

Research paper

Biostratigraphy of the Ulleung Basin, East Sea (Japan Sea)

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ABSTRACT

An interpretation of both micropaleontological and palynological analyses was carried out for eleven wells from the Ulleung Basin, East Sea (Japan Sea). Based on bioevents of microfossil groups (calcareous nannofossils, foraminifera, diatoms, dinocysts, spores and pollen) twenty-three datums are established. The biostratigraphic and paleoenvironmental data indicate significant tectonic events such as subsidence (17 Ma), closing of the Korea Strait (15 Ma), and uplift in Dolgorae deformed region (12.5–10.2 Ma) of the basin. The high resolution sequence biostratigraphy, correlated with wireline log and seismic data, provided to be effective for constraining the interpretation of depositional systems tracts of the basin. The Paleogene reworked taxa in Neogene section suggest that the provenance of sediments of the basin was southern offshore basins of Korea, and/or south-western Japan (Kyushu area) and the Fukue Basin.

1. Introduction

Numerous wells were drilled in the Ulleung Basin, western part of the East Sea (Japan Sea) for the purpose of hydrocarbon exploration. These exploration wells extended near the basin bottom, although they did not reach lowermost sediments of basin rifting and basement rocks (Figs. 1 and 5). The thick marine sediments of the wells yielded abundant calcareous, siliceous, and organic microfossils enabling fine biostratigraphic zonation as well as stratigraphic and chronological divisions (Figs. 2 and 3). Stratigraphic correlation between the wells and paleo-environmental changes recognized from microfossil data. Seismic surveys were also intensively carried out across the wells for well correlation. Tectonics and depositional evolution were reconstructed based on seismic reflection profiles.

Biostratigraphy has been used in sequence stratigraphic studies principally to interpret local depositional cycles and to compare with regional frameworks (Haq et al., 1988). The fossil abundance patterns are very useful for constraining the interpretation of depositional systems tracts. Fossil abundance peaks are used to identify condensed sections and abundance minima are good indicators for sequence boundaries (Armentrout, 1996, Fig. 4). These varying abundance patterns of microfossils are considered to be closely related to depositional environments controlled by relative sea level changes which suggest positive applicability of biostratigraphy in sequence stratigraphy in the Ulleung Basin. Many characteristic abundance variations of microfossils

are observed in sediments of the basin, especially in marine fossil contents. The foraminifera and dinocysts assemblages contained age diagnostic species which are able to give precise geologic ages for depositional events.

Interpretation of depositional cycles from seismic reflection has become a major research topic since the introduction of sequence stratigraphy. Depositional cycles are determined using seismic reflection profiles in the basin. However, age control often remains controversial or only long-term cycles are able to be determined.

When biostratigraphy is integrated with seismic reflection and wireline log data, it is highly effective in establishing the high-resolution bio-stratigraphic sequence stratigraphy and depositional frameworks of the basin (Fig. 5). This study focuses on the contribution of biostratigraphy to sequence stratigraphy. It also aims to clarify the evolution of tectonic events of the East Sea (Japan Sea) by methodology of fine zonation of sediments, age control of depositional events, and variation of organic world in depositional systems tracts.

2. Material and methods

The samples studied for biostratigraphy were the ditch cuttings collected every 10–30 m intervals from eleven wells (Gorae 1, Gorae 1–2, Gorae V, Gorae VII-1X, Dolgorae I, Dolgorae II, Dolgorae IIA-1X, Dolgorae III-1, Dolgorae III-2, Dolgorae VII, and Hongge-1) drilled in the Ulleung Basin (Fig. 1). Sidewall cores and conventional cores were

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also processed if they were available.

The stratigraphic surfaces including sequence boundary and maximum flooding surface were interpreted based on the abundance patterns of dinocysts, foraminifera, diatom, and spore and pollen. For correlating sequence biostratigraphic analysis in basin-wide, seismic and well log sequence stratigraphic analyses were also conducted on the basis of seismic-reflection terminations and log-motif patterns, respectively, on the regional sections along eleven wells (Fig. 1).

3. Results and discussion

3.1. Micropaleontology

3.1.1. Calcareous nannofossils

Calcareous nannofossils are rich in Plio-Pleistocene succession, but rare to barren in Miocene sediments. Age diagnostic taxa of Pleistocene are *Calcidiscus macintyreii* (Last Appearance Datum (LAD): 1.60 Ma [NN19; CN13b]), *Gephyrocapsa* spp. (>4 μm) (First Appearance Datum (FAD): 1.73 Ma [NN19; CN13b/CN13a]), and *Discoaster brouweri* (LAD: 1.93 Ma [NN19/NN18; CN13a/CN12d]). Pliocene index species are *Spinolithus* spp. (subtop) (LAD: 3.54 Ma [NN16; CN12a]). Age indicator species for Miocene are *Discoaster brouweri* (FAD: 10.76 Ma [NN8; CN6]), *Coccolithus miopelagicus* (LAD: 10.97 Ma [NN7; CN5b]), *Cyclacargolithus floridanus* (LAD: 11.85 Ma [NN7; CN5b]), *Coronocyclus nitescens* (LAD: 12.12 Ma [NN6; CN5a]), *Reticulofenestra pseudumbilica*

(FAD: 12.83 Ma [NN6; CN5a]), *Cyclacargolithus floridanus* (LAD common: 13.28 Ma [NN6; CN5a]), *Calcidiscus macintyreii* (FAD: 13.36 Ma [NN6; CN5a]) (Table 1).

Based on calcareous nannofossils biozonation of Martini (1971) and Okada and Bukry (1980) biozones of the basin are established from bottom to top as followings; Rare to Barren Zone (Miocene), NN13–NN15 (CN10c–CN11b) Zone (5.3–3.6 Ma), NN16 (CN12a–b) Zone (3.6–2.58 Ma), and NN17–NN19 (CN12c–CN14a) Zone (2.58–1.2 Ma).

In some drilled wells of the basin Paleogene specimens are found in the Miocene sediments as a result of reworking processes. In well Gorae I, Micro-Strat Inc (1994) reported that Paleogene aff. ?*Markalius*, *Discoaster subloboensis*, *Discolithina* cf. *distincta*, *Fasciculithus* cf. *involutus* in the lower part of the well and regarded these depths as Upper Paleocene–Lower Eocene. Rexilius and Powell (2016) reported reworked specimens of Early/Middle Eocene species of *Discoaster diastypus* at the depth of 3720/25m in Hongge-1 well. According to foraminifera, dinocysts, spores, and pollen in this study, however, these fossils are reworked ones and the sections are Middle Miocene. The Paleogene specimens are considered to be transported from neighboring area such as southwestern Japan (Kyushu area) or the Fukue Basin and the Cheju Basin (offshore southern Korea), where Paleogene sediments are well developed.

