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HEAVY-MINERAL ASSEMBLAGES IN QUATERNARY SEDIMENTS OF THE PHILIPPINE SEA AS INDICATORS OF SUBDUCTION/COLLISION-RELATED TECTONICS

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Abstract. 287 heavy-mineral compositions of sediments, including 139 original analyses and 148 analyses from literature, have allowed outlining the major mineralogical provinces in the Philippine Sea region. Three of these provinces are characterized by domination of arc volcaniclastic minerals (clinopyroxene, orthopyroxene, and hornblende). They cover almost all within-sea basins as well as the Izu-Mariana, central and northern Ryukyu, and northeastern Philippine arcs. Their provenances are located on volcanic island arcs associated with subduction with weak plate coupling. In areas of the Taiwan and Yap Islands, where local plate collisions occur, mineral suites derived from erosion of metamorphic and intrusive rocks get dominant (epidote, actinolite, garnet, zircon, and others). In the vicinity of the central and southern Philippine arc, where subduction is most likely associated with strong plate coupling, sediments are characterized by complex heavy-mineral assemblages. They contain in sufficient amounts minerals derived from both arc volcanism and erosion of metamorphic and intrusive rocks. There also were noted marked differences between island arcs in composition of their volcaniclastic heavy-mineral suites, which may be linked to differences between modes of the associated subduction and types of the arc basement.

1. Introduction

Geology of the Philippine Sea region is very complex. This is, at least in part, resulted from great variations in tectonics along convergent boundaries surrounding the Philippine Sea plate. On the eastern boundaries, which are associated with ensimatic island arcs, subduction of the Pacific plate beneath the Philippine Sea plate occurs along the Izu-Bonin and Mariana Trenches (Karig, 1974; Hussong and Uyeda, 1982). In the area of the central Mariana Trench, it is near to normal, with weak plate coupling (Uyeda and Kanamori, 1979). In the area of Izu-Bonin Trench, subduction also is associated with weak plate coupling, but has a sufficient strike-slip component (Uyeda and Kanamori, 1979; Simkin *et al.*, 1989). To the south, in the areas of Yap and western Caroline Islands, there is a collision between island arc and a relatively rigid and buoyant block of oceanic lithosphere (Hawkins and Batiza, 1977; Eguchi, 1984). On the northwestern boundaries associated with ensialic island arcs, near to normal subduction of the Philippine Sea plate beneath the Eurasian plate occurs along the northern Ryukyu Trench. Nature of plate coupling is not defined there, but modern back-arc spreading in the Okinawa Trough suggests that it is rather weak than strong. There are subduction with a significant strike-slip component in areas of the Nankai Trough and southern Ryukyu Trench, and continent-arc collision in the Taiwan area (Konishi, 1965; Katsumata and Sykes, 1969; Chai, 1972; Karig, 1974; Uyeda, 1974; Uyeda and Kanamori, 1979; Herman *et al.*, 1979; Page and Suppe, 1981; Seno and Eguchi, 1983). On the southwestern boundaries associated with ensialic island arcs as well, there is a complex pattern of strike-slip and thrust faulting, which includes subduction of the Eurasian plate beneath the Philippine Sea plate along the Manila Trench, subduction of the Celebes Sea plate beneath the Philippine Sea plate along the Cotobato Trench, and subduction of the Philippine Sea plate beneath the Eurasian plate along the Philippine Trench and East Luzon Trough (Murphy, 1973; Cardwell *et al.*, 1980; Hamburger *et al.*, 1983; Lewis and Hayes, 1983; Hayes and Lewis, 1984; Barcelona, 1986; Nichols *et al.*, 1990). Nature of coupling are not clear in this region (Brooks *et al.*, 1984), but intense compressive tectonics on the Philippine Islands suggest strong plate coupling associated with subduction there.

The significant variety of subduction led to that of subduction-related volcanism. In particular, island-arc tholeiites predominate on the Izu-Bonin (ensimatic) arc (Sharaskin, 1992) whereas calc-alkaline lavas predominate on the southwestern Japan, northern Ryukyu and Philippine (ensialic) arcs, as well as on the Mariana (ensimatic) arc (Scott, 1983; Sharaskin, 1992). There certainly are less manifested variations in volcanism between arcs within each of these two major ranges. In the areas where subduction is associated with significant strike-slip motions (the Nankai Trough, southwestern Ryukyu Trench, and southwestern Mariana Trench) and where it has been replaced by collision (the Taiwan and Yap areas), island-arc volcanism is absent. In addition, extreme tectonic uplift occurs in the cases of collision (Chai, 1972; Hawkins and Batiza, 1977).

A tensional and/or unstress tectonic regime seems to dominate in back-arc areas of the Philippine Sea plate, although some faulting (for example, the Central Basin and Yap fracture zones) occurs therein (Brooks *et al.*, 1984; Svarichevsky and Wang, 1992).

Previously, we have found a general linkage between tectonic settings and heavy-mineral assemblages in sediments deposited under them (Nechaev, 1987, 1991; Nechaev and Derkachev, 1989; Nechaev *et al.*, 1989). In particular, it was defined that island-arc volcaniclastic suite represented by green clinopyroxene (augite-diopside series), orthopyroxene (mainly hypersthene), green and brown hornblende (including oxyhornblende), and, rarely, olivine, predominates among heavy minerals in the areas controlled by subduction with weak plate coupling, including back-arc areas associated with tensional or unstress tectonic regime. In fracture zones, a complex assemblage, including both arc volcaniclastic and intrusive-metamorphic suites occurs in various combinations although volcaniclastic minerals prevails in most of the cases studied. In the areas of collision, the association of epidote (group), pale-colored and blue-green amphiboles (tremolite-actinolite-hornblende series), garnet, chloritized mafic minerals, olivine, and, in certain cases, zircon, tourmaline, staurolite, andalusite, kyanite, monazite, and sillimanite, all derived from metamorphic and intrusive rocks, predominates. Moreover, we have found that volcaniclastic suite derived from ensialic arcs contains sufficient amounts of hornblende while that derived from ensimatic arcs contains hornblende only in negligible amounts.

In this study, a linkage between heavy-mineral assemblages and tectonic settings, associated with convergent plate boundaries around the Philippine Sea plate, will be examined with more details. For that, 139 new (original) heavy-mineral analyses in addition to 148 such analyses from the literature, that is 287 analyses totally, will be used (Suzuki, 1975; Skornyakova *et al.*, 1978; Murdmaa *et al.*, 1980; Nechaev, 1987, 1991; Nechaev *et al.*, 1989). Most analyses (all from the literature) represent Quaternary sediments. This data set has allowed the standard statistical procedures to distinguish mineral provinces of the sea and its surroundings that was impossible previously.

2. Methods

For mineral analysis, the 0.05–0.1 mm fraction was separated from sediments by wet sieving. After that, heavy minerals were extracted using tribromomethane (2.89 g/cm^3). The minerals were identified using the petrographic microscope and immersion oils. The mineral compositions were defined by counting at least 300 mineral grains in each analysis. All the mineral analyses were carried out by A. N. Derkachev and N. A. Nikolaeva from the Pacific Oceanological Institute, Russian Academy of Sciences (Table 1).

Methodology of the data interpretation included standard statistical procedures. Cluster and *R*-mode factor analyses (Formatsyi, 1978; Shymanovich, 1982; Davis, 1986; Derkachev and Nikolaeva, 1992) were made to distinguish major mineralogical provinces in the Philippine Sea and adjacent island arcs and trenches. For that, percentages of heavy minerals given in Table 1 (127 original analyses) in addition to some of those from literature (36 analyses completely comparable with ours with respect to the sample preparation and analytical methods, all from Skornyakova *et al.*, 1978; Murdmaa *et al.*, 1980; Nechaev, 1991) were recalculated to exclude lithoclasts, authigenic minerals (iron hydroxides, glauconite, and pyrite), fish debris, and opaque minerals. In this procedure, a total content of transparent clastic minerals was taken as 100%. The cluster analysis distinguished several heavy-mineral assemblages, generally representing major mineralogical provinces in the Philippine Sea region. After that, average mineral

Table 1. Percentage of minerals in heavy fraction (0.05–0.1 mm) of sediments.

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Assemblage	Sample	Cpx	Opx	Hb1	Hb2	Hb3	Hb4	Op	Hd	L	Ep	Grn	Zr	Ap	Sph	Trm	Rt	Chl	St	Ol	Act	Mus	Mi	Bi	Cc	FD	Glc	Py	Ba	Gph
East Arc province																														
Izu-Mariana Arc and Trench																														
IA2	V3483	16.3	1.1	1.7	-	-	-	0.3	10.4	69.2	-	-	-	0.3	-	-	-	-	-	0.8	-	-	-	-	-	-	-	-	-	-
IA2	V3485	27.0	1.3	0.3	-	-	-	3.0	7.6	59.9	-	-	-	1.0	-	-	-	-	-	tr	-	-	-	-	-	-	-	-	-	-
IA2	V3514	27.7	1.1	2.2	-	-	-	0.8	23.8	41.5	-	-	-	0.3	-	-	-	-	-	2.2	-	-	-	0.3	-	-	-	-	-	-
IA2	V3498	23.0	1.5	0.5	-	-	-	4.5	10.8	58.5	-	-	-	-	-	-	-	-	-	1.3	-	-	-	-	-	-	-	-	-	-
IA2	V3500	13.2	-	0.9	-	-	-	6.9	41.1	36.5	0.5	-	-	0.5	-	-	-	-	-	-	-	-	-	-	-	0.5	-	-	-	-
IA2	4N58	31.1	3.2	-	-	-	-	2.4	21.0	41.4	0.3	-	-	0.3	-	-	-	-	-	-	-	-	-	-	0.3	-	-	-	-	-
IA2	4N54	13.0	2.6	1.2	-	-	-	32.5	-	3.4	0.7	-	-	-	-	-	-	-	-	-	-	-	-	0.2	26.7	5.0	-	-	14.7	-
IA2	4N48	26.0	1.2	-	0.5	-	-	3.0	40.5	12.6	0.2	-	0.5	2.0	-	-	-	2.2	-	1.7	-	-	-	-	-	-	-	9.6	-	-
IA2	4N61	32.3	1.0	-	-	-	-	0.3	2.1	63.1	0.3	-	-	0.3	-	-	-	-	-	-	-	-	-	0.5	-	-	-	-	-	-
Mariana Trough																														
IA2	17M1406	56.0	7.7	-	0.5	-	0.3	24.0	0.8	5.1	0.3	-	-	0.5	-	-	-	-	-	4.8	-	-	-	-	-	-	-	-	-	-
IA2	17M1407	25.7	0.7	5.1	1.1	-	0.2	5.9	15.3	43.4	0.9	-	0.4	-	-	-	-	-	-	0.9	-	-	-	0.2	-	0.2	-	-	-	-
Nankai Trough																														
IA3	4K7545	10.4	1.9	1.9	0.9	-	-	2.8	12.7	62.9	0.9	-	-	0.3	-	-	-	-	-	1.0	0.3	-	0.3	3.5	-	-	-	-	-	-
IIA2	4K7538	27.0	33.4	14.9	-	-	0.7	11.5	1.0	0.7	1.7	-	-	3.0	-	0.3	0.3	2.0	-	-	1.0	-	0.3	1.7	-	-	-	-	0.3	-
Shikoku Basin																														
IIIB1	4K7546	23.3	6.1	14.5	-	-	-	8.3	12.3	29.8	1.8	-	-	0.9	-	-	-	-	-	1.3	-	-	-	1.8	-	-	-	-	-	-
IA1	4K7542	35.9	21.5	2.9	1.0	-	0.2	9.4	8.4	18.6	0.2	-	0.2	1.0	-	-	-	0.2	-	0.2	0.2	-	-	-	-	-	-	-	-	-
IA3	4K7541	19.2	8.1	2.6	-	-	4.5	8.4	53.3	-	-	-	-	-	-	-	-	-	-	3.9	-	-	-	-	-	-	-	-	-	-
IA1	4K7548	21.4	13.2	3.1	0.3	-	-	0.8	53.4	4.8	1.1	-	-	1.1	-	-	-	-	-	-	-	-	0.3	-	0.3	0.3	-	-	-	-
IA3	4N62	24.3	8.0	-	9.7	-	-	-	27.8	14.6	-	-	-	0.7	-	-	-	-	-	-	-	-	-	0.3	-	2.4	-	-	12.1	-
Northwestern Area of the Philippine Sea																														
IA1	4K7539	45.9	25.3	1.3	0.3	-	-	1.8	17.9	5.1	0.3	-	-	-	-	-	-	-	-	0.3	-	0.3	0.3	0.9	-	-	-	0.3	-	-
IA1	14P804	51.2	20.8	0.8	0.8	-	tr	20.6	2.1	0.8	1.0	-	-	2.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 1. (continued).

