

MULTIVARIATE ANALYSIS OF HEAVY MINERAL ASSEMBLAGES OF SEDIMENTS FROM THE MARGINAL SEAS OF THE WESTERN PACIFIC

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ABSTRACT

Heavy mineral data of sediments from the marginal seas of the Western Pacific (Bering, Okhotsk, Japan, East China, Philippine, Banda, etc.), from the Tonga and Vanuatu Trenches and from adjacent areas have been evaluated using multivariate statistics and correlation, factor, cluster and discriminant analyses. The overall characteristics of heavy mineral assemblages and the regional variability of mineral associations are described and interpreted. Despite the large latitudinal and environmental range of the study basins, the complexity of source rocks and volcanic signatures are clearly reflected in the distribution of heavy mineral assemblages. Results allowed identification of several mineralogical provinces, linked to distinct hinterland complexes and associated tectonic controls. Q-mode factor analysis differentiated four major groups of assemblages of distinctive provenance. R-mode factors helped to define representative mineral associations, which best characterise the mineral composition of the sediments of the individual marginal seas, and led to the delineation of eight provinces.

Lithogeodynamic discriminant diagrams, based on average values of heavy mineral compositions, identify assemblages which are most typical of differing types of magmatic and metamorphic rocks, and discriminate between them and those associated with other crustal lithologies. Changing compositions of the heavy mineral assemblages indicate a clear trend from simple geodynamic environments to composite ones, including oceanic uplifts, young island arcs, evolved and mature island arcs, marginal-continental volcanic ranges, fold belts, ancient cratons and platforms.

Keywords: heavy mineral assemblages; marginal seas of the Western Pacific; multivariate statistics; indicators of sedimentary environments; lithogeodynamic diagrams.

1. INTRODUCTION

Heavy mineral studies provide unique and essential information for determining sediment provenance and constraining the evolution of sedimentary basins, correlating sedimentary successions and mapping the distribution of mineral resources. An actualistic model, based on analysis and mapping of the distribution patterns of detrital heavy minerals in modern settings, and constrained by factors that control the formation and distribution of particular assemblages, is a prerequisite of basin analysis. Numerous studies on sedimentary mineralogy have indicated that the main factors determining the composition of mineral assemblages are the structural position of the sedimentary basin, the lithology of the supplying provinces, climate, processes occurring during sediment transport, the dynamics of the depositional environment and, finally, diagenesis (Baturin, 1947; Kukhareno, 1961; Strakhov, 1963; Van Andel, 1964; Grossgeim, 1972; Dickinson and Suczek, 1978; Pettijohn, 1981; Maynard et al., 1982; Kazansky, 1983; Viyding, 1984; Valloni, 1985; Berger, 1986; Morton and Hallsworth, 1999, etc.).

In this paper we consider the impact of factors that influence the distribution of heavy mineral assemblages in specific marine environments and, using the results of multivariate statistics, interpret the interrelationship of the assemblages with the tectonic setting of their depositional basins (see also Nechaev, 1991; Nechaev and Ispording, 1993). In particular, we have focused on the formation of modern heavy mineral suites in the marginal seas of an active continental margin within the Western Pacific, presenting data that hitherto was not available to many researchers.

2. MATERIALS AND METHODS

Heavy mineral analyses were performed on surface sediments (0–10 cm) collected from marginal seas of the Western Pacific, situated in different climatic belts and geodynamic environments (Fig. 1). Material (about 1200 analyses) was obtained by the authors from the Okhotsk, Japan, East China, Philippine and South China Seas. The Banda and Sulawesi Seas, Lau Basin and Tonga trench sediments were studied to a lesser degree (56 analyses). Published data on mineral compositions of sediments from the Bering, Okhotsk, Yellow and East China Seas were also included to obtain a representative database (Gershanovich, 1955; Petelin, 1957; Aleksina, 1962; Lisitsin, 1966; Suzuki, 1975a, 1975b; McManus et al., 1977; Murdmaa et al., 1979, 1980; Suzuki, 1985; Lee et al., 1988; Chen, 1989; Malinovsky et al., 1990; Derkachev et al., 1993; Qin et al., 1996; and others).

Heavy mineral analyses were carried out using the technique described by Petelin (1961) as 'immersion method': sediment samples were wet-sieved using 0.1 and 0.05 mm sieves. Heavy mineral fractions (density $> 2.89 \text{ g/cm}^3$) were extracted from the 0.1 to 0.05 mm fractions using bromoform (CHBr_3) and analysed under a polarising microscope, in an immersion liquid of 1.655 refractive index. Not less than 300 grains were identified and counted in each sample. Rock fragments, unidentifiable grains as well as authigenic and opaque minerals (glauconite, collophane, ilmenite, hematite, magnetite, leucoxene, iron and manganese hydroxides, etc.) were excluded from the total sum to obtain uniform, comparable data on transparent

assemblages for the characterisation of mineralogical provinces. The sum of transparent minerals was recalculated to a value of 100% and the abundance of each heavy mineral species was scaled accordingly. The mineralogical zones identified in the marginal seas in an earlier study were computed using Q-mode cluster analysis (Derkachev et al., 1989, 1993; Derkachev and Nikolaeva, 1995, 1999a; Nechaev and Derkachev, 1995; Derkachev, 1996).

The significance rating of the mineral assemblages as defining discrete heavy mineral provinces was evaluated by discriminant analysis (Afifi and Azen, 1982; Le Maitre, 1982). Results indicated rather high efficiency with > 85% confidence levels. Multivariate statistical methods are widely used to estimate the principal patterns in the formation and distribution of mineral assemblages. Identification of the paragenetic relationships of the heavy mineral assemblages is based on methods of correlation analysis, Q- and R-mode cluster and factor analyses. Examples of the successful application of these methods to sedimentological and detrital heavy mineral studies are well known (Imbrie and Van Andel, 1964; Knebel and Creager, 1973; Egiazarov, 1981; Firek and Shideler, 1977; McManus et al., 1977; Chen et al., 1982; Wang and Liang, 1982; Chen et al., 1984; Carriquiry and Sánchez, 1999; Wong, 2002 and many others). In this study, programmes and algorithms, published by Davis (1977) and modified for an IBM PC by Utkin (2002), were used as the basic software.

3. RESULTS AND INTERPRETATION

3.1. Q-Mode Factor Analysis

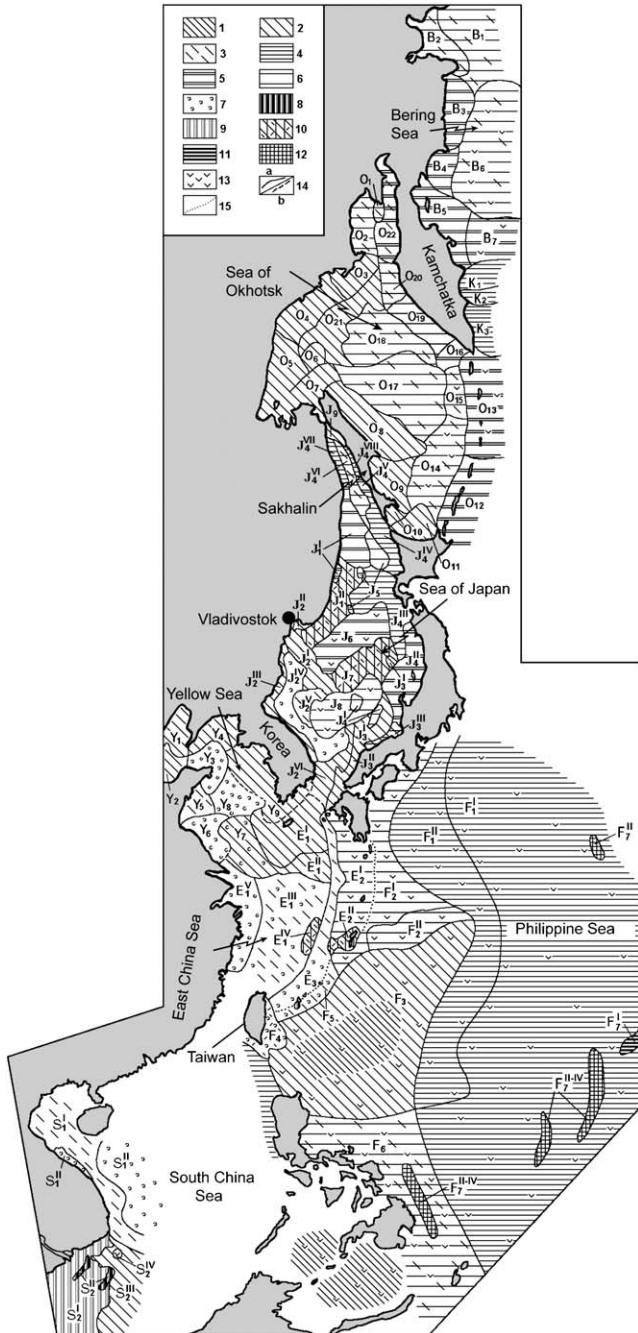
Comparison of average values of heavy mineral compositions (147 mineral assemblages) in the mineral provinces, recognised on the basis of Q-mode factor analysis (Table 1), has allowed us to establish the regional variability in mineral distribution and ascertain the reasons causing this variability. The results indicated that 88.4% of all variability in the distribution of minerals could be attributed to five factors. A considerable percentage of the total dispersion is accounted for by the first two factors with a contribution of 33.8 and 31.6%, respectively. The loads of the next three factors are insignificant, and they range from 3.7 to 9.7%.

Fig. 1 shows that most of the mineralogical provinces are combined into two major groups.

