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HEAVY CLASTIC MINERALS IN UPPER PALEOZOIC-LOWER MESOZOIC BEDDED CHERTS OF THE SIKHOTE-ALIN TERRANES, RUSSIAN FAR EAST

(First Attempt of Study)

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Abstract

This report is based on 33 heavy-mineral analyses combined with microprobe analyses of olivine, pyroxene, amphibole and garnet. The heavy minerals are *the first* extracted from Upper Paleozoic-Lower Mesozoic bedded cherts and associated sedimentary rocks situated in the Samarka and Taukha Accretionary-Wedge Terranes (the Sikhote-Alin Mountains, southern Russian Far East). Actualistic interpretation of the data enables us to define tectonic settings at the place and time of these rocks deposition. Permian chert contains the association of olivine, Mg-orthopyroxene, Mg-clinopyroxene, amphibole, garnet and spinel derived from metaophiolites. It indicates the tectonic setting is like that in the modern intraoceanic collision zones. The Ti-clinopyroxene assemblage from Upper Triassic-Lower Jurassic cherts, mudstones and tuffs, which is derived from the within-plate basalts, points to the intraoceanic seamounts and fracture zones. Mesozoic deposits contain also zircon, tourmaline and sphene which amount is increasing with time. It likely reflects drifting of the depositional places from intraoceanic to passive-continental-margin conditions along tectonic zones oblique to the continent-ocean border. Heavy-mineral analysis of the pelagic deposits such as chert, limestone and claystone is recommended for wide use in order to define tectonic settings associated with the ancient oceanic and deep-sea basins as well as the global geological evolution.

1. Introduction

The previous investigation of Cenozoic (mainly aternary) marine sediments in the oceanic and marginal- environments has revealed that their heavy-clastic- ieral assemblages are reliable indicators of tectonic ings at and around their depositional places (Nechaev l Derkachev, 1989; Nechaev, 1991a,b; Nechaev and hording, 1993). These data may be compared with those ited to the ancient sedimentary rocks in order to define logical history of the ocean and continental margins. e of the advantages in such a study is that any kind of imentary deposits, not only sands and sandstones used the similar purposes traditionally (for instance, kinson, 1985 and references therein), may serve as a irce of the interesting information. Heavy mineral ilyses of claystones and calcareous oozes have already n used to correlate major tectonic, volcanic and lrothermal events in the Cenozoic history of the lippine and Japan Seas (Nechaev, 1991a). In our present rk, we extended the study to the Permian-Lower Jurassic lded cherts and associated rocks situated as tectonic lusions in the accretionary-wedge terranes of Sikhote- n (southern Russian Far East).

Origin of siliceous deposits located now on the Circum- ific continental margins is of great interest since many researchers consider them as relicts of the ancient oceans. There is an animated discussion of this matter because most of Paleozoic and Mesozoic siliceous rocks may not be comparable with pelagic sediments accumulated in the present ocean and seas. The major differences consist in the following: the ancient siliceous deposits are chiefly poor in terrigenous components and bedded in structure whereas siliceous sediments in the modern ocean are also rather pure but homogeneous in structure and those in marginal seas are bedded but contain abundant terrigenous material (Hein and Karl, 1983 and references therein). However, comparison between modern and ancient siliceous deposits and associated rocks based on their sequence, structure, geochemistry, and biofossils (chiefly Radiolaria) have allowed researchers to conclude that all of them accumulated in the areas of high bioproductivity (Jones and Murchey, 1986, and references therein). Such areas may be located in various plate-tectonic settings. The suggestions on a tectonic situation related to the origin of the ancient pelagic deposits are inferred mainly on evidence from the associated rocks. For instance, chert associated with ophiolites are believed to be originated in basins with the oceanic-type earth's crust. Indeed, certain magmatic rocks can serve as reliable indicators of tectonic settings but, in many cases, it is a problem to prove that sedimentary deposits located near them in terranes were associated with them originally. Thus, it is necessary to find evidence on the tectonic environment from the siliceous deposits themselves.

On these pages, we will introduce interested researchers to an untraditional way of studying bedded cherts and associated sedimentary rocks to define tectonic settings around their depositional places. *As far we know, this is the first attempt to study the accessory clastic minerals in siliceous deposits.*

2. Data and Methods

Samples used in this study were collected during the field works carried out by teams of the Yuzhno-Primorskaya Geologos'emochnaya Expeditsiya (Geological Survey «Primorgeologiya»), and Far East Geological Institute (Russian Academy of Sciences) for the last five years (Fig. 1).

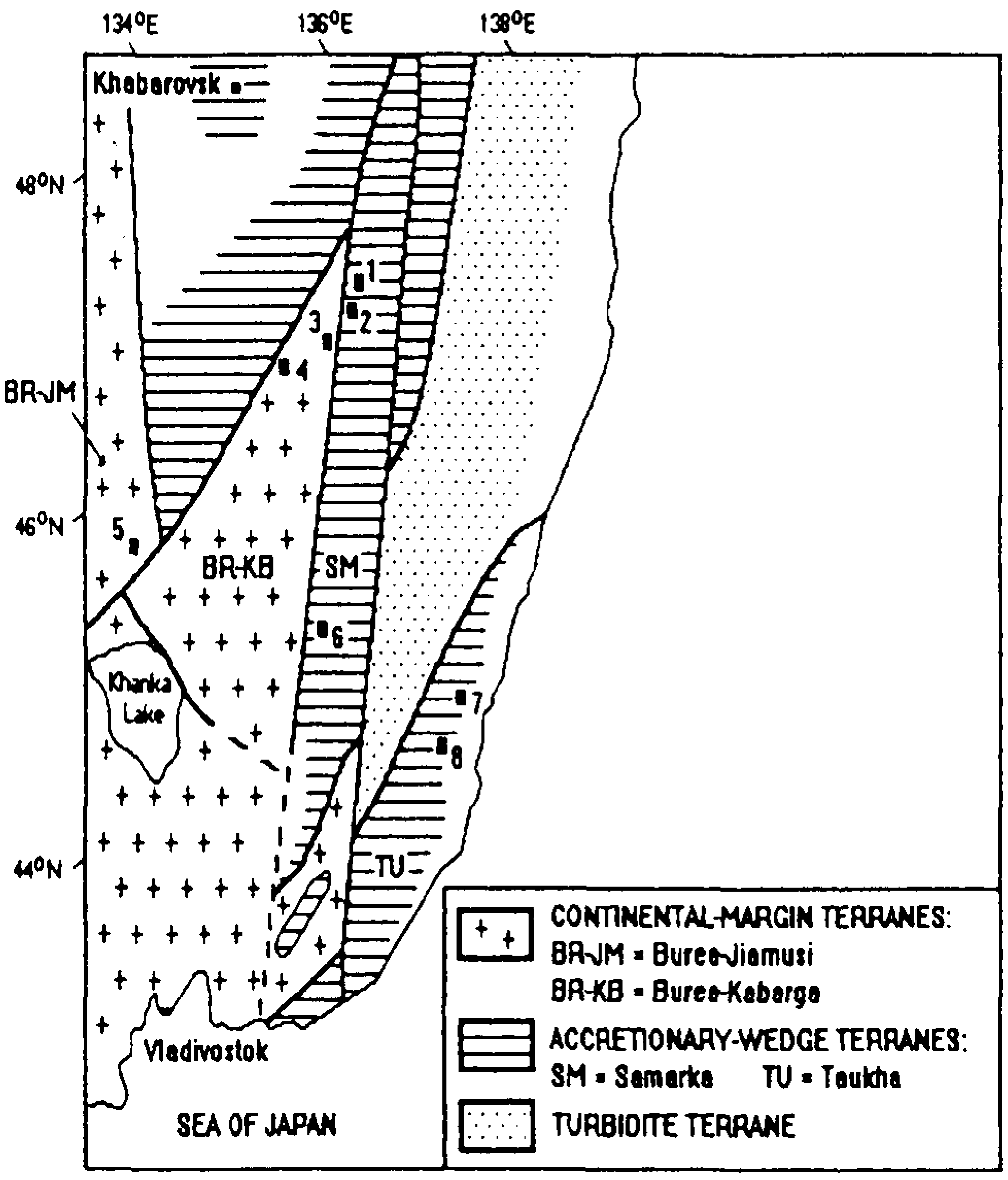

Fig. 1. Map of Terranes in the Sikhote-Alin and Adjacent Territores (simplified from Khanchuk et al., 1991; and Khanchuk, 1992). Solid lines indicate borders between terranes. Letters in caps indicate the studied terranes. Numbers indicate the studied areas (see Fig. 3 for information about lithology and stratigraphy at these locations).

Dating of all the rocks collected were made by Eugene S. Panasenko (Yuzhno-Primorskaya Geologos'emochnaya Expeditsiya) and Valeria S. Rudenko (Far East Geological Institute) on the basis of the radiolarian analysis (Panasenko et al., 1990; Rudenko and Panasenko, 1990 a,b,c).

For the mineralogical analyses, a 0.01-0.25 mm fraction was separated from the sedimentary rocks by sieving after the rough crushing. Afterwards, heavy minerals were extracted from the fraction in 2.9 g/cm^3 of tribromomethane. The heavy minerals were identified using the petrographic microscope. The mineral composition was determined by counting (Table 1). Authigenic minerals and lithoclasts were not counted. When necessary, mineral identification was carried out with help of immersion oils and an electron-microprobe analyzer. All the mineralogical analyses were made by Valentina I. Tikhonova, Nina V. Trushkova, and Vladimir I. Taskaev in laboratories of the Far East Geological Institute.

Unfortunately, the samples used for the heavy-mineral analysis were not intended for that initially. As a result, some of them were not large enough (less than 1 kg) for extracting representative amount of heavy clastic minerals (at least 200 grains). Nevertheless, we consider them suitable for this study where the main purpose is to find a way to further investigations.

