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Evolution of Neogene Sedimentary Basins in the Eastern Continental Margin of Korea

한반도 동해 대륙주변부 신제삼기 퇴적분지의 진화

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Abstract : Seismic reflection profiles from the eastern continental margin of Korea delineate three major Neogene sedimentary basins perched on the shelf and slope regions: Pohang-Youngduk, Mukho and Hupo basins. The stratigraphic and structural analyses demonstrate that the formation and filling of these basins were intimately controlled by two phases of regional tectonism: transtensional and subsequent contractional deformations. In the Oligocene to Early Miocene, back-arc opening of the East Sea induced extensional shear deformation with dextral strike-slip movement along right-stepping Hupo and Yangsan faults. During the transtensional deformation, the Pohang-Youngduk Basin was formed by pull-apart opening between two strike-slip faults; in the northern part, block faulting caused to form the Mukho Basin between basement highs. As a result of the back-arc closure, the stress field was inverted into compression at the end of the Middle Miocene. Under the compressive regime, two episodes (Late Miocene and Early Pliocene) of regional deformation led to the destruction and partial uplift of the basin-filling sequences. In particular, during the second episode of compressive deformation, the Hupo fault was reactivated with an oblique-slip sense, which resulted in an opening of the Hupo Basin as a half-graben on the downthrown fault block.

Key Words : East Sea continental margin, sedimentary basin, strike-slip fault, seismic stratigraphy

요 약

한반도 동해 대륙주변부에서 취득한 에어건 탄성파 탐사자료에 의하면, 이 지역에는 포항-영덕분지, 묵호분지, 후포분지 등, 세 개의 주요 신제삼기 퇴적분지가 대륙붕 및 대륙사면에 형성되어 있다. 이들 퇴적분지에서의 탄성파층서 및 구조분석 결과, 분지의 형성과 퇴적물 충진은 주향이동신장성(transtensional) 및 차후의 압축성(contractional) 광역지구조운동과 밀접한 관계를 갖고 있는 것으로 보인다. 동해 후열도분지가 확장되기 시작하던 올리고세와 전기 마이오세 동안, 한반도 동해 대륙주변부에는 신장성 전단력(tensional shear stress)이 작용하여 후포단층과 양산단층을 따라 우수주향이동 단층운동이 일어났으며, 이들 평행한 두 단층 사이의 중첩부에는 당겨열림작용(pull-apart opening)에 의해 포항-영덕 분지가 형성되었다. 한편, 한국대지(Korea Plateau)와 접한 동해 대륙주변부에서는 블럭단층운동으로 인해 융기된 고기저(basement highs) 사이에 묵호분지가 형성되었다. 그 후 중기 마이오세 말에 동해가 닫히기 시작하면서, 연구지역의 응력장은 신장성에서 압축성으로 전환되었으며, 후기 마이오세와 전기 플라이오세, 두 번에 걸쳐 지각변형이 일어나면서 분지를 충진한 퇴적층이 변형되었고, 일부지역에서는 융기가 일어났다. 특히, 전기 플라이오세 동안에는 후포단층이 사교이동양상(oblique-slip sense)을 보이면서 재활성화 되었으며, 이로 인해 반지구(half-graben)형태의 후포분지가 형성되었다.

주요어 : 동해대륙주변부, 퇴적분지, 주향이동단층, 탄성파층서

INTRODUCTION

The eastern continental margin of Korea is underlain by Neogene and Quaternary sequence resting on Precambrian to Paleogene basement composed of gneiss, granite and sedimentary and volcanic rocks (Huntec Ltd., 1967; Schlüter and Chun, 1974; Kim, 1981). Thick Neogene sediments are accumulated largely in some structure-controlled sedimentary basins that have been folded and faulted in response to the back-arc opening and closing of the East Sea (Sea of Japan) (Chough and Barg, 1987; Yoon and Chough, 1992). In this study, we analyze stratigraphic and structural characteristics of the Neogene sedimentary basins, based on closely spaced seismic reflection data from the continental margin between 36° 05'N and 37° 50'N (Fig. 1). The data grid mainly consists of single-channel airgun profiles (35 transverse and 13 tie lines) obtained by the Geological Survey of Korea (GSK) and the Geological Survey of Germany (GSG) in 1972 (Schl ter and Chun, 1974), the Korea Institute of Energy and Re-

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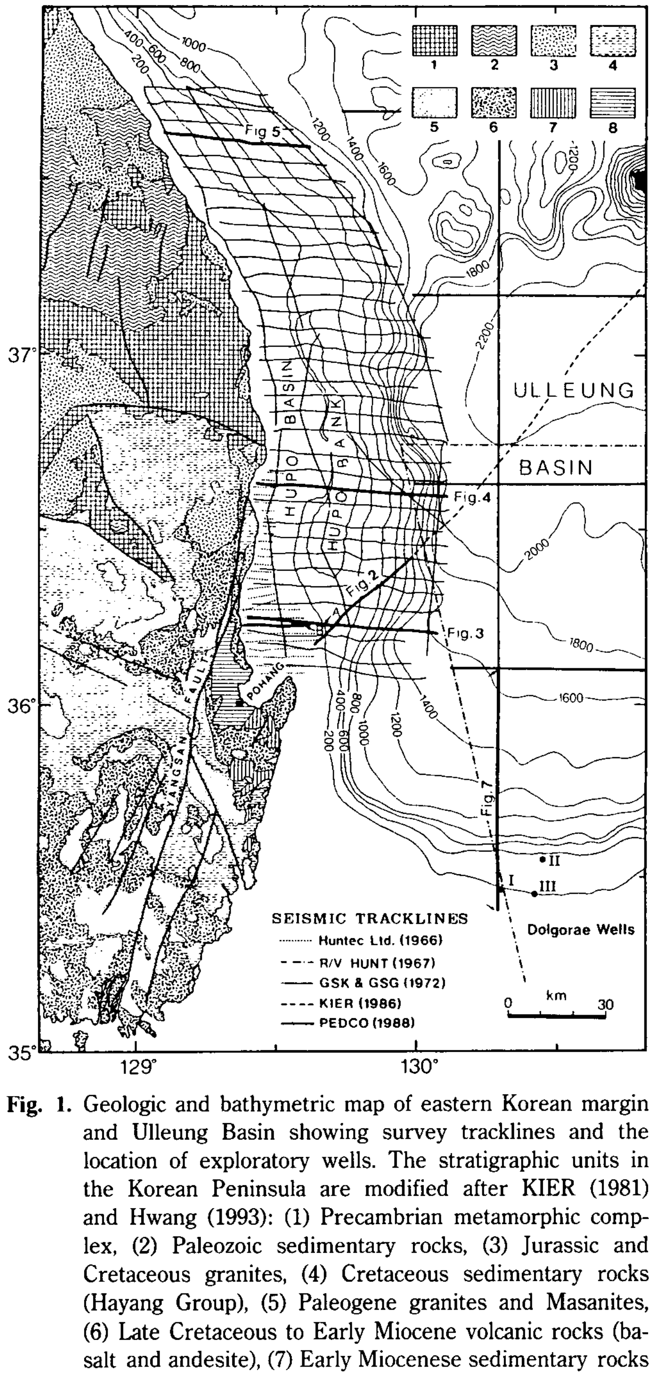

Fig. 1. Geologic and bathymetric map of eastern Korean margin and Ulleung Basin showing survey tracklines and the location of exploratory wells. The stratigraphic units in the Korean Peninsula are modified after KIER (1981) and Hwang (1993): (1) Precambrian metamorphic complex, (2) Paleozoic sedimentary rocks, (3) Jurassic and Cretaceous granites, (4) Cretaceous sedimentary rocks (Hayang Group), (5) Paleogene granites and Masanites, (6) Late Cretaceous to Early Miocene volcanic rocks (basalt and andesite), (7) Early Miocenese sedimentary rocks (Yangbuk Group), (8) Middle to Late Miocene sedimentary rocks (Yeonil Group). Bathymetry of the Korea Plateau and the Ulleung Basin is compiled from Japan Maritime Safety Agency (1966), Chough and Lee (1992) and Lee *et al.* (1993). Locations of seismic profiles of Figs. 4, 5, 6 and 7 are shown. Contour interval is 200 m. GSK: Geological Survey of Korea, GSG: Geological Survey of Germany, KIER: Korea Institute of Energy and Resources, PEDCO: Korea Petroleum Development Corporation.

sources (KIER) in 1986, and the Huntec Limited in 1966. Additional multi-channel seismic reflection data from the Korea Petroleum Development Corporation (PEDCO) were used to make a chronostratigraphic correlation with the Dolgorae exploratory wells (Fig. 1).

