

Research Article

Micropaleontological and seismic observations for early developmental stage of the southwestern Ulleung Basin, East Sea (Japan Sea)

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Abstract The Ulleung Basin is located in the southwestern part of the East Sea (Japan Sea) and contains thick Neogene sediment. Detailed examination of the stratigraphic distribution of dinoflagellates was carried out on samples from the onshore Pohang Basin (E well) and two wells (Gorae I and Dolgorae VII) in the southwestern Ulleung Basin, to investigate the early evolution of the basin. The results show that thick syn-rift sediments mainly consist of terrestrial deposits and are widespread over the basin. This supports an extensional tectonic origin for the basin. The initiation of the deposits dates back to 17–16.4 Ma. Furthermore, well-preserved Eocene to Oligocene dinoflagellate taxa found in Miocene deposits of wells implies that the age of initial rifting might be Oligocene or earlier. Our results provide constraints for understanding the opening process of the East Sea.

Key words: biostratigraphy, paleoenvironment, Pohang Basin, syn-rift, Ulleung Basin.

INTRODUCTION

The East Sea (Japan Sea) was formed by Tertiary back-arc rifting associated with subduction of the Pacific Plate under the Eurasian Plate (Karig *et al.* 1975; Tamaki 1986, 1988; Tamaki *et al.* 1992) (Fig. 1). Several different models of the opening process of the East Sea are presented. Otofujii and Matsuda (1987) analyzed paleomagnetic records from Japanese Islands and presented a two-door model for the opening process. According to their model, southwest Japan was rotated clockwise through more than 40° with respect to the eastern margin of Eurasia since 20 Ma. More than 80% of the overall clockwise rotation occurred between about 16 and 14 Ma (Otofujii *et al.* 1991). The rotational pivot was located to the east of the Tsushima Islands. However, Jolivet and Tamaki (1992) proposed that the East Sea had been generated through a pull-apart motion since 25 Ma in the embryonic Japan Basin, guided by two large dex-

tral strike-slip fault systems, one east of Korea and the other west of northeast Japan and Sakhalin. The Ulleung Basin is located in the southwestern part of the East Sea and contains thick Neogene sediment (Fig. 1). The tectonic importance of the basin is highlighted by controversial tectonic models for the evolution of the East Sea: the area has been proposed both as a rotational pivot in the two-door model, and a dextral strike-slip shear zone in the pull-apart model.

Many authors have proposed tectonic histories of the Ulleung Basin. Chough and Barg (1987) suggested three stages: rifting and spreading (Oligocene to Middle Miocene) and two closings (Late Miocene and 2–1 Ma). Park (1992) envisioned five phases: extension (Latest Cretaceous to Earliest Paleogene), contraction (Early Miocene), strike-slip (middle Late Miocene), structural arch (late Late Miocene to Pliocene) and renewed strike-slip (Pleistocene). Choi *et al.* (1994) suggested four stages: rifting (Oligocene), extension and subsidence (Early Miocene to early Middle Miocene), compression and uplifting (middle Middle Miocene to early Late Miocene) and compression (Late Miocene to present). Chough

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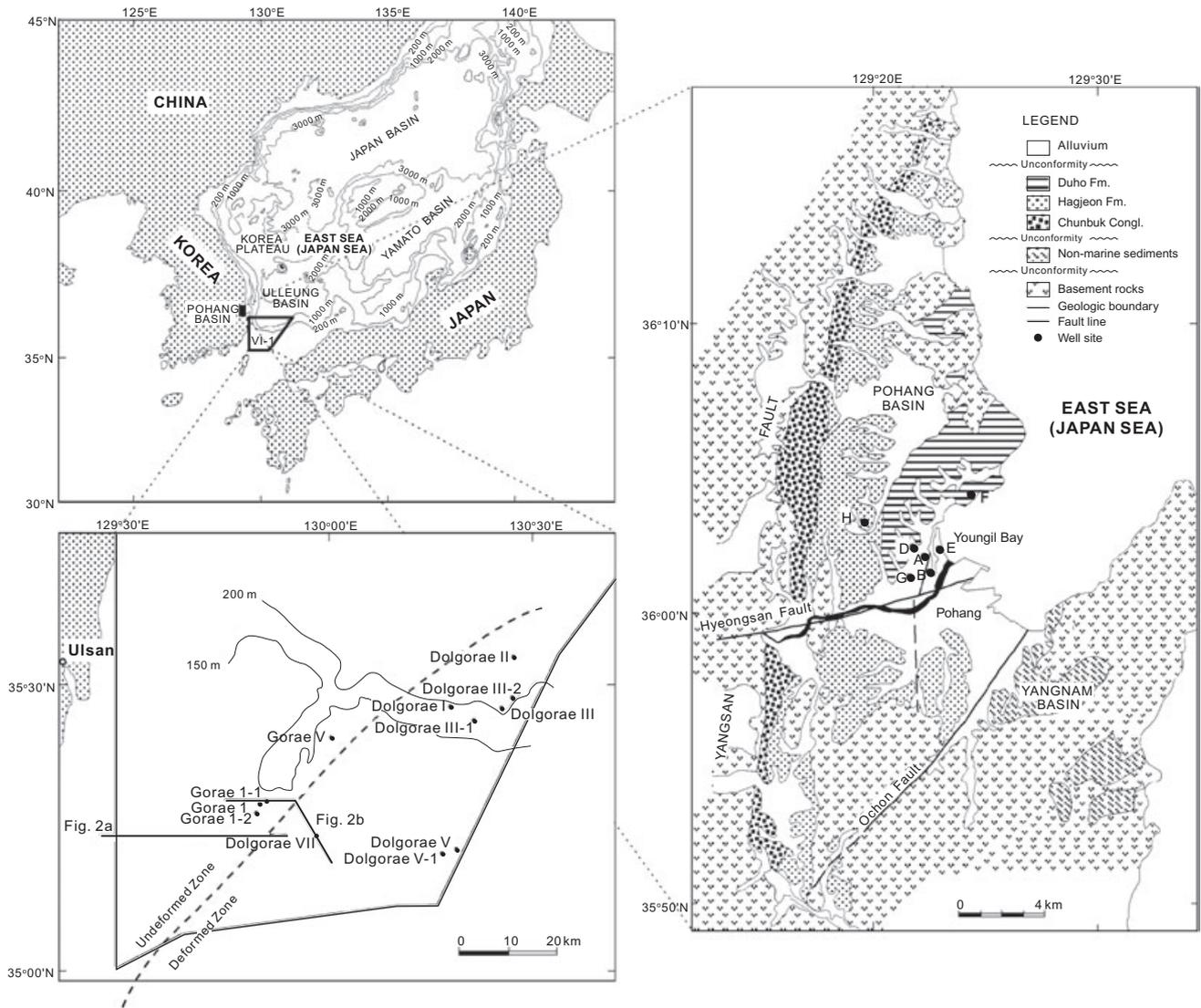