Factor I (with a 33.8% contribution to the variance) defines the first group of provinces, which includes those next to the continental coast containing ancient cratons and orogens with granitic and metamorphic rocks (western coast of the Okhotsk Sea, Korean Peninsula, China and Indochina) (Table 2). The main heavy mineral assemblage in these provinces is represented by brown-green and green hornblende and epidote, with subsidiary actinolite, high-grade metamorphic minerals (kyanite, staurolite, andalusite, sillimanite), and stable minerals (zircon, sphene, tourmaline, garnet, rutile, anatase). Detrital calcites are also present, although their contents vary from province to province (Table 1).

Some heavy mineral assemblages, clearly different in origin from those considered above, also occur in this group. These are volcanoclastic assemblages, represented

mainly by hornblende (including brown hornblende and oxyhornblende). Apatite, hypersthene and clinopyroxene are present as an admixture. They typically occur in the West Philippine Province (Philippine Sea), in the central part of the Sulawesi and Sulu Seas, and in the northern part of the Coral Sea. The sediments of the Sanyin



Province (south-eastern part of the Japan Sea) have a specific mineral composition typified by high concentrations of hornblende and hypersthene. The oxyhornblende–hypersthene association is characteristic of the products of volcanic eruptions from southwest Japan (Daysen Volcano, etc.) (Tsukui, 1984).

Factor II (with a 31.6% contribution to the variance) comprises the second group of provinces that contain heterogeneous assemblages of differing origin. Heavy minerals here are the products of intensive Neogene-Quaternary and contemporary volcanic activity. Mineral diversity is low, consisting mostly of clino- and orthopyroxenes with the prevalence of clinopyroxenes, often accompanied by high

Fig. 1. Heavy mineral provinces of the sediments in the marginal seas of the Western Pacific. Provinces and subprovinces: *Bering Sea Provinces* (Lisitsin, 1966; McManus et al., 1977): B₁, Eastern part of the Anadyr Gulf; B₂, Western part of the Anadyr Gulf; B₃, Koryakian; B₄, Olutor Gulf; B₅, South-western mixed; B₆, South-eastern; B₇, Komandor. *Eastern Kamchatka coast Provinces* (Aleksina, 1962): K₁, North Kronotsk; K₂, South Kronotsk; K₃, Avacha. *Okhotsk Sea Provinces* (Petelin, 1957): O₁, Taygonos; O₂, Shelikhov Gulf; O₃, Koni-Pyagina; O₄, Okhotsk-Chalomzhinsk; O₅, Ayan-Okhotsk; O₆, Iona Island; O₇, Sakhalin Bay; O₈, North Sakhalin; O₉, South Sakhalin; O₁₀, Aniva; O₁₁, Hokkaido; O₁₂, South Kuril; O₁₃, North Kuril; O₁₄, Southern deep-water basin; O₁₅, Eastern border of deep-water basin; O₁₆, First Kamchatka; O₁₇, First Central; O₁₈, Second Central; O₁₉, Second Kamchatka; O₂₀, Third Kamchatka; O₂₁, Northern; O₂₂, Fourth Kamchatka. *Japan Sea Provinces* (Derkachev, 1996): J₁^I, –Kuznetsovo; J₁^{II}, South-Eastern; J₂^I, Tumangan-South-Primorye; J₂^{II}, Ussuri Bay; J₂^{III}, –Eastern Korean; J₂^{IV}, –Mica; J₂^V, –East Korean Rise; J₂^{VI}, Korean Strait; J₃^I, –Oki; J₃^{II}, Eastern part of the Korean Strait; J₃^{III}, –Vakasa; J₄^I, Oki-Kita-Oki; J₄^{II}, Western Honshu; J₄^{III}, Oshima-Okusiri; J₄^{IV}, Moneron-Rebun; J₄^V, –Delangle; J₄^{VI}, Central part of the Tatar Strait; J₄^{VII}, –Sovgavan; J₄^{VIII}, Lamanon-Coastal; J₅, North-western submarine Rises; J₆, Central Japan Sea; J₇, Yamato; J₈, Ulreung-do; J₉, Aleksandrovsk. *East-China Sea Provinces* (Derkachev and Nikolaeva, 1995): E₁, East-China (E₁^I, E₁^{II}, E₁^{III}, E₁^{IV}, E₁^V subprovinces); E₂, Island-arc (E₂^I, E₂^{II} subprovinces); E₃, Okinawa Trough. *Yellow Sea Provinces* (Chen et al., 1982; Shen et al., 1984; Chen, 1989): Y₁, Northern part of the Bohai Gulf; Y₂, Southern part of the Bohai Gulf; Y₃, Pentsai-Haiyan; Y₄, Lyaodun; Y₅, Qingdao; Y₆, Huanghe River old delta; Y₇, Eastern part of the Yellow Sea; Y₈, Central part of the Yellow Sea (transitional); Y₉, South-western Korea. *Philippine Sea Provinces* (Nechaev and Derkachev, 1995): Eastern Island arcs (F₁^I, F₁^{II}, subprovinces); North-western Island arcs (F₂^I, F₂^{II}, subprovinces); F₃, West –Philippine; F₄, Taiwan; F₅, Sakishima; F₆, Philippine; deep-water trenches (F₇^I, – Mariana; F₇^{II-IV}, – Yap; Palau, Philippine—subprovinces). *South China Sea Provinces* (Derkachev and Nikolaeva, 1997): Annam-Hainan (S₁^I, S₁^{II}, subprovinces); Mekong (S₂^I, S₁^{II}, S₂^{III}, S₁^{IV}, subprovinces). Note: The mineral assemblages of the provinces were discriminated by cluster analysis. The mean values of mineral compositions in the provinces illustrated here are shown in Table 1. Provinces 1–9 as represented by factors: 1–3 *factor I* (epidote-hornblende* assemblage) with factor loadings: 1, 0.9–1.0; 2, 0.75–0.9; 3, 0.5–0.75; 4–6 *factor II* (olivine-orthopyroxene-clinopyroxene assemblage) with factor loadings: 4, 0.9–1.0; 5, 0.75–0.9; 6, 0.5–0.75; 7, *factor III* (hornblende-mica assemblage); 8–9, *factor IV* (hornblende-epidote-zircon assemblage with an increased background of the tourmaline, anatase, garnet) with factor loadings: 8, 0.75–1.00; 9, 0.5–0.75; 10, hornblende-clinopyroxene-epidote assemblage with an increased content of chlorite and actinolite; 11, olivine assemblage of the deep-water trenches; 12, epidote-actinolite-chlorite-hornblende assemblage of the deep-water trenches; 13, volcanoclastic assemblage; 14, boundaries of provinces and subprovinces (a, established; b, supposed); 15, boundary between provinces of the East China and Philippine Seas. Note: * minerals are listed in order of increasing abundance.

Table 1. Mean percentages of provincial heavy mineral composition of surface sediments in the marginal seas of the Western Pacific

