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Infill history of the Ulleung Basin, East Sea (Sea of Japan) and implications on source rocks and hydrocarbons

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Abstract

The Ulleung Basin in the East Sea (Sea of Japan) has experienced back-arc opening in the Miocene and partial closure since the middle Miocene. Uplift along the southern basin margin, caused by the back-arc closure, resulted in a series of anticlines and thrusts, providing large volumes of sediments into the basin. Mass-transport deposits dominated in the southern basin while turbidite and hemipelagic sedimentation prevailed in the northern basin. One-dimensional basin modeling shows that late postrift, early late-Miocene marginal-marine and prodeltaic sediments are buried too shallow to generate hydrocarbons. The main phase of oil generation in the synrift lacustrine and early-postrift marginal-marine facies (late Oligocene–early Miocene in age) beneath the southern basin margin occurred in the late early to early middle Miocene, predating the tectonic uplift. This significantly reduces the chances of large oil accumulations in the southern basin margin. The dominance of massive, non-uniform sediments in the southern basin, together with the lack of preferred avenues such as faults, are not favorable for the lateral migration of hydrocarbons, sourced possibly from basinal muds in the north, to the traps in the southern basin margin. Source rocks for the recently discovered gas in the southwestern shelf are probably the lacustrine and marginal-marine sediments that have been expelling gas at least since the late middle Miocene.

Keywords: Ulleung Basin; Back-arc basin; Source rocks; Basin modeling

1. Introduction

The East Sea (Sea of Japan) (Fig. 1) is a mature continental-margin back-arc basin that has evolved rapidly since the early Oligocene (Ingle, 1992). It is now in an early stage of compressive destruction or closure (Chough & Barg, 1987). The East Sea consists of three deep basins (Japan, Yamato, and Ulleung Basins), separated by submerged continental remnants such as the Korea Plateau, Oki Bank, Yamato Ridge, and Kita–Yamato Ridge. Deep drilling by the Deep Sea Drilling Project (Ingle et al., 1975) and the Ocean Drilling Program (ODP) (Ingle et al., 1990; Tamaki et al., 1990a) has provided significant information on geology and stratigraphy of the Japan and Yamato Basins. The deep Ulleung Basin, on the other hand, has yet to be drilled and little is known about its stratigraphy. Multichannel seismic reflection surveys and exploratory drilling in the southwestern margin of the Ulleung Basin have revealed that thick Miocene strata were folded and faulted by contractional tectonism associated with the back-arc closure (Chough & Barg, 1987; Park, 1998).

Many convergent margin basins, including back-arc basins, are petroliferous (Selley & Morrill, 1983). Back-arc basins in Western Indonesia have giant oil and gas fields (Selley & Morrill, 1983) that have produced over three quarters of the total crude oil of the nation (Pertamina, 2000). High heat flow and steep geothermal gradients during rifting and seafloor spreading appear to have enhanced oil and gas generation in Western Indonesia (Selley & Morrill, 1983). Cook Inlet, part of the arc-trench system off the southern coast of Alaska, is also petroliferous (North, 1985). The North Sakhalin Basin behind the Kuril Trench-Islands has produced oil and gas for decades (Sabirova & Allen, 2000). Recently discovered offshore fields in the North Sakhalin Basin are estimated at 3.5 billion bbl of oil and 1.5×10^{11} m^3 of gas for two projects alone (Sabirova & Allen, 2000). The eastern side of the Yamato Basin is one location where all the requirements for oil and gas accumulation are met (Marsaglia, 1995), but the sizes of

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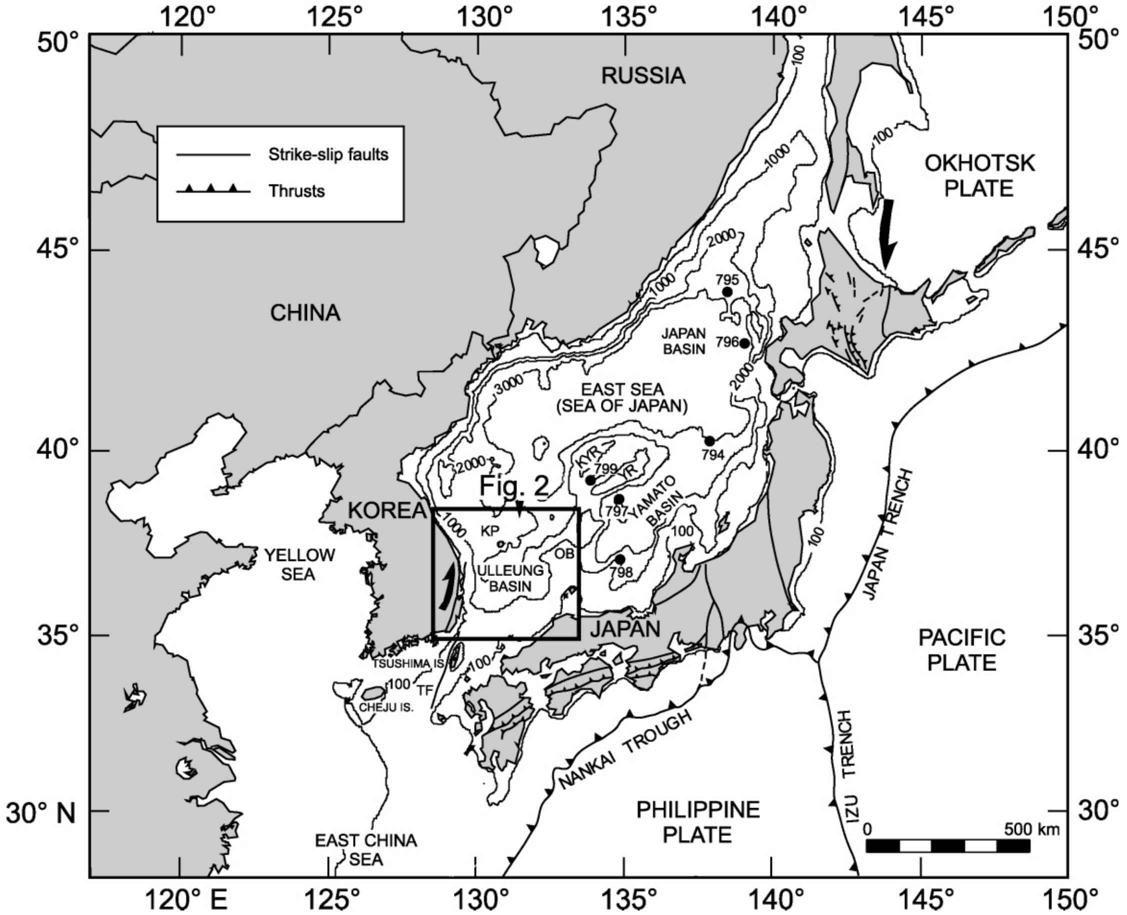

Fig. 1. Physiographic and tectonic map of the East Sea (Sea of Japan). The box represents the Ulleung Basin shown in Fig. 2. Dots represent the Ocean Drilling Program (ODP) sites. KP, Korea Plateau; OB, Oki Bank; YR, Yamato Ridge; KYR, Kita–Yamato Ridge; TF, Tsushima fault. Contour interval in meters. Modified after Jolivet and Tamaki (1992); Lee et al. (1999).

the oil and gas fields in the region are small. Most of these oil and gas fields are located in Neogene onshore basins of the northern Honshu (Kikuchi, Tono, & Funayama, 1991).

The recent discovery of a commercially viable gas accumulation in the southwestern shelf of the Ulleung Basin (Petzet, 2000) has proven that there is an active petroleum system in the area. The gas is trapped in a structural nose truncated updip by a shale-fill submarine canyon (Choi & Jang, 2000). However, despite extensive seismic surveys and a number of exploratory wells, petroleum systems in the area have rarely been studied. The principal reservoirs for the gas accumulation are known to be deltaic or marginal-marine sands (PEDCO, 1998) but source rocks remain poorly understood mainly because no wells have penetrated organic matter-rich sediments that may have hydrocarbon potential.

Although the general sedimentation pattern in the Ulleung Basin has been described (Chough & Lee, 1992; Lee, 1992), detailed stratigraphic studies defining temporal and spatial distribution of depositional elements are rare. Lee, Kim, Han, and Kim (2001), based on the interpretation of regional multi-channel seismic reflection profiles, suggested that the southern Ulleung Basin was filled mostly by mass-transport deposits formed by various mechanisms (e.g. slides, debris flows, and high-density turbidity currents, etc.), while the northern basin was dominated by hemipelagic sediments and distal turbidites. The southern basin margin appears to have remained the main sediment sources throughout much of the basin history.

In this study, we: (1) review the infill history of the Ulleung Basin, (2) discuss its implications on source rocks, and (3) examine the thermal maturity and petroleum generation potential of the basin, using one-dimensional (1D) basin modeling. A regional N–S, multi-channel seismic reflection profile and segments of other seismic reflection profiles (see Fig. 2 for location) are presented to illustrate the depositional facies in the basin. Data set from the Dolgorae-1 well (see Fig. 2 for location) in the southern shelf of the basin and from a dummy well (see Fig. 2 for location), located on the northern, distal part of the basin, were used for basin modeling. The Korea National Oil Corporation (KNOC) provided the seismic profiles and the Dolgorae-1 well data.