Fig. 1 Study area with well locations (circles) and offshore seismic profiles (thick line). Bathymetry in meters. Fm, formation; Congl, conglomerate.

et al. (1997) and Yoon *et al.* (2002) advocated three stages: extension and subsidence (Early to Middle Miocene), compression and uplift (Middle to Late Miocene) and subsidence (Pliocene). The last two histories are similar except for the cause of the initial subsidence: the former hinted at extensional tectonics, whereas the latter emphasized dextral strike-slip movement. Kim *et al.* (1998) examined the nature of the crust of the Ulleung Basin with seismic wide-angle reflection and refraction data, and proposed that the opening models of the southwestern East Sea should incorporate seafloor spreading and the influence of a mantle plume rather than the extension of the crust of the Japan Arc. More recently, Kim *et al.* (2003) investigated crustal and sedimentary velocity structures across the Korean margin into the

adjacent Ulleung Basin from multichannel seismic (MCS) reflection and ocean bottom seismometer data. They concluded that the Korean margin was rifted above the anomalously hot asthenospheric mantle, which accreted onto the margin during continental breakup in Late Oligocene to Early Miocene times.

These previous studies have mainly focused on analyses of seismic profiles (Minami 1979; Chough & Barg 1987; Itoh *et al.* 1992; Yoon *et al.* 2003). This is because accessibility to the samples of drilled sediments had been limited. Precise reconstruction of tectonic events and environmental history needs a combination of seismic analysis and drilled well data. Recently, in the research of the Ulleung Basin interdisciplinary co-work has become possible, because various explorations

have been carried out as a result of high potential for hydrocarbon resources, and accumulated research material and data, such as drilled samples and seismic images, were made available.

To establish a biostratigraphic and paleoenvironmental framework for the early developmental stage (older than 15 Ma) of the southwestern Ulleung Basin and Pohang Basin, the present study provides detailed stratigraphic distribution of dinoflagellates, which have better preservation and age control than the other microfossils, from two offshore wells (Gorae I and Dolgorae VII) and one onshore well (E well) (Fig. 1). Pohang Basin is a continental margin equivalent of the Ulleung Basin. We also used seismic profile running across the studied wells to authenticate data quality (Figs 1,2a,b). In addition, we examined significance of occurrence of well-preserved Eocene to Oligocene dinoflagellate taxa found in Miocene sediments of the Dolgorae III-1 and III-2 wells.

GEOLOGICAL SETTING

Most of the geological information on the Ulleung Basin is based on seismic interpretations of MCS profiles and analyses of drilled well samples (Korea Petroleum Development Corporation 1989a,b; Nester & Mitchum 1989; Chough *et al.* 1997; Shin *et al.* 1997; Lee *et al.* 1999; Yoon *et al.* 2002). The MCS reflection data have been acquired by the Korea National Oil Corporation (KNOC) since 1970. These data indicate that the total thickness of Tertiary sediment in the Ulleung Basin is about 7.5–8.0 km (Nester & Mitchum 1989; Park 1990), and that the basin is divided into two zones based on the degree of structural deformation of infill strata (Deformed and Undeformed Zones; Fig. 1; Park 1990). The boundary between the two zones is characterized by a 6- to 8-km-wide, north-east-trending thrust belt comprising several parallel thrust faults and associated folds (Park 1998; Yoon *et al.* 2002). The Deformed zone (or 'Dolgorae' area) south of the thrust belt is characterized by uplift and folding and faulting of the Miocene succession as a result of back-arc closing caused by changes in the motion of the Philippine Sea Plate (Chough & Barg 1987; Lee *et al.* 1999). This zone extends eastward into the southeastern Ulleung Basin, where ENE-trending folds are present (Minami 1979; Itoh *et al.* 1992; Choi *et al.* 1994; Itoh 2000). In the Undeformed Zone (or 'Gorae' area), the sedimentary successions are comparatively undisturbed except for a broad anticlinal

fold zone in the middle (anticlinal flexure; Chough *et al.* 1997). Eight Dolgorae wells were drilled in the Deformed Zone, and four Gorae wells were drilled in the Undeformed Zone between 1987 and 1995, except Dolgorae I, which was drilled in 1972–1973 (Fig. 1). The well drilled at the margin of the basin attains more than 4-km thick sedimentary succession, which consists mainly of turbiditic marine sandstone, shale and mudstone that yield diverse, abundant and well-preserved microfossils (Korea Petroleum Development Corporation 1989a,b; Figs 3,4).

