the occurrence of slab tearing and detachment, in which magmas are mainly sourced from the upwelling asthenosphere materials, either with some contribution of subduction materials (Muria) or completely no contribution from subduction zone (Bawean island).

slab. Only after Pliocene has the arc been experiencing trench-ward evolution. This is especially observable in western and central Java. The central Java region that experienced strongest Neogene compression seems to be also the most affected region by the roll-back effect of cooling slab since Mio-Pliocene, as seen from the biggest trench-ward arc shift distance in Java and the only region that experiences backarc magmatism in Java.

9.2. *The causes of geochemical evolution of volcanic arcs*

Many aspects of geochemical variations of volcanic rocks are observed in Java, some of which can be explained using well-accepted theory of island arc magmatism but others are still speculative. The positive relationship between increasing depths of the subducted slab and increasing K_2O contents of the magmas has been widely interpreted due to the lower degree of partial melting towards the deeper level (e.g., Tatsumi and Eggins, 1995; Nakagawa, 1999). Towards a deeper zone, the hydrous phase is also bearing K-rich phlogopite rather than amphibole that is more stable at shallower level; as the results magmas generated at deeper level have higher contents of K_2O contents. On the other hand, the causes of increasing K_2O contents towards younger magmas are not so conclusive. We argue that younger volcanic arcs in Java were produced by deeper subducted slab than the older ones (due to the cooling slab) so that the slab is richer in K-bearing phlogopite rather than amphibole. Worldwide, the volcanic arcs usually show a consistent depth of subducted slab underneath the volcanic front of about 110 km (Tatsumi and Eggins, 1995). In Java, quaternary volcanic fronts are variably located in the ranges of about 120-175 km above the subducted slab (Figs. 1 and 3) that are significantly deeper than the world average.

9.3. *Petrogenesis of island arc magmas*

A 3D visualization of subduction state and petrogenesis of island arc magmas in Java is illustrated in Figure 12. The main magma source in Java is considered partial melting of mantle wedge, triggered by hydrous fluids released from the dehydrated slabs. In many places partial melting occurred at several different depths producing double volcanic chains. The primary magma composition is basalt, with K_2O contents increasing to the deeper melting point (backarc-side). During migration to upper crustal levels, the primary parental basalts are modified by fractional crystallization, accumulation, and crustal assimilation.

The presence of adakitic rocks that occur erratically among other ‘normal island arc’ rocks but systematically

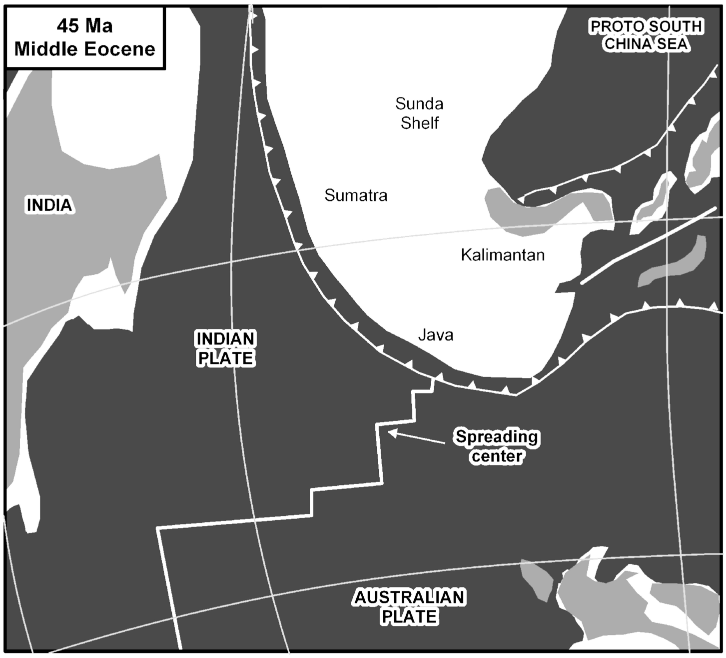


Fig. 13 Reconstruction of geologic setting of Java island at 45 Ma (Middle Eocene) by Hall (2002). During this period the oceanic floor being subducted along Java trench consisted of the Mesozoic Indian plate in west, Jurassic Australian plate in east, and a spreading center in between (active during the Late Cretaceous-Early Tertiary). This model supports the partial melting of a hot MORB subducted along Java trench as source of adakitic rocks in eastern Java. The map is redrawn from Hall (2002, Fig. 16).

occur only in central and east Java demonstrates that another type of primary magma is present in eastern Java. This magma has an original intermediate composition and is generated by partial melting of basaltic source rather than mantle peridotite. There are still two possible sources of adakitic magmas in eastern Java: a hot subducted oceanic plate and/or basalt underplate. The clues for the first option come from the geodynamic reconstruction of Java (Hall, 2002) that suggested the presence of an active spreading center between Indian and Australian plates and being subducted somewhere in eastern part of Java island since the initiation of Java trench 50 to 40 Ma (Fig. 13). This model implies the presence of relatively young (hot) basalt being subducted at Java trench even for today's standard (<50 Ma). On the other hand, the basalt underplate source is supported by the fact that eastern Java is underlain mainly by oceanic crust. If this is the reason, then adakitic rocks should also be present in islands east of Java (i.e., Bali, Lombok, Sumbawa, and Flores).