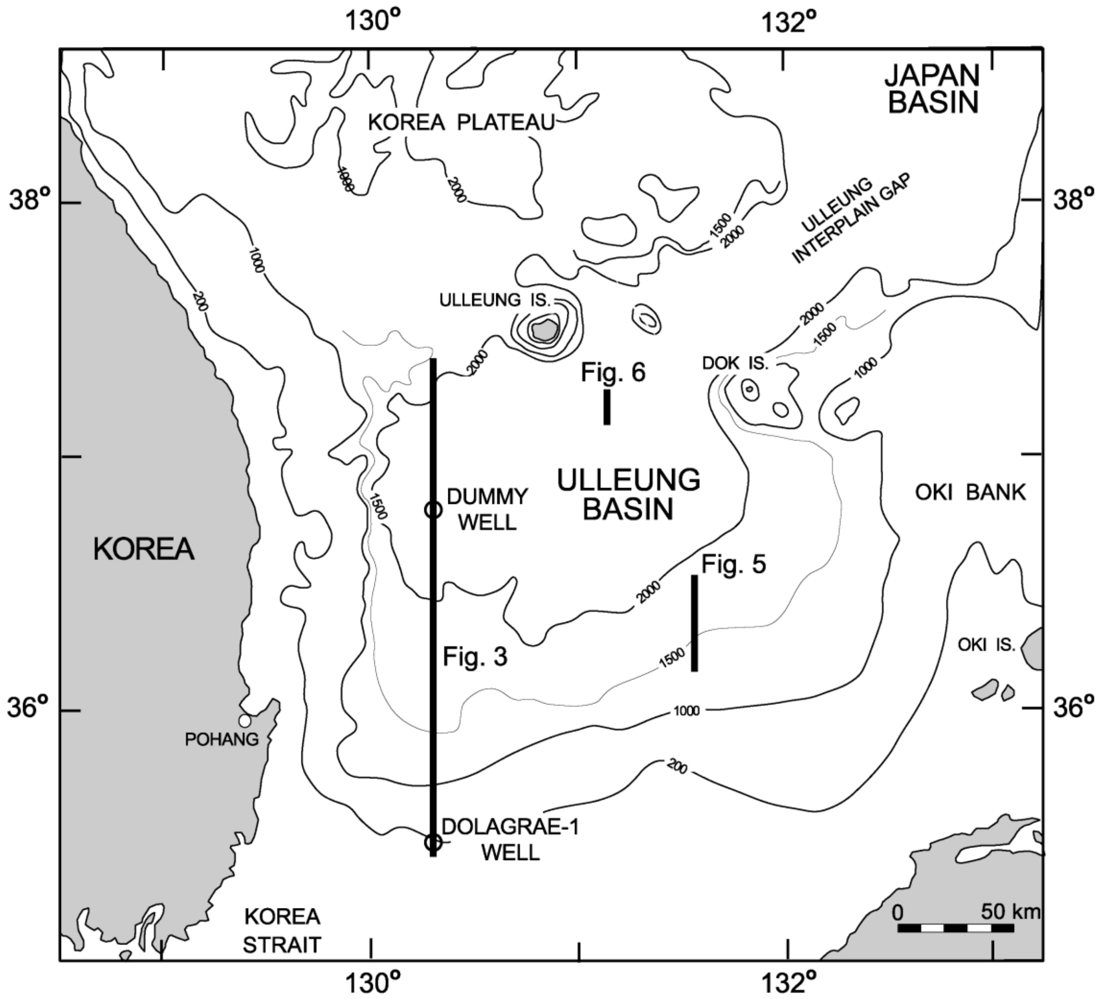

Fig. 2. Bathymetry of the Ulleung Basin. Heavy lines and respective figure numbers indicate locations of seismic profiles shown in other figures. Contour interval in meters.

2. Tectonic and geologic setting

The East Sea is a back-arc basin lying on the complex border between the eastern margin of the Eurasian Plate and the Philippine Sea and Pacific-Okhotsk plates (Tamaki & Honza, 1985) (Fig. 1). The opening of the East Sea was initiated by crustal thinning in the northeastern Japan Basin in the early Oligocene, followed by seafloor spreading in the late Oligocene (Tamaki, Suyehiro, Allan, Ingle, & Pisciotto, 1992). While seafloor spreading continued in the Japan Basin, the southern East Sea underwent crustal extension, leading to the opening of the Yamato and Ulleung Basins (Tamaki et al., 1992).

Paleomagnetic data from the Japanese islands suggest that the southern East Sea was opened by the rapid clockwise rotation (40–54°) of SW Japan in the early middle Miocene (Otofuji & Matsuda, 1987). The rotational opening requires an impossibly high drifting rate (up to 60 cm/yr) at the eastern end of SW Japan (Jolivet & Tamaki, 1992; Uyeda, 1991) and does not agree with the data from the ODP drilling that indicate a progressive opening of the southern East Sea since the late Oligocene–early Miocene (Tamaki et al., 1992). Lallemand and Jolivet (1985), based on onland and offshore structural data, proposed that the East Sea opening was initiated by a pull-apart, guided by two large right-lateral strike-slip fault systems on eastern and western sides of the sea (Fig. 1). Yoon and Chough (1995) proposed a combination pull-apart rotational model for the opening of the Ulleung Basin that includes less than 30° of rotation of SW Japan in the middle Miocene. More recently, Lee, Kim, Suh, and Hong (1999), based on seismic reflection profiles and ocean bottom seismometer data, suggested that the Ulleung Basin formed largely by N–S (pull-apart) extension, followed by a short period of seafloor spreading.

In the late middle Miocene, changes in plate motions and subduction mode along the subduction zones, east and southeast of the Japanese Island arc, caused back-arc closure and crustal shortening (Chough & Barg, 1987). This contractional event resulted in a series of northeast-trending anticlines and thrusts in the southern margin of the Ulleung Basin. Rates of uplift along the southern Ulleung

Basin margin, estimated from a balanced cross-section restoration, suggest that the back-arc closure may have begun in the early middle Miocene (Lee et al., 2001).

The Ulleung Basin is bounded by the steep continental slope of the Korean Peninsula to the west and by the rugged Korea Plateau to the north (Fig. 2). The gentle slopes of the Oki Bank and the Japanese islands form the eastern and southeastern basin margins, respectively. Water depths range from less than 1500 m in the south to over 2300 m in the northeast where the basin joins the deeper Japan Basin through the Ulleung Interplain Gap. The Ulleung Basin can be outlined approximately by the 1500-m bathymetric contour.

3. Infill history and source rock implications

3.1. Infill history: review and discussion

Back-arc basins initiate by crustal extension, producing first rifts and then new oceanic crust by seafloor spreading (Karig, 1971; Packham & Falvey, 1971). In contrast to the Japan Basin, magnetic lineations are apparently absent in the Yamato and Ulleung Basins (Isezaki, 1986). This led Tamaki et al. (1992) to propose that the Yamato and Ulleung Basins are underlain by extended continental or arc crust. Chough, Lee, and Yoon (2000) further suggested that volcanic sills are interlayered in the extended continental crust in the Ulleung Basin. ODP drilling that penetrated the uppermost part of the acoustic basement in the basinal area of the Yamato Basin encountered thick volcanic sill/flow-sediment complexes at the base (Tamaki et al., 1990a). The sediments immediately above or intercalated in the volcanic sills and flows do not indicate deposition in non-marine or continental environments. Extended continental crust often contains thick non-marine sediments deposited during initial rifting stage. Thus, ODP drilling in the Yamato Basin may not have penetrated the actual basement rocks. Alternatively, the basement in the basinal area of the Yamato Basin may not be extended continental crust.

The acoustic basement in much of the central part of the Ulleung Basin does not exhibit graben-and-horst topography, deemed to be characteristic of the initial rift phase of back-arc basin development, indicating non-brittle or ductile deformation and thus oceanic crust (Lee et al., 1999). The crustal velocity structure further suggests that the deep Ulleung Basin is underlain by thicker-than-normal (Kim et al., 1994), embryonic oceanic crust (Lee et al., 1999). Therefore, the sedimentary section in the deep Ulleung Basin consists mostly of postrift sediments deposited during and after the spreading phase, whereas that in the basin margins contain both a synrift non-marine unit and a postrift sequence that grades upward from non-marine to paralic and to deeper marine facies. Gross seismic facies analysis of the basin-fill sequence in the deep Ulleung Basin (Chough & Lee, 1992) suggests that the lower part of the basin-fill sequence is dominated by volcanic flows/sills and clastics/volcaniclatics, whereas the upper part of the basin fill consists largely of turbidites and hemipelagic sediments.

The isopach map of the basin-fill sequence in the Ulleung Basin reveals two subbasins or depocenters separated by a basement high (Lee et al., 2001). The regional N–S seismic reflection profile (Fig. 3) shows the two depocenters and the overall basin-fill geometry. The deep Ulleung Basin did not experience significant tectonic perturbations so that the sedimentary strata in the deep basin are generally horizontal and undeformed except locally by volcanic structures and minor faulting. The basement in the middle of the section in Fig. 3 appears to be cut by a thrust fault but this fault is seen only locally in the southwestern corner of the basin. Contractional deformation along the southern basin margin associated with the back-arc closure may have propagated locally into the basin, causing uplift or thrusting of the crustal blocks (Lee et al., 2001). The basin fill is thickest (>5.2 s in two-way travel time) in the southern basin and thins northward, exhibiting an overall wedge-like geometry. This pattern suggests that the southern margin was the main sediment source throughout much of the basin history. The maximum thickness of the basin fill in the northern basin is less than 2.5 s in two-way travel time.