| Provinces, subprovinces | cpx | opx | ol | npx | hb ₁ | hb ₂ | hb ₃ | hb ₄ | act | Nam | ep | gr | zr | ap | sph | tou | an | chl | mt | mi | ca | ba | Quantity of samples | |
|------------------------------|--------|-------|------|------|-----------------|-----------------|-----------------|-----------------|------|------|-------|------|------|------|------|------|------|------|------|------|------|----|---------------------|-------|
| Bering Sea | | | | | | | | | | | | | | | | | | | | | | | | |
| B ₁ | 29.00 | 3.57 | | | 33.65 | | | | 2.82 | | 19.88 | 3.30 | 2.82 | 2.37 | – | – | – | 2.59 | – | – | – | | | |
| B ₂ | 32.47 | 9.14 | | | 27.35 | | | | 2.71 | | 17.05 | 2.48 | 4.51 | 2.03 | – | – | – | 2.26 | – | – | – | | | |
| B ₃ | 40.19 | 4.57 | | | 21.53 | | | | 2.31 | | 18.77 | 2.67 | 3.07 | 1.91 | – | – | – | 4.98 | – | – | – | | | |
| B ₄ | 48.43 | 3.31 | | | 16.13 | | | | 2.94 | | 19.33 | 1.38 | 2.30 | 2.30 | – | – | – | 3.88 | – | – | – | | | |
| B ₅ | 49.68 | 3.08 | | | 30.07 | | | | 2.19 | | 9.87 | 0.48 | 0.97 | 1.70 | – | – | – | 1.96 | – | – | – | | | |
| B ₆ | 33.63 | 5.33 | | | 32.53 | | | | 2.04 | | 14.19 | 1.22 | 2.04 | 3.29 | – | – | – | 5.73 | – | – | – | | | |
| B ₇ | 50.53 | 2.76 | | | 25.65 | | | | 0.79 | | 12.96 | 1.58 | 1.38 | 1.78 | – | – | – | 2.57 | – | – | – | | | |
| Eastern Kamchatka coast | | | | | | | | | | | | | | | | | | | | | | | | |
| K ₁ | 62.40 | 24.00 | | | 7.40 | 2.90 | | 2.00 | | | 1.00 | – | 0.30 | – | – | – | – | – | – | – | – | | | |
| K ₂ | 62.00 | 24.30 | | | 10.90 | 1.19 | | 1.20 | | | 0.40 | – | 0.01 | – | – | – | – | – | – | – | – | | | |
| K ₃ | 54.40 | 24.10 | | | 8.80 | 4.40 | | 1.29 | | | 6.60 | – | 0.01 | 0.40 | – | – | – | – | – | – | – | | | |
| Sea of Okhotsk | | | | | | | | | | | | | | | | | | | | | | | | |
| O ₁ | 38.36 | 7.08 | | | 10.62 | | 23.89 | 7.67 | | | 7.37 | 1.77 | 1.77 | | 1.47 | | | | | | | | | |
| O ₂ | 35.78 | 7.57 | | | 12.16 | | 14.22 | 6.19 | | | 18.58 | 0.92 | 3.44 | | 1.14 | | | | | | | | | |
| O ₃ | 22.78 | 3.61 | | | 23.33 | | 24.17 | 5.00 | | | 18.33 | 0.83 | 1.39 | | 0.28 | | | | | | | | 0.28 | |
| O ₄ | 12.44 | 3.34 | | | 13.04 | | 36.06 | 3.33 | | | 25.14 | 2.12 | 3.02 | | 1.51 | | | | | | | | | |
| O ₅ | 11.83 | 2.16 | | | 12.63 | | 36.29 | 2.69 | | | 30.08 | 1.35 | 1.35 | | 1.08 | | | | | | | | 0.54 | |
| O ₆ | 17.07 | 8.04 | | | 22.20 | | 21.71 | 4.86 | | | 20.73 | 1.96 | 1.96 | | 1.47 | | | | | | | | | |
| O ₇ | 9.03 | 1.93 | | | 12.87 | | 33.85 | 1.15 | | | 25.77 | 5.77 | 5.39 | | 4.04 | | | | | | | | | 0.20 |
| O ₈ | 7.68 | 1.73 | | | 7.67 | | 34.41 | 1.25 | | | 35.38 | 3.72 | 3.96 | | 3.46 | | | | | | | | | 0.74 |
| O ₉ | 12.67 | 2.34 | | | 8.45 | | 39.44 | 0.94 | | | 27.22 | 1.88 | 3.76 | | 3.30 | | | | | | | | | |
| O ₁₀ | 20.11 | 5.32 | | | 20.74 | | 20.71 | 1.18 | | | 20.11 | 4.16 | 5.92 | | 1.75 | | | | | | | | | |
| O ₁₁ | 17.38 | 1.07 | | | 7.45 | | 36.15 | 0.71 | | | 28.03 | 1.77 | 4.97 | | 2.47 | | | | | | | | | |
| O ₁₂ | 50.41 | 35.23 | | | 5.31 | | 1.52 | 1.52 | | | 2.67 | 0.19 | 0.37 | | 0.11 | | | | | | | | | 2.67 |
| O ₁₃ | 51.06 | 31.08 | | | 7.03 | | 1.11 | 4.81 | | | 2.20 | 0.12 | – | | – | | | | | | | | | 2.59 |
| O ₁₄ | 30.03 | 13.8 | | | 7.15 | | 21.90 | 1.90 | | | 19.99 | 0.95 | 1.43 | | 0.95 | | | | | | | | | 1.90 |
| O ₁₅ | 41.86 | 4.25 | | | 12.09 | | 2.61 | 28.76 | | | 5.89 | – | 0.31 | | 0.31 | | | | | | | | | 3.92 |
| O ₁₆ | 41.12 | 9.44 | | | 13.86 | | 6.11 | 5.56 | | | 12.25 | 0.54 | 0.54 | | – | | | | | | | | | 10.58 |
| O ₁₇ | 26.84 | 6.08 | | | 8.95 | | 13.60 | 3.58 | | | 9.66 | 0.72 | 0.72 | | 0.72 | | | | | | | | | 29.13 |
| O ₁₈ | 33.05 | 5.50 | | | 18.22 | | 16.10 | 8.05 | | | 10.60 | 2.12 | 1.26 | | 0.43 | | | | | | | | | 4.67 |
| O ₁₉ | 38.03 | 26.26 | | | 10.56 | | 5.44 | 4.83 | | | 4.83 | 9.06 | 0.90 | | – | | | | | | | | | 0.09 |
| O ₂₀ | 33.26 | 24.38 | | | 11.96 | | 7.42 | 7.66 | | | 8.84 | 4.31 | 1.45 | | 0.72 | | | | | | | | | – |
| O ₂₁ | 27.21 | 9.89 | | | 14.49 | | 20.17 | 8.83 | | | 15.89 | 1.05 | 1.42 | | 0.71 | | | | | | | | | 0.34 |
| O ₂₂ | 42.85 | 10.17 | | | 13.46 | | 7.14 | 11.26 | | | 9.08 | 3.58 | 2.19 | | 0.27 | | | | | | | | | – |
| Japan Sea | | | | | | | | | | | | | | | | | | | | | | | | |
| J ₁ ^I | 50.23* | | 0.06 | | 10.65 | | | | 0.02 | 0.01 | 34.78 | 0.73 | 1.18 | 0.90 | 0.57 | 0.21 | 0.11 | 0.15 | 0.12 | 0.25 | 0.03 | | | 45 |
| J ₁ ^{II} | 18.08 | 4.47 | 0.01 | | 18.43 | 0.29 | 0.09 | 0.01 | 0.05 | | 53.62 | 0.83 | 1.38 | 1.07 | 0.33 | 0.21 | 0.29 | 0.21 | 0.10 | 0.53 | | | | 54 |
| J ₂ ^I | 14.43 | 3.24 | 0.20 | 0.11 | 35.28 | 2.48 | 3.84 | 0.38 | 2.67 | 0.18 | 25.00 | 1.29 | 1.96 | 1.38 | 1.56 | 0.15 | 0.42 | 0.73 | 0.08 | 4.45 | 0.17 | – | | 17 |
| J ₂ ^{II} | 32.67* | | 0.02 | | 49.98 | | | | 0.01 | | 12.04 | 2.61 | 0.96 | 0.65 | 0.38 | 0.05 | 0.01 | | 0.53 | 0.09 | | | | 50 |

Table 1 (Continued)

| Provinces, subprovinces | cpx | opx | ol | npx | hb ₁ | hb ₂ | hb ₃ | hb ₄ | act | Nam | ep | gr | zr | ap | sph | tou | an | chl | mt | mi | ca | ba | Quantity of samples |
|-------------------------------|-------|-------|-------|-----|-----------------|-----------------|-----------------|-----------------|-------|------|-------|------|-------|------|------|-------|------|-------|------|-------|------|------|---------------------|
| F ₁ ^{II} | 76.32 | 6.63 | 2.56 | – | 5.81 | 0.88 | 0.06 | 0.99 | 0.42 | 0.01 | 2.84 | 0.33 | 0.16 | 1.27 | – | – | 0.03 | 0.47 | 0.15 | 0.59 | 0.09 | 0.39 | 40 |
| F ₂ ^I | 32.39 | 49.65 | – | – | 5.90 | – | 1.29 | 0.46 | 1.14 | – | 3.71 | 0.56 | 0.45 | 0.66 | 0.39 | 0.14 | 0.55 | 1.72 | 0.12 | 0.83 | 0.04 | – | 17 |
| F ₂ ^{II} | 26.78 | 32.03 | 0.03 | – | 17.31 | 2.02 | 4.71 | 1.81 | 1.03 | – | 4.44 | 1.14 | 1.34 | 1.16 | 0.50 | 0.45 | 1.08 | 1.12 | – | 3.02 | – | 0.03 | 13 |
| F ₃ | 32.02 | 5.62 | 0.34 | – | 43.40 | 2.06 | 0.40 | 6.50 | 0.43 | – | 2.71 | 0.11 | 0.21 | 1.33 | 0.07 | 0.21 | 0.13 | 1.35 | 0.04 | 3.02 | 0.03 | 0.02 | 36 |
| F ₄ | 4.74 | 0.23 | 0.07 | – | 5.83 | 1.23 | – | 1.95 | 0.47 | – | 6.82 | 0.40 | 0.55 | – | – | 0.16 | 0.24 | 52.80 | 0.08 | 23.13 | 1.30 | – | 4 |
| F ₅ | 11.79 | 5.48 | 0.04 | – | 14.50 | 1.48 | 2.50 | 3.09 | 1.73 | 0.18 | 9.04 | 0.25 | 0.40 | 1.37 | 0.29 | 0.89 | 0.28 | 4.70 | 0.14 | 40.48 | 1.37 | – | 8 |
| F ₆ | 43.76 | 2.55 | 0.01 | – | 18.10 | 1.40 | 0.90 | 1.10 | 6.00 | – | 22.25 | – | – | 0.70 | 0.01 | – | 0.01 | 2.80 | – | 0.41 | – | 0.0 | 4 |
| F ₇ ^I | 26.50 | 3.10 | 46.70 | – | 1.90 | – | 8.80 | 0.50 | 2.20 | – | 10.30 | – | – | – | – | – | – | – | – | – | – | – | 3 |
| F ₇ ^{II} | 7.10 | – | 1.50 | – | 69.27 | – | – | – | – | – | 22.10 | 0.01 | 0.01 | – | 0.01 | – | – | – | – | – | – | – | 3 |
| F ₇ ^{III} | 11.25 | 3.40 | 3.30 | – | 8.44 | 1.10 | – | 0.20 | 12.80 | – | 55.10 | 0.30 | 0.50 | 0.50 | 0.40 | 0.01 | 0.10 | 1.70 | 0.10 | 0.60 | 0.10 | 0.10 | 5 |
| F ₇ ^{IV} | 25.80 | 5.70 | – | – | 28.20 | 5.40 | – | 1.10 | 2.70 | 0.20 | 21.80 | 0.80 | 1.60 | 0.60 | 0.30 | 1.80 | 0.40 | 2.30 | – | 3.00 | – | – | 2 |
| South-China Sea | | | | | | | | | | | | | | | | | | | | | | | |
| S ₁ ^I | 1.64 | 0.59 | 0.27 | – | 26.74 | – | – | – | 7.74 | 0.24 | 33.57 | 1.98 | 5.44 | 0.62 | 1.52 | 3.34 | 2.42 | 3.83 | 0.83 | 7.69 | 1.54 | – | 44 |
| S ₁ ^{II} | 1.64 | 0.90 | 0.52 | – | 16.61 | – | – | – | 3.58 | – | 10.43 | 0.37 | 1.11 | 0.26 | 0.39 | 2.76 | 0.62 | 2.36 | 0.13 | 51.76 | 6.56 | – | 13 |
| S ₂ ^I | 2.26 | 1.36 | – | – | 14.12 | – | – | – | 0.14 | – | 20.51 | 1.51 | 22.50 | 1.95 | 0.93 | 12.40 | 3.81 | 0.32 | 7.82 | 4.22 | 6.15 | – | 17 |
| S ₂ ^{II} | 1.10 | 0.96 | 0.07 | – | 13.66 | – | – | – | 1.66 | 0.17 | 22.06 | 3.38 | 34.66 | 0.66 | 2.14 | 6.67 | 3.57 | 0.72 | 1.28 | 4.98 | 2.26 | – | 31 |
| S ₂ ^{III} | 1.96 | 0.53 | – | – | 29.27 | – | – | – | – | – | 39.91 | 0.66 | 11.35 | 1.00 | 0.32 | 7.63 | 1.25 | – | 2.46 | 3.24 | 0.42 | – | 21 |
| S ₂ ^{IV} | 3.31 | 8.23 | 4.78 | – | 27.43 | – | – | – | 1.28 | 0.06 | 22.45 | 2.66 | 12.96 | 1.13 | 3.17 | 3.95 | 1.87 | 1.57 | 0.69 | 3.58 | 0.88 | – | 12 |