Regarding the backarc magmatism, there is a mixed geochemical signature between subduction-related volcanic arc magmatism and non-volcanic arc magmatism. Some evidence shows a continuous spectrum between arc magmas and backarc ones, such as the continuous spectrum between high-K and shoshonitic magmas shown on both sides. Among backarc volcanoes themselves there are significantly different geochemical patterns. The Lasem volcano shows the most similar features with other volcanic arc volcanoes, while the Muria volcano shows mixed features between volcanic arc and non volcanic arc in most geochemical constraints. The Bawean volcanism shows the strongest evidence for non-volcanic arc affinities. Earthquake hypocenters indicate the presence of vertical aseismic zone at depths between 270 and 500 km deep in central-east Java, interpreted as an inactive subduction in this section associated with the detachment of the slab. The upper and lower parts of this breaking slab are more or less located underneath Muria volcano and Bawean island, suggesting the genetic relationship between the occurrences of slab windows and backarc magmatism (Fig. 12). The slab windows are potential places for upwelling of deeper mantle, producing a small degree of partial melting that is associated with very high contents of K_2O that resemble the formation of island arc basalt. In Muria case, this magma might have mixed with another magma produced by the hydrated peridotite containing hydrous phlogopite or K-amphibole at such great depths of down-dragged mantle wedge and subducted crust (Tatsumi and Eggins, 1995).

Table 2 Distributions of metallic deposit occurrences within Tertiary volcanic centers. Total amount of metallic deposit records is 220.

volcanic centers	Metallic deposits	Percentage
Oligoocene	123	55.9
Lower Miocene	130	59.1
Upper Miocene	115	52.3
Pliocene	64	29.1
All Tertiary	205	93.2

9.4. *Metallic deposits and arc magmatism*

There is strong evidence for spatial relationship between volcanic centers and gold mineralization. During fieldwork such relationships have been observed in several areas such as Selogiri, Tumpangpitu, Karangbolong, and Kulon Progo, where porphyry and base metal veins are found within intrusive complex of Tertiary volcanic centers. The field observation is supported by GIS spatial analysis through intersecting two evidence maps: locations of Tertiary volcanic centers (Fig. 4) and locations of metallic mineral deposits (Fig. 11). The analysis shows that 93.2 % (205 out of 220) metallic deposits are located within all Tertiary volcanic centers combined (Table 2).

The oldest volcanic centers of Oligocene and Lower Miocene are spatially associated with more metallic deposits (55.9 and 59.1 %) compared to younger volcanic centers. In many places in Java mineralization is associated with long-lived (overlapping) volcanic centers, such as in Bayah dome region (Lower Miocene to Pliocene), Ciemas (Lower-Upper Miocene), Kulon Progo (Oligocene to Upper Miocene), Pacitan area (Oligocene-Upper Miocene) and Merubetiri (Oligocene-Upper Miocene). As each volcanism event produced mineralization, this situation gives an overlapping effect that older volcanic terrains contain more (accumulated) numbers of metallic occurrences. The Pliocene volcanic centers host the smallest number of metallic deposits due to following reasons: 1) Pliocene volcanoes are not deeply eroded enough to reveal mineralization, 2) limited exposures of Pliocene volcanic centers in Java, perhaps are mostly covered by Quaternary units. So far there is no convincing evidence of mineral deposits of Quaternary ages, perhaps due to limited erosion that has been affecting the Quaternary units. There is no evidence of mineralization so far observed in the backarc magmatism region in Java. This may be due to the relatively young age of backarc magmatism events (latest of Miocene to Quaternary), mostly they occurred undersea, or because of the weak link between backarc magmatism and subduction zone.

9.5. Ages and geodynamics clues to metallic deposits

There is clear evidence that younger deposits are dominated by epithermal gold deposits, while older ones by porphyry-related deposits. The simplest explanation is that most epithermal gold deposits form at shallow crustal levels (<1 km according to Cooke and Simmons, 2000; below paleowater table of 50 to 700 m according to Hedenquist et al., 2000). Boiling, an effective process to produce high-grade gold ores, usually occurs in the shallow part of hydrothermal systems and gold grades tend to increase towards upper level, e.g., Hishikari and other epithermal deposits in Kyushu island, Japan (Izawa, 2001). Therefore, less eroded epithermal systems (or young deposits) are the most prospective for discovering high-grade gold deposits.

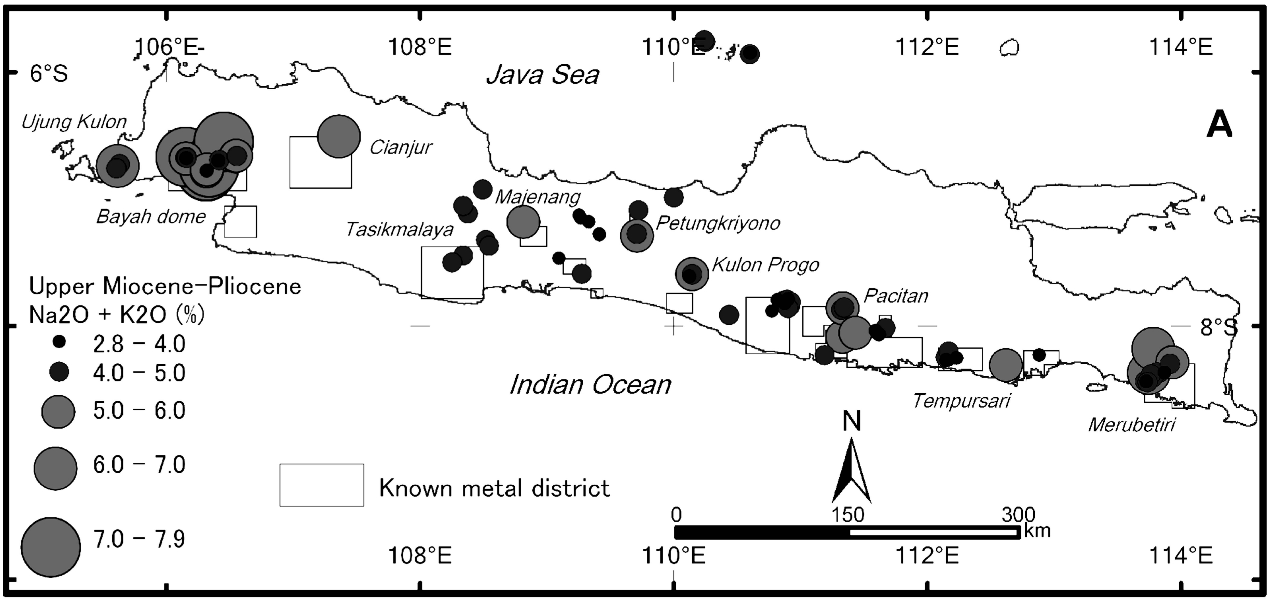
Such general relationship is applicable in the case of Java island and regional geodynamics of volcanic centers has taken part determining style distribution of deposits. The western Java is more dominated by epithermal gold deposits of younger ages, while the eastern Java by intrusion-related mineralization of older ages (Fig. 11). The westernmost Java became a rotational pole of counterclockwise rotation during the Tertiary, resulting in much overlapping Tertiary volcanic centers. Therefore, the exposed volcanic units (and associated mineral deposits) in west Java are dominated by younger units and epithermal style mineralization. The domination of epithermal deposits in west Java in turn giving contribution on its higher gold concentration.