The stratigraphic interpretation (Fig. 3(b)) of the regional profile was refined from that of the same profile published by Lee et al. (2001). Geologic ages of the interpreted horizons, except for the bottom two horizons including the top of the acoustic basement, were taken from those of the sequence boundaries defined by Park (1998) that are constrained by biostratigraphic data from the Dolgorae-1 well. The top of the acoustic basement was assumed to be earliest early Miocene (ca. 24 Ma?) in age beneath the southern shelf where the basement consists most likely of continental crust that underwent extension during the late Oligocene and early Miocene (Tamaki et al., 1992). The 20-Ma horizon in the southern basin was linearly interpolated between the top of the acoustic basement and the 15.5-Ma horizon. Much of the basement in the central and northern parts of the basin is probably comprised of younger oceanic crust (Lee et al., 1999). The ages of basement basalt in the Yamato Basin, determined by $^{40}Ar-^{39}Ar$ radiometric analyses, range from 18 to 21 Ma (Tamaki et al., 1992). The age of the oceanic crust in the northern Ulleung Basin was assumed to be 20 Ma (early middle Miocene).

The seismic facies types of the basin-fill sequence of the Ulleung Basin (Fig. 3), recognized by Lee et al. (2001), include: (1) variable amplitude, poor-to-low continuity reflections with hummocky and/or structureless to chaotic zones (seismic facies 1), suggesting massive, non-uniform deposition; (2) low-to-high amplitude, moderate-to-good continuity reflections (seismic facies 2), suggesting uniform deposition; and (3) packages of multiple layers of short, complex, and irregular, high-amplitude reflections (seismic facies 3). Seismic facies 1, dominant in the southern basin

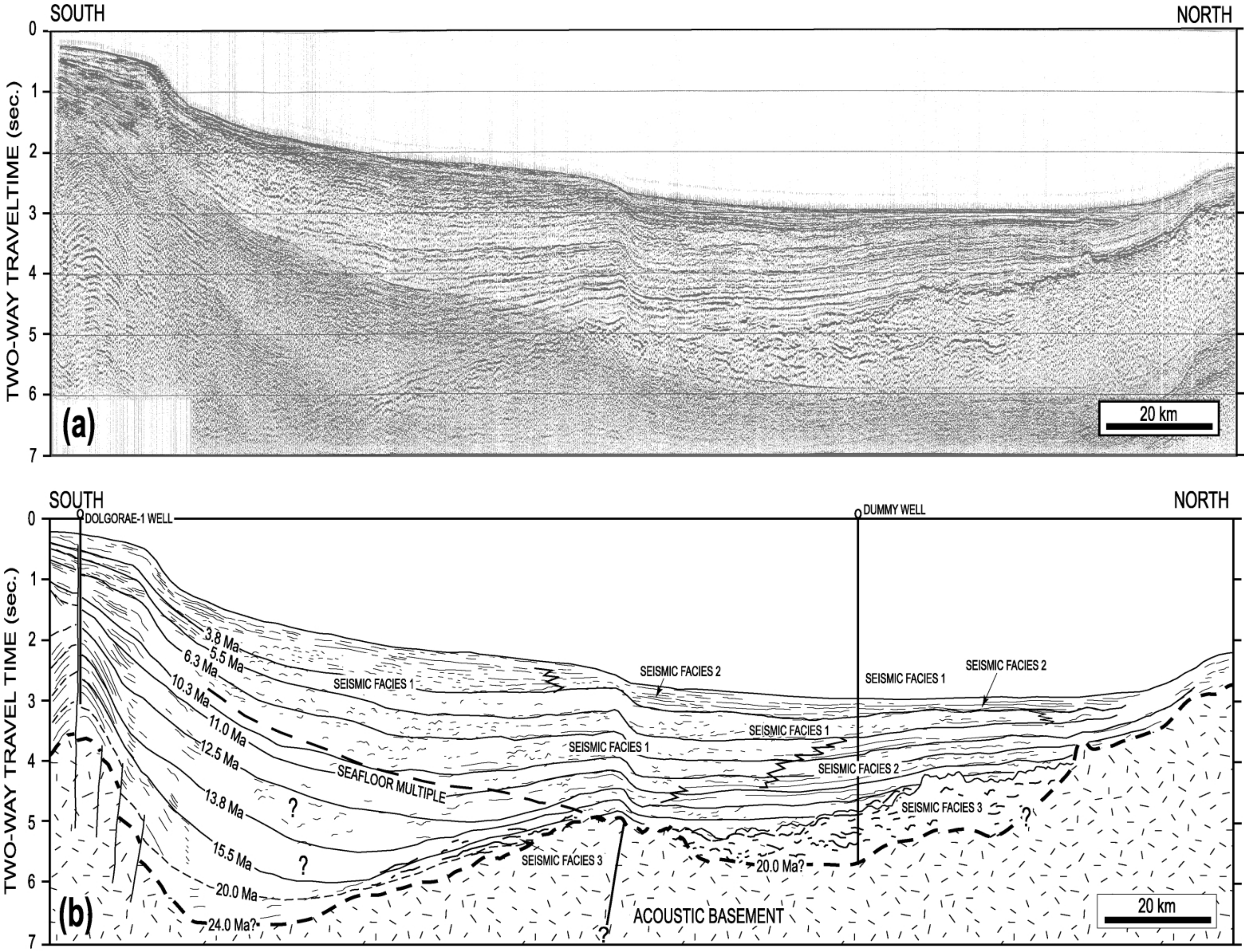

Fig. 3. (a) Regional N–S seismic profile (b) and its stratigraphic interpretation. Two subbasins or depocenters are separated by a basement high. The basin fill is thickest in the southern basin and thins northward, suggesting that southern basin margin was the main sediment source. Much of the southern basin and the southern part of the northern basin are characterized by seismic facies 1 (mass-transport deposits). The northern, distal part of the basin is dominated by seismic facies 2 (distal turbidites/hemipelagic sediments). Seismic facies 3 (volcanic sill/flow-sediment complexes) occurs immediately above the acoustic basement in the northern basin, indicating extensive volcanic activity during the early phase of basin spreading. See Fig. 2 for location. Stratigraphic interpretation was refined from Lee et al. (2001).

and the southern part of the northern basin, is interpreted as mass-transport deposits. Seismic facies 2 is seen mostly in the central, northern, and northeastern parts of the basin, away from terrigenous sediment sources and interpreted as distal turbidites/hemipelagic sediments or basinal muds. Seismic facies 3 occurs in the deepest part of the basin fill in the northern basin. Its seismic character is very similar to that of the basaltic sill/flow-sediment complexes that form the uppermost part of the acoustic basement in the Yamato Basin. Seismic facies 3 is interpreted as volcanic sills and flows intercalated with clastic and pyroclastic sediments deposited during the early phase of back-arc sedimentation.

The uplifted regions or uplands along the southern basin margin provided large volumes of sediments into the basin. Much of this sediment supply was deposited directly onto the base of slope and basin floor, resulting in widespread mass-transport deposits, especially in the southern basin, at least since the late middle Miocene (Lee et al., 2001). The ODP drilling in other back-arc basins in the western Pacific revealed that the early phase of back-arc sedimentation is dominated by mass-transport processes carrying clastic and pyroclastic materials into the basins (Silver et al., 1990; Einsele, 1992; Taylor, 1992). Much of the deeper part of the basin fill in the southern Ulleung Basin may also consist of mass-transport deposits although deep burial and deterioration of data quality as well as seafloor multiple make it difficult to detail seismic character.

The estimated sediment accumulation rate in the southern Ulleung Basin during the main phase (late middle Miocene) of uplift is approximately 1.3 km/myr that is an order of magnitude greater than those before and after the main uplift phase (Lee et al., 2001). The maximum two-way travel time sediment thickness (>5.2 s) in the southern Ulleung Basin is more than twice those (approximately 2.0 s; Ishiwada, Honza, & Tamaki, 1984) in the Japan and Yamato Basins where basinal turbidite and hemipelagic sedimentation has prevailed throughout the Neogene and Quaternary (Tamaki et al., 1992). Because the Ulleung Basin is younger than the Japan Basin, sedimentation in the southern Ulleung Basin was probably even more massive, dominated by mass-transport deposits.

The first appearance of a shelf edge in the southern Ulleung Basin margin in the earliest late Miocene (11–10.3 Ma) (Lee et al., 2001) marks the shelf-slope transition, characterized by prograding or regressive complexes of deltaic facies (Fig. 3). With waning tectonic movements along the southern basin margin, the volume of sediments entering the basin decreased significantly. Nevertheless, the dominance of seismic facies 1 in the southern basin indicates that sediment mass-movements persisted along the southern basin margin throughout much of the basin history. In the latest late Miocene, mass-transport deposits retreated rapidly in an updip direction, resulting in a radical change in sedimentary facies in the northern basin from coarse-grained, high-energy deposits to low-energy turbidites and hemipelagic sediments (Lee et al., 2001).

