Provenance of turbidite sands from IODP EXP 1301 in the northwestern Cascadia Basin, western North America

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A R T I C L E   I N F O

Article history:
Received 7 April 2007
Received in revised form 24 October 2008
Accepted 31 January 2009

Keywords:
Cascadia Basin
Juan de Fuca ridge
turbidite sands
heavy minerals

Abstract

The northwestern Cascadia Basin of western North America accumulated high-sedimentation-rate sequences during the Pleistocene sea-level low-stands. The continental shelf was largely exposed at that time, and rivers and estuaries delivered large sediment fluxes directly to the deep ocean. The IODP EXP1301 core, which was taken from the middle portion of the Cascadia Basin, is well preserved and exhibits the deeper and — more distal sedimentary facies. The lithology in this location is composed of two units, 1) hemipelagic mud with a thin sand layer and 2) thick, coarsening upward silt–sand turbidites with a small proportion of granules at the top. We will focus on the detailed sand-grain proportions in order to understand the origin of these sediments. We determined the modal proportions of the heavy minerals, and the chemical composition of olivine and orthopyroxene in fourteen samples. These are characterized by an abundance of amphibole, pyroxenes and epidote, and the presence of minerals derived from peridotite. There is no drastic change in the modal and mineral compositions of the sands and silts between the turbidite and hemipelagic sequences. There were two probable drainage systems on the continent, the Frazer and Columbia rivers, which shed turbidites into the Cascadia Basin after 1.6 Ma, especially at 0.46–0.76 Ma. Based on a comparison of the modal and mineral compositions, the Northern Cascadia Basin has been supplied with sediments, mainly from the Frazer River, through the Straits of Juan de Fuca, by Pleistocene to Holocene turbidites.

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1. Introduction

Many studies of the minerals in sands have taken place at sites in the Cascadia Basin of western North America. One of these, IODP drilling site 1301, is close to previous drilling sites 1023–1032, from Leg 168 (Fig. 1). Underwood and Hoke (2000) studied light minerals and lithic fragments in Late Pliocene to Holocene sediments of the previous sites and concluded that the likely source areas include the Olympic Peninsula and Vancouver Island. Referring to the submarine-channel system and global geology of the likely provenance terrane, Underwood et al. (2005) inferred that turbidity currents via the Straits of Juan de Fuca were the most active source of the sediments in Leg 168 over the past million years. Scheidegger et al. (1973) studied heavy minerals at three sites on the Astoria Fan, in the southern part of the Cascadia Basin, and concluded that most of the sands were derived from the Columbia River. Chamov and Murdmaa (1995) studied both heavy and light minerals at sites on the Cascadia margin, close to the mouth of the Straits of Juan de Fuca. They found a change of heavy mineral assemblage in the sequence: an amphibole–pyroxene– epidote assemblage in Holocene to lower Pleistocene sediments and an amphibole–epidote assemblage in lower Pleistocene to upper Pliocene sediments. They concluded that this change was not attributable to a difference in provenance, but was due to the dissolution of heavy minerals.

One of the approaches to provenance studies of sand and sandstones is based on determining the relative abundances of the detrital minerals. Although this provides a strong basis for interpreting provenance, we must seriously consider any possibility of post-depositional dissolution of the detrital minerals, as has been discussed by several researchers (e.g. Pettijohn, 1941; Morton, 1984; Smale and Morton, 1987). Determining whether detrital minerals have remained stable or have been dissolved is a primary consideration for provenance interpretation. In addition, the chemical composition of heavy minerals in sand and sandstone provides additional information on provenance (Yokoyama et al., 1990; Morton, 1991). Recently, the age analysis of detrital monazite and zircon has been used to decipher provenance, since both minerals are usually treated as being stable (e.g. Suzuki et al., 1991; Tsutsuami et al. 2003).

The purpose of this study is to describe heavy minerals in the latest Pliocene to Holocene sequence at IODP drilling site 1301, based on various mineral-identification methods used in previous studies of the Cascadia Basin, and to discuss their provenance. Light minerals, such as quartz and feldspar, are less source-diagnostic, so we
analyzed the modal proportions of heavy minerals and the chemical compositions of olivine, orthopyroxene and monazite in the core samples.