The Pohang Basin represents north–south-oriented and is the largest Tertiary onshore basin in the southern Korean Peninsula (Fig. 1). It contains a Neogene marine succession about 1000 m thick. The lower part of the succession consists of conglomerate and sandstone, whereas the upper part consists of mudstone, siltstone and sandstone. Crystalline basement consisting of Cretaceous granite and Early Tertiary volcanic rock is exposed west of the Yangsan Fault (Yoon 1992) and in the middle of the basin. Yun (1986) established three formations in the Pohang Basin: the Chunbuk Conglomerate, the Hagjeon Formation and the Duho Formation, in ascending order. Seven deep wells were drilled to the Cretaceous basement in the middle part of the basin (Fig. 1a–h).

MATERIALS AND METHODS

Two adjacent wells (Gorae I and Dolgorae VII) were selected from the 12 wells in the southwestern Ulleung Basin, because the former and latter are placed at the Undeformed Zone and Deformed Zone, respectively (Fig. 1). In addition, we examined one onshore well (E well) from the Pohang Basin. Relevant seismic profiles were also chosen from survey lines passing closed to the two wells. The MCS reflection data were acquired by KNOC and processed by commercial companies in 1989 (Fig. 2b) and 1992 (Fig. 2a,b).

Ditch cutting samples were collected at 30-m intervals from Gorae I and Dolgorae VII wells. Microfossil samples were collected at 10 m intervals from E well from Pohang Basin. These samples were processed for organic microfossils (dinoflagellate, pollen and spores) with standard preparation methods (Evitt 1984; Moore *et al.* 1991). In the present study, dinoflagellate index taxa are discussed for biostratigraphy. The overall preservation condition of the dinoflagellates is good without any corrosion, severe mechanical

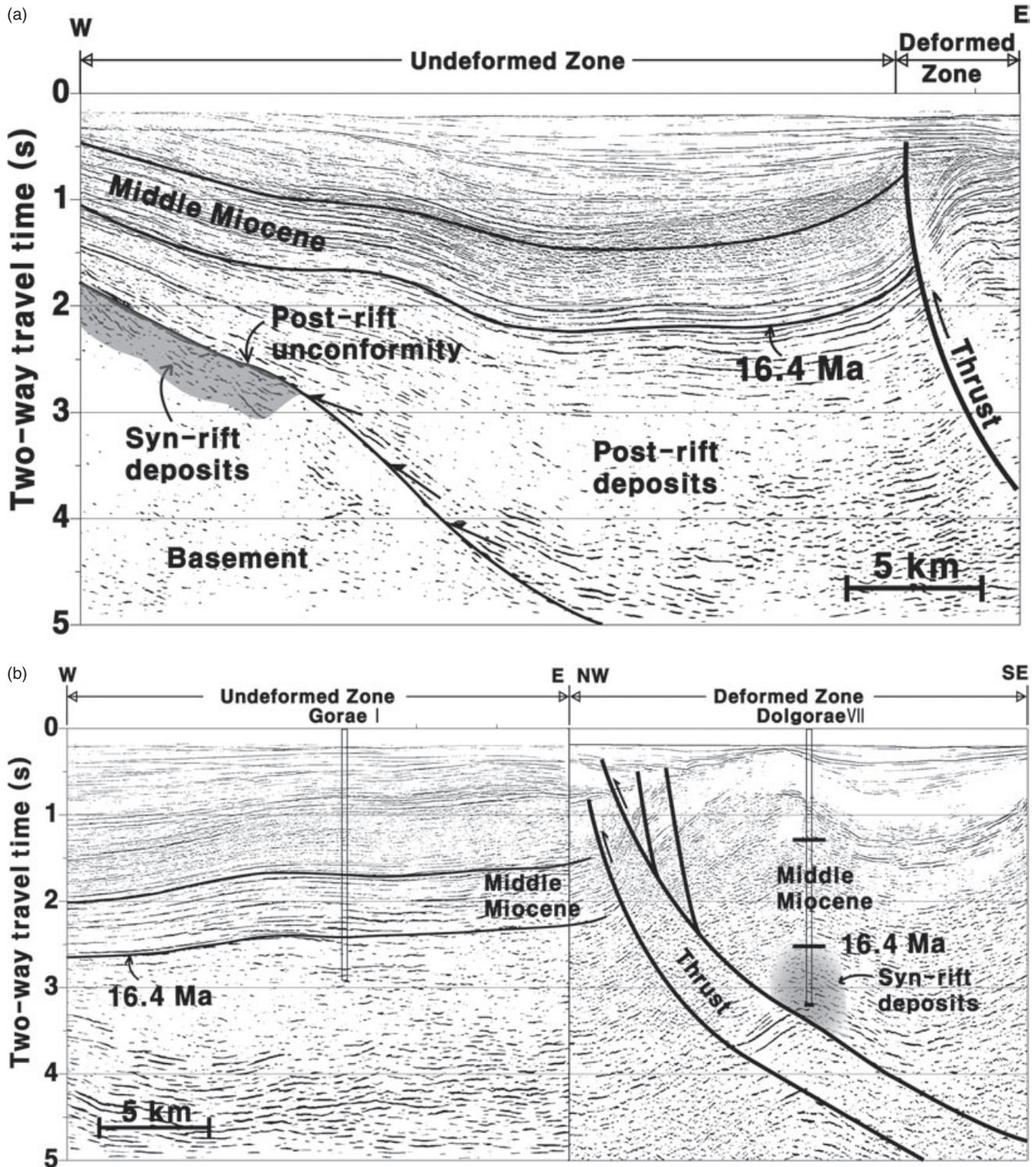


Fig. 2 (a) West–east oriented seismic profile showing syn-rift basin (shaded area) and post-rift unconformity (PRU) in the Undeformed Zone and thrust belts in the Deformed Zone. Seismic data were obtained and processed by KNOC in 1992. See Figure 1 for profile location. The PRU is interpreted by both the onlapping (arrows) of overlying post-rift deposits and the tilting of underlying syn-rift fills (shaded area). (b) Composite seismic profile between the Gorae I well (Undeformed Zone; left), and the Dolgorae VII well (Deformed Zone; right). Seismic data were obtained and processed by Korea National Oil Corporation in 1989 (right) and 1992 (left). See Figure 1 for location. The interpretation of the syn-rift deposits is mainly based on the age and lithology of non-marine section (shaded area) in the Dolgorae VII well. Key horizons of the post-rift deposits in the Undeformed Zone cannot be traced into the Deformed Zone across the thrust belt, which has been formed since 15 Ma.

