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Spatial Distribution and Provenance of Detrital Minerals of Surface Sediment in the Okhotsk Sea

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The Okhotsk Sea is a distinctive marginal sea in the northwestern Pacific Ocean, which is characterized by the prevalence of seasonal sea ice in winter. Sediment is sourced from the around region through sea ice transportation, rivers input, and volcanic eruptions. Surface sediments of the Okhotsk Sea shelf vary greatly in grain size, and the sand content is generally high, which is conducive to source-to-sink studies using ice-rafted detritus (IRD),detrital minerals and single mineral geochemistry methods. In this paper, the 63–125 μm grain size fraction was selected for the detrital minerals analysis of surface sediments (top 0–10 cm) from 58 sediment stations and 15 stations samples has been chosen for garnet chemistry. These stations are mainly located in the south central Okhotsk Sea. The distribution and composition of the heavy minerals are influenced by material derived from the Amur River, the north shelf (Okhotsk-Chukotka volcanic belt), Sakhalin Island, the Kamchatka Peninsula, and the Kuril Islands. The detrital mineral results show that hornblende, epidote and garnet are terrigenous material indicators. High contents of fresh hypersthene can be used as an indicator of volcanic eruption materials. And high content of abraded hypersthene can be used as an indicator of Okhotsk-Chukotka volcanic materials. In the northern Okhotsk Sea, the southward moving sea ice produced in Sakhalin Bay collides with the sea ice produced off the east coast of Sakhalin Island, which causes the sea ice to accumulate to the southeast. This results in the deposited ice-rafted debris having a southeastward facing fan shape, and the geochemical analysis of the garnet supports this conclusion. From west to east, the amount of material from Sakhalin Island gradually decreases, while the amount of material from the Amur River and Chukchi-Kamchatka increases.

Keywords: Okhotsk Sea, heavy minerals, surface sediment, sea ice, provenance, garnet geochemistry

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INTRODUCTION

Heavy mineral analysis methods are usually used to interpret the provenance, transport pathways, and geochemistry of sediments, especially in source-to-sink studies (Sevastjanova et al., 2012; Nicholson et al., 2013). In general, sediment that is rich fine sand on a shelf has a high heavy mineral content, particularly in estuaries and subaqueous deltas (Wang et al., 2007). Heavy mineral analysis methods are often used in studies of the source of fine sands, especially on shelves where river input of heavy minerals can provide abundant information about the sediment source, sedimentary environment, and hydrodynamic conditions (Zhang et al., 2015; Wang et al., 2019). Based on studies of the types and assemblages of heavy minerals, suitable representative single mineral indicators can be chosen for geochemical analysis, which allows for the more effective determination of the sources of sediments and the sedimentary environment (Morton et al., 2005; Li et al., 2015; Garzanti et al., 2016; Krippner et al., 2016).

In recent years, surface sediment stations for detrital provenance study have been located in the mouth of the Amur River and off the northeastern coast of Sakhalin Island (Astakhov et al., 2005; Sattarova et al., 2013). Among them, the sites for studying IRD and detrital minerals are mainly located in the east (Sakamoto et al., 2005). Cores with more sediment analysis indicators, including geochemistry, IRD, and detrital minerals, are mainly located in the south central Okhotsk Sea [e.g., cores PC-7R, LV28-40 (42 and 44), and OS03-1] (Gorbarenko et al., 2007, 2010, 2014; Nürnberg et al., 2011; Zou et al., 2015). Fewer studies have been conducted on the sediment cores from the northern shelf of the Okhotsk Sea (Gorbarenko et al., 2007).

The study of detrital minerals and their assemblages in core samples from the south central Okhotsk Sea shows that the heavy mineral contents are very high in the fine sand grain size fraction, and the hornblende, hypersthene, and garnet contents vary significantly. In particular, the garnet content varied in accordance with the paleoclimate changes, which indicates that the provenances of the sediment were also transitional (Wang et al., 2017). Studies of the provenance of surface sediments in the Okhotsk Sea using detrital grains have mainly concentrated around Sakhalin Island, which is located in the western part of the Deryugin Basin (Gorbarenko et al., 2002; Nicholson et al., 2013). This material was transported across the Deryugin Basin and into the south central Okhotsk Sea by sea ice. In previous studies, which were limited by the distribution of the research stations (Yasuda et al., 2014), the material diffusion ranges of the Amur River and Sakhalin Island were generally underestimated. Therefore, according to the topography, the sediment diffusion paths, and mineral provinces, surface sediments in representative areas were selected for use in this study. The heavy mineral compositions of the sediments were analyzed, and garnet was selected for geochemical analysis in order to discuss the material sources of the sediments in the Okhotsk Sea, with particular attention being paid to the diffusion of materials along the Amur River, the north shelf of the Okhotsk Sea, and the coast of Sakhalin Island.

GEOLOGIC SETTING

The Okhotsk Sea is a marginal sea in the western Pacific Ocean. It is adjacent to the Bering Sea to the north and is connected to the Sea of Japan by the Soya Strait and the Tatar Strait. To the west is the Siberian mainland. The Okhotsk Sea is surrounded by the Kamchatka Peninsula and the Kuril Islands to the east (**Figure 1**). The sea has a sub-arctic to arctic climate, accompanied by a monsoon climate. The northern and western parts of the Okhotsk Sea have a polar climate. This sea area penetrates into the Asian continent and is adjacent to the polar region of the Northern Hemisphere. The cold arctic air intrudes into the Gulf of Shelikhov. Moreover, the northwestern shelf of the Okhotsk Sea contains a vast shallow region along the coast, which makes it the coldest of the far eastern seas (Minervin et al., 2015). Every year in November, sea ice begins to form along the northern coast of the Okhotsk Sea, reaching its maximum area in April of the following year and dissolving in June-July (Nihashi et al., 2011). In winter, the dominant polynyas mainly occur in three regions: the northwestern and northern shelves of the Okhotsk Sea and the Gulf of Shelikhov. The interglacial caves in the northwestern shelf contribute 55% of the total sea ice, and the second largest area of ice formation is in the Gulf of Shelikhov, which contributes about 25% of the total sea ice (Martin et al., 1998). Under the influence of the rotation of the Earth, the runoff of the Amur River deviates to the right and forms a semi-closed anticyclone circulation. Some of the runoff diffuses northward along the coast of Sakhalin Island, forming the Amur River coastal flow (Zhabin et al., 2010). Studies have shown that the polynyas in eastern Sakhalin are a possible source of dense shelf water, which merges with that formed on the northern and northwestern shelves of the Okhotsk Sea (Fukamachi et al., 2009).