3.2. Source rock implications

About half of the exploratory wells drilled in the southern Ulleung Basin margin encountered some gas but no oil has been recovered, suggesting that the petroleum systems in the area are gas-prone. Geochemical analyses of gas samples from one of the wells in the inner shelf of the southwestern basin margin indicate a dominantly coaly source (PEDCO, 1998). Small amounts of condensates were also collected from this well. The condensates appear to have originated from the same coaly source. There were probably minor contributions to the condensates from a marine source as well (W.J. Kwak, personal communication, 2000).

The infill history of the Ulleung Basin suggests various depositional environments favorable for the accumulation of organic matter-rich sediments (Fig. 4). Source rocks with gas-prone type III kerogen (e.g. coaly shale) were probably deposited in paralic or marginal marine environments. The sedimentary strata that were penetrated by the Dolgorae-1 well consist mostly of marine (neritic to basinal environments) deposits. Coastal-plain deposits comprise a brief interval in the late Miocene when the tectonic uplift along the southern basin margin reached its peak, indicating that marine environments were pervasive in the region. Another well located in the inner shelf to the southwest of the Dolgrae-1 well encountered thick (ca. 1 km) shallow-marine and coastal/delta-plain sediments of middle to late Miocene age that were deposited during the main phase of the tectonic uplift (Shin, 2000). The continued uplift exposed the present-day inner shelf of the southern basin margin, truncating these sediments. Paralic deposits with source rock potential may also be found in the deeper part of the sedimentary section beneath the southern basin margin. However, the rapid initial back-arc subsidence (Park, Tamaki, & Kobayashi, 1990) quickly inundated the area, probably limiting the deposition of marginal-marine sediments to the very early phase of the back-arc subsidence.

Oil-prone source rocks (e.g. lacustrine sediments) containing type I kerogen are likely to be found in the synrift sequence that was deposited in grabens or half grabens formed during the initial rift phase of the basin development. Proprietary seismic data from the southwestern margin of the basin show a number of half grabens filled with thick (~ 1 s in two-way travel time) synrift sediments in the basement (Shin, 2000). Lacustrine sediments may also have been deposited in floodplain lakes in the marginal marine environments.

Other possible source rocks include marine facies such as prodeltaic muds and hemipelagic sediments or basinal muds. Prodeltaic muds can overcome the effects of oxidation and biological destruction of organic matter due to rapid sedimentation (Zimmerle, 1995). Prodeltaic muds may be found in the late Miocene and younger section along the southern Ulleung Basin margin because deltaic

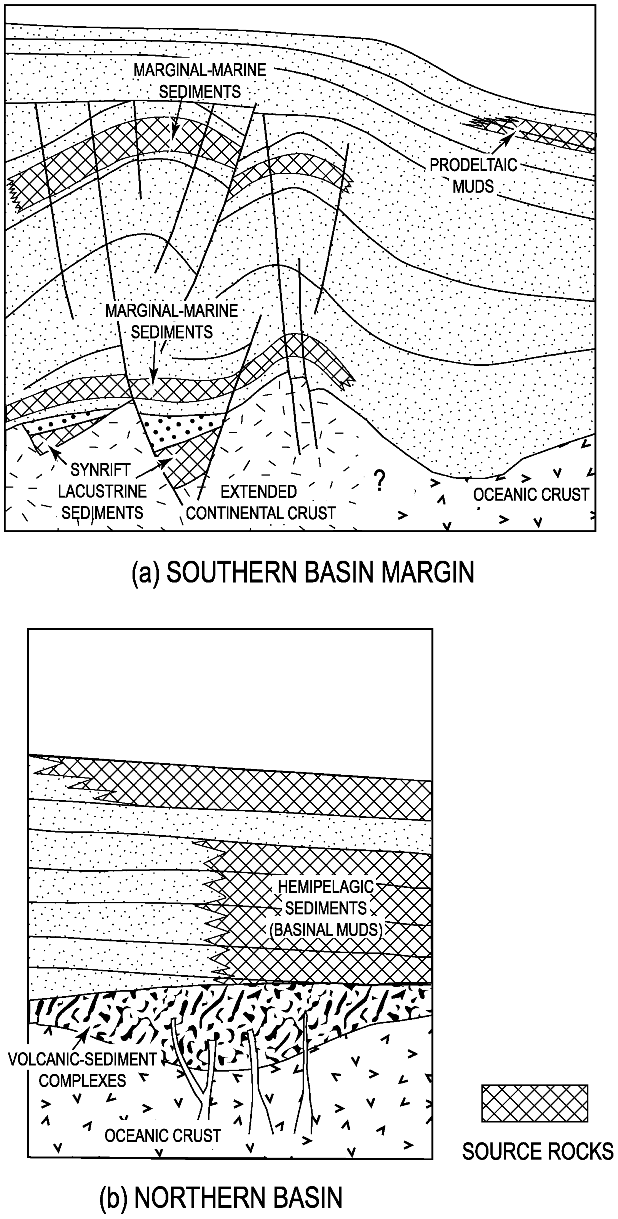

Fig. 4. Schematic diagrams showing: (a) possible source rocks in the southern basin margin (b) and the northern, distal part of the basin.

progradation began in the earliest late Miocene, as evidenced by the first appearance of a distinct morphologic shelf edge. However, the sedimentary section along the present-day base-of-slope region in the southern basin is dominated by discontinuous and hummocky or chaotic reflections (seismic facies 1) (Figs. 3 and 5). This suggests that sediment failures and mass movements continued along the southern margin until very recently, limiting the low-energy, quiet deposition of prodeltaic muds in the area. Continuous, uniform reflections, indicative of low-energy, uniform deposition (e.g. prodeltaic muds), are seen only locally (Fig. 5). Wedges or lenses of structureless or chaotic seismic facies, characteristic of debris-flow deposits (Nardin, Hein, Gorsline, & Edwards, 1979; Stoker, Harland, & Graham, 1991), dominate the shallow part of the sedimentary section (Fig. 5). High-resolution seismic reflection data also show recent active mass movements along the slope of the southern margin of the Ulleung Basin (Lee & Suk, 1998).

Because the East Sea is a semi-enclosed marginal sea with shallow sills, lowered sea level and/or tectonic uplift along its peripheral regions resulted in periods of basin isolation and stagnation (Ingle et al., 1990), providing anoxic conditions favorable for preservation of organic matter (Lee, Park, & Kim, 2000). However, the massive sedimentation in the Ulleung Basin most likely diluted organic matter. The sediment accumulation rates (ca. 30–130 cm/kyr; Lee et al., 2001) in the southern basin during the Miocene are much greater than the optimum sediment accumulation rates (1–10 cm/kyr; Bjørlykke, 1984) for good source rocks. On the other hand, hemipelagic sediments or basinal muds deposited in the northern, distal part of the basin may have good source rock potential. The sedimentary sequence in the northern basin (Fig. 6) is characterized by continuous, uniform reflections (seismic facies 2), suggesting distal turbidites/hemipelagic sediments or basinal muds. Minor faulting locally disrupted these sediments. Total organic carbon contents in the Neogene and Quaternary hemipelagic sediments recovered at ODP site 794 (see Fig. 1 for location) in the Yamato Basin range from less than 0.2% (very poor) to over 6% (very good) (Tada & Iijima, 1992).

Organic matter-rich sediments that may be intercalated between the volcanic sills and flows in the deepest part of the sedimentary section in the northern basin are probably overmature or severely altered due to the excessive heat associated with the volcanism.

4. Basin modeling

Source rocks in the Ulleung Basin can be grouped into two, based on their locations of occurrence: (1) synrift lacustrine and postrift marginal-marine facies that may be found beneath the southern shelf of the basin and (2) basinal muds comprising the basin fill in the northern, distal part of the basin (Fig. 4). To evaluate the petroleum potential of these source rocks, we modeled the stratigraphy versus time (geohistory) and thermal history for the two locations using GENEX® (version 2.2.0), which is a numerical simulation program for 1D basin modeling. Procedures in GENEX® basin modeling include: (1) backstripping and decompaction, (2) temperature reconstruction, and (3) kinetic modeling. GENEX® can compute the detailed thermal maturity of source rocks and the amount of expelled and residual hydrocarbons, but we examined only the geohistory and petroleum generation history because no quantitative information on source rocks are available. The three fraction kinetic model (Beicip-Franlab, 1995) was used to reproduce