However, epithermal deposits are in fact also found at many other districts and were formed at different geologic ages, such as the Miocene Cibaliung at westernmost Java (Harijoko et al., 2004), the Pliocene (?) Petungkriyono in central Java, and the Miocene (?) Gunung Gembes at Pacitan, east Java. The difference is that these deposits do not have metal concentrations as high as those in the Bayah dome. We find some other clues from the geodynamics point of view that may contribute to this. Different with other epithermal districts, the Bayah dome became a site of continuous volcanic centers from Eocene to late Pliocene (Fig. 4), suggesting repeated processes of magmatic-epithermal events may contribute on larger accumulation of gold. Some petrochemical evidence from Pb and Re-Os isotopes data in Bayah dome (Marcoux and Milesi, 1994; Alves et al., 1999) demonstrate that Pliocene volcanics and gold deposits are highly radiogenic and crustal in origin. Such a crustal source of Pliocene gold deposits in Bayah dome should be attributed by continental basement of west Java (Fig. 1). However, as the Bayah dome is richer in gold than other districts in western Java, a thicker crust due to overlapping Tertiary volcanic centers in Bayah dome may have taken part. Another important geodynamic factor is that the volcanic centers in Bayah dome suddenly migrated to the north (Danau volcano) and to east (Salak volcano) since the Quaternary, so that Pliocene volcanics are largely uncovered by Quaternary ones.

In contrast, eastward from Bayah dome, Pliocene volcanic centers are considerably north of the older belts and are also largely covered by Quaternary volcanoes. These two geodynamic aspects explain why Late Neogene volcanic centers in central-eastern Java so far do not have major epithermal deposits. The largely uncovered older volcanic centers to the south are now deeply eroded so that most of the upper parts of gold-rich epithermal systems may have been already removed. As the result, the metallic deposits in eastern Java are dominated by porphyry-related mineralization associated with the emplacement of older Tertiary porphyritic stocks at depths about 2 km (Sillitoe, 2000).

9.6. Tectonic regime of metallic deposits

Comparison of the locations of metallic mineral districts in Java with gravity anomaly map (Figs. 2 and 11) reveals following conclusions regarding the tectonic regime. The most striking evidence is the coincident locations between the most prominent metal districts in Java such as Bayah dome, Pacitan, and Merubetiri districts with among the narrowest zones of high gravity anomaly. As these high gravity anomalies represent locations of volcanic belts, it means that major metal districts are located within narrow volcanic belt segments. This evidence once again emphasizes the importance of overlapping volcanic centers for concentrating mineralization.



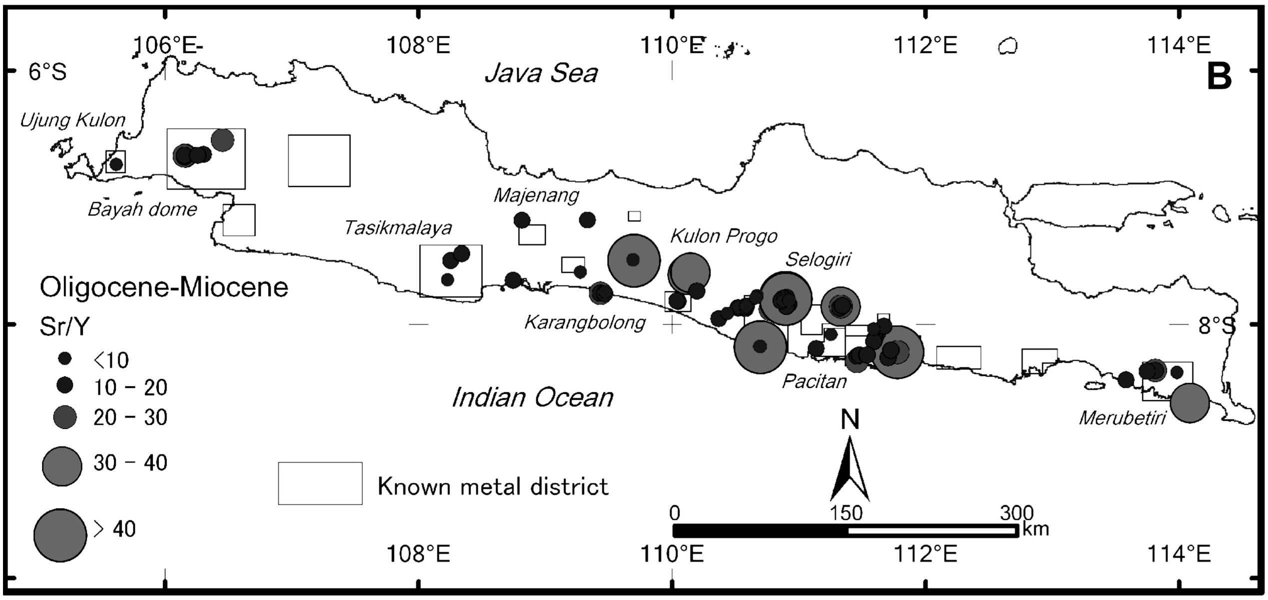


Fig. 14 Spatial relationships between epithermal deposits and Upper Miocene-Pliocene alkaline volcanic centers (A) and between porphyry deposits and Oligocene-Upper Miocene high Sr/Y magmas (B).