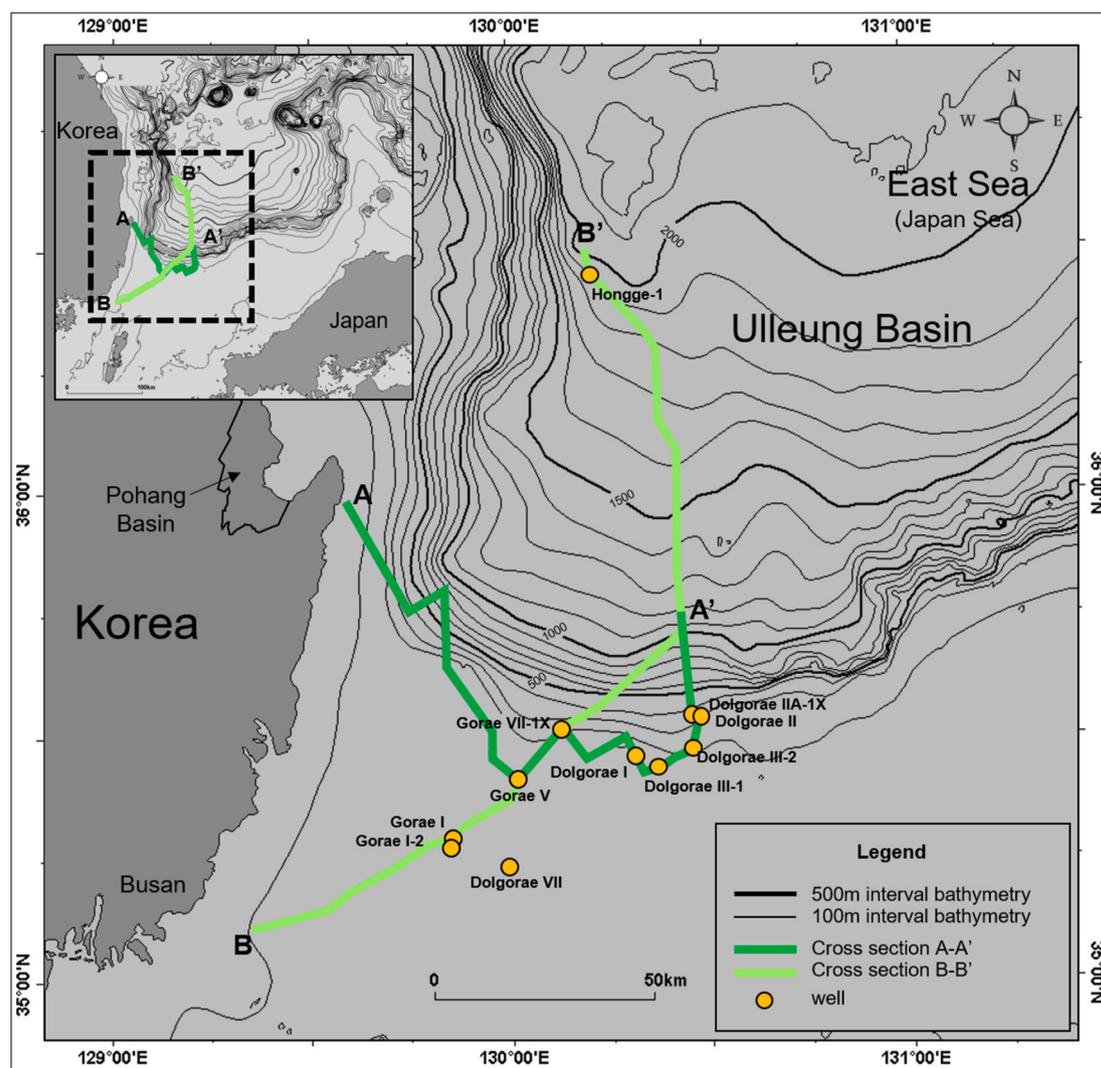


Fig. 1. Location map of the study area with well locations. See Fig. 5 for cross sections A-A' and B-B'.

3.1.2. Foraminifera

Calcareous foraminifera are abundant in the upper part of the wells, whereas arenaceous deep sea assemblages occur constantly in the lower depths. The low abundance of calcareous benthonic and planktonic taxa is probably due to a cool-water, restricted-circulation depositional setting (Nomura, 1992).

Useful age-indicators of planktonic foraminifera species found in the wells are *Globorotalia truncatulinoides* (FAD: 2.58 Ma [N21; PL5]), *Sphaeroidinellopsis seminulina* (LAD: 3.59 [N19-20; PL4/3]), *Spirosignolinella compressa* (LAD: 3.6 Ma [N19-N20; PL4/PL3]), *Neogloborotalia acostaensis* (Trans dext.-sinis) (Coiling change: 6.77 Ma [N17a; M13b]), *Neogloboquadrina acostaensis* (FAD: 10.6 Ma [N14; M11]), *Neogloboquadrina pseudopachyderma* (FAD: 11.7–12.6 [12.3] Ma [N12; M9b]), and *Globorotalia peripheroronda* (LAD: 12.8–14.6 [13.0] Ma [N12; M9b]) (Table 2). Arenaceous types such as *Cyclammina ezoensis*, *Spirosignolinella compressa* and *Martinotiella communis* are common in the Miocene sediments of the Ulleung Basin, Yamato Basin and Japan Basin indicating middle bathyal or deeper environment (Kato, 1992; Nomura, 1992).

Foraminiferal biozonation established by faunal change of foraminifera is strongly related to facies showing locally diachronous zonal boundary from neritic to bathyal area as a result of marine transgression or regression (Fig. 3). Foraminiferal biozones of the Gorae region representing shallow marine sedimentary deposit are classified into *Martinotiella communis* Zone (17–15 Ma; slope–outer shelf), Rare to Barren Zone (15–5.3 Ma; inner shelf–coastal) from bottom to top. The so-called Dolgorae deformation region is characterized by following foraminiferal biozones; *Cyclammina japonica* Zone (15–14 Ma; basin floor), *Martinotiella communis* Zone (14–10.2 Ma; slope–outer shelf), Rare to Barren Zone (10.2–5.3 Ma; coastal–inner shelf), *Cassidulina laevigata* Zone

(5.3–2.58 Ma; inner–middle shelf), and *Globorotalia truncatulinoides* Zone (2.58–1 Ma; middle–outer shelf) in ascending order (Lee, 1994) (Figs. 2 and 3).

Age diagnostic taxa and faunal abundance patterns of foraminifera suggest that the Dolgorae deformed region is tectonically characterized by unconformities or hiatus between 12.5 Ma and 10.2 Ma. The geologic age of the unconformities varies from 12.5 Ma to 10.2 Ma according to the positions of wells on the subsurface-anticlinal structures. Especially the compressional regime is distinct and results in environmental change from basin floor–slope to coastal–inner shelf based on drastic reduction of abundance of arenaceous assemblages of foraminifera. In the Gorae undeformed region, these unconformities are weakly developed compared to the Dolgorae region. The Gorae region of shallow environments was changed from slope–outer shelf to inner shelf–coastal at 15 Ma referring consistent occurrence of arenaceous assemblage of forams and relatively abundant dinocysts. The shallowing after 15 Ma seems to be caused by compressional tectonic setting related to blocking of the Korea Strait. By the horizon of 17 Ma in the well Dolgorae VII arenaceous assemblage of foraminifera begin to occur consistently as marine dinoflagellate first appeared abundantly 17 Ma in the Pohang Basin, SE Korea (Byun, 1995, Fig. 1).