At ODP site 1026 (which is almost the same site as EXP 1306), an off-ridge site in the Cascadia Basin, the age of the basement is 3.586 Ma, and the first silty turbidity currents arrived at 1.6 Ma (Su et al., 2000; Underwood et al., 2005). These sediments contain landward erosional input from the Ice Ages (Fisher et al., 2005; Haug et al., 2005). The west coast of the middle portion of the North American Cordillera region, which is more than 1800 km long × 600–
900 km wide area, contains only two large river systems, the Frazer and Columbia rivers, which produce eroded fluvial discharge to the Pacific Ocean. To discover the origin of the suspended river sediments in the Cascadia Basin, it is important to understand the climatic conditions during the Ice Ages (Pliocene–Holocene). We also tested sands from the Frazer and Columbia rivers to gain insights into the consistent source of turbidite sediments to the Cascadia Basin.

2. Analytical procedures

Pleistocene to Holocene sediments found in cores drilled in the Cascadia Basin (Fig. 1) are divided into two sequences: turbidites and hemipelagic sediments (Shipboard scientific party, 1997; Fisher et al., 2005, Fig. 2). These clastics are composed mainly of silt–sand turbidite and hemipelagic mud, with a small proportion of granules. Fourteen samples in the sequence were analyzed in detail, twelve of which are poorly consolidated sands from the upper unit I (Turbidite sequence) and two of which are very fine to silty sands from unit II (Hemipelagic sequences, Fig. 2). Standard thin sections of the clasts in the granules were made to determine the original rock types for the minerals in the sands. Photomicrographs of the representative clasts are shown in Fig. 3. For comparison with sands in the likely provenance areas, two areal sand samples were collected from the Vancouver fan-delta formed by the Frazer River, and from the Columbia River riverfront (Fig. 1).
The procedures used for to separate and identify heavy minerals in the sands and silts were described in detail by Yokoyama et al. (1990). The sand samples were sieved. The fractions used for analyses were 63–250 μm in width (Fig. 4). Silty samples were just washed in running tap water to remove fine particles. The studied grains in silts are less than 100 μm, far finer than the ones in the sands. The specific gravity of the methylene iodite was reduced to 2.82 to recover composite grains and aggregates of the heavy and light minerals. Carbonates, micaceous minerals and authigenic pyrite were not subjected to examination, and magnetic fractions were removed prior to the separation of the heavy minerals.

Most of the minerals were identified from an X-ray profile done with an Energy Dispersive Spectrometer (EDS). Many grains were composed of a single mineral species, but composite grains and aggregates were also common. For the latter, we measured the major constituent. A total of 230 to 350 grains were identified in the sands, but only about 150 grains in the silts, due to the restricted number of the samples available for this study (Table 1). In the X-ray profiles, minerals with the same chemical compositions were described as polymorphs, i.e. TiO₂ polymorphs for rutile, anatase and brookite and Al₂SiO₅ polymorphs for sillimanite, kyanite and andalusite. Epidote-group minerals make up one of the major heavy mineral suites. Their compositions varied from...
zoisite to epidote, and are tentatively and collectively denoted as “epidote” here. The modal proportions of orthopyroxene and cummingtonite were obtained through chemical-composition analysis using an electron microprobe analyzer, as mentioned below. The modal proportions of the heavy minerals are listed in Table 1. The relative proportions of the representative minerals are shown in Fig. 5.