Assemblage	Sample	Cpx	Opx	Hb1	Hb2	Hb3	Hb4	Op	Hd	L	Ep	Grn	Zr	Ap	Sph	Trm	Rt	Chl	St	Ol	Act	Mus	Mi	Bi	Cc	FD	Glc	Py	Ba	Gph
Parece-Vela Basin																														
IA2	3V55	17.6	1.1	0.5	-	-	-	4.7	6.6	63.8	-	-	-	0.5	-	-	-	-	-	0.3	0.3	-	-	-	-	4.7	-	-	-	-
IA2	3V3	24.8	1.3	2.6	-	-	-	4.5	0.3	63.5	0.8	-	-	0.8	-	-	-	-	-	0.5	-	-	-	-	-	0.8	-	-	-	-
IA2	3V6	19.9	1.6	1.3	-	-	-	2.9	8.2	63.6	0.3	-	-	0.3	-	-	-	-	-	-	-	-	-	-	-	1.9	-	-	-	-
IA2	17M1408	44.8	1.1	6.2	2.4	-	0.3	0.5	1.6	22.0	3.2	-	0.3	0.3	-	-	-	4.3	-	0.5	2.7	1.9	1.3	1.9	-	4.3	-	0.5	-	-
Kyushu-Palau Ridge																														
IA2	33B2830/1	23.3	3.7	-	-	-	2.8	4.3	13.7	-	1.5	-	-	0.4	-	-	-	-	-	-	0.2	-	-	0.2	-	49.8	-	-	-	-
IA2	33B2830/2	66.5	1.8	-	-	-	-	1.8	23.4	6.2	-	-	-	0.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IA2	33B2829	48.6	4.6	1.5	-	-	1.0	24.3	12.4	-	1.5	-	0.3	-	-	-	-	-	-	-	-	-	-	-	-	5.8	-	-	-	-
IA2	33B2828/1	35.8	1.8	-	-	-	-	4.6	16.4	17.2	2.4	-	-	tr	-	-	-	-	-	-	-	-	-	-	-	21.7	-	-	-	-
IA2	33B2828/2	42.3	5.6	8.2	1.5	-	1.5	23.1	6.7	-	1.5	-	-	3.4	0.2	-	-	-	-	-	0.4	0.2	0.2	-	-	5.0	-	-	-	-
IA1	33B2827	22.0	7.0	-	-	-	1.6	1.6	13.8	9.4	0.2	-	-	0.5	0.2	-	-	tr	-	-	-	-	tr	-	-	43.6	-	-	-	-
IA1	33B2827/23-40	15.2	12.1	-	-	-	0.3	0.3	6.9	-	0.8	0.2	-	0.5	-	-	-	0.9	-	-	0.2	-	0.2	-	-	62.5	-	-	-	-
IA2	33B2826	6.8	1.6	-	-	-	1.0	0.2	2.0	-	0.4	-	-	0.6	-	-	-	-	-	-	-	-	-	-	-	87.4	-	-	-	-
IA1	33B2826/45-66cm	24.6	16.5	-	-	-	1.0	8.7	1.6	-	0.4	-	0.2	1.2	0.2	-	-	0.2	-	-	0.2	-	-	-	-	44.4	-	-	0.9	-
IA1	33B2826/66-102cm	36.8	11.4	-	-	-	3.6	7.8	0.8	-	0.8	0.2	-	0.8	-	-	-	-	-	-	-	-	-	-	-	37.8	-	-	-	-
IA1	33B2826/109-120cm	17.4	3.9	-	-	-	0.4	1.3	0.9	-	0.4	0.4	-	0.6	-	-	-	-	-	-	-	-	-	-	-	74.3	-	-	0.4	-
IA3	33B2824	9.0	2.2	-	-	-	5.1	0.4	1.6	3.2	0.9	-	0.2	0.5	-	-	-	0.2	-	-	-	-	-	-	-	64.3	-	12.3	-	-
IA2	33B2823	1.2	-	-	-	-	1.7	32.6	56.5	-	0.2	0.2	-	6.6	-	-	-	0.6	-	-	0.2	0.2	-	-	-	-	-	-	-	-
IA2	33B2821/1	19.9	2.0	-	3.9	-	1.3	tr	47.9	4.6	0.7	-	-	0.5	-	-	-	0.2	-	-	-	-	0.2	-	-	18.4	-	-	0.4	-
IA2	33B2821/2	28.6	3.4	-	0.8	-	0.8	1.0	26.5	26.9	0.8	-	-	2.2	0.2	-	-	-	-	-	-	-	-	-	-	8.9	-	-	-	-
IA2	33B2820	12.6	2.1	-	-	-	1.0	0.6	25.7	9.5	0.4	-	-	0.2	-	-	-	-	-	-	-	-	-	-	-	44.8	0.4	-	2.7	-
West Philippine Basin																														
IA1	54V6824	20.2	6.6	3.6	0.4	-	0.4	13.6	7.4	2.0	3.4	-	0.2	1.4	-	-	-	1.0	-	1.0	0.2	-	0.2	0.8	-	37.5	-	-	-	-
IA1	4N70	20.1	13.8	0.9	-	-	-	-	40.6	-	-	-	-	0.5	-	-	-	-	-	-	0.4	-	-	0.5	-	23.2	-	-	-	-
IA2	54V6818	53.0	4.2	10.1	1.7	-	2.0	5.9	9.6	1.1	3.7	-	0.6	0.3	-	-	-	0.3	-	0.3	0.6	-	0.6	3.7	-	-	-	2.5	-	-
IA2	54V6816	56.3	3.9	8.6	1.3	-	0.8	5.4	12.2	1.3	4.9	-	tr	0.3	tr	-	-	-	-	0.3	2.1	-	-	0.3	-	-	-	2.3	-	-

Table 1. (continued).

Assemblage Sample Cpx Opx Hb1 Hb2 Hb3 Hb4 Op Hd L Ep Grn Zr Ap Sph Trm Rt Chl St Ol Act Mus Mi Bi Cc FD Glc Py Ba Gph

Table 1. (continued).

Assemblage	Sample	Cpx	Opx	Hbl	Hb2	Hb3	Hb4	Op	Hd	L	Ep	Grn	Zr	Ap	Sph	Trm	Rt	Chl	St	Ol	Act	Mus	Mi	Bi	Cc	FD	Glc	Py	Ba	Gph
Northwest Arc province																														
Ryukyu Arc and Trench																														
IIA1	14P794	37.8	47.8	3.2	-	-	1.3	2.9	1.9	2.6	1.6	-	0.3	-	-	-	-	-	-	-	0.3	-	0.3	-	-	-	-	-	-	-
IIA1	14P797	30.3	48.1	7.3	-	0.7	0.7	0.7	2.0	2.0	1.6	0.3	tr	2.6	tr	0.7	tr	0.7	0.3	-	-	-	1.0	1.0	-	-	-	-	-	tr
IIA1	14P799	33.3	58.0	2.0	-	tr	0.3	1.0	0.7	2.7	0.7	0.3	tr	tr	tr	-	0.6	tr	-	-	tr	0.3	-	-	-	-	-	-	-	-
IIA1	14P800	39.1	53.2	2.0	-	-	0.3	0.7	1.0	1.0	0.3	0.7	0.3	0.7	-	-	-	0.7	-	-	-	tr	-	-	-	-	-	-	-	tr
IIA1	14P801	38.2	54.4	1.3	-	-	0.3	0.3	1.0	2.3	0.3	0.3	-	tr	0.3	-	tr	-	-	-	-	-	1.3	-	-	-	-	-	-	-
IIA2	14P814	30.2	37.0	10.0	-	3.6	1.0	2.0	4.3	3.0	4.0	1.0	tr	1.0	0.7	0.3	0.3	0.7	-	-	-	0.3	0.7	-	-	-	-	-	-	-
IIA1	14P812	36.9	43.2	4.6	-	1.3	0.7	0.7	4.9	1.3	2.6	tr	-	0.7	tr	0.3	0.6	1.6	-	-	0.3	-	0.3	-	-	-	-	-	-	-
IIA2	14P825	16.0	23.9	16.0	-	3.6	-	5.4	-	-	5.7	0.9	2.1	0.9	0.3	0.3	0.9	7.8	-	-	4.8	0.6	8.2	2.4	-	-	-	-	-	-
IIA1	14P832	29.1	35.9	8.3	-	0.9	0.3	1.6	3.2	1.9	5.4	tr	0.6	0.3	tr	tr	tr	4.1	-	-	5.8	-	1.9	0.6	-	-	-	-	-	-
IIA1	14P834	20.4	48.1	9.2	-	1.2	0.9	2.4	0.6	1.5	5.0	0.6	1.5	1.2	0.3	tr	3.8	0.3	0.6	-	1.5	0.3	0.3	tr	-	-	-	0.3	tr	-
IIA1	14P889	14.7	23.3	3.0	-	6.3	0.3	5.0	5.0	4.7	13.7	2.0	0.7	1.3	1.3	-	1.6	13.3	-	-	3.3	-	0.3	-	-	-	-	-	-	tr
IIA2	14P887	14.4	18.4	4.8	0.3	10.7	-	6.7	18.4	3.2	6.9	1.9	4.3	1.9	1.1	1.1	1.4	-	-	-	1.3	0.5	2.1	0.5	-	-	-	-	-	-
IIA1	14P892	26.1	46.1	9.8	-	2.3	0.3	3.9	1.6	3.6	2.6	-	0.3	0.7	0.3	-	-	-	0.7	-	0.7	-	0.3	-	-	-	-	0.7	-	-
IIA1	14P884	28.6	39.5	8.3	-	1.2	-	3.8	4.1	1.8	1.8	0.6	1.5	0.3	0.6	-	tr	1.2	-	-	0.3	0.6	0.3	-	-	-	-	5.6	-	-
IIA1	14P891	24.1	39.6	4.0	-	2.6	0.7	5.6	9.6	2.0	5.3	1.3	0.3	0.7	0.3	tr	0.7	0.7	-	-	1.0	1.0	0.3	-	-	-	-	0.3	-	-
IIA2	14P928	9.2	12.5	5.9	-	4.6	0.3	25.0	9.5	4.6	10.5	4.6	3.3	0.3	2.3	-	5.6	0.7	-	-	0.3	-	0.7	-	-	-	-	-	-	tr
Southwestern Ryukyu province																														
Ryukyu Arc and Trench																														
IIIB3	14P927	14.0	4.8	22.2	0.3	-	0.3	17.9	13.3	3.8	15.0	1.0	1.8	0.3	-	1.3	0.5	1.3	-	-	0.5	-	1.3	0.3	-	-	-	-	-	0.3
IIA2	17P7087	18.9	20.2	21.0	0.8	1.3	9.6	0.5	6.4	2.6	1.6	1.6	1.3	0.5	tr	1.9	0.8	-	-	-	1.3	0.5	8.0	1.1	-	-	-	-	-	-
IIIA3	17P7083	27.7	5.1	14.7	1.8	7.5	7.9	0.9	8.5	5.5	7.5	0.2	0.9	0.4	0.7	1.1	0.2	0.7	-	-	3.5	1.1	2.6	0.9	0.4	-	-	-	0.2	-
IIIC1	17P7092	9.0	9.3	13.4	0.3	2.0	1.7	tr	10.2	6.4	7.2	tr	0.8	2.0	tr	0.6	tr	0.6	-	-	2.3	4.9	26.2	1.7	1.2	-	-	-	-	-
V	14P929	13.3	13.3	8.8	-	7.3	-	7.6	0.7	3.5	26.5	0.7	0.3	2.2	2.2	0.3	0.6	6.6	0.3	-	3.8	0.3	1.6	-	-	-	-	-	-	tr
IIIC1	17P7094	5.0	6.8	14.5	-	8.0	0.3	0.3	10.7	5.0	4.1	tr	1.2	1.5	0.6	0.9	0.9	1.2	0.3	-	3.8	5.9	24.6	1.2	3.3	-	-	-	-	tr
VII	17P7060	1.0	1.6	6.7	-	tr	-	1.3	0.3	37.2	4.1	6.0	11.7	-	3.8	5.4	5.3	1.0	0.3	-	tr	1.0	12.7	-	0.3	-	-	-	-	0.3
VII	17P7069	0.9	1.5	1.5	0.6	0.3	-	tr	2.0	9.4	3.6	2.4	20.6	4.8	2.1	3.9	4.5	0.6	0.3	-	-	-	37.8	1.2	1.8	-	-	-	-	0.3
IIIA1	17P7078	9.1	-	0.1	0.1	0.3	0.4	28.0	2.3	1.9	0.5	0.1	-	0.1	1.1	0.2	0.5	0.2	-	0.5	0.3	3.6	0.2	0.1	0.1	-	-	-	-	50.3