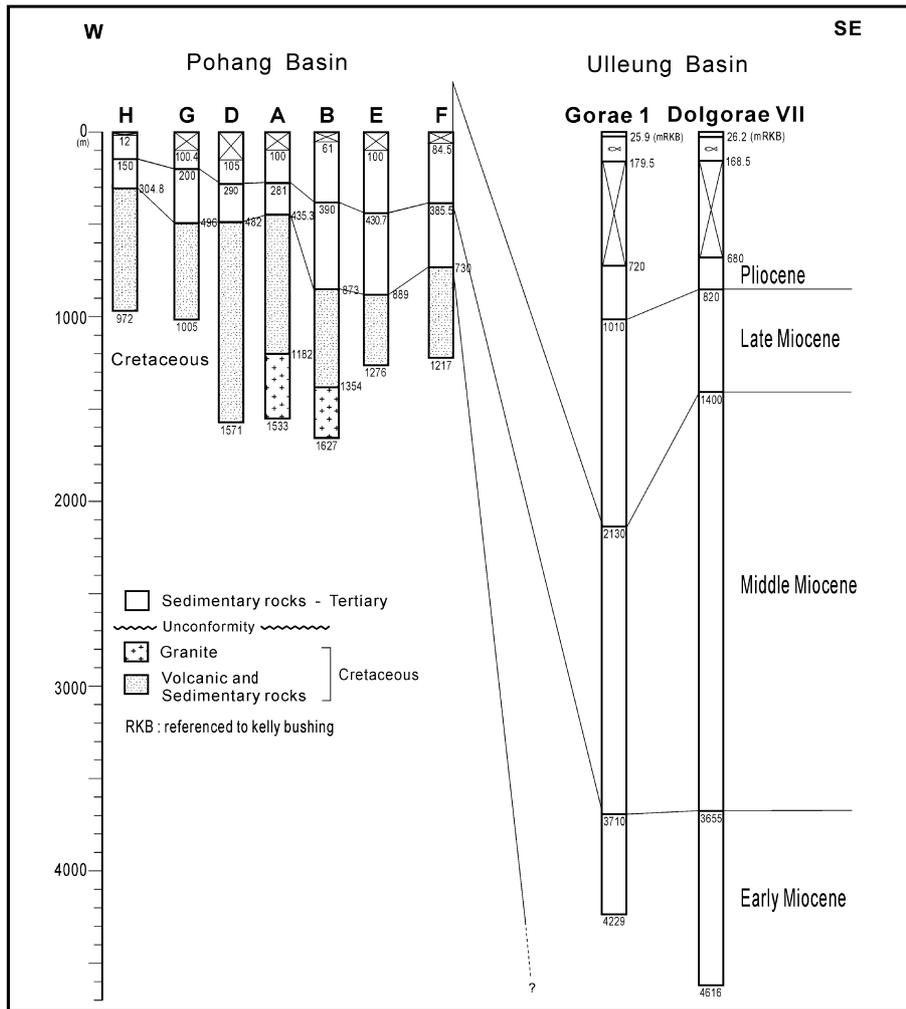


Fig. 3 Chronostratigraphic correlation among wells in the onshore Pohang Basin and the offshore Ulleung Basin, Korea. See Figure 1 for well locations.

destruction and color change. For this reason index species of pollen and spores were studied only in sections where marine microfossils do not occur. Several biohorizons and biostratigraphic zones were immediately recognized based on the first appearance datum (FAD) and last appearance datum (LAD) of marker species and microfossil assemblages (Fig. 5).

RESULTS

ULLEUNG BASIN

Gorae I well

Although organic microfossils are abundant in the lower parts of the section, no dinoflagellate index fossil with a LAD in the Early Miocene is present below the 16.4 Ma horizon (Table 1). On the basis of the stratigraphic range of the pollen taxa *Symplocopollenites vestibulum* (FAD: 3680 mRKB

[meter referenced to kelly bushing]; Middle Miocene, 16.4 Ma, Song *et al.* 1985) and *Ilexpollenites iliacus* (FAD: 3560 mRKB; Middle Miocene, 16.4 Ma, Song *et al.* 1985), we infer an Early Miocene age for the lowermost part of Gorae I (3710 mRKB–4229 mRKB) (Fig. 5). Therefore, the characteristics of the dinoflagellate assemblages and the stratigraphic range of pollen and spore taxa indicate that the oldest age of sediment in the Gorae I well is coeval with or older than the age of the oldest marine sediment in the Pohang Basin.