Additionally, this also means a relatively compressive tectonic regime on a major mineral district. The occurrences of V-shape sharp gravity gradients that bound the locations of major metal districts demonstrate that major metal districts are bound by coupled regional, deep-seated first-order strike-slip faults formed by northward compression along the subduction zone (Fig. 2). The combined evidence suggests that major metal districts in Java are spatially associated with overlapping volcanic centers due to compressive tectonic environment, bound by regional faults. Compressive tectonic setting is also suggested by Sillitoe (2000) for the typical emplacement of large high-grade gold-rich porphyry deposits.

9.7. Petrochemical clues for metallic deposits

Using analogies from case studies in other countries and applying those to Java through trial-and-error GIS spatial analysis evaluations using petrochemical data of volcanic rocks, some spatial and possibly genetic relationships between petrochemistry of host volcanic rocks and gold mineralization are found. First, there is a strong positive spatial relationship between high alkaline Late Tertiary (Upper Miocene-Pliocene) volcanic rocks and locations of epithermal gold mineralization. Figure 14 clearly demonstrates that the most prominent epithermal gold district in Java (i.e., Bayah dome of west Java) is associated with the highest values of total alkali (K_2O+Na_2O) contents of host volcanic rocks. This is also true for K_2O/SiO_2, K_2O/Na_2O (Fig. 8), and Rb/K (Fig. 9) ratios that systematically higher in Bayah dome region. Note that not all volcanic rocks in Bayah dome in fact have high alkali contents; however the overall rocks from Bayah dome have the highest alkali contents among all arc magmas in Java island. Together with anomalously higher Rb/K ratio (Fig. 9), it is suggested that epithermal mineralization is associated with more evolved rocks than common arc volcanics. Other areas beyond Bayah dome that are considered prospective for epithermal mineralization are Ujung Kulon and Cianjur (west Java), Pacitan and Merubetiri (east Java) (Figs. 11 and 14A). Porphyry-related occurrences at Pacitan also have an associated low sulfidation epithermal gold prospect at Gunung Gembes (JICA-JOGMEC, 2004). Central Java, on the other hand, has low to moderate-K and K/Na ratios, and is thus considered less prospective.

Another spatial relationship is observed between distribution of porphyry-related ore deposits and Lower Tertiary (Oligocene to Upper Miocene) volcanic centers with high Sr/Y (Fig. 14B) and low K_2O/Na_2O ratios. These features are related with more influence of partial melting of basaltic materials to produce adakitic melts as discussed in previous sections. Oligocene-Miocene volcanic centers in eastern Java are therefore more prospective for porphyry-related mineralization such as porphyry Cu-Au, skarn Fe, skarn Zn-Cu-Pb, and base metals veins. These areas include the Selogiri, Pacitan, and Merubetiri (east Java) and perhaps also Kulon Progo district in central Java (Figs. 11 and 14B).

There are therefore contrasting styles of mineralization based on rock alkalinity. The porphyry-related mineralization is associated with low- to medium-K affinity, while epithermal gold mineralization is associated with medium-K to shoshonitic affinity. The level of K contents is certainly affected by the age factor (Fig. 6), but the K contents of Bayah dome volcanic rocks are in fact still higher than other areas of the same age (Fig. 9). Additionally some Miocene intrusive rocks such as G. Limbung in Bayah dome area also have high alkali contents (Alderton et al., 1994). On the other hand, porphyry mineralization in Batu Hijau mine, Sumbawa island is also associated with low- to moderate-K intrusive rocks (Garwin, 2002; Idrus, 2005) despite of its young age (Pliocene). Therefore, we argue the levels of K contents are not merely related with their ages but also other factors that in turn might be affecting the styles and amount of gold deposition.

10. Conclusions

In Java island, regional crustal geology, compositions of subducted slabs, and tectonics history determined the spatial-geochemical geodynamics of arc magmatism, as well as regional metallogeny. The main magma source in Java is partial melting of mantle wedge, triggered by hydrous fluids released from dehydrated slabs. Most primary basalts have been modified into more evolved compositions before reaching the earth's surface. In eastern Java where the crust is oceanic and the hot slab is likely to be present, adakitic magmas are also present. Horizontal, northward compressive forces are considered to have been relatively stronger than vertical downward force during Tertiary that caused backarc-ward migration of volcanic centers. Such strong horizontal forces have formed deep-seated crustal faults, imaged by regional gravity map as V-like sharp gravity gradients. Compression in central Java was at the highest level during Upper Miocene-Pliocene resulting in backarc-ward migration of volcanic centers. This was soon followed by slab detachment, backarc magmatism, and roll-back effect. The backarc volcanoes are likely to be produced by magma mixing between subduction-related magma and magma produced by upwelling lower mantle through slab window.