3.1.3. Diatoms

In the Ulleung Basin siliceous microfossils and diatoms are generally abundant in Plio-Pleistocene successions, while they are rare to barren in Miocene. Useful age diagnostic taxa are *Thalassiosira antiqua* (FAD: 5.6–7.0 Ma; LAD: 2.1–2.7 Ma), *Thalassiosira convexa* (FAD: 2.9–3.9 Ma; LAD: 2.3–2.6 Ma), *Neodenticula seminae* (FAD: 2.6 Ma), *Neodenticula kamschatica* (FAD: 6.6 Ma, 7.4 Ma; LAD: 2.5–2.9 Ma; Last Common (LC): 2.61–2.68 Ma), and *Thalassiosira oestrupii* (FAD: 5.10 Ma, 5.49 Ma)

Age (Ma)	Period	Epoch	Age/Stage	Foraminifera Zone Ulleung Basin LEE (1994)	Dinocyst Zone Ulleung Basin Byun (1995)	Pollen Zone Ulleung Basin KIER (1988)		Pollen Zone Japan & Yamato Basins Yamanoi (1992)
						Zone A Taxodiaceae-Fagus Zone	Zone B Carya - Liquidambar Zone	
0-25	Quat.	Pleistocene	M-L	Tarantian to Gerasian	<i>Globorotalia truncatulinoides</i> Zone	<i>Filissphaera filifera</i> Zone	Zone A1 <i>Metasequoia</i> Subzone	
			E					
	Neogene	Pliocene	L	Piacenzian	<i>Cassidulina laevigata</i> Zone	<i>Spiniferites ellipsoideus</i> Zone	Zone A2 <i>Fagus</i> Subzone	
			E	Zanclean	Rare to barren Zone			
			Late	Messinian	Rare to barren Zone			
				Tortonian				
		Miocene	Middle	Serravallian	<i>Martinotiella communis</i> Zone	<i>Systematophora placantha</i> Zone	Zone B Carya - Liquidambar Zone	
				Langhian	<i>Cyclammina japonica</i> Zone			
			Early	Burdigalian	Rare to barren Zone			
				Aquitanian				
Paleogene	Oligocene	Late	Chattian	Zone C Pinaceae - Taxodiaceae Betulaceae - Ulmaceae Zone	Zone C Pinaceae - Taxodiaceae Betulaceae - Ulmaceae Zone			
		Rupelian						

Fig. 2. Comparison of biozonations for onshore and offshore basins of Korea and Japan.

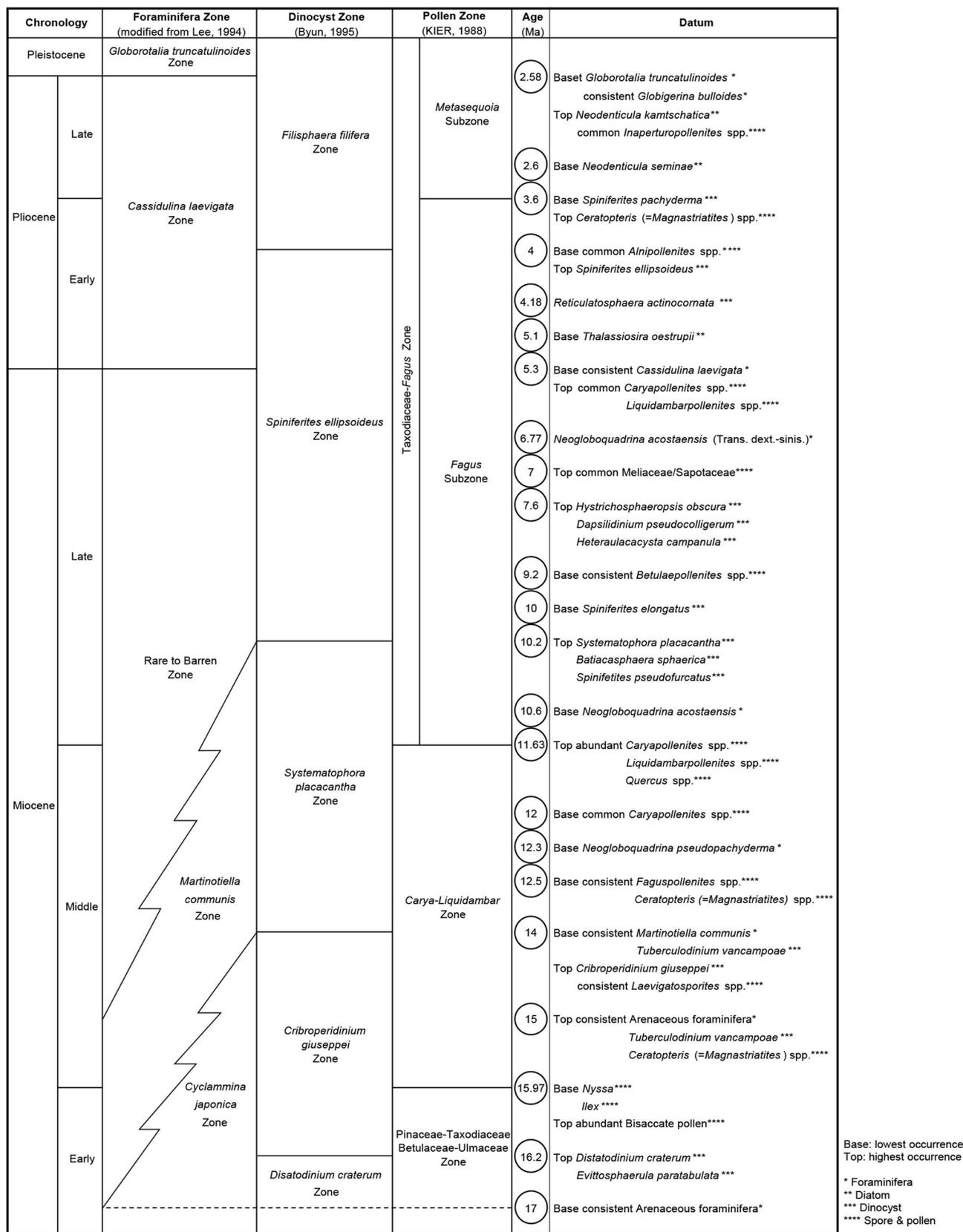


Fig. 3. Micropaleontological and palynological zones of the Ulleung Basin with bioevents.

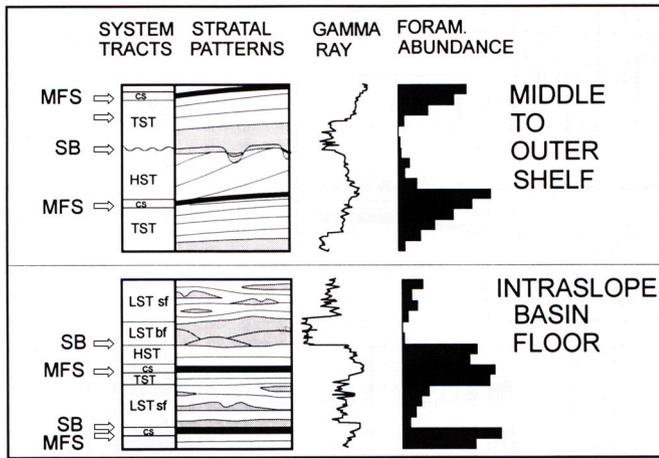


Fig. 4. Schematic illustration of possible systems tracts and stratal pattern interpretations based on wireline log gamma ray and well-cutting foraminiferal abundance for the Mobil well A158-1 (Armentrout, 1996).

(Table 3).

Biozonation of diatoms after Koizumi et al. (2009) is established from bottom as followings; Rare to Barren Zone (Miocene), *Neodenticula kamschatica* Zone (7.4–5.49 Ma), *Thassiosira oestrupii* Zone (5.49–3.53–3.95 Ma), *Neodenticula koizumii* - *Neodenticula kamschatica* Zone (3.53–3.95–2.61–2.68 Ma), *Neodenticula koizumii* Zone (2.61–2.68–2.0 Ma), and *Actinocyclus oculatus* Zone (2.0–1.01–1.46 Ma).