Abbreviations for minerals: cpx, clinopyroxene; opx, orthopyroxene; ol, olivine; npx, alkaline pyroxene; hb₁, brown-green hornblende; hb₂, brown hornblende; hb₃, green hornblende; hb₄, basaltic hornblende; act, actinolite; Nam, alkaline amphibole; ep, epidote group (epidote, clinozoisite and zoisite); gr, garnet; zr, zircon; ap, apatite; sph, sphene; tou, tourmaline; an, sum of anatase, brookite and rutile; chl, chlorite; mt, metamorphic minerals (staurolite, andalusite, kyanite, sillimanite); mi, sum of micas; ca, non-biogenic carbonate; ba, barite.

Notes: Dash, the mineral was not found; blank, the mineral was not determined. Full names of the provinces and subprovinces are given in the caption of Fig. 1.

*Sum of clinopyroxene and orthopyroxene.

Table 2. Q-mode factor loadings for mean provincial heavy mineralogical compositions of the surface sediments within the marginal seas of the Western Pacific

| Provinces, subprovinces | Factor I (33.8%) | Factor II (31.6%) | Factor III (9.7%) | Factor IV (9.6%) | Factor V (3.7%) |
|-------------------------------|---------------------|----------------------|----------------------|---------------------|--------------------|
| Bering Sea | | | | | |
| B ₁ | 0.69 | 0.56 | 0.08 | 0.16 | 0.05 |
| B ₂ | 0.59 | 0.66 | 0.07 | 0.18 | 0.08 |
| B ₃ | 0.47 | 0.75 | 0.06 | 0.15 | 0.04 |
| B ₄ | 0.34 | 0.88 | 0.05 | 0.13 | 0.03 |
| B ₅ | 0.49 | 0.78 | 0.06 | 0.06 | 0.03 |
| B ₆ | 0.64 | 0.64 | 0.08 | 0.12 | 0.05 |
| B ₇ | 0.44 | 0.87 | 0.06 | 0.08 | 0.02 |
| Eastern Kamchatka coast | | | | | |
| K ₁ | 0.17 | 0.95 | 0.02 | 0.02 | 0.12 |
| K ₂ | 0.18 | 0.95 | 0.03 | 0.01 | 0.12 |
| K ₃ | 0.23 | 0.92 | 0.03 | 0.04 | 0.13 |
| Sea of Okhotsk | | | | | |
| O ₁ | 0.67 | 0.63 | 0.07 | 0.07 | 0.06 |
| O ₂ | 0.62 | 0.65 | 0.07 | 0.15 | 0.06 |
| O ₃ | 0.84 | 0.37 | 0.09 | 0.11 | 0.05 |
| O ₄ | 0.87 | 0.22 | 0.09 | 0.16 | 0.06 |
| O ₅ | 0.86 | 0.20 | 0.09 | 0.16 | 0.05 |
| O ₆ | 0.85 | 0.31 | 0.09 | 0.14 | 0.08 |
| O ₇ | 0.86 | 0.17 | 0.09 | 0.21 | 0.05 |
| O ₈ | 0.82 | 0.15 | 0.09 | 0.23 | 0.05 |
| O ₉ | 0.86 | 0.23 | 0.09 | 0.18 | 0.05 |
| O ₁₀ | 0.81 | 0.38 | 0.08 | 0.20 | 0.06 |
| O ₁₁ | 0.82 | 0.31 | 0.09 | 0.21 | 0.04 |
| O ₁₂ | 0.13 | 0.87 | 0.02 | 0.04 | 0.19 |
| O ₁₃ | 0.20 | 0.89 | 0.03 | 0.03 | 0.17 |
| O ₁₄ | 0.64 | 0.59 | 0.08 | 0.14 | 0.11 |
| O ₁₅ | 0.65 | 0.65 | 0.08 | 0.05 | 0.04 |
| O ₁₆ | 0.48 | 0.75 | 0.08 | 0.11 | 0.07 |
| O ₁₇ | 0.51 | 0.53 | 0.12 | 0.18 | 0.06 |
| O ₁₈ | 0.72 | 0.57 | 0.09 | 0.09 | 0.05 |
| O ₁₉ | 0.38 | 0.73 | 0.04 | 0.07 | 0.18 |
| O ₂₀ | 0.51 | 0.67 | 0.06 | 0.09 | 0.18 |
| O ₂₁ | 0.76 | 0.49 | 0.08 | 0.11 | 0.08 |
| O ₂₂ | 0.54 | 0.74 | 0.06 | 0.09 | 0.07 |
| Japan Sea | | | | | |
| J ₁ ^I | 0.29 | 0.74 | 0.04 | 0.16 | 0.01 |
| J ₁ ^{II} | 0.49 | 0.29 | 0.07 | 0.25 | 0.05 |
| J ₂ ^I | 0.82 | 0.28 | 0.16 | 0.17 | 0.06 |
| J ₂ ^{II} | 0.77 | 0.50 | 0.08 | 0.08 | 0.02 |
| J ₂ ^{III} | 0.86 | 0.21 | 0.20 | 0.12 | 0.06 |
| J ₂ ^{IV} | 0.43 | 0.13 | 0.87 | 0.11 | 0.05 |
| J ₂ ^V | 0.71 | 0.40 | 0.24 | 0.22 | 0.09 |

Table 2 (Continued)

| Provinces, subprovinces | Factor I (33.8%) | Factor II (31.6%) | Factor III (9.7%) | Factor IV (9.6%) | Factor V (3.7%) |
|--------------------------------|---------------------|----------------------|----------------------|---------------------|--------------------|
| J ₂ ^{VI} | 0.85 | 0.09 | 0.13 | 0.22 | 0.07 |
| J ₃ ^I | 0.86 | 0.25 | 0.18 | 0.11 | 0.09 |
| J ₃ ^{II} | 0.85 | 0.12 | 0.18 | 0.19 | 0.08 |
| J ₃ ^{III} | 0.72 | 0.28 | 0.12 | 0.15 | 0.21 |
| J ₄ ^I | 0.52 | 0.62 | 0.11 | 0.07 | 0.19 |
| J ₄ ^{II} | 0.37 | 0.71 | 0.08 | 0.11 | 0.19 |
| J ₄ ^{III} | 0.25 | 0.94 | 0.11 | 0.04 | 0.03 |
| J ₄ ^{IV} | 0.14 | 0.97 | 0.02 | 0.04 | 0.00 |
| J ₄ ^V | 0.21 | 0.73 | 0.01 | 0.44 | 0.01 |
| J ₄ ^{VI} | 0.58 | 0.68 | 0.11 | 0.18 | 0.01 |
| J ₄ ^{VII} | 0.20 | 0.95 | 0.04 | 0.08 | 0.00 |
| J ₄ ^{VIII} | 0.16 | 0.97 | 0.05 | 0.08 | 0.00 |
| J ₅ | 0.45 | 0.45 | 0.09 | 0.23 | 0.02 |
| J ₆ | 0.24 | 0.88 | 0.14 | 0.07 | 0.01 |
| J ₇ | 0.48 | 0.48 | 0.26 | 0.22 | 0.08 |
| J ₈ | 0.45 | 0.67 | 0.40 | 0.08 | 0.05 |
| J ₉ | 0.83 | 0.31 | 0.11 | 0.21 | 0.03 |
| East China Sea | | | | | |
| E ₁ | 0.73 | 0.15 | 0.32 | 0.24 | 0.06 |
| E ₁ ^I | 0.75 | 0.13 | 0.17 | 0.26 | 0.06 |
| E ₁ ^{II} | 0.75 | 0.15 | 0.36 | 0.21 | 0.07 |
| E ₁ ^{III} | 0.61 | 0.12 | 0.55 | 0.21 | 0.05 |
| E ₁ ^{IV} | 0.45 | 0.26 | 0.14 | 0.30 | 0.10 |
| E ₂ | 0.21 | 0.64 | 0.07 | 0.06 | 0.27 |
| E ₂ ^I | 0.12 | 0.61 | 0.04 | 0.05 | 0.29 |
| E ₂ ^{II} | 0.20 | 0.72 | 0.09 | 0.14 | 0.22 |
| E ₃ | 0.61 | 0.47 | 0.42 | 0.15 | 0.10 |
| Yellow Sea | | | | | |
| Y ₁ | 0.80 | 0.04 | 0.09 | 0.31 | 0.05 |
| Y ₂ | 0.86 | 0.05 | 0.16 | 0.19 | 0.05 |
| Y ₃ | 0.16 | 0.00 | 0.98 | 0.07 | 0.05 |
| Y ₄ | 0.76 | 0.03 | 0.45 | 0.16 | 0.05 |
| Y ₅ | 0.74 | 0.02 | 0.38 | 0.21 | 0.05 |
| Y ₆ | 0.37 | 0.02 | 0.91 | 0.13 | 0.04 |
| Y ₇ | 0.76 | 0.03 | 0.43 | 0.17 | 0.05 |
| Y ₈ | 0.49 | 0.02 | 0.69 | 0.15 | 0.05 |
| Y ₉ | 0.88 | 0.05 | 0.09 | 0.18 | 0.06 |
| Philippine Sea | | | | | |
| F ₁ ^I | 0.07 | 0.95 | 0.02 | 0.02 | 0.13 |
| F ₁ ^{II} | 0.11 | 0.98 | 0.03 | 0.02 | 0.03 |
| F ₂ ^I | 0.13 | 0.59 | 0.03 | 0.04 | 0.29 |
| F ₂ ^{II} | 0.47 | 0.58 | 0.10 | 0.07 | 0.24 |
| F ₃ | 0.75 | 0.50 | 0.12 | 0.03 | 0.06 |
| F ₄ | 0.14 | 0.08 | 0.40 | 0.05 | 0.04 |