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Mineral abbreviation: opx = orthopyroxene, cpx = clinopyroxene, amp = calcic amphibole, ol = olivine, gar = Ca-poor garnet, epi-epidote group minerals, pum = pumpellyite, tit = titanite, ilm = ilmenite, spi = Cr-spinel, mon = monazite, cum = cummingtonite, gr-an = grossular and andradite, Ti = TiO2 polymorphs, zir = zircon, apa = apatite, tor = tourmaline, all = allanite, sta = staurolite, sil = Al2SiO5 polymorphs, chl = chloritoid, cro = crossite, uva = uvarovite, rie = riebeckite.
Fig. 5. Histograms of representative heavy minerals in sands from IODP cores, Frazer River and Columbia River. Abbreviations of the minerals are the same as Table 1.
In previous studies of Cascadia Basin sands, minerals were discriminated using standard optical microscopy. Optical identification depends highly on skill and experience, and mistakes in identification can be made owing to randomly orientated grains. In addition, opaque minerals cannot be distinguished using normal optical methods. Although the present X-ray methodology cannot distinguish polymorphs, X-ray profiles allow the correct identification of all grains, including both rare and opaque minerals. In addition, this method can divide garnets into Fe-rich garnet and Ca-rich garnet.

The chemical compositions of olivine and orthopyroxene were analyzed with an electron-microprobe analyzer (EPMA, JEOL 8800), and these two minerals were confirmed to be compositionally variable using EDS profiles. We also analyzed monazite, which is usually present as a trace or in scarce amounts in sands. The age of the monazite was obtained from the Pb, Th, and U content, using the methods of Suzuki and Adachi (1991). Detailed information on age analyses using the equipment we employed is described in Santosh et al. (2006).

3. Heavy mineral species

More than twenty heavy mineral species were present in the sands from site 1301; about two hundred grains were identified in most samples (Table 1). The major minerals throughout the sequence were amphibole and epidote, similar to those described for sands of the Cascadia Basin (Scheidegger et al., 1973; Chamov and Murdmaa, 1995). Pyroxene, garnet and ilmenite occurred in subordinate amounts. Pumpellyite, which has not been described in previous studies, was also common throughout the sequence. Olivine was present only in the upper zone of the sequence. Minor or rare minerals included cummingtonite, Ca-rich garnet, zircon, allanite, staurolite and Al₂SiO₅ polymorphs. Crossite, a mineral representative of high-pressure metamorphic rocks, was present in one sample. Monazite was counted in only one sample (C3H-5W), but is more or less present in most samples. Pyroxenes in the upper sequence were often surrounded by clear or devitrified glass, suggesting their origin as volcanic ash or rock. The etching of pyroxenes due to dissolution,
which is characterized by saw-edged rims, is present in the lower sequence (Fig. 4), as observed in previous studies of Cascadia Basin sands (Scheidegger et al., 1973; Chamov and Murdmaa, 1995). These textures show that these minerals, which were rare or absent in the lower sequence, were dissolved or decomposed following deposition.

Sand samples from both the Frazer and Columbia rivers have mineral assemblages roughly similar to those in the IODP samples. Common minerals included calcic amphibole, pyroxenes, epidote and ilmenite. However, there was a clear difference between the two river samples. Olivine was a common mineral in the sample from the Frazer River, whereas it was scarce in the Columbia River sand. Amphibole and epidote were the most abundant of the heavy minerals, in sands from both site 1301 and the Frazer River. In contrast, clinopyroxene was the most abundant mineral in sand from the Columbia River.

Normal thin section observation of clasts in granules indicated that various rock types occurred in the provenance. Weakly metamorphosed rocks were the most common rock types, and include phyllite, meta-chert, meta-sandstone and meta-basalt. Other common rock types include quartz diorite, basalt, andesite, amphibolite and serpentinite; gneiss was rare. Calcic amphibole, the most common mineral in the core samples, could have been derived from diorite, amphibolites or andesitic volcanic rocks. Epidote is mostly derived from weakly metamorphosed rocks. Pumpellyite is present in metabasalt. Basaltic clasts with olivine and pyroxenes were rare.

4. Chemical composition

The chemical compositions of olivine and orthopyroxene were used to study provenance. They have simple structural formulae, and their compositions are represented by XMg, $100 \times \frac{Mg}{(Mg + Fe)}$, in Figs. 6 and 7.