3.1.4. Dinocysts

Organic-walled dinoflagellate cysts are diverse and abundant through the all wells of the basin enabling precise biozonation based on

Table 1
Calcareous nannofossil bioevents for the wells in the Ulleung Basin.

Datum	Age
T <i>Calcidiscus macintyre</i>	1.60 Ma ^a (NN19; CN13b)
B <i>Gephyrocapsa</i> spp. (>4 mm)	1.73 Ma ^a (NN19; CN13b/CN13a)
T <i>Discoaster brouweri</i>	1.93 Ma ^a (NN19/NN18; CN13a/CN12d)
T <i>Sphenolithus</i> spp. (subtop)	3.54 Ma ^a (NN16; CN12a)
T <i>Reticulofenestra pseudumbilica</i>	3.70 Ma ^a (NN16/NN15; CN12a/CN11b)
B <i>Discoaster brouweri</i>	10.76 Ma ^a (NN8; CN6)
T <i>Coccolithus miopelagicus</i>	10.97 Ma ^a (NN7; CN5b)
T <i>Cyclicargolithus floridanus</i>	11.85 Ma ^b (NN7; CN5b)
T <i>Coronocyclus nitescens</i>	12.12 Ma ^a (NN6; CN5a)
B <i>Reticulofenestra pseudumbilica</i>	12.83 Ma ^b (NN6; CN5a)
Top common <i>Cyclicargolithus floridanus</i>	13.28 Ma ^a (NN6; CN5a)
B <i>Calcidiscus macintyre</i>	13.36 Ma ^b (NN6; CN5a)

T: Top/Highest occurrence; B: Base/Lowest occurrence; NN: Zonation by Martini (1971); CN: Zonation by Okada and Bukry (1980).

^a Lourens et al. (2004).

^b Hilgen et al. (2012).

FAD and LAD of index taxa.

Important index dinocysts are *Spiniferites pachyderma* (FAD: 3.6 Ma), *Spiniferites ellipsoideus* (LAD: 4.0 Ma), *Reticulatosphaera actinocornata* (LAD: 4.18 Ma), *Spiniferites* cf. *pseudofurcatus* (LAD: 4.18 Ma), *Dapsilodinium pseudocolligerum* (LAD: 7.4 Ma, 7.6 Ma), *Hystrichosphaeriopsis obscura* (LAD: 7.4 Ma, 7.54 Ma, 7.6 Ma), *Heteraulacacysta campanula* (LAD: 7.4 Ma, 7.6 Ma), *Spiniferites elongates* (FAD: 10 Ma), *Batiacapsphaera sphaerica* (LAD: 10.2 Ma), *Spiniferites pseudofurcatus* (LAD: 10.2 Ma), *Systematophora placacantha* (LAD: 10.2 Ma), and *Cribroperidinium giuseppi* (LAD: 14 Ma), *Distatodinium craterum* (LAD: 16.2 Ma), *Evittosphaerula paratabulata* (LAD: 16.2 Ma) (Table 4).

Dinocysts biozones established for onshore and offshore sediments are *Distatodinium craterum* Zone (17–16.2 Ma), *Cribroperidinium giuseppi*

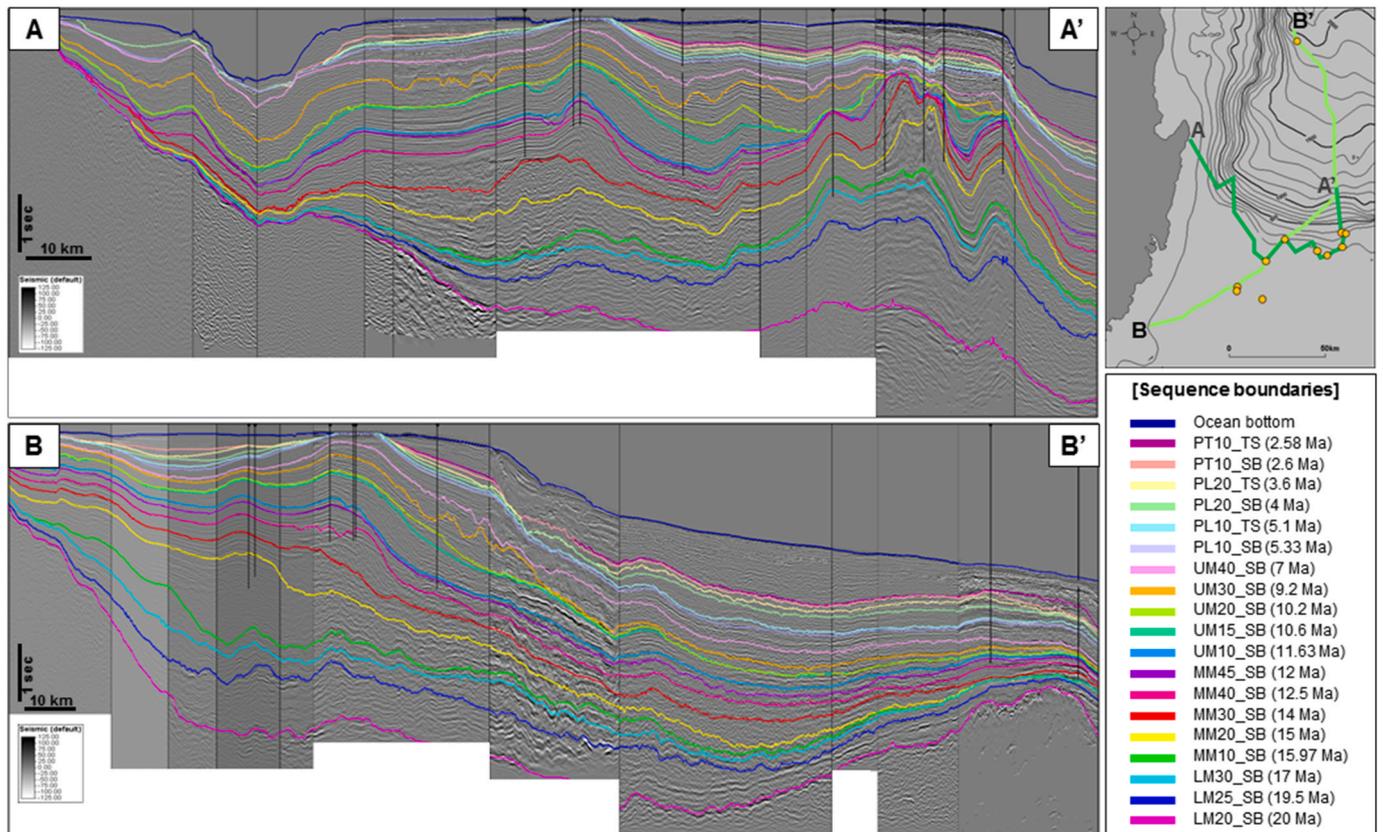


Fig. 5. Seismic profiles, oriented approximately in the depositional strike (A-A') and dip (B-B') directions, showing sequence boundaries from 20 Ma to the present. The sequences older than 20 Ma including the basin basement are not presented in this study.

Table 2
Foraminiferal bioevents for the wells in the Ulleung Basin.