Table 2 (Continued)

| Provinces, subprovinces | Factor I (33.8%) | Factor II (31.6%) | Factor III (9.7%) | Factor IV (9.6%) | Factor V (3.7%) |
|-------------------------------|---------------------|----------------------|----------------------|---------------------|--------------------|
| F ₅ | 0.36 | 0.23 | 0.88 | 0.09 | 0.07 |
| F ₆ | 0.45 | 0.75 | 0.07 | 0.11 | 0.03 |
| F ₇ ^I | 0.21 | 0.42 | 0.03 | 0.06 | 0.03 |
| F ₇ ^{II} | 0.91 | 0.11 | 0.09 | 0.09 | 0.04 |
| F ₇ ^{III} | 0.38 | 0.18 | 0.07 | 0.25 | 0.05 |
| F ₇ ^{IV} | 0.72 | 0.51 | 0.14 | 0.16 | 0.06 |
| South China Sea | | | | | |
| S ₁ ^I | 0.68 | 0.05 | 0.23 | 0.33 | 0.05 |
| S ₁ ^{II} | 0.23 | 0.03 | 0.96 | 0.13 | 0.05 |
| S ₂ ^I | 0.41 | 0.07 | 0.12 | 0.79 | 0.05 |
| S ₂ ^{II} | 0.34 | 0.04 | 0.10 | 0.85 | 0.05 |
| S ₂ ^{III} | 0.66 | 0.05 | 0.12 | 0.41 | 0.05 |
| S ₂ ^{IV} | 0.71 | 0.12 | 0.14 | 0.45 | 0.11 |

Note: Factor loadings only for mineralogical provinces/subprovinces listed in Table 1, are shown here.

concentrations of opaque minerals (magnetite, titanomagnetite, ilmenite) and, in some areas, olivine. The grains are fresh, idiomorphic, and are often enclosed by volcanic glass. Mineral assemblages of this type extend as a continuous belt along the system of island arcs and can be traced up to a few hundreds of kilometres in marginal seas, widening especially in bordering areas of the Pacific Ocean (Fig. 1). Assemblages with maximal values of factor loadings characterise provinces related to ensimatic (young) island arcs (Mariana, Izu-Bonin, Tonga, Vanuatu) where clinopyroxene-rich assemblages with subordinate olivine dominate. Assemblages with smaller factor loading values are peculiar to mature and evolved (Aleutian, Kurile-Kamchatka, Japanese, Nansey, Philippine, Sunda) island arcs with widespread occurrence of the calc-alkaline magmatic rocks (Kuno, 1959; Kovalenko, 1987). These assemblages are characterised by high orthopyroxene content. Explosive volcanic activity is the main source of clastic minerals here: the areal extent of the numerous ash-falls can be tracked in the sediments as pure inter-layers of pyroclastics or as dispersed volcanoclastics at distances of over 1000 km (Machida and Arai, 1976, 1978; Arai et al., 1981; Machida and Arai, 1983).

In addition to the volcanoclastic island-arc provinces described above, *Factor II* combines provinces that are derived from volcanic and volcanoclastic rocks of basic to intermediate composition (including plateau basalts) of Neogene-Quaternary age. Provinces of this type adjoin northern Sikhote-Alin, the western coast of Sakhalin, the coast of northern Kamchatka and Koryack (Fig. 1). They are characterised by heavy mineral assemblages dominated by clinopyroxenes and with comparatively increased content of hornblendes and epidote (Table 1).

Factors III and IV incorporate mineral assemblages that have sharply different hydraulic properties. *Factor III* makes a 9.7% contribution to the variance and characterises mineral assemblages with a high content of most hydraulically

susceptible minerals, mainly micas. Similar assemblages have been found in the Japan Sea near the eastern Korean coast (Mica Province), Yellow (Provinces Bohai Gulf, Pentsai-Haiyan; Shen et al., 1984; Likht, 1997) and East China Seas (Yangtze Province). Abundant mica serves as a good indicator of quiet or low energy hydrodynamic conditions in the depositional environment (Derkachev et al., 1983). In the Japan Sea, areas of high mica concentrations and sedimentary rates are found at the foot of the Korean continental slope extending into bathyal basins. Similar conditions occur in some coastal areas, at large river mouths and in halistatic zones (the central, slack-water, parts of the gyres formed by the currents, where fine-grained sediments accumulate) of the Yellow and East China Seas (Milliman and Meade, 1983; Shen et al., 1984; Chen, 1989; Derkachev and Nikolaeva, 1995; Derkachev, 1996).

A zircon/rutile/anatase/garnet assemblage is defined by *Factor IV* with a contribution to the variance of 9.6%, and is restricted to the wide shelves of large bays (East Korean, Peter the Great and Delangle in the Japan Sea), the Korean Strait, the East China outer shelf and the south-western part of the South China Sea (Mekong Shelf). It generally has a local distribution and belongs either to relict sediments of submarine coastal-slope facies, or to bottom areas that are subjected to the influence of strong tidal currents (Oki Strait in the Japan Sea, the area near Qingdao Peninsula in the Yellow Sea, etc.) (Shen et al., 1984; Yokota et al., 1990; Derkachev, 1996).

Factor V (with a contribution to the variance of 3.7%) defines volcanoclastic assemblages with orthopyroxene dominating over clinopyroxene. Typical examples of these assemblages are found in the provinces adjoining Kyushu Island and the northern part of Ryukyu island arc (Suzuki, 1975a; Derkachev and Nikolaeva, 1995).

When evaluating the regional variability in the distribution of mineral assemblages, it is necessary to note specific assemblages, which were not distinctly reflected by the Q-factor analysis (the values of factor loadings on each of the factors are lower than 0.5). These include hornblende/clinopyroxene/epidote assemblages with the dominance of epidote and rather high contents of chlorite and actinolite, formed mainly by the breakdown and erosion of greenschist facies metasedimentary and metavolcanic rocks. Such assemblages usually occupy areas adjacent to ancient marginal-continental volcanic belts of pre-Cenozoic age (Okhotsk-Chukotka, Sikhote-Alin, Honshu-Korean) (Belyiy, 1998). The south-eastern province of the Japan Sea, adjoining the Sikhote-Alin volcanic belt, is representative of such assemblages. A similar composition characterises assemblages in some Japan Sea rises (provinces of the north-western submarine rises and Yamato) (Fig. 1, Table 1).

Subaqueous destruction of metabasites, ultrabasics, amphibolites, actinolite-chlorite-epidote schists, gabbros, etc., which form raised blocks on the oceanic crust, release mineral assemblages that are distributed in deep-water trenches within the Western Pacific (Mariana, Yap, Palau, Philippine, Tonga). These metaophiolite-derived assemblages are spatially disconnected and usually occupy small areas on the slopes and on the bottom of trenches. The proportions of the main minerals in these assemblages (clinopyroxenes, chlorite, green hornblende, actinolite, epidote) can vary in the various trenches, as a function of parent rock composition (Skornyakova et al., 1978; Murdmaa et al., 1980; Derkachev et al., 1989; Nechaev and Derkachev, 1995). Enstatite-bronzite, olivine, diopside, chromite and other diagnostic minerals

(with chlorite aggregates, serpentine and talc in the light fraction) are present as accessory minerals in assemblages of some trenches, especially where outcrops of ultrabasics are present (Mariana, Yap, Tonga).