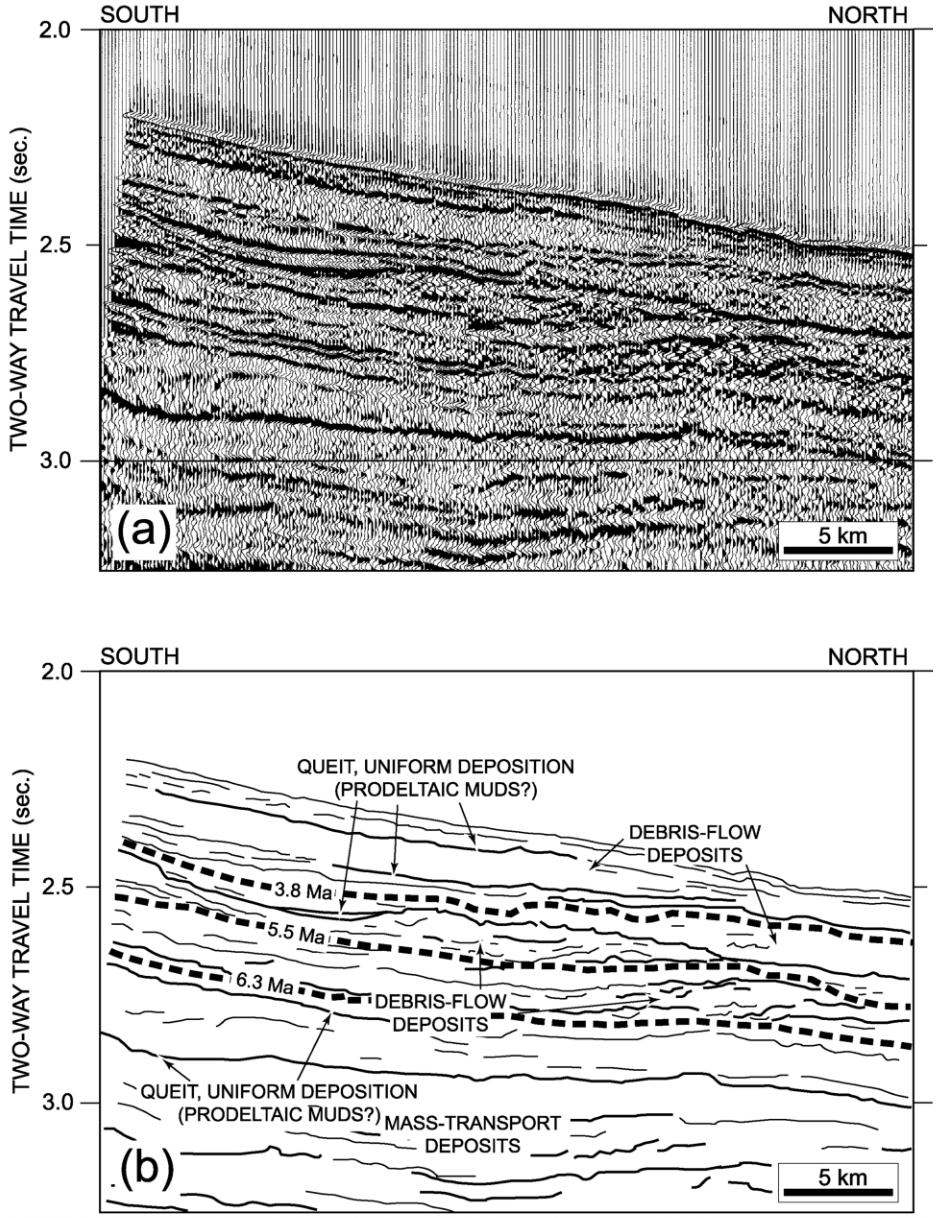

Fig. 5. (a) Seismic profile from the base-of-slope region in the southern basin margin and (b) its interpretation. Discontinuous and hummocky or chaotic reflections (seismic facies 1), indicating massive sedimentation, occur throughout the section. Wedges or lenses of structureless or chaotic seismic facies, characteristic of debris-flow deposits, dominate the shallow part of the section. Continuous, uniform reflections, indicative of low-energy, uniform deposition (e.g. prodeltaic muds), are seen only locally.

the influence of time and temperature on hydrocarbon generation. The kinetic models predict hydrocarbon formation more accurately than simpler models (Ungerer, Burrus, Doligez, Chénet, & Bessis, 1990). The three fraction kinetic model considers oil, gas, and solid carbon residue as generated fractions.

We used two wells in the basin modeling: (1) the Dolgorae-1 well (Fig. 7(a)) for the source rocks beneath the southern shelf and (2) the dummy well (Fig. 7(b)) located in the northern basin for the basinal muds. The Dolgorae-1 well penetrated 4265 m of early Miocene through Pleistocene sediments. To model the entire sedimentary section in the southern basin margin, the Dolgorae-1 well was extended beyond the actual bottom depth to the basement and assumed to have penetrated synrift sequence. Source rocks in the Dolgorae-1 well include gas-prone marginal-marine sediments deposited during the early postrift phase and during the peak of the tectonic uplift, and oil-prone lacustrine sediments in the synrift sequence. The synrift source rocks were assumed to lie below the 24-Ma horizon. The coastal-plain deposits comprising the brief interval in the late Miocene section of the well do not contain source-quality organic matter but were assumed to be source rocks for the sake of modeling. Paleobathymetries at the Dolgorae-1 well site were modified from the geohistory curve by Chough and Barg (1987) and Ingle (1992).

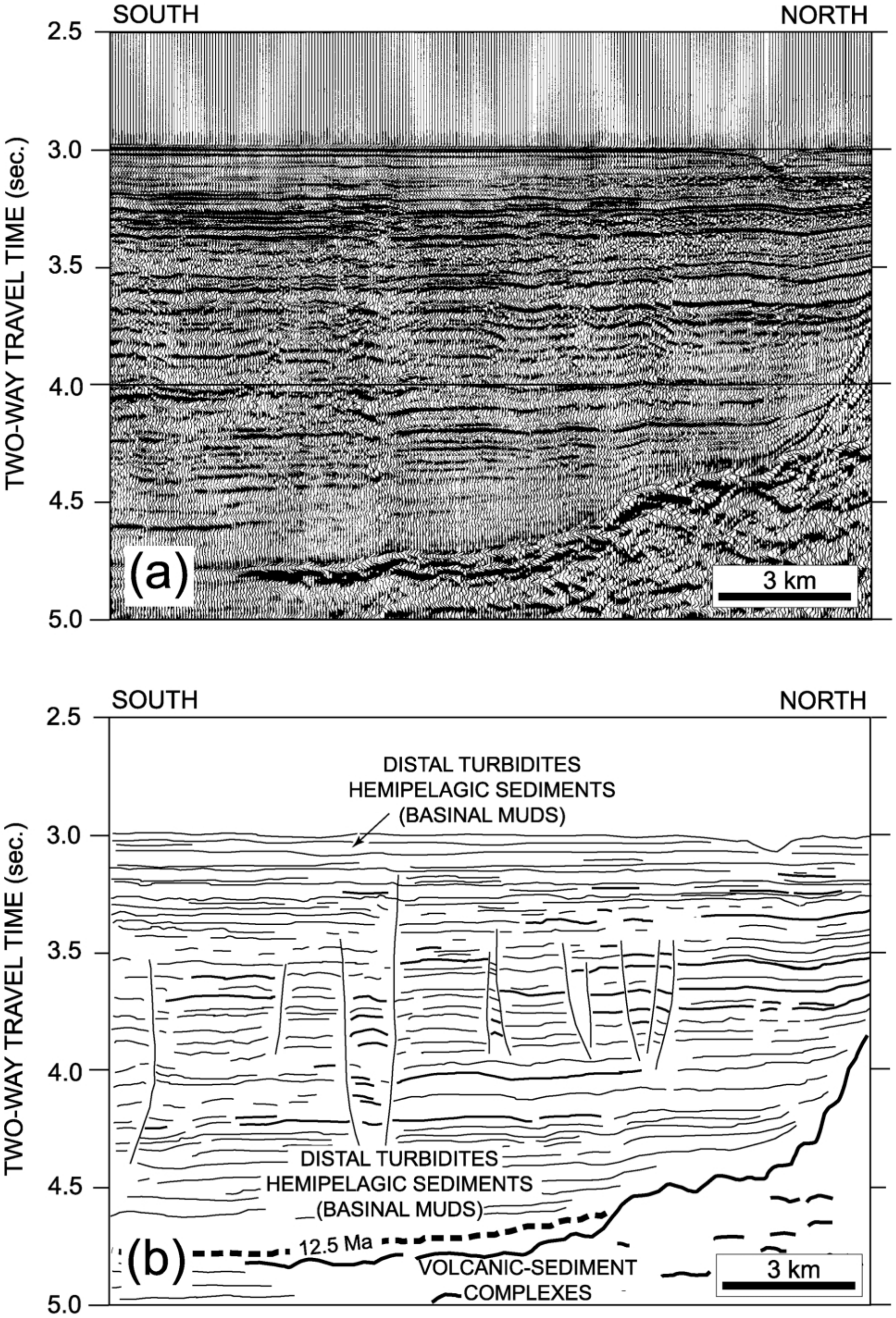

Fig. 6. (a) Seismic profile from the northern, distal part of the basin and (b) its interpretation. Continuous, uniform reflections (seismic facies 2), suggesting distal turbidites/hemipelagic sediments or basinal muds, are the dominant in the section. Minor faulting disrupted the sediments locally.

We assumed that the uplift at the well site began in the early middle Miocene (ca. 14 Ma; Lee et al., 2001) and peaked in the early late Miocene (ca. 10 Ma) that corresponds to the brief interval of the coastal-plain facies.