Dolgorae VII well

Oil exploration wells drilled in the Ulleung Basin did not penetrate to the basement (Figs 3,4). Non-marine and marginal-marine sediment was recovered from the Dolgorae VII well, which is located in the most uplifted area (Table 2; Fig. 2b). The strata in the lower part (total depth 4616 mRKB–

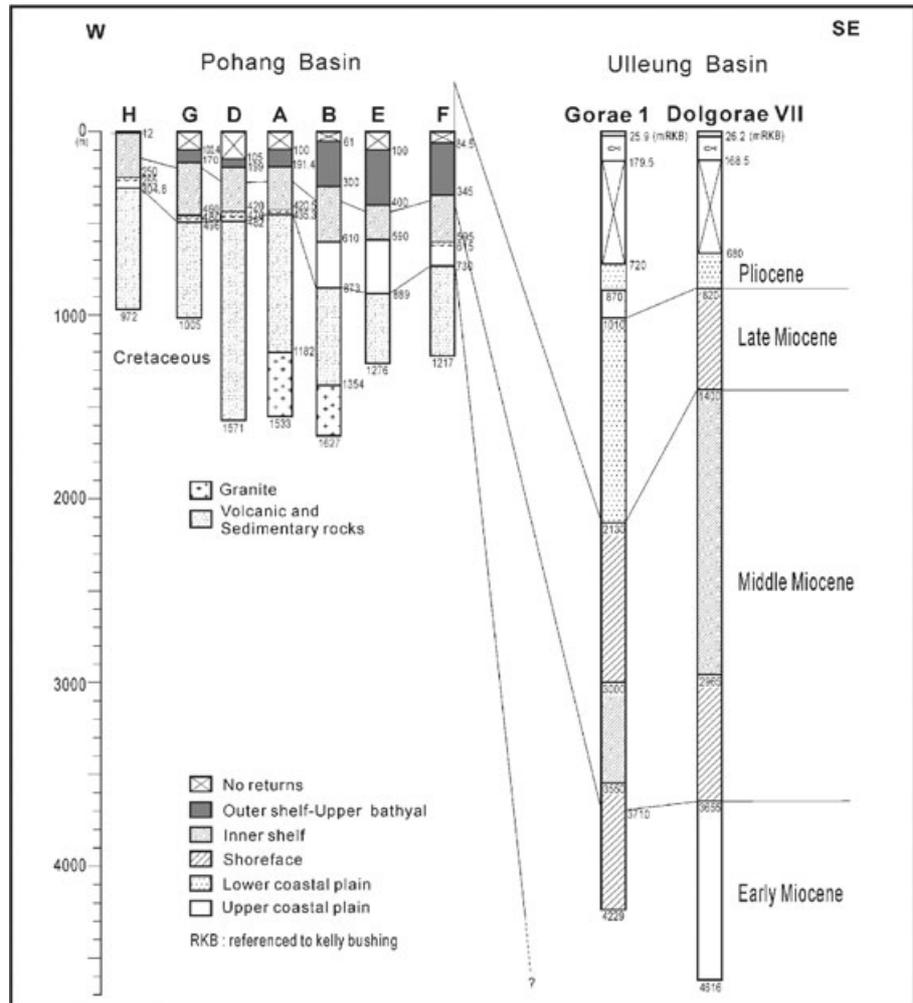


Fig. 4 Paleoenvironments of wells in the onshore Pohang Basin and the offshore Ulleung Basin, Korea. See Figure 1 for well locations.

3655 mRKB) consist of thickly bedded, dark-gray alternating mudstone and sandstone containing abundant coalified plant debris and no dinoflagellates. Between 4350 mRKB and 3655 mRKB, however, sparse arenaceous foraminifera are present, including *Cyclamina japonica* (one specimen), *Haplophragmoides compressum* (three specimens), *H. sp. A* (two specimens) and arenaceous indet. (two specimens) (Lee 1994).

The thickness and sediment composition of the strata below 4350 mRKB, together with the abundance of plant fragments and lack of dinoflagellates, indicate that this lowest unit consists of sediment deposited in a terrestrial environment. In the strata between 4350 mRKB and 3655 mRKB, the appearance of sparse, small arenaceous foraminifera probably reflects the onset of brackish conditions. This unit separates non-marine strata of the lowermost part from the overlying marine sediment, in which dinoflagellates and other marine microfossils gradually appear and increase upward. The latter deposits record

near-coastal to shallow marine environments in Figure 6.

If these interpretations are correct, marine sediment overlying the terrestrial succession would be the oldest sediment known to record marine transgression over the southern margin of the Ulleung Basin. The presence of *Cribroperidinium giuseppei* (LAD of 14.0 Ma: Matsuoka *et al.* 1987) at 2695 mRKB suggests the contact zone between syn-rift and marine deposits in the Dolgorae VII well is older than 14 Ma. A further constraint is given by the first appearance of an index species of pollen, *Ilexpollenites iliacus* (FAD: Middle Miocene, 16.4 Ma, Song *et al.* 1985) close to the contact at 3690 mRKB. This suggests the age of the contact is about 16.4 Ma and the lowermost section of the well is older than 16.4 Ma.

THE POHANG BASIN

The sediments E well (total depth 660 m) are composed of dark-gray alternating mudstone

