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Characteristics of the late Quaternary tephra layers in the East/Japan Sea and their new occurrences in western Ulleung Basin sediments

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Abstract

The lithologic characteristics, stratigraphic relationships, and areal distribution of late Quaternary tephra layers have been determined based on four piston cores, recovered from the western Ulleung Basin of East/Japan Sea. The results show that, using morphological and major element compositional data, volcanic glass shards dispersed in tephra layers are identical to those of fallout deposits of the Ulleung–Oki (ca. 9.3 ka), Aira–Tanzawa (ca. 22 ka), and Ulleung–Yamato (ca. 33 ka). The lapilli tephra layers (Ulleung–Oki and Ulleung–Yamato) originating from Ulleung Island consist predominantly of pumice-type glass shards associated with minor amounts of alkali-feldspar, biotite, and plagioclase. On the other hand, the ash layers (including the Aira–Tanzawa ash) derived from the Japanese islands are mainly composed of bubble-wall and/or plane-type glasses that contain higher SiO_2 and lower Al_2O_3 than the lapilli tephra layers. The occurrence of tephra layers in the western Ulleung Basin and their stratigraphic correlation extend the distribution of pumice-type glass shards about 50–100 km west of the previously known fallout zone.

Keywords: tephra layers; glass shards; Ulleung Basin; East Sea; late Quaternary

1. Introduction

The East/Japan Sea is a marginal sea in the northwestern Pacific Ocean that is connected with the open ocean through straits with 12–140 m depths (Chough et al., 2000). Such shallow water depths of the straits imply that the East Sea has been strongly affected by glacio-marine sea-level changes during the late Quaternary, which controlled inflows of ocean water and the volume of continental runoff (Shackleton, 1987; Oba et al., 1991; Minoura et al., 1997).

The Ulleung Basin in the SW East Sea (Fig. 1) has been also affected by such paleoceanographic fluctuations, so that sediment cores from the basin generally show a lithologic change from late Pleistocene turbidites to Holocene hemipelagic muds (Lee et al., 1996; Bahk et al., 2000). Several ash layers provide a useful tool for the stratigraphic correlation of these late Quaternary turbidite and hemipelagic sediments. In the eastern Ulleung Ba-

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sin, the well-known ash layers are the Ulleung–Oki (U–Oki) and Ulleung–Yamato (U–Ym) layers erupted from the Nari Caldera of Ulleung Island about 9.3 ka and 33 ka, respectively (Arai et al., 1981; Machida and Arai, 1983; Oba et al., 1991). Another prominent ash layer is the Aira–Tanzawa (AT) ash layer, which was erupted from the Aira Caldera in southern Kyushu Island about 22 ka (Fig. 1; Machida and Arai, 1992).

However, little is known about the mineral composition and occurrence of tephra layers in the western Ulleung Basin. Moreover the western limits of U–Oki and U–Ym tephra layers have not yet been defined. Therefore, the present study focuses on investigating the tephra deposits found in piston cores drilled from the western Ulleung Basin. In particular, the purpose of the present study is: (1) to document the lithologic characteristics of the tephra layers, (2) to analyze the major element compositions of volcanic glasses found in the tephra layers, and (3) to determine the stratigraphic relationships of the tephra layers. Finally, possible areal distribution and minimum limit of the tephra layers in the western Ulleung Basin are suggested and then discussed.

2. Material and analytical methods

In the East Sea, there are three main basins, the Japan, Yamato, and Ulleung basins. Among these main basins, the Ulleung Basin is located in the southwestern part of East Sea, surrounded by continental slopes of the Korean Peninsula and southwestern Honshu Island, and by the volcanic islands Ulleung, Dok and Oki (Fig. 1; Chough et al., 2000). Four piston cores were obtained from this Ulleung Basin during the Korea Institute of Geoscience and Mineral Resources' 2001 Survey for their study on gas hydrates (Fig. 1). These cores, along with three piston cores collected from the southwestern part of Ulleung Basin in 2000, were used in this study (Fig. 1).

In the laboratory, the cores were cut: one half of each core was preserved as an archive core, the other half was further processed. In the cores, tephra layers were recognized by direct observations with a hand lens and then confirmed by microscopic observations on washed samples (> 63 μm) prepared for micropaleontologic analysis.