The Okhotsk Sea is characterized by wide continental shelf in the north and deep water depth in the south. There are three large basins in the Okhotsk Sea, namely Deryugin basin in the west, Tinro basin in the east and Kuril basin in the south. The central submarine plateau is distributed between basins, including the Oceanology Institute Rise in the north and the Academy of Science Rise in the south (**Figure 1**), with water depths about 1000m, and the sediment thickness is 200–2,000 m (Mazarovich, 2011), Pleistocene–Holocene, drift sedimentation occurred on the Academy of Science Rise only (Karp et al., 2006). The Okhotsk Sea has continental crust 10–40 km thick, except for the Kurile Basin, the south western part of which is overlain by sedimentary cover 4,000–7,000 m thick. In the north, the Okhotsk-Chukotka volcanic belt extends along the shore. Its basement is composed of Permian–Triassic and Jurassic–Lower Cretaceous island arc complexes, Paleozoic and Mesozoic paleo-oceanic and island arc rock associations of ancient accretionary complexes, main rock types are dacite, basalt, granitoids, andesite, rhyolite and some acid-basic mixed composition (Mazarovich, 2011; Tikhomirov et al., 2012; Ivolga et al., 2016). The sedimentary cover of the shelf is 3000–5000m thick, reaching 8000–9000m in isolated depocenters (Mazarovich, 2011). In the east, volcanic rocks of the Kurile-Kamchatka island arc compositions are wide span from basalt to rhyolite, from tholeiitic to calc-alkaline (Bindeman et al., 2004; Dessert et al., 2009), especially, in the Kamchatka Peninsula, it is dominated by the Neogene arc and related cover rocks, the volcanic complex consists of basalt, dolerite-basalt, siliceous mudstone (Soloviev et al., 2006). In the west, the Okhotsk Sea is framed by the fold–nappe structure of the Hokkaido–Sakhalin

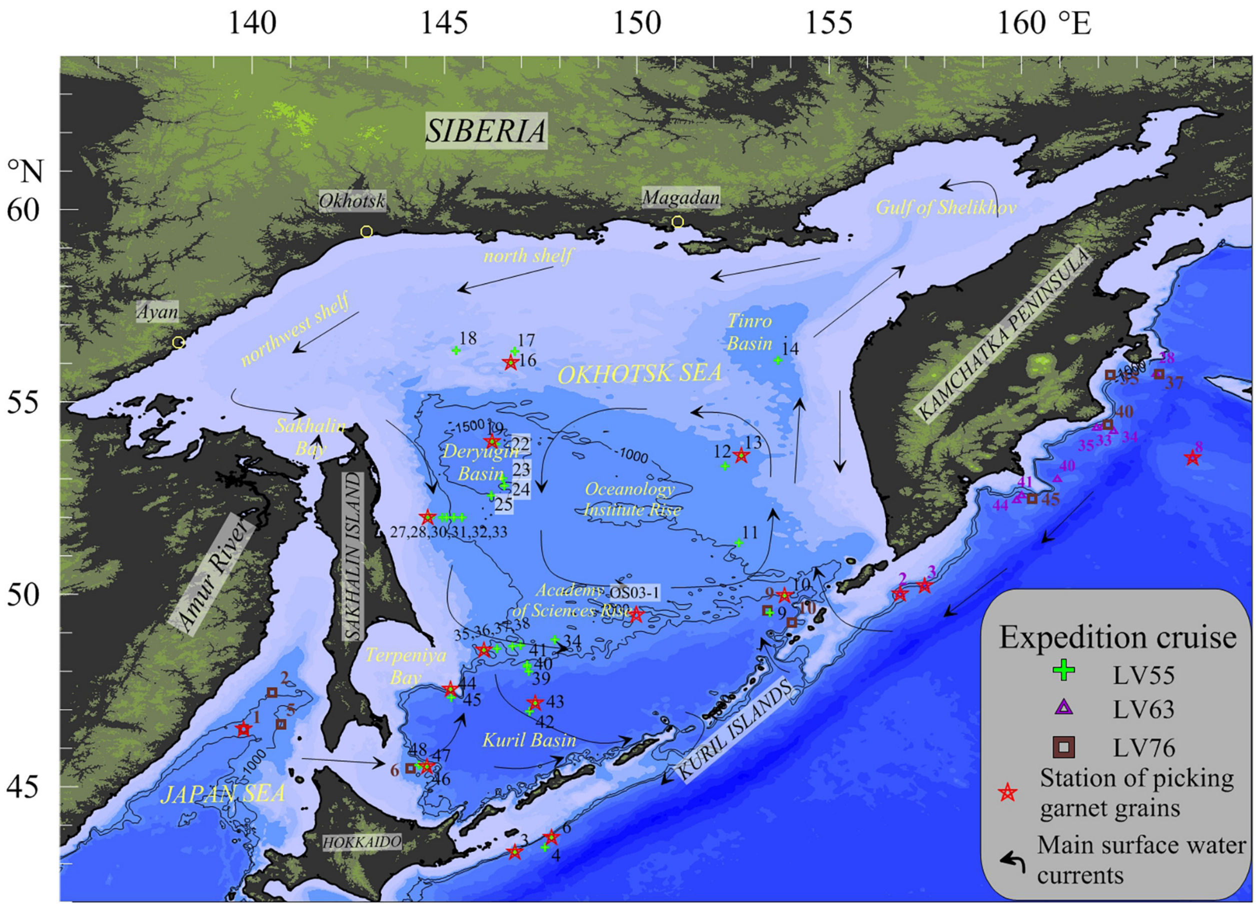

FIGURE 1 | Map showing the sampling sites in the Okhotsk Sea. Surface water current routes modified after Gorbarenko et al. (2014).

region (Mazarovich, 2011). The lithology of the north Sakhalin Island are ultrabasic igneous rock, metasedimentary rocks and mature sandstone (Nicholson et al., 2013), and the lithology of the south Sakhalin Island are mainly Mesozoic accretionary complex rocks (Weaver et al., 2004), including Jurassic–Early Cretaceous continental basalts (Grannik, 2014).

SAMPLES AND METHODS

Surface sediments were obtained on China-Russian Joint Cruises LV55, LV63, and LV76. Detrital mineral analysis was conducted on the 0.063–0.125 mm grain size fraction of 58 surface sediment (top 0–10 cm) samples. The laboratory analysis process for obtaining the sample was as follows. An approximately 200 g sediment sample was obtained, with a high content sand. Then, the sample was dried, and the dry weight of the sediment was obtained. The sample was kept in a beaker containing water. Next, the clay and detrital minerals in the mixture were separated by wet sieving, and the 63–125 μm grain size fraction (very fine sand) was obtained. This size fraction was dried and weighed, and then, it was separated using bromoform ($CHBr_3$) as the separation liquid (density of 2.89 g/ml). Once the minerals were separated, the light and heavy minerals were collected. The heavy minerals were identified and qualitatively and quantitatively analyzed using a binocular microscope and a polarizing microscope and the oil immersion method. The number of grains identified in each sample was greater than 300, and the grain percentage (%) of each mineral species was determined (see Wang et al., 2015 for method).

The garnet contents of surface sediments varied, and in the northern Okhotsk Sea, they were very low. The sediment sample size was not large enough to obtain 50 grains of garnet, the number of selected garnet grains was low, and for some stations it was not found. For the geochemical analysis of the garnet, a maximum of 58 grains were handpicked from the bulk heavy mineral fraction using a binocular microscope. We picked grains from 15 surface sediment stations and 2 samples of OS03-1 core, obtained 394 data of garnet geochemistry. Before the analysis, all of the grains were coated with gold to ensure conductivity, and their element contents were determined using a Quanta-200 scanning electron microscope (SEM) equipped with an EDAX energy dispersive analytical X-ray system operated at 15 kV, with a counting time 60 s for Si, Ti, Al, Cr, Fe, Mg, Mn, Ca, and O (see Wang et al., 2015 for method). The analysis was completed at the Experimental Center of the First Institute of Oceanography, Ministry of Natural Resources, China.