Datum	Age
T <i>Globigerinoides extremus</i>	1.99 Ma ^g (N21; PL6)
B <i>Globorotalia truncatulinoides</i> [Pac.]	2.58 Ma ^h (N21; PL5)
B <i>Globorotalia tosaensis</i>	3.35 Ma ^h (N21; PL5)
T <i>Sphaeroidinellopsis seminulina</i> [Pac.]	3.59 Ma ^e (NN19-20; PL4/3)
T <i>Pulleniatina primalis</i>	3.66 Ma ^h (N19-N20; PL3)
B <i>Globorotalia crassaformis</i> senu lato	4.31 Ma ^e (N19-N20; PL2)
B <i>Pulleniatina primalis</i>	6.60 Ma ^c (N17a/N17b; M13b)
X <i>Neogloboquadrina acostanensis</i> (coiling dextral to sinistral)	6.77 Ma ^c (N17a; M13b)
B <i>Globigerinoides extremus</i>	8.93 Ma ^e (N16; M13b)
B <i>Neogloboquadrina acostaensis</i>	10.6 Ma ^f (N14; M11)
B <i>Neogloboquadrina pseudopachyderma</i>	11.7–12.6 [12.3] Ma ^d (N12; M9b)
T <i>Globorotalia peripheroronda</i>	12.8–14.6 [13.0] Ma ^d (N12; M9b)

T: Top/Highest occurrence; B: Base/Lowest occurrence; N: Zonation by Blow (1969); M and PL: Zonation by Wade et al. (2011).

^a Hays et al. (1969).

^b Keigwin (1982).

^c Srinivasan and Sinha (1992).

^d Hayashi and Takahashi (2002).

^e Lourens et al. (2004).

^f Hayashi and Takahashi (2008).

^g Wade et al. (2011).

^h Hilgen et al. (2012).

Table 3
Diatom bioevents for the wells in the Ulleung Basin.

Datum	Age
T <i>Talassiosira antiqua</i>	2.1–2.7 Ma ^a
T <i>Thalassiosira convexa</i>	2.3–2.6 Ma ^a
B <i>Neodenticula seminae</i>	2.6 Ma ^a
T <i>Neodenticula kamschatica</i>	2.5–2.9 Ma [2.50 Ma] ^a , 2.58 Ma ^b
LC <i>Neodenticula kamschatica</i>	2.61–2.68 Ma ^c
B <i>Thalassiosira antiqua</i>	5.7 Ma [Japan Basin] ^a , 6.3–7.0 Ma [Yamato Basin] ^a
B <i>Thalassiosira oestrupii</i>	5.10 Ma ^a
B <i>Thalassiosira oestrupii</i> s.l.	5.49 Ma ^c
B <i>Neodenticula kamschatica</i>	6.6 Ma ^a , 7.4 Ma ^c

T: Top/Highest occurrence; B: Base/Lowest occurrence; LC: last common or consistent occurrence.

^a Koizumi (1992).

^b Pushkar et al. (1999).

^c Koizumi et al. (2009).

Zone (15–14 Ma; basin floor), *Systematophora placacantha* Zone (14–10.2 Ma; slope–outer shelf), *Spiniferites ellipsoideus* Zone (10.2–4 Ma; coastal–inner shelf), and *Filisphaera filifera* (4–1 Ma; middle–outer shelf) (Byun, 1995; Byun and Yun, 1997; Yun et al., 1997, 1999a, 2007; Yun and Yi, 2002) (Figs. 2 and 3).

Many researchers investigated the environmental and climatic distribution of modern and extinct dinocysts in marine sediments (Wall et al., 1977; Harland, 1983; Wrenn and Kokinos, 1986). They divided environments into inner neritic, outer neritic, and oceanic based on the oceanic species of *Impagidinium* and *Nematosphaeropsis*, shelf and slope taxa of *Operculodinium centrocarpum*, and inner neritic components of *Lingulodinium machaerophorum*, *Operculodinium israelianum*, *Polysphaeridium zoharyi*, *Spiniferites ramosus*, *Spiniferites membranaceous* and *Tuberculodinium vancampoeae*. Paleooceanographic conditions were reconstructed considering the occurrence of cold water species like *Operculodinium centrocarpum* and *Spiniferites elongates*, and warm water ones such as *Operculodinium israelianum*, *Lingulodinium machaerophorum* and *Lingulodinium filiform*. Tushima warm current indicators, *Tuberculodinium vancampoeae* and *Polysphaeridium zoharyi*, and oligotrophic water species *Impagidinium striatum* (Kim et al., 2019) are also useful

Table 4
Dinoflagellate cysts bioevents for the wells in the Ulleung Basin.

Datum	Age
B <i>Spiniferites pachyderma</i>	3.6 Ma ^c
T <i>Spiniferites ellipsoideus</i>	4 Ma ^{a,d}
T <i>Reticulatosphaera actinocornata</i>	4.18 Ma ^f
T <i>Spiniferites</i> cf. <i>pseudofurcatus</i>	4.18 Ma ^f
T <i>Dapsilidinium pseudocolligerum</i>	7.0 Ma ^d , 7.4 Ma ^e , 7.6 Ma ^g
T <i>Heteraulacacysta campanula</i>	7.4 Ma ^e , 7.6 Ma ^g
T <i>Hystrichosphaeropsis obscura</i>	7.4 Ma ^e , 7.54 Ma ^f , 7.6 Ma ^g
B <i>Spiniferites elongatus</i>	10 Ma ^h
T <i>Batiacasphaera sphaerica</i>	10.2 Ma ^d
T <i>Systematophora placacantha</i>	10.2 Ma ^d
T <i>Spiniferites pseudofurcatus</i>	10.2 Ma ^d
T <i>Pentadinium laticintum</i>	11.21 Ma ^f
T <i>Cribroperidinium giuseppi</i>	14 Ma ^h
T <i>Evittosphaerula paratabulata</i>	16.2 Ma ^d
T <i>Distatodinium craterum</i>	16.2 Ma ^h

T: Top/Highest occurrence; B: Base/Lowest occurrence.

^a Matsuoka et al. (1987).

^b Powell (1992).

^c Byun (1995).

^d Stover et al. (1996).

^e de Verteuil and Norris (1996).

^f Brinkhuis and Powell (2004).

^g Dybkjaer and Piasecki (2010).

tools in paleoenvironmental interpretation. In the case of the Dolgorae deformed region of the basin, the oceanic taxa of *Impagidinium* and *Nematosphaeropsis* abruptly disappeared at early Late Miocene (10.2 Ma) with sudden decreased total abundance. The cold-water current prevailed from Middle Miocene to early Late Miocene (ca. 15–10.2 Ma), whereas warm-water current (paleo-Tsushima current) with the intermittent influx of cold-water current becomes stronger during Late Miocene to Pliocene. At the beginning of the Early Pleistocene the basin was controlled by cold-water current (Byun, 1995; Yun et al., 1997).

The paleoenvironment is closely coupled with geotectonics in the basin and gives important clues for reconstruction of tectonic evolution. Paleocological analysis using dinocysts indicates closure of the Korea Strait at 15 Ma, since Tsushima warm current indicators, *Polysphaeridium zoharyi* and *Tuberculodinium vancampoeae* decrease and begin to increase again later than 14 Ma (Byun and Yun, 1997; Yun and Yi, 2002).

Among microfossils of the basin dinocysts are most abundant and appear consistently from bottom to top of all wells. The total abundance is vertically changing, because the microfossil abundance patterns are closely related to sea level curves and depositional environments of sedimentary deposits. Therefore, the changing of abundance patterns enables precise sequence bio-stratigraphic analysis. Generally, condensed sections of depositional systems tracts are represented by microfossil abundance peaks and sequence boundaries are indicated by microfossil abundance minima (Armentrout, 1996, Fig. 4). The total abundance patterns of dinocysts in conjunction with wireline log and paleobathymetric data are particularly useful for location of condensed sections, sequence boundaries, and for constraining the interpretation of depositional systems tracts. Specifically, high resolution sequence bio-stratigraphic analysis indicates sequence boundaries, marine flooding surfaces, or deep-sea turbidites in the well sediments of the basin.