The methods of the heavy-mineral-analysis interpretation were described in the previous publications (Nechaev and Derkachev, 1989; Nechaev, 1991a,b; Nechaev and Isphording, 1993). Here, we would like to emphasize that they consist in definition of the quantitative interrelationships between the following mineral assemblages:

(1) GM – indicatory minerals of acidic magmatic (granitic) and metamorphic complexes (zircon, tourmaline, monazite, staurolite, andalusite, sillimanite and kyanite);

(2) MT – common minerals from basic metamorphics such as greenshists and amphibolites (pale and blue-green amphiboles, epidote and garnet);

(3) MF – common mafic minerals of magmatic rocks (olivine, all pyroxenes and green-brown hornblende);

The dominating GM is characteristic of modern sediments on passive continental margins. MF is prevailing in the present Pacific region including: (1) spreading zones like that on the East Pacific Rise where olivine is the most abundant; (2) hot spots and fracture zones like the Hawaiian and Clarion ones where brown Ti-rich augite (Cpx1) is indicative, and (3) island arcs, active continental margins, and deep basins inside the ocean and in marginal seas where association of orthopyroxene (Opx), green clinopyroxene (mostly augite - Cpx2) and common hornblende (Hb) is dominant. Note that all the listed mafic minerals are mainly volcanic in origin. As an anomaly, MF containing olivine, orthopyroxene, green clinopyroxene (mostly diopside - Cpx2) and common hornblende (Hb), all derived from metaophiolites, is characteristic of sediments in the plate-collision zones occurring now in areas of the Yap Trench (the western Pacific) and Amirantus Trench (Indian Ocean) and in the northwestern Philippine Sea (Daito Basin) in Middle Eocene.

In the present work, it is important to specify the arc-volcaniclastic and metaophiolitic associations both of which contain orthopyroxene, clinopyroxene and hornblende. For this purpose, we used the microprobe analyses of clastic minerals from the studied sedimentary rocks (Table 2) in comparison to those from magmatic and metamorphic rocks, which they are most likely derived from. In addition, microprobe analyses of minerals from the Cenozoic sediments of the Philippine and Japan Seas, which are undoubtedly island-arc volcaniclastic in origin (Nechaev, 1987 and 1991a,b), and those from Cenozoic sediments of the Amirantus Trench (Indian Ocean), derived probably from metaophiolites (Derkachev, personal communication), were involved in this comparison.

3. Geological Setting

According to the modern tectonic scheme (Fig. 1), the Sikhote-Alin and adjacent regions consist of terranes divided into three types: continental-margin, accretionary-wedge, and turbidite (Khanchuk et al., 1989, 1991).

The Burea-Kabarga and Burea-Jiamusi Terranes are parts of the continental-margin superterrane containing: (1) Proterozoic gneisses, marble, and amphibolites, (2) Late Precambrian and Cambrian clastic rocks intensely metamorphosed at epidote-amphibolite and greenshist facies; (3) Devonian-Early Cretaceous shallow-sea and continental clastic deposits associated with subduction- and rift-related magmatic rocks of the Devonian and Permian age (Fig. 2). The rocks are intruded by the Silurian collision-related and Permian subduction-related granites. The shallow-sea and non-marine sandstones of the Late-Carboniferous, Late-Triassic and Late-Jurassic ages are arkosic in composition. Among heavy clastic minerals of these rocks, zircon and tourmaline (GM components) are dominating (see below).

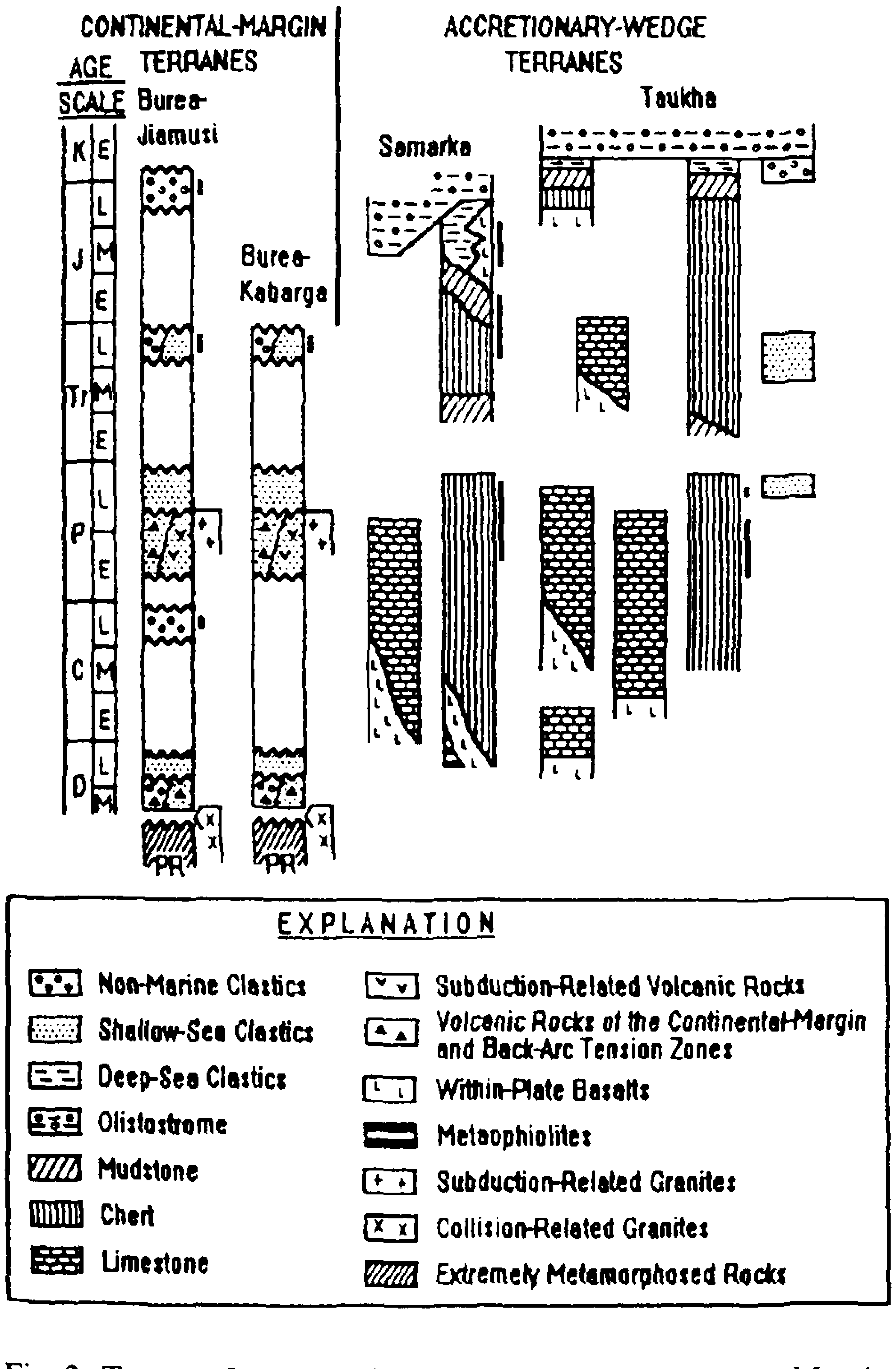

Fig. 2. Tectono-Stratigraphic Columns of the Continental-Margin and Accretionary-Wedge Terranes Showing the Sample-Collecting Areas (solid lines next to the right side of columns).

The turbidite terrane contains the Berriasian-Albian turbidites and the Aptian-Albian volcanic-arc rocks resting upon the Late Jurassic oceanic-crust fragments. Mineralogy of the turbidite sandstones in this terrane is close to those of Upper Paleozoic and Mesozoic sandstones from the continental-margin terranes (Markevich, 1978).

The Samarka and Taukha Terranes, which deposits were involved in this study, are sections of the accretionary-wedge system consisting of the turbidite-olistostrome matrix and synsedimentation allochthonous inclusions (Fig. 2). The Samarka-Terrane turbidite-olistostromes are Mid-Late Jurassic to Early Cretaceous in age (Khanchuk et al., 1989). The allochthons consist of: (1) Middle Paleozoic ophiolites associated with chert containing the Late Devonian-Permian radiolarians and conodonts, and limestones with the Carboniferous-Permian foraminifers; (2) Late Permian and Mid-Late Triassic clastic rocks; and (3) siliceous deposits with the Late Permian-Early Jurassic radiolarians and conodonts associated with the within-plate volcanic rocks (Mazarovich, 1985; Golozubov and Melnikov, 1986; Khanchuk et al., 1989; Volokhin et al., 1989). Petrology and structure of ultramafic and gabbroic rocks indicate that the Samarka-Terrane ophiolites were formed under the high pressure that might be on deep horizons of a thick oceanic-plateau crust (Khanchuk and Panchenko, 1991) or in the stress conditions related to the tectonic movements between blocks of the oceanic crust (Vysotskiy and Okovity, 1990). As a result, some of mafic minerals from these ophiolites are specific in chemical composition. In particular, certain pyroxenes and amphiboles have rather high contents of Al2O3. Thus, we can distinguish them among all the studied clastic minerals for this research.

The Taukha Terrane is close in composition and structure to the Samarka Terrane but has three specific distinctions: (1) its turbidites and olistostromes are younger (Valanginian to Barremian); (2) no gabbro and ultrabasic rocks were found there; and (3) large blocks of reef limestones associated with high-titanium basalts and hyaloclastites, all considered as fragments of the Paleozoic and Early Mesozoic seamounts, are characteristic of this terrane (Khanchuk et al., 1989, and references therein).

The studied siliceous deposits are located in the accretionary-wedge terranes either as tectonic units in the imbricated-thrust structures of melange or as blocks and clasts in olistostromes. In such conditions, only the micropaleontological study in addition to detailed lithological descriptions has allowed their original stratigraphy to be defined in general (Rybalka, 1987; Buryi, 1989; Volokhin et al, 1989; Rudenko and Panasenko, 1990a,b,c; see Fig. 3).

The Permian siliceous deposits are commonly bedded in structure. As usual, the beds are 2.5-6 cm in thickness and consist of gray, olive-gray and reddish-brown chert. The interbedded layers (up to 1-2 cm in thickness, usually 0.5-1 mm) are represented by siliceous mudstones. The reddish-brown cherts are the most often in the lower stratigraphic units where they have the banded-laminae structure formed by the alternation of beds and laminaes (1-2 mm in thickness) with various contents of iron hydroxides. All the cherts contain radiolarians and sponge spicules. Occasionally, conodonts are found. Commonly, Radiolaria are the prevailing biofossils in cherts but, sometimes, the sponge spicules dominate (Rudenko and Panasenko, 1990a,b,c). In cherts of the Sakmarian and Midian age, clasts of the altered volcanic glass are presented. Locally, volcanic glass is associated with psammitic grains of hyaloclastites and redeposited cherts (Sample 37-35, the Amba-Mount location, Samarka Terrane).