Table 1. (continued).

Assemblage	Sample	Cpx	Opx	Hb1	Hb2	Hb3	Hb4	Op	Hd	L	Ep	Grn	Zr	Ap	Sph	Trm	Rt	Chl	St	Ol	Act	Mus	Mi	Bi	Cc	FD	Glc	Py	Ba	Gph
IIIC2	17P7077	5.9	-	tr	0.2	0.5	0.2	20.6	8.2	4.6	0.2	0.2	0.6	0.3	0.5	0.2	1.0	0.1	-	0.7	0.7	3.3	0.2	0.2	-	-	-	-	0.2	51.5
IIIC1	17P7075	7.9	5.8	11.3	1.1	2.6	6.1	0.3	9.5	7.9	5.5	tr	tr	1.6	-	1.8	0.3	0.6	0.3	-	2.1	2.1	29.9	2.6	0.3	-	-	-	-	0.5
IIIC1	23V16	3.0	4.7	6.2	0.5	2.7	-	1.5	29.6	2.0	13.2	0.5	-	0.3	-	0.8	-	1.2	-	-	0.3	3.7	27.4	-	2.5	-	-	-	-	-
IIIC1	23V15	2.3	0.3	6.9	-	-	tr	4.1	23.5	-	3.3	0.3	tr	-	0.3	-	-	1.5	-	-	-	4.3	52.0	1.0	0.3	-	-	-	-	-
Northwestern Area of the Philippine Sea																														
IIA1	14P803	34.0	52.7	1.3	-	0.3	0.3	1.6	1.6	3.0	1.7	-	-	tr	-	0.3	tr	1.6	-	-	0.3	0.3	1.0	-	-	-	-	-	-	-
IIA1	14P837	27.7	47.1	5.6	tr	0.3	tr	8.6	1.7	-	2.0	-	0.7	-	-	-	tr	0.7	-	-	-	-	-	-	-	-	-	5.6	-	-
IIA2	14P879	16.3	26.0	0.3	13.1	0.3	0.3	33.0	7.7	0.7	1.3	-	0.7	-	tr	-	tr	-	-	-	-	0.3	-	-	-	-	-	-	-	-
IIA2	14P881	27.7	19.2	10.2	0.3	21.5	1.3	2.6	2.0	2.3	2.3	-	0.3	0.3	-	0.3	-	-	-	-	1.3	tr	0.7	-	-	-	-	7.6	-	-
IIA2	14P840	26.9	32.8	26.7	0.7	1.0	0.7	4.3	3.6	1.0	1.0	-	-	-	-	tr	tr	-	-	-	0.7	-	0.3	-	-	-	-	0.3	-	-
IIA2	14P882	22.1	38.6	17.2	-	2.6	0.3	3.0	1.6	2.6	6.0	0.7	tr	-	tr	0.7	0.3	1.9	tr	-	1.0	tr	0.7	-	-	-	-	0.7	-	-
IIA1	14P883	30.4	42.6	10.6	-	2.3	0.3	0.7	1.3	4.0	4.6	-	0.3	0.3	0.7	0.3	-	0.3	tr	-	1.3	-	-	-	-	-	-	-	-	-
IIA2	4K7558	25.5	13.0	20.0	1.0	-	1.0	15.7	9.7	8.8	1.7	-	-	1.7	-	-	-	-	-	-	-	-	1.0	1.0	-	-	-	-	-	-
IA2	4K7559	35.8	4.3	12.3	-	-	-	11.2	18.9	4.6	1.4	-	0.2	0.2	-	-	-	-	-	-	0.5	0.2	0.2	0.2	0.7	9.3	-	-	-	-
IIA2	4N64	14.9	28.6	17.9	-	-	3.0	3.5	22.3	7.1	0.8	-	0.2	1.0	-	-	-	-	-	-	-	-	-	0.2	-	-	0.5	-	-	-
IIA2	4N69	17.6	17.8	11.2	-	-	0.7	0.5	37.7	3.4	0.2	-	0.2	0.7	-	-	-	-	-	0.2	-	-	-	1.0	-	8.8	-	-	-	-
Taiwan province																														
VI	4K7596	2.4	-	0.8	0.3	-	-	0.5	1.6	1.6	1.3	-	0.3	-	-	-	-	38.9	-	0.3	0.3	37.0	9.1	1.9	3.5	-	-	0.3	-	-
VI	23V4	8.6	0.3	11.7	1.1	-	6.1	-	-	1.4	4.2	-	-	-	-	-	-	62.1	-	-	-	2.8	0.8	0.6	0.3	-	-	-	-	-
VI	23V3	3.6	0.4	4.4	2.1	-	0.6	1.7	19.4	13.2	14.0	1.0	1.3	-	-	0.4	0.4	29.9	0.2	-	1.0	1.7	2.9	1.0	0.8	-	-	-	-	-
VI	23V7/5-18cm	2.0	-	3.4	0.3	-	0.6	-	13.9	-	0.3	-	-	-	-	-	0.3	53.7	-	-	-	22.4	2.0	1.1	-	-	-	-	-	-
IIIB1	23V7/52-62cm	32.4	4.0	14.7	5.6	-	5.1	8.9	4.7	17.7	3.3	-	-	0.2	-	-	-	1.4	-	-	0.7	0.2	-	1.2	-	-	-	-	-	-
IIIB1	23V7/69-77cm	36.3	3.0	12.4	4.6	-	6.4	5.6	4.3	11.9	3.3	-	-	0.5	-	-	-	8.6	-	0.3	0.8	0.5	0.5	1.0	-	-	-	-	-	-
IIIB1	23V7/87-108cm	43.2	1.7	14.4	6.9	-	8.6	7.2	3.9	11.1	0.6	-	-	-	-	-	-	1.1	-	0.8	-	-	0.3	0.3	-	-	-	-	-	-
VI	23V2	0.7	0.3	1.7	-	-	0.3	-	31.1	4.9	6.4	-	0.5	0.3	-	0.3	0.3	43.7	-	-	0.3	2.5	4.0	0.3	2.7	-	-	-	-	-
West Philippine Sea province																														
Gagua Ridge Area																														
IIIA2	23V8/20cm	13.9	-	31.1	2.3	-	27.5	1.3	2.0	6.6	-	-	-	0.3	-	-	-	1.3	-	-	-	5.6	-	8.0	-	-	-	-	-	-

Table 1. (continued).

Table 1. (continued).