The glass shards from each tephra layer were observed with a scanning electron microscope (SEM) to classify volcanic glass shards according to their shape and surface texture. Major element compositions of volcanic glasses were analyzed on individual glass shards with an energy-dispersive X-ray analyzer (SEM-EDX). The glass analyses totalled ca. 92–98%, with the deficiency mainly due to secondary hydration; thus, the analyses were normalized to 100% for comparative purposes (Table 1). The goal of the geochemical analyses was to correlate the shards either to the well

Table 1
Average compositions of volcanic glass shards obtained in the study cores

Tephra layer	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	K_2O	Na_2O	Reference
U–Oki	62.60	0.48	20.64	2.70	0.15	0.25	1.51	6.68	4.99	Machida and Arai (1992)
	64.96	0.31	19.09	1.61	0.26	0.26	1.01	7.53	5.10	Park et al. (2002)
	63.78	0.37	19.16	2.21	0.11	0.21	1.16	5.92	7.08	This study
	(1.88)	(0.20)	(0.79)	(1.20)	(0.10)	(0.23)	(0.52)	(1.49)	(1.71)	
U–Ym	65.25	0.14	19.38	0.87	0.06	0.09	0.86	7.01	6.34	Ryu et al. (2001)
	63.82	0.13	19.13	2.00	0.16	0.10	0.76	5.15	8.75	This study
	(2.32)	(0.12)	(0.35)	(1.62)	(0.15)	(0.10)	(0.31)	(1.03)	(1.70)	
AT	78.99	0.15	12.30	1.15	0.03	0.15	0.99	3.24	3.00	Machida and Arai (1992)
	77.53	0.31	12.09	1.99	0.15	0.22	1.43	3.37	2.91	Park et al. (2002)
	75.80	0.14	13.61	1.03	0.10	0.13	0.68	4.48	4.03	This study
	(4.96)	(0.12)	(3.11)	(0.54)	(0.11)	(0.13)	(0.31)	(3.76)	(2.28)	
AL	76.64	0.17	13.12	1.15	0.06	0.09	0.84	4.36	3.58	This study
	(4.00)	(0.14)	(2.19)	(0.46)	(0.08)	(0.12)	(0.32)	(3.04)	(1.28)	

Key: U–Oki, Ulleung–Oki; U–Ym, Ulleung–Yamato; AT, Aira–Tanzawa ash; AL, other ash layers. Analyses presented as a mean and standard deviation (in brackets). Normalized to 100% on a volatile-free basis. Total Fe expressed as FeO.

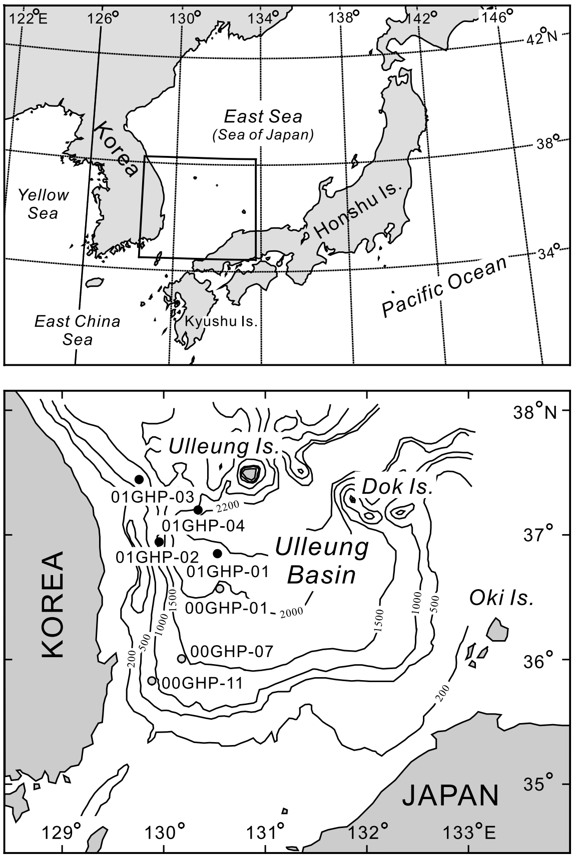

Fig. 1. Bathymetry of the Ulleung Basin of the East Sea and location of piston cores. Closed circles indicate study cores, gray circles are cores referenced in the literature (Park et al., 2002; Kim et al., 2003).

documented Ulleung eruptions or to other known tephra layers that originated from Japan.