Olivine, which was present only in the upper zone, is rich in XMg, having a roughly bimodal chemical distribution with peaks at 90 and 80. The composition ranges of olivine have been well studied in many rock types (e.g., Deer et al., 1992). Based on previous studies, olivine with an XMg of around 90 is likely to have been derived from a peridotite such as dunite, harzburgite and lherzolite, whereas XMg-poor olivine comes from volcanic rock such as basalt and basaltic andesite. At the top of the sequence, XMg-rich olivine is more abundant than XMg-poor olivine. Orthopyroxene showed a wide compositional variation, with an XMg from 92 to 54 across all samples. The major peak position of XMg was at 62 to 70, but differed from sample to sample. Mg-rich orthopyroxenes with an XMg around 90 and 80 were derived from

![Fig. 7. Compositional variation of orthopyroxene in IODP core, Frazer River and Columbia River samples. Vertical axis is shown as number of analyzed grain.](image-url)
peridotite and basalt, respectively, similar to the parental rocks of olivine. Orthopyroxene with an XMg of less than 70 was probably derived from andesitic or dacitic volcanic rocks.

5. Monazaite age

We counted 68 monazite grains in the upper portion of Unit 1 (C3H-5W) of site 1301. The age of the monazite fell into three ranges (Fig. 8); 1) abundant 200–50 Ma, 2) one grain, 700 Ma, and 3) five grains, 1800 Ma. Most fell within the 200–50 Ma range, which is similar to the granitic rocks in the Cascade Range — the western coast of the continent (Dickinson, 1981). A small peak was also present at around 1800 Ma, which reflects high-grade basement rocks of inland Western America (Gabrielse and Yorath, 1992).

6. Discussion

While both the Frazer and Columbia Rivers contain a huge amount of drainage from the Cordillera, their geological settings are very different (Fig. 9). The Frazer River drainage is one of the best places in the Cordillera to make a transect. It is divided into five tectonic belts (Wheeler et al., 1996; Reed et al., 2005), from west to east, as follows: 1) Insular belt which formed an accreted complex with an arc–trench system (Wrangellia Terrane), 2) Coastal belt which formed the Cascade Mesozoic granitoids, 3) Intermontane belt, which is a Triassic–Jurassic accreted arc–trench complex with Cretaceous granitoids, 4) Omineca belt consisting of high-grade metamorphic rock with a Proterozoic metamorphic complex containing middle Proterozoic metamorphic rocks, and 5) Cordilleran foreland belt, consisting of fold-and-thrust belts with the Belt-Purcell Supergroup of middle

![Simplified Geologic map of the Cordillera](image_url)
Proterozoic high-grade rock. In contrast, the Columbia River drainage basin has six tectonic units (Wheeler et al., 1996; Reed et al., 2005). From west to east they are: 1) Cascade active volcanic zone, which covers an accretionary complex, 2) Columbia flood basalt, which is distributed over a huge area in this drainage, 3) Intermontane belt, which is part of an accreted-arc complex, 4) Mesozoic granitoids and Miocene volcanics, 5) Belt-Purcell Supergroup, which is a middle Proterozoic continental shelf-shallow water sequence, 6) Basin and Range province. There were many Miocene to Holocene volcanoes that covered both drainages.

6.1. Modal proportions and chemical compositions

Although the modal proportions and chemical compositions of the heavy minerals in sands of the IODP cores provided information on the sands’ provenance, it was important to check the stability and dissolution of the heavy minerals, as has been noted by many researchers (Pettijohn, 1941; Morton, 1984; McBride, 1985). In a previous study of Cascadia Basin sands, Scheidegger et al. (1973) noted that the dissolution of orthopyroxene increases with increased depth. Since Pettijohn (1941) studied the stabilities of heavy minerals, olivine has been treated as one of the least resistant heavy minerals, decomposing easily via diagenetic process. In the sequence at site 1301, olivine was present only in the upper part (Fig. 5 and Table 1). The absence of olivine in the lower part was due entirely to dissolution, which is supported by the presence of orthopyroxene with $X_{Mg}=90$ in the lower part of the turbidite sequence. Olivine evidently was derived from the same or a related peridotite body consisting mainly of Mg-rich olivine and orthopyroxene. Hence, it is reasonable to conclude that olivine with $X_{Mg}=90$ was present during deposition of the sediment, even in its lower part.