Assemblage	Sample	Cpx	Opx	Hb1	Hb2	Hb3	Hb4	Op	Hd	L	Ep	Grn	Zr	Ap	Sph	Trm	Rt	Chl	St	Ol	Act	Mus	Mi	Bi	Cc	FD	Glc	Py	Ba	Gph
IIIB1	23V9	39.3	0.9	20.1	8.6	-	6.0	4.0	5.2	13.8	0.3	-	tr	0.3	-	-	-	0.3	-	0.3	0.3	-	-	0.6	-	-	-	-	-	-
IIIA4	23V10	22.9	2.4	47.7	-	0.5	14.4	-	-	7.2	1.9	-	-	0.8	-	-	-	-	-	0.5	-	-	-	1.6	-	-	-	-	-	-
IIIA4	23V10/30-54cm	24.7	1.6	37.7	1.6	-	8.7	10.3	1.4	11.4	-	-	-	tr	-	-	-	0.8	-	0.5	-	0.5	-	0.8	-	-	-	-	-	-
IIIB1	23V10/54-70cm	44.0	2.3	30.6	-	-	5.5	2.9	-	9.4	2.6	-	-	-	-	-	-	-	-	0.3	-	0.3	-	1.9	-	-	-	-	-	-
IIIA3	23V10/70-90cm	28.8	0.3	27.6	1.8	-	5.5	11.2	10.8	6.1	0.9	-	-	0.6	-	-	-	0.6	-	0.3	-	1.2	-	4.3	-	-	-	-	-	-
IIIC2	23V12	11.5	0.8	9.9	2.5	-	5.2	-	41.8	1.7	3.6	-	-	0.4	-	-	-	11.5	-	-	0.2	3.8	3.1	4.0	0.2	-	-	-	-	-
Northwestern Area of the Philippine Sea																														
IIIB1	17M1394	29.5	6.8	25.2	0.6	-	1.8	16.0	10.7	3.7	1.2	0.3	-	2.5	-	-	-	-	-	-	-	-	0.3	1.2	-	-	-	-	-	-
IIIB1	4K7552	31.4	10.7	26.5	1.8	1.8	-	9.2	6.4	8.5	1.5	-	0.6	0.3	-	-	-	-	-	0.3	-	-	-	0.3	-	0.6	-	-	-	-
IIIA4	4N66	18.0	19.1	39.3	-	-	3.6	-	8.0	2.7	2.7	-	1.9	1.6	-	-	-	-	-	-	-	-	-	1.1	-	1.9	-	-	-	-
IIIA4	4N63	25.8	11.9	53.6	-	-	0.9	-	-	2.9	-	-	0.3	2.3	-	-	0.6	-	-	-	-	-	-	0.6	-	0.6	-	-	0.6	-
IIIA4	4K7560	17.8	4.7	43.2	0.6	1.2	-	13.4	7.9	6.7	0.3	-	-	2.0	-	-	0.3	0.3	-	-	-	-	0.3	0.9	-	0.6	-	-	-	-
IIIA3	4K7599	16.9	0.9	13.8	2.7	-	10.2	0.9	26.9	6.2	5.3	-	0.4	-	0.4	-	-	3.6	-	-	-	4.9	5.3	1.3	-	-	-	-	-	-
IIIA4	4K7561	14.9	9.3	25.7	0.6	0.3	0.6	6.8	19.0	14.0	1.9	-	0.3	2.5	-	-	-	-	-	-	0.6	-	-	0.6	-	2.8	-	-	-	-
IIIA2	23V6/30-60cm	17.3	-	14.0	3.9	-	46.8	2.2	0.6	2.2	2.8	-	-	0.3	-	-	-	2.0	-	1.1	-	3.6	-	3.1	-	-	-	-	-	-
IIIC1	23V6/110-120cm	23.5	1.1	12.0	4.3	-	3.2	2.4	4.6	6.0	0.8	-	-	0.8	-	-	-	5.1	-	0.3	-	32.5	1.6	1.6	-	-	-	-	-	-
IIIA3	23V6/150-167cm	23.8	0.3	22.3	5.1	-	11.4	3.0	5.1	5.3	3.0	-	-	1.0	-	-	-	14.7	-	0.5	-	2.5	-	2.0	-	-	-	-	-	-
IIIB1	17M1395	27.1	7.1	23.4	-	-	1.7	22.4	10.2	5.1	0.7	0.3	-	1.7	-	-	0.3	-	-	-	-	-	-	-	-	-	-	-	-	-
IIIA4	33B2836	23.3	1.6	66.1	-	-	1.3	0.5	1.0	2.9	1.0	-	-	1.0	-	-	-	-	0.3	-	0.3	-	-	0.8	-	-	-	-	-	-
IIIA4	33B2836/16-25cm	25.8	6.6	55.2	-	-	2.2	3.4	0.5	3.6	0.9	-	-	1.0	-	-	-	-	0.2	-	-	-	-	0.5	-	-	-	-	-	-
IIIA4	33B2836/25-50cm	17.7	3.9	71.0	-	-	2.8	0.5	0.5	1.5	0.5	-	-	1.3	-	-	-	-	-	-	-	-	tr	0.3	-	-	-	-	-	-
IIIA4	33B2836/50-79cm	25.3	7.8	53.2	-	-	3.0	1.6	1.8	4.4	1.4	-	-	1.2	-	-	-	-	-	-	-	-	-	0.2	-	tr	-	-	-	-
IA3	33B2834	27.4	0.4	1.2	-	-	-	3.1	35.4	14.6	-	-	-	13.6	-	-	-	-	-	0.6	-	-	-	0.4	-	0.4	-	-	2.9	-
IA2	33B2835/1	74.6	-	17.9	-	-	1.2	0.6	2.3	1.7	-	-	-	1.2	-	-	-	-	-	-	-	-	-	-	-	0.6	-	-	-	-
IIIA4	33B2835/2	32.2	5.0	53.9	-	-	1.2	1.9	0.6	2.8	0.9	-	-	0.9	-	-	-	-	-	-	-	-	-	0.6	-	-	-	-	-	-
IIIA1	3V45	2.6	-	79.2	0.5	-	3.6	3.6	6.2	-	-	-	-	2.8	-	-	-	-	-	-	-	-	-	1.5	-	-	-	-	-	-
IIIB1	3V17	45.3	7.6	33.7	1.3	-	1.1	7.1	2.4	1.3	-	-	-	0.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IIIA4	3V16	16.9	3.3	62.8	1.9	-	2.1	4.8	5.0	0.5	0.3	-	-	2.4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IIIA1	3V46	3.4	0.3	73.6	-	-	1.2	15.5	1.9	0.9	-	-	0.3	2.2	-	-	-	-	-	-	-	-	0.6	-	-	-	-	-	-	-

Table 1. (continued).

Assemblage	Sample	Cpx	Opx	Hb1	Hb2	Hb3	Hb4	Op	Hd	L	Ep	Grn	Zr	Ap	Sph	Trm	Rt	Chl	St	Ol	Act	Mus	Mi	Bi	Cc	FD	Glc	Py	Ba	Gph
West Philippine Basin																														
IIIB1	3V33	14.1	0.9	12.5	0.6	-	0.3	5.9	44.1	4.4	0.6	-	-	0.9	-	-		0.3	-	0.3	-	-	-	-	-	15.0	-	-	-	-
IIIB1	4K7588	4.3	0.1	2.2	-	-	0.1	-	88.0	-	2.5	-	-	-	-	-	-	-	-	0.1	1.5	-	0.1	1.0	-	-	-	-	-	-
IIIB2	4K7589	19.9	3.0	29.5	2.5	1.8	-	1.4	5.7	2.7	20.6	0.5	-	0.2	0.2	-	-	3.7	-	-	5.5	0.2	0.7	2.1	-	-	-	-	-	-
V	4K7575	0.3	-	0.6	-	-	-	1.4	1.4	-	54.7	-	0.9	0.3	1.1	-	0.3	0.6	-	-	38.6	-	-	-	-	-	-	-	-	-
IIIB1	4K7583	39.8	3.7	19.0	-	-	0.5	9.3	12.0	1.9	5.1	-	-	1.9	0.5	0.5	-	0.5	-	1.4	0.9	-	-	-	-	3.2	-	-	-	-
IIIA4	4K7574	24.9	8.6	33.3	1.5	1.7	-	7.7	6.4	11.4	1.0	-	0.3	1.2	-	-	0.3	0.5	-	0.3	-	-	-	-	0.5	0.5	-	-	-	-
Philippine Arc province																														
Manila Trench																														
IA2	4K7595	32.1	3.3	7.1	2.4	-	0.6	4.5	4.5	36.3	3.6	-	-	0.3	-	-	-	0.9	-	1.8	0.6	0.3	0.9	-	0.9	-	-	-	-	-
IA1	17M1416	32.7	5.3	2.1	-	-	0.6	10.9	4.4	41.0	0.9	-	-	-	-	-	-	-	-	1.5	0.3	-	-	0.3	-	-	-	-	-	-
IIIB2	17M1412	0.0	0.0	0.0	-	-	-	0.0	0.0	0.0	0.0	-	-	0.0	-	-	-	0.0	-	-	0.0	0.0	0.0	-	-	0.0	-	0.0	0.0	-
IIIB2	17M1413	26.9	2.3	13.9	0.9	-	0.3	9.0	3.5	26.9	11.3	-	0.3	1.7	-	-	-	1.2	-	0.3	1.5	0.3	-	-	-	-	-	-	-	-
Philippine Trench																														
IIIB2	17M1421	34.0	2.6	6.6	0.7	2.6	1.0	8.3	3.8	11.1	22.5	-	-	0.2	0.2	-	0.2	3.1	-	0.2	2.4	-	0.2	-	-	-	-	0.2	-	-
V	17M1419/25-30cm	5.7	0.8	11.6	3.3	-	0.5	30.8	6.4	0.5	25.2	0.8	1.0	1.0	0.3	-	0.3	1.0	-	-	9.8	0.5	0.3	0.3	-	-	-	-	-	-
IIIB2	4K7590	19.3	1.2	20.9	-	-	0.7	1.4	9.3	5.6	26.0	0.2	-	0.2	0.9	-	-	2.8	-	-	9.7	0.7	0.2	0.7	0.2	-	-	-	-	-
IIIB2	54V6810	29.1	3.8	21.6	0.3	-	1.8	3.0	6.5	3.3	19.8	-	0.5	0.8	0.5	-	-	2.5	-	-	4.5	-	-	2.0	-	-	-	-	-	-
IIIB2	54V6812	33.9	2.8	15.3	1.0	2.3	-	2.5	6.8	3.5	20.6	0.5	-	1.0	0.3	-	-	2.0	-	1.0	5.8	-	0.5	0.3	-	-	-	-	-	-
IA2	54V6808	71.3	1.7	6.8	2.0	-	2.0	3.7	5.7	1.7	1.4	-	-	2.0	-	-	-	1.0	-	-	0.3	-	-	0.3	-	-	-	-	-	-
Yap-Palau province																														
IIIB2	4K7569	20.7	1.2	14.4	0.6	-	-	10.8	20.4	9.9	9.3	-	-	0.6	-	-	-	1.2	-	-	7.5	-	0.3	-	-	1.8	-	0.9	0.3	-
V	17M1429	10.7	4.2	2.3	-	-	-	0.2	13.7	2.3	53.5	-	-	0.7	0.2	0.2	-	5.3	0.2	0.9	4.2	tr	0.7	-	0.2	-	-	-	0.5	-

Cpx=clinopyroxene; Opx=orthopyroxene; Hb=hornblende (1=brownish green, 2=brown, 3=green, 4=dusky brown); Op=black opaque minerals (magnetite, ilmenite, chromite); Hd=brown opaque minerals (iron hydroxides); L=lithic fragments; Ep=epidote (group); Grn=garnet; Zr=zircoon; Ap=apatite; Sph=sphene; Trm=tourmaline; Rt=rutile and anatase undistinguished; Chl=chlorite; St=staurolite, corundum, and andalusite undistinguished; Ol=olivine; Act=actinolite; Mus=muscovite; Mi=green mica; Bi=biotite; Cc=calcite; FD=feesh debris; Gln=glauconite; Py=pyrite; Ba=barite; Gph=glaucophane; tr=trace abundance.

Table 2. Average heavy-mineral compositions (%) of the sample groups defined by cluster analysis.