3. Results

3.1. Sedimentary facies in the cores

The cores consist predominantly of olive gray to dark olive gray (5GY 5/1–5GY 4/1 after Standard Soil Color Charts by Oyama and Takehara, 1989) hemipelagic and turbidite muds that are partly interbedded with volcanic layers (Fig. 2). The hemipelagic facies is mainly dominated by bioturbated and crudely laminated muds. The thick turbidite sequences include thinly laminated mud, homogeneous mud, and laminated sandy silt (Bahk et al., 2000). According to the vertical distribution of the sedimentary facies, the upper and lower parts of the cores are dominated by the hemipelagic facies, whereas the fine-grained turbidite facies is mainly present in the middle part of the cores (Park et al., 2002), except for core 01GHP-03 which has an additional turbidite facies at depth (Fig. 2).

The fine-grained sediments in the cores are largely subdivided into four mud facies: laminated mud, homogenous mud, bioturbated mud, and crudely laminated mud. In the laminated mud facies, laminae are mostly less than a few mm thick and consist of silt–clay couplets. Among them, the silt laminae mainly consist of several kinds of microfossils (e.g. planktonic foraminifera and diatoms) and terrigenous material such as quartz, plagioclase, alkali-feldspar, and biotite flakes. In the cores, this facies usually occurs with the homogenous mud facies. The bioturbated mud facies is characterized by some burrow structures (circular to oval tube cross-sections). The thickness of the bioturbated facies is highly variable (a few cm to nearly 1 m). In the crudely laminated mud facies, laminae are less sharp and more irregular than those in the laminated mud facies. Particularly this facies is characterized by poorly sorted mud and commonly contains well-preserved planktonic foraminifera.

3.2. Tephra layers and their geochemistry

A total of 5 lapilli tephra and 16 ash layers occur in the study cores (Fig. 2). These volcanic layers range in thickness from 3 mm to several cm. Fig. 3 shows the three main morphologies of glass shards found in the cores. These morphologies are: (A) pumice-type (Fig. 3A), (B) very thin- and plane-type (Fig. 3B), and (C) bubble-wall glass shards (Fig. 3C). The pumiceous glasses are mostly translucent to pale brown, while the plane-type or bubble-walled flakes of tephra are almost transparent and very thin.

The chemical compositions of the glass shards in the cores are very similar to those of shards that occur in cores from the eastern Ulleung and Yamato basins (Furuta et al., 1986; Machida