The reworked Paleogene specimens are often observed in Neogene sediments. They are rare but well-preserved dinocysts of Eocene to Oligocene age such as *Adnatosphaeridium* cf. *multispinosum*, *Areosphaeridium diktyoplokus*, *Deflandrea phosphoritica*, *Ovoidinium verrucosum*, *Spinidium* sp., *Wetzeliella* cf. *meckelfeldensis*, and *Wilsonidinium* cf. *lineidentatum* preserved mainly in Middle Miocene, rarely in the Late Miocene or even in the Pliocene successions of the Dolgorae wells (Byun, 1995; Yun et al., 1997). These reworked Paleogene taxa were reported widely in offshore Korea such as in the Cheju Basin (wells: Geobuk-1, Okdom-1, Domi-1, Sora-1) (Yun et al., 1999b, 2008), the Fukue Basin,

and SW Japan (Kyushu) (Kurita, 2004).

3.1.5. Spores and pollen

On the basis of age diagnostic taxa and floral assemblage changes of spores and, geologic age and paleo-climatic change were determined. Twelve bio-stratigraphic palyno-datums were established (Fig. 3). The Lower boundary of Pleistocene is recognized by last occurrence of common *Inaperturopollenites* spp.; boundary between Late and Early Pliocene by last occurrence of *Ceratopteris* (*Magnastriatites*); boundary between Pliocene and Miocene by last occurrence of common *Cryapollenites* spp. and *Liquidambarpollenites* spp.; boundary between Late and Middle Miocene by last occurrence of abundant occurrence of *Cryapollenites* spp., *Liquidambarpollenites* spp., *Quercus* spp.; boundary between Middle and Early Miocene by first occurrence of *Nyssa* spp., *Ilex* spp., and last occurrence of abundant Bisaccate pollen. The zonation is based on index species and prominent changes in the abundances of key pollen species through the Miocene to Pleistocene, which are reflected by climatic changes.

Among spores and pollen following taxa are useful for specific climate interpretation in the East (Japan) Sea area: *Pinus*, *Tsuga*, *Picea*, and *Fagus* for cool element and *Liquidambarpollenites*, *Carya*, *Quercus*, and Sapotaceae/Meliaceae for warm element. These species indicate that Early Miocene is cold temperate, Middle Miocene is warm temperate, Late Miocene is transitional temperate from warm to cold, and Plio-Pleistocene is cool temperate environment. Each palyno-datums are age calibrated using foraminifera, diatoms, and dinocysts chronology.

The pollen zonation of this study is principally based on KIER pollen zone (KIER, 1988) established for the Gorae and Dolgorae wells and Yamanoi's zones (Yamanoi, 1992) for ODP Leg 127 (Japan Sea) (Fig. 2). These pollen zones are characterized by floral changes caused by paleoclimatic variation in Miocene. Yamanoi (1992) classified the paleoclimate into cool temperate of NP1, warm temperate of NP2, transitional temperate of Zone NP3, and cool temperate of NP4 by means of abundance variation of *Liquidambar*, and Ever green *Quercus* (warm element), *Carya* (moderate), and *Fagus* (cool element). Yamanoi (1992) calibrated time scale of his zones established for the ODP sites 794, 795, 796, and 797, Yamato and Japan basins referring age determinations from diatoms and calcareous nannofossils researches. He estimated ages of the boundaries between NP4/NP3, NP3/NP2, and NP2/NP1 to be about 7 Ma, 13 Ma, and 17–18 Ma, respectively (Fig. 2). For the six wells (Gorae I, Gorae V, Gorae V-4, Gorae VII-1X, Dolgorae IIA-1X, Dolgorae VII), Noon and Waton (2004) proposed palynology zonal scheme (U1–U4: Quaternary–Pliocene, U5: Late Miocene, U6–?U8: Middle Miocene, ? U8–U10: Early Miocene–possible to Oligocene) with sixteen palynology datums. Some of datums are characterized by regionally significant events, but they are not calibrated by index fossils.

Paleogene spores and pollen such as, *Corollina*, *Gothanipollis bassensis*, *?Cerodinium*, *Cicatricosisporites dorogensis*, *Momipites coryloides*, *Meyeripollis naharkotensis* are reported in the Neogene sediments of Gorae VII-1X and Hongge-1 in the basin (Noon et al., 2004). They are presumed to be specimens reworked from the Eocene to Oligocene deposits of the Cheju Basin, Domi Basin, and JDZ (Korea-Japan Development Zone).

3.2. Summary

Based on bioevents of microfossil groups (calcareous nannofossils, foraminifera, diatoms, dinocysts, and spores and pollen) twenty-three datums were determined (Fig. 3). Among twenty-three datums sixteen ones were based on the biochronology of marker species, and seven datums were recognized by floral and faunal changes related to regional tectonics and geohistorical changes of paleoclimate. Calcareous and siliceous microfossils were abundant in Plio-Pleistocene succession of the wells, while organic microfossils occurred throughout all sediment depths of the wells. Therefore, foraminifera and diatoms were useful for

Plio-Pleistocene biozonation (Fig. 3). Although foraminifera yielded a few age diagnostic taxa, its assemblage allowed establishment of four biozones depending its characteristic occurrence patterns caused by depositional and paleo-environmental changes. The strongly facies-related zones were diachronous from shallow marine to deep-sea (Fig. 3). Dinocysts which were relatively abundant regardless of wells enabled four biozones based on index taxa. Abundant pollen and spores contained age diagnostic pollen species and assemblage changes with paleoclimatic variation. Based on significant palynological events twelve datums were established. Each datum was bio-chronologically calibrated by index fossils like nannofossils, diatoms, foraminifera, and dinocysts and by abundance patterns of marine foraminifera and dinocysts (Fig. 3).

The high resolution sequence biostratigraphy correlated with wire-line log data and seismic sequence stratigraphy was very useful for locating condensed sections, marine flooding surfaces, sequence boundaries, and turbidites and for constraining the interpretation of depositional systems tracts in the basin (Figs. 4 and 5). Patterns of microfossils abundance such as species composition, abundance and diversity were closely related to depositional environment that was in turn conditioned by tectonic setting (Fig. 5). By the horizon of 17 Ma in the well Dolgorae VII arenaceous foraminifera began to occur consistently as marine dinoflagellate appeared abundantly first 17 Ma in the Pohang Basin (Byun, 1995, Fig. 1). At 15 Ma in the Gorae region deep marine foraminifera taxa like arenaceous assemblage disappear indicating shallow marine environment, while warm water type such as *Tuberculodinium vancampoe* and *Polysphaeridium zoharyi* becomes rare in the Dolgorae region. This was credited to blocking of the Korea Strait and Kuroshio warm-current. This phenomenon at 15 Ma is also observed in the Pohang Basin. Just before closing of the Korea Strait at 15 Ma warm-water taxa of dinocysts such as *T. vancampoe* and *Operculodinium israelianum*, and warm-water species of benthic foraminifera like *Stilostomella* spp., *Neouvirgerina proscidea*, *Bulimina striata*, *Oridorsalis umbonatus* occurred very abundantly suggesting the paleoenvironment prevailed by warm current (Jung, 1993; Byun, 1995; Byun and Yun, 1997). Around 12.5 Ma the Dolgorae deformed region turned to be influenced by compressional forces building many folds. Micropaleontological and seismic sequence stratigraphic interpretation suggested that these compressional movements of various scales took place from 12.5 Ma to 10.2 Ma depending well sites in the Dolgorae deformed region. Among them the one at 10.2 Ma (LAD of *Systematophora placantha*) was remarkable being accompanied by drastic bathymetric change from basin floor–slope to coastal–inner shelf. This was supported by the abrupt reduction of total abundance and deep-water species such as arenaceous assemblages of foraminifera and deep-sea indicators of *Impagidinium* and *Nematosphaeropsis* of dinocysts.