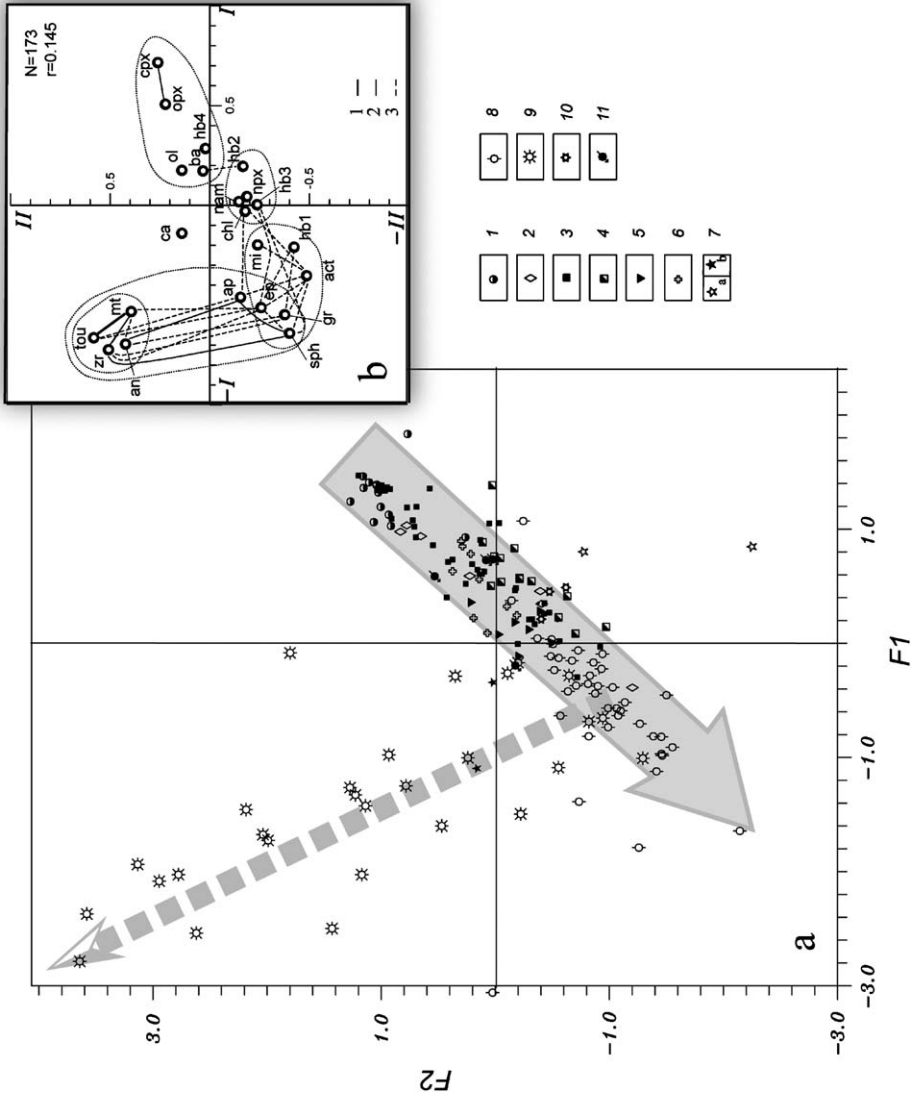
Towards the central areas of the basins, the influence of coastal supply diminishes, with the formation of mixed mineral assemblages in the central deep-water areas of the Bering, Okhotsk and (to a lesser degree) Japan Seas. Fig. 1 shows that individual features of terrigenous-mineralogical provinces can be traced up to a few hundreds of kilometres (usually 150–250 km) from the coast. This distance is greater for the seas with wide shelves: the East China and southwest part of the South China (Sunda Shelf). The areal spread of minerals in the volcanoclastic provinces is much wider.

3.2. R-Factor Models

R-factor models help to define the main mineral associations, which best characterise the mineral composition of the sediments of the individual marginal seas. Analysis of several tens of R-factor diagrams of the mineral composition of sediments, plotted for individual mineralogical provinces, has revealed a regular combination of minerals with considerable statistical stability and consistent correlations (Derkachev and Nikolaeva, 1995, 1997; Nechaev and Derkachev, 1995; Derkachev, 1996). The make-up of these mineral associations, as will be seen below, is a function, primarily, of the lithology of their source rocks, the nature of volcanism (defined by the plate tectonic setting) and the hydrodynamics of the bottom waters. R-factor analysis of the integrated dataset was based on both regular sampling for all marginal seas (1200 analyses) and sampling of average values of mineral contents for separate provincial assemblages. Results have indicated a strong correspondence with the main features of the mineral assemblages in the source formations, thus proving the potential of the method. Mean values plotted in Fig. 2 show that *Factor I* reflects key differences in the nature of heavy mineral associations, caused by tectonic discontinuity in the continent-ocean transition zone. We interpret this factor as the *factor of geodynamic setting*.

The plot of factor values in Fig. 2 shows that mineral assemblages, associated with the geodynamic environments of island arcs, deep-water trenches and back-arc spreading, generally have $F1 > 0$. This clearly reflects a trend in the evolution of magmatism in a continent-ocean transition zone. Mineral assemblages reflecting features of both island arc magmatism on the oceanic basement (epioceanic or young island arcs) and associated deep-water trench environments show $F1 > 1$. The olivine/clinopyroxene suite with the dominance of clinopyroxene is most widespread in these environments.

Assemblages associated with island arcs, founded on more mature subcontinental or continental crust (epicontinental or mature and evolved island arcs), occupy an isolated position. Differentiated calc-alkaline igneous rocks with increased content of orthopyroxene and—for some areas (the back arcs)—of hornblende, are more widespread here in comparison with ensimatic island arcs. The two-pyroxene (orthopyroxene/clinopyroxene) assemblages and, to a lesser degree, clinopyroxene/orthopyroxene/hornblende suites (with dominant brown-green, brown hornblendes and oxyhornblende) are most typical for this geodynamic environment.



Mineral assemblages representing mature continental crust have $F_1 < 0$ and are clustered in the left part of the plot (Fig. 2a). They define a clear trend in mineral density (dashed arrow), as a result of hydrodynamic differentiation of the clastic material by wave action and tidal currents. This process is highlighted by *Factor II* and is interpreted as *the factor of hydrodynamics*. This factor contrasts mineral associations with different hydraulic properties, for example: zircon/anatase (rutile)/tourmaline versus actinolite/hornblende/micas/apatite (Fig. 2b).

The other factors discriminate between mineral associations, reflecting the petrographic composition of particular rock complexes in the source areas. These associations are: (a) sphene/garnet/apatite; (b) epidote/green and brown-green hornblende; (c) various micas, etc. Mineral constituents of alkaline volcanic rocks from areas of active tectono-magmatic regimes form independent suites. The association of alkali pyroxene/alkali amphibole/brown hornblende (Fig. 2b) is the most clearly expressed and is reflected by *Factor III*. Its typical occurrences are the Central Japan Sea and Ulreung-do Provinces in the Japan Sea. The high contents of both alkali pyroxenes and alkali amphiboles (on an average 12.9 and 9.5%, respectively), together with a predominance of clinopyroxenes over orthopyroxenes, are distinctive features of the Central Japan Sea mineral assemblage. Alkali pyroxenes and alkali amphiboles are not found in such high amounts in any other area of the marginal seas within the Western Pacific. They are connected with activity of the Korean Baegdusan Volcano (Machida et al., 1981). The clinopyroxene/brown hornblende/oxyhornblende/biotite/apatite association, most typical for eruptions of the

Fig. 2. R-mode factor model of detrital mineral composition in the marginal seas of the Western Pacific, based on mean heavy mineral contents of the assemblages in the heavy mineral provinces. (a) The position of mineral assemblages on the plot of factor values: along the X-axis, values of the first factor (F_1); along the Y-axis, values of the second factor (F_2). 1–11, mineral assemblages with affinities to: 1, island arcs on the oceanic basement, or young island arcs (olivine-clinopyroxene assemblage); 2, deep-water trenches; 3, evolved and mature island arcs (predominantly orthopyroxene-clinopyroxene assemblage); 4, the same, but with the predominance of volcanogenic hornblende; 5–6, Meso-Cenozoic marginal-continental volcanic belts; 5, hornblende-epidote-pyroxene assemblage; 6, the same, but with the predominance of clinopyroxene; 7, the areas of renewed tectonics and magmatism with: a, acid alkaline magmatism (Baegdusan, Ulreung-do Volcanoes), b, basaltic magmatism (volcanoes of the Vietnamese Shelf); 8, ancient consolidated areas with the prevalence of sedimentary, granitic and metamorphic rocks; 9, the same, but within shelves with active hydrodynamics of near-bottom waters; 10, the areas of island arc-continent collision with the primary involvement of mica-chlorite assemblages (Taiwan Island); 11, mixed mineral suites of the Central Okhotsk Sea. *Solid arrow* indicates the evolutionary trend of detrital mineral distribution, controlled by the geodynamics of the sedimentary environment (a trend from simple geodynamic conditions for oceanic crust toward composite processes for consolidated continental crust). *Dashed arrow* shows a trend of evolving heavy mineral assemblages as a response to near-bottom water hydrodynamic processes causing mineralogical differentiation. (b) Main heavy mineral assemblages on the plot of factor loadings: N , quantity of data (based on mean values of provincial assemblages); r , significant (at 95%) correlation coefficient. Lines—significant positive correlations between minerals: 1, strong (>0.5); 2, moderate (0.3–0.5); 3, weak (<0.3). *Circles with dotted lines* outline main heavy mineral associations. Abbreviations for minerals are given in the Table 1.

Ullreung-do volcano (Japan Sea) (Machida et al., 1984), is expressed to a lesser degree.

3.3. Influence of Grain Size, Mineral Stability and Climate

For the marginal seas (Okhotsk, Japan, etc.), the common tendency of detrital mineral dispersal coincides with grain-size trends from coarse-grained sands and gravels to silty-clays and appears to be connected with mineralogical differentiation by hydraulic processes (Derkachev and Nikolaeva, 1993, 1997). Correlation analysis between grain size and heavy mineral content showed for the coarse suites a positive correlation between high-density heavy minerals (opaque minerals, zircon, garnet, sphene, anatase and metamorphic minerals). The opposite behaviour is characteristic for minerals with lower density and greater hydraulic mobility (micas, brown-green hornblende, actinolite and calcite), which concentrate in fine-grained deposits.