Pyroxenes were almost absent in the hemipelagic sediments at the bottom of the sequence (Fig. 5). Since an etched texture developed in the lower part of the turbidite sequence (Fig. 4), and because the mineral assemblage (except for pyroxenes) was similar to that in the upper part of the turbidite sequence, we conclude that the pyroxenes in the hemipelagic sequence have been almost totally dissolved. Other minerals were not as strongly dissolved in the upper sequence.

While discussing the modal proportions of minerals in sediments, it should be noted that the proportion of a given mineral strongly depends on the specific densities of minerals and selected grain size; in general, heavy minerals enrich small-grain-size fractions. Since the grain size of silt is finer than that of sand, the modal proportions of silts may not equal those of sands. However, the specific densities of the major and common minerals treated in this study fall into a narrow range of 3.1 to 3.5. In the list of minerals in Table 1, the heavy minerals with a density of more than 4.0 are ilmenite, zircon, garnet, monazite and spinel. For the major and common heavy minerals (except ilmenite), we can use silts and sands equally well for a discussion of mineral proportions.

As shown in Figs. 6 and 7, amphibole and epidote were the most abundant minerals, while pyroxenes were present in subordinate amounts throughout the sequence. Pumppellyite and titanite were consistently present in the sequence. Although dissolution took place in the lower part of the sequence, we conclude that the mineral assemblage was not significantly altered. This is supported by analyses of light minerals and lithic fragments at nearly the same site in the Cascadia Basin by Underwood and Hoke (2000), who reported that the modal proportions were equal in most samples.

6.2. Depositional age and tectonic setting

The depositional age of the sand at the bottom of the sequence at site 1301 is Pleistocene, with an age of about 1.6 Ma according to microfossils. The Juan de Fuca Plate was converging to the northeast at a rate of about 44 km/Ma (e.g. Demets et al., 1990). The paleogeographic position of this site at 1.6 Ma ago was about 70 km southwest of its present location, about 270 km from the western coast of the continent. Since most of the sediments are much younger, and the major heavy and light minerals remain roughly constant throughout the sequence, such a dislocation is not crucial to the following discussion about the provenance of the sands.

During the high stand after 1 Ma, the sands in the Cascadia Basin were transported from the neighboring continental land-mass. Geographically, the rivers that most probably provided sands to site 1301 are the Fraser and Columbia (Figs. 1, 9). There are two reports on heavy minerals in the Cascadia Basin: site 176 by Scheidegger et al. (1973) at the mouth of the Columbia River, and site 888 by Chamov and Murdmaa (1995) near the Straits of Juan de Fuca, where the Fraser River empties through the Straits of Georgia. Since the mineral assemblage of sand in the lower part of the sequence at the drill site was altered owing to dissolution, we compared the sands from near the top of the sequence with sands collected from the rivers, assuming that the drainage system for the top samples from the dredged core was similar to the present system. Amphibole and epidote in sands at site 176 were more abundant than at sites 888 and 1301. Sands at the latter sites are similar to each other except for the modal proportions of olivine: rare at site 888 and common at site 1301. As far as modal composition is concerned, the top of the sequence at site 1301 was similar to that of sand from the Fraser River studied herein. Overall, it is probable that the sands at site 1301 came mainly from the Fraser River.

Despite the correlations between the modal proportions of sands from site 1301 and from the Fraser River, chemical analyses do not strongly reflect this correlation. For example, two peaks are present in the olivine composition of samples from both places (Fig. 6). However, the IODP samples were much richer in olivine with $X_{Mg}=90$. Such an olivine was derived from peridotite. The largest peridotite body in the Cascade Range is situated about 100 km southeast of Vancouver city (Ragan, 1967), and has an area of approximately 90 km². A river cuts through the peridotite body and transports sand towards the Straits of Juan de Fuca, but it has a different drainage basin than does the Fraser River. Sand from the Fraser River was collected at the fan delta in the city of Vancouver. Collectively, the sand in the Cascadia Basin is a mixture from many rivers sources emptying into the Straits of Juan de Fuca. Both the olivine and orthopyroxene in the peridotite body have chemical compositions with $X_{Mg}=90$. Although additional analyses of sands from the potential sources are required to determine the source of each mineral, it is probable that olivine with $X_{Mg}=90$ is more abundant in sand of the Straits of Juan de Fuca than in the fan delta at the city of Vancouver. At the top of the sequence from site 1301, X_{Mg}-rich olivine is abundant. It is probable that the peridotite body was uplifted recently and eroded widely.