The Dolgorae deformed region was uplifted by compression, consequent thrust and folding. The uplifted sediments were eroded to be redepositing in the morphologically lower and younger formations. In the Ulleung Basin, reworked age diagnostic fossils may cause misinterpretation on formation age of sediment deposits because they indicate older age than the sediment age.

The Paleogene reworked taxa of calcareous nannofossils, dinocysts, and spores and pollen which were yielded sporadically in the younger Neogene sediments functioned as a good indicator for provenance of sediments. The possible source areas are regarded as southern offshore basins of Korea, and/or southwestern Japan (Kyushu area) and the Fukue Basin, all with Paleogene successions.

4. Conclusions

The Ulleung Basin, East Sea (Japan Sea) proved to be a very ideal place for bio-sequence stratigraphy, since it is relatively small and confined quasi-inland sea reflecting sensitively paleoenvironmental changes in its sediments and fossil assemblages (Fig. 1). In consequence correlation between wells was successfully performed by the downhole

occurrence of chronostratigraphically and paleoecologically significant species and by floral and faunal discontinuities recognized by rapid changes in biofacies assemblages, fossil abundance, and diversity. On the base of these bioevents of microfossil groups and species (calcareous nannofossils, foraminifera, diatoms, dinocysts, and spores and pollen) twenty-three datums (biohorizons) were first established in the East Sea (Japan Sea) (Fig. 3). The high resolution sequence biostratigraphy is positively correlated with wireline log and seismic data in the Ulleung Basin and simultaneously enabled the determination of depositional cycles and tectonic events of the Ulleung Basin (Fig. 5). Provenance of the sediments was identified by Paleogene reworked taxa of calcareous nannofossils, dinocysts, and spores and pollen, which yielded sporadically in the younger Neogene sequences.

Author statement

Songsuk Yi: Conceptualization, Methodology, Writing - original draft preparation; Hyesu Yun: Conceptualization, Writing - original draft preparation, Supervision; Bitna Park: data interpretation, Software, Visualization; Woong Mo Koo: data interpretation, writing-reviewing and editing; Seunghak Yoo: data interpretation; Sora Kang: Writing - original draft preparation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

- Armentrout, J.M., 1996. High resolution sequence biostratigraphy: examples from the Gulf of Mexico Plio-Pleistocene. In: Howell, J.A., Aitken, J.F. (Eds.), *High Resolution Sequence Stratigraphy: Innovations and Applications*, vol. 104. Geological Society Special Publication, pp. 65–86.
- Blow, W.H., 1969. Late middle Eocene to recent planktonic foraminiferal biostratigraphy. *Proceedings 1st International Conference Planktonic Microfossils*, Geneva 1, 199–422, 1967.
- Brinkhuis, H., Powell, A.J., 2004. *Mesozoic-Cenozoic Dinoflagellate Cyst Biostratigraphy*, Short Course. University of Urbino, Italy, 2004, LPP Foundation Publication, Utrecht.
- Byun, H., 1995. *Cenozoic Dinoflagellate Cysts from the Pohang Basin and the Southern Margin of the Ulleung Basin, Korea*. Unpublished Ph.D. Thesis, Chungnam National University, p. 283.
- Byun, H., Yun, H., 1997. Late Cenozoic dinocysts from the exploration wells of the Pohang basin and the continental shelf of Korea. In: 15–30. October 9–11, 1997 and. In: Nishimura, S., Tsuchi, R. (Eds.), *Proceedings of Sixth International Congress on Pacific Neogene Stratigraphy and IGCP-355*, Kyongju, Korea, pp. 15–30. San Jose, Costa Rica, September 13, 1996.
- de Verteuil, L., Norris, G., 1996. Miocene dinoflagellate stratigraphy and systematics of Maryland and Virginia. *Micropaleontology* 42 (Suppl. ment), 172.
- Dybkaer, K., Piasecki, S., 2010. Neogene dinocyst zonation for the eastern north sea basin, Denmark. *Review of Paleobotany and Palynology* 161, 1–29.
- Haq, B., Hardenbol, J., Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: Wilgus, C.K., Posamentier, Ross, C.A., Kendall, C.G. St C. (Eds.), *Sea Level Change: an Integrated Approach*, vol. 42. Society of Economic Paleontologists and Mineralogists, Special Publication, pp. 71–108.
- Harland, R., 1983. Distribution maps of recent dinoflagellate cysts in bottom sediments from the North Atlantic Oceanic and adjacent seas. *Palaeontology* 26, 321–387, 43–48.
- Hayashi, H., Takahashi, M., 2002. Planktonic foraminiferal biostratigraphy of the Miocene arakawa group in central Japan. *Rev. Mex. Ciencias Geol.* 19, 190–205.
- Hayashi, H., Takahashi, M., 2008. Numerical age of the planktonic foraminiferal zonal boundary between N15 and N16 in the mid-latitude northwest Pacific region. *Bull. Geol. Surv. Jpn.* 59, 415–422.
- Hays, J.D., Saito, T., Opdyke, N.D., Burkle, L.H., 1969. Pliocene-Pleistocene sediments of the equatorial Pacific: their paleomagnetic biostratigraphic and climatic record. *Geol. Soc. Am. Bull.* 80, 1481–1514.
- Hilgen, F.J., Lourens, L.J., Van Dam, J.A., Beu, A.G., Boyes, A.F., Cooper, R.A., Krijgsman, W., Ogg, J.G., Piller, W.E., Wilson, D.S., 2012. The Neogene period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), *The Geological Time Scale 2012*. Elsevier, pp. 923–978. With contribution by.
- Jung, K.K., 1993. Benthic foraminiferal assemblages and paleoenvironmental analysis of the Miocene in the Pohang Basin, Korea. *J. Paleontol. Soc. Korea* 29, 464–476.
- Kato, M., 1992. Benthic foraminifera from the Japan sea: leg 128. In: Pisciotto, K.A., Ingle Jr., J.C., Von Breyman, M.T., Barron, J. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific, Results*, 127/128. Pt1, pp. 365–392, 1992.
- Keigwin Jr., L.C., 1982. Neogene planktonic foraminifera from deep sea drilling project Sites 502 and 503. In: Prell, W.L., Gartner, J.V., et al. (Eds.), *Initial Results of the Deep Sea Drilling Project*, vol. 68, pp. 269–288.
- Kim, Y., Yi, S., Kim, G.-Y., Lee, E.M., Kong, S., 2019. Palynological study of paleoclimate and paleoceanographic changes in the Eastern South Korea Plateau, East Sea, during the Plio-Pleistocene climate transition. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 520, 18–29.
- Koizumi, I., 1992. Diatom biostratigraphy of the Japan Sea: leg 127. In: Pisciotto, K.A., Ingle Jr., J.C., von Breyman, M.T., Barron, L., et al. (Eds.), *Proceedings of the ODP, Sci. Results*, 127/128. Ocean Drilling Program, College Station, TX, pp. 249–289 part 1.
- Koizumi, I., Sato, M., Matoba, Y., 2009. Age and significance of Miocene diatoms and diatomaceous sediments from northeast Japan. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 272, 85–98.
- Korea Institute of Energy and Resources (KIER), 1988. *Micropaleontological Study and Petroleum Geochemical Evaluation of Dolgorae III, Offshore Korea Block VI-1*. Prepared for Korea petroleum Development Corporation, p. 224.
- Kurita, H., 2004. *Preliminary Study of Paleogene Dinoflagellate Stratigraphy from the Southwest Japan*. Science Report of Niigata University, Series E (Geology), p. 133.
- Lee, H.Y., 1994. *Neogene Foraminifera Biostratigraphy of the Southern Margin of the Ulleung Basin, East Sea, Korea*. Seoul National University, Unpublished Ph.D. Thesis, pp. 1–377, 11pls.
- Lourens, L.J., Hilgen, F.J., Shackleton, N.J., Laskar, J., Wilson, D., 2004. The Neogene period. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), *A Geologic Time Scale 2004*. Cambridge University Press, pp. 409–440.
- Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci, A. (Ed.), *Proceedings of the Second Planktonic Conference, Rome*, vol. 2. Edizioni Tecnoscienza, pp. 739–785.
- Matsuoka, K.G., Bujak, J.P., Shimazaki, T., 1987. Late Cenozoic dinoflagellate cyst biostratigraphy from the west coast of northern Japan. *Micropaleontology* 33 (3), 214–229, 2pls.
- Micro-Strat Inc, 1994. *Integrated Sequence Stratigraphic Analysis of the PEDCO Gorae #1, Block VI-1, Ulleung Basin, Offshore Southeast Korea*. Prepared for the Korea Petroleum Development Corporation, Unpublished, p. 52.
- Nomura, A., 1992. Miocene benthic foraminiferas at sites 794, 795 and 797 in the Sea of Japan with reference to the foram sharp line in the Honshu Arc, 1992. In: Pisciotto, K.A., Ingle Jr., J.C., Von Breyman, M.T., Barron, J. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific, Results*, pp. 493–540, 127/128, Pt 1.
- Noon, S.W., Setiani, H., Pane, Y., 2004. Well Gorae VII-1X, Ulleung Basin, offshore Korea: biostratigraphy and paleoenvironments of the interval 560–3897 m (file No. Biostrat-03061). In: Prepared for Korea National Oil Corporation, pp. 1–4, 1-14, Appendices 1-5, Enclosures.
- Noon, S.W., Waton, P.V., 2004. Dolgorae VII, Gorae I, Gorae V, Gorae V-4, Gorae VII-1X, and dolgorae IIA-1X: biostratigraphy data revise correlation and new palynological zonation scheme (file No. Biostrat-04026). In: Prepared for Korea National Oil Corporation, pp. 1–18, 1-26, Appendices 1-2, Enclosures.
- Okada, H., Bukry, D., 1980. Supplementary modification and introduction of code numbers to the low-latitude coccolith zonation (Bukry, 1973; 1975). *Mar. Micropaleontol.* 5 (3), 321–325.
- Powell, A.J., 1992. *Dinoflagellate cysts of the tertiary system*. In: Powell, A.J. (Ed.), *A Stratigraphic Index of Dinoflagellate Cysts*. Chapman & Hall, London, pp. 155–229. Plate 1-11.
- Pushkar, V.S., Roof, S.R., Cherepanova, M.V., Hopkins, D.M., Brigham-Grette, J., 1999. Paleogeographic and paleolimatic significance of diatoms from Middle Pleistocene marine and glaciomarine deposits on Baldwin Peninsula, Northwestern Alaska. *Palaeogeography, Palaeoclimatology, Palaeoecology* 152, 67–85.
- Rexilius, J., Powell, S., 2016. *Micropaleontological analysis of hongge-1, Ulleung Basin, block 8/6-1N, Republic of Korea*. In: ISC Biostrat, Prepared for Woodside Energy (Korea) Pte. Ltd, 1-10, Appendix 1-6.
- Srinivasan, M.S., Sinha, D.K., 1992. Late Neogene planktonic foraminiferal events of the southwest Pacific and Indian Ocean: a comparison. In: Tsuchi, R., Ingle Jr., J. C. (Eds.), *Pacific Neogene Environment, Evolution and Events*. Univ. Tokyo Press, Tokyo, pp. 203–220.
- Stover, L.E., Brinkhuis, H., Damassa, S.P., Verteuil, L. de, Helby, R.J., Monteil, E., Patridge, A.D., Powell, A.J., Riding, J.B., Smelror, M., Williams, G.L., 1996. Chapter 19. Mesozoic-Tertiary dinoflagellates, acritarchs and prasinophytes. In: Jansouin, J., McGregor, D.C. (Eds.), *Palynology: Principles and Applications*, vol. 2. American Association of Stratigraphic Palynologists Foundation, pp. 641–750.