RESULTS

Heavy Minerals Species

The major heavy minerals in surface sediments from the Okhotsk Sea are hypersthene, hornblende, and epidote. The total average content of these minerals is up to 65.86% (**Table 1**). The sediments contained abundant iron oxides (magnetite, hematite, and limonite), ilmenite, and titanium oxides, and the total average content of these minerals is 19.02%. The average augite content is 7.05%. The sum of the average contents of the stable minerals, such as garnet, zircon, monazite, rutile, tourmaline, and sphene, is 1.75%, and the average garnet content is the highest (up to 1.49%). The other minerals identified include micas (biotite, muscovite, and hydrobiotite), authigenic minerals (e.g., siderite and pyrite), and minerals that only occasionally occurred (e.g., tremolite, apatite, staurolite, and kyanite). Ferromagnetic pellet grains were also found in the sediments. The weathered debris (alterites) in sediments has an average content of 4.15%.

The hornblende grains are mainly columnar and granular. In the northwestern part of the Okhotsk Sea, the hornblende grains are mainly green and light green (**Figure 2**, LV55-17), while fresh, brown, sub-angular grains (**Figure 2**, LV55-28) are found in the sediments near Sakhalin Island. Most of the hornblende grains are dark green, black-green, or brown in the sediments off the western coast of the Kamchatka Peninsula. These grains have abraded surfaces and variable larger grain sizes, which is characteristic of IRDs (**Figure 2**, LV55-14). The sediments from the western shelf of the Okhotsk Sea and off the northern coast of Sakhalin Island have high hornblende contents, which decrease in strips from the shallow to deep water, and the Deryugin Basin is an obvious boundary area for content change (**Figure 3A**). As can be seen from **Figure 3A**, the station with the highest hornblende content is located in the southern Deryugin Basin and off the eastern coast of Sakhalin Island. The stations with low hornblende contents are located around the Kamchatka Peninsula.

The epidote grains are mainly yellow green, with abraded and transparent surfaces. There are also a few fresh short columnar or opaque granular grains with obvious transparent-translucent crystal edges (**Figure 2**, LV55-17). In the sediments from the western shelf of the Okhotsk Sea, the surfaces of the epidote grains are heavily abraded. However, there are very fresh and angular grains in the sediments off the eastern coast of Sakhalin Island and surrounding the Kuril Islands. Fresh grains are also found in the sediments off the west coast of the Kamchatka Peninsula (**Figure 2**, LV63-3). The stations with the highest epidote contents are mainly located on the western shelf of the Okhotsk Sea, and the stations with the low contents are located around the Kamchatka Peninsula, especially off the east coast of the Kamchatka Peninsula (**Figure 3B**).

The garnet grains are mostly irregular and colorless, but some are pink or red. The grains in the sediments from the northwestern Okhotsk Sea are mainly colorless and light pink (**Figure 2**, LV55-17). The grains in the sediments off the eastern coast of Sakhalin Island and around the Kuril Islands are mostly pink or dark red; for example, the LV55-28 sediments from the middle and eastern Okhotsk Sea contain a high content of pink garnets (**Figure 2**). There are two regions with high garnet contents in the Okhotsk Sea. One is off the eastern coast of Sakhalin Island, and the other is off the western coast of the Kamchatka Peninsula. The distribution trends of the garnet content show an outward increase (**Figure 3C**). On the north-central and central continental shelves, the garnet content is very low, and garnet is rare in the sediments off the eastern coast of the Kamchatka Peninsula. The garnet content is high in the sediments of the Amur River estuary and off the eastern coast of Sakhalin Island (Derkachev and Nikolaeva, 2007; Nicholson et al., 2013), which is consistent with the distribution of garnet found in this study.

Hypersthene is a common mineral in the sediments of the Okhotsk Sea. The hypersthene grains are mainly short columnar and granular and are light brown and green, with rough and abraded crystal surfaces and tear-like fractures. On the western and northwestern shelves of the Okhotsk Sea, small hypersthene grains with abraded surfaces are commonly found, and fresh grains are rare. In the sediments off the eastern coast of Sakhalin Island, the hypersthene grains are mostly light brown crystal fragments (**Figure 2**, LV55-28). In the sediments off the western coast of the Kamchatka Peninsula and around the Kuril Islands, the grains are larger and have rough surfaces (**Figure 2**, LV63-3). The sediments around the Kamchatka Peninsula and the southern Kuril Islands have higher hypersthene contents. Moreover, the sediments off the eastern coast of Sakhalin Island and on the northwestern shelf of the Okhotsk Sea have lower hypersthene contents (**Figure 3D**).

The magnetite grains are mainly black to light black, irregular granular, with a weak metallic luster. In the sediment off the southern coast of the Kamchatka Peninsula, the magnetite grains are very fresh, and volcanic glass is adhered to the surfaces of the grains. The grains are diamond dodecahedrons and octahedrons. Hypersthene and magnetite are abundant in the volcanic ash layers in the sediments of the Okhotsk Sea. Their contents are particularly high in the K2 volcanic layer (Wang et al., 2017). The sediment around the Kamchatka peninsula has high magnetite contents (**Figure 3E**).

The augite grains are mostly green and light green and even have a turbid color on the surface. The fresh grains in the sediment off the eastern coast of Sakhalin Island are green and short columnar. The high augite contents are mainly distributed off the eastern coast of Sakhalin Island, and they decrease from west to east in the Okhotsk Sea. The low augite contents mainly occur in the sediments around the Kuril Islands and Kamchatka Peninsula, with the exception of the high augite content in the sediments of Kamchatka Bay (**Figure 3F**).

The other diagnostic minerals include mica, zircon, and authigenic minerals (siderite and pyrite). Biotite is one of the main micas. It is mainly distributed in the sediments on the northern, eastern, and southwestern shelves of the Okhotsk Sea, while it is rare or absent in the southern-central Okhotsk Sea and around the Kuril Islands. The zircon grains are colorless

TABLE 1 | Contents of the dominant heavy minerals in surface sediments of the Okhotsk Sea (%).

	Southern Okhotsk Sea			Near Kamchatka Peninsula			NW Okhotsk Sea			SW Okhotsk Sea			Okhotsk Sea		
	Average value	**Minimum**	**Maximum**	**Average value**	**Minimum**	**Maximum**	**Average value**	**Minimum**	**Maximum**	**Average value**	**Minimum**	**Maximum**	**Average value**	**Minimum**	**Maximum**
	n = 10			**n = 22**			**n = 14**			**n = 12**			**n = 58**		
Hornblende	17.20	4.67	35.75	9.33	0.74	35.73	28.20	17.01	47.35	34.92	23.85	40.70	20.54	0.74	47.35
Epidote	7.87	1.47	15.60	3.88	0	14.47	17.61	8.63	28.06	17.96	9.32	25.37	10.80	0	28.06
Garnet	1.71	0.25	4.18	0.22	0	2.10	1.60	0.40	3.38	3.50	0.89	5.93	1.49	0	5.93
Sphene	0.05	0	0.29				0.02	0	0.26				0.01	0	0.29
Hypersthene	36.86	10.48	71.01	58.58	29.10	72.41	19.65	3.54	33.04	5.81	1.31	10.68	34.52	1.31	72.41
Zircon	0.12	0	0.54	0.05	0	0.59	0.09	0	0.44	0.22	0	0.82	0.12	0	0.82
Augite	6.86	0.74	16.67	3.96	0	15.16	8.37	4.13	19.96	11.33	7.00	17.06	7.05	0	19.96
Ilmenite	0.70	0	1.71	0.68	0	4.92	1.29	0.59	1.97	2.14	1.31	3.74	1.13	0	4.92
Magnetite	11.14	0	28.22	14.08	2.56	22.88	3.79	0.48	7.89	6.72	0.94	17.88	9.57	0	28.22
Hematite	2.95	0.74	6.36	2.76	0.55	22.64	4.02	0.48	14.16	6.45	0.41	28.45	3.86	0.41	28.45
Limonite	4.51	0.57	11.56	2.59	0	11.25	6.71	1.90	10.57	4.25	1.24	13.35	4.26	0	13.35
Authigenic pyrite	3.13	0	30.14	0.01	0	0.30	0.11	0	0.70				0.57	0	30.14
Siderite	0.51	0	2.00	0.08	0	0.61	1.48	0	3.32	0.83	0	1.79	0.65	0	3.32
Transparent volcanic glass (in light minerals)	6.83	0	29.08	6.60	0	54.69	0.28	0	0.92	0.10	0	0.55	3.77	0	54.69
Brown volcanic glass (in light minerals)	0.54	0	3.14	10.31	0	54.38	0.07	0	1.02	0	0	0	4.02	0	54.38