The seismic sequence analysis delineates three seismic sequence units bounded by two seismic-reflection discontinuities that are Late Miocene and Early Pliocene in age. The deformation style and chronostratigraphic control of the acoustic basement and sedimentary sequence suggest that the margin has undergone transtensional deformation during the Oligocene to Early Miocene time and later two episodes of compressional deformation in Late Miocene and Early Pliocene. Within this stratigraphic and structural context, we reconstruct tectonic evolution of the sedimentary basins in the eastern continental margin of Korea.

PHYSIOGRAPHY

In the continental margin south of Samchuk, the shelf is flat and narrow (<20 km wide); the shelf break generally occurs at water depth of 150 m and passes into a steep slope (up to 8° in slope gradient). The most striking features in the upper slope include a submarine ridge (Hupo Bank) and a trough (Hupo Basin) aligned parallel to the coastline (Fig. 1). The Hupo Bank is about 100 km long and varies in width from less than 1 km to 14 km. It shows a relatively flat top and lies between 10 and 200 m below sea level. The Hupo Basin is about 230 m deep at the eastern boundary and shoals gradually to the west where prograding sedimentary sequences are built out from the shelf break. In the absence of remarkable terrigenous input through large fluvial systems, the slope lacks distinctive submarine canyons and fans. Instead, the steep mid-to-lower slope is shaped dominantly by large-scale slope failures and associated mass-flow deposits (Chough *et al.*, 1992). The failure scars generally occur at water depths between 300 and 1500 m, which are usually accompanied downslope by failed sediment masses. The continental slope abruptly passes into the flat basin floor of the Ulleung Basin at water depths between 1500 and 2100 m.

To the north of 37°10'N, the continental margin is bounded on the east by the Korea Plateau, and submarine ridges and troughs are no longer recognized (Fig. 1). The shelf break generally occurs at water depth of 150 m, where the shelf abruptly passes into a broad and gently-dipping slope. The slope gradient is generally less than 3° and increases northward; the northern steeper slope meets a trough at water depth of about 1200 m which extends northward into the Japan Basin. Small transverse channels and gullies are headed near the shelf break, extending to a water depth of about 800 m (Lee *et al.*, 1991).

SEISMIC STRATIGRAPHY

Acoustic Basement

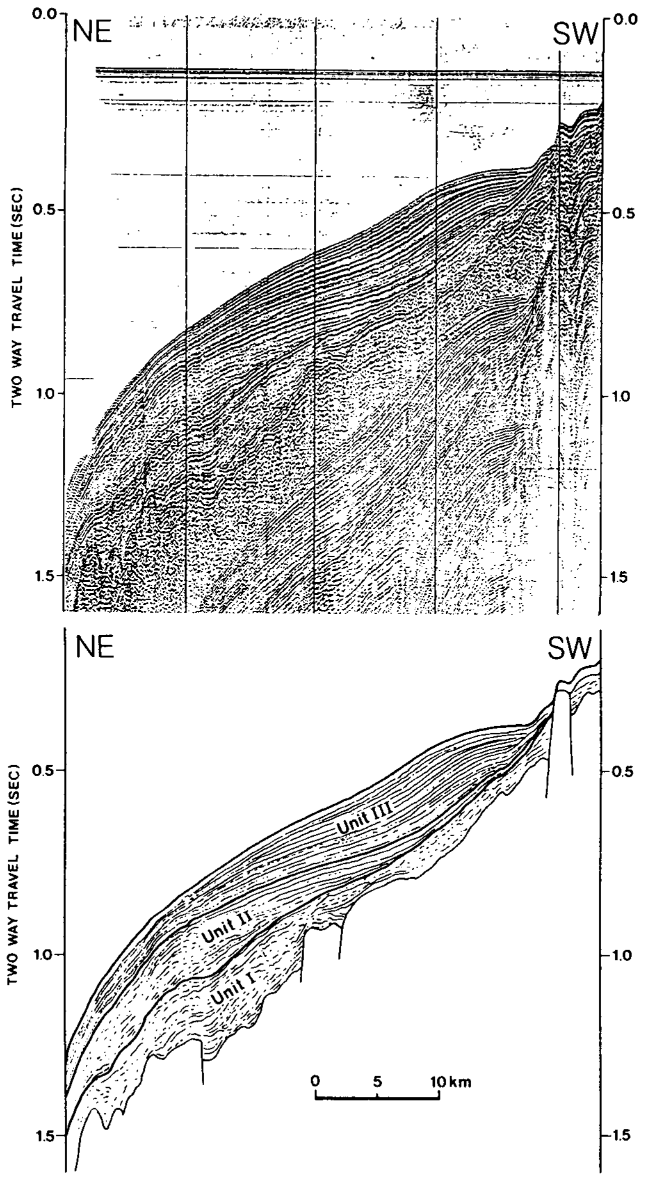

Fig. 2. Seismic profile and interpretation from the outer shelf and slope regions off Pohang (for location, see Fig. 1). Three sequence units are identified by seaward shift of coastal onlap. Units I and II are commonly characterized by faintly-stratified reflection with low amplitude and continuity, whereas unit III shows relatively well-stratified reflection. Acoustic basement is either acoustically opaque or very weakly stratified, and offset by some basement faults.

The acoustic basement of the study area is characterized by either a faintly-stratified reflection or an opaque reflection (lack of internal reflectors) (Figs. 2 through 5). The former occurs in some parts of the continental shelf south of Uljin and north of Samchuk, and the latter is dominantly identified from the other part of the shelf and slope regions. A seismic refraction survey (Schluter and Chun, 1974) discriminated these two characteristic basements with interval velocities of 4.4 km/sec and 5.6 km/sec for the former and the latter, respectively. The basement shows a complex series of elongated ridges, troughs, and domes, except in the shelf region (Fig. 6A) where the basement surface is marked by a relatively even and high-amplitude reflection doublet (Figs. 2 and 3). The ridges and troughs trend generally north-south and are in some cases bounded by near-vertical faults. The irregular morphology of the basement delineates some intra-shelf and intra-slope sedimentary basins (Fig. 6A). Beneath the lower slope, acoustic basement is much steeper (more than 30°) than that of the upper-to-mid slope, characterized by a low relief and relatively even surface showing small-scale hyperbolic reflection (Fig. 4). This basement escarpment most likely represents the tectonic boundary between the eastern Korean continental margin and the Ulleung Basin.

Sedimentary Sequences

An isopach map of entire sedimentary succession in the eastern continental margin of Korea illustrates that sediments are dominantly accumulated in intra-shelf and intra-slope sedimentary basins including Youngduk, Hupo and Mukho basins (Fig. 6B). The sedimentary sequence of this region is divided into three seismic-stratigraphic units: I, II and III in ascending order; the unit boundaries are recognized by major lapout discordant surfaces and by contacts of contrasting reflection character (Fig. 2).

The lower seismic sequence (unit I) is characterized both by a faintly- to moderately-stratified reflection with variable amplitude and continuity and by a significant structural deformation in part (Fig. 2). The unit is variable in thickness depending on the basement topography. Thicker than 0.6 sec of sediment is accumulated in structural lows between basement highs, whereas it is thin or absent over the shelf north of the Youngduk Basin and on basement highs (Figs. 4 and 5). In the shelf and upper slope, unit I shows an erosional, discordant upper boundary marked by relatively flat and high-amplitude reflectors (Fig. 3). This unconformable surface is correlated with the flat top of some basement highs and, further downslope, with the conformable bounding surface underlying seismic unit II. In the Youngduk Basin, interval velocity of the unit is suggested to be about 2.5 km/sec (Huntec Ltd., 1968).

The middle seismic sequence (unit II) dominantly occurs in the slope region and shows a coastal onlap onto seismic unit I (Figs. 2 and 3). It is characterized by moderately- to faintly-stratified reflection with partly transparent reflection; the unit thickness reaches up to 0.5 sec (Fig. 2). Sedimentary sequence within unit II is often disrupted by various-scale compressive deformation structures including reverse faults and anticlinal folds (Figs. 4 and 5).

The uppermost seismic sequence (unit III) occurs mainly as sediment fill in the Hupo Basin and sheet-drape deposit

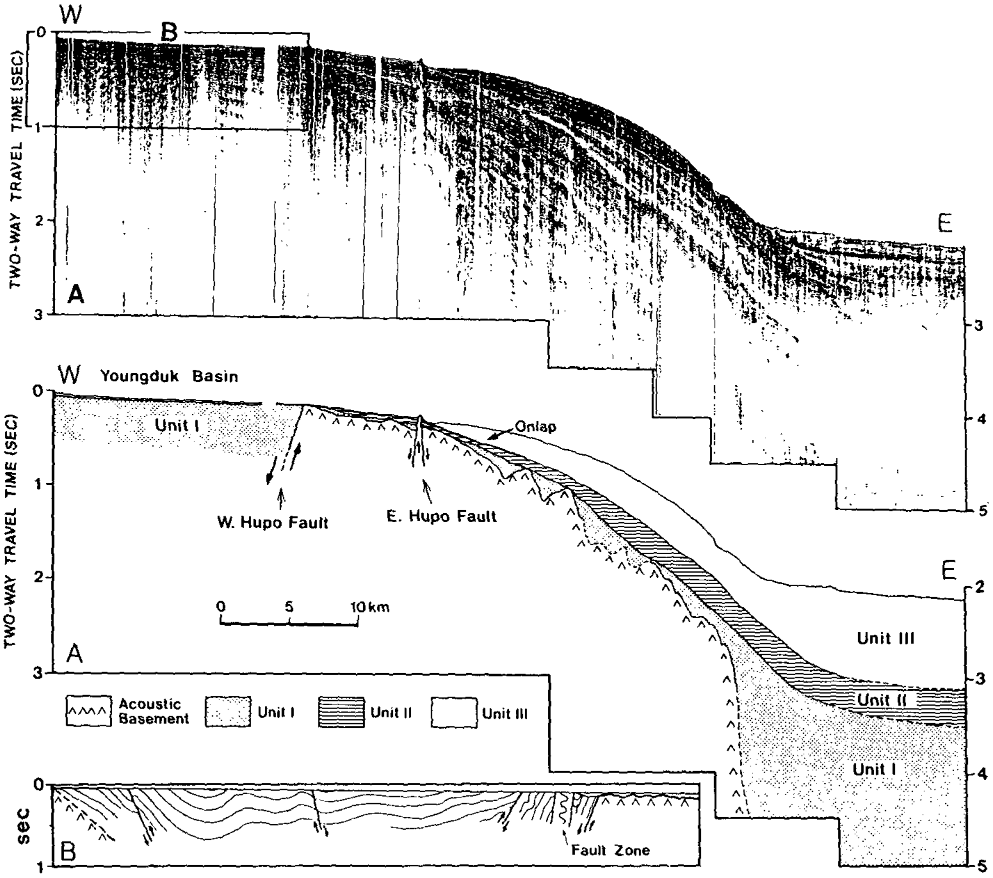

Fig. 3. Seismic profile and interpretation (A) of single-channel airgun profile (GSK & GSG Line 4), and line-drawing (B) of Huntec Ltd. (Line 21; modified from Huntec Ltd., 1968). For location, see Fig. 1. On the shelf, thin (less than 30 m) veneer of sediment (unit III) unconformably overlies acoustically stratified and deformed sedimentary sequence (unit I) of Pohang-Youngduk Basin. The Pohang-Youngduk Basin is bounded on the east by western branch of Hupo fault that shows normal sense of offset, whereas the basin fill (unit I) exhibits compressive deformation structures including thrust faults and folds. This is indicative of structural inversion from extensional to compressional stress. Sedimentary sequence in the slope region can be divided into three units. The lower two units show commonly variable reflection (opaque to well stratified), and they are bounded by a conformable surface correlated with the unconformity in the shelf region. The uppermost unit III is characterized by well-stratified reflection and onlaps onto unit II in the upper slope.

on the slope region. It generally consists of undeformed, acoustically moderately- to well-stratified sequence showing subparallel, continuous reflection (Figs. 2 through 5). Within the Hupo Basin, unit III has a wedge-shaped, onlap-fill geometry and is up to about 0.7 sec in thickness. In the shelf and Hupo Basin, unit III unconformably overlies either the acoustic basement or the underlying units I and II. In the slope region, the unit is less than 0.35 sec in thickness and conformably overlies the unit II sequence (Fig. 2). Acoustically, unit III on the steep slope shows moderately to faintly stratified and partly transparent reflections. The upper part of the unit was frequently remolded by large-scale slope failures on the steep mid-to-lower slope. Interval velocities of the units I and II are inferred to be commonly less than 2.0 km/sec, as indicated by Schlüter and Chun (1974).

Chronostratigraphy

The acoustic basement of the eastern Korean margin is most likely an extension of crystalline or consolidated sedimentary rock complex exposed along the coastal region. To the north of Hupo, the coastal region is largely composed of Precambrian gneiss and Paleozoic sedimentary rocks that were intruded by Jurassic to Cretaceous granites (Fig. 1). This rock complex seems to extend to the continental shelf region where it forms acoustically opaque basement with a partial weakly-stratified reflection, showing relatively subdued morphology. On the other hand, off the coast south of Uljin, the basement dominantly shows faintly-stratified reflection in the shelf region and acoustically opaque reflections with very irregular morphology on the slope (Fig. 6A). This strongly indicates that the basement is composed of consolidated sedimentary rocks and extrusive or intrusive igneous rocks. The composite basement is most probably an extension of the Cretaceous Kyungsang Group and NE-SW

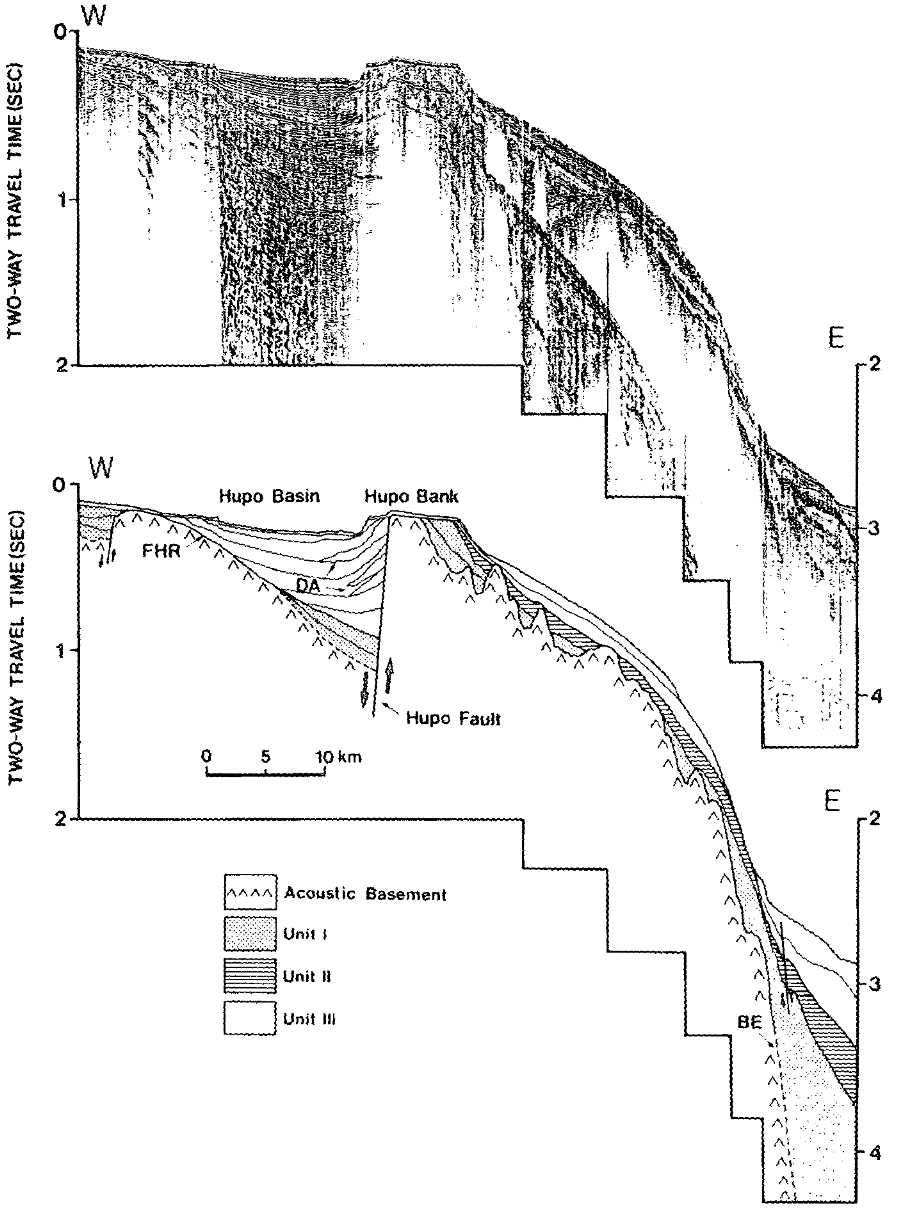

Fig. 4. Single-channel airgun profile across Hupo Basin and interpretation (GSK & GSG Line 12; for location, see Fig. 1). Acoustic basement is characterized by lack of internal reflectors and offset by Hupo fault which shows high-angle fault plane and normal sense of offset. Acoustic basement in the shelf region is characterized by a relatively flat and high-amplitude reflection doublet (FHR), whereas the slope basement is marked by irregular volcanic domes and mounds. In the lower slope, slope gradient of the acoustic basement becomes much steeper (>30°), forming basement escarpment (BE). The Hupo Basin, embanked to the east by a submarine ridge (Hupo Bank), is filled with acoustically faintly- or well-stratified sedimentary sequences (unit III) which are occasionally intercalated with debris aprons (DA) built out from the Hupo Bank. Units I and II in the Hupo Bank and the slope region are faintly stratified and fill the underlying rugged acoustic basement. The unit III in the slope shows well-stratified reflections onlapping onto unit II sequence.

trending volcanic belt that consists mainly of andesite, felsite and basalt extruded through the widespread Cretaceous sedimentary succession (Fig. 1). The K-Ar datings of volcanic rocks indicate that the volcanic belt north of Pohang was formed by two episodes of volcanic activity: Middle Eocene (50~44 Ma) and Early Miocene (22~20 Ma) (Jin *et al.*, 1989; Lee *et al.*, 1992).

The unit I never reaches to the coast except in the southern Youngduk Basin (Fig. 3B). There, the unit I sequence can be correlated with the marine deposit (Yeonil Group) exposed near Pohang (Fig. 6B), based on spatial distribution and similarity in internal sequence configuration (e.g. structural deformation) (Huntec Ltd., 1968; Choi *et al.*, this volume). The Yeonil Group occurs to the east of Yangsan fault system, where it comprises east-dipping sequence of conglomerate, sandstone and mudstone unconformably overlying

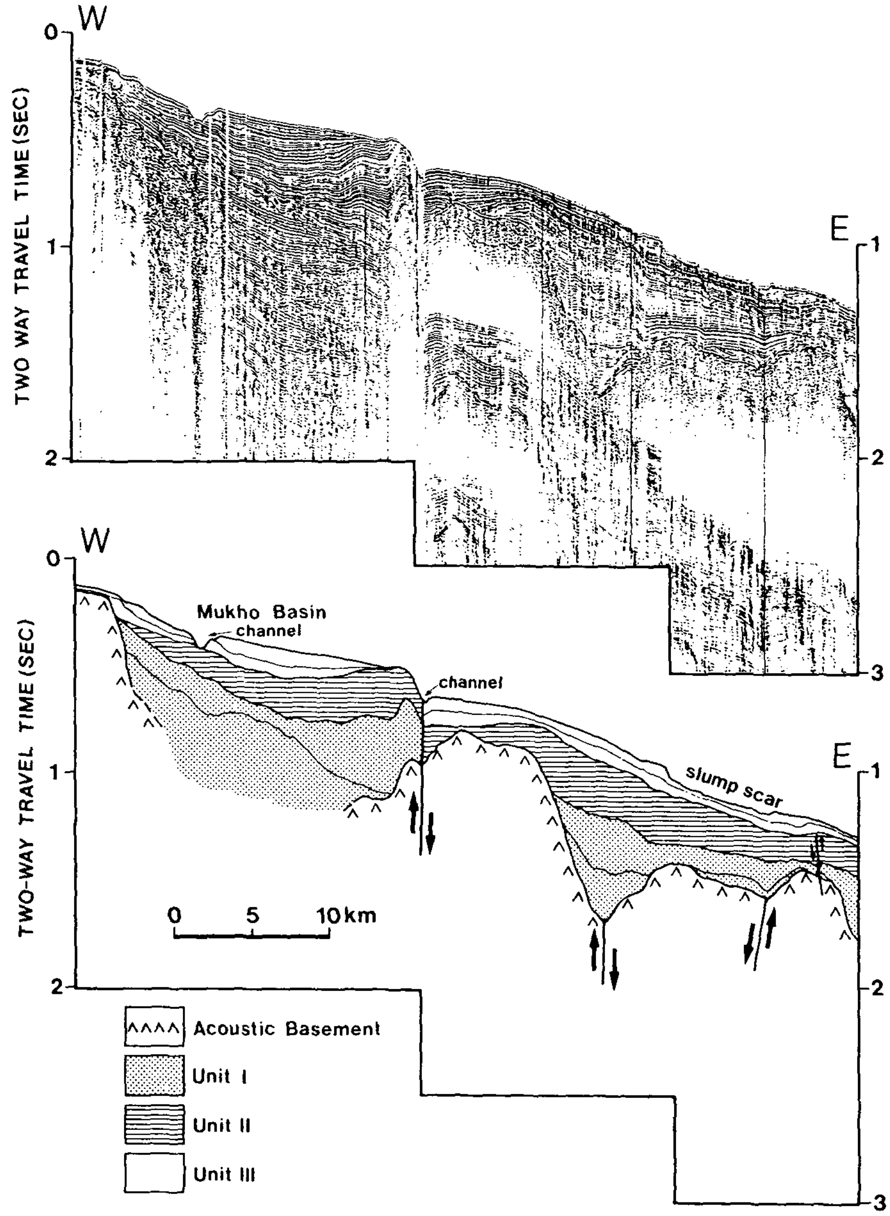

Fig. 5. Single-channel airgun profile across Mukho Basin and interpretation (GSK & GSG Line 32; for location, see Fig. 1). Acoustic basement shows very weakly stratified and partly opaque reflection. The Mukho Basin is bounded seaward by a basement high that was deformed by some basement faults. Units I and II are characterized by well- to faintly-stratified reflection with variable amplitude and continuity; the sequence in the eastern margin of the basin was uplifted by a compressive fault. The uppermost, well-stratified sequence (unit III) is dissected by submarine channels and slump scar downslope.

the Eocene igneous rock complex. Sedimentologic studies reveal that the sequence was formed in fan-delta systems and adjacent deeper marine environments (Choe and Chough, 1988; Chough *et al.*, 1990). Paleontologic studies of the Yeonil Group based on siliceous micro fossils (Lee, 1975; Koh, 1986; Ling *et al.*, 1988), planktonic and benthic foraminifers (Yoo, 1969; Kim, 1970, 1988; Kim and Choi, 1977; Kim, W.H., 1990), and mollusks (Yoon, 1975) suggest Early to Late Miocene in age of the sequence.

The time constraint for the sequence boundaries between sedimentary units can be established by chronostratigraphic framework in the Ulleung Basin which is based on the analyses of exploratory wells (Dolgorae I, IIand III) in the southern margin of the Ulleung Basin and multi-channel seismic profiles (Figs. 1 and 7) (KIER, 1982; Chough and Barg, 1987; Kim, S.H., 1990; Lee, 1992). According to this framework, the erosional sequence boundary between units I and II off Pohang can be correlated with the stratigraphic boundary between the Upper Miocene and the Lower Pliocene (ca. 5.5 Ma) in the Ulleung Basin (Fig. 7). The sequence boundary between units II and III off Pohang is correlated with the Early Pliocene sequence (ca. 4.5 Ma) of the Ulleung Ba-

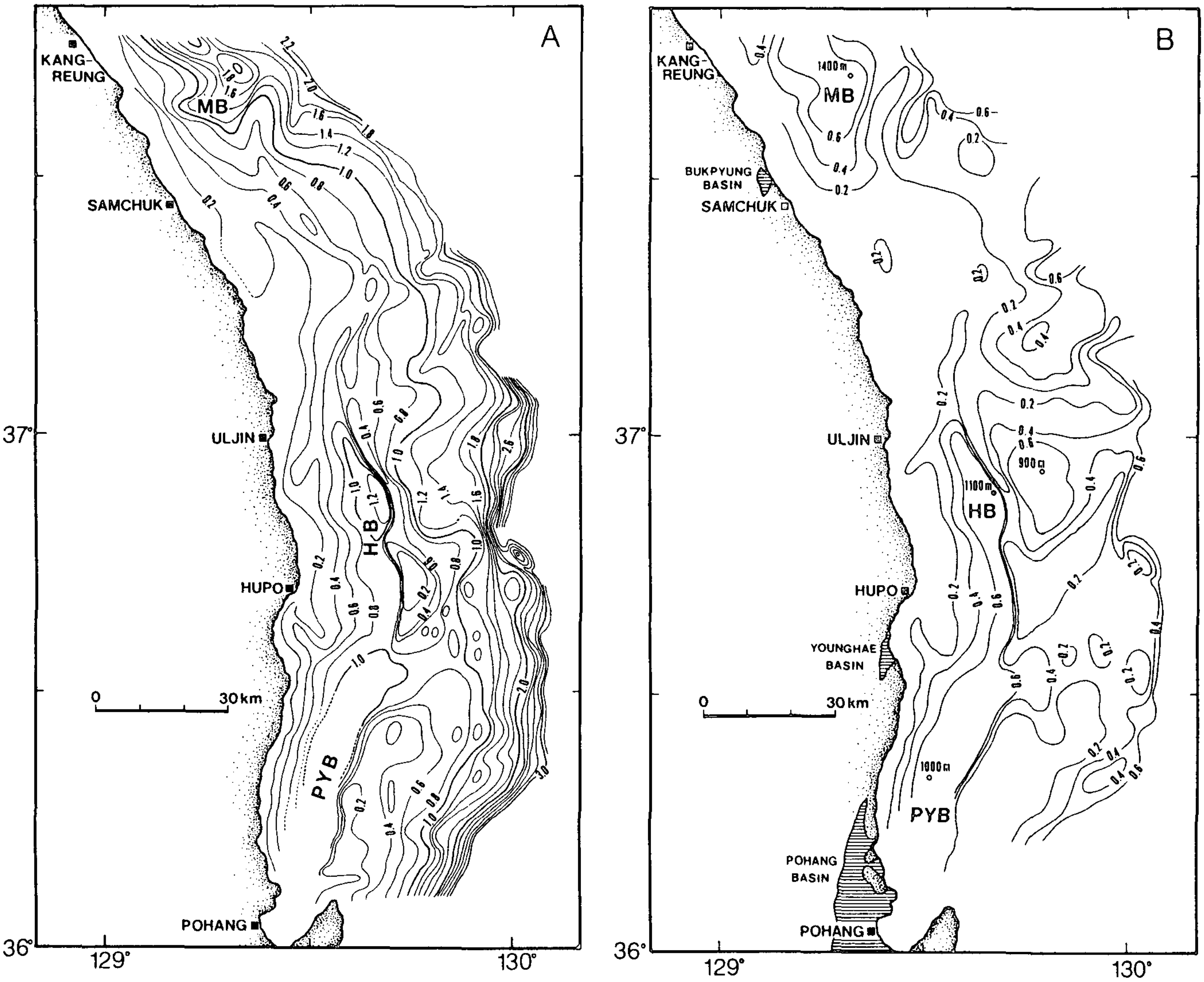

Fig. 6. Acoustic basement map (A) and isopach map of entire sedimentary sequence (B). The acoustic basement map shows depth to the upper surface of acoustic basement below sea level. Dots and numbers (in meters) in the isopach map denote the deepest position and the maximum sediment thickness in each sedimentary basin. Compiled from single-channel seismic profiles. Contours in seconds (two-way travel time). HB: Hupo Basin, MB: Mukho Basin, PYB: Pohang-Youngduk Basin.

sin (Fig. 7).

GEOLOGIC STRUCTURES

Strike-slip Fault Systems

The N-S trending Hupo fault is the most prominent deformation structure in the margin (Fig. 8). It is traced over more than 120 km with three segments. The northern segment runs along the western foot of the Hupo Bank and bifurcates into two curvilinear branches in the south of Hupo: the eastern branch along the shelf break and the western branch in contiguity with the eastern flank of the Youngduk Basin. The Hupo fault has typical fault-zone features characteristic of strike-slip deformation, including a narrow, laterally-persistent curvilinear trace, a steep fault plane and an offset involving the basement (e.g., Harding 1985, 1990; Sylvester, 1988). Especially, master faults generally have a throughgoing linear or curvilinear trace because significant lateral displacement cannot be accommodated where there are frequent structural discontinuities or abrupt changes in fault orientation (Christie-Blick and Biddle, 1985).

The northern and eastern segments of the Hupo fault apparently offset sedimentary units I and II as well as the acoustic basement (Figs. 2 through 4). The western segment, however, appears as a buried normal fault that offsets only the acoustic basement; it seems to have controlled major opening event of the Youngduk Basin. These features suggest at least two periods of deformation along the Hupo fault. The initial movement was most likely achieved in the Early

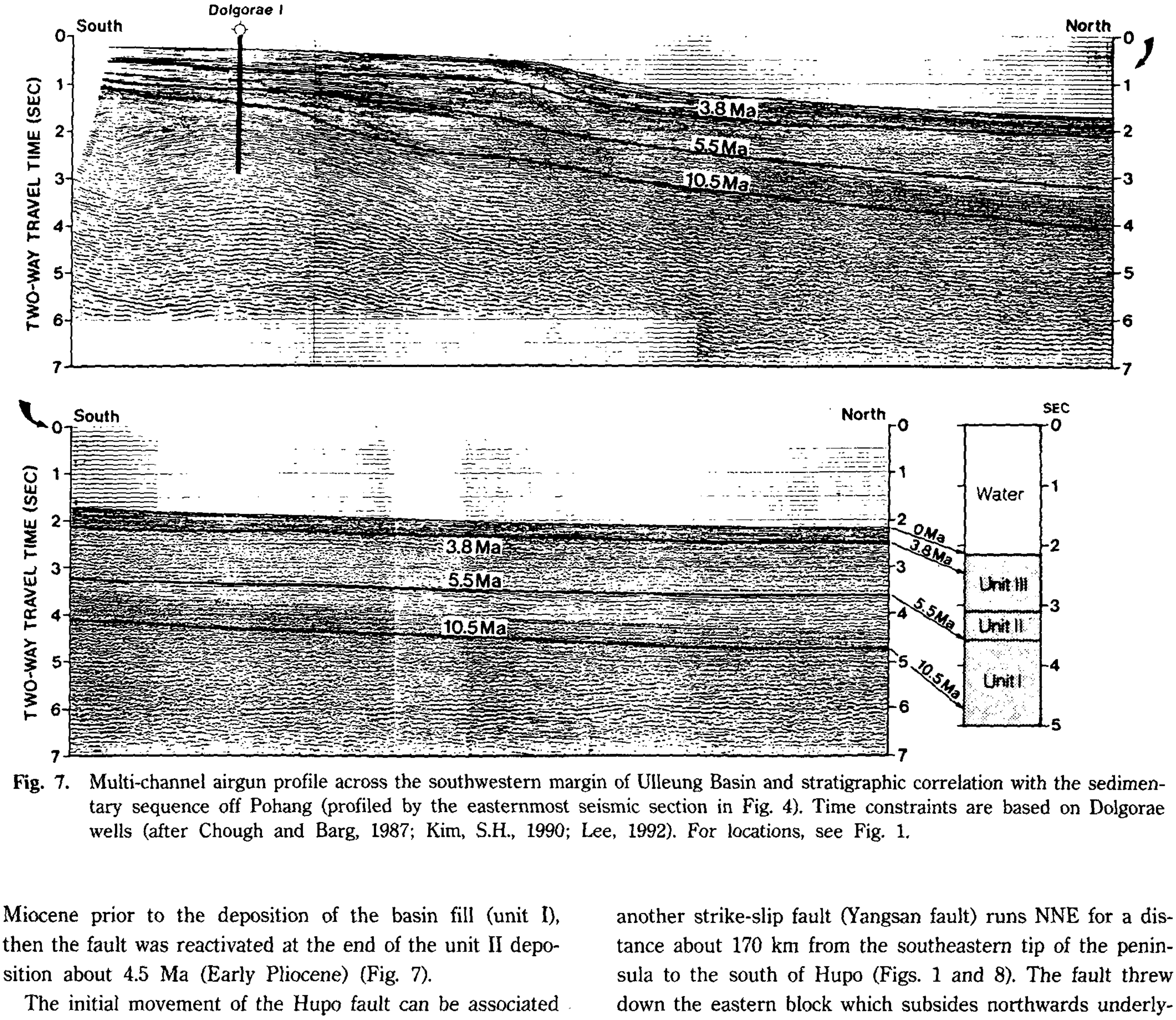

Fig. 7. Multi-channel airgun profile across the southwestern margin of Ulleung Basin and stratigraphic correlation with the sedimentary sequence off Pohang (profiled by the easternmost seismic section in Fig. 4). Time constraints are based on Dolgorae wells (after Chough and Barg, 1987; Kim, S.H., 1990; Lee, 1992). For locations, see Fig. 1.

Miocene prior to the deposition of the basin fill (unit I), then the fault was reactivated at the end of the unit II deposition about 4.5 Ma (Early Pliocene) (Fig. 7).

The initial movement of the Hupo fault can be associated with other coeval basement deformation structures, i.e. NNE-SSW trending normal faults adjacent to the northern part of the Hupo fault (Fig. 8). They are arranged in a left-handed en echelon pattern forming a linear belt subparallel to the overall trend of the northern Hupo fault. The combination of the en echelon faults and the coeval, throughgoing master fault can be explained within the context of a strike-slip wrench deformation (Harding, 1990). According to the field and laboratory observations (Bishop, 1968; Harding, 1974, 1985), en echelon normal faults are intimately associated with divergent shear deformation along the wrench fault systems, in which they are commonly concentrated within discrete bands along one or both sides of the strike-slip master fault. Furthermore, based on the strain ellipse model of simple shear (cf. Harding, 1974; Fig. 8), the spatial relationship between en echelon faults and the Hupo fault indicates a dextral strike-slip movement (Fig. 8).

Along the southeastern coast of the Korean Peninsula, another strike-slip fault (Yangsan fault) runs NNE for a distance about 170 km from the southeastern tip of the peninsula to the south of Hupo (Figs. 1 and 8). The fault threw down the eastern block which subsides northwards underlying the Miocene Pohang Basin. The fault movement appears to have dissected the Eocene rhyolitic tuff extruded by 45 Ma (Shibata *et al.*, 1979), which is, in turn, concealed by the Middle Miocene sequence of the Yeonil Group that is an onland extension of unit IA (Chang *et al.*, 1990; Hwang, 1993). This indicates that the last fault movement occurred during the period of Middle Eocene-Early Miocene and is most likely coeval with the initial strike-slip movement of the Hupo fault. Pre-faulting geometric reconstruction of the Cretaceous sedimentary sequence along both sides of the Yangsan fault suggests that the fault experienced a dextral strike-slip movement with a lateral displacement of about 35 km. The dextral motion is also evidenced by NE-SW trending en echelon normal faults on the eastern fault block which deformed non-marine deposits of the Early Miocene Yangbuk Group (Fig. 1) (Lee, 1989). The strain ellipse model suggests that the en echelon faults are a consequence of NW-SE extensional stress due to NNE-SSW dextral strike-slip motion of the Yangsan fault (Fig. 8). Along these NE-SW tension gashes, the Yangbuk Group was intruded by basaltic dikes with a K-Ar age ranging from 18.5~20.5 Ma (Lee, 1989). This indicates that the fault movement occurred prior to the late Early Miocene.

Contractional Structures

The compressive deformation is suggested by reverse and thrust faults, conspicuous within units I and II in Youngduk Basin and in the upper to middle slope region (Figs. 3 and 5). They are usually traced for a short distance and discontinuous across the seismic grid; some laterally-persistent faults commonly strike NNE or NNW with eastward-dipping fault planes. In the Youngduk Basin, thrust faults and anticlinal folds are truncated by an angular unconformity that is correlated with the downslope onlap boundary between sedimentary units I and II (Fig. 3). This indicates that the basin deformation most probably occurred in the Late Miocene time, prior to the deposition of unit II.

In the slope region, the basement/sediment-involved faults with steep (>70°) fault plane are usually accompanied with anticlinal folds in the upthrown fault block (Fig. 5). The faulting is generally confined within units I and II, which indicates that the compressive deformation occurred at the end of unit II deposition (i.e. Early Pliocene). It is coeval with the reactivated strike-slip deformation of Hupo fault along the northern and eastern segments, which was most likely reactivated with an oblique-slip sense of offset under the convergent shear stress regime.

Structural Development

According to the analyses of ODP drilling data (Legs 127 and 128), the East Sea (Sea of Japan) was extending from 32 Ma to 10 Ma during which major opening was accompanied with vigorous volcanism and thermo-tectonic subsidence (Tamaki et al., 1992). A quantitative subsidence analysis of onshore and offshore Neogene sequences in the East Sea region (Ingle, 1992) demonstrates that the rate of the back-arc subsidence between 23 Ma and 19 Ma was higher than those expected from the thermal subsidence pattern presented by Parsons and Sclater (1977). This accelerated basin subsidence reflects major opening phase of the sea characterized by a rapid crustal extension and spreading of the back-arc basin (Ingle, 1992).

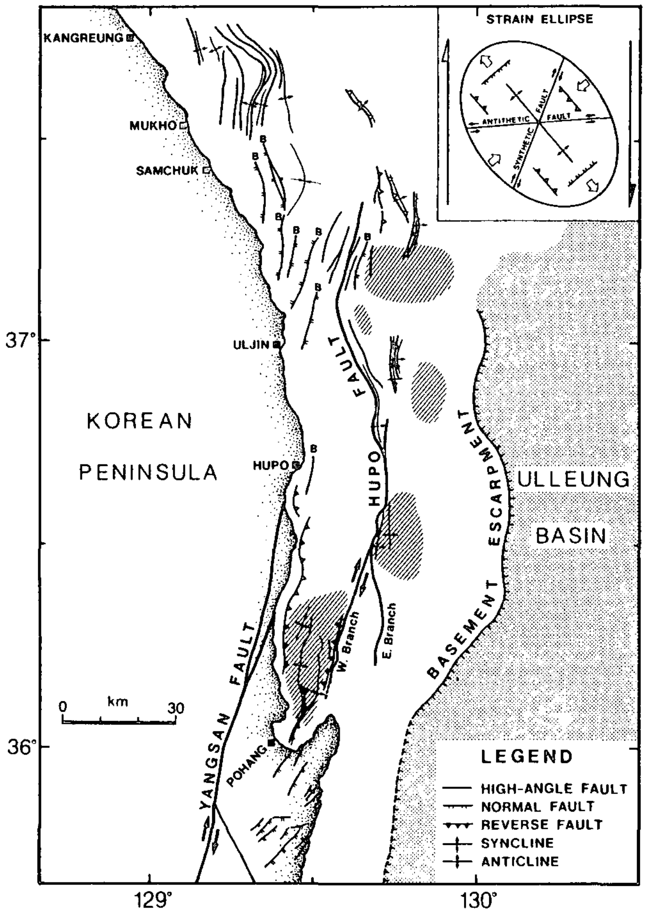

Fig. 8. Structural map of the eastern Korean continental margin showing right-stepping strike-slip master faults (Hupo and Yangsan faults) and associated en echelon normal faults as well as reverse faults and folds. Faults with symbol B generally offset only the basement leaving the overlying sedimentary sequence undeformed. Hatched areas denote the regions where sedimentary sequences are deformed by reverse faults and folds with a short lateral trace.

During the major opening phase of the East Sea in the Early Miocene (23~19 Ma), the eastern continental margin of Korea seems to have been placed under N-S dextral shear stress regime, as indicated by dextral strike-slip deformations along the Hupo and Yangsan faults. The activation of the dextral shear zone on the west of the expanding East Sea strongly implies a southward drift of the southwest Japanese Arc detached from the Korean Peninsula. As southwest Japan migrated southward, a main shear displacement zone was established most likely along the tectonic boundary between the continental crust and extending crust of the deep basin, which is represented by the steep basement escarpment along the base of continental slope off the Korean Peninsula (cf. Suh *et al.*, 1993; Fig. 8). In association with the major shear displacement along the tectonic boundary, we suggest, the Hupo and Yangsan faults were concurrently activated forming a right-stepping strike-slip fault system as a secondary shear zone within the rigid continental crust.

Two episodes of compressional deformation in the study area coincide in timing with closing phase of the East Sea since Late Miocene (cf. Chough and Barg, 1987; Ingle, 1992). Based on the tectonic history analysis in the southern margin of the Ulleung Basin, Chough and Barg (1987) demonstrates that the margin underwent a compressive regional deforma-

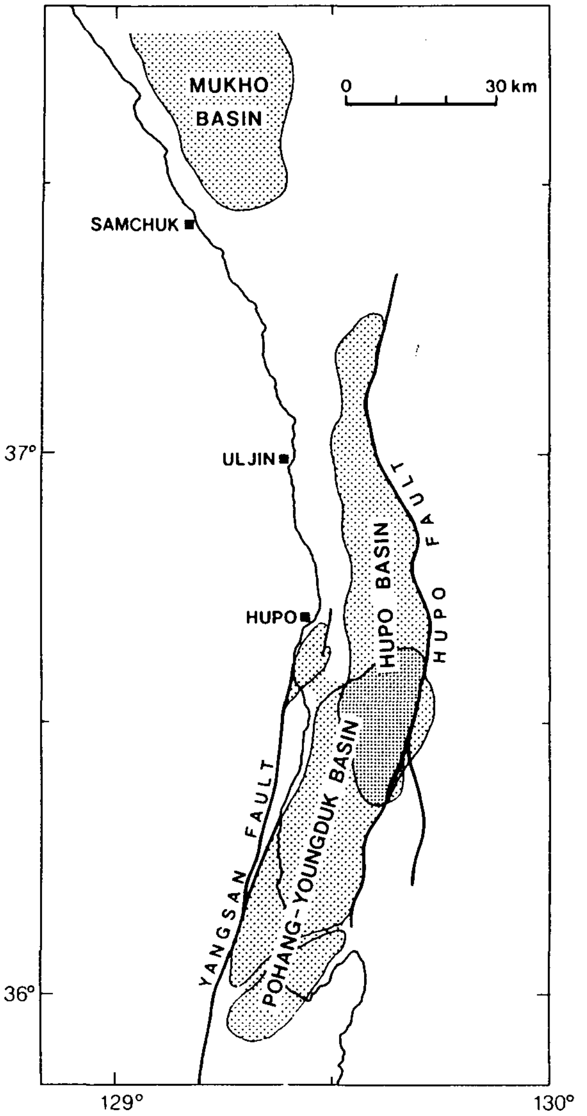

Fig. 9. Outline of Tertiary sedimentary basins in the eastern continental margin of Korea.

tion associated with tectonic uplift at the end of the Middle Miocene (11~12 Ma); they attribute this event to onset of the back-arc closure resulted from northwestward retreat of subduction hinge (or SW Japanese Arc) at the Ryukyu Trench. Since the Pliocene, eastward motion of the Amurian plate has also contributed to the compressional stress regime in the Ulleung Basin margin (Tamaki and Honza, 1985; Chough and Barg, 1987). Hence, the compressional uplift and deformation in the eastern continental margin of Korea can be explained as results of convergent and compressive regional tectonism caused by changes in plate motions. In the Japanese Arc and its peripheral region, the tectonic reorganization as a result of the basin closure has also episodically created widespread regional uplift and destruction of Miocene basins inlatest Miocene and in the late Pliocene to Pleistocene time (Ingle, 1992).

SEDIMENTARY BASINS

Pohang-Youngduk Basin

The Pohang-Youngduk Basin is a parallelogramatic graben between right-stepping Yangsan and Hupo faults (Fig. 9). The coeval dextral strike-slip motion along the two bounding master faults postulates a pull-apart opening because right-stepping dextral strike-slip faults generally produce a zone of tension and depression between two master faults. Evidence for the pull-apart opening can be provided by morphological and structural characteristics of the basin (cf. Sylvester, 1988; Jolivet *et al.*, 1991). The Pohang-Youngduk Basin consists of a main and two marginal basins which are divided by the basement highs (Fig. 9). The main basin is a deep and narrow (15~20 km wide) trough with a longitudinal dimension of about 60 km. The marginal basins comprise shallower depressions that extend northeastward. The northern extent of the basin terminates against the basement high off Hupo and open toward the northeast.

The basin is dominantly filled with unit I sequence deposited in the Miocene and is unconformably overlain by a thin (less than 30 m) veneer of Quaternary sediment (Fig. 3). The basin-filling sequence does not exceed 700 m in thickness except in the center of the main basin where it reaches up to 1,000 m (assuming interval velocity of the unit to be 2500 m/sec, Huntec Ltd., 1968) (Fig. 6B). The basin-filling sequence in the southwestern part of the basin (i.e. Yeonil Group in the Pohang Basin) is composed of conglomerate, sandstone and shale which were deposited in prograding marine fan-delta systems (Chough *et al.*, 1989; Hwang and Chough, 1990). Sedimentary sequence in the northern marginal basin reaches about 300 m in thickness and the western part of the sequence crops out in the coastal region (i.e. Younghae Basin) (Fig. 6B). The lower part of the sequence is suggested to have been deposited in non-marine environments, whereas the upper fossiliferous sequence is correlated with the upper Miocene sequence of the Yeonil Group in the Pohang Basin (Kim, 1970, 1977).

Mukho Basin

The Mukho Basin is a slope-perched depositional basin that is bordered on the east by a basement ridge projecting northward (Figs. 5 and 6A). It is 20~30 km wide and more than 35 km long (Fig. 9) and filled with more than 1400 m-thick sedimentary sequence in the northern part (Schluter and Chun, 1974) (Fig. 6B). The acoustic basement is characterized by subparallel, discontinuous and low-amplitude reflection and partly by opaque reflection without internal reflectors, which appears to be an extension of Precambrian gneiss and Paleozoic sedimentary rocks that occur in the coastal region (Fig. 1). Rugged morphology of the basement is strongly indicative of block faulting that is traced for a short distance; the basin occurs as a basement depression between basement highs uplifted by complex block faulting (Fig. 5).

Basin-filling sequences of units I and II are characterized by moderately- to faintly-stratified reflection with variable amplitude and continuity. They are highly disturbed by compressional deformation structures including various-scale faults and folds (Fig. 5). The deformation structures mostly diminish near the upper boundary of unit II which indicates that the structural deformation occurred at the end of unit II deposition. The structural axis changes in strike from N-S in the southern part to the NW-SE in the northern part (Fig. 8). A major fault zone occurs along the eastern margin of the basin and is accompanied with anticlinal folds within the uplifted western fault block (Fig. 5). The uppermost unit III is characterized by undeformed, post-deformation sequence which is less than 150 m in thickness and acoustically well stratified showing subparallel, high-amplitude reflection.

Hupo Basin

The Hupo Basin is a intra-shelf half-graben bounded on the east by flat-topped Hupo Bank (Fig. 4). It was formed by uplifting of Hupo Bank during the compressive deformation (Early Pliocene) along the Hupo fault. The basin is 5~17 km wide and 95 km long, extending north ward (Fig. 9). It is filled with both Miocene sediment (unit I) and Early Pliocene-Quaternary sediment (unit III). The acoustically faintly-stratified lower unit is about 0.25 second in maximum thickness and correlated with the unit I sequence in the Youngduk Basin and in the slope region (Fig. 4). The upper boundary of unit I is an eastward-dipping (3~5°) high amplitude reflector onto which unit III onlaps (Fig. 4). The landward shift of coastal onlap is indicative of progressive deepening of the basin probably due to sediment loading and compaction. Individual reflectors are slightly inclined eastward and increases in dip in the deeper part. The sequences can be subdivided into more than 3 subunits which are bounded by onlap sequence boundaries. Along the western margin of the basin, at least 3 sets of prograding sequence are identified in the upper part; individual set (13~30 km in width) has prograded 2~5 km eastward. In the eastern margin of the basin, the entire sequence of unit III reaches up to 0.7 second in thickness and faintly or crudely stratified. They form sediment aprons built out from the Hupo Bank, which are tapered toward the center of the basin interfingering with the sequences from the shelf break (Fig. 4).

BASIN EVOLUTION

During the major back-arc opening of the East Sea in the Early Miocene, southwest Japan drifted southward detached from the East Asian continent. This tectonic movement was guided on the west by a dextral shear displacement zone along the western margin of the Ulleung Basin. Within this

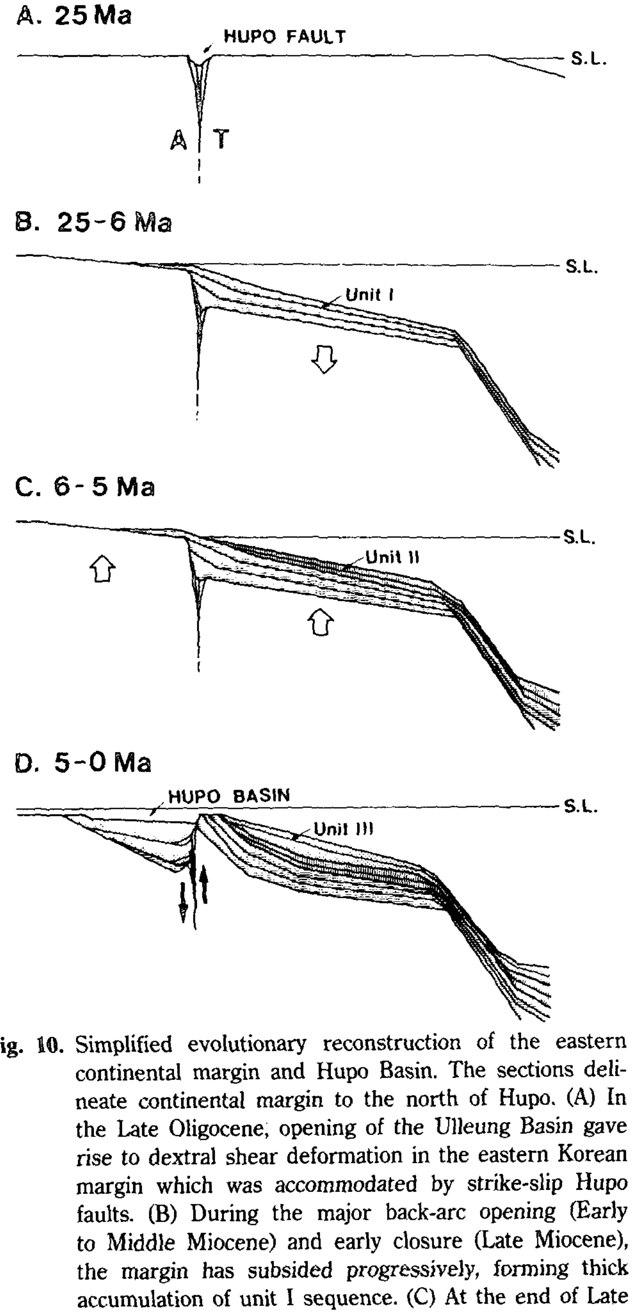

Fig. 10. Simplified evolutionary reconstruction of the eastern continental margin and Hupo Basin. The sections delineate continental margin to the north of Hupo. (A) In the Late Oligocene, opening of the Ulleung Basin gave rise to dextral shear deformation in the eastern Korean margin which was accommodated by strike-slip Hupo faults. (B) During the major back-arc opening (Early to Middle Miocene) and early closure (Late Miocene), the margin has subsided progressively, forming thick accumulation of unit I sequence. (C) At the end of Late Miocene, compressive tectonism due to the back-arc closure led to uplift of the margin and consequently to lowering of relative sea level. In the Early Pliocene, sediments from the Korean Peninsula bypassed the shelf and were deposited on the slope, piling up the sequences of unit II. (D) At the middle of the Early Pliocene, the Hupo fault was reactivated with an oblique-slip displacement, during which the eastern block (i.e. Hupo Bank) was upthrown shaping the Hupo Basin. Since the Early Pliocene, unit III sequence has been accumulated in progressively deepening Hupo Basin and the slope region.

regional shear zone, the Hupo and Yangsan faults were activated forming a right-stepping strike-slip fault system (Fig. 10A). The dextral shear movement along the fault system resulted in a rapid pull-a part opening of the Pohang-Youngduk Basin between the two master faults. The Pohang-Youngduk Basin was initially sediment-starved due to the rapid tectonic subsidence associated with the strike-slip fault movement; it was subsequently filled with terrigenous sediments (unit I) supplied by fan-delta systems. On the other hand, the northern part of the eastern Korean margin experienced a block faulting between the rigid continental crust (Korean Peninsula) and the extending crust (Korea Plateau). This structural deformation resulted in the formation of Mukho Basin on the downthrown fault block.

In the Early Miocene (ca. 18~20 Ma), the strike-slip deformation and volcanic activity in the eastern continental margin of Korea seems to have been practically terminated and the margin began to subside progressively as a result of thermal contraction of the crust. This led to the thick accumulation of marine sediment (unit I) in the shelf- and slope-perched basins and others, giving rise to a landward shift of coastal onlap over the margin (Fig. 10B).

In the late Middle to the early Late Miocene time, the back-arc opening of the East Sea ceased and consequently the stress field of the margin was inverted from tension to compression (Chough and Barg, 1987; Ingle, 1992). The compressive stress regime resulted in the contractive deformation and uplift of the basin-filling sequence (unit I) of Youngduk Basin at the end of Late Miocene. On the other hand, the uplift of the margin resulted in erosion of unit I, which gave rise to an angular unconformity in the shelf region. During the Early Pliocene, the margin seems to have been tectonically quiescent, and sediments from the Korean Peninsula bypassed the shelf and were deposited on the slope forming unit II sequence (Fig. 10C).

At the middle of Early Pliocene, the second episode of compressive regional deformation occurred over the margin. This was accompanied by a convergent strike-slip movement along the northern and newly-formed eastern branches of the Hupo fault as well as widespread contractive faulting and folding in slope sequences. During the strike-slip reactivation of Hupo fault, the eastern block (i.e. Hupo Bank) was uplifted forming a half-graben, the Hupo Basin (Fig. 10D). Sediments from the coast and the uplifted Hupo Bank were deposited in the Hupo Basin forming thick onlapping sequence of unit III, whereas a thinner sequence was deposited in the progressively deepening slope due to the obstruction of Hupo Bank (Fig. 10D). Since the Early Pliocene, the eastern Korean continental margin has attained its present tectonic and depositional settings.

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