Assemblage	Cpx	Opx	Hbl	Hb2	Hb3	Hb4	Ep	Grn	Zr	Ap	Sph	Trm	Rt	Chl	St	Ol	Act	Mus	Mi	Bi	Cc	Ba	Gph
East Arc province																							
IA1(20)	63.3	27.1	2.9	0.4	-	1.1	1.3	0.2	tr	1.6	tr	-	-	0.2	0.5	0.5	0.2	tr	0.2	0.2	tr	0.2	-
IA2(40)	76.3	6.6	5.8	0.9	tr	1.9	2.8	0.3	0.2	1.3	-	-	tr	0.5	0.2	2.5	0.4	0.1	0.2	0.3	tr	0.4	-
IA3(4)	48.1	14.2	3.9	5.5	-	10.5	2.3	-	0.3	1.4	-	-	-	0.3	-	3.7	0.4	-	0.4	4.2	-	5.5	-
Northwest Arc province																							
IIA1(17)	32.4	49.7	5.9	-	1.3	0.5	3.7	0.5	0.5	0.7	0.4	0.1	0.6	1.7	0.1	-	1.2	0.2	0.5	0.1	tr	-	-
IIA2(13)	26.8	32.0	17.3	2.0	4.7	1.8	4.4	1.1	1.3	1.2	0.5	0.5	1.1	1.1	-	tr	1.0	0.2	2.0	0.8	-	tr	-
West Philippine Sea province																							
IIIA1(7)	5.2	1.8	72.2	0.5	tr	1.6	10.9	0.4	0.3	1.5	tr	0.8	0.2	0.3	0.2	-	1.0	0.2	2.7	0.4	0.1	-	-
IIIA2(2)	16.8	-	24.7	3.4	-	39.9	1.5	-	-	0.3	-	-	-	1.8	-	0.6	-	5.0	-	6.0	-	-	-
IIIA3(4)	31.5	2.0	25.6	3.6	2.2	11.4	5.4	tr	0.4	0.6	0.4	0.3	tr	6.0	-	0.3	1.0	3.3	2.8	2.8	0.1	tr	-
IIIA4(13)	26.1	8.0	56.7	0.6	0.4	3.6	1.2	-	0.3	1.7	-	-	0.1	0.2	tr	0.1	0.1	tr	tr	0.7	tr	tr	-
IIIB1(14)	48.0	6.4	30.1	3.1	0.2	3.7	3.5	tr	tr	1.2	tr	tr	0.2	1.2	-	0.6	0.5	0.1	0.2	0.9	-	-	-
Philippine Arc province																							
IIIB2(4)	43.7	2.5	18.0	1.4	0.9	1.1	22.2	-	-	0.7	tr	-	tr	2.8	-	tr	6.0	tr	0.2	0.2	-	0.1	-
IIIB3(2)	25.8	5.7	28.2	5.4	-	1.1	21.8	0.8	1.6	0.6	0.3	1.8	0.4	2.3	-	-	2.7	-	1.8	1.2	-	-	0.2
Southwestern Ryukyu province																							
IIIC1(6)	10.2	5.8	13.3	1.2	3.2	2.3	7.6	0.2	0.4	1.2	0.2	0.9	0.2	2.1	0.1	tr	1.7	10.7	35.3	1.7	1.6	-	0.1
IIIC2(2)	16.6	4.5	18.2	2.2	0.4	5.6	13.5	0.4	0.4	1.8	0.6	1.0	0.4	12.4	0.2	-	1.8	5.0	10.9	4.0	0.6	-	0.4
VII(2)	1.3	2.2	6.3	0.3	0.2	-	5.4	6.3	21.2	2.7	4.3	6.6	6.8	1.1	0.4	-	tr	0.8	31.7	0.7	1.3	-	0.4
Taiwan province																							
VI(4)	4.7	0.2	5.8	1.2	-	2.0	6.8	0.4	0.6	-	-	0.2	0.2	52.8	tr	tr	0.5	17.5	4.3	1.4	1.3	-	-
Yap-Palau province*																							
IV(3)	26.6	3.1	1.9	-	8.8	0.5	10.3	-	-	-	-	-	-	-	-	46.7	2.2	-	-	-	-	-	-
V(6)	12.0	5.4	8.8	0.9	1.4	0.1	50.8	0.3	0.5	0.9	0.7	0.1	0.2	2.7	0.1	2.7	11.5	0.2	0.5	tr	tr	tr	-

In the first column, number in brackets indicates a number of analyses used to calculate the group mean.
* Assemblage IIIA1 (see West Philippine Sea province) is also characteristic of this province.
Cpx=clinopyroxene; Opx=orthopyroxene; Hb=hornblende (1=brownish green, 2=brown, 3=green, 4=dusky brown); Ep=epidote (group); Grn=garnet; Zr=zircon; Ap=apatite; Sph=sphene; Trm=tourmaline; Rt=rutile and anatase undistinguished; Chl=chlorite; St=staurolite, corundum, and andalusite undistinguished; Ol=olivine; Act=actinolite; Mus=muscovite; Mi=green mica; Bi=biotite;Cc=calcite; Ba=barite; Gph=glaucophane; -=not found; tr=trace abundance.

compositions of these assemblages (Table 2) were compared with mineral compositions of individual samples, which had not been included in the statistics because of some difference in the sample preparation and analytical methods (112 analyses from Suzuki, 1975; Nechaev, 1987; Nechaev *et al.*, 1989). The comparison was carried out on the basis of major mineral characteristics such as: (1) total content of pyroxenes and hornblende (major volcaniclastic minerals) versus total content of olivine, epidote, garnet, actinolite, chlorite, glaucophane, colorless and green mica, zircon, tourmaline, staurolite, rutile, anatase and sphene (major minerals derived from metamorphic and intrusive rocks); and (2) interrelationship between clinopyroxene, orthopyroxene, and hornblende. Choosing these mineral components, we were based on our previous work on heavy-mineral assemblages from sediments as indicators of major crystalline rocks in their provenances (Nechaev, 1987, 1991; Nechaev and Derkachev, 1989; Nechaev *et al.*, 1989). As a result, all the mineral analyses available were "distributed" between the assemblages that allowed mineral provinces of the Philippine Sea region to be outlined as carefully as possible.

3. Sources of Samples and Data

All the samples used for our analyses were taken from the collection of the Pacific Oceanological Institute, Far Eastern Branch, Russian Academy of Sciences. They were obtained in several marine cruises on different Russian research vessels, as indicated in Appendix and Fig. 1. More detailed information on the sediments studied is available in the initial cruise reports kept in the archive of the Shirshov Oceanological Institute (Moscow, Russia).

The data used in addition to those presented in Table 1 were compiled from literature (Suzuki, 1975; Skornyakova *et al.*, 1978; Murdmaa *et al.*, 1980; Nechaev, 1987, 1991; Nechaev *et al.*, 1989; see also Fig. 1).

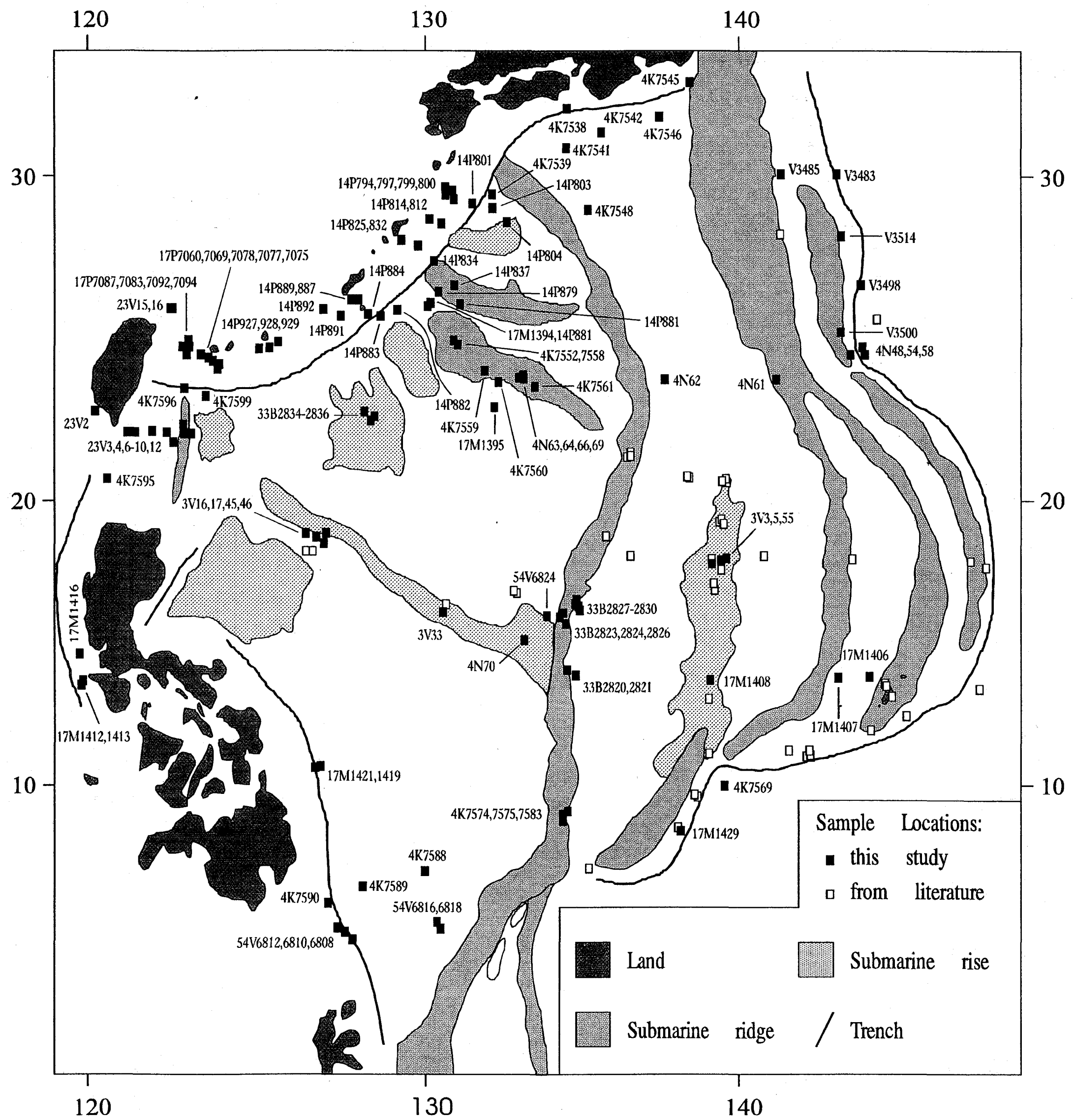

Fig. 1. Map of the Philippine Sea region (simplified after Svarichevsky, this volume) showing the sample locations. Data from literature were compiled from Suzuki, 1975; Skornyakova *et al.*, 1978; Murdmaa *et al.*, 1980; Nechaev, 1987, 1991; Nechaev *et al.*, 1989.

4. Results

As a result of cluster analysis, seven mineralogical provinces were distinguished in the surface sediments of the Philippine Sea and its margins. Below, we will describe heavy-mineral assemblages for each province.