A combination of several geodynamic aspects during the Cenozoic arc magmatism in Java corresponds with the observed concentrations of ore deposits. Although relationship between magnetite-series magmatism and sulfide mineralization is notable, there are various detailed aspects that are involved in determining the final styles and quantity of precious metals concentrations. In Java mineralization is exclusively associated with subduction-related magmas. The effects of slab detachment, upwelling asthenosphere, and roll-back of arcs for concentration of gold deposits (Blundell, 2002) do not apply in Java. Deep-seated first-order crustal faults focus the locations of volcanic centers as well as metalliferous fluids. Low grade porphyry copper-gold deposits tend to develop associated with volcanic centers formed during the early stages of island arc development, and the source of metals and sulfur is from partial melting of basaltic parental materials. Consequently this mineralization type is concentrated in eastern Java where the lower crust is mafic, a hot slab is likely being subducted, and where the Lower Tertiary volcanic centers are not covered by younger volcanoes. On the other hand, high-grade low sulfidation epithermal deposits are formed in later stages of arc development, associated with younger volcanic centers that overly the older ones. Crustal materials are the likely source of gold in the low-sulfidation epithermal system.

Petrochemical data of volcanics can be integrated in regional scale area selection: 1) high Sr/Y and Na_2O/K_2O ratios are considered more prospective for porphyry mineralization, and 2) high K_2O, total alkali, and K_2O/Na_2O ratio are more favorable for epithermal mineralization.

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References

Alderton, D., Harmon, R., Sloane, H. and Sudharto, T. (1994) Fluid inclusion and stable isotope studies at Gunung Limbung Cu/Pb/Zn deposit, west Java. Journal of Southeast Asian Earth Sciences, 10, 25–38.

Alves, S., Schiano, P. and Allègre, C.J. (1999) Rhenium–osmium isotopic investigation of Java subduction zone lavas. Earth and Planetary Science Letters, 168, 65–77.

Angeles, C. A., Prihatmoko, S. and Walker, J. S. (2002) Geology and alteration-mineralization characteristics of the Cibaliung epithermal gold deposit, Banten, Indonesia. Resource Geology, 52, 329–339.

Arif, J. and Baker, T. (2004) Gold paragenesis and chemistry at Batu Hijau, Indonesia: Implications for gold-rich porphyry copper deposits. Mineralium Deposita, 39, 523–535.

Basuki, A., Aditya Sumanagara, D. and Sinambela, D. (1994) The Gunung Pongkor gold-silver deposit, West Java, Indonesia. Journal of Geochemical Exploration, 50, 371–391.

Bellon, H., Soeria-Atmadja, R., Maury, R. C., Suparka, M. E. and Yuwono, Y. S. (1989) Chronology and petrology of back-arc volcanism in Java. Proceedings of the Regional Conference in Geology, Mineral and Hydrology Resources SE Asia.

Ben-Avraham, Z. and Emery, K. O. (1973) Structural framework of the Sunda Shelf. Bulletin of American Association of Petroleum Geologists, 57, 2823–2366.

Blundell, D. J. (2002) The timing and location of major ore deposits in evolving orogen: the geodynamic context. *in* Blundell, D. J., Neubauer, F. and Von Quadt, A. (eds.) The Timing and Location of Major Ore Deposits in an Evolving Orogen. Geological Society, London, Special Publications, 204, 1–12.

Bogie, I. and MacKenzie, K. M. (1998) The application of a volcanic facies model to an andesitic stratovolcano hosted geothermal system at Wayang Windu, Java, Indonesia, Proceedings of 20th NZ Geothermal Workshop, 265–270.

Bronto, S. (1990) Galunggung 1982-83 high-Mg basalt: Quaternary Indonesian arc primary magma. Proceedings XIX Annual Convention of the Indonesian Association of Geologists (IAGI), Bandung, 126–143.

Budiman, I., Nasution, J., Sobari, I. and Simamora, W. H. (2000) Gravity anomaly map of western part of Indonesia scale 1:2,000,000. Geological Research and Development Centre, Bandung.

Camus, G., Gourgaud, A., Mossand-Berthommier, P.-C. and Vincent, P.-M. (2000) Merapi (Central Java, Indonesia): An outline of the structural and magmatological evolution, with a special emphasis to the major pyroclastic events. Journal of Volcanology and Geothermal Research, 100, 139–163.

Carlile, J. C. and Mitchell, A. H. G. (1994) Magmatic arcs and associated gold and copper mineralization in Indonesia. Journal of Geochemical Exploration, 50, 91–142

Carn, S. A. and Pyle, D. M. (2001) Petrology and geochemistry of the Lamongan volcanic field, East Java, Indonesia: Primitive Sunda arc magmas in an extensional tectonic setting? Journal of Petrology, 42, 1643–1683.

Cloetingh, S. and Wortel, R. (1986) Stress in the Indo-Australian plate. Tectonophysics, 132, 49-61

Cooke, D. R. and Simmons, S. F. (2000) Characteristics and genesis of epithermal gold deposits. *in* Hagemann, S. G. and Brown, P. E. (eds.) Gold in 2000. Reviews in Economic Geology, 13, 221–244.

Corbett, G. J. and Leach, T. M. (1998) Southwest Pacific Rim Gold-copper Systems: Structure, Alteration and Mineralization. SEG Bulletin Special Publication, 6, 237p.

Defant, M. J. and Drummond, M. S. (1990) Derivation of some modern arc magmas by melting of young subducted lithosphere. Nature, 347, 662–665.

Garrison, J. M. and Davidson, J. P. (2003) Dubious case for slab melting in the Northern volcanic zone of the Andes. Geology, 31, 565–568.

Garwin, S. (2002) The geologic setting of intrusion-related hydrothermal systems near the Batu Hijau porphyry copper-gold deposit, Sumbawa, Indonesia. *in* Goldfarb, R. J. and Nielsen, L. (eds.) Integrated Method for Discovery: Global Exploration in the Twenty-first Century. SEG Special Publication, 9, 333–366.