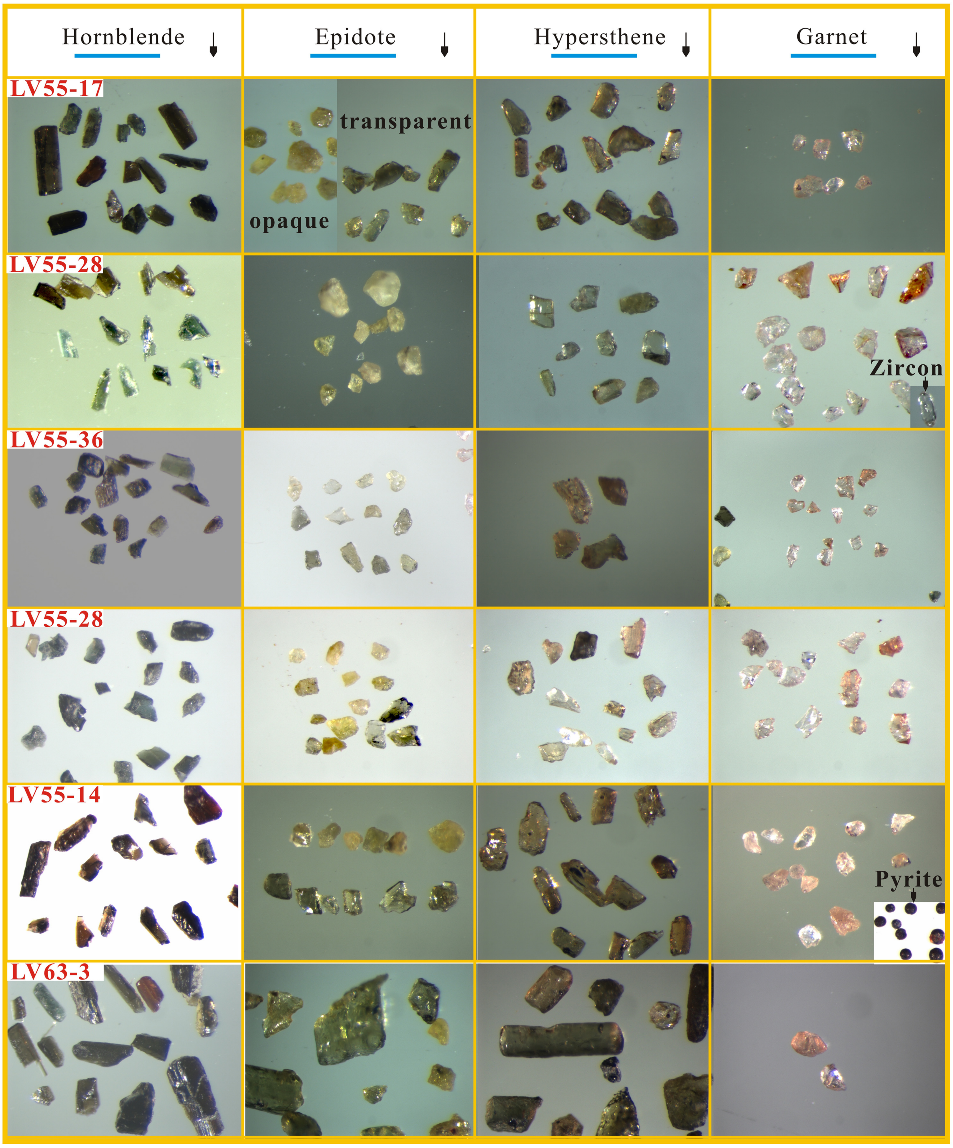

FIGURE 2 | Microscopic observations of the major heavy minerals. Blue bar = 500 μm.

and transparent dipyramidal crystals (**Figure 2**, LV55-28). The zircon contents are low and mainly occur in the sediments off the eastern coast of Sakhalin Island. The siderite grains are opaque and slightly circular, and they mainly occur in the sediments of the Deryugin Basin. The pyrites grains are mostly red brown spheroids and granular aggregates, some of which are black in color due to oxidation. These mainly occur in the sediments of the western Okhotsk Sea (**Figure 1**, LV55-14) and the northern part of the Sea of Japan (**Figure 1**, LV76-2).

Geochemistry of the Garnet

The geochemistry of the garnet was analyzed to investigate the provenance of the sediments. The reason behind this decision is that the garnet is mainly derived from the mainland and source rocks, which are mostly mafic and ultramafic rocks, including schist and gneiss. The practice of determining the provenance of sediments based on the composition of the garnet has been successfully used in previous studies (Krippner et al., 2014; Schneider et al., 2016; Huber et al., 2018). Garnet is also abundant in the sediments of the Amur River, which are widely distributed and regionalized (Nicholson et al., 2013). Based on the heavy mineral distributions, we picked garnet grains from four sedimentary provinces (**Table 1** and **Figure 4A**), which may represent garnet terminus provenances. These four provinces are the area around the Kamchatka Peninsula (**Figure 4B**), the southern Okhotsk Sea (**Figure 4C**), the northwestern Okhotsk Sea (**Figure 4D**), and the southwestern Okhotsk Sea (**Figure 4E**). For comparison purposes, garnets were also picked from the upper sediments of core OS03-1 (**Figure 4F**), which is located in the southern central Okhotsk The provenance of the sediments