4.1 East Arc province

This province covers the eastern part of the Philippine Sea including the Izu-Bonin and northern Mariana Trenches, Izu-Bonin and Mariana Arc, Mariana Trough, West Mariana Ridge, Parece-Vela Basin, Nankai Trough, Shikoku Basin, Kyushu-Palau Ridge, and southeastern West Philippine Basin (Figs. 2 and 3). Its heavy-mineral assemblages (IA1, IA2, and IA3 in Table 2) are dominated by two-pyroxene suite, in which green clinopyroxene (commonly augite, 63.3, 76.3 and 48.1% in group means) prevails over orthopyroxene (commonly hypersthene, 27.1, 6.7, and 14.2%). Small amounts of olivine (0.5, 2.5, and 3.7%) and apatite (1.6, 1.3, and 1.4%) characterize most of these assemblages as well. Pyroxenes, olivine, and apatite are often associated with brown and colorless volcanic glass, groundmass of volcanic rocks, plagioclase, magnetite, and, rarely, ilmenite. Their grains are, as a rule, fresh and crystalline-shape. Microprobe analyses of these minerals evidence that they are chiefly derived from volcanoes of the Izu-Bonin and Mariana (both ensimatic) arcs (Nechaev, 1987, 1991). Their transportation to the west, into the deep basins, is carried out mostly by pumice drifted with the surface water flows: the North Passat (trade-wind) current and Kuroshio counter-current (Danchenkov, 1977). These water flows have caused, respectively, the southern (south of 20°N) and northern (north of 28°N) advancements of the province to the west (Fig. 3). On the western flanks of the province, contents of minerals, which are characteristic of the adjacent provinces, are growing up. So, we can see the increasing orthopyroxene,

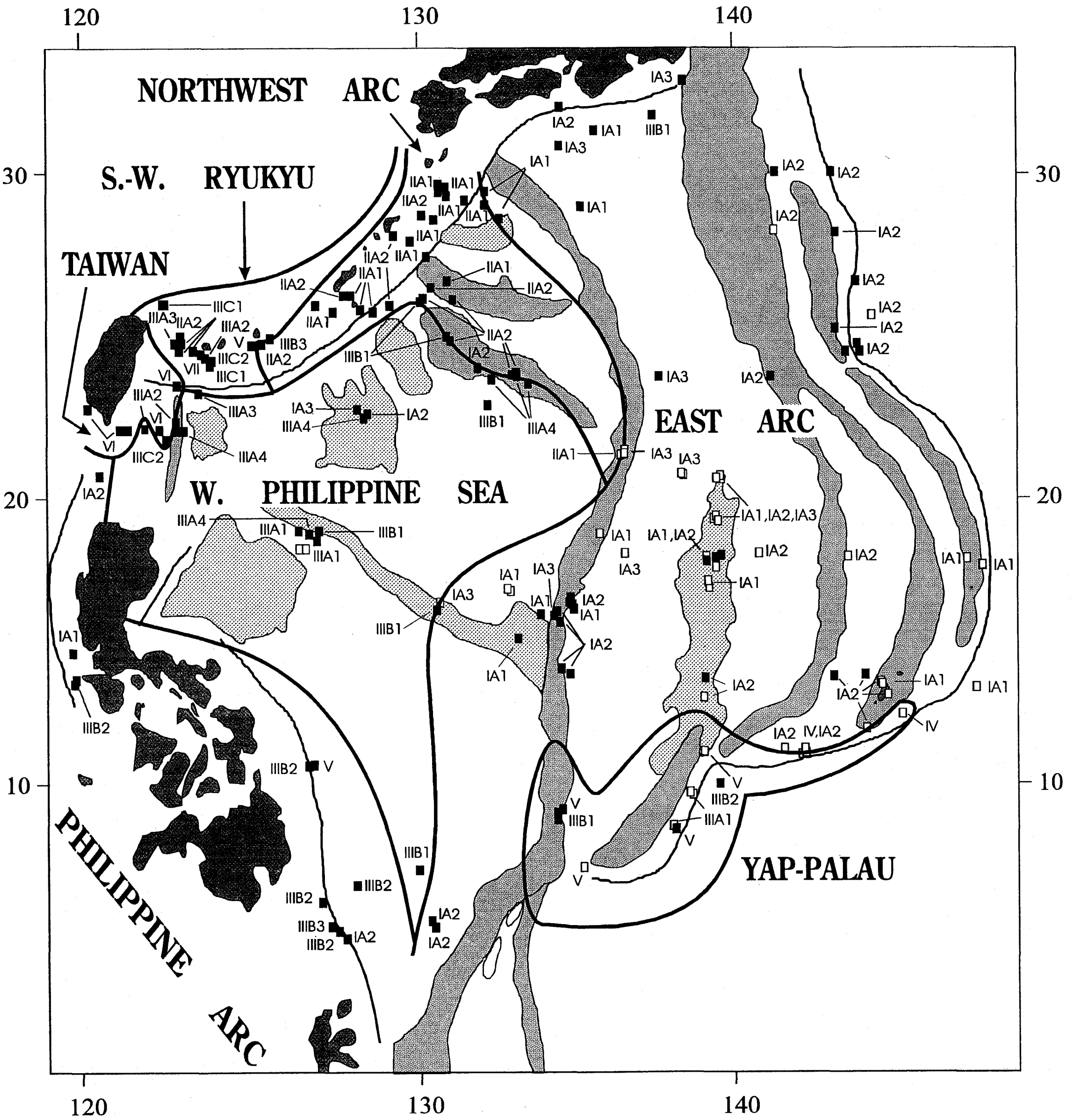

Fig. 2. Map of the Philippine Sea region (simplified after Svarichevsky, this volume) showing the heavy-mineral assemblages distribution and mineralogical provinces of Quaternary sediments (see Table 2 for the average compositions of assemblages).

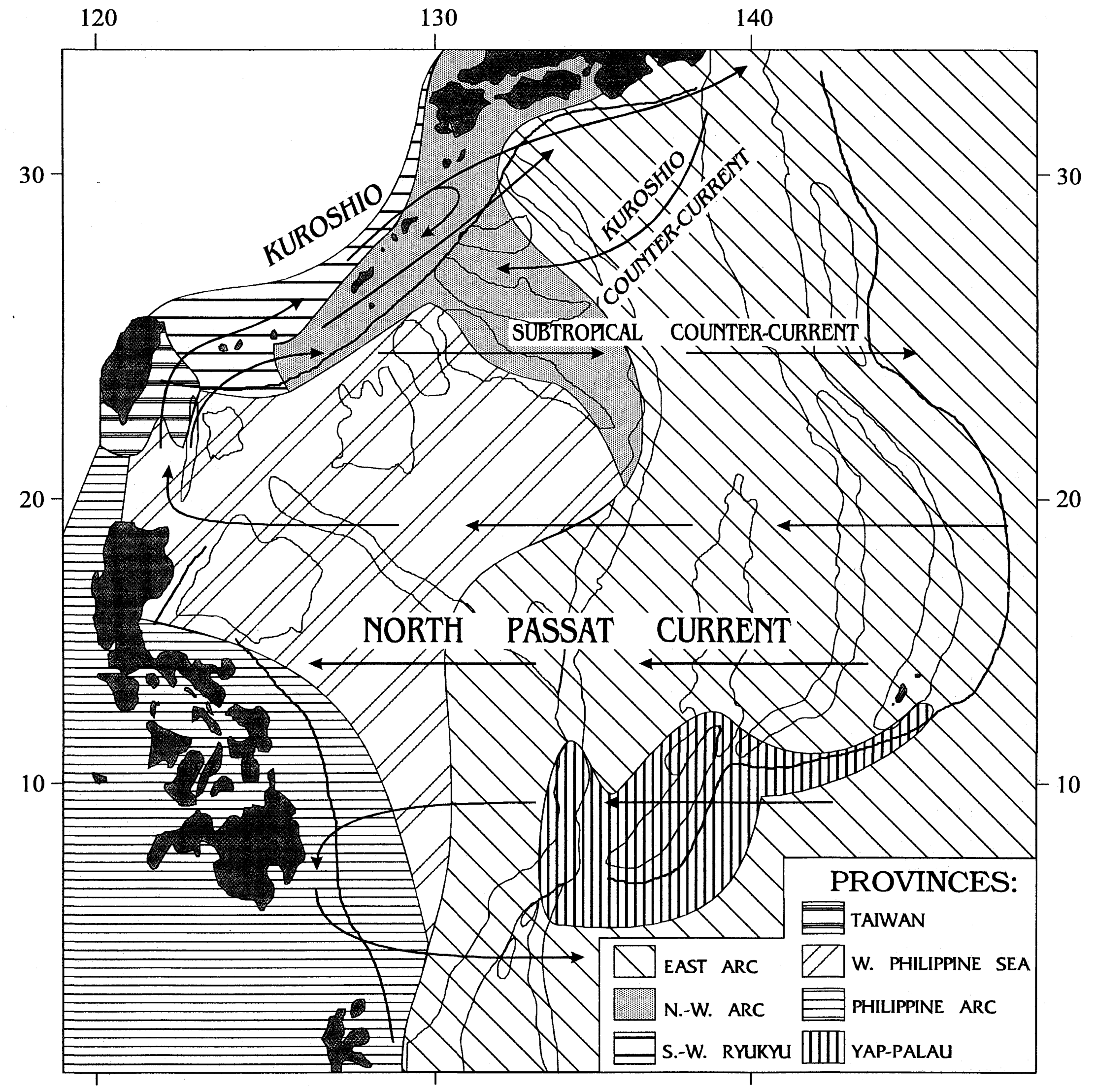

Fig. 3. Map of the Philippine Sea region (simplified after Svarichevsky, this volume) showing mineralogical provinces and surface water currents (simplified after Danchenkov, 1977).

hornblende, and biotite contents in assemblage IA3 distributed mostly in the Shikoku Basin, northern Kyushu-Palau Ridge, and northeastern West Philippine Basin (Table 2, Fig. 2). Sediment supply resulted from erosion of intrusive and metamorphic rocks is limited in the East Arc province. Nevertheless, relatively high contents of epidote, actinolite, and chlorite were found in sediments from the trenches, associated with subduction on the eastern boundaries of the Philippine Sea plate, as well as from local basins and narrow gullies associated with faulting in the intraplate environments (Skornyakova *et al.*, 1978; Murdmaa *et al.*, 1980; Nechaev *et al.*, 1989). Perhaps, some increasing of olivine contents in sediments from the Izu-Bonin Trench (samples V3483, V3514, V3496, 4N48 in Table 1; Suzuki, 1975) is due to submarine erosion of ultramafics exposed on the specific diapiric seamounts (Ishii *et al.*, 1992; Lelikov *et al.*, this volume). High barite content (up to 40% in sample 4N54, Table 1) in sediments on the island slope of the Izu-Bonin Trench near its connection to the Mariana Trench probably indicates some hydrothermal deposits eroded in this area.

4.2 Northwest Arc province

This province covers the central and northern Ryukyu arc-trench area and extends into the Philippine Sea between the Oki-Daito and Kyushu-Palau Ridges (Fig. 2). As the previous one, it is represented by heavy-mineral assemblages with dominating pyroxenes. However, orthopyroxene is more abundant (50–32% in group means) than clinopyroxene (32–27%) here (assemblages IIA1 and IIA2, Table 2). The highest orthopyroxene contents (>50%) are noted in the area of Kyushu and northern Ryukyu Islands. Hornblende contents in this province are higher than those in the East Arc province, they are growing to the south, where assemblage IIA2 with Hb = 25.9% in average and up to 39% in the individual sample values prevails (see Fig. 2). This assemblage is also characterized by relatively high amounts of garnet, zircon, tourmaline, sphene, and anatase (Table 2).