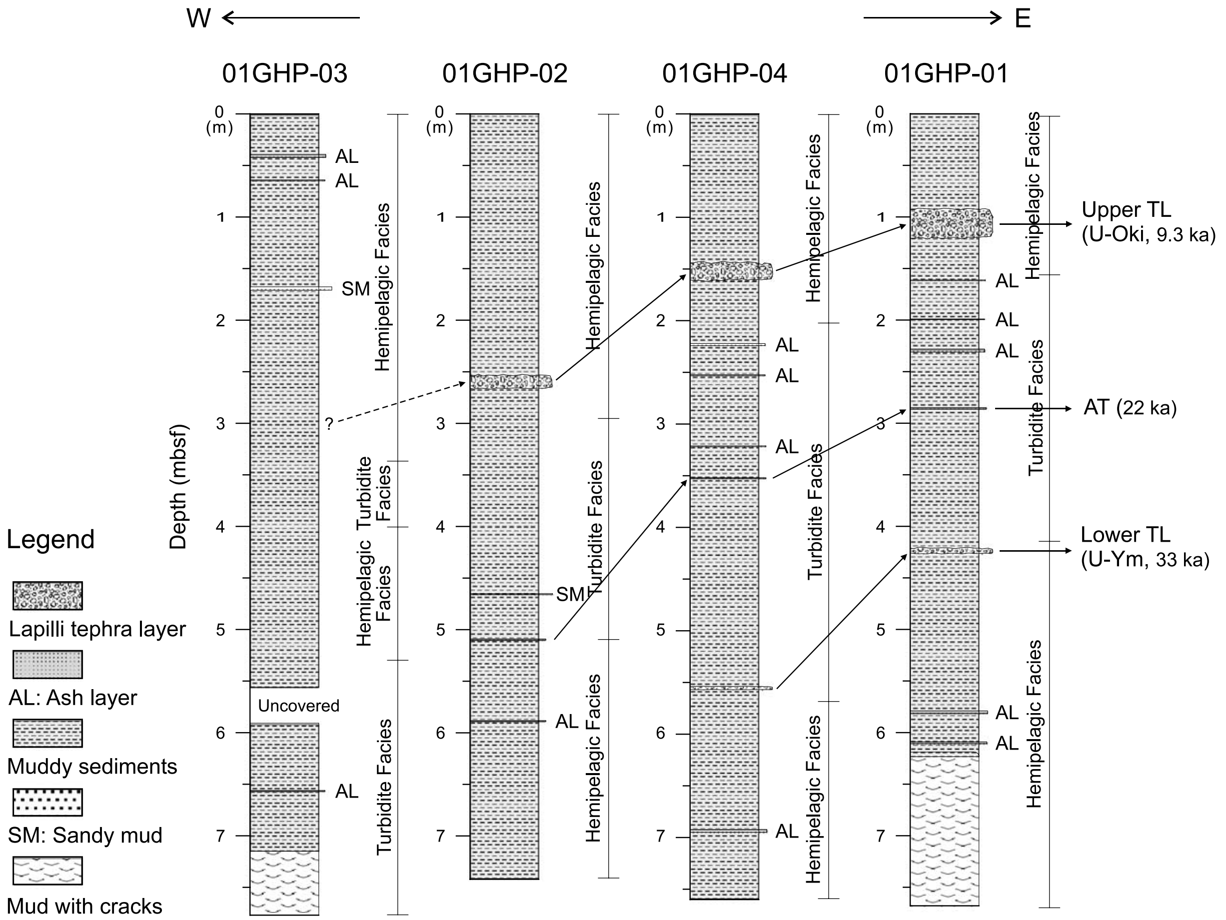

Fig. 2. Distribution of mud facies and interbedded volcanic layers in the cores (key: TL, lapilli tephra layer) and inferred tephrochronologic correlation using tephra layers of core sediments (key: U–Oki, Ulleung-Oki; U–Ym, Ulleung–Yamato; AT, Aira–Tanzawa ash). ^{14}C ages of tephra layers are taken from Machida and Arai (1983, 1992).

and Arai, 1992). The lapilli tephra layers in the study cores consist predominantly of pumice-type shards associated with minor amounts of alkali-feldspar, biotite, and plagioclase. The shards have high alkali contents (Na_2O+K_2O = average 12.2 wt%) and relatively high FeO (average 2.15 wt%) (Table 1). Thus, the chemical compositions of the lapilli tephra layers are alkaline (Fig. 4A), with a prevailing sodic character (Fig. 4B).

In contrast, the ash layers, mainly consisting of plane-type and/or bubble-wall glass shards, have 5–11 wt% alkalis (average 8.1 wt%) and 0.5–1.6 wt% FeO (average 1.12 wt%) (Table 1). Another characteristic chemical feature of the ash layers is their high content of SiO_2, ranging from 75 to 80 wt% (Fig. 4A). The content of Al_2O_3 also shows a conspicuous difference between the lapilli tephra and ash layers, averaging 19 and 13 wt%, respectively (Table 1).