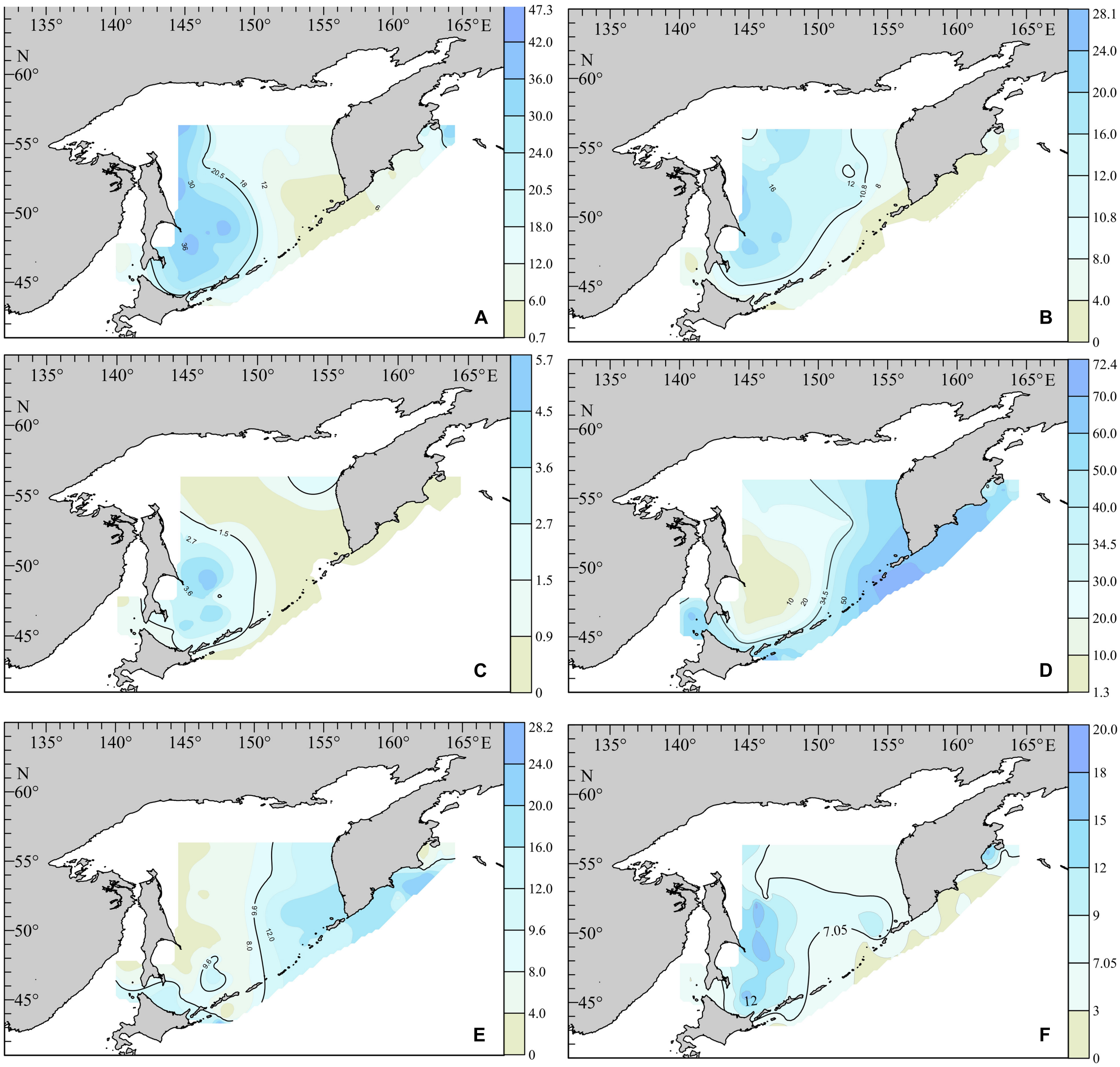

FIGURE 3 | Distribution of the heavy mineral contents of surface sediments in the Okhotsk Sea (%). Bold line is the distribution of the average value. **(A)** Hornblende, **(B)** Epidote, **(C)** Garnet, **(D)** Hypersthene, **(E)** Magnetite, and **(F)** Augite.

in the core has been well established through heavy mineral data (Wang et al., 2017).

The garnet types of surface sediments are mainly types A, Bi, and Bii (**Figure 4A**). Type Ci is rare, and type D is even rarer in the Okhotsk Sea and surrounding areas. Type Cii is absent. The garnet content is relatively low in the sediment around the Kamchatka Peninsula, and the garnet is mainly type Bi, followed by type B. However, the type of garnet varies significantly in the different regions. At station LV55-10 near the Kuril Islands, the garnet is mainly type A; at station LV63-8 off the eastern coast of the Kamchatka Peninsula, the garnet is mainly type B; at station LV55-13 off the western coast of the Kamchatka Peninsula, it is type Bi; and off the southeastern coast of the Kamchatka Peninsula, it is types Bi and A (**Figure 4B**). In the southern Okhotsk Sea, from the Tatar Strait to the Kuril Islands, the garnet is types A and Bi, with a trend from A to Bi (**Figure 4C**). In the northern and southern Kuril Islands, there are different types of garnet (**Figures 4B,C**). The types are mainly types A, Bi, and B (**Figures 4D,E**) in the western Okhotsk Sea (off the eastern coast of Sakhalin Island), and from north to south, the amount of type Ci increases. In the upper sediments of core OS03-1, the garnet is mainly types A and Bi, which is similar to the sediments off the western coast of the Kamchatka Peninsula and the eastern coast of Sakhalin Island (**Figures 4F,H**).