Factor analysis indicates that orthopyroxene and clinopyroxene have a positive correlation between themselves and negative correlations with all other components of the assemblages IIA1 and IIA2. So, pyroxenes and other minerals of these assemblages are of different origin. Pyroxenes are chiefly derived from Kyushu and northern Ryukyu Islands (encialic island arc), where great (caldera-creating) volcanic explosions occurred in the Late Pleistocene and Recent time (Machida and Arai, 1976, 1978; Miyachi and Miyachi, 1988). The relatively high hornblende content in the southern part of the province (see the distribution of assemblage IIA2 on Fig. 2) may be explained chiefly by the influence of other volcanic sources located between Luzon and Taiwan Islands (see below). Most of pyroxene and hornblende grains are fresh, crystalline-shape (mostly prismatic), and often covered by colorless volcanic glass that supports their pyroclastic origin. Configuration of the province, which does not correspond to the pattern of surface water currents (Fig. 3), suggests that transportation of volcaniclastic material from the northern Ryukyu Arc into the intrasea region is carried out rather by wind than by water flows. Zircon, tourmaline, garnet, anatase, and sphene, which are relatively abundant in the southern area of the province, where the recent volcanism is absent, positively correlate with epidote, actinolite, and chlorite. All they are most likely derived from local erosion and weathering of Tertiary metamorphic and sedimentary rocks composing the Ryukyu Arc and Daito and Oki-Daito Ridges (Sato and Suzuki, 1977; Hashimoto, 1978; Sato, 1980; Kizaki, 1986). Perhaps, some of hornblende grains associated with metamorphic minerals in assemblage IIA2 are of the same origin.

4.3 Southwestern Ryukyu province

This province covers the area around the Sakishima-Gunto islands in the southwestern Ryukyu arc. According to the previous data (Derkachev and Nikolaeva, 1992), it extends into the Okinawa Trough and northern areas of the East China Sea following the main stream of the Kuroshio water current (Fig. 3). Below, we will describe mineralogy of the southeastern part of the province located to the east of the Sakishima-Gunto islands. Its main assemblages (IIIC1, IIIC2, and VII in Table 2) are dominated by minerals commonly derived from granites and metamorphic rocks (zircon, tourmaline, colorless and green mica, epidote, chlorite, garnet, sphene, rutile, anatase, actinolite, and glaucophane). This mineral suite is resembling that distributed on the East China Sea shelf: sediments of both Southwestern Ryukyu and East China Sea provinces contain high content of green mica (Derkachev and Nikolaeva, 1992). Meanwhile, the southwestern Ryukyu sediments differ from those distributed elsewhere in the region by the relatively high contents of glaucophane. This mineral associated with other metamorphic debris is most likely derived from local sources, in particular Phanerosoic metamorphic rocks of the Yaeyama group including glaucophane-bearing shists and conglomerates of the Tomura Formation (Kizaki, 1986). The arc-volcaniclastic suite, normally composing mineral assemblages of the southwestern Ryukyu area in minor amounts, is similar to those composing assemblages IIIA3, IIIB1 and IIIB3 which are more common to the south of the southwestern Ryukyu province (in the West Philippine Sea and Philippine Arc provinces, see Fig. 2). In few samples, volcaniclastic minerals get dominant. The transportation of these minerals from the Philippine Arc well corresponds to the way of Kuroshio water current (Danchenkov, 1977). Thus, we suppose that there are the three following sediment supplies to the southwestern Ryukyu arc-trench area: (1) clastic material derived from local weathering and erosion of the recently non-volcanic island arc; (2) terrigenous material transported by water currents from the East China Sea shelf; and (3) pyroclastic debris (pumice) drifted with the Kuroshio water current from the Philippine Islands.

4.4 Taiwan province

This province is located off the Taiwan Island (Fig. 2). Its heavy-mineral assemblage (VI in Table 2) is characterized by the highest (in the entire region) contents of chlorite (52.8% in average) and colorless mica (17.5%), as well as by the lowest content of orthopyroxene (0.2%). High calcite content is also characteristic of this assemblage. Many of mica and chlorite grains include fine crystals of black opaque minerals and rutile that is specific for this province as well. The main source of this mineral assemblage is the pre-Tertiary Tananao metamorphic complex of Taiwan, which consists of mica- and chlorite-rich shists, marble, and more rare acid plutonic rocks, gneiss and migmatite. This complex is being severely eroded as a result of the current tectonic uplift in the Central Range (Ho, 1982; Biq *et al.*, 1985). Distribution of the metamorphic mineral suite is carried out by bottom water currents, which advancement to the east is limited by the Gagua Ridge stretching out along 123°E.

The arc volcaniclastic material, which is similar (Hb > Cpx > Opx) to that dominating in the West Philippine Basin, compose the Taiwan area surface sediments in small amounts (compare assemblages VI and IIIA in Table 2). However, it is more abundant in samples from some deep in the cores obtained in the area (see contents of Cpx, Opx, and Hb in samples from cores 23V7 and 23V6, Table 1). This observation suggests the impulsive character of sediment supply from Taiwan.

4.5 West Philippine Sea province

This province extends from the Luzon-Taiwan area of the Philippine island arc into the West Philippine Basin (Fig. 2). Its heavy-mineral assemblages (IIIA1, IIIA2, IIIA3, IIIA4, and IIIB1 in Table 2) are distinguished by the highest contents of hornblende (37–74% in group means and up to 92.3% in individual samples values, Tables 2 and 3). Biotite and apatite are relatively abundant here as well. Many grains of hornblende, biotite, apatite, pyroxenes, and opaque minerals (mainly magnetite) and some of zircon gains are fresh, crystalline-shape, and covered by colorless volcanic glass that suggests their pyroclastic origin. The same is supported by comparison (on the basis of microprobe analyses) between hornblende, pyroxenes, magnetite, and plagioclase from pelagic sediments, associated volcanic ash and pumice, and those from volcanic rocks of the ensialic island arcs (Nechaev, 1987, 1991). The main sources of these minerals are most likely volcanoes of the northern Luzon, Babuyan and Batan Islands located in the western area of the province. These volcanoes, composed chiefly of hornblende-bearing andesites, are well known for their high explosivity (Lelikov and Ostapenko, 1978). Regional distribution of hornblende, which is the dominant component of the assemblages noted, well corresponds to the water current system in the sea. Maximal contents of this mineral are noted in the area between the North Passat current and Subtropical counter-current where anticyclonic gyres occur (Fig. 3). The latter promotes the pumice drift far to the east from its source. It is possible as well that the concentration of hornblende in the central part of the sea is partly resulted from the most powerful volcanic explosions on the remote island arcs. A number of ash layers noted in the area supports this idea (Nechaev, 1987). If so, a ratio of hornblende versus pyroxenes in the volcaniclastic material may serve as an indicator of volcanic explosivity. In this terms, the northeastern Philippine arc volcanism is the most explosive in the Philippine Sea region.

Factor analysis distinguishes several mineral suites combined in various proportions in assemblages IIIA1, IIIA2, IIIA3, IIIA4, and IIIB1. The association of green-brown hornblende and apatite contrasts with all other minerals. Clinopyroxene has no positive correlations with any other mineral. Almost all the metamorphic minerals positively correlate with each other, but these correlations are weak. The most significant suites among them are as following: (1) epidote-garnet-tourmaline-anatase-actinolite-mica-calcite and (2) green hornblende-epidote-sphene-actinolite. These minerals are distributed mostly outside the province, in the areas of southwestern Ryukyu, Yap, and Palau Islands, where assemblages IIIA1, IIIA4, and IIIB1 occur as well (see Fig. 2).

4.6 Philippine Arc province

This province surrounds Philippine Islands excluding the area off the northeastern Luzon Island (Fig. 3). Its main assemblages (IIIB2 and IIIB3 in Table 2) are characterized by high contents of epidote (22.2–21.8% in group means), hornblende (21.4–34.7%), actinolite (6–2.7%), and, sometimes, chlorite and biotite. Pyroxenes are abundant as well, but their contents (Cpx = 43,7–25.8 and Opx = 2.5–5.7% in group means) are commonly less than that in the average heavy-mineral composition of the entire region. Relatively high amounts of garnet, zircon, tourmaline, sphene, anatase, and glaucophane in the average composition of assemblage IIIB3 are found only in sediments distributed outside the province (Sample 14P927 from the southwestern Ryukyu Arc).

Small number of heavy-mineral analyses does not allow factor analysis to be applied for distinguishing the mineral suites of different origin among the assemblages IIIB2 and IIIB3. Nevertheless, the complex mineral compositions of these assemblages and their distribution suggest that they are derived chiefly from the two local sources, both belonging to the Philippine island arc. Epidote, actinolite, chlorite, and, partly, green hornblende, biotite, and pyroxenes are resulted from weathering and erosion of metamorphosed magmatic rocks: green shists and amphibolites, including metaophiolites (Geological map, 1963). The metaophiolitic material in sediments is indicated by enstatite, diopside, and chromian spinel found in small amounts in all the samples from the island slope of the Philippine Trench. Most grains of augite, hypersthene, green-brown and brown hornblende, oxyhornblende, and biotite, which are fresh, crystalline-shape, and associated with volcanic glass, are of volcanic origin. So, we suppose that the pyroclastic and erosion-related contributions to sediments of the Philippine Arc province are close in volume although their interrelationship changes significantly from place to place. Where the volcaniclastic suite dominates, it resembles assemblage IA2 (with prevailing clinopyroxene that is common in the East Arc province), but has the higher amount of hornblende.

4.7 Yap-Palau province

Specific mineral assemblages (IIIA1, IV, and V in Table 2) are distributed in the southern Mariana, Yap, and Palau Trenches. They contain abundant debris of metamorphic and intrusive rocks (epidote, hornblende, actinolite, and sometimes, olivine, chlorite, sphene and biotite), that disturbs the domination of volcaniclastic clinopyroxene in the eastern part of the region. Among other minerals, here are noted diopside, enstatite-bronzite, chromian spinel, serpentine, which are characteristic of metamorphosed ultrabasic rocks (Skornyakova *et al.*, 1978; Murdmaa *et al.*, 1980). The only possible source of all the minerals mentioned is a complex of metaophiolites and metabasites composing the southern Mariana, Yap and Palau ridges (Shiraki, 1971; Hawkins and Batiza, 1977; Evlanov *et al.*, 1979; Savelyeva *et al.*, 1980; Sharaskin *et al.*, 1980). Strong erosion of the basement rocks is promoted by collisional tectonics (in particular intense tectonic uplift) in this area (Hawkins and Batiza, 1977; Eguchi, 1984). Volcaniclastic suite distributed there in minor amounts does not differ from that dominating in assemblages IA1 and IA2 (note that most hornblende grains are likely derived from the metamorphic rocks).

5. Heavy-Mineral Assemblages as Indicators of Subduction/Collision-Related Tectonics

In the previous paragraphs, we have noted that, in the region, there are three heavy-mineral provinces (the Southwestern Ryukyu, Taiwan and Yap-Palau provinces) with the dominant mineral suites derived from erosion and weathering of metamorphic and intrusive rocks (Fig. 4). These provinces cover areas in the close vicinity of local plate collisions, where severe tectonic uplift and strike-slip motions are taking place. Volcanic activity is currently absent there. Consequently, volcaniclastic material presented in these provinces sediments in minor amounts are derived either from the distant arc volcanism or from the local erosion of ancient volcanic rocks.