3.3. Tephrostratigraphic correlation of the cores

The morphologies and major element compositions of glass shards from the lapilli tephra layers suggest that the upper and lower lapilli tephra layers (Upper and Lower TL in Fig. 2) are equivalent to the tephra layers that originated from Ulleung Island (Machida and Arai, 1992; Chun et al., 1998; Ryu et al., 2001; Park et al., 2002). In addition, such high alkali contents (12.2 wt%)

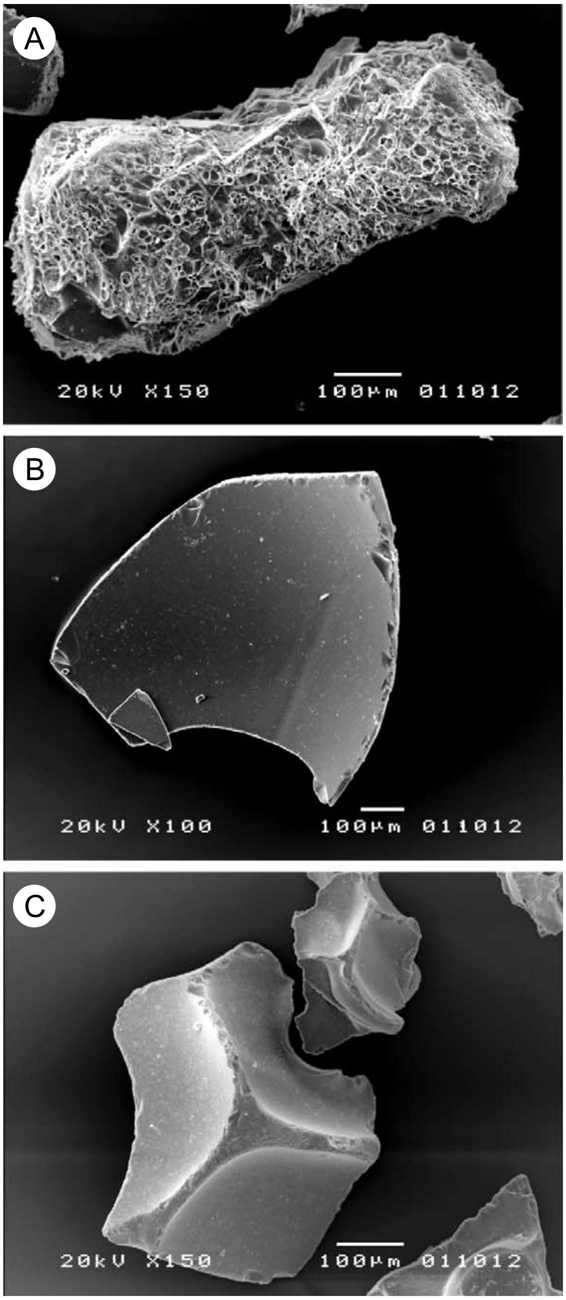

Fig. 3. SEM microphotographs of representative volcanic glass shards. (A) Frothy glass shard from the lower unit of Ulleung–Oki tephra layer. (B) Very thin- and plane-type glass shard showing smooth and slightly curved surface from the Aira–Tanzawa ash layer. (C) Bubble-wall glass shards from the Aira–Tanzawa ash layer.

have not been found in any other tephra layer originating from the Japanese islands (Furuta et al., 1986). Furthermore, their vertical distribution and facies boundaries in the cores suggest that the upper and lower lapilli tephra layers are actually identical to the U–Oki and U–Ym tephra layers, respectively (Fig. 2). Although the chemical composition of glass shards in both the upper and lower lapilli tephra layers is very similar (Fig. 4), the upper lapilli tephra layer (U–Oki) is characteristically subdivided into upper and lower units, in which the lower unit is usually thicker and contains more lithic fragments and coarse lapilli than the upper unit. These two units of the upper lapilli tephra layer are characteristic of the U–Oki tephra layer in the Ulleung Basin. The age of this U–Oki tephra layer is estimated to be about 9.3 ka by ^{14}C dating of associated organic sediments, whereas the ^{14}C age of the U–Ym tephra layer is approximately about 33 ka (Machida and Arai, 1983; Oba et al., 1991).

In the cores, 2–4 ash layers are found between the U–Oki and U–Ym tephra layers (Fig. 2). If the average sedimentation rates between the U–Oki and U–Ym tephra layers (12–17 cm/kyr) are considered, the ash layers found at core depths of 285–286.5 cm (core 01GHP-01) and 352–352.4 cm (core 01GHP-04) correspond approximately to the age of the AT ash layer (22 ka BP; Machida and Arai, 1983). Our SEM observations also suggest that these ash layers, including the ash in core 01GHP-02 (core depth 504–506.5 cm), are correlative with the previously known AT ash layer (Machida and Arai, 1992; Eden et al., 1996; Chun et al., 1998). The AT ash layer is usually very fine-grained and contains more than 95% of plane-type and bubble-wall glass fractions in the whole material (>63 μm) (Arai et al., 1977; Machida and Arai, 1983, 1992).