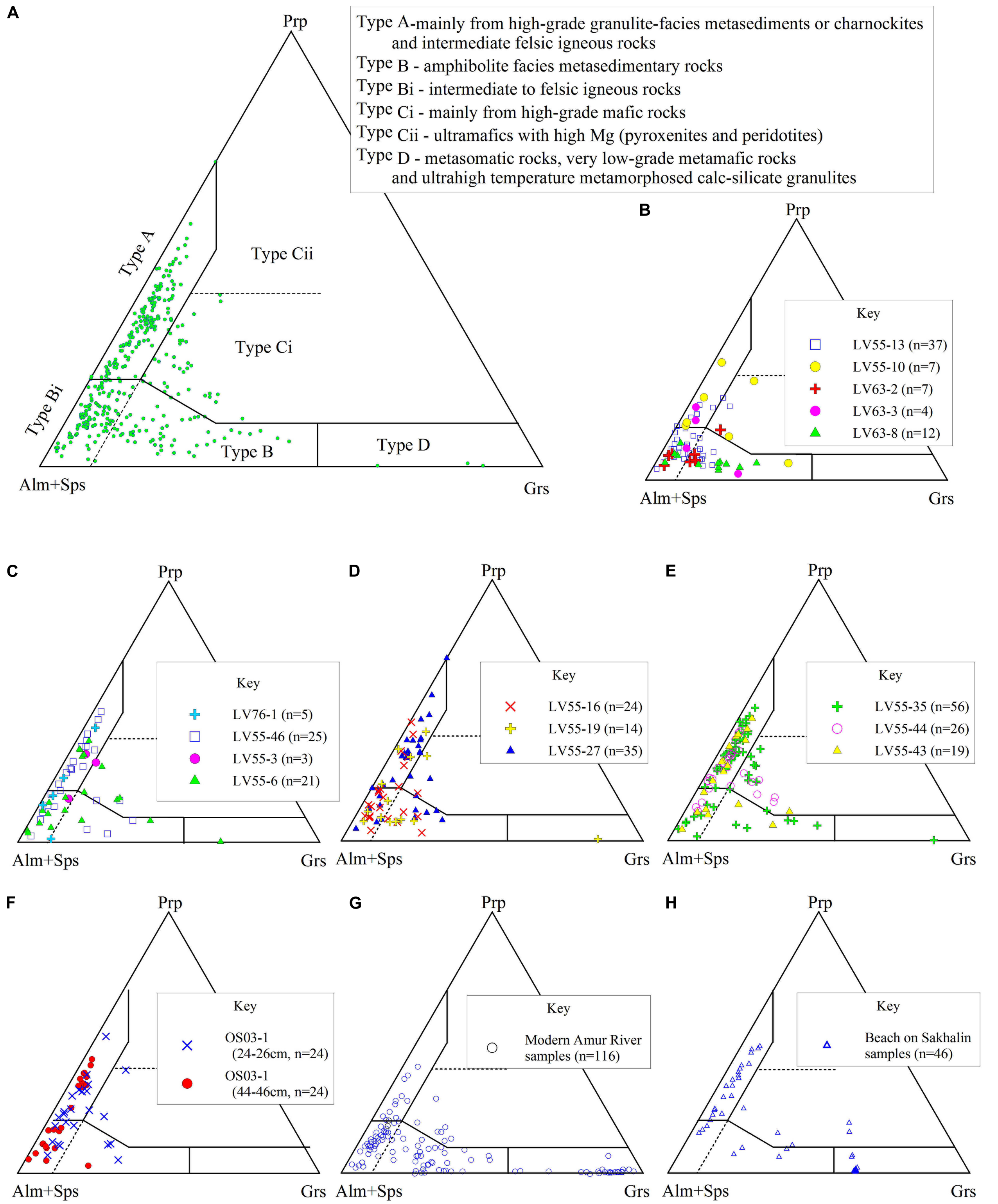

FIGURE 4 | Almandine+spessartine, grossular, and pyrope ternary garnet classification diagrams of Mange and Morton (2007) and Krippner et al. (2016) showing the compositions of the garnets. **(A)** The diagram of all grains of picking samples in surface sediment. **(B)** Samples of surrounding the Kamchatka Peninsula. **(C)** Samples of the southern Okhotsk Sea. **(D)** Samples of the northeast Sakhalin Island. **(E)** Samples of the southeast Sakhalin Island. **(F)** Samples of the core OS03–1 in the south central Okhotsk Sea. **(G)** Samples of the modern Amur River (Nicholson et al., 2013). **(H)** Samples of beach on the Sakhalin Island (Nicholson et al., 2013).

DISCUSSION

Heavy mineral analysis is particularly suitable for studying the material sources of surface sediments in the Okhotsk Sea. The first reason for this is that the sediment grain size is primarily fine sand. The Amur River has a high content of fine sand, and the eastern coast of Sakhalin Island and the northern shelf of the Okhotsk Sea have prevalent sea ice in winter, which results in ice-rafted debris. The second reason is that the material inputs are derived from different areas, i.e., in the Sakhalin Bay, sediment is dominated by river input; on the northern shelf of the Okhotsk Sea, sediment is dominated by volcanic debris and coastal erosion materials transported by sea ice; and off the west coast of the Kamchatka Peninsula and around the Kuril Islands, sediment is dominant by volcanic detrital material. The compositions and contents of the detrital minerals are different in these regions. The variations and distributions of the detrital minerals form different characteristic zones in the Okhotsk Sea, representing different material sources and transport paths.

Provenance Indicator Minerals

The distribution of the heavy minerals in the Okhotsk Sea is mainly controlled by transportation by sea ice, input from rivers, the collapse of glaciers, and volcanic eruptions. Sea ice is the dominant transport mode, and it is mainly focused on the periphery of the Okhotsk Sea. The collapse of glaciers and volcanic eruptions mainly occur around the Kamchatka Peninsula. Volcanic eruption products are widely distributed and have short periods. The eruption of KO (Kurile Lake Volcano, Kamchatka Peninsula) was the largest eruption in the volcanic belt on the Kamchatka Peninsula and the Kuril Islands in the Holocene (Gorbarenko et al., 2002; Ponomareva et al., 2004). The Amur River input also affects the deposition of sediments in the shelf area in the western Okhotsk Sea (Wong et al., 2003), which is the first large river in the Far East Russia with a runoff of 3.25×10^{11} m^3/a, and the sediment discharge reaches 5.2×10^7 ton/a (Dagg et al., 2004). A large amount of fresh water and sediment are input into the northwestern Okhotsk Sea. The injection of fresh water from the Amur River is an important factor in the Okhotsk Sea water circulation pattern. Furthermore, it is a necessary condition for the formation of the North Pacific Intermediate Water, and it provides the energy necessary for the sea ice to carry sediments to the south during the Siberian monsoon (Simizu et al., 2014). With the expansion of sea ice, the Amur River material is transported into the southern and central parts of the Okhotsk Sea and deposited. In general, the sand contents of surface sediments of the northern and western Okhotsk Sea are high, especially in Sakhalin Bay (Sakamoto et al., 2005), the grain size parameters of the sediment reflect the characteristics of the river input. Old Amur River delta deposits have been discovered in the northern part of Sakhalin Bay (Weaver et al., 2004). There are about 30 active volcanoes in the southeastern Okhotsk Sea, including the northern Kuril Islands and the southern part of the Kamchatka Peninsula. The input of volcanic material is obviously dominant in the sediments in this region (Dessert et al., 2009), while in most areas of the Okhotsk Sea, the sediments are derived from terrigenous materials (Gorbarenko et al., 2002). In core OS03-1, which is located in the south-central Okhotsk Sea, the detrital grains are mainly silicate minerals, including hornblende, epidote, and hypersthene (Wang et al., 2017). The trace element geochemistry also shows that volcanic materials and terrigenous materials transported by the Amur River and sea ice in this area (Zou et al., 2015).

There are many kinds of detrital minerals in the sediment of the Okhotsk Sea, including hornblende, epidote, hypersthene, augite, and garnet (Lisitzin, 2002; Derkachev and Nikolaeva, 2007). In the modern sediment of the Amur River, the main heavy minerals are epidote and hornblende, and the content of these two minerals is greater than 60%; while along the eastern coast of Sakhalin Island, the dominant heavy minerals are olivine, garnet, hornblende, and epidote, and the content of hornblende and epidote gradually increases from north to south (Nicholson et al., 2013). It can be concluded that hornblende, epidote, and garnet are indicators of terrigenous material, which is enriched on the northwestern shelf of the Okhotsk Sea. Hypersthene is mainly enriched on the periphery of the Kamchatka Peninsula and on the northeastern shelf of the Okhotsk Sea (Derkachev and Nikolaeva, 2007), and thus, hypersthene can be used as an indicator of volcanic material. Hypersthene mainly occurs in volcanic eruption material, and volcanic debris minerals are distributed throughout the entire sea, it is rich in some of the volcanic ash layers (Hasegawa et al., 2011). For example, the KO volcanic ash layer covers almost the entire Okhotsk Sea, and the K2 volcanic ash layer (Nemo Volcanic eruption, Nemo-III caldera, Onekotan Island) is distributed around the eastern coast of Sakhalin Island (Derkachev et al., 2016). The hypersthene contents of these ash layers are very high, especially that of the K2 layer (Wang et al., 2017). The volcanic rocks on the south Kamchatka Peninsula are mainly double-pyroxene dacites (Izbekov et al., 2004), which are rich in orthopyroxene (primarily hypersthene). In the sediments around the Kamchatka Peninsula, the hypersthene come from directly eruption material into the sea, carried by sea ice, and input by rivers and glaciers in the coastal zones. In the Bering Sea, the hypersthene distribution can be used as an alternative indicator of the distribution of volcanic materials derived from the Kamchatka Peninsula (Lisitzin, 2002). On the western shelf of the Okhotsk Sea, hypersthene also occurs in the sediment off the eastern coast of Sakhalin Island and in the sediment of the Amur River, but the contents in these areas are relatively low (Nicholson et al., 2013). The high hypersthene contents are commonly accompanied by high magnetite and volcanic glass contents, indicating a volcanic eruption source, which is usually true for the contents of the volcanic ash layers (Wang et al., 2017). Thus, this type of hypersthene is very common (**Figure 2**, LV63-3) and has high contents in surface sediments around the Kamchatka Peninsula and the Kuril Islands. However, hypersthenes of sediment of the northern shelf are abraded in grains surfaces, and eruption source characteristics are not obvious in shape, which indicates that the sediments were mainly transported by sea ice (**Figure 2**, LV55-17). The low hypersthene contents on the northern shelf indicate coastal material from river input or transportation by sea ice when the surface characteristics of the grains do not