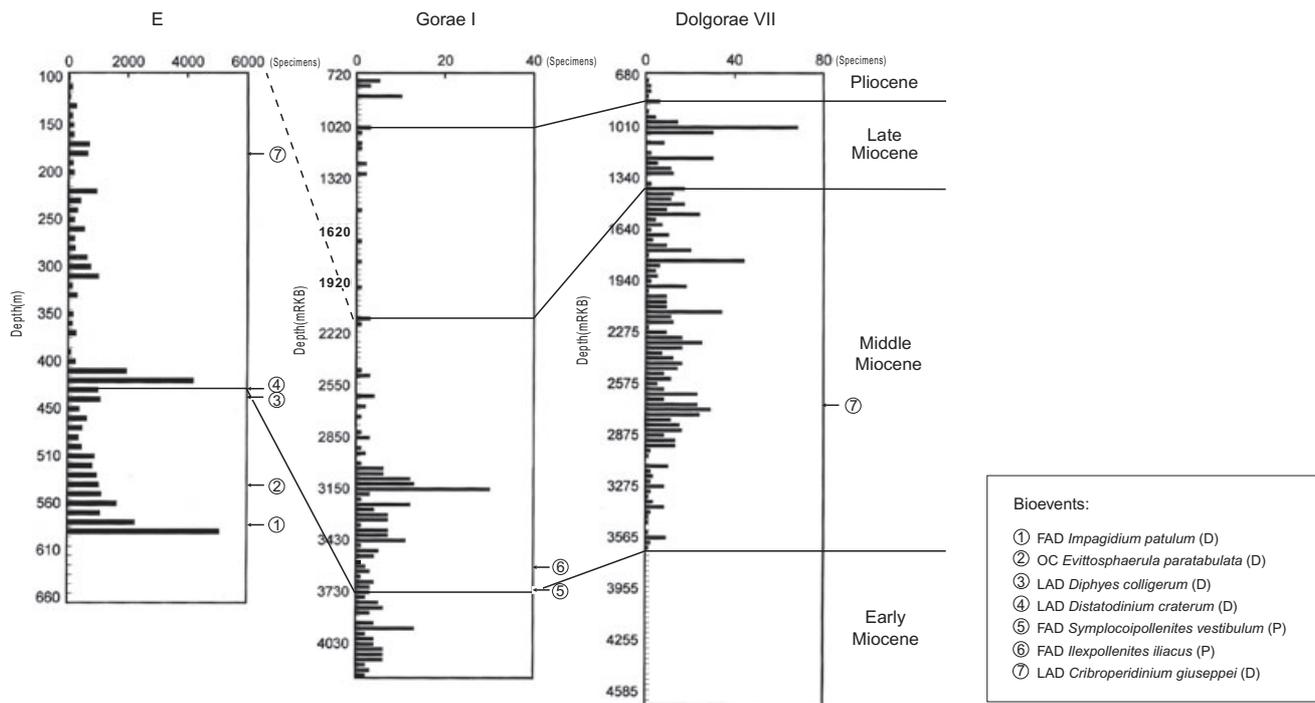


Fig. 5 Biostratigraphic correlation and microfossil abundance in well E (Pohang Basin) and the Gorae I and Dolgorae VII wells (offshore Ulleung Basin). See Figure 1 for well locations. Circled numbers represent bioevents indicated by index fossils. D, dinoflagellates; FAD, first appearance datum; LAD, last appearance datum; N, calcareous nannofossils; OC, occurrence; P, palynomorphs.

and sandstone. The deposits below 600 m do not yield any marine fossils but abundant plant fragments including pollen and spores (Table 3; Fig. 5). It indicates that the lowermost interval is deposited under non-marine environment being regarded as syn-rift sediments (Figs 4,6). At a depth of 590 m marine microfossil suddenly began to occur abundantly suggesting abrupt change of non-marine environment to full marine environment. On the basis of the occurrence of dinoflagellates *Distatodinium craterum* (LAD: 16.2 Ma, Powell 1992) found at 430.7 m, *Diphyes colligerum* at 440 m and *Evittosphaerula paratabulata* (LAD: 16.2 Ma, Stover *et al.* 1996; LAD: 16.3 Ma, Williams *et al.* 1993) at 540 m, the depth of 430.7 m is regarded as the top of the Early Miocene or the boundary between the Early and Middle Miocene. The first occurrence of *Impagidium patulum* (FAD: 17 Ma, Williams *et al.* 1993) occurs at the depth 580 m, and the lowermost part of the E well down to a depth of 580 m is considered to be older than 16.4 and younger than 17 Ma. Therefore, the rifting in the Pohang Basin accompanied by first marine transgression is presumed to be initiated by this time.

DISCUSSION

Differences in tectonic subsidence rate can be used to classify different stages in the evolution of the extensional basins (McKenzie 1978), and the geometry of the basin-fill can be stratigraphically classified into pre-, syn- and post-rift phases. Consequently, the boundary between syn- and post-rift phases commonly represents an unconformity, which is termed the post-rift unconformity, and is recognized in the seismic profile by the erosional truncation of underlying tilted syn-rift fill and the onlap of overlying post-rift strata (Bally 1983). A 3-D seismic survey (southern area portrayed in Fig. 2a) undertaken by KNOC shows several 6- to 7-km-wide half-grabens bounded by a NNE-trending normal fault (Shin *et al.* 1997; Shin 2000). Shin *et al.* (1997) inferred that Oligocene and Early Miocene syn-rift fill with a thickness of ca 0.8 s (two-way travel time) overlies the acoustic basement in these half-grabens. On the seismic image of Figure 2a, we observe the existence of the post-rift unconformity and underlying syn-rift basin across the marginal side of the Undeformed Zone. However, the unconformity along the continental edge cannot be traced into either the deeper