The other ash layers found in the cores (AL in Fig. 2) are compositionally similar to the AT ash layer (Table 1). Thus it is likely that both the AT and the other ash layers were derived from the Japanese islands (Machida and Arai, 1992). However, these ash layers, compared to the AT ash, lack typical plane-type glasses and contain somewhat more bubble-wall glass shards and lithic fragments. Thus, it was possible to discriminate

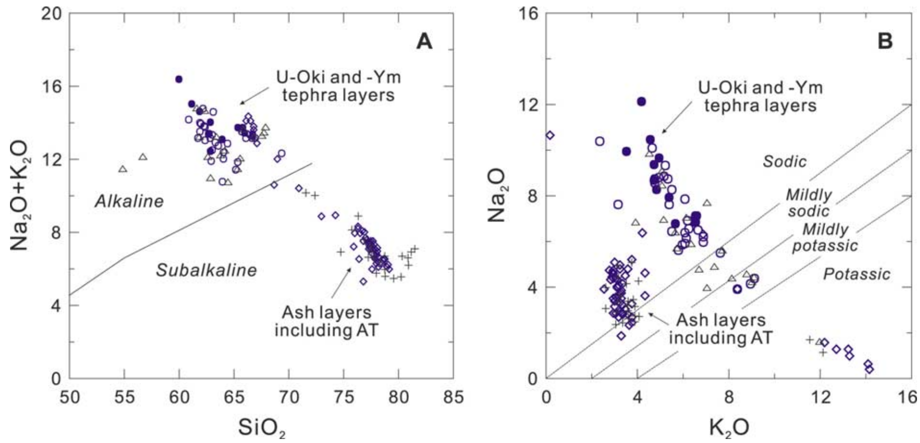

Fig. 4. (A) Alkaline vs. SiO_2 diagram indicating the alkaline affinity of the Ulleung–Oki (U–Oki, closed circles) and Ulleung–Yamato (U–Ym, open circles) tephra layers derived from Ulleung Island. (B) Na_2O vs. K_2O diagram indicating the prevailing sodic to mildly potassic character of the U–Oki and U–Ym layers (key: AT, Aira–Tanzawa ash layer). Open triangles and cross shapes represent the data of the Ulleung and AT tephras from the previous studies, respectively (Machida and Arai, 1992; Ryu et al., 2001; Park et al., 2002).

between the AT and the other ash layers in the cores.

4. Discussion

As mentioned above, the U–Oki tephra layer is present in the three cores 01GHP-01, 01GHP-02, and 01GHP-04, whereas the U–Ym tephra layer is found in only two cores, i.e. 01GHP-01 and 01GHP-04. However, no tephras originating from Ulleung Island were found in core 01GHP-03 (Fig. 2) which is located in the northwesternmost part of the Ulleung Basin (Fig. 1). Nevertheless, the possible depth of the U–Oki tephra in core 01GHP-03 can be presumed using the facies distribution pattern, because in cores 01GHP-01, 01GHP-02, and 01GHP-04, the U–Oki tephra layer usually occurs near the base of the hemipelagic facies (Fig. 2).

According to Machida et al. (1981, 1984) and Machida and Arai (1992), the U–Oki tephra layer is found in the southern part of the East Sea and also in central Japan (Kinki and Sanin provinces on Honshu Island) including Lake Biwa (Fig. 5). Therefore, the previously known fallout distribution suggests a predominant NW wind regime. The occurrence of the U–Oki and U–Ym tephra layers in the four study cores and the three reference cores (Park et al., 2002; Kim et al., 2003) indicates that the known fallout distribution of coarse glass shards (>63 μm) can be extended to the west about 50 km for the U–Ym tephra and about 100 km for the U–Oki tephra (Fig. 5). This implies that the late Quaternary Ulleung eruptions at about 9.3 ka and 33 ka were somewhat greater than previously estimated (see Machida and Arai, 1992; Chun et al., 1997). However, additional studies, especially in the southern area of the Ulleung Basin and the western Japanese islands, are necessary to completely define the western limits of the U–Oki and U–Ym tephra layers.