The large latitudinal extent of the Western Pacific marginal seas allows us to estimate whether the climatic factor essentially influences the behaviour of detrital mineral assemblages from north to south. For this purpose, we have taken mean values of mineral groups (stable, moderately stable and unstable to chemical weathering according to Berger, 1986) for the studied provinces. The interrelations of these mineral groups were considered for regions with different climate (Fig. 3). The comparative analysis has shown that immature mineral assemblages are characteristic for sediments in all studied seas. Tectonic activity in adjoining land and seabed along with volcanic processes are the main reasons for the presence of immature

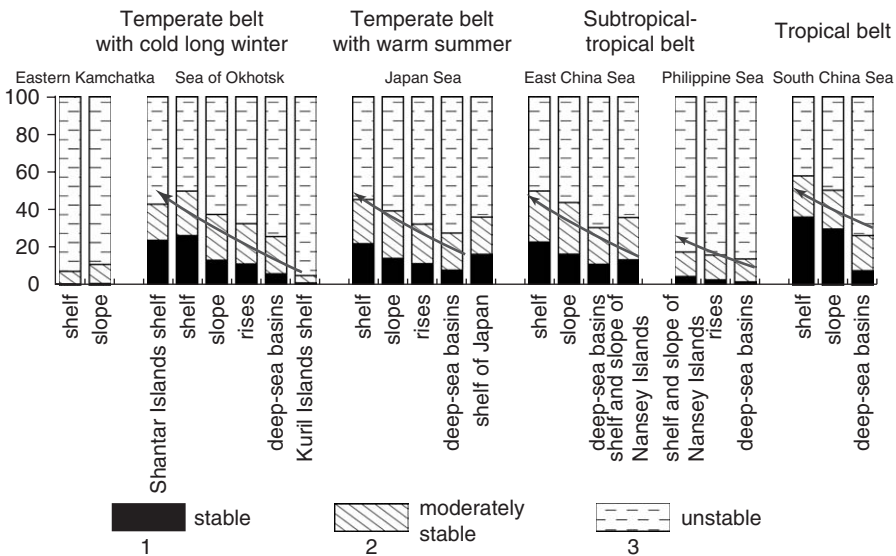


Fig. 3. Comparison of mean values for stable, moderately stable and unstable minerals within sedimentary basins grouped according to climatic belts and main structural elements of the seabed. 1–3, Percentage of mineral groups according to their stability under weathering. Arrows show a trend of the maturity increase for mineral assemblages within different climatic belts.

heavy mineral assemblages. Neotectonic movements on land with renewed activities on both ancient platform and folded areas have created significant topography. As a result, intensive erosion, exceeding the thickness of the weathering zone, ensured the delivery of fresh clastic material to the marginal seas. Increased erosion during tropical cyclones (typhoons) also exerted considerable influence on the character of the detrital mineral assemblages. Consequently, vast masses of clastic material were transported outside the coastal zone and bypassed it without any significant hydraulic sorting or mineralogical differentiation.

However, a small but noticeable increase in mineral maturity can be observed from the subarctic belt to the subequatorial zone. Derkachev and Nikolaeva (1993, 1999) discerned this tendency by mapping the distribution of the stability coefficient in the mineral assemblages, calculated as the ratio of stable minerals to moderately stable and unstable ones. They found that a considerable scatter of the stability coefficient values is characteristic for detrital mineral assemblages of a subequatorial belt. Overall, the values vary from high, as in sediments of shelves with an active hydrodynamic regime (e.g., the Mekong River shelf) to rather low, peculiar to continental slope environments and deep-water basins of the South China Sea (Fig. 3). The large transit rivers (Mekong, Red, etc.) draining strongly dissected mountains with high rates of erosion, cutting into unaltered bedrock, mask the influence of the climatic factor. However, the influence of the climatic factor is more strongly expressed in north-eastern areas of the Siam Gulf near the Cambodian coast and on northern coast of the Bakbo Gulf, where the land is drained by river systems flowing through a thick weathering zone (Chen and Zhang, 1986; Li and Ye, 1987; Derkachev and Nikolaeva, 1999a), but such areas have limited distribution.

The above indicates that climatic factor, even within the subequatorial belt, does not reflect the features of detrital mineral compositions of the Western Pacific marginal seas. The structural position of sedimentary basins, the petrography of source complexes and the hydrodynamics of the drainage systems exert greater influence on mineral compositions and formation of the sediments than climate. In our case, it is possible to conclude with confidence that the detrital mineral composition of the marine basins carries and maintains individual signatures of respective source rock lithologies despite some homogenisation and simplification resulting from environmental and hydrodynamic factors. Fig. 3 illustrates the proportions of heavy minerals with differing stabilities in a series of marine basins situated in different climatic zones. A trend with decreasing mineral maturity in a sequence of depositional environments from shelf-continental slope-submarine rises to deep-water basins is clearly noticeable in this figure. All these conclusions are supported by Q- and R-mode factor analyses.

Consequently, we have made an attempt to assess whether heavy mineral assemblages can be used as indicators of particular geodynamic environments within zones of near-continental depositional settings. Using data on individual heavy mineral abundances, heavy minerals were grouped into discrete suites according to their genetic affinities to particular magmatic and metamorphic rocks. Eight heavy mineral suites were recognised from four (A–D) distinct rock types:

A: mafic intrusive and effusive rocks of variable composition:

1. olivine/clinopyroxene,
2. orthopyroxene,

3. brown hornblende/oxyhornblende,
 4. alkali pyroxene/alkali amphibole;
- B: acid intrusive rocks of sialic type:
5. green hornblende/brown-green hornblende,
 6. zircon/apatite/sphene (GM);
- C: greenschist facies metamorphic rocks (MT₁):
7. epidote/actinolite/tremolite/chlorite;
- D: high-grade metamorphic rocks (MT₂):
8. garnet/anatase/rutile/staurolite/andalusite/kyanite/sillimanite/tourmaline/
calcite.

3.4. Discriminant Analysis

Variations in the detrital mineral spectra of sediments is best studied using comparative analysis of average values of both the provincial mineral assemblages and those in the individual areas of a particular basin. Therefore, to obtain fully representative heavy mineral compositions, we have analysed data not only from the marginal seas of the Western Pacific but also from other areas of the world's oceans, located in different climatic belts and different geodynamic environments (published data on detrital mineral assemblages from the Atlantic, Arctic and Indian Oceans, as well as from the Mediterranean, Baltic and North Sea, the Sea of Azov, and the Black, Aral and Caspian Sea were used. However, references are too numerous to be listed here). The resultant representative dataset, comprising 320 mineral assemblages, was processed by discriminant analysis with the calculation of the equations of linear discriminant functions (df1, df2, df3) (see Fig. 4). This calculation was made with the use of the statistical software 'STATGRAPHICS':

$$\begin{aligned}
 df_1 &= -5.678x_1 - 5.703x_2 - 5.738x_3 - 5.659x_4 - 5.705x_5 \\
 &\quad - 5.78x_6 - 5.743x_7 - 5.742x_8 + 571.785 \\
 df_2 &= -59.797x_1 - 59.714x_2 - 59.739x_3 - 59.717x_4 - 59.764x_5 \\
 &\quad - 59.825x_6 - 59.704x_7 - 59.674x_8 + 5976.46 \\
 df_3 &= -30.154x_1 - 30.098x_2 - 30.147x_3 - 30.059x_4 - 30.206x_5 \\
 &\quad - 30.108x_6 - 30.149x_7 - 30.139x_8 + 3015.14,
 \end{aligned}$$

where x_1 = sum of clinopyroxene and olivine, x_2 = orthopyroxene, x_3 = brown-green and green hornblende, x_4 = brown hornblende and oxyhornblende, x_5 = sum of epidote, actinolite and chlorite, x_6 = sum of garnet, anatase, rutile, staurolite, andalusite, corundum, sillimanite, tourmaline and calcite, x_7 = sum of zircon, sphene and apatite, x_8 = sum of alkali pyroxene and alkali amphibole.

In calculating discriminant function values, the sum of minerals used in the equations was taken as 100%. Opaque and authigenic minerals, mica and rock fragments were excluded from the calculation. Discriminant analysis has revealed an intimate relationship between heavy mineral assemblages and the structural setting of the studied sedimentary basins. The points of discriminant function values were plotted on two diagrams to achieve the best characterisation of mineral assemblages.

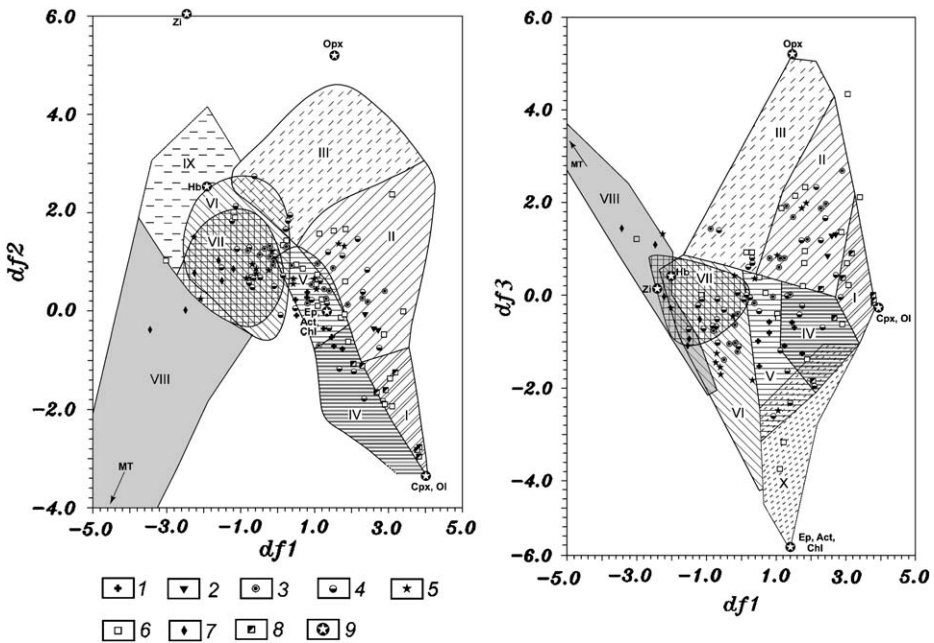


Fig. 4. Lithogeodynamic diagrams, reflecting the dependence of composition of heavy mineral assemblages on the geotectonic setting of sedimentary basins. I–VIII, fields of location of the imaging points for heavy mineral assemblages of different types of geodynamic environments: I, young island arcs on oceanic basement, evolved (II) and mature (III) island arcs; IV, young folded areas with evolving primary Cenozoic volcanogenic and volcanogenic-sedimentary rocks, along with areas of active tectonics and magmatism with Pliocene-Quaternary effusive basaltic volcanism, forming thick covers of plateau basalts; V, Meso-Cenozoic marginal-continental volcanic belts; VI, areas of ancient Precambrian fold belts with primary sedimentary, granitic and metamorphic rocks; VII, Precambrian cratons and intermediate massifs comprising granitic and metamorphic complexes; VIII, ancient platforms; IX, field of the mineral assemblages with high proportions of stable minerals (predominantly zircon) formed by hydraulic differentiation processes; X, field of mineral assemblages formed by destruction of altered ultrabasic rocks, including ophiolites. 1–9, assemblages in mineral provinces of the Seas: 1, Bering; 2, eastern coast of the Kamchatka; 3, Okhotsk; 4, Japan; 5, East China; 6, Philippine; 7, South China; 8, Tonga Trench; 9, the position of the hypothetical mineral assemblages with the 100% content of clinopyroxene and olivine (Cpx, Ol), orthopyroxene (Opx), brown-green and green hornblende (Hb), zircon, apatite, sphene (Zr), group of greenschist facies metamorphic minerals: epidote, chlorite, actinolite (Ep, Act, Chl), group of high-rank metamorphic minerals of: tourmaline, rutile, anatase, kyanite, staurolite, sillimanite, andalusite, calcite (MT).