Gertisser, R. and Keller, J. (2003) Trace element and Sr, Nd, Pb and O isotope variations in medium-K and high-K volcanic rocks from Merapi Volcano, Central Java, Indonesia: Evidence for the involvement of subducted sediments in Sunda arc magma genesis. Journal of Petrology, 44, 457–489.

Gill, J. B. (1981) Orogenic Andesite and Plate Tectonics. Springer-Verlag, New York, 390p.

Green, T. H. (1980) Island arc and continent-building magmatism – A review of petrogenic models based on experimental petrology and geochemistry. Tectonophysics, 63, 367-385.

Hall, R. (1996) Reconstructing Cenozoic SE Asia. *in* Hall, R. and Blundell, D. J. (eds.) Tectonic Evolution of Southeast Asia. Geological Society of London Special Publication, 106, 153–184.

Hall, R. (2002) Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. Journal of Asian Earth Sciences, 20, 353–431.

Hamilton, W. B. (1979) Tectonics of the Indonesian Region. Professional Paper 1078, U. S. Geol. Surv., Washington, DC, 345p.

Harijoko, A., Sanematsu, K., Duncan, R. A., Prihatmoko, S. and

Watanabe, K. (2004) Timing of the mineralization and volcanism at Cibaliung gold deposit, western Java, Indonesia. Resource Geology, 54, 187–196.

Hedenquist, J. W., Arribas, A., Jr. and Gonzalez-Urien, E. (2000) Exploration for epithermal gold deposits. *in* Hagemann, S. G. and Brown, P. E. (eds.) Gold in 2000. Reviews in Economic Geology, 13, 245–277.

Hedenquist, J. W., Izawa, E., Arribas, A., Jr. and White, N. C. (1996) Epithermal gold deposits: Styles, characteristics, and exploration. Resource Geology Special Publication 1.

Hutchison, C. S. (1982) Indonesia. *in* Thorpe, R. S. (ed.) Andesites. 208–224, John Wiley and Sons, Norwich, Great Britain.

Idrus, A. (2005) Petrology, geochemistry and compositional changes of diagnostic hydrothermal minerals within the Batu Hijau porphyry copper-gold deposit, Sumbawa island, Indonesia. Doctor dissertation, RWTH Aachen, 352p.

Imai, A. (2002) Metallogenesis of porphyry Cu deposits of the western Luzon Arc, Philippines: K-Ar ages, SO_3 contents of microphenocrystic apatite and significance of intrusive rocks. Resource Geology, 52, 147–161.

Imai, A. and Ohno, S. (2005) Primary ore mineral assemblage and fluid inclusion study of the Batu Hijau porphyry Cu-Au deposit, Sumbawa, Indonesia. Resource Geology, 55, 239–248.

Ishihara, S. (1981) The granitoid series and mineralization. Economic Geology, 75th Anniversary Volume, 458-484.

Ishihara, S. and Murakami, H. (2004) Granitoid types relates to Cretaceous plutonic Au-quartz vein and Cu-Fe skarn deposits, Kitakami Mountains, Japan. Resource Geology, 54, 281–298.

Izawa, E. (2001) Epithermal gold mineralization in Kyushu, Japan. *in* Izawa, E., Watanabe, K. and Taguchi, S. (eds.) Proceedings of the International Symposium on Gold and Hydrothermal Systems, Fukuoka, 1–4.

JICA-JOGMEC (2004) Report on the Mineral Exploration in the East Java Area, the Republic of Indonesia – Consolidated Report. Japan International Cooperation Agency and the Japan Oil, Gas and Metals National Corporation Report, Tokyo.

JICA-MMAJ (1996) Report on the Cooperative Mineral Exploration in the Tasikmalaya Area, West Java, Phase II, 200p.

Katili, J. A. (1975) Volcanism and plate tectonics in the Indonesian island arcs. Tectonophysics, 26, 165–188.

Kay, R. W. (1978) Aleutian magnesian andesites: Melts from subducted Pacific ocean crust. Journal of Volcanology and Geothermal Research, 4, 117–132.

Kerrich, R., Goldfarb, R., Groves, D. and Garwin, S. (2000) The geodynamics of world-class gold deposits: characteristics, space-time distribution, and origins. *in* Hagemann, S. G. and Brown, P. E. (eds.) Gold in 2000. Reviews in Economic Geology, 13, 501–544.

Kohno, Y., Setijadji, L. D., Utami, P., Harijoko, A., Pecskay, Z., Imai, A. and Watanabe, K. (2005) Geochronology and petrogenetic aspects of Merapi-Merbabu-Telomoyo-Ungaran volcanoes, central Java, Indonesia. Proceedings Joint Convention HAGI-IAGI-PERHAPI, Surabaya, 222–234

KMPC (1993) Report on the Joint Mineral Exploration in the Pacitan-Ponorogo Area, East Java, the Republic of Indonesia, Phase III. Korea Mining Promotion Corporation, 255p.

LeBas, M. J., LeMaitre, R. W., Streckeisen, A. and Zanettin, B. (1986) A chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology, 27, 745–750.

Lemigas (2001) Potensi hidrokarbon kawasan Jawa Tengah selatan dan Jawa Barat selatan. Report for Pertamina, unpublished (in Indonesian).

Leterrier, J., Yuwono, Y. S., Soeria-Atmadja, R. and Maury, R. C. (1990) Potassic volcanism in Central Java and South Sulawesi, Indonesia. Journal of Southeast Asian Earth Science, 4, 171–181.

MacPherson, C. G. and Hall, R. (2002) Timing and tectonic controls in the evolving orogen of SE Asia and the western Pacific and some implications for ore generation. *in* Blundell, D. J., Neubauer, F. and Von Quadt, A. (eds.) The Timing and Location of Major Ore Deposits in an Evolving Orogen. Geological Society, London, Special Publications, 204, 49–68.