Table 1 Dinoflagellates distribution in the Gorae I well, Ulleung Basin

Species	Early Miocene		Middle Miocene		Late Miocene		Epoch	
	D. craterum Zone	C. giuseppei Zone - S. placacantha Zone	S. ellipsoideus Zone	E. Plio.	L. Plio.	Epoch	Depth (mRKB)	Species
Achomosphaera crassipellis								
Achomosphaera sp. cf. A. ramulifera								
Batacasphaera sp.								
Brigantedinium asymmetricum								
Brigantedinium cariacens								
Brigantedinium grande								
Brigantedinium irregulare								
Brigantedinium simplex								
Brigantedinium spp.								
Capillicysta fusca								
Cleistosphaeridium sp.								
Filipsphaera filifera								
Halodinium sp. cf. H. major								
Heteraulacacysta campanula								
Hystriochosphaeropsis sp.								
Hystriochosphaeropsis variabilis								
Impagidinium cf. patulum								
Lejeuneicysta benimensis								
Lejeuneicysta sp. cf. L. cinctoria								
Lejeuneicysta fallax								
Lejeuneicysta hyalina								
Lejeuneicysta sp. cf. L. hyalina								
Lejeuneicysta sp. A								
Lejeuneicysta sp. B								
Lejeuneicysta spp.								
Lingulodinium machaerophorum								
Microdinium sp.								
Multispinula sp. A								
Multispinula sp. B								
Multispinula quanta								
Multispinula sp.								
Nematosphaeropsis labrynthea								
Operculodinium centrocarpum								
Polysphaeridium inflectosporium								
Reticulatosphaera acinocornata								
Selenopemphix sp. A								
Selenopemphix sp. cf. S. armata								
Selenopemphix coronata								
Selenopemphix crenula								
Selenopemphix nephroides								
Spiniferites benitoli								
Spiniferites bulboides								
Spiniferites sp. cf. S. ellipsoideus								
Spiniferites sp. cf. S. firmus								
Spiniferites mirabilis								
Spiniferites ovatus								
Spiniferites pachyderma								
Spiniferites pseudolurcatus								
Spiniferites ramosus ramosus								
Spiniferites recurvata								
Spiniferites spp.								
Systematophora sp.								
Thalassiphora sp.								
Xanderodinium variabile								
Pedicularium sp.								
TOTAL								

Area Time	Pohang Basin (7 drilled wells)	Undeformed Zone (Gorae I)	Deformed Zone (Dolgorae VII)
16.4 Ma	Outer shelf	Inner shelf	Shoreface (since ~ca 16 Ma)
	Inner shelf	Shoreface	Terrestrial
17 Ma	Shoreface	Marine after terrestrial (interpreted from seismic data)	
	Terrestrial		

Fig. 6 Paleoenvironmental summary for the early basin, based on analysis of microfossils from the drilled wells.

part of the Undeformed Zone as a result of the acoustic limitation or the Deformed Zone across the trust belt which obstructs the seismic interpretation.

It is common that the syn-rift sediment is characterized by the terrestrial origin (e.g. US Atlantic continental margin; Poag & Valentine 1988). Our results show that the sediments are dominated by barren zones (289-m thick in the Pohang Basin and 961-m thick in the Ulleung Basin, respectively) and horizons yielding only pollen and spores (Fig. 4). Therefore, we regard the sediments as non-marine sediment and syn-rift origin. The syn-rift sediments are developed all over the study area. Along the coastal margin of the southwestern Ulleung Basin, the structure of the post-rift unconformity is present (Fig. 2b; Shin 2000). In a pull-apart model, thick accumulations of syntectonic sediment are limited to the vicinity of the strike-slip fault(s). Thus, ubiquitous syn-rift sediment as well as the existence of post-rift unconformity supports that extensional rift model of early developmental stage of the basin (Chough *et al.* 1997; Shon *et al.* 2001) rather than a pull-apart model as suggested by many workers (Hwang *et al.* 1995; Yoon & Chough 1995; Yoon *et al.* 1997, 2002; Lee *et al.* 1999).

The syn-rift sediment is covered by marine successions in the Pohang Basin and the southwestern margin of the Ulleung Basin. On the basis of our biostratigraphic data, there is a possibility that marine sediment was being deposited in the Gorae I area at 16.4 Ma, whereas terrestrial sediments were accumulating in the Dolgorae VII area where marine sedimentation did not begin until 16 Ma. This remarkable difference in depositional environment over a short distance about 12 km at present can be attributed to the presence of half-grabens and syn-rift sediment, both of which resulted from extensional tectonic activity.

Biostratigraphic work has been conducted on samples from the Hole of Ocean Drilling Program

Legs 127 and 128 drilled in the Yamato Basin of East Sea (Burekle *et al.* 1992; Nomura 1992; Rahman 1992; Yamanoi 1992). The oldest marine sediment is late Early Miocene in the basin, based on the calcareous nannofossil *Helicosphaera ampliaperta* Zone (15.7–18.4 Ma) in the Holes 797B and 797C, Leg 127 (Rahman 1992). Pollen analysis indicates an age equivalent to the pollen zone NP-1/NP-2 boundary (17–18.5 Ma) in the Hole 797C, Leg 127 (Yamanoi 1992). However, the dated strata cover more than 370 m of alternations of volcanic and sedimentary rocks containing marine microfossils such as *Cyclammmina* (700 m, Hole 797 C-22R-5, 146–150 cm; Nomura 1992), dinoflagellate cysts (760 m, Hole 797 C-30R-2, 73–75 cm; Yamanoi 1992) and calcareous nannofossils (530 m, Hole 797C-5R-3, 16–17 cm). Thus, the timing of the initial marine transgression is likely earlier than previously assumed, as illustrated by Nomura (1992; 22 Ma) and Yamanoi (1992).

It is noteworthy that sediments occur with rare but well-preserved Eocene to Oligocene dinoflagellate taxa (Powell 1992; Stover *et al.* 1996), such as *Deflandrea phosphoritica* (54–25.2 Ma; Eocene to Oligocene), *Adnatosphaeridium* cf. *multispinosum* (52–39.4 Ma; Eocene), *Areosphaeridium dictyoplokus* (51–36 Ma; Eocene), *Spinidinium* sp., *Wetzelliella* cf. *meckelfeldensis* (Ypresian, Early Eocene–Mid Lutetian, Middle Eocene) and *Wilsonidinium* cf. *lineidentatum* found from the Miocene deposits in the Dolgorae III-1 and III-2 wells (Fig. 1). The dinoflagellates suggest that Eocene to Oligocene sediment is present near the study area. In contrast, Paleogene sediment has not been recovered from any wells that reached non-marine basement in the study area. There are two scenarios for explaining the occurrence of Eocene to Oligocene dinoflagellate taxa.

