Thesis for the Degree of Master of Engineering

Interpretation of multi-channel seismic data from the Ross Sea, Antarctica

by
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Department of Energy Resources of Engineering
The Graduate School

Pukyong National University
February 2010

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(남극, 로스해의 다중채널 탄성파 자료 해석)

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Abstract

Analysis of multi-channel seismic data from the Ross Sea, Antarctica, reveals five Cenozoic subbasins (Eastern, Northern, Central, and Central High basins and Central Trough), separated by structural highs and faulted blocks (Central and Coulman highs and Hallett Ridge). The subbasins show a typical rift-basin development: faulted basement and synrift and postrift sedimentation separated by an unconformity. The maximum depths of the Eastern, Central, and Northern basins, Central Trough, and Central High Basin are about 10,000 m, 7,000 m, 5,000 m, 4,000 m, and 3,000 m, respectively. Restoration of a depth-converted seismic profile crossing the Central High, Central High Basin, Central Trough and part of the southernmost Coulman High suggests that the postrift subsidence was interrupted by local uplift in the late Early Miocene.

Seismic profiles from the Eastern Basin were interpreted further to investigate the evolution of sedimentary sequences along the western and southwestern margins of the basin. Postrift sedimentation evolved from a ramp phase to a regressive shelf-slope phase in the middle Early Miocene. The shelf margin appears to have prograded northeastward in the late Early Miocene and Late Miocene-Early Pliocene. The shelf-margin progradation in the late Early Miocene is characterized by sigmoidal clinoform and accompanied by a distinct prograding package in the upper shelf, formed probably beneath the grounded ice. The self margin progradation in the Late Miocene-Early Pliocene is characterized by steep foreset and eroded topset beds, typical of till deltas formed in front of advancing ice. The shelf-margin progradation may be related to the growth of the West Antarctic Ice Sheet. Each phase of progradation was followed by aggradation.

Key words: Antarctica, Ross Sea, Eastern Basin, ice grounding, shelf-margin progradation

남극, 로스해의 다중채널 탄성파 자료 해석

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요약

남극해 Ross Sea에서 취득한 다중채널 탄성파 탐사자료의 해석으로 기반암의 구조(Central and Coulman highs and Hallett Ridge)로 나누어진 5개의 신생대 퇴적분지(Eastern, Northern, Central, Central High basins, Central Trough)를 확인하였다. 이러한 분지들은 열개동시, 열개후 퇴적과 이를 구분하는 부정합면의 전형적인 열개분지 발달의 특징을 보인다. Eastern, Central, Northern basins, Central Trough, Central High Basin의 최대 퇴적층 두께는 각각 약 10,000 m, 7,000 m, 5,000 m, 4,000 m, 3,000 m이다. 깊이로 변환한 Central High, Central High Basin, Central Trough, 그리고 Coulman High 남부를 가로지르는 탄성파 단면의 재구성은 후기 마이오세에 부분적인 융기가 있었음을 시사한다.

Eastern Basin의 탄성파 자료는 분지의 서쪽과 남쪽 주변부의

퇴적층 발달을 조사하기 위하여 보다 자세히 해석되었다. 열개후 퇴적은 초기 마이오세 중기에 사면퇴적 형태에서 대륙붕-대륙사면 퇴적 형태로 진화하였다. 초기 마이오세 후기의 대륙붕 전진구축(progradation)은 sigmoidal clinoform의 특징을 보이며 내대륙붕 일부 지역에서 전진구축 퇴적체가 관찰되는데 이는 빙하의 이동과 관계 있는 것으로 보인다. 후기 마이오세-전기 플라이오세의 대륙붕 전진구축은 급한 경사의 foreset과 침식을 받은 topset을 보이는데 이는 전진하는 빙하의 전면에 퇴적되는 전형적인 till 삼각주의 특징이다. 대륙붕 전진구축 후에는 상방구축(aggradation)이 진행되었다.

색인어: 남극해, Ross Sea, Eastern Basin, 빙하 grounding, 대륙붕 전진구축

Table of Contents

List of Tables

List of Figures

1. INTRODUCTION

The Ross Sea (Fig. 1) lies along the Pacific margin of the Jurassic rift in Antarctica (Schmidt and Rowley, 1986), covering an area of 750,000 km^2 (Cooper et al., 1990). Water depths (200-1100 m) of the Ross Sea are significantly deep for a continental shelf and increase landward toward ice sheets like in other regions around the Antarctic margin (Cooper et al., 1990; De Santis et al., 1999). The landward increasing and unusually great water depths are probably due to glacial erosion and sediment and ice loading (ten Brink and Cooper, 1992) or ice sheet advances and retreats (Santis et al., 1999) or crustal thinning (Fitzgerald et al., 1986; Stern et al., 1992).

The sedimentary basins in the Ross Sea were formed largely by rifting during and since the breakup of the proto-Pacific margin of Gondwana in the Late Cretaceous (Davey, 1981). These basins are underlain by large basement grabens, filled with thick (> 3 km) rift-related sediments, which in turn are overlain by a widespread and thick (2-6 km) glacial sedimentary section (Cooper et al., 1990). Houtz and Meijer (1970) and Houtz and Davey (1973) identified a prominent erosional surface in the shallow (2-42 m) part of the glacial sedimentary section on the inner shelf, “the Ross Sea Unconformity,” which was inferred to be a late Pleistocene glacial unconformity. The age

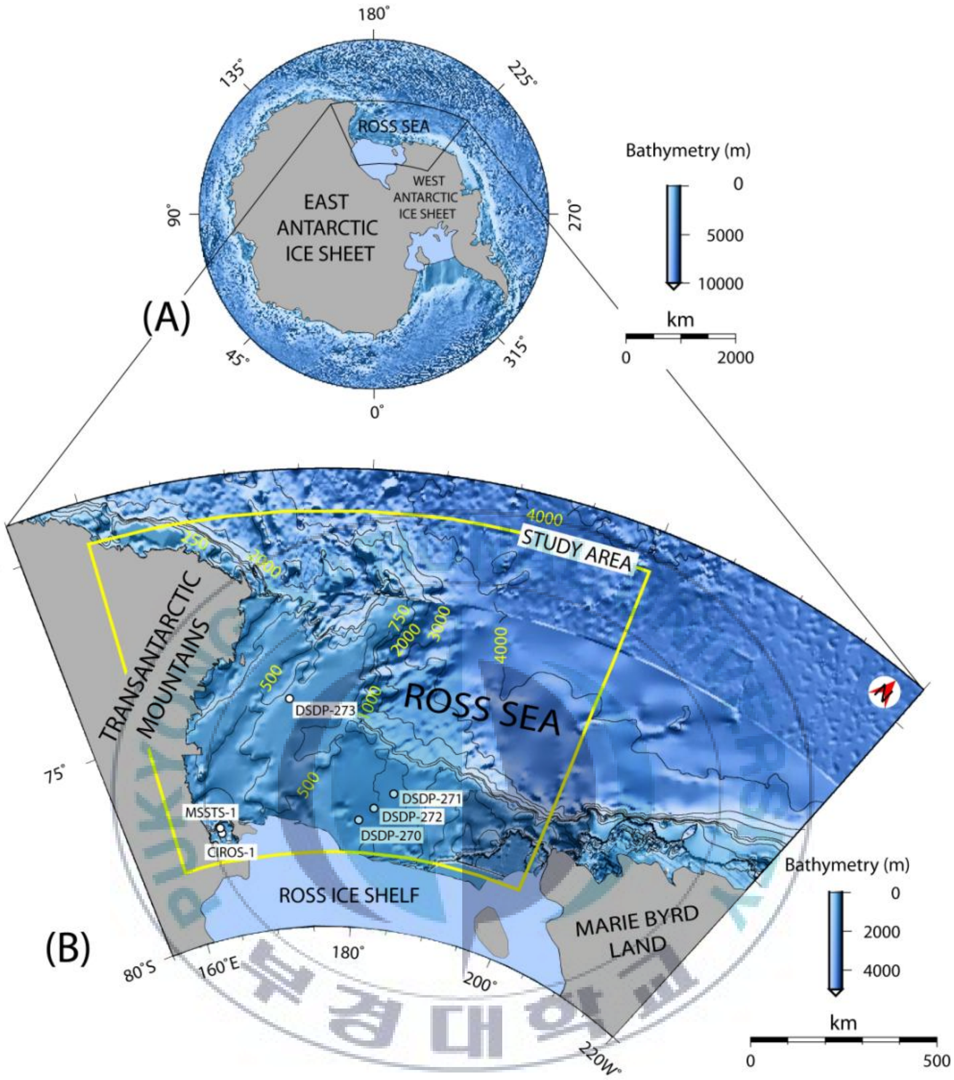

Figure 1. (A) The Antarctica and Ross Sea. (B) Bathymetry of the Ross Sea and the Deep Sea Drilling Project (DSDP) and McMurdo Sound Sediment, Tectonic Studies (MSSTS), and Cenozoic Investigations in the western Ross Sea (CIROS) drill sites. Bathymetry in meters.

(14.7-4.0 Ma; Savage and Ciesielski, 1983) of the Ross Sea Unconformity was supported by the Deep Sea Drilling Project (DSDP) Leg 28 drilling, which penetrated the unconformity at sites 270, 271, and 272 (Hayes and Frakes, 1975). High-resolution seismic data further show that the Ross Sea Unconformity is an amalgamated surface on the inner shelf that diverges into several unconformities on the mid and outer shelf (Alonso et al., 1992; Mosola and Anderson, 2006).

Sedimentary sequences in the Ross Sea are very important in the study of Antarctic glacial fluctuations and dynamics because approximately 25% of the drainage from the Antarctic Ice Sheet has drained into the Ross Sea (Hughes, 1973; Barrett, 1975). The Antarctic Ice Sheet is divided into the East (EAIS) and West Antarctic Ice Sheets (WAIS) (Bartek et al., 1997) (Fig. 1A). The EAIS is a thick (~ 4,800 m), terrestrial ice sheet grounded on the continent above sea level (Bartek et al., 1997). On the other hand, the WAIS is a topographically unconstrained (Hambrey and Barrett, 1993), marine-based ice sheet and strongly affected by global sea-level changes (Mercer, 1968; Hughes, 1973). The continental shelf of the Ross Sea today is characterized by glacial valleys incised by multiple advances of ice streams, draining both the EAIS and WAIS (Anderson and Bartek, 1992).

The Antarctic Ice Sheet switched from an earlier warm regime to the modern cold one during the Middle Miocene (~16 Ma to ~ 10 Ma) (Shackleton and Kennett, 1975; Woodruff et al., 1981; Wright et al., 1992; Rebesco and Camerlenghi, 2007) with significant long-term cooling and several stepped expansions of ice volume on Antarctica (Chow and Bart, 2003). The Middle Miocene ice-volume increase was probably associated with the large EAIS. West Antarctica is believed to have remained substantially ice-free until the latest Miocene (Kennett and Barker, 1990). De Santis et al. (1995) suggested that the first evidence of a grounded polar ice-sheet across the eastern Ross Sea exists in the Late Miocene-Early Pliocene section. However, direct geologic evidence suggests that ice cover on West Antarctica during the Middle Miocene may have been more extensive than traditionally thought (Chow and Bart, 2003). Seismic-stratigraphic studies of the Ross Sea outer shelf also show that grounded ice existed during the Middle Miocene (Anderson and Bartek, 1992). Chow and Bart (2003) suggest at least five shelf-wide grounding events of the WAIS during the Middle Miocene. Thus, whether there was a substantial growth of the WAIS during the Middle Miocene remains in debate. The number of grounding events and the extent of grounded ice on the Ross Sea shelf during the Middle Miocene also have not been determined. A recent study (Sorlien et al., 2007), based on seismic reflection data from the easternmost Ross Sea, even show glacial erosion and deposition during the Oligocene, suggesting that parts of the WAIS may have formed much earlier.

The glacial evolution in the Eastern Ross Sea can be divided largely into two stages: (1) the early fully glacial stage (Late Oligocene and/or Early Miocene) (Cooper et al., 1991a; Anderson and Bartek, 1992), (2) the late fully glacial stages (Late Miocene-Early Pliocene) (Hinz and Block 1984; De Santis et al., 1995; Brancolini et el., 1995a, b). De Santis et al. (1999) divided the glacial evolution of the Eastern Basin further into four stages: (1) an early glacial stage (pre-Miocene-Early Miocene) when tidewater glaciers and small ice caps developed, while the basin was still subsiding and was influenced by marine sedimentation; (2) a transitional stage (Early-Middle Miocene) during which the basin was gradually filled with sediments, and ice caps expanded onto the continental shelf; (3) a fully glacial stage (Late Miocene-Pliocene) during which a large and thick ice sheet formed; and (4) a late fully glacial stage (Pliocene-present) during which the continental shelf was deepened and the sedimentation was reduced and mainly influenced by glacial processes. Bart (2003) suggested at least two WAIS expansions during the early part of the Middle Miocene. However, the exact timing of the glacial evolution and whether or not the WAIS or the EAIS affected the Eastern Basin remain not well understood.

Continental shelf and margins of Antarctica are characterized by well developed prograding wedges with eroded topsets and steep foresets. These units are interpreted as till deltas, deposited during multiple advances and retreats of the ice sheet on the continental shelf (Cooper et el., 1991; Larter and Barker, 1989). The prograding wedges overlie more regular, sub-parallel aggrading sequences, interpreted as pre-glacial deposits (Brancolini, 2005). The transition from generally aggrading seismic sequences to prograding sequences was interpreted as the onset of a large-sized grounding ice sheet across the continental shelf (Cooper et al., 1991a). The anomalous high velocity layer in the Late Miocene-Early Pliocene section, identified from seismic reflection and refraction tomography data, may represent the hard sediments that were eroded and compacted by the load of the WAIS during its expansion on the continental shelf (Accaino et al., 2005).

In this study, I analyzed the public-domain (www.scar-sdls.org) multi-channel seismic reflection data (> 30 000 km) from the Ross Sea to map basement structure and key unconformity surfaces. The seismic sequences along the western and southern margins of the Eastern Basin were analyzed further to investigate the glacial history (Early Miocene-present time) in the area.

2. GEOLOGIC SETTING

The Ross Sea developed in response to extensional tectonism during the break-up of Godwana in the Cretaceous (Davey, 1981; Anderson, 1999). The Ross Sea and its southern continuation under the vast floating Ross Ice Shelf form the Ross Embayment, overlying the West Antarctic Rift System (WARS) between the East (EAIS) and West Antarctic Ice Sheet (WAIS) (Fig. 1a). The Ross Embayment is bounded by the Transantarctic Mountains in the west and by the Marie Byrd Land in the east (Cooper et al., 1990) (Fig. 2).

The Ross Sea region, including the Ross Embayment, is characterized by thinned (19-27 km) continental crust and large early-rift grabens in the basement (Cooper et al., 1995). The Ross Sea region has been affected by four major tectonic events (Davey and Brancolini, 1995): (1) rifting and extension in the Early Cretaceous, (2) a second phase of extension that started in the Late Cretaceous, followed by thermal subsidence, (3) uplift and denudation of the Transantarctic Mountains in the Early Eocene, followed by further subsidence of the Ross Embayment, and (4) active volcanism and uplift in the western Marie Byrd Land in the Oligocene. The Early Cretaceous rifting and extension was coeval with and probably triggered by the subduction of the Pacific-Phoenix spreading ridge at the margin (Richard et al., 1994).

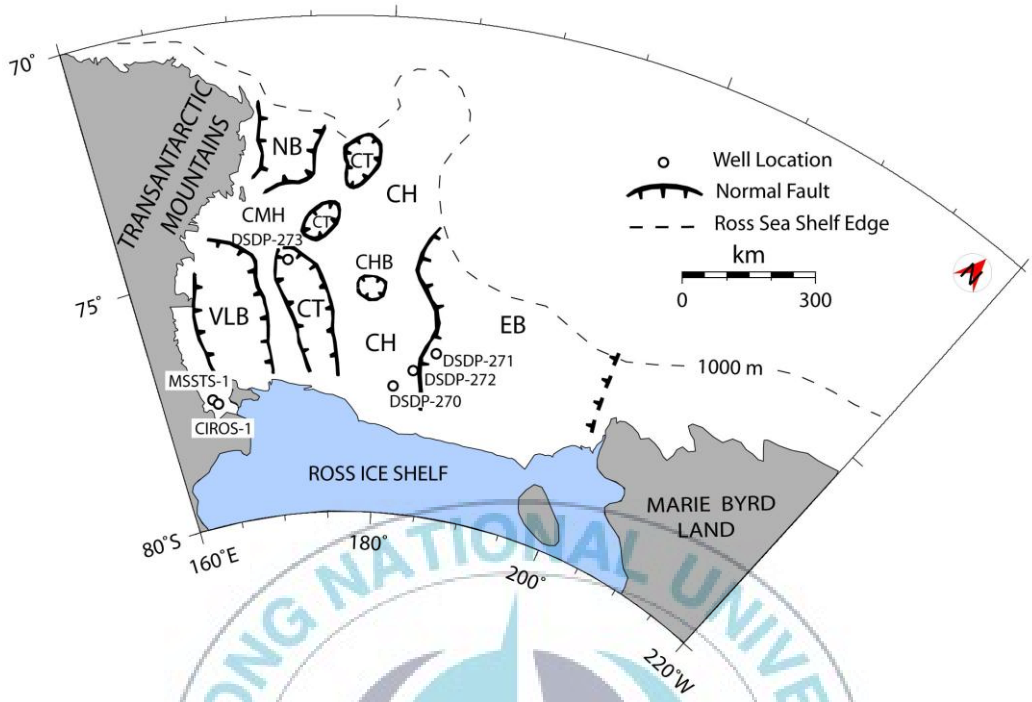

Figure 2. Tectonic map of the Ross Sea showing the continental margin, major extensional basins and the DSDP, CIROS and MSSTS drill sites location. EB, Eastern Basin; CHB, Central High Basin; CT, Central Trough; VLB, Victoria Land Basin; NB, Northern Basin; CH, Central High and CMH, Coulman High (modified from Davey and Brancolini, 1995).

The second phase of extension, related to the onset of seafloor spreading between Antarctica, New Zealand and Australia, is characterized by rapid cooling of crustal rocks and prolonged stability (Weissel et al., 1977). Basement grabens, formed during rifting and extension, were filled with nonmarine and marine sediments with layered volcanic rocks; much of the infilling occurred during the Late Cretaceous-Paleogene (Cooper et al., 1990). The uplift and denudation of the Transantarctic Mountains corresponds to plate tectonic changes from the cessation of Tasman Sea spreading to the onsets of spreading between western Ross Sea and the South Tasman Rise and Australia and Antarctica (Davey and Brancolini, 1995). Volcanism that started in the Oligocene gave rise to the volcanic and igneous bodies of the western Ross Sea and Marie Byrd Land (LeMasurier, 1990). The volcanic activity, accompanied by block faulting and uplift, was facilitated by the reactivation of fault in a transtensional mode. The volcanism and uplift continue today (Le Masuries and Rex, 1989).

The Ross Sea contains a thick sedimentary section of Mesozoic and mid-late Cenozoic age (Cooper and Davey, 1987). The sedimentary section is up to 14 km thick in the rift grabens and up to 8 km in the unconformably overlying, presumed glacial sequences (Cooper et al., 1990). Main sedimentary depocenters or basins have been identified in the Ross Sea region

(Hinz and Block, 1984; Cooper et al., 1990, 1991b, 1995): the Northern Basin, Victoria Land Basin, Central Trough, and Eastern Basin. The Victoria Land Basin is characterized by a thick (up to 14 km) layered sediments, extensive basement faulting, and deformation of sedimentary section in the Terror Rift (Cooper et al., 1990). The Northern Basin contains up to 5 km of sediments inferred to be of Late Eocene/Oligocene age and younger, forming a prograding wedge on the continental margin (Brancolini et al.,1995). In the Central Trough, the total sedimentary section is up to 5-6 km thick over the early rift graben and the sedimentary strata are nearly horizontal with minor deformation (Cooper et al., 1990). The basement beneath the central part and flanks of the trough are extensively eroded (Cooper et al., 1990). The maximum sediment thickness above the early rift graben in the Eastern Basin is similar to that in the Central Trough. Much of the sedimentary section in the Eastern Basin consists of a prograding sequence above the regional unconformity that tops the early rift grabens (Cooper et al., 1990). This thick prograding package dips and thickens seaward (Cooper et al., 1990).

The number of depositional units in the Early Miocene and younger sediments in the Ross Sea region, bounded by unconformities, range form five to eleven (Table 1) (Hinz and Block, 1984; Anderson and Bartek, 1992; ANTOSTRAT, 1995; Brancolini et al., 1995; Bart et al., 2000). At least four major unconformities, suggesting four episodes of extension, were recorded in the VLB (Davey and De Santis, 2005). Furthermore, a model has been proposed for the evolution of the Victoria Land Basin, invoking five phases of tectonic activity and associated sediment accumulation patterns (Fielding et al., 2006). Phase 1 (pre-latest Eocene) involved regional uplift and erosion of the Transantarctic Mountains to the immediate west of the basin. Phase 2 (latest Eocene to Early Oligocene) was an early rift stage, characterized by sediment accumulation in laterally restricted grabens. Phase 3 (Early Oligocene to Early Miocene) was the main rift stage, in which sediment accumulation was no longer confined to grabens in the west of the basin, but formed an eastward-thickening wedge into the centre of the basin. Phase 4 (Early Miocene) was a consequence of passive thermal subsidence, producing a relatively even blanket of sediment across the entire basin. Phase 5 (post-Early Miocene) was associated with the Terror Rift (Cooper et al., 1987) in the southwestern corner of the Ross Sea and gave rise to a succession containing both young magmatic rocks and young faults and which thickens markedly into a central depocenter.

Table 1. Seismic sequences in the Northern Basin (NB) Ross Sea and correlation with previous studies. Modified from Bart et al. (2000).

Bart et al., 2000	ANTOSTRAT, 1995; Brancolini et al., 1995			Anderson & Bartek, 1992		Hinz & Block, 1984
	Units in NB	Bounding Unconformities	Age assigned	Units in NB	Revised age assignment	
Unit 1	RSS-8	Seafloor - RSU1	Pleistocene - late Pliocene	Units 1- 8[a] (undiffer-entiated)	Pliocene - Pleistocene	Seafloor - U1
Unit 2						
Units 3 - 9	RSS-7	RSU1 - RSU2	early - late Pliocene			U1 - U2
Unit 10	RSS-6	RSU2 - RSU3	early Pliocene - late Miocene	Unit 9 (top[a])	early Pliocene - lete Miocene (?)	U2 - U3
middle Miocene	RSS-5	RSU3 - RSU4	middle Miocene	Unit 9 (base)	middle Miocene	U3 - U4
early Miocene	RSS-4	RSU4 - RSU4a	early Miocene	Unit 10	early Miocene	U4 - U4A

Note that [a]Unit 8 and the top of the Unit 9 were not sampled at any of the DSDP Leg 28 drill sites.

3. DATA AND METHODS

Data used in this study consists of: (1) more than 30,000 km of multi-channel seismic reflection profiles, acquired by various institutions and organizations and complied by the Antarctic Offshore Acoustic Stratigraphy (ANTOSTRAT) project, using the Antarctic Seismic Data Library System (SDLS) (Childs et al., 1994; Cooper, 1995), (2) time-depth charts at the Deep Sea Drilling Project (DSDP) and Cenozoic Investigations in the Western Ross Sea (CIROS) sites (ANTOSTRAT, 1995) (Fig. 3). Kingdom Suite® (version 8.4) was used for seismic data interpretation and mapping. Unconformities, including the top of the acoustic basement, were identified based on erosional truncation, toplap, onlap or downlap surfaces.

One represented seismic profile was depth-converted and imported to 2DMove® (version 5.1) for balanced cross-section restoration to better understand the structural development of the area. The time-depth conversion was made based on the time-depth chart from the DSDP site 270 (Cooper et al., 1995). Restoration of the depth section was carried out by successfully stripping off (backstripping) each sequence and restoring faults and folds so that the paleo-seafloor was restored to a continuous layer with topography. Decompaction correction, assuming the porosity-depth for 50% shale/50% sand, was accomplished during backstripping. If the top horizon shows erosional truncation after backstripping, the eroded layers were restored by projecting the horizons that terminate at the top surface, assuming constant thickness and parallel geometry.

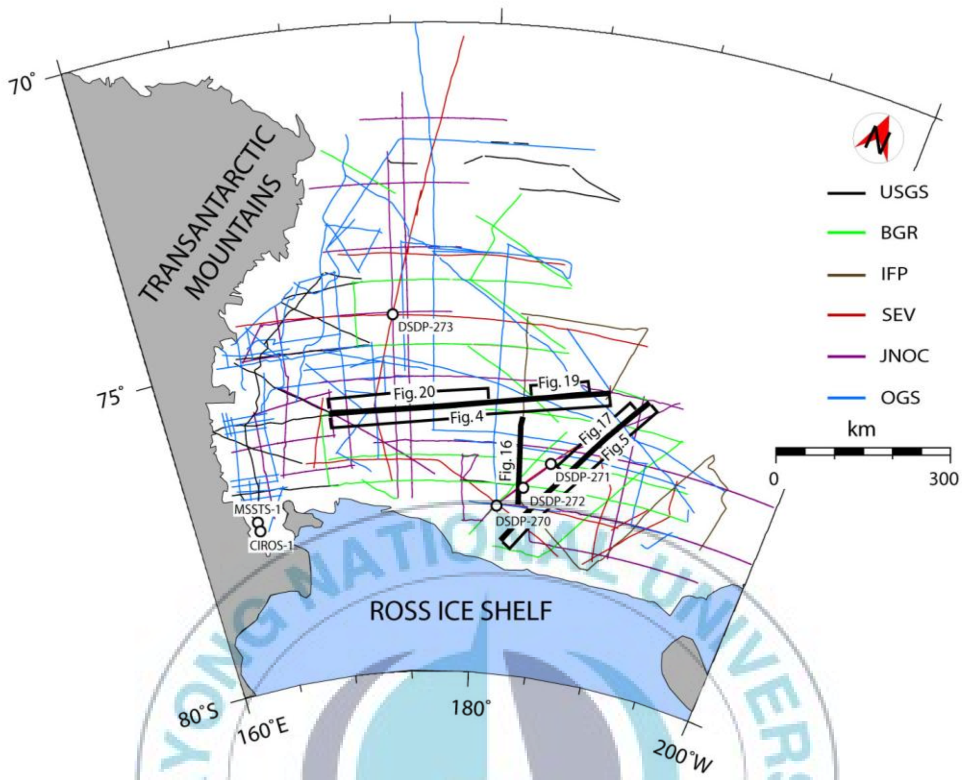

Figure 3. Study area and distribution of multi-channel seismic data (> 30,000 km) and the DSDP, CIROS and MSSTS drill sites location. Heavy black lines with numbers indicate seismic profiles shown in other figures. USGS, United States Geological Survey (United States); BGR, Bundesanstalt für Geowissenschaften und Rohstoffe (Germany); IFP, Innovation Energie Environnement (France); SEV, Sevmorgeologia (Russia); JNOC, Japan National Oil Corporation (Japan); OGS, di Oceanografia e di Geofisica Sperimentale (Italy).

4. RESULTS

4.1 Seismic Sequence Boundaries

I identified and mapped the top of acoustic basement and eleven regional unconformities (Figs. 4, 5). The unconformity surfaces or sequence boundaries, including the top of the acoustic basement, are referred to as SB1 to SB12, from oldest to youngest. The sequences bounded by the top of the basement and the regional unconformity surfaces are referred to as S1 to S12, from oldest to youngest. The geologic ages of SB1, SB3, SB6, SB7, SB8, SB10, SB11 and SB12 were estimated from direct correlation with the published reports (Davey, 1981; ANTOSTRAT, 1995 and Brancolini et al., 1995) (Fig. 6). The geologic ages of SB4, SB5 and SB9 were estimated from correlation with major falls in eustatic sea level curve (Haq et al., 1987). The geologic age of SB2 was assumed to be the same as that of the oldest sediment recovered by the CROS-1 well.

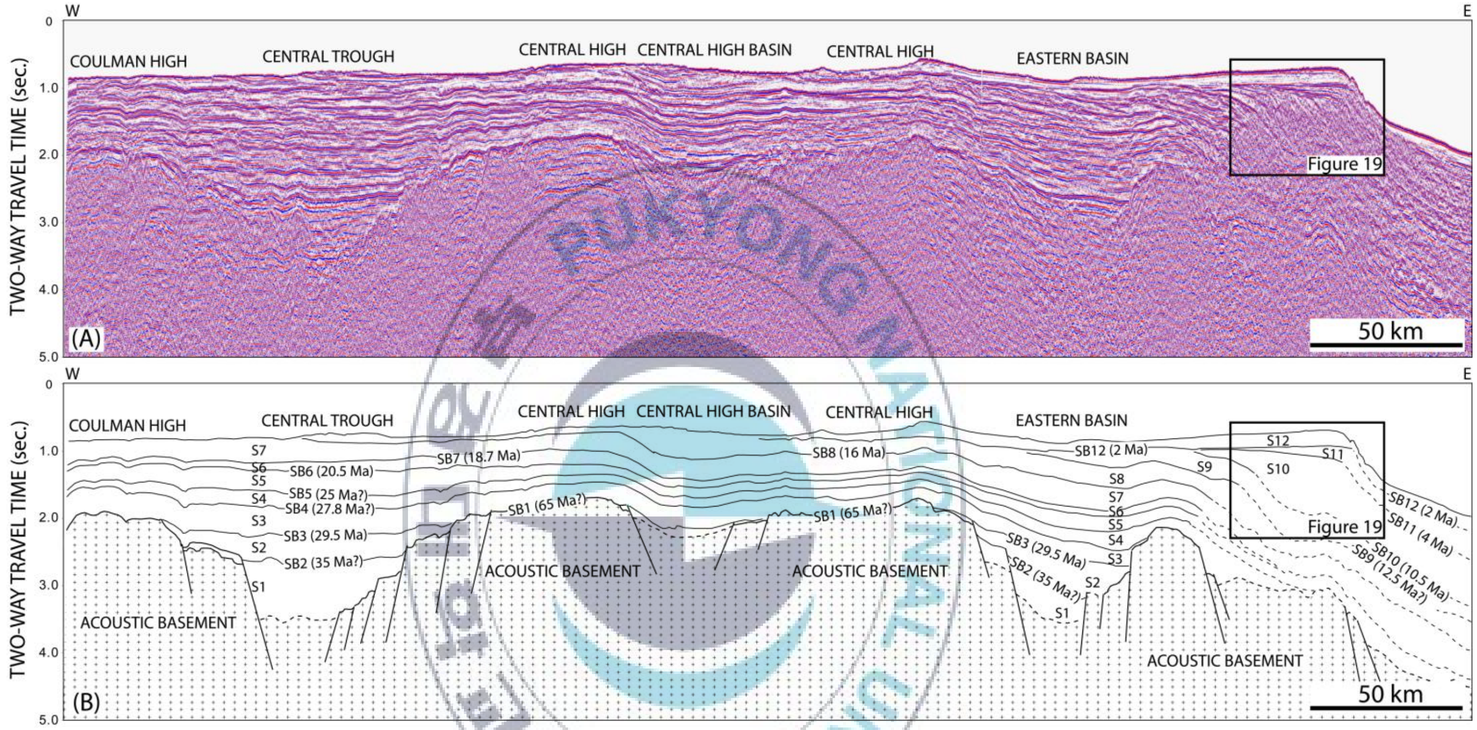

Figure 4. (A) Seismic profile crossing the Eastern Basin, Central High, Central High Basin, Central Trough and part of the Coulman High in E-W direction. (B) Interpretation of (A). The interpreted section exhibits major structural features of the area and all the sequence boundaries. SB2 and SB3 are recognized across the continental shelf. The box indicates Fig. 19. See Fig. 3 for location.

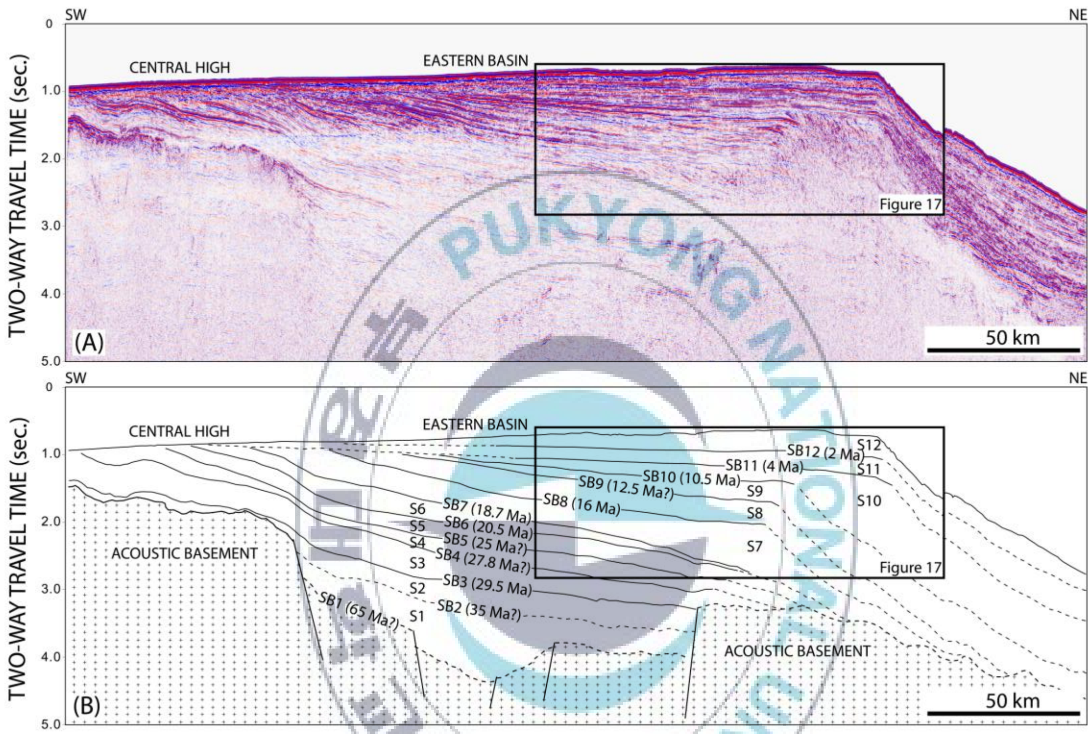

Figure 5. (A) Seismic profile traversing the Eastern Basin in SW-NE direction. (B) Interpretation of (A). The interpreted section exhibits all the unconformity surfaces and seafloor erosion on the shelf at the continental margin of the Eastern Basin. The continental shelf edge appears to have developed after SB6. The box indicates Fig. 17. See Fig. 3 for location.

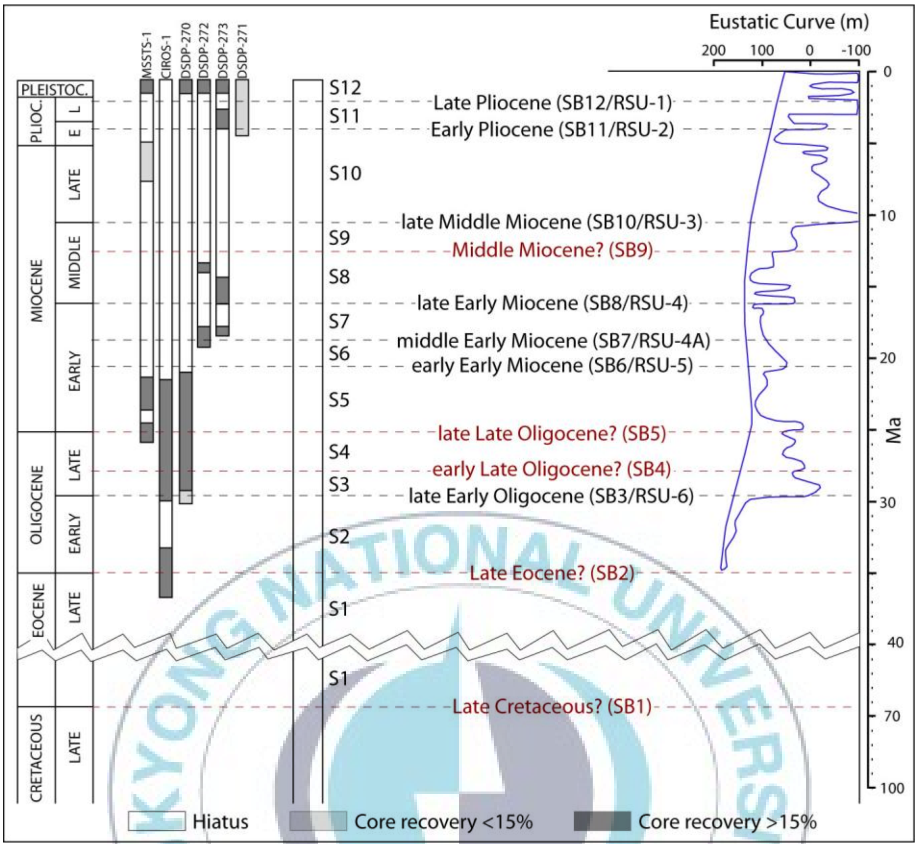

Figure 6. Geologic ages of sequence boundaries, correlated with existing core data estimated from the correlation with eaustatic sea level curve (Haq et al., 1987). Modified from Brancolini et al. (1995).

4.1.1 SB1 (Top of the Acoustic Basement, Late Cretaceous)

SB1 corresponds to the top of acoustic basement (Figs. 4, 5). The depth-structure map of SB1 reveals the main structural features in the area, including the Northern Basin Hallett Ridge, Central Basin, Central Trough, Coulman High, Central High, Central High Basin and Eastern Basin from northwest to southeast (Fig. 7). These structural features formed largely by rifting in the Late Cretaceous (Davey, 1981). The maximum depths of the Eastern Basin, Central Basin, Northern Basin and Central High Basin reach more than 10,000 m, 7,000 m, 5,000 m, 4,000 m and 3,000 m, respectively. The Northern Basin, Central Basin, and Central Trough are graben basins whereas the Eastern Basin is bounded by normal faults in the south and southwest and extends beyond the northern and eastern boundaries of the study area. A steep and narrow N-S trending basement high separates the Central Basin, Central Trough and Northern Basin. The Central High, separating the Central Basin, Central Trough and Eastern Basin, consists of three shallow (< 1,000 m) structures. The Coulman High (< 1,000 m) forms the boundary between the Northern Basin and the Central Trough. Most basement faults are oriented N-S, parallel to the regional structural trend of the area.

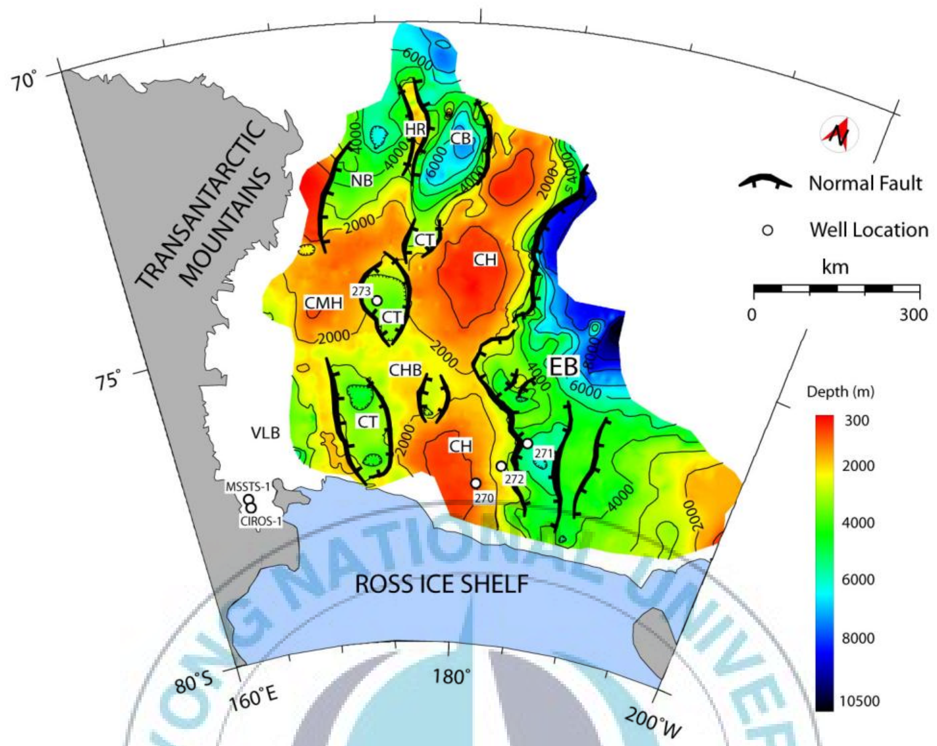

Figure 7. Depth-structure map of SB1 (top of the acoustic basement, Late Cretaceous). Basement faults are oriented N-S, parallel to the regional structural trend of the area. Most basins and troughs formed in the basement grabens. NB, the Northern Basin; HR, the Hallett Ridge; CB, the Central Basin; CT, the Central Trough; CH, the Central High; CMH, the Coulman High; CHB, the Central High Basin; VLB, the Victoria Land Basin; EB, the Eastern Basin. Contour interval is 1,000 m.

4.1.2 SB3 (late Early Oligocene, 29.5 Ma)

SB3 or RSU-6 of ANTOSTRAT (1995) and Brancolini et al. (1995) is a prominent unconformity with high amplitude (Fig. 4). It terminates against the basement highs and/or major faults and is seen in the Central Trough, Eastern Basin and part of the Central High Basin (Figs. 4, 8). The depths of SB3 range from less than 500 m in the southwestern margin of the Eastern Basin. The distribution of faults cutting SB3 is the same as that cut SB1; however, the faults caused only minor displacement.

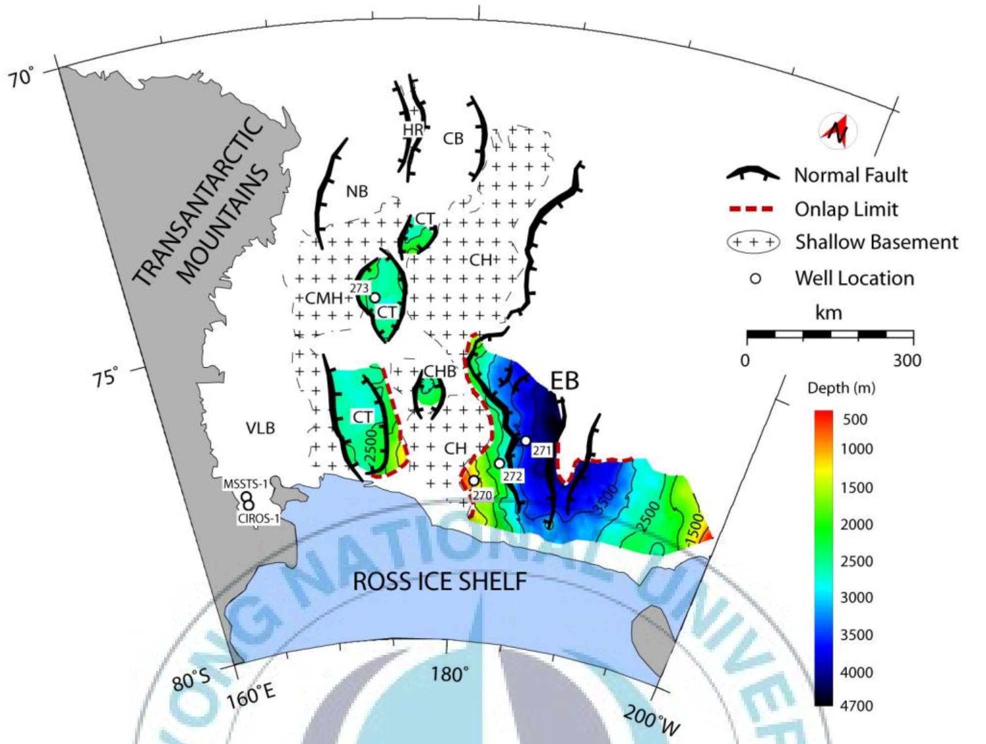

Figure 8. Depth-structure map of SB3 (late Early Oligocene). The faults cutting SB3 remain almost the same as those cutting SB1. NB, the Northern Basin; HR, the Hallett Ridge; CB, the Central Basin; CT, the Central Trough; CH, the Central High; CMH, the Coulman High; CHB, the Central High Basin; VLB, the Victoria Land Basin; EB, the Eastern Basin. Contour interval is 500 m.

4.1.3 SB7 (middle Early Miocene, 18.7 Ma)

SB7 or RSU-4A of ANTOSTRAT (1995) and Brancolini et al. (1995) is seen across the western Ross Sea and southwestern Eastern Basin (Fig. 9). The depths of SB7 reach over 4,000 m, 3,500 m, 1,500 m and 1,500 m in the Northern Basin, Eastern Basin, Central Trough and Central High Basin, respectively. It is truncated by seafloor erosion in the Central High, part of the Coulman High and along the southern margin of the Eastern Basin. It downlaps onto SB6 in the northeastern Eastern Basin. The number of faults reduced significantly, compared with that cut SB1 and SB3.

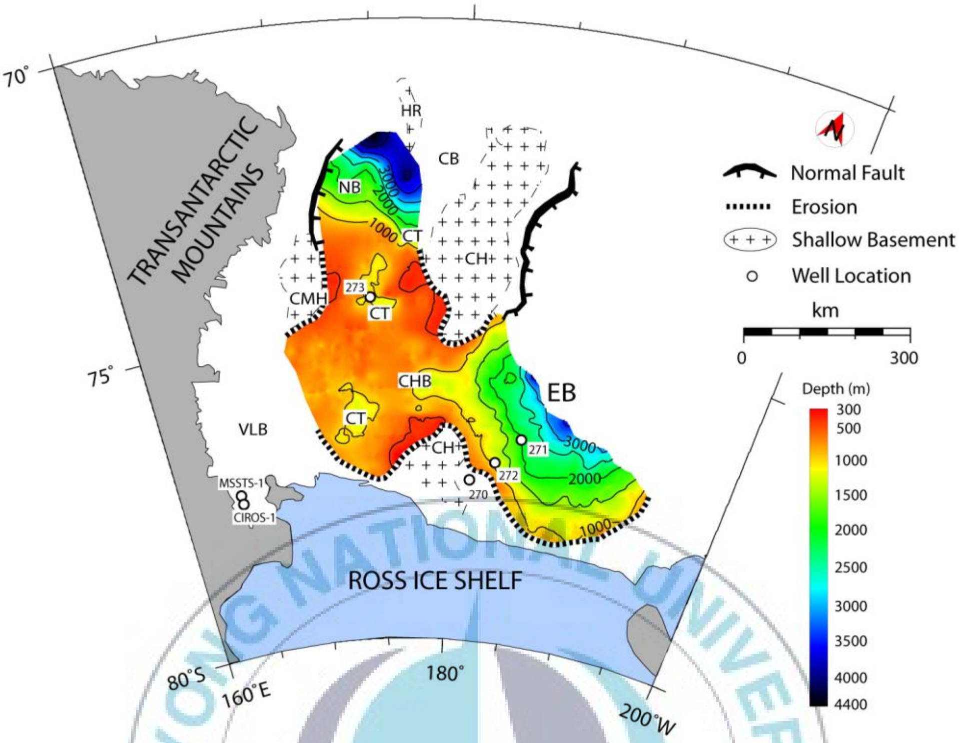

Figure 9. Depth-structure map of SB7 (middle Early Miocene). NB, the Northern Basin; HR, the Hallett Ridge; CB, the Central Basin; CT, the Central Trough; CH, the Central High; CMH, the Coulman High; CHB, the Central High Basin; VLB, the Victoria Land Basin; EB, the Eastern Basin. Contour interval is 500 m.

4.1.4 SB8 (late Early Miocene, 16 Ma)

SB8 or RSU-4 of ANTOSTRAT (1995) and Brancolini et al. (1995) is seen in the Central Trough, Central High Basin, and southern Eastern Basin (Fig. 10). It is truncated by erosion at the seafloor in the Central High and Coulman High. The depths of SB8 range from 300 m in the Central Trough and Central High Basin to over 6,000 m in the southern Eastern Basin.

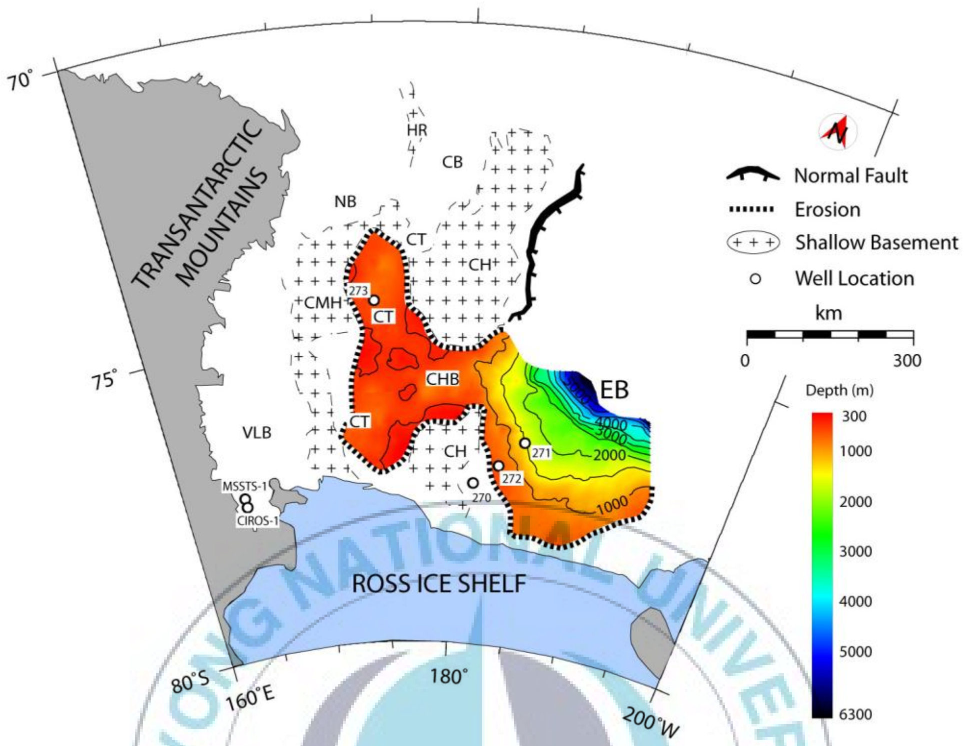

Figure 10. Depth-structure map of SB8 (late Early Miocene). The faults cutting SB8 decreased compare to those cutting SB7. NB, the Northern Basin; HR, the Hallett Ridge; CB, the Central Basin; CT, the Central Trough; CH, the Central High; CMH, the Coulman High; CHB, the Central High Basin; VLB, the Victoria Land Basin; EB, the Eastern Basin. Contour interval is 500 m.

4.1.5 SB11 (Early Pliocene, 4 Ma)

SB11 or RSU-2 of ANTOSTRAT (1995) and Brancolini et al. (1995) is seen only in the southernmost part of the Eastern Basin (Fig. 11). It forms an angular unconformity (Fig. 5). The unconformity is truncated by seafloor erosion and/or SB12 over much of the western part of the area. The number of faults cutting SB11 is the same as that cutting SB8. The depths of SB11 range from 600 m to up to about 6,000 m.

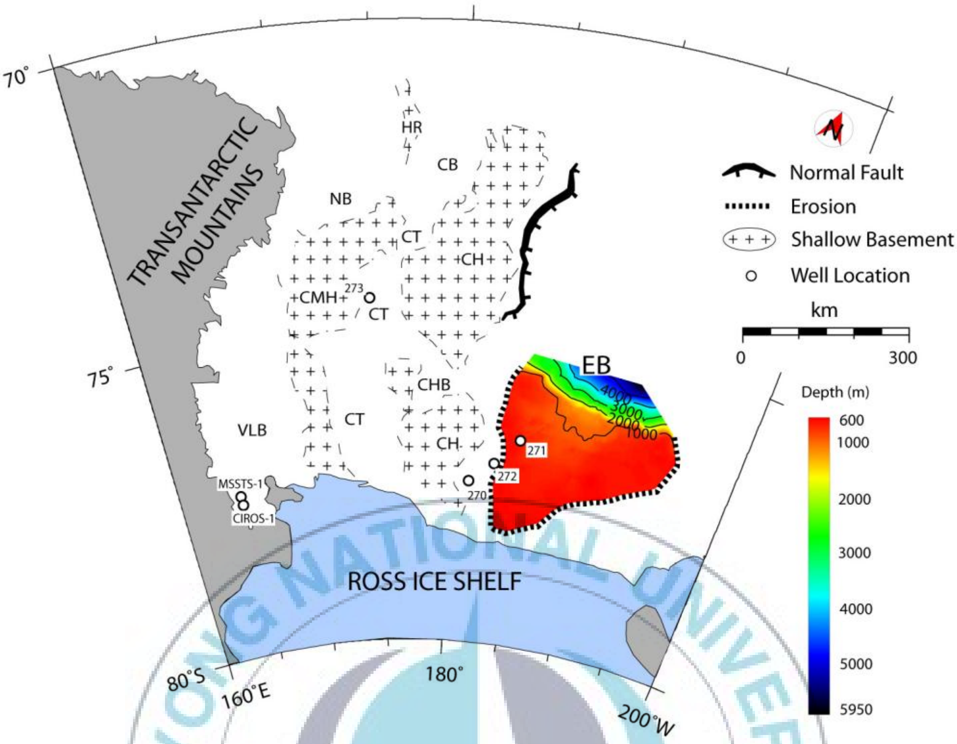

Figure 11. Depth-structure map of SB11 (Early Pliocene). NB, the Northern Basin; HR, the Hallett Ridge; CB, the Central Basin; CT, the Central Trough; CH, the Central High; CMH, the Coulman High; CHB, the Central High Basin; VLB, the Victoria Land Basin; EB, the Eastern Basin. Contour interval is 1,000 m.

4.2 Seismic Sequences and Sediment Thickness Maps

4.2.1 Total Sediment Thickness

The total sediment thicknesses range from about 100 m over the basement highs to more than 5,700 m in the Eastern Basin (Fig. 12). The maximum sediment thicknesses in the Eastern Basin, Northern Basin, Central Trough, Central Basin and Central High Basin reach more than 5,000 m, 4,000 m, 4,000 m 3,000 m and 2,000 m, respectively.

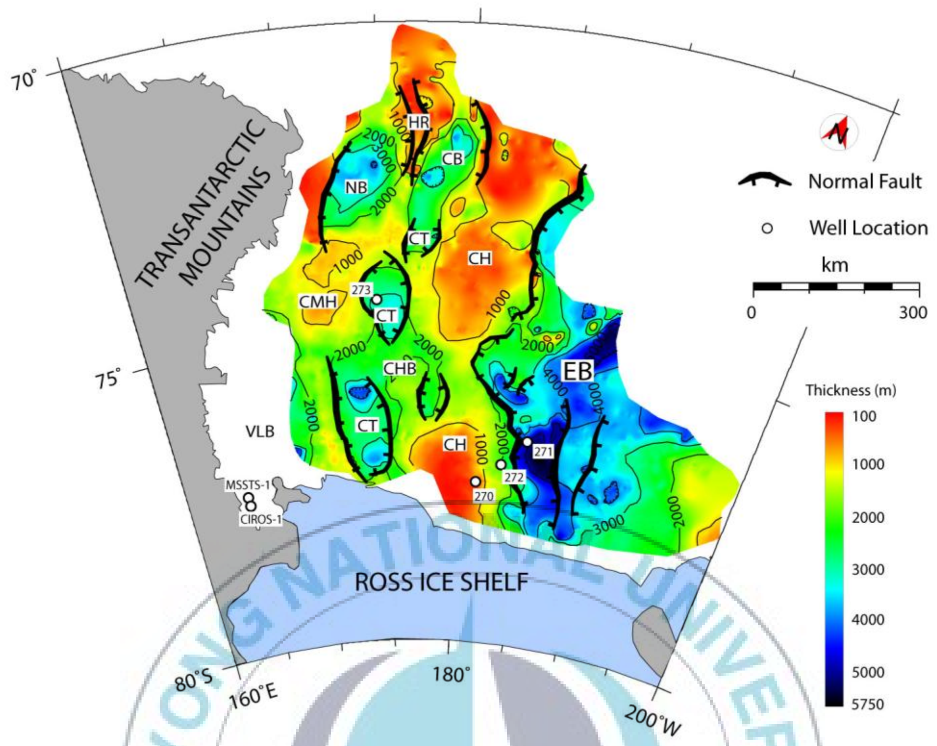

Figure