Marcoux, E. and Milesi, J. P. (1994) Epithermal gold deposits in West Java, Indonesia: geology, age and crustal source. Journal of Geochemical Exploration, 50, 393–408.

Martin, H. (1999) Adakitic magmas: Modern analogues of Archaean granitoids. Lithos, 46, 411–429.

McInnes, B. I. A., Evans, N. J., Sukarna, D., Permanadewi, S., Garwin, S., Belousova, E., Griffin, W. L. and Fu, F. (2004) Thermal histories of Indonesian porphyry copper-gold deposits determined by U-Th-He, U-Pb, Re-Os, K-Ar and Ar-Ar methods. SEG 2004 Extended Abstracts, 343–346.

Metchalfe, I. (1996) Pre-Cretaceous evolution of SE Asian terranes. *in* Hall, R. and Blundell, D. J. (eds.) Tectonic Evolution of Southeast Asia. Geological Society Special Publication, 106, 97–122.

Milesi, J. P., Marcoux, E., Sitorus, T., Simandjuntak, M., Leroy, J. and Bailly, L. (1999) Pongkor (west Java, Indonesia): a Pliocene supergene-enriched epithermal Au-Ag-(Mn) deposit. Mineralium Deposita, 34, 131–149.

Miyazaki, K., Sopaheluwakan, J., Zulkarnain, I. and Wakita, K. (1998) A jadeite-quartz-glaucophane rock from Karangsambung, central Java, Indonesia. The Island Arc, 7, 223–230.

Nakagawa, M. (1999) Origin of spatial compositional variations in differentiated arc volcanics at arc-arc junctions: A case study of major and trace element variations in Quaternary volcanics from Hokkaido, Japan. Resource Geology Special Issue, 20, 161–176.

Nicholls, I. A. and Whitford, D. J. (1983) Potassium-rich volcanic rocks of the Muriah complex, Java, Indonesia: Products of multiple magma sources? Journal of Volcanology and Geothermal Research, 18, 337–359.

Nicholls, I. A., Whitford, D. J., Harris, K. L. and Taylor, S. R. (1980) Variation in the geochemistry of mantle sources for tholeiitic and calc-alkaline mafic magmas, Western Sunda volcanic arc, Indonesia. Chemical Geology, 30, 177–199.

Nishimura, S., Nishida, J., Yokoyama, T. and Hehuwat, F. (1986) Neo-tectonics of the Strait of Sunda, Indonesia. Journal of Southeast Asian Earth Sciences, 1, 81–91.

Oyarzun, R., Márquez, A., Lillo, J., López, I. and Rivera, S. (2001) Giant versus small porphyry copper deposits of

Cenozoic age in northern Chile: Adakitic versus normal calc-alkaline magmatism. Mineralium Deposita, 36, 794–798.

Packham, G. (1996) Cenozoic SE Asia: Reconstructing its aggregation and reorganization. *in* Hall, R. and Blundell, D. J. (eds.) Tectonic Evolution of Southeast Asia. Geological Society Special Publication, 106, 123–152.

Peacock, S. M., Rushmer, T. and Thompson, A. B. (1994) Partial melting of subducting oceanic crust. Earth and Planetary Science Letter, 121, 227–244.

Peccerillo, A. and Taylor, S. R. (1976) Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey. Contributions to Mineralogy and Petrology, 58, 63–81.

Pertamina (1989) Laporan penyelidikan lapangan daerah Cicauh Selatan, Jawa Barat. Unpublished report (in Indonesian).

Pertamina-ITB (2002) Regional Tectonic Study of Java and Hydrocarbon Potential of Central Java and West Java Basins. Unpublished report.

Prihatmoko, S., Digdowirogo, S. and Kusumanto, D. (2002) Potensi cebakan mineral di Jawa Tengah dan Daerah Istimewa Yogyakarta. Proceedings XXXII Annual Convention of the Indonesian Association of Geologists (IAGI)(in Indonesian).

Puspito, N. T. and Shimazaki, K. (1995) Mantle structure and seismotectonics of the Sunda and Banda arcs. Tectonophysics, 251, 215–228.

Rahardjo, W., Sukandarrumidi, and Rosidi, H. M. D. (1995) Geological Map of the Jogjakarta Sheet, Jawa. Geological Research and Development Centre, Bandung.

Rosana, M. F. and Matsueda, H. (2002) Cikidang hydrothermal gold deposit in western Java, Indonesia. Resource Geology, 52, 341–352.

Saefudin, I. (1994) Pentarikhan jejak belah terhadap batuan terobosan dait dan andesit daerah Pacitan, Jawa Timur. Jurnal Geologi dan Sumberdaya Mineral, 4, 18–36 (in Indonesian).

Sapei, T., Suganda, A. H., Astadiredja, K. A. S. and Suharsono (1992) Geological Map of the Jember Quadrangle, Jawa. Geological Research and Development Centre, Bandung.

Scaillet, B. and Prouteau, G. (2001) Oceanic slab melting and mantle metasomatism. Science Progress, 84, 335–354.

Setijadji, L. D. and Watanabe, K. (2005) On the progress design of integrated geologic analysis system: Object-relational database model and visualization for earth resources. Resource Geology, 55, 267–280.

Setijadji, L. D., Kajino, S., Kohno, Y., Barianto, D. H., Akmalluddin, Imai, A. and Watanabe, K. (2005) Reconstruction of Cenozoic volcanic centers in Java island (Indonesia): A key for understanding the geodynamics of subduction zone. Proceedings of the 3rd International Workshop on Earth Science and Technology, Fukuoka, 433–443.