The Triassic-Lower Jurassic bedded cherts are gray, dark gray, and, rarely, reddish-brown. Like the Permian ones, they commonly contain radiolarians and, not so often, conodonts. No sponge spicules were found. The stratigraphic transition between Paleozoic and Mesozoic deposits has not been found in the studied outcrops but, in some locations where the earliest Triassic sequences are revealed, siliceous rocks relatively rich in terrigenous material (mud-, clay- and siltstones), underlie cherts (Volokhin, 1985 and Volokhin et al., 1989). Upwards, the Lower Jurassic cherts are gradually replaced by siliceous mudstones and then terrigenous silt- and sandstones of the Lower-Jurassic to Lower-Cretaceous age (Fig. 2 and 3).

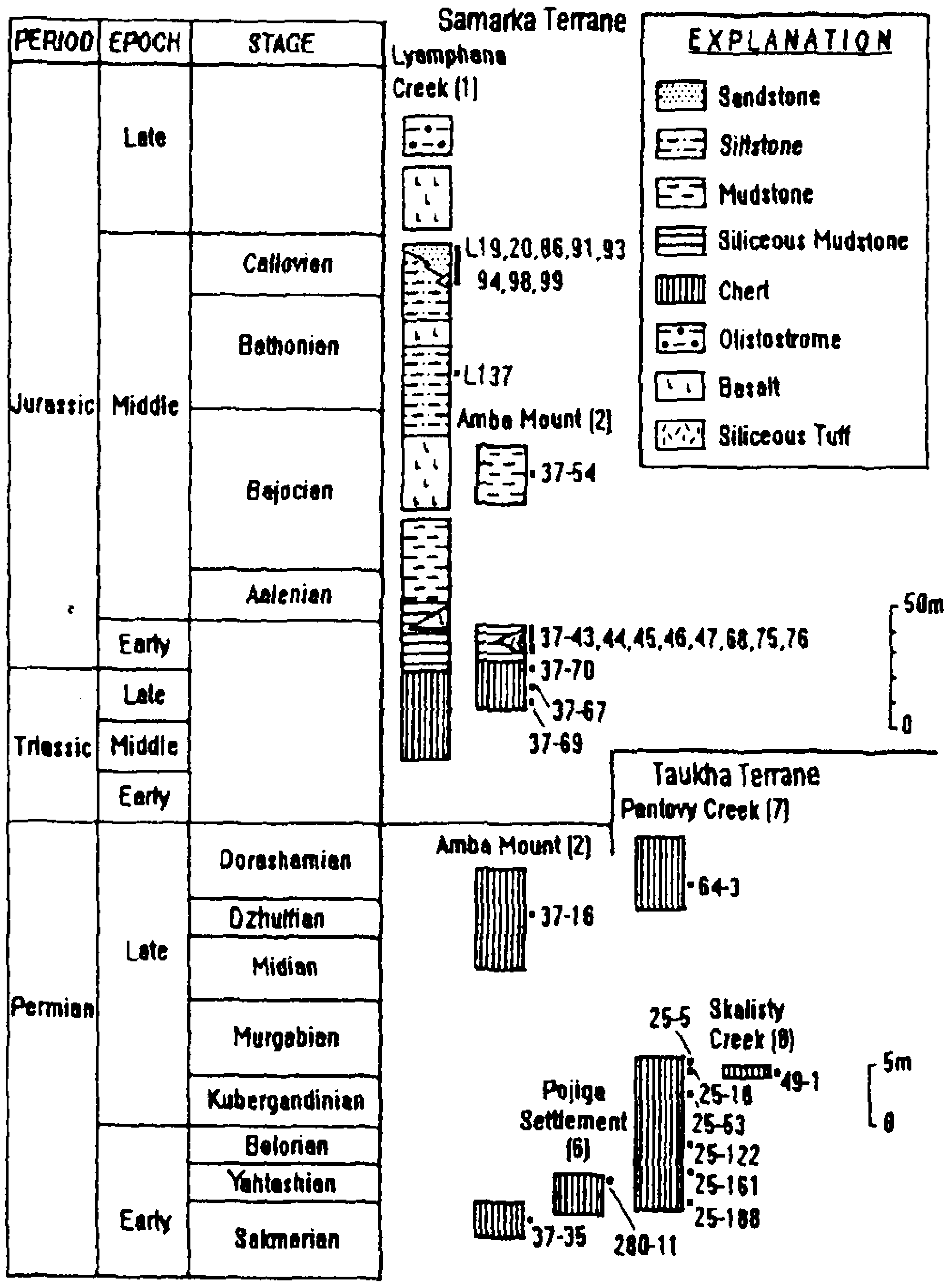

Fig. 3. Lithology and Stratigraphy at the Studied Areas of the Samarka and Taukha Terranes Showing the Sample-Collecting Points. Numbers in brackets indicate the studied areas, numbers next to the sample-collecting points indicate samples (see Table 1 for the heavy-mineral compositions of the sampled rocks).

The Lower-Jurassic siliceous mudstones are bedded and (or) homogeneous in structure, gray or reddish-brown in color, and radiolarian in composition. As a terrigenous component, they contain clay and silt (mostly quartz and feldspar). Among siliceous mudstones of the Amba Mount, there are layers of acidic tuff containing the silt- and sand-size clasts of altered volcanic glass and felsite (50-60%) in addition to the common constituents of siliceous mudstones (Fig. 3, samples 36-46 and 36-47).

In the Lyamphana-Creek location, the Middle Jurassic siltstones interbedded with thin (up to 1 m) layers of sandstones are associated with basic volcanic rocks: hyaloclastites, high-titanium basalts, picrite-basalts and diabases. There, the Bajocian-Bathonian sandstones consist mainly of the lithoclasts represented by cherts (90%), siltstones, claystones and tuffs. In the upper sections, sandstones are arkosic. In average composition, they have: quartz — 28%, feldspar — 40%, and lithoclasts — 32%. There are rather big amounts (up to 40%) of the andesite and dacite grains among lithoclasts in these rocks.

4. Results

We have studied heavy-mineral compositions in 3 samples of the Permian cherts, 3 samples of Triassic cherts, 8 samples of Upper-Triassic to Early Jurassic siliceous mudstones and tuffs, 2 samples of the Middle Jurassic siltstones and 9 samples of the Middle-Jurassic sandstones from 2 locations in the Samarka Terrane, and 8 samples of the Permian cherts from 2 locations in the Taukha Terrane, that is a total of 33 analyses (Table 1).

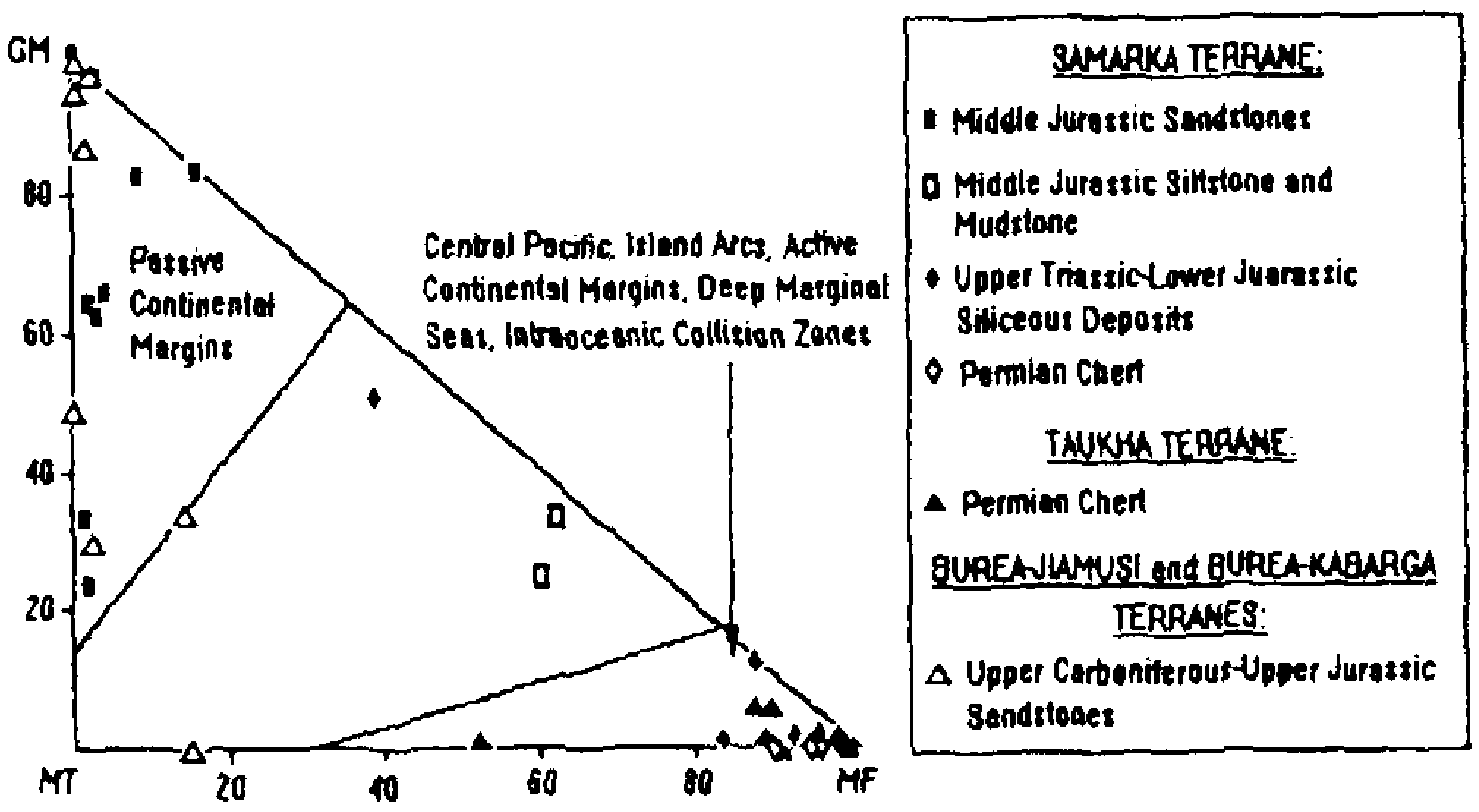

Fig. 4. GM-MT-MF Interrelationships in Sedimentary Rocks from the Continental-Margin and Accretionary-Wedge Terranes (points) in Comparison with Those in Quaternary Sediments of the Different-Type Tectonic Settings of the World (fields). The latter are determined on the basis of average compositions compiled from the literature (Aleksina, 1962; Isphording, 1963; Lee et al., 1988; Lisitsyn, 1966; Martens, 1928; McMaster, 1954; Murdmaa and Kazakova, 1980; Murdmaa et al., 1980; Nechaev and Derkachev, 1989; Nechaev, 1991a,b; Petelin, 1957; Sato, 1980; Scheidegger et al., 1973; Suzuki, 1975). In addition, the personal data of Alexander N. Derkachev (Pacific Oceanological Institute, Far Eastern Branch, Russian Academy of Sciences) were used for delineation of the fields.