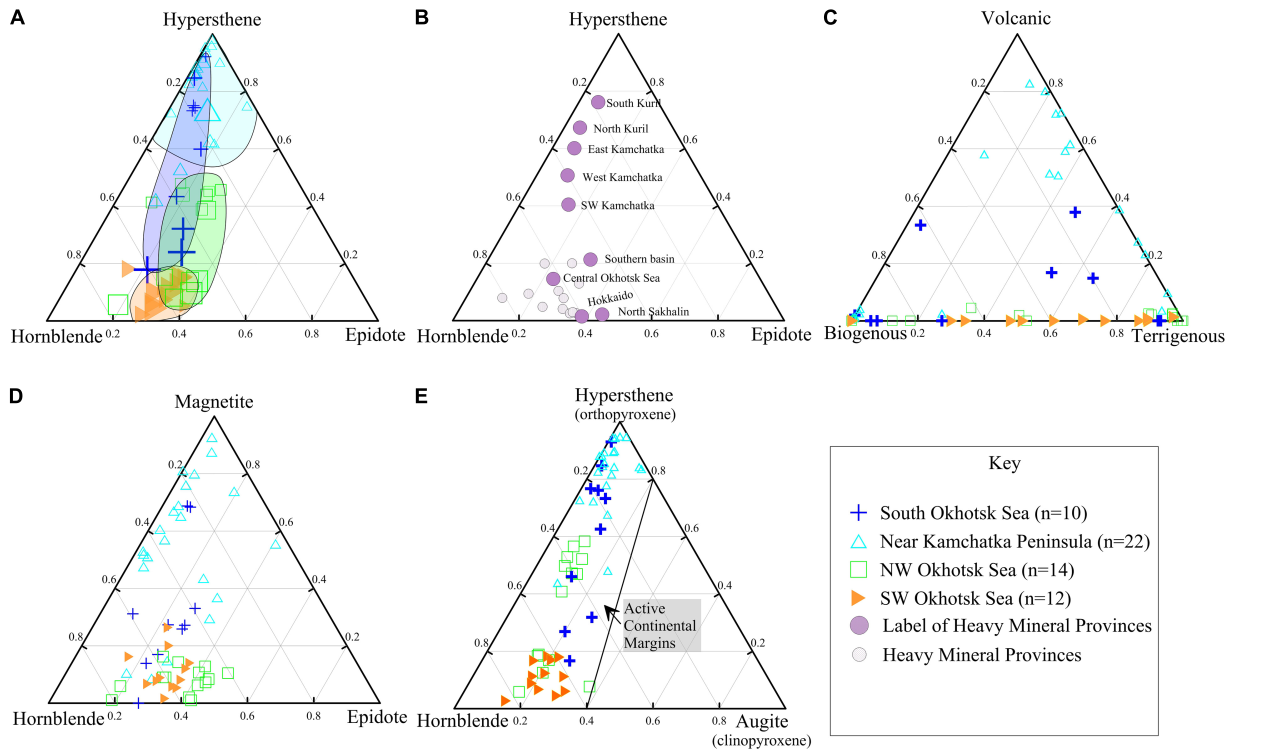

FIGURE 5 | Detrital provenance analyses of surface sediment samples based on the mineral contents. **(A)** Plot of Hornblende-Epidote-Hypersthene, larger symbols indicate higher content of garnet. **(B)** Plot of Hornblende-Epidote-Hypersthene of heavy minerals provinces in the Okhotsk Sea (Wang et al., 2017 modified after Derkachev and Nikolaeva (2007) that cited from Petelin (1957)). **(C)** Plot of Biogenous-Terrigenous-Volcanic grains, biogenous data is foraminifera tests content, terrigenous data is quartz content, volcanic data are contents of brown and transparent volcanic glasses, these dada are obtained from light mineral in 63-125 μm grain size fraction. **(D)** Plot of Hornblende-Epidote-Magnetite. **(E)** Plot of Hornblende-Augite (clinopyroxene)-Hypersthene (orthopyroxene) that indicates various geodynamic settings (Markevich et al., 2007).

indicate a volcanic eruption derivation (no obvious volcanic glass adhesion). In this case, the morphology of the volcanic debris has been abraded during the transportation by sea ice, which indicates that they were remodeled before they became marine sediments rather than directly entering sediments as fresh volcanic minerals (Bigg et al., 2008, who cited Conolly and Ewing, 1970). Because it is associated with high contents of terrigenous minerals, hypersthene can be used as an indicator of sea ice transportation from the west coast of the Kamchatka Peninsula and the northeastern shelf of the Okhotsk Sea.

Material Transport Paths

The main heavy minerals in surface sediments of the Okhotsk Sea are hornblende, epidote, hypersthene, augite, garnet, and magnetite (**Table 1**). The hornblende, epidote, and other terrigenous detrital minerals are mainly from the sediments along the northern shelf of the Okhotsk Sea, the Amur River input, and the eastern coast (bays) of Sakhalin Island. The hypersthene and magnetite are mainly distributed on the eastern shelf of the Okhotsk Sea and around the Kamchatka Peninsula and the Kuril Islands. According to ternary Hypersthene (Magnetite)–Hornblende–Epidote diagrams, the compositions of the heavy minerals from the stations near the Kamchatka Peninsula are obviously affected by a material source along the Kamchatka Peninsula (**Figures 5A,B,D**), and the contents of volcanic detrital minerals (volcanic glass) in sediments from these stations are relatively high (**Figure 5C**). The hypersthene contents of the sediments from the northwestern shelf are significantly lower than those of the sediments around the Kamchatka Peninsula (**Figure 5A**), while the content of volcanic material (volcanic glass) is very low or even zero, and the content of biogenous particles such as foraminifera is relatively high (**Figure 5C**). The epidote content is relatively high, indicating that the materials along the coast of Sakhalin Island have a significant impact. On the southwestern shelf of the Okhotsk Sea, the variation in the heavy mineral composition is relatively stable, and the debris mainly includes the sediments from the coast of Sakhalin Island and those carried by the sea ice from the Amur River. Another feature is that the content of the stable minerals (garnet, zircon, and tourmaline) is relatively low in the Okhotsk Sea. The stable mineral content is greatly affected by terrigenous materials and is mainly due to physical weathering of cold areas, so the influence of the mineral stability factor on the mineral composition is relatively weak in the Okhotsk Sea. The Hornblende – Augite (clinopyroxene) - Hypersthene (orthopyroxene) diagram (**Figure 5E**) can allow division of the continental and oceanic arc-derived detritus (Markevich et al., 2007), all studied sediments belong to active continental margin.