Shinomiya, J. (2005) Study on Mineralization of Porphyry Copper Deposit at Selogiri, Java, Indonesia. Graduate thesis, Kyushu University, unpublished (in Japanese).

Sillitoe, R. H. (2000) Gold-rich porphyry deposits: Descriptive and genetic models and their role in exploration and discovery. *in* Hagemann, S. G. and Brown, P. E. (eds.) Gold in 2000. Reviews in Economic Geology, 13, 315–345.

Simandjuntak, T. O. and Barber, A. J. (1996), Contrasting tectonic styles in the Neogene orogenic belts of Indonesia. *in* Hall, R. and Blundell, D. J. (eds.) Tectonic Evolution of Southeast Asia. Geological Society Special Publication, 106, 185-201.

Sitorus, K. (1990) Stratigrafi dan geokimia kaldera Idjen, Jawa Timur, Indonesia. Proceedings of the Indonesian Geologist Association Annual Meeting, 247–289 (in Indonesian).

Soeharto, R. S. and Hilman, P. M. (1997) Laporan eksplorasi mineral logam mulia dan logam dasar di daerah Jember, Jawa Timur. Directorate of Mineral Resources, 16p. (in Indonesian).

Soeria-Atmadja, R., Maury, R. C., Bellon, H., Joron, J. L., Cyrille, Y., Bougault, H. and Hasanuddin (1985) The occurrence of back-arc basalts in western Indonesia. Proceedings XIV Annual Convention of the Indonesian Association of Geologists (IAGI), Jakarta, 125–132.

Soeria-Atmadja, R., Suparka, M. E. and Yuwono, Y. S. (1991) Quaternary calc-alkaline volcanism in Java with special reference to Dieng and Papandayan-Galunggung complex. Proceedings of the International Conference in Volcanology and Geothermal Technology.

Soeria-Atmadja, R. Maury, R. C., Bellon, H., Pringgoprawiro, H., Polves, M. and Priadi, B. (1994) Tertiary magmatic belts in Java. Journal of Southeast Asian Earth Science, 9, 13–27.

Sujatmiko and Santoso, S. (1992) Geological Map of the Leuwidamar Quadrangle, Java. Geological Research and Development Centre, Bandung.

Sukarna, D. (1998) Petrogenesa diorite gunung Malang, daerah Bayah: bukti-bukti geokimia dan kimia mineral. Jurnal Geologi dan Sumberdaya Mineral, Geological Research and Development Centre, Bandung, 2-12 (in Indonesian).

Sumantri, T. A. F. and Hartono, T. (1998) Mineralisasi hidrotermal di daerah Gombong selatan, Kebumen, Jawa Tengah. Proceedings XXVII Annual Convention of the Indonesian Association of Geologists (IAGI), Yogyakarta (in Indonesian).

Sunardi, E. and Kimura, J. (1998) Temporal chemical variations in late Cenozoic volcanic rocks around the Bandung Basin, West Java, Indonesia. Journal of Mineralogy, Petrology, and Economic Geology, 93, 103–128.

Sunarya, Y. (1997) Potensi dan prospek emas di Jawa Barat. Special Publication of the Directorate of Mineral Resources, 19p. (in Indonesian).

Syafrizal, Imai, A., Motomura, Y. and Watanabe, K. (2005) Characteristics of gold mineralization at the Ciurug vein, Pongkor gold-silver deposit, west Java, Indonesia. Resource Geology, 55, 225–238.

Tatsumi, Y. and Eggins, S. (1995) Subduction Zone Magmatism. Blackwell Science, Ann Arbor, 211p.

Thanden, R. E., Sumadirdja, H., Richards, P. W., Sutisna, K. and Amin, T. C. (1996) Geologic Map of the Magelang and Semarang Sheets, Java. Geological Research and Development Centre, Bandung.

Untung, M. and Sato, Y. (1978) Gravity and Geological Studies in Java, Indonesia. Geological Survey of Indonesia Special Publication, 6, 207p.

Van Bemellen, R. W. (1949) The Geology of Indonesia. vol. 1A. Martinus Nijhoff, the Hague, 732p.

Vukadinovic, D. and Sutawidjaja, I. (1995) Geology, mineralogy and magma evolution of Gunung Slamet Volcano, Java, Indonesia. Journal of Southeast Asian Earth Science, 11, 135–164.

Warmada, I. W., Lehmann, B. and Simandjuntak, M. (2003) Polymetallic sulfides and sulfosalts of the Pongkor epithermal gold-silver deposit, West Java, Indonesia. Canadian Mineralogist, 41, 185–200.

Wheller, G. E., Varne, R., Foden, J. D. and Abbott, M. J. (1987) Geochemistry of Quaternary volcanism in the Sunda-Banda arc, Indonesia, and three-component genesis of island-arc basaltic magmas. *in* Weaver, S. D. and Johnson, R. W. (eds.) Tectonic Controls on Magma Chemistry. Journal of Volcanology and Geothermal Research, 32, 137–160.

Whitford, D. J. (1975) Strontium isotopic studies of the volcanic rocks of the Sunda arc, Indonesia, and their petrogenetic implications. Geochimica et Cosmochimica Acta, 39, 1287–1302.

Widi, B. N. and Matsueda, H. (1998) Epithermal Gold-silver-tellurides Deposit of Cineam, Tasikmalaya District, West Java, Indonesia. Special Publication the Directorate of Mineral Resources, Directorate General of Geology and Mineral Resources Indonesia, No. 96.

Widiyantoro, S. and Van der Hilst, R. (1996) Structure and evolution of lithospheric slab beneath the Sunda arc, Indonesia. Science, 271, 1566–1570.

Wikarno, R., Hardjono, T. and Graha, D. S. (1993) Distribution of Radiometric Ages in Indonesia, Scale 1:5,000,000. Geological Research and Development Centre, Bandung.