First, the Paleogene cysts might be reworked from the Northern Kyushu area. Kurita *et al.* (2003) reports Paleogene dinoflagellates from Northern Kyushu Coal-bearing Basin. However, we suggest an adjacent area close to the Ulleung Basin is a more likely source site of the reworked dinoflagellates, because they are well preserved, and the dinocyst species composition of the study area is different from that of Kyushu, Fukue and the Cheju Basins (northern part of East China Sea Shelf Basin [Yun *et al.* 1999; KNOC 2004]). Second, the sediment of this age is confined to a narrow zone where marine transgression inundated a valley during an early stage of East Sea formation. Considering well preserved dinoflagellates, we

Table 3 Dinoflagellates distribution in the E well, Pohang Basin

Species	Early Miocene			Middle Miocene			Epoch
	D. craterum Zone			C. giuseppi Zone			
Depth (m)	Biozones			S. placacantha Z.			
Achomosphaera sp. cf. A. callosa							1100
Achomosphaera crassipellis							1100
Baïacasphaera spherica							1100
Bilectatodinium tepikiense							1100
Brigantodinium sp.							1100
Capilicysta fusca							1100
Capilicysta granulopellis							1100
Cordosphaeridium sp. nov.							1100
Cribrerodinium giuseppi							1100
Dapsilodinium pseudocoligerum							1100
Diphyes colligerum							1100
Diphyes sp. A							1100
Distatodinium craterum							1100
Distatodinium paradoxum							1100
Evittosphaerula paratatulata							1100
Heteraulacacysta campanula							1100
Hystrichokolpoma poculum							1100
Hystrichokolpoma rigaudiae							1100
Hystrichokolpoma salacium							1100
Hystrichokolpoma sp.							1100
Hystrichosphaeridium sp.							1100
Hystrichosphaeridium tubiferum brevispinosum							1100
Hystrichosphaeropsis obscura							1100
Hystrichostrogylon membraniphorum							1100
Impagidinium aculeatum							1100
Impagidinium japonicum							1100
Impagidinium paradoxum							1100
Impagidinium patulum							1100
Impagidinium striatum							1100
Impagidinium verolum							1100
Impagidinium sp. A							1100
Impagidinium sp.							1100
Lejeunecysta beninensis							1100
Lejeunecysta brassensis							1100
Lejeunecysta communis							1100
Lejeunecysta diversiforma							1100
Lejeunecysta fallax							1100
Lejeunecysta globosa							1100
Lejeunecysta granosa							1100
Lejeunecysta hyalina							1100
Lejeunecysta lata							1100
Lejeunecysta olivae							1100
Lejeunecysta pulchra							1100
Lejeunecysta spatiosa							1100
Lejeunecysta spp.							1100
Lingulodinium brevispinosum							1100
Lingulodinium machaerophorum filiform							1100
Lingulodinium machaerophorum machaerophorum							1100
Lingulodinium sadoense							1100
Melittosphaeridium choanophorum							1100
Nematosphaeropsis labrynthea							1100
Nematosphaeropsis lemniscata							1100
Operculodinium centrocarpum							1100
Operculodinium israelianum							1100
Operculodinium longispinigerum							1100
Operculodinium placitum							1100
Pentadinium laticinctum							1100
Polysphaeridium infectospinosum							1100
Polysphaeridium zoharyi							1100
Polysphaeridium sp. A of Byun & Yun							1100
Pterodinium cingulatum							1100
Reticulatosphaera actinocornata							1100
Selenopemphix coronata							1100
Selenopemphix naphroides							1100
Spiniferites adnatus							1100
Spiniferites belerius							1100
Spiniferites bentonii							1100
Spiniferites bulloideus							1100
Spiniferites delicatus							1100
Spiniferites hexatypicus							1100
Spiniferites membranaceus							1100
Spiniferites mirabilis							1100
Spiniferites pseudofurcatus							1100
Spiniferites ramosus granomembranaceus							1100
Spiniferites ramosus granosus							1100
Spiniferites ramosus membranaceus							1100
Spiniferites ramosus ramosus							1100
Spiniferites strictus							1100
Spiniferites sp. A							1100
Spiniferites spp.							1100
Systematophora placacantha curta stat. nov.							1100
Systematophora placacantha marginoculeolatus sp. nov.							1100
Systematophora placacantha placacantha							1100
Systematophora placacantha reductus ssp. nov.							1100
Trinovantodinium sp. A							1100
Tuberculodinium vancampoae							1100
Xandarodinium variable							1100
Xandarodinium xanthum							1100
TOTAL	726	456	726	726	456	726	726

believe that the Paleogene marine influence of the East China Sea seems to have extended northward close to the study area before the East Sea opening along the Korea Strait.

CONCLUSIONS

The interpretation of extensional rift origin for the study area contradicts the models of previous work. In a pull-apart model, the Ulleung (Yoon & Chough 1995; Yoon *et al.* 1997, 2002; Lee *et al.* 1999) and Pohang (Hwang *et al.* 1995) basins formed as a result of strike-slip tectonics, suggesting that thick accumulations of syntectonic sediment are limited to the vicinity of the strike-slip fault(s). However, the wide occurrence of the post-rift unconformity and syn-rift sediment cannot be explained in a pull-apart model. Also, the estimated age (older than 17 Ma) of the syn-rift sediment suggests that the crustal block movement during the formation of the syn-rift basin occurred in the study area before the clockwise rotation during 16–14 Ma (Otofuji *et al.* 1991) in the two-door model.

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