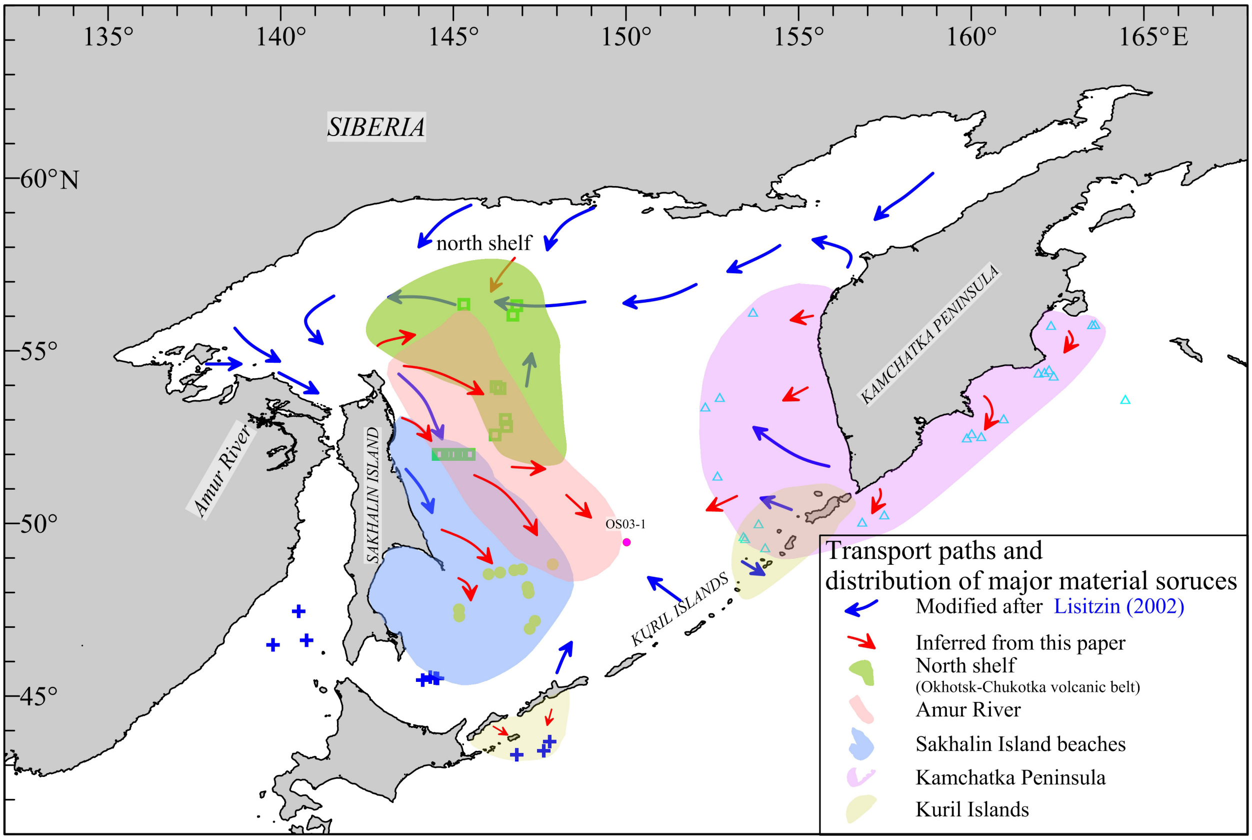

FIGURE 6 | Transport paths and distribution area of major material sources of the heavy minerals.

According to the distribution of the heavy minerals, there are three major material source areas (i.e., input from the Amur River, the northern shelf of the Okhotsk Sea, the coast of the Kamchatka Peninsula) and two secondary areas (i.e., the east coast (bays) of Sakhalin Island and the Kuril Islands) (**Figure 6**). Detrital mineral is transported by sea ice from east to west along the shoreline of the Gulf of Shelikhov and into the Okhotsk Sea. In the northern part of Sakhalin Bay, there is an intersection between the material input by the Amur River and the coastal materials derived from the northeastern Okhotsk Sea. The materials in this area are mainly coastal materials from the northern shelf of the Okhotsk Sea, and the detrital isotope geochemistry (Sr and Nd isotope ratios) shows that the lithogenic material of the Amur River accounts for about 20% (Yasuda et al., 2014). In terms of the heavy mineral composition, the hypersthene and hornblende contents are almost uniform, and the garnet content is slightly lower. This also indicates that sediment in the northern part of Sakhalin Bay has two sources: the terrigenous material from the Amur River and the volcanic detrital material from the continental shelf in the northern Okhotsk Sea (Okhotsk-Chukotka volcanic belt). Off the eastern coast of Sakhalin Island, the heavy minerals (i.e., hornblende and epidote) are mainly derived from the Amur River and the coast of Sakhalin Island, and the heavy mineral content gradually increases from north to south. Due to the combined actions of the Siberian wind and the currents of the Okhotsk Sea, the sea ice moves southward along the coast, as does the sea ice produced along the eastern coast of Sakhalin Island. These two sets of sea ice are pushed together from different directions and sources, causing all of the sea ice to move to the central and eastern parts of the Okhotsk Sea (Minervin et al., 2015). The IRDs carried by the sea ice should be transported into the southern and central parts of the Okhotsk Sea, where its distribution pattern becomes fan-shaped. The sediment in this area contains a large amount of river material and coastal material from the northern shelf and Sakhalin Island. The geochemical classification of the garnet also supports this conclusion and reveals more details. Compared with the garnets in the Amur River and on the Sakhalin Island beaches (**Figures 4F,G**) (Nicholson et al., 2013), the garnets from the sediments off the northeastern and southeastern coasts of Sakhalin Island are mainly from the Amur River and the coast of Sakhalin Island (**Figures 4D,E**). In the north-south direction, the Amur River garnets dominate of the sediments from the northern stations (**Figure 4D**); while in the southern station, the amount of material from Sakhalin Island gradually increases and becomes dominant (**Figure 4E**). In the east-west direction, the garnet from the western station (**Figure 4E**, LV55-44) is almost completely derived from the beaches of Sakhalin Island, while the characteristics of the sediments from the eastern station indicate that their source was the Amur River (**Figure 4E**, LV55-43).

CONCLUSION

Based on the heavy mineral assemblages of surface sediments of the Okhotsk Sea, five terrigenous sources were identified: the Amur River, the Okhotsk-Chukotka volcanic belt (the northern shelf of the Okhotsk Sea), the Kamchatka Peninsula, the Sakhalin Island beaches (bays) and the Kuril Islands. Among them, the indicator minerals of terrestrial materials derived from the Amur River and Sakhalin Island are hornblende, epidote, and garnet. The indicator mineral for the Okhotsk-Chukotka volcanic belt is hypersthene with smooth and eroded surfaces, while fresh hypersthene (with volcanic glass adhered to the surface and/or associated with high magnetite contents) is an indicator mineral for the Kamchatka Peninsula and the Kuril Islands. Based on the mineral assemblages and the garnet geochemistry, the sediments off the eastern coast of Sakhalin Island were mainly transported by sea ice. The materials off the coast of Sakhalin Island and on the northern shelf are distributed in a fan shape along Sakhalin Island and toward the southeast. The detrital minerals near Sakhalin Island are dominated by beach material, and further to the east the dominant sources are the Amur River and the northern shelf of the Okhotsk Sea. The transport path of these material sources is consistent with the mineral data for the core from the south-central Okhotsk Sea, which is taken at the Academy of Sciences Rise. This study demonstrates the interactions between the Amur River input and the materials from Sakhalin Island and the Okhotsk-Chukotka volcanic belt.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

XS took charge of these cruises and gave guide for this study. JZ gave many designs and took sediment in cruises. YL took sediment in cruises. ZY modified the manuscript for garnet geochemistry. SG was one of two chief scientists in these cruises. All authors contributed to the article and approved the submitted version.

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