The dummy well is located in the western part of the northern basin along the regional N–S seismic profile (Fig. 3(b)). The sedimentary section above the volcanic sill/flow-sediment complexes at the dummy well site appears to be dominated by basinal muds except for mass-transport deposits of the early Pliocene interval (5.5–3.8 Ma) (Fig. 3). Thus, the dummy well was constructed based on the data from ODP site 794, located on the abyssal plain of the northern Yamato Basin where fine-grained hemipelagic sedimentation has prevailed at least since the early middle Miocene (Tamaki et al., 1990b). For the time-to-depth conversion at this well, we used the depth and interval velocity data from ODP site 794. To estimate paleobathymetries at

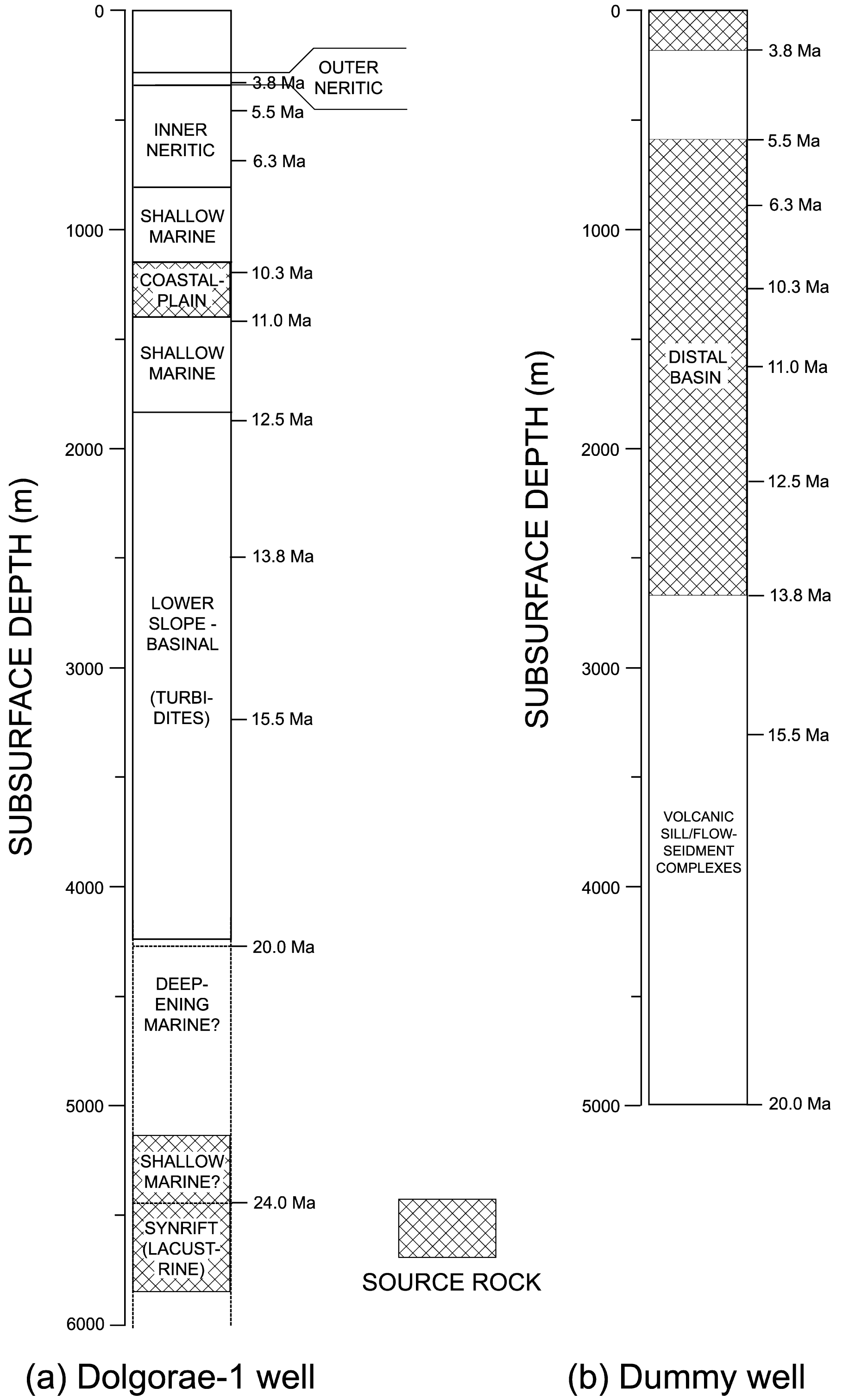

Fig. 7. Lithologic columns of (a) the Dolgorae−1 well and (b) the dummy well. The Dolgorae-1 well was extended beyond the actual bottom depth (4265 m) to the basement and assumed to have penetrated synrift sequence. The sedimentary section above the volcanic sill/flow−sediment complexes at the dummy well site is dominated by basinal muds except for mass-transport deposits of the early Pliocene interval (5.5−3.8 Ma).

the dummy well site, we backtracked the well site to its original depth of deposition using the age-depth relation for back-arc basins proposed by Park et al. (1990). This backtracking technique with decompaction correction has been used to reconstruct the temporal variations of the calcite compensation depth in major ocean basins (e.g. van Andel, 1975) and in the East Sea (Lee et al., 2000). We assumed that the initial water depth at the dummy well site was 1700 m, which is the average of the initial water depths at ODP sites 794, 795, and 797 (Lee et al., 2000).

The heat flow and grain thermal conductivity for the dummy well site were taken from those measured at ODP site 794, reported by Nobes, Langseth, Kuramoto, Holler, and Hirata (1992), Tamaki et al. (1990b), respectively. The present-day heat flow at ODP site 794 is 103 mW/m^2 that is much higher than the regional mean values of the various parts of the world (Sclater, Jaupart, & Galson, 1980). For example, the mean surface heat flow of oceanic basins is 78.2 mW/m^2. Thus, the heat flow at ODP site 794 probably reflects a contribution from the thermal anomaly associated with back-arc opening. The dummy well was assumed to have penetrated the oceanic basement of early Miocene age (ca. 20 Ma) that formed during the earliest phase of seafloor spreading in the Ulleung Basin.

Most input parameters involved in basin modeling generally have varying degrees of uncertainty (Poelchau, Zwach, Hantschel, & Welte, 1999). The key input parameters for the basin modeling for the Dolagorae-1 and dummy wells are listed in Table 1. Default values were used for some of the other input parameters that are either usually unknown (e.g. basal heat flow, pressure regime) or adjusted within reasonable boundaries to fit observations (e.g. crustal density and conductivity) (Beicip-Franlab, 1995).

Rifting heat flow hypothesis (Beicip-Franlab, 1995) was applied to the Dolgorae-1 well to account for the increase of heat flow during rifting due to the progressive thinning of the asthenosphere basement and the advection of heat at the asthenosphere temperature (1333 °C) across the lithosphere boundary. The rifting and crustal extension (beta factor or extension ratio = 1.4) were assumed to have begun in the earliest early Miocene (ca. 24 Ma) and ended in the middle early Miocene (ca. 20 Ma). Because GENEX® does not include seafloor spreading in the thermal data, the rifting heat flow hypothesis was also applied to the dummy well to handle the increase of heat flow during seafloor spreading, but the beta factor was assumed to be 1.0 because there was no extension of the oceanic basement. The seafloor spreading was assumed to have lasted from the middle early Miocene (ca. 20 Ma) to the middle Miocene (ca. 14 Ma).

The burial and geohistory plots with hydrocarbon windows for the Dolgorae-1 and dummy wells are shown in Figs. 8 and 9, respectively. The onset of oil generation in the synrift sequence at the Dolgorae-1 well location occurred in the late early Miocene (ca. 17 Ma). Oil generation in the deep marginal-marine sediments began at the beginning of the middle Miocene (ca. 16 Ma). The main phase of oil generation ceased at about 14 Ma. The main phase of gas generation began in the late middle Miocene (ca. 12 Ma). The tectonic uplift along the southern Ulleung Basin margin apparently did not affect source rock maturity at the Dolgorae-1 well location because the burial depth (depth from the seafloor) of the source rocks continued to increase (Fig. 8(a)). Maximum burial at the Dolgorae-1 well location is the present day. The shallow

Table 1
Key input parameters for 1D basin modeling

Dolgorae-1 well			Dummy well		
Horizon (Ma)	Subsurface depth (m) (present-day)	Paleobathymetry (m)	Horizon (Ma)	Subsurface depth (m) (present-day)	Paleobathymetry (m)
3.8	316	193	3.8	190	2420
5.5	457	145	5.5	590	2513
6.3	695	130	6.3	900	2554
10.3	1200	30	10.3	1280	2710
11.0	1416	930	11.0	1630	2729
12.5	1872	1790	12.5	2150	2753
13.8	2499	2145	13.8	2650	2757
15.5	3237	2150	15.5	3300	2725
20.0	4400	1438	20.0	5000	1700
24.0	5443	0			
Basement crustal thickness					
35 km			9.5 km[a]		
Surface temperature					
8 °C[b]			0.5 °C[c]		
Geothermal gradient: 3.8 °C/100 m[d]			Surface heatflow: 103 mW/m^2 [e]		
Source rock kerogen type					
Type III (marginal-marine sediments)			Type II (basinal muds)		
Type I (lacustrine sediments)					

[a] Lee et al. (1999).
[b] Yang and Park (1992).
[c] Kim and Kim (1996).
[d] Kwak (personal communication, 2000)
[e] Tamaki et al. (1990b).