The first diagram is plotted in a plane of the 1st and 2nd discriminant functions (Fig. 4a), and the second in a plane of the 1st and 3rd ones (Fig. 4b). The use of two diagrams has facilitated the recognition of details, which could be missed if only one diagram was used. Assemblages associated with deep-water trenches (*field X*) appear more clearly on the second diagram (Fig. 4b). Heavy mineral suites representing discrete crustal lithologies are easily recognized in the diagrams from a change in the

trend of mineral assemblages from oceanic to continental areas (Fig. 4). This is also confirmed by R-mode factor analysis (as discussed above).

In the search for signatures of particular geodynamic environments for sedimentary basins, Romanovsky (1991, 1998) introduced the term 'lithogeodynamics'. According to his suggestion, lithogeodynamics is the science studying lithological indicators of past geological regimes. It allows the identification of objective and reliable lithological features (in our case these are detrital mineral assemblages) of tectonic regimes in which sedimentary sequences are formed. The author uses this term for the diagrams shown in Fig. 4, because they essentially reflect the unique geotectonic features of the studied sedimentary basins. For example, detritus from intra-oceanic uplifts and young island arcs, comprising predominantly clinopyroxenes and to a lesser extent olivines, differ considerably in composition from all other environments (*field I*). The typical mineral assemblages in this case are the products of Mariana, Izu-Bonin, Tonga-Kermadec and Vanuatu island arcs. Higher amounts of olivine, in varying proportions, and the appearance of titaniferous clinopyroxene (Nechaev, 1991) is characteristic for mineral assemblages of intra-oceanic uplifts.

Mineral assemblages of evolved and mature island arcs scatter within well-defined areas (*fields II and III*), separate from other fields in the plot. The main sources of clastic material supply are the differentiated volcanic island-arc complexes of mainly calc-alkaline series, which are characterised by two-pyroxene {clinopyroxene-orthopyroxene (hypersthene)} assemblages (Kuno, 1959; Kovalenko 1987; Miyashi and Miyashi, 1988). Mature island arcs (Aleutian, Kurile-Kamchatka, Japanese, Ryukyu, Philippine, Sunda, New Zealand, etc.) are characterised by strong explosive volcanic activity and, as a result, pyroclastic material is scattered at considerable distances and becomes intermixed with sediments of the contiguous deep-water basins. Mineral assemblages, characteristic of the Japanese island arc (Suzuki, 1975a, 1975b, 1985; Yokota et al., 1990), cluster within the field of mature island arcs (*field III*) and those of pyroclastic flows of many volcanoes from Kyusyu and Honshu islands (Miyashi and Miyashi, 1988) tend towards the same field. Products of volcanism, associated with water-saturated magmas are widely distributed in back-arc zones of mature island arcs with rather thick continental crust. Accordingly, the influence of explosive volcanism of this type is reflected in the mineral compositions of sediments of the surrounding seas. Hydrous aluminosilicates are predominant as the ferromagnesian phase, including volcanogenic brown-green hornblendes with subordinate biotite, brown hornblende, oxyhornblende and hypersthene (Table 1). They are most common in areas adjoining southwest Japan, the northern part of the Philippine Arc (Luson, Batan, Babuyan Islands) and to the east of New Guinea. On the discriminant-functions diagrams they cluster in the far left part of *field III* (Fig. 4a). The virtual absence of metamorphic (MT₁ and MT₂) and sialic (GM) mineral groups distinguishes them from those hornblende-rich assemblages that define fold belts of continental areas (see below).

Detrital mineral assemblages derived from marginal-continental, volcano-plutonic belts (Sikhote-Alin, Okhotsk-Chukotka, Honshu-Korean, etc.) occupy a distinct position (*field V*) on the diagrams (Fig. 4a, b). Increased amounts of sialic minerals and rather high pyroxene content, combined with the presence of the epidote group (the latter are typical of greenschist facie metamorphics: MT₁), are

characteristic for these assemblages. The field in which they are located is partially overlapped by that of island-arc assemblages.

In mineral assemblages of source provinces, the amount of metamorphic minerals shed by greenschist facies (MT_1) rocks decreases with the emergence of more basic effusive rocks and the rejuvenation of magmatism within marginal-continental volcanic belts. Consequently, a definite trend towards primitive, olivine-clinopyroxene dominated, suites of young island arcs (Fig. 4a) is highlighted by the distribution of points signalling the mineral assemblages of these environments (*field IV*). The provinces, bordering the Olutor-Koryak coast of the Bering Sea and the northwest coast of the Japan Sea (Kuznetsovo and Sovgavan Provinces), are representative of this mineral suite. It should be noted that the mineral assemblages from areas adjacent to Pliocene-Quaternary plateau basalts occupy the same field, e.g., the Sovgavan (northern Sikhote-Alin), Orlov (western Sakhalin), Shkotovo (southern Primorye). Other plateau basalts are located outside the studied Western Pacific areas (Emelyanov, 1979; Kharin et al., 1979; Emelyanov and Kharin, 1982).

Mineral assemblages from deep-water trenches overlap *fields IV and V*, and form a trend along a line $Ol, Cpx \rightarrow Ep, Act, Chl$. This geodynamic environment is enhanced in Fig. 4b, where the assemblages occupy a distinct field (*field X*). *Field X* is partially overlapped by the fields of marginal-continental volcanic belts (*field V*) and areas of renewed tectono-magmatic activity (*field IV*).

Detritus from mature continental crust differs in mineral composition (Fig. 4), being dominated by brown-green and green hornblende-rich assemblages, with subordinate epidote and accessory minerals from granitic and metamorphic rocks. The typical representatives of similar mineral assemblages are those of the Western Okhotsk Sea (including the Amur River Basin), and all assemblages along the coast of Korea, China and Indochina. On the diagrams of Fig. 4 they fall into fields, controlled by different mineral groups (GM and MT). The assemblages adjoining to ancient fold belts, with the predominance of granitic-metamorphic and sedimentary rocks, occupy *field VI*. Heavy minerals derived from pre-Cambrian cratons of ancient platforms trend towards *field VII*. These fields partially overlap, and are shown clearly only in Fig. 4b (in the direction of MT_1 mineral group) in the field defining VI, caused by the increase in contribution from metasedimentary rocks of ancient fold belts.

Highly mature polycyclic suites, derived from granitic and metamorphic rocks (GM and MT_2), characterise the cratonic cover sediments of ancient platforms (East European, North American, Australian etc.) and form two distinct fields (*VIII and IX*). *Field VIII* comprises assemblages of cover rocks on ancient platforms, while *field IX* depicts the most mature suite, dominated by zircon. Heavy mineral accumulations formed by hydraulic sorting, e.g., placer deposits, and those resulting from high-energy conditions on the shelves, also point towards *field IX*. As a rule, similar assemblages are conjugated with Recent and relict (Pleistocene) beach facies and with those on underwater coastal slopes. The typical locations of such assemblages are those on the Sunda Shelf (South China Sea), and some areas of the outer shelf of the East China and Japan Seas (Yokota et al., 1990; Derkachev and Nikolaeva, 1995, 1999; Derkachev, 1996). Heavy minerals released by the disintegration of weathering crust, and those eroded from microcontinents (Seychelles), also trend

towards *field IX*. Intensive weathering of granites (dominant type of rocks on the Seychelles) under wet tropical climate have resulted in the concentration of stable minerals with a predominance of zircon (Korotky and Raszhigaeva, 1992; Derkachev et al., 1997).

4. CONCLUSIONS

Multivariate and comparative analyses of the spatial distribution of heavy mineral assemblages, as presented in this paper, show that the detrital mineral composition of marginal seas within the Western Pacific is determined, primarily, by the structural position of these seas in the zone of continent to ocean transition. Hydrodynamic and, to a lesser extent, climatic factors have an appreciable influence.

Lithogeodynamic diagrams show a strong relationship between the composition of heavy mineral assemblages and the structural setting of the sedimentary basins. The evolutionary trends of geodynamic sedimentary environments, connected with an increase in maturity of the earth's crust, are clearly expressed. The increased frequency of both hornblendes and diagnostic minerals of granitic and metamorphic rocks in heavy mineral assemblages within sedimentary basins indicates an increasingly sialic continental crust with time in the study region. It is connected with structural processes and is reflected in oceanic uplifts, juvenile island arcs, evolved and mature island arcs, marginal-continental volcanic belts, fold belts of different age and ancient cratons and platforms.

Only the largest structural elements are outlined in this paper but they can be complemented and refined further with the availability of new data. The authors hope that the current study, based on heavy mineral compositions in modern settings, will provide a model that may be useful for the geodynamic reconstruction of ancient sedimentary basins. Such work can be integrated with QFL studies based on framework components. We recognise that our multivariate analysis and the diagrams presented herein reflect modern depositional conditions. Therefore, when using this approach on ancient successions, interpretation of results must be made with caution, especially for those that are known to be affected by post-depositional modification. In the latter case complementing the geodynamic study with geochronology, geochemistry and varietal studies of heavy minerals have a considerable potential for increasing resolution.

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