- Wade, B.S., Pearson, P.N., Berggren, W.A., Palike, H., 2011. Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. *Earth Sci. Rev.* 104, 111–142.
- Wall, D., Dale, B., Lohman, G.P., Smith, W., 1977. The environment and climatic distribution of dinoflagellate cysts in modern marine sediments from regions in the north and south Atlantic oceans and adjacent sea. *Marine Micropaleontology* 2, 121–200.
- Wrenn, J.H., Kokinos, J.P., 1986. Preliminary comments on Miocene through Pleistocene dinoflagellate cyst from de soto canyon, gulf of Mexico. *AASP Contrib. Ser.* 17, 169–226.
- Yamanoi, T., 1992. Miocene pollen stratigraphy of Leg 127 in the Japan Sea and comparison with the standard Neogene pollen floras of northeast Japan, 1992. In: Pisciotto, K.A., Ingle Jr., J.C., von Breyman, M.T., Barron, J., et al. (Eds.), *Proceedings of the Ocean Drilling Program. Scientific Results*, pp. 471–491, 127/128, Pt. 1.
- Yun, H., Yi, S., 2002. Biostratigraphy and paleoceanography for the Gorae and Dolgorae wells, offshore Korea, and their implications to Neogene tectonic history. In: Tateish, M., Kurita, H. (Eds.), *Development of Tertiary Sedimentary Basins Around Japan Sea (East Sea)*. Niigata University, pp. 65–78.
- Yun, H., Byun, S.H., Oh, J., Bak, Y., 2008. Biostratigraphy of Block VI-2, Offshore, Republic of Korea. Chungnam National University, Prepared for Korea National Oil Corporation, p. 220 (in Korean).
- Yun, H., Lee, E.H., Bak, Y.S., Kang, S.R., Bae, B.Y., Seo, S.H., 1999a. Biostratigraphy of Ulleung Basin, Continental Shelf of Korea. Chungnam National University, Prepared for Korea National Oil Corporation, p. 116 (in Korean).
- Yun, H., Yi, S., Oh, J., Byun, H., 1997. Tertiary system of Korea. *J. Paleontol. Soc. Korea* 3, 1–30.
- Yun, H., Yi, S., Oh, J., Byun, H., Shin, K., 2007. Microplaeontological and seismic observation for early development stage of the southwestern Ulleung Basins, East Sea (Japan Sea). *Isl. Arc* 16, 262–275.
- Yun, H., Yi, S., Yi, Sa, Kim, J.H., Byun, H.S., Kim, G.-H., Park, D.B., 1999b. Biostratigraphy and paleoenvironment of the Cheju sedimentary basin – based on materials from exploration wells, geobuk-1 and okdom-1. *J. Paleontol. Soc. Korea* 15 (1), 43–94 (In Korean with English Abstract).