On the other hand, the huge drainage area of the Columbia River contains a variety of igneous, metamorphic and sedimentary rocks, which are also provenance candidates for sands in the Cascadia Basin. Many dams have been constructed along the Columbia River. Whetten et al. (1969) described heavy minerals in the sand from dam reservoirs and found that hornblende and pyroxenes show the most variations over the length of the river. The sample for the present study was collected from weakly consolidated terrace sand along the riverside below the lowest dam, Bonneville. It may be flooding sand that was deposited prior to the dams being built. Clinopyroxene was the most abundant mineral in the sand, similar to sands from the lower dam reservoirs. Although the sand may not be representative of the river, and the modal proportions of heavy minerals from the river differ greatly from those at site 1301 (Fig. 5).

In addition, the orthopyroxene composition in the drainage basin of the Columbia River is iron-rich, and therefore it is probable that this basin is not a candidate for the provenance of sands at site 1301 (Fig. 7). The wide range in orthopyroxene composition for the sands at site 1301 implies that the Fraser River was the main source. The
position of the XMg peak in the orthopyroxene varies from sample to sample at site 1301. There are many active volcanoes along the margin of the adjacent continent. Volcanism has continued at least since the Late Pliocene and has periodically produced huge volumes of ash. Even though orthopyroxene is derived from both volcanic flows and ash falls, its contribution from ash falls would be much greater in the Cascadia Basin. As a result, the modal proportion and shifts in peak position for orthopyroxene may be related to an eruption just prior to the deposition of the sand.

Monazites from the IODP core samples have roughly three age ranges: 1) abundant, 200–50 Ma, possibly from the Cascade Mesozoic batholith, 2) minor, 700 Ma, probably from Neoproterozoic basement, and 3) some, 1800 Ma, from Mesoproterozoic high-grade basement rock in the eastern Cordillera area. The Cascade Mesozoic batholith and the Mesoproterozoic high-grade basement rocks are more widely distributed along the Fraser River than along the Columbia River. Although there is no age datum from the rivers, the variations in monazite age mentioned above support the idea that monazite in the IODP core was derived mainly from the Fraser River drainage basin.

7. Conclusions

Mineral source in sediments at the Cascadia Basin were studied by modal proportion and chemical composition of heavy minerals. Minerals were identified by X-ray EDS profile and analyses by EPMA. They are characterized by the abundance of amphibole, pyroxenes and epidote, and the presence of minerals derived from peridotite. There is no drastic change in modal and mineral compositions of the sands and silts in the turbidite and hemipelagic sequences. The following points suggest that the presumable origin of the sediments is mainly from the Fraser River drainage basin.

1) The modal proportion of heavy mineral is similar to that from the Fraser River.
2) Olivine or orthopyroxene derived from peridotite is present throughout the sequence. Huge peridotite body occurs in the Fraser River drainage basin.
3) Olivine is scarce in the Columbia River, suggesting that the river is not suitable for the drainage system for the sediment in IODP site 1301.
4) Various rock species are observed in granules in IODP site 1301. They are phyllite, meta-chert, meta-sandstone, meta-basalt and granitoids. Various tectonic units support the Fraser River as the provenance of the sediment in site 1301.

Acknowledgements

The authors are very grateful to Ms. M. Shigeoka for her help with modal and chemical analysis and heavy mineral separation. Thanks are due to Andrew T. Fisher, Tetsuro Urabe and Adam Klaus for helpful comments and suggestions on IODP EXP 301.

References