5. Conclusions

(1) The study cores consist predominantly of hemipelagic and turbidite mud facies that are partly interbedded with lapilli tephra and ash layers.

(2) A total of 21 lapilli tephra and ash layers occur in the study cores. The glass shards found in the tephra layers exhibit three main morphologies: pumice-type, very thin- and plane-type, and bubble-wall glass shards.

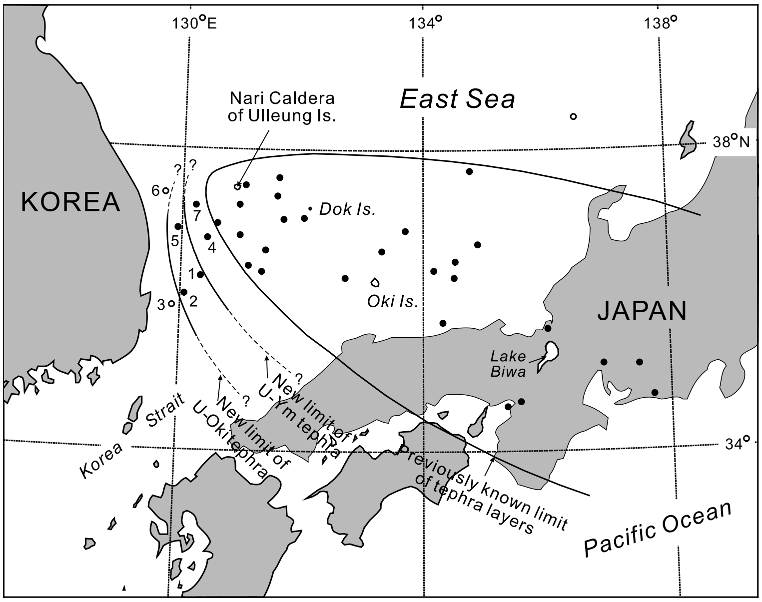

Fig. 5. Map showing the previously known distribution of fallout from the Ulleung eruption and the new minimum limits of Ulleung–Oki (U–Oki) and Ulleung–Yamato (U–Ym) tephra layers in the East Sea (key: 1, 00GHP-01; 2, 00GHP-07; 3, 00GHP-11; 4, 01GHP-01; 5, 01GHP-02; 6, 01GHP-03; 7, 01GHP-04). Closed circles indicate cores with the U–Oki tephra layer, open circles cores without the U–Oki tephra layer. Reference cores from Chough (1982), Oba et al. (1991), Machida and Arai (1992), Lee et al. (1996), Minoura et al. (1997), Bahk et al. (2000, 2001), Gorbarenko and Southon (2000) and Kim et al. (2003).

(3) The upper and lower lapilli (U–Oki and U–Ym) tephra layers consist mainly of pumice-type glass shards associated with minor amounts of alkali-feldspar, biotite, and plagioclase. Glass shards in these tephra layers contain a high alkali content (average 12.2 wt%) and a relatively large amount of FeO (average 2.15 wt%). The ash layers, however, consist mainly of plane-type and/or bubble-wall glass shards. They contain an average of 8.1 wt% total alkalis and an average of 1.12 wt% FeO, and characteristically have higher SiO_2 contents and lower Al_2O_3 contents than the lapilli tephra layers.

(4) In the cores, the U–Oki (9.3 ka), AT (22 ka), and U–Ym (33 ka) tephra layers were recognized based on morphologies and major element composition of glass shards as well as other petrographic features. Sedimentation rates in the western Ulleung Basin were relatively high, ranging from 12.1 cm/kyr between the AT and U–Ym tephras in core 01GHP-01 to 19.3 cm/kyr between the U–Oki and AT tephras in core 01GHP-02.

(5) Correlation of the Ulleung tephra layers in the western Ulleung Basin extends their known distribution 50–100 km to the west.

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