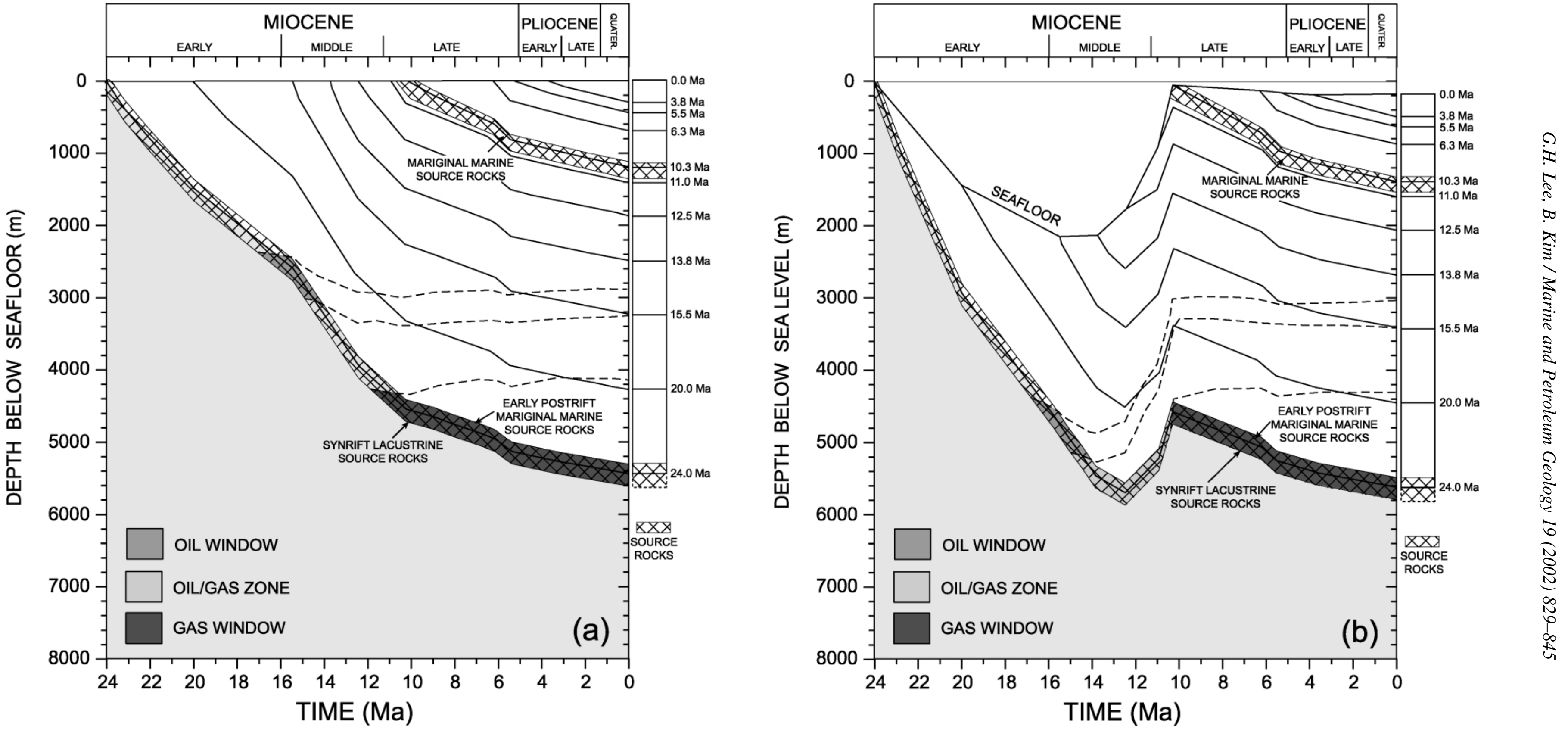

Fig. 8. Burial (a) and geohistory curves (b) for the Dolgorae-1 well. Sequence of sedimentation and subsidence for the well location is shown in black lines. Dashed lines are hydrocarbon window boundaries. The main phase of oil generation began in the late early Miocene (ca. 17 Ma) and ceased in the early middle Miocene (ca. 14 Ma). The main phase of gas generation began in the late middle Miocene (ca. 12 Ma).

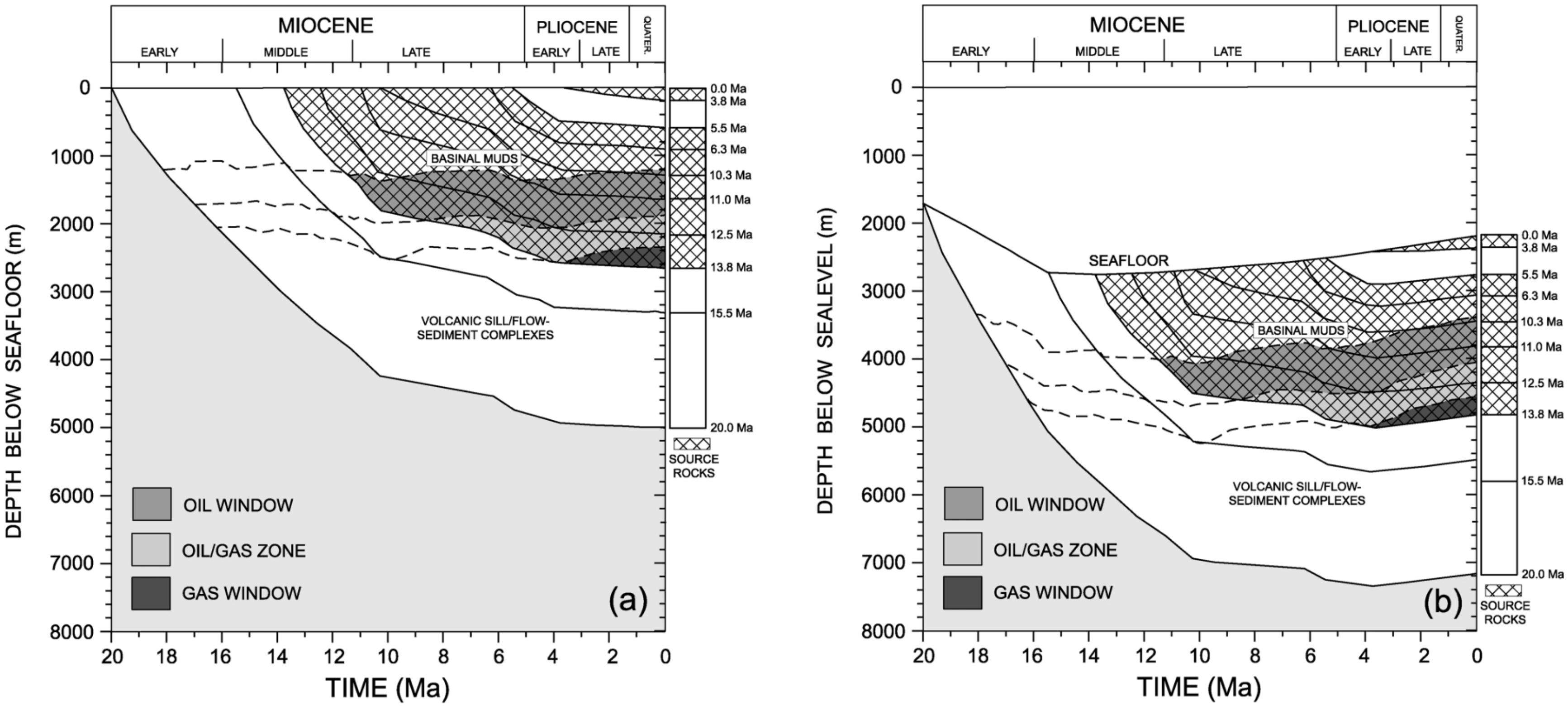

Fig. 9. (a) Burial and (b) geohistory curves for the dummy well. Sequence of sedimentation and subsidence for the well location is shown in black lines. Dashed lines are hydrocarbon window boundaries. The main phases of oil and gas generation began in the latest middle Miocene (ca. 11.5 Ma) and the early Pliocene (ca. 4 Ma), respectively. The top of the oil window has remained at about 1000–1300 m depth below the seafloor.