Three other provinces (East Arc, Northwest Arc, and West Philippine Sea provinces) are almost completely volcaniclastic. They represent large areas within the Philippine Sea plate, which are continued into the areas of island arcs and trenches associated with subduction, volcanism, and tensional tectonics. In certain cases, some strike-slip motions also occur there. In these settings, subduction-related volcanism is the dominant process supplying clastic material to sediments even if these sediments are being deposited far away from any island arcs. Volcaniclastic debris is distributed over the spacious basins between arcs as a result of volcanic explosions and the consequent transportation of pyroclastics with winds and water currents. Metamorphic and intrusive (basement) rocks are prevented from erosion and weathering in the provenances because they are commonly buried under thick piles of volcanic deposits. Some increasing contents of the metamorphic and intrusive detritus have been found only in sediments associated with the local tectonic features like Yap and Central Basin fracture zones within the Philippine Sea plate and diapiric seamounts in the Izu-Bonin Trench.

The Philippine Arc province is transitional with respect to the ratio between the basement erosion-related and volcaniclastic contributions to sediments. This is due to the specific tectonic regime, in which several subduction zones, often facing one against others, are associated with significant strike-slip motions, compressional tectonics, and arc volcanism.

The observations presented above only confirm and, to some degree, develop our previous conclusions (Nechaev, 1987, 1991; Nechaev and Derkachev, 1989). To go further in studying the linkage between heavy-mineral assemblages and tectonic settings associated with convergent plate boundaries, we should examine spatial distribution of arc volcaniclastic minerals in sediments of volcanic island arcs and associated trenches. This will allow us to distinguish mineral suites indicating different types of arc volcanism, which, in its turn, reflects the mode of subduction and type of the arc basement.

Diagram on Fig. 5 shows variations in relative contents of orthopyroxene, hornblende, clinopyroxene and olivine, which are the major arc-volcaniclastic heavy minerals, in Quaternary sediments of volcanic

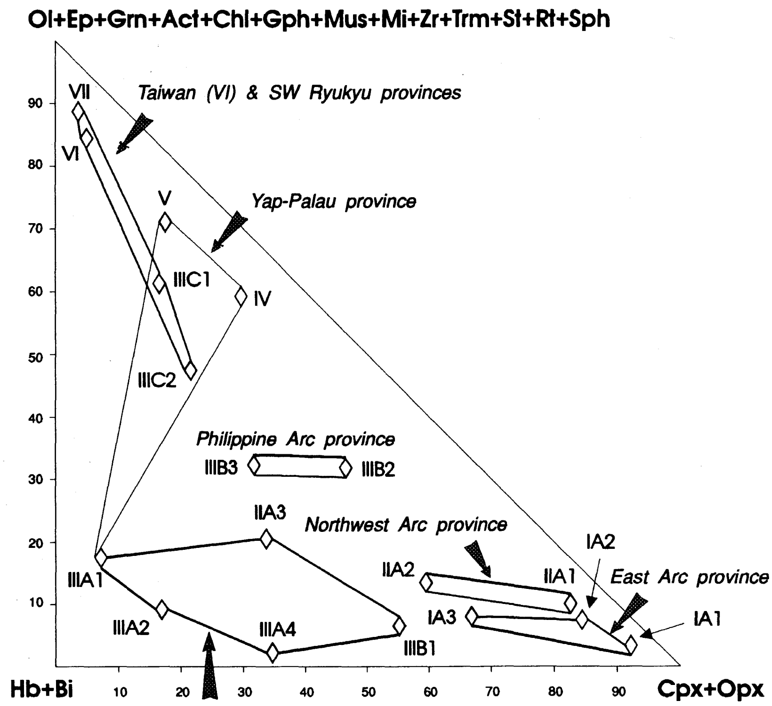

Fig. 4. Interrelationship (%) between minerals indicative of metamorphic and intrusive rock sources (olivine, epidote, garnet, actinolite, chlorite, glaucophane, muscovite, green mica, zircon, tourmaline, staurolite, rutile, anatase, and sphene), major volcaniclastic minerals (orthopyroxene and clinopyroxene), and hornblende and biotite in the provinces of the Philippine Sea region (on the basis of group means from Table 2). Hornblende-biotite component is placed at the right-angle corner of the diagram because these minerals are commonly derived from volcanic sources as well as from metamorphic and intrusive rocks.

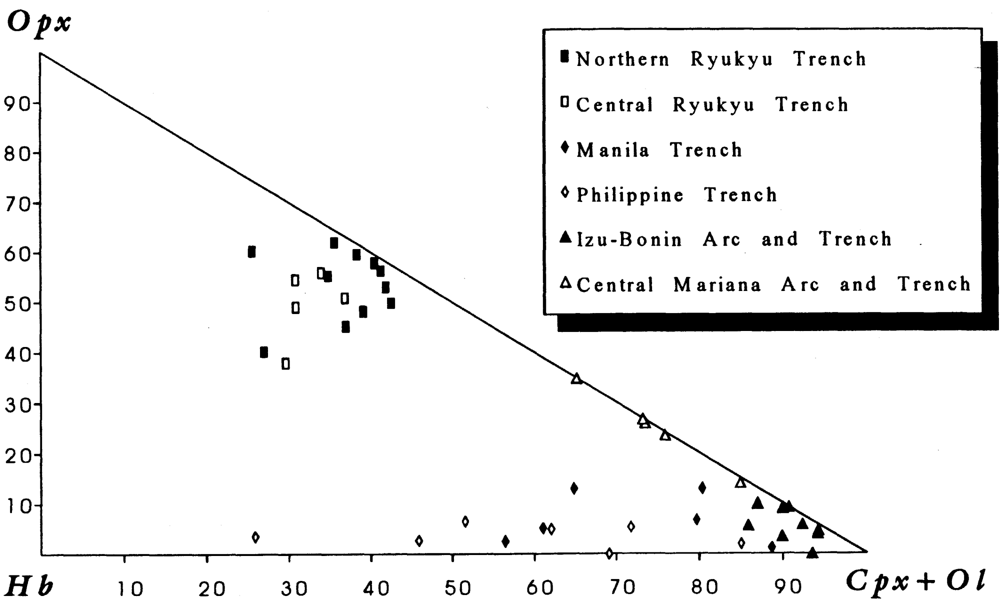

Fig. 5. Interrelationship (%) between major volcaniclastic minerals (orthopyroxene, olivine and clinopyroxene, and hornblende) in sediments from different island arcs and trenches (on the basis of individual sample values from Table 1 and Suzuki, 1975; Skornyakova *et al.*, 1978; Murdmaa *et al.*, 1980; Nechaev, 1987, 1991; Nechaev *et al.*, 1989).

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island arcs (Izu-Bonin, Mariana, Ryukyu, and Philippine) and associated trenches. As one can see, clinopyroxene and olivine predominate among volcaniclasic minerals of the Izu-Bonin ensimatic island arc. This well corresponds to the fact that arc tholeiite is a leading rock type there, calc-alcaline lavas occur in minor amounts, and alkaline volcanites are absent (Sharaskin, 1992). Subduction in the area of the Izu-Bonin Trench is associated with significant strike-slip motions and weak plate coupling (Uyeda and Kanamori, 1979; Simkin *et al.*, 1989).

Volcaniclastics of the Mariana (also ensimatic) island arc, associated with normal subduction and weak plate coupling, differ from those of the Izu-Bonin arc by the higher content of orthopyroxene. The difference in mineralogy probably indicates the difference in volcanic rock composition between the two arcs mentioned. On the Mariana arc, calc-alkaline lavas predominate, tholeiites are common, and alkaline rocks are very rare (Sharaskin, 1992). This is, most likely, the case of ensimatic island arc, which magmatism is well and freely developed in the background of normal subduction with weak plate coupling (Uyeda and Kanamori, 1979; Simkin *et al.*, 1989).

In the area of the northern and central Ryukyu (ensialic) arc, orthopyroxene is more abundant than clinopyroxene, clinopyroxene is more abundant than hornblende, and olivine is very rare. In contrast to the Izu-Bonin and Mariana arcs where the volcaniclastic suites are almost completely lacking of hornblende, content of this mineral on the Ryukyu arc is, in many cases, sufficient. Here, calc-alkaline and alkaline lavas occur in marked amounts while tholeiites are relatively rare (Sharaskin, 1992). Like the Mariana-arc magmatism, magmatism of the Ryukyu arc is likely running in the background of normal subduction with weak plate coupling (Uyeda and Kanamori, 1979; Simkin *et al.*, 1989). However, it is developed on the sialic rock basement.

In the vicinity of the Philippine (ensialic) island arc, orthopyroxene and olivine occur in minor amounts while clinopyroxene and hornblende predominate among arc-volcaniclastic heavy minerals (Fig. 5). Interrelationship between the last two minerals significantly changes from place to place, hornblende being concentrated in the northeastern area of the arc (see the paragraph "West Philippine Sea province" above). As noted, the latter probably indicates that the local volcanism in this area is the most explosive

Table 3. Heavy-mineral assemblages indicatory of subduction/collision-related tectonic settings.

Subduction	Associated Island Arc	Recent Arc Volcanic Rocks	Volcaniclastic heavy-mineral suites	Heavy-mineral suites derived from the basement erosion
Normal subduction with weak plate coupling	Ensimatic (central Mariana)	Calc-alkaline, tholeiitic, alkaline*	Dominant: Cpx+Ol>Opx>Hb	Negligible
Normal subduction with weak plate coupling	Ensialic (northern and central Ryukyu)	Calc-alkaline, alkaline, tholeiitic*	Dominant: Opx>Cpx+Ol>Hb	Negligible
Subduction with strike-slip component and weak plate coupling	Ensimatic (Izu-Bonin)	Tholeiitic, calc-alkaline*	Dominant: Cpx+Ol>>Opx>Hb	Minor
Subduction with strike-slip component and strong plate coupling	Ensialic (Philippine)	Calc-alkaline	Major: Cpx+Ol>Hb>>Opx and Hb>Cpx+Ol>>Opx	Minor but sufficiant: Ep, Act, Chl, Hb, Bi, Cpx, Opx
Collision between ensimatic island arc (Yap) and buyoant block of oceanic lithosphere (Caroline Islands area)		Absent	Minor, derived mostly from the adjacent volcanic arcs	Major: Ep, Hb, Act, Ol, Chl, Sph, Bi
Collision between ensialic island arc (Taiwan) and continent (Eurasia)		Absent	Minor, derived mostly from the adjacent volcanic arcs	Major: Chl, Mus, Zr, Trm, Ep, Grn, Sph,, An, Act, Gph

* Rock types are listed in according to their frequency (first type is the most often). Mineral abbreviations are the same as those in Table 2.

in the Philippine Sea region. Recent volcanic rocks of the Philippine arc are poorly described in the literature available to us. Nevertheless, hornblende and two-pyroxene calc-alcaline andesites are commonly noted here (Lelikov and Ostapenko, 1978). There are several subduction zones, sometimes facing one against others, in the area of Philippine Islands. Most of them, if not all, are associated with significant strike-slip motions and strong plate coupling. Perhaps, this tectonic regime locally stimulates intense assimilation of the earth's crust material in the island arc magmas. As a result, the magmas are enriched by water, that, in its turn, leads to high explosivity of volcanism and extreme crystallization of hornblende and other water-bearing minerals.

6. Conclusion

Quaternary sediments of the Philippine Sea region contain heavy-mineral assemblages, which distinctly indicate various tectonic settings and arc volcanism on the Philippine Sea plate boundaries (Table 3). We hope that these observations will help other researchers in studying the geological history of terranes composing modern and ancient plate margins.

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