In order to learn what these analyses indicate in general, we should compare them with the average heavy-mineral compositions of Quaternary sediments from different plate-tectonic settings of the world. For this comparison, the GM-MT-MF interrelationship is used (Fig. 4). The composition of the Carboniferous-Jurassic sandstones from Burea-Kabarga and Burea-Jiamusi terranes are shown on Fig. 4 to represent the continental-margin provenance. Our evidence suggests that most of the studied siliceous deposits, in which the MF assemblage is dominant, are comparable with modern sediments accumulated in the oceanic and deep-marginal-sea conditions or on the active continental margins and island arcs whereas most of the overlying terrigenous rocks with the prevailing GM assemblage correspond to the passive-continental-margin environment. One of Upper Triassic-Lower Jurassic siliceous tuffs (Sample 37-47) as well as the Bajocian mudstone (37-54) and Bathonian siltstone (L137) representing the transitional layers between siliceous and terrigenous deposits (Fig. 3) are also transitional in heavy-mineral composition (Fig. 4). Thus, we may suppose that Upper Triassic-Middle Jurassic sedimentary rocks recorded either the gradual approach of the oceanic-plate or island-arc blocks to the continent or the conversion of active continental margin into the passive one.

To understand better, what were the tectonic settings around depositional places of the Permian and Mesozoic siliceous rocks, the heavy-mineral characteristics (Hb-(Ol+Cpx2+Opx)-Cpx1) of these rocks may be compared with those of the Cenozoic (mostly Quaternary) sediments from the areas representing the major types of plate boundaries and within-oceanic-plate zones. It is shown on Fig. 5 that heavy-mineral assemblages of Mesozoic siliceous deposits are close to those of sediments accumulated in the intraoceanic fracture zones like the Clarion and Clipperton ones or in the areas of intraoceanic ridges and rises like the Hawaiian Ridge and Magellan Rise. The Permian cherts contain the Ol-Cpx2-Opx-Hb assemblage corresponding to the following tectonic settings: (1) convergent plate boundaries including the deep-marginal-sea, island-arc and trench regions in the northwestern Pacific and oceanic basins like the East Pacific and Guatemala where the dominant heavy clastic minerals are arc-type volcaniclastic in origin (Nechaev and Derkachev, 1989, Nechaev, 1991a,b); (2) intraoceanic collision zones like those occuring now in areas of the Yap and Amirantus Trenchs, and in areas of the Daito Basin in the Middle Eocene (Philippine Sea) where the metaophiolitic minerals are predominant (Murdmaa et al., 1980; Sato, 1980; Nechaev, 1991a,b; Derkachev, personal communication).

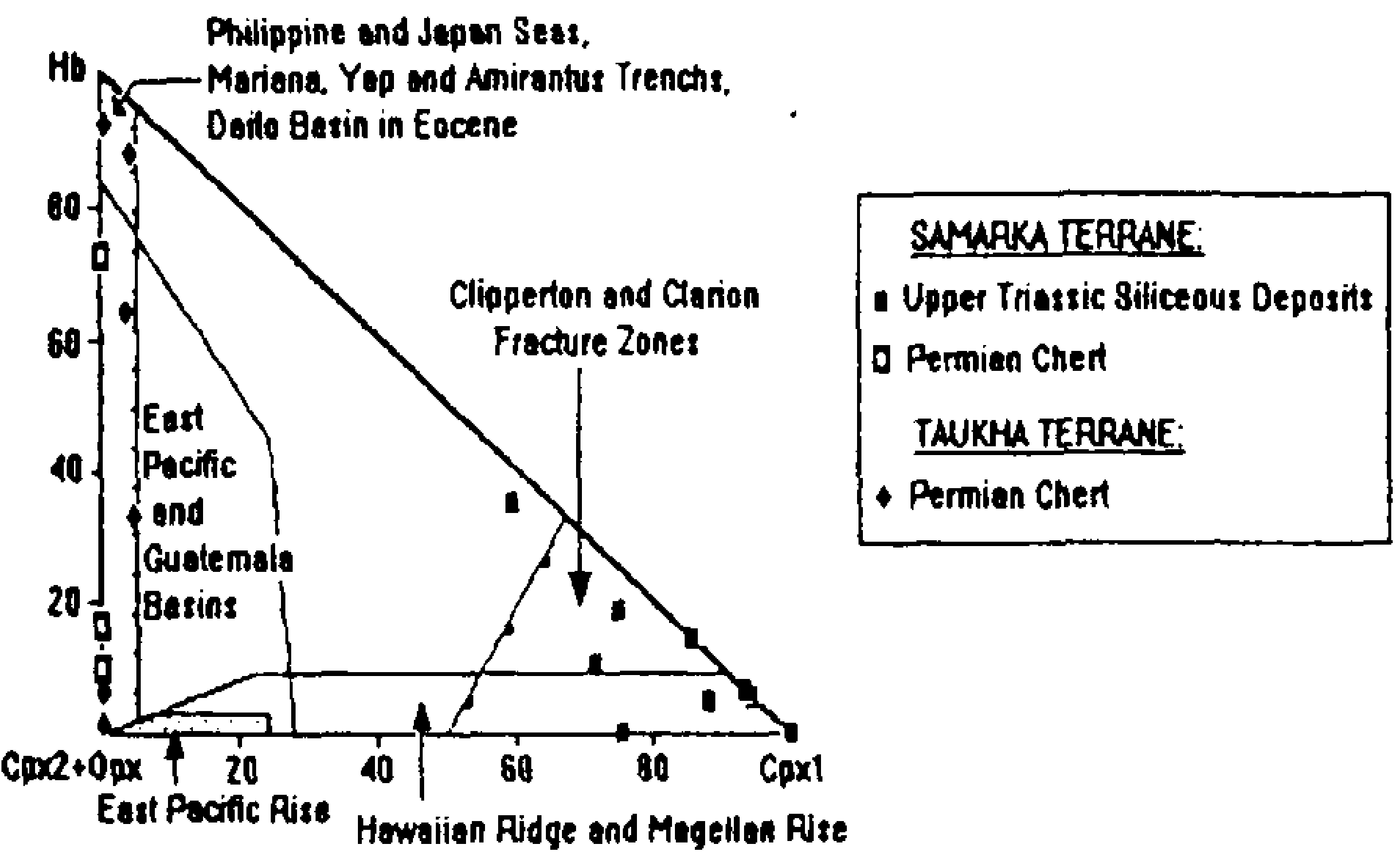

Fig. 5. Hb-(Ol+Cpx2+Opx)-Cpx1 Interrelationships in Siliceous Deposits from the Samarka and Taukha Terranes (points) in Comparison with Those in Cenozoic Sediments of the Certain-Type Tectonic Settings of the World (fields). The latter are determined on the basis of data from the literature (Murdmaa and Kazakova, 1980; Murdmaa et al., 1980; Nechaev and Derkachev, 1989; Nechaev, 1991a,b; Sato, 1980). In addition, the personal data of Alexander N. Derkachev (Pacific Oceanological Institute, Far Eastern Branch, Russian Academy of Sciences) were used for delineation of the fields.

To define the major sources of mafic minerals from the Mesozoic and Paleozoic siliceous rocks closer and to check our previous suggestions, we used the microprobe analyses (Table 2). On Fig. 6-9, the most distinctive chemical characteristics indicating olivine (Ol - Fig. 6), brown and green clinopyroxenes (Cpx1 and Cpx2 - Fig. 7), orthopyroxene (Opx - Fig. 8) and amphiboles (Hb and Am - Fig. 9) from magmatic and metamorphic rocks of the possible sources are shown. We can see that most of mafic minerals from the studied siliceous rocks are close in chemical composition to those from metamorphosed gabbroic and ultramafic rocks (metaophiolites) and metabasalts of the Samarka and Taukha Terranes. Moreover, the metabasaltic assemblage (Cpx1-Hb-Am) is prevailing in Triassic-Lower Jurassic siliceous mudstones and tuffs whereas the metaophiolitic one (Ol-Cpx2-Opx-Hb-Am) is dominant in Permian cherts. It should be noted that there are some additional clastic minerals completing the metaophiolitic assemblage of the studied sedimentary rocks. These are Ca-Fe garnet (grossular-andradite), spinel (hercynite), and ilmenite (see Table 2) close in chemical composition to those from metaophiolites of the Samarka Terrane (Vysotskiy and Okovity, 1990; Khanchuk and Panchenko, 1991), as well as sphene and magnetite (Table 1).

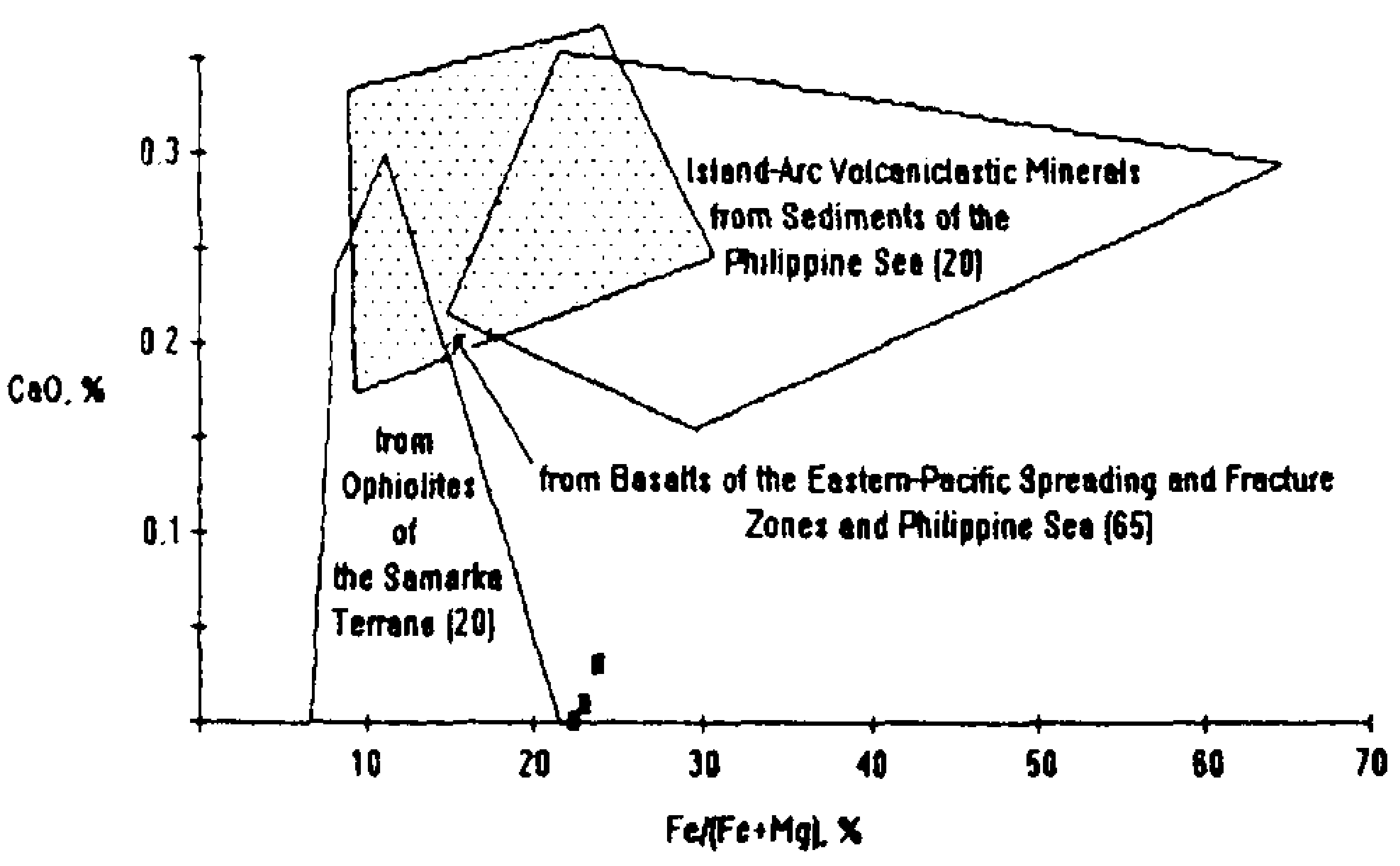

Fig. 6. Comparison between Olivines from the Studied Siliceous Deposits (points) and Those from the Magmatic and Metamorphic Rocks of the Possible Provenances and Certain-Type Tectonic Settings (fields). Number in brackets indicates number of the microprobe analyses used to outline the fields. The data were compiled from Bougault et al. (1982), Dick et al. (1980), Dmitriev (1980), Fodor and Klaus (1975), Fodor and Rosendahl (1980), Fodor et al. (1980), Khanchuk and Panchenko (1991), Mattey and Muir (1980), Mattey et al. (1981), Nechaev (1987 and 1991a), Ridley et al. (1974), Sharaskin (1982), Thompson and Humphris (1980), Vysotskiy (1989), Vysotskiy and Okovity (1990), Zakariadze et al. (1981). In addition, the personal data bases of this papers authors and Alexander N. Derkachev (Pacific Oceanological Institute, Far Eastern Branch, Russian Academy of Sciences) were used for delineation of the fields.

Note that, the fields of minerals indicating different types of magmatic and metamorphic rocks on Fig. 6-9 are, in many cases, overlapping. What is more, some compositions of clastic minerals from the siliceous deposits are situated outside (but close to) fields of the defined source-rock minerals. Thus, we can not make our previous definitions for all of the analyzed grains, but the data presented enables us to determine the major mineral assemblages.

Cpx1 dominating in Mesozoic siliceous deposits and metabasalts of the Samarka and Taukha Terranes is close in composition to clinopyroxene from volcanic rocks of the spreading, hot-spot and fracture zones located in the ocean and marginal seas (Fig. 7). It confirms our previous supposition that the heavy-mineral assemblage from Upper Triassic-Lower Jurassic siliceous mudstones and tuffs indicates the tectonic settings of intraoceanic fracture zones or seamounts (see Fig. 5). Unfortunately, we can not define this situation more accurately because minerals in volcanic rocks from both of these settings are similar.

Olivine, green clinopyroxene, orthopyroxene and amphiboles (Ol-Cpx2-Opx-Hb-Am) dominant in Permian cherts and derived mostly from metaophiolites are of the same type as those from sediments of the Amirantus Trench where the local intraoceanic collision is happening (Fig. 6-9). Therefore, we suggest that Permian cherts of the Samarka and Taukha Terranes were deposited nearby some collision zone. This collision was most likely intraoceanic (that is between blocks of simatic or ensimatic lithosphere) since Permian cherts of the Samarka and Taukha Terranes are totally lacking of heavy minerals indicative of the sialic rock material (GM assemblage). It is impossible to answer if this collision was regional or global because our data characterize only one region. However, most likely it was not local since the Permian rocks have been sampled for this study in four locations situated rather far one from the others and in two different terranes. We have to extend the research to the other regions to define the extent of the Permian collision.

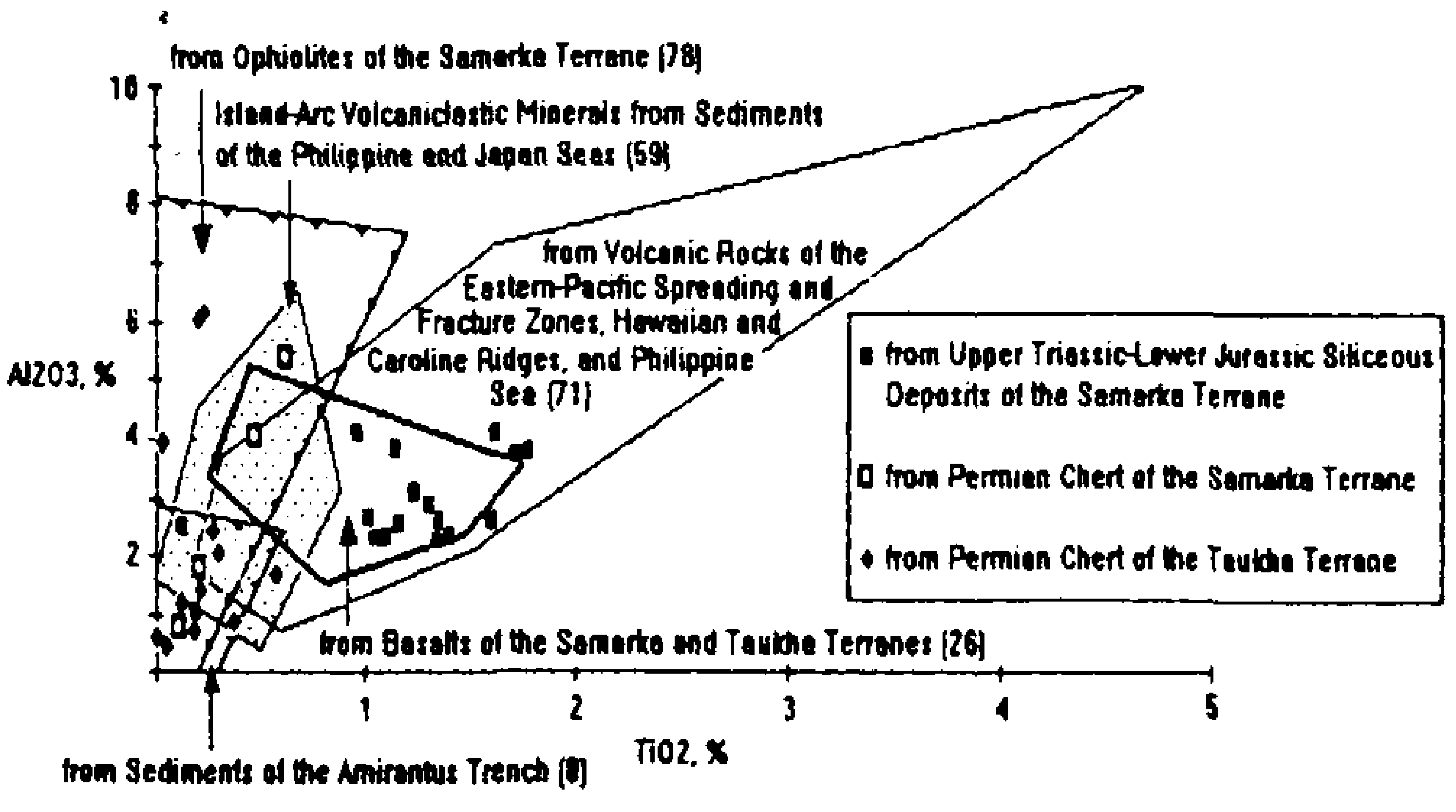

Fig. 7. Comparison between Clinopyroxenes from the Studied Siliceous Deposits (points) and Those from Magmatic and Metamorphic Rocks of the Possible Provenances and Certain-Type Tectonic Settings (fields). Number in brackets indicates number of the microprobe analyses used to outline the fields. The sources of data are referenced on Fig. 6.

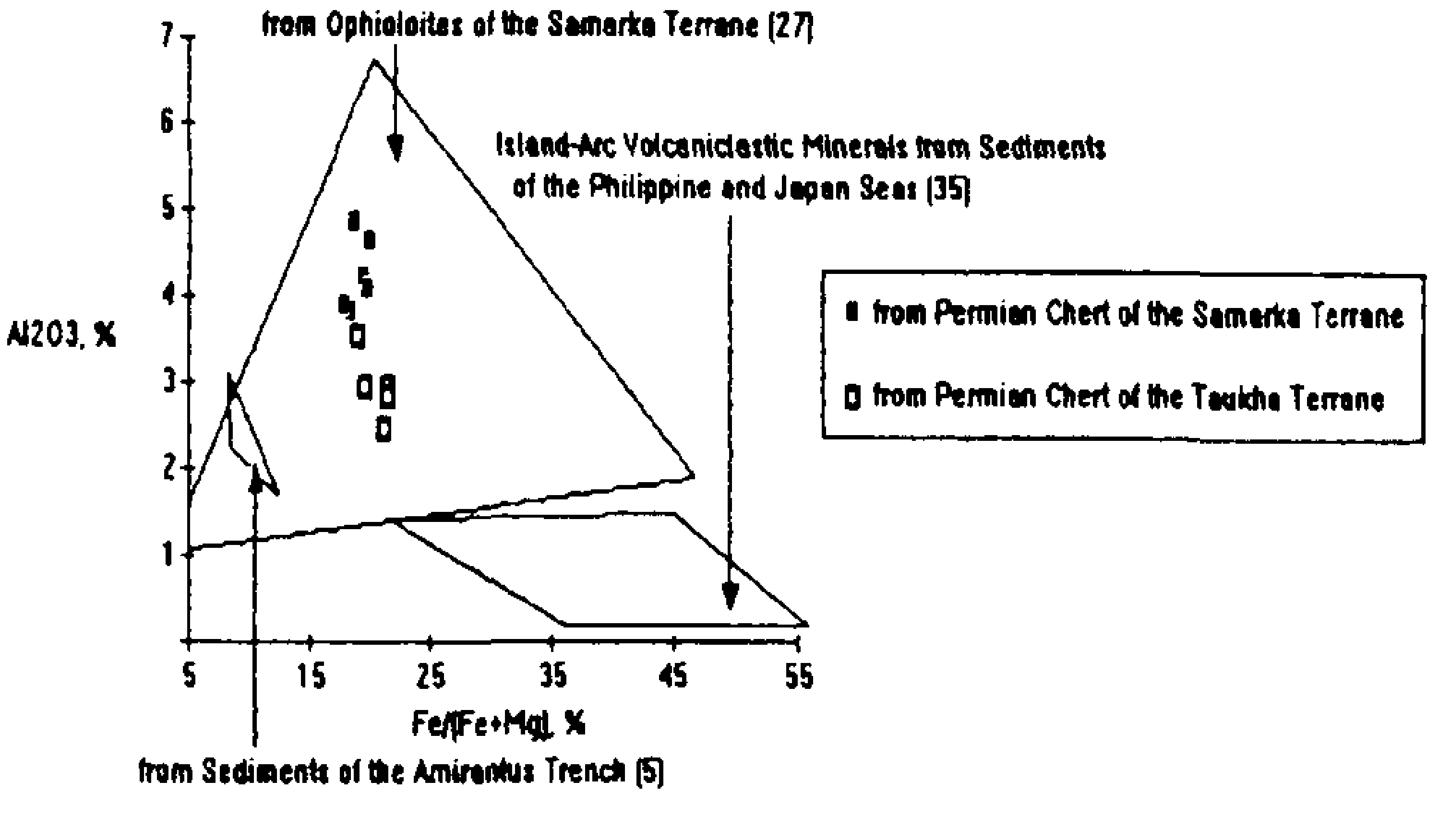

Fig. 8. Comparison between Orthopyroxenes from the Studied Siliceous Deposits (points) and Those from Magmatic and Metamorphic Rocks of the Possible Provenances and Certain-Type Tectonic Settings (fields). Number in brackets indicates number of the microprobe analyses used to outline the fields. The sources of data are referenced on Fig. 6.

Thus, our evidence suggests that bedded cherts of the Sikhote-Alin accretionary-wedge terranes were deposited most likely in the intraoceanic conditions far away from any continental margins including that containing the Burea-Kabarga and Burea-Jiamusi Terranes located now in close vicinity. In the Permian, the deposition took place in or nearby some tectonic collision zone at least regional in scale. Because of the lack in data, we do not know what happened just after. However, in the Late Triassic, the tectonic situation recorded by cherts was quite different. Since that time to Early Jurassic, the siliceous deposits were accumulated in the ocean either close to seamounts like the Hawaiian ones or in fracture zones like those in the modern Eastern Pacific. At the same time and in Middle Jurassic, the depositional places were drifting to the continent. In the Callovian time when terrigenous sands had become a dominating type of sediments, they were situated obviously nearby the continental margin represented by the Burea-Kabarga and Burea-Jiamusi Terranes. Afterwards, the accretion recorded by Mid-Upper Jurassic olistostromes started.

It should be noted here that the indicated approach of the oceanic depositional area to continent was not closely connected with normal subduction. Otherwise, we must have found the widespread mineral assemblage derived from the subduction-related volcanism (Cpx2-Opx-Hb) in the studied Mesozoic deposits as it was defined in modern sediments of the western Pacific (Nechaev and Derkachev, 1989; Nechaev, 1991a,b). Tectonic movements oblique to the ancient continent-ocean border might be more appropriate for explanation of this phenomena. They completely correspond to the combination of basalt-derived clinopyroxene (Cpx1) and sialic rocks-derived zircon, tourmaline and sphene in transitional layers between siliceous (pelagic) and terrigenous (shallow-sea) units of the examined sequence (see heavy-mineral compositions of siliceous mudstones and tuffs in Table 1).

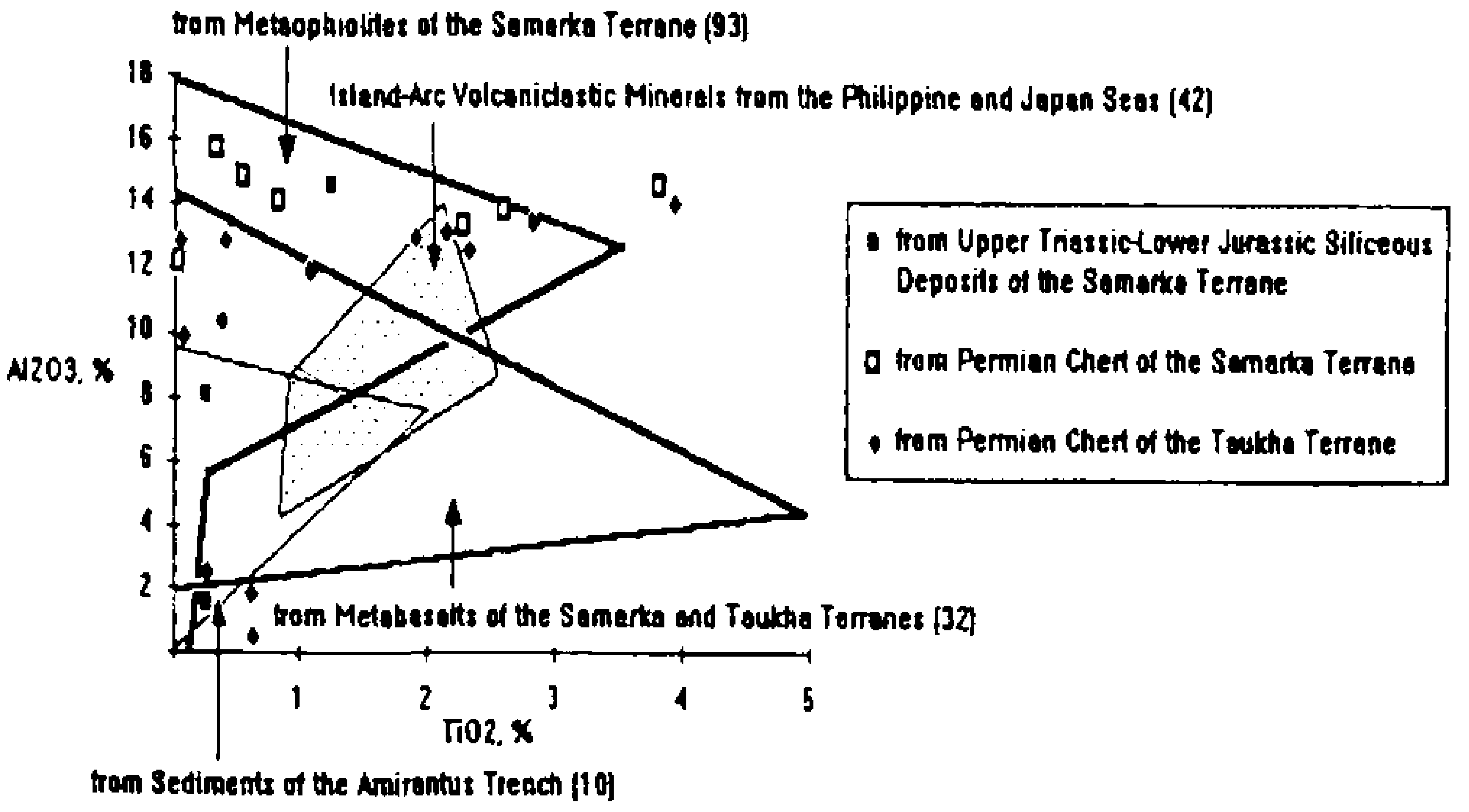

Fig. 9. Comparison between Amphiboles (Hb and Am) from the Studied Siliceous Deposits (points) and Those from Magmatic and Metamorphic Rocks of the Possible Provenances and Certain-Type Tectonic Settings (fields). Number in brackets indicates number of the microprobe analyses used to outline the fields. The sources of data are referenced on Fig. 6.

Table 1

Percentage of Heavy Clastic Minerals in the 0.01-0.25 mm Fraction from Sedimentary Rocks of the Samarka and Taukha Terranes

Age	Lithology	Sample	Ol	Cpx1	Cpx2	Opx	Hb	Am	Ep	Grn	Zr	Trm	Sph	Rt	An	Lcx	Ap	Mt	Ilm	Sp	No.
Lyamphana Creek (1), Samarka Terrane																					
J2Bth-Clv	Sandstone	L19	---	---	---	---	---	---	---	---	98.0	1.5	---	0.5	---	---	---	---	---	---	200
J2Bth-Clv	Sandstone	L20	---	---	0.4	---	---	---	1.1	13.7	4.3	0.4	45.5	---	---	25.3	3.6	---	4.7	1.1	277
J2Bth-Clv	Sandstone	L86	---	---	9.2	0.4	0.7	---	0.4	---	52.8	0.7	---	---	---	24.3	1.1	---	8.5	2.1	284
J2Bth-Clv	Sandstone	L89	---	---	0.5	0.5	1.6	---	---	30.8	55.3	2.9	1.4	0.5	---	---	1.4	---	4.8	1.6	208
J2Bth-Clv	Sandstone	L91	---	---	1.8	---	0.4	---	---	15.6	30.0	4.2	---	0.7	0.4	6.8	1.3	---	37.9	0.9	454
J2Bth-Clv	Sandstone	L93	---	---	2.6	---	---	---	---	29.2	46.2	6.1	---	1.3	0.3	3.8	1.3	---	8.3	1.6	312
J2Bth-Clv	Sandstone	L94	---	---	1.8	0.3	3.9	---	0.7	4.9	50.7	0.3	0.3	0.3	---	8.2	0.7	---	28.0	0.7	304
J2Bth-Clv	Sandstone	L98	---	---	0.6	---	0.9	---	---	55.5	23.4	4.6	---	0.3	---	2.9	1.2	---	9.8	0.9	346
J2Bth-Clv	Sandstone	L99	---	---	1.5	---	0.2	---	---	0.2	31.7	8.4	---	---	---	---	1.5	---	57.6	---	417
J2Bth	Siltstone	L137	---	---	35.0	2.6	2.6	---	---	10.3	16.2	---	---	---	---	---	0.9	---	23.1	9.4	117
Amba Mount (2), Samarka Terrane																					
J2	Sil. mudst.	37-54	---	24.7	---	---	8.2	---	1.2	1.2	16.5	1.2	---	---	10.6	---	---	34.1	2.4	---	85
J1	Sil. mudst.	37-43	---	76.4	---	---	12.7	---	1.8	3.6	1.8	---	---	---	---	---	1.8	1.8	---	---	55
J1	Sil. mudst.	37-44	---	86.0	---	---	0.5	---	1.4	---	0.5	---	0.5	---	---	---	0.5	10.4	0.5	---	222
J1	Sil. mudst.	37-68	---	66.4	16.6	---	10.6	---	0.7	0.4	0.7	---	---	---	---	---	0.4	1.8	1.8	1.1	271
Tr3-J1	Sil. mudst.	37-45	---	36.7	3.3	---	21.7	3.3	3.3	---	---	---	---	---	---	---	---	31.7	---	---	60
Tr3-J1	Sil. tuff	37-46	1.3	77.0	3.9	.0.7	4.6	0.7	0.7	0.7	2.0	---	0.7	---	---	---	---	7.9	---	---	152
Tr3-J1	Sil. tuff	37-47	---	35.7	0.0	---	2.0	---	8.2	2.0	50.0	---	---	---	1.0	1.0	---	---	---	---	98
Tr3-J1	Sil. mudst.	37-70	---	62.0	17.7	2.5	---	11.4	3.8	---	---	1.3	---	---	---	---	1.3	---	---	---	79
Tr3-J1	Sil. mudst.	37-75	---	38.9	---	---	---	---	---	---	5.6	---	5.6	---	27.8	---	5.6	16.7	---	---	18
Tr3-J1	Chert	37-76	---	65.6	6.3	---	15.6	---	---	---	---	---	---	---	6.3	---	---	6.3	---	---	32
Tr3Nor	Chert	37-67	---	87.1	---	---	6.1	---	0.7	0.2	---	---	---	---	---	---	---	0.7	5.1	---	428
Tr3Crn-Nor	Chert	37-69	---	70.9	6.0	---	17.9	---	---	---	1.3	---	---	---	---	---	0.7	3.3	---	---	151
P2Dzl	Chert	37-16	---	---	73.3	1.7	15.0	5.0	5.0	---	---	---	---	---	---	---	---	---	---	---	60
P1Sak	Chert	37-35	0.5	---	10.5	14.7	67.3	2.7	1.1	---	0.3	---	---	---	---	---	0.3	0.3	1.6	0.8	373
Pojiga Settlement (6), Samarka Terrane																					
P1Yht	Chert	280-11	---	---	85.1	---	9.6	2.1	3.2	---	---	---	---	---	---	---	---	---	---	---	94
Pantovy Creek (7), Taukha Terrane																					
P2Dor	Chert	64-3	---	---	84.4	---	6.3	3.1	6.3	---	---	---	---	---	---	---	---	---	---	---	32
P2Mrg	Chert	25-5	---	2.9	25.7	---	51.4	---	---	5.7	5.7	---	---	---	---	---	2.9	5.7	---	---	35
P2Mrg	Chert	25-16	---	0.2	7.0	---	88.5	---	---	0.5	0.5	---	---	---	0.2	0.7	0.5	1.4	0.5	---	427
P2Kub	Chert	25-53	---	3.9	52.4	---	28.2	1.9	1.7	1.7	5.8	---	---	---	---	---	1.7	2.9	1.9	---	103
P1Bol	Chert	25-122	---	---	87.2	0.2	11.1	---	0.2	0.2	0.2	---	0.2	---	---	---	---	0.2	0.2	---	415
P1Yht	Chert	25-161	0.4	2.0	3.3	---	43.3	42.4	0.4	0.4	1.5	---	---	---	1.3	0.2	0.7	1.1	1.8	1.1	453
P1Sak	Chert	25-188	---	---	79.6	---	9.3	3.7	5.6	---	1.9	---	---	---	---	---	---	---	---	---	54
Skalisty Creek (8), Taukha Terrane																					
P2Mrg	Chert	49-1	---	---	97.6	---	2.0	---	0.5	---	---	---	---	---	---	---	---	---	---	---	205

Note: - Ol = olivine; Cpx = clinopyroxene (1-brown, 2-green); Opx = orthopyroxene; Hb = green and brown amphibole; Am = pale-colored amphibole; Ep = epidote (group); Grn = garnet; Zr = zircon; Trm = tourmaline; Sph = sphene; Rt = rutile; An = anatase; Lcx = leucoxene; Ap = apatite; Mt = magnetite; Ilm = ilmenite; Sp = spinel; No. = number of grains counted; --- = not found.

Table 2

Electron Microprobe Analyses (%) of Clastic Minerals from Sedimentary Rocks of the Samarka and Taukha Terranes

Source	Tr$_3$-J$_1$ siliceous deposits of the Samarka Terrane																
Mineral	Ol	Cpx1	Cpx1	Cpx1	Cpx1	Cpx1	Cpx1	Cpx1	Cpx1	Cpx1	Cpx1	Cpx1	Cpx1	Cpx1	Cpx1	Cpx1	Cpx2
Sample	37-46	37-43	37-44	37-44	37-44	37-45	37-45	37-47	37-70	37-70	37-67	37-67	37-67	37-69	37-69	37-69	37-45
SiO_2	38.39	51.42	50.10	50.99	50.52	51.36	50.74	51.40	50.80	52.45	49.08	50.25	49.05	51.55	51.02	50.46	51.37
TiO_2	0.01	1.30	1.01	1.04	1.14	1.34	1.60	1.40	1.23	1.10	1.35	1.16	1.72	0.96	1.62	1.77	0.13
Al_2O_3	0.06	2.88	2.67	2.33	3.81	2.32	2.61	2.31	3.09	2.31	2.58	2.57	3.72	4.11	4.09	3.79	2.51
Cr_2O_3	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
FeO	20.29	6.91	6.76	7.86	6.39	8.59	11.38	8.65	7.21	6.64	7.72	6.26	7.62	7.45	7.64	8.77	4.67
MnO	0.28	0.18	0.19	0.27	0.21	0.26	0.48	0.28	0.16	0.18	0.18	0.18	0.19	0.18	0.24	0.21	0.16
MgO	39.44	16.74	16.25	16.55	15.79	15.77	12.97	14.34	16.48	16.65	16.02	16.67	15.58	15.55	15.31	14.67	18.52
CaO	---	21.67	21.83	21.74	21.92	21.77	20.84	21.25	22.05	21.88	21.19	20.86	21.70	22.03	21.75	21.31	22.66
Na_2O	0.02	1.51	0.45	0.42	0.40	0.52	0.64	0.44	0.52	0.40	0.58	0.43	0.49	0.56	0.56	0.52	0.27
K_2O	---	0.07	0.01	0.02	---	0.01	0.02	---	0.02	0.02	0.02	0.02	0.01	0.03	0.02	0.03	0.03
Total	98.49	102.68	99.27	101.22	100.18	101.94	101.28	100.07	101.56	101.63	98.72	98.40	100.08	102.42	102.25	101.53	100.32

Source	Tr$_3$-J$_1$ siliceous deposits of the Samarka Terrane							P chert of the Samarka Terrane								
Mineral	Cpx2	Hb	Hb	Hb	Grn	Grn	Ilm	Ol	Cpx2	Cpx2	Cpx2	Cpx2	Opx	Opx	Opx	Opx
Sample	37-45	37-46	37-70	37-67	37-47	37-47	37-68	37-35	37-16	37-35	37-35	37-35	37-35	37-35	37-35	37-35
SiO_2	51.61	43.49	53.38	47.72	39.35	39.59	---	39.13	50.43	50.34	52.13	51.88	53.85	52.76	51.93	51.82
TiO_2	0.19	1.23	0.27	0.25	0.24	0.02	51.90	0.02	0.11	0.62	0.21	0.47	0.31	0.29	0.37	0.07
Al_2O_3	1.04	14.55	1.60	8.03	22.84	23.19	0.16	0.59	0.77	5.37	1.79	4.06	3.84	4.37	4.87	4.63
Cr_2O_3	---	---	---	---	...	...	0.02	---	---	1.09	0.31	---	0.21	0.26	0.20	0.06
FeO	5.23	6.37	10.49	11.12	11.54	11.40	47.91	22.32	6.92	4.30	4.65	9.90	12.07	11.86	11.50	12.42
MnO	0.29	0.12	0.45	0.33	0.48	0.42	0.12	0.40	0.24	0.17	0.16	0.43	0.30	0.29	0.24	0.31
MgO	19.67	19.62	17.49	17.35	...	...	0.61	40.03	16.59	14.66	15.60	12.62	29.92	27.49	28.05	28.02
CaO	22.57	13.25	13.36	11.97	23.45	23.81	---	0.03	25.67	21.51	21.26	21.34	1.18	1.36	0.83	1.08
Na_2O	0.20	2.10	0.51	1.18	...	0.02	---	0.03	0.82	0.84	0.46	0.76	0.04	0.18	0.07	0.04
K_2O	0.04	0.72	0.16	0.42	0.02	0.03	---	---	0.01	0.01	---	0.02	---	0.03	---	---
Total	100.84	101.45	97.71	98.37	97.92	98.48	100.73	102.55	101.56	98.91	96.57	101.48	101.72	98.88	98.06	98.45

Source	P chert of the Samarka Terrane (continued)										P chert of the Taukha Terrane				
Mineral	Opx	Opx	Hb	Hb	Hb	Hb	Hb	Am	Am	Sp	Sp	Ol	Cpx2	Cpx2	Cpx2	Cpx2
Sample	37-35	37-35	37-35	37-35	37-35	37-35	37-35	37-35	37-35	37-35	37-35	25-161	49-1	25-5	25-5	25-16
SiO_2	53.16	55.49	41.44	42.91	47.67	44.33	42.21	44.15	44.09	---	---	38.23	54.67	50.90	53.95	51.65
TiO2	0.16	0.30	3.81	2.28	0.03	0.82	2.59	0.54	0.33	---	---	0.06	0.21	0.57	0.18	0.27
Al_2O_3	4.13	3.91	14.58	13.28	12.17	14.07	13.81	14.85	15.72	62.01	61.97	0.02	1.43	1.71	0.71	2.45
Cr_2O_3	---	---	0.36	---	---	0.50	---	0.28	---	---	---	---	---	---	---	---
FeO	12.92	11.18	7.81	11.89	8.17	6.85	7.74	6.37	6.90	21.52	22.46	21.48	6.88	8.06	4.96	5.26
MnO	0.35	0.30	0.14	0.21	0.18	0.13	0.14	0.12	0.10	0.11	0.19	0.37	0.23	0.13	0.19	0.17
MgO	29.39	28.64	16.02	14.39	17.27	15.41	16.42	17.89	16.88	13.64	13.68	40.10	17.79	16.90	17.08	18.06
CaO	1.80	1.10	11.33	11.74	11.61	11.27	11.18	11.50	11.88	---	---	0.01	18.61	20.47	23.31	21.80
Na_2O	0.03	0.05	2.93	2.49	1.37	2.33	2.94	2.77	2.82	---	---	0.01	0.22	1.23	0.17	0.17
K_2O	---	0.03	0.49	0.16	0.04	0.70	0.79	0.48	0.42	---	---	0.02	0.01	0.07	0.03	---
Total	101.94	101.00	98.91	99.35	98.51	96.41	97.82	98.95	99.14	97.28	98.3	100.30	100.05	100.04	100.58	99.83

Table 2 (continued)

Electron Microprobe Analyses (%) of Clastic Minerals from Sedimentary Rocks of the Samaeka and Taukha Terranes

Source P chert of the Taukha Terrane (continued)

Mineral	Cpx2	Cpx2	Cpx2	Cpx2	Cpx2	Cpx2	Cpx2	Cpx2	Cpx2	Cpx2	Opx	Opx	Opx	Opx	Opx	Hb	Hb
Sample	25-16	25-53	25-53	25-53	25-122	25-122	25-161	25-161	25-188	25-188	25-161	25-161	25-161	25-161	25-161	25-161	25-161
SiO2	50.77	55.20	50.54	50.34	52.43	52.06	50.49	53.18	51.29	50.68	53.91	54.51	53.61	53.44	52.54	52.21	43.48
TiO2	---	0.05	0.30	0.37	0.12	0.28	0.23	0.20	0.11	0.03	0.18	0.04	0.06	0.03	0.02	0.62	1.59
Al2O3	0.59	0.47	2.08	0.89	1.20	1.60	6.12	6.01	1.15	3.96	2.95	2.83	3.56	2.95	2.44	1.85	11.18
Cr2O3	---	---	---	---	---	---	1.05	1.13	---	---	0.16	0.04	---	---	---	0.66	0.69
FeO	5.94	5.40	4.95	4.89	4.18	5.76	3.00	4.00	6.75	8.29	14.07	13.96	12.45	13.03	14.33	11.60	9.76
MnO	0.19	0.26	0.19	0.14	0.16	0.20	0.10	0.11	0.21	0.49	0.37	0.35	0.28	0.41	0.38	0.20	0.15
MgO	15.48	16.47	17.51	17.38	18.90	16.47	16.82	20.72	15.42	15.28	28.78	28.68	29.70	29.89	29.88	16.19	15.80
CaO	25.44	22.38	23.74	23.82	23.79	23.88	22.47	15.87	22.69	22.07	0.74	0.74	0.69	0.56	0.53	12.47	11.85
Na2O	0.04	0.13	0.19	0.50	0.09	0.21	0.29	0.29	1.03	1.35	0.03	0.03	0.01	0.04	0.22	0.24	2.53
K2O	0.02	0.02	0.03	0.02	0.02	0.03	---	---	0.06	0.07	---	---	---	---	0.04	0.01	0.11
Total	98.47	100.38	99.53	98.35	100.89	100.49	100.57	101.51	98.71	102.22	101.19	101.18	100.36	100.35	100.38	96.05	97.14

Source P chert of the Taukha Terrane (continued)

Mineral	Hb	Hb	Hb	Hb	Hb	Hb	Hb	Hb	Hb	Hb	Hb	Am	Am	Am	Ilm	Ilm
Sample	25-161	25-161	25-161	25-161	25-161	25-161	25-161	25-161	25-161	25-161	25-188	25-161	25-161	25-161	25-122	25-188
SiO2	43.73	43.85	42.40	42.70	47.49	54.96	43.75	41.97	42.46	43.79	47.33	44.14	49.24	45.69	---	---
TiO2	1.90	0.39	3.92	2.32	0.37	0.26	2.82	2.14	2.32	1.07	0.63	0.05	0.08	0.44	52.10	46.80
Al2O3	12.93	12.83	14.04	12.60	10.35	2.55	13.43	13.13	12.56	11.88	0.51	12.82	9.85	13.38	0.11	0.30
Cr2O3	0.12	0.40	0.59	1.31	0.07	0.06	---	---	0.01	---	---	---	---	---	0.18	0.02
FeO	10.01	13.33	7.58	10.00	10.99	11.81	10.79	10.40	10.95	7.21	14.06	8.97	7.01	5.81	47.53	47.19
MnO	0.19	0.18	0.17	0.19	0.13	0.25	0.18	0.15	0.18	0.13	0.16	0.16	0.16	0.13	0.35	2.88
MgO	13.61	13.16	15.03	16.51	14.12	16.98	14.56	14.26	14.32	18.42	21.14	16.24	18.86	19.93	0.04	0.18
CaO	11.99	12.18	11.26	10.71	14.28	12.79	11.77	11.55	11.47	11.16	11.82	11.57	12.15	12.12	---	---
Na2O	1.72	2.20	2.85	2.73	1.42	0.34	2.06	2.45	2.60	2.78	0.72	2.36	1.50	2.76	---	---
K2O	0.20	0.07	0.61	0.28	0.03	0.02	0.15	0.18	0.15	0.49	0.32	0.03	0.01	0.25	---	---
Total	96.40	98.59	98.45	99.35	99.25	100.02	99.51	96.23	97.02	96.93	96.69	96.34	98.86	100.51	100.31	97.37

Note: Ol = olivine; Cpx = clinopyroxene (1-brown, 2-green); Hb = green and brown amphibole; Am = pale-colored amphibole; Grn = garnet; Ilm = ilmenite; Sp = spinel; --- = not found.

5. Discussion

One of the major problems in geology of the Sikhote-Alin and adjacent territories is: whether all of the deposits were accumulated close to each other or whether there were big distances between some of them at the time of deposition. We have tried to come closer to resolving this problem by using of the actualistic approach. At the same time, we recognize that geological conditions in the past might be somewhat different from the present. For instance, heavy-clastic-mineral assemblages rich in the high-titanium basalt or ophiolitic components (Cpx1 or Ol-Cpx2-Opx-Hb-Am), indicating the specific areas of the modern oceans, might be distributed much more widely in the Early Mesozoic and Late Paleozoic oceans. Now, they are poor in sediments from most of the oceanic and marginal-sea basins where the arc-type volcaniclastic minerals or terrigenous material suppress them. However, the subduction-related volcanism and continental erosion might be not so widely developed in the mentioned periods of the past. Then, intraoceanic seamounts, ridges, and fracture zones would be the major sources of heavy clastic minerals into any basins outside the continent. If this is the case, some of our suggestions made in the «RESULTS» section would not be correct. To check them, we have to extend this study to the other regions. Wide comparison of heavy-clastic-mineral assemblages from Paleozoic and Mesozoic sedimentary rocks with those from the Cenozoic sediments could also improve our understanding of the global geological evolution.

Finally, we would like to debate the possible argument against using the heavy clastic minerals as indicators of tectonic settings. Many researchers believe that so called intrastratal solution distorts original heavy-mineral compositions of sediments with time by destroying their components in different degree (Pettijohn, 1941 and many others later). Olivine and pyroxenes are recognized as the most unstable in pore water minerals whereas garnet, zircon, tourmaline and sphene are considered as the most stable ones. We do not totally oppose this opinion but our analyses indicating sporadic olivine and the pyroxene-rich assemblages in Upper Paleozoic and Lower Mesozoic deposits and the assemblages rich in garnet, zircon, tourmaline and sphene in the overlaying sedimentary rocks (see Table 1) convince us that intrastratal solution has not altered the studied compositions significantly.

6. Conclusion

The actualistic interpretation of heavy-clastic mineral assemblages from sedimentary rocks of the Samarka and Taukha Terranes enables us to obtain new information on tectonic settings surrounding their depositional place. In particular, the association of olivine, orthopyroxene, green clinopyroxene, amphibole, garnet and spinel from Permian cherts indicates a tectonic setting like that in the modern intraoceanic collision zones. The Ti-rich clinopyroxene assemblage of Upper Triassic-Lower Jurassic cherts, mudstones and tuffs points to the intraoceanic seamounts and fracture zones like those in the central and eastern Pacific. Increasing amounts of terrigenous minerals (zircon, tourmaline, sphene) in Upper Triassic-Middle Jurassic deposits reflect drifting from intraoceanic to passive-continental-margin conditions that was probably connected with tectonic movements oblique to the continent-ocean border.

Because of the lack in data, we did not try to define origin of the studied deposits in detail. It was not a purpose of this investigation. The major task was to interest other researchers in study of heavy-clastic minerals from sedimentary rocks probably oceanic or deep-sea in origin. We also hoped to interest researchers in cooperation on this matter.

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