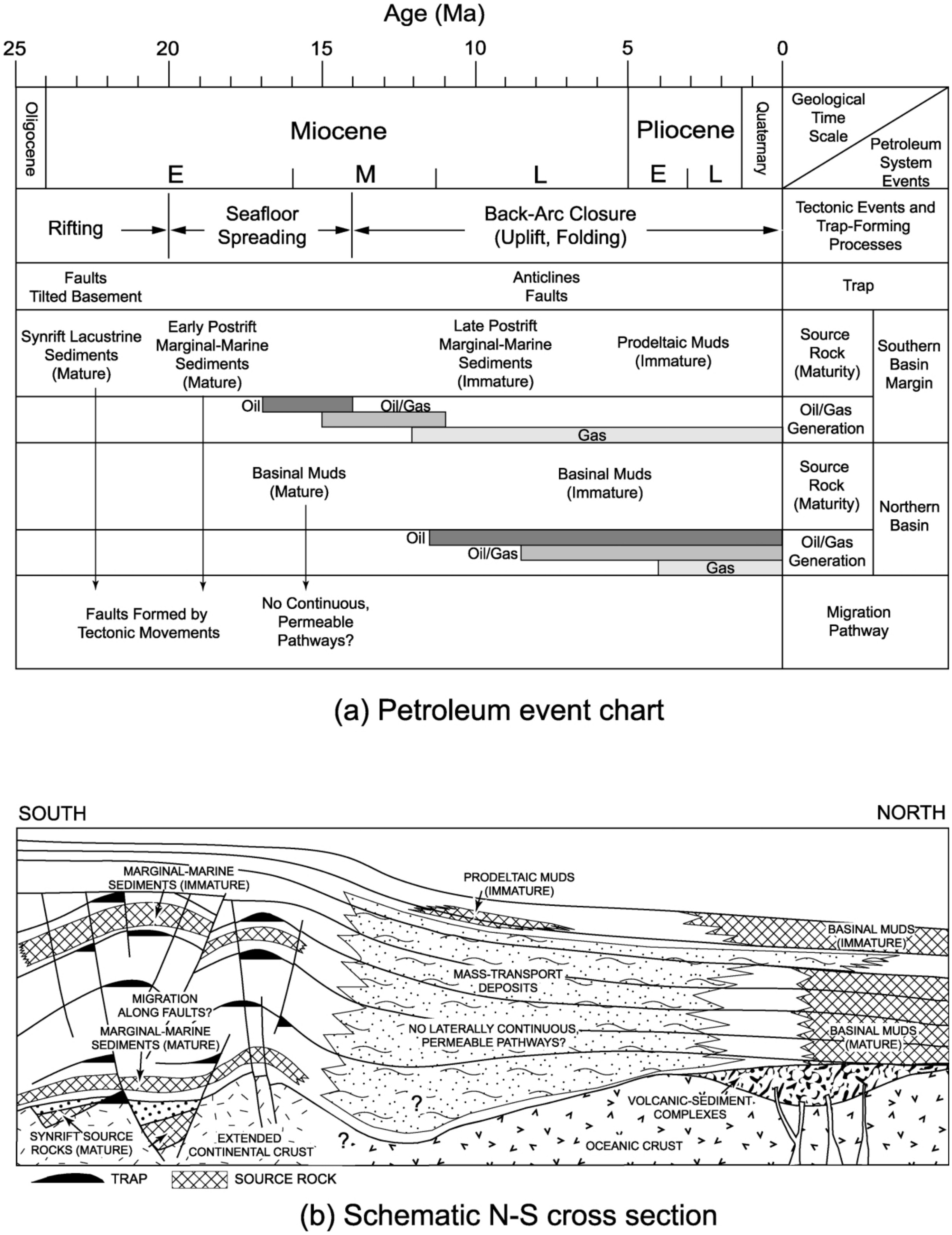

Fig. 10. (a) Petroleum event chart for the Ulleung Basin and (b) schematic cross-sectional diagram illustrating distribution of source rocks, structural traps, and hydrocarbon migration. The main phase of oil generation in the source rocks beneath the southern shelf predated the tectonic uplift that created large traps along the southern basin margin. The dominance of massive, non-uniform sediments in the southern basin and the lack of preferred avenues are not favorable for the lateral migration of hydrocarbons from the basinal muds in the northern basin to the traps in the south. Source rocks for the gas accumulations in the southern shelf are probably the deep, marginal-marine and lacustrine sediments that have been generating gas at least since late middle Miocene.

marginal marine source rocks are thermally immature. Prodeltaic muds that may be found further seaward of the Dolgorae-1 well are also immature.

The main phase of oil generation at the Dummy well site began in the latest middle Miocene (ca. 11.5 Ma). The top of the oil window has remained at about 1000–1300 m depth below the seafloor, indicating that source rocks as young as middle late Miocene in age can expel oil. The main phase of gas generation began in the early Pliocene (ca. 4 Ma). The thicknesses of oil and gas windows are over 750 m. Maximum burial at the dummy well location is the present day.

5. Discussion: from source to trap

Shown in Fig. 10 are: (a) the summary of petroleum events in the Ulleung Basin and (b) a schematic cross-sectional diagram illustrating distribution of source rocks, structural traps, and hydrocarbon migration. The source rocks with potential to generate hydrocarbons include: (1) marginal-marine sediments deposited during the early phase of basin development, (2) lacustrine sediments deposited in the graben and half-graben lake systems formed during the basin rifting, and (3) basinal muds in the northern, distal part of the basin. Marginal-marine sediments deposited during the main phase of the tectonic uplift along the southern basin margin and prodeltaic muds found in the upper part of the section in the southern basin are buried too shallow to generate hydrocarbons. Prodeltaic muds may also be insignificant in volume. The thick marginal marine sediments found beneath the inner shelf to the southwest of the study area, which were deposited during the main phase of the tectonic uplift, may have source potential but they probably also occur above the oil window. These sediments appear to have experienced extensive uplift (>2 s in two-way travel time; Shin, 2000).

Basin modeling indicates that the main phase of oil generation in the deep source rocks at the Dolgorae-1 well location occurred in the late early–early middle Miocene, which predated the tectonic uplift that created large anticlinal traps along the southern Ulleung Basin margin. This significantly reduces the chances of large oil accumulations in the area, because traps should be created before or during hydrocarbon migration to retain oil and gas. Older and deeper traps formed during the initial rifting phase of the Ulleung Basin such as faults and tilted (weathered and fractured) basement blocks may have accumulated oil if their trap integrity had not been disrupted by the tectonic uplift associated with the back-arc closure. These traps have never been tested.

The main phase of gas generation in the deep source rocks at the Dolgorae-1 well location began in the late middle Miocene and is active today, thus postdating the tectonic uplift. This is probably why the southern Ulleung Basin margin is gas-prone with the gas trapped mainly in the anticlinal structures formed by the tectonic uplift. Source rocks for the recently discovered gas in the shelf to southwest of the basin, therefore, are probably the deep, marginal-marine and lacustrine sediments. Gas from these source rocks likely migrated vertically into the anticlinal traps along fractures and faults that developed in association with the tectonic uplift.

The basinal muds in the northern, distal part of the basin appear to have hydrocarbon generation potential at least since the latest middle Miocene. The shallow oil window (<1300 m below seafloor) is probably due to the high heat flow in the area. In the Sumatra Basin in Western Indonesia, sediments at depths of even less than 1000 m are oil productive because of very high heat flow (Selley & Morrill, 1983). Nevertheless, large traps are not likely in the northern Ulleung Basin because much of the deep basin and its margins did not experience significant tectonic perturbations. The dominance of massive sediments in the southern basin, together with the lack of preferred conduits (e.g. faults) in the basin-fill sedimentary strata, probably limited continuous permeable (carrier) beds that can facilitate the migration of hydrocarbons from the basinal muds to the traps in the south. Moreover, the traps in the southern basin margin may be beyond the range of lateral, secondary migration for the hydrocarbons sourced possibly from the kitchen area in the northern basin. Distance covered by secondary migration are in the range of 10–100 km although distances of over 100 km are not unreasonable, provided privileged migration avenues such as regional unconformities are available (Tissot & Welte, 1978). Distance also affects the amount of oil or gas that reaches a trap due to the increase in residual oil or gas left in the migration conduit with increasing distance (Cornford, 1990).

6. Summary and conclusions

1. The back-arc closure in the East Sea caused strong tectonic activity and uplift along the southern Ulleung Basin margin, resulting in a series of anticlines and thrusts. The uplifted regions provided large volumes of sediments to the basin, which were transported mostly by mass-transport processes. As a result, the southern basin is dominated by mass-transport deposits while the northern, distal part of the basin is filled with distal turbidites and basinal, hemipelagic sediments.
2. Source rocks in the Ulleung Basin can be grouped into two, based on their locations: (1) synrift lacustrine and early postrift marginal-marine facies (late Oligocene–early Miocene in age) that may be found deep beneath the southern shelf of the basin and (2) basinal muds comprising much of the basin fill in the northern, distal part of the basin. Marginal-marine sediments, deposited during the main phase of active uplift along the southern basin margin, and prodeltaic muds, deposited after the deltaic progradation began along the southern basin margin, are buried too shallow to generate hydrocarbons.

3. The dominance of massive, non-uniform sediments, together with the lack of preferred avenues, are not favorable for the lateral migration of hydrocarbons, sourced possibly from the basinal muds in the northern, distal part of the basin, to the traps along the southern basin margin. These traps may also be beyond the range of lateral migration for the hydrocarbons sourced from the basinal muds.
4. The main phase of oil generation in the early-postrift marginal-marine and lacustrine sediments occurred in the late early to early middle Miocene, predating the tectonic uplift that created large traps along the southern basin margin. This significantly reduces the chances of large oil accumulations. Older and deeper traps may contain oil.
5. Source rocks for the recently discovered, large gas accumulation in the shelf to southwest of the Ulleung Basin are probably the deep, marginal-marine and lacustrine sediments that have been generating gas at least since the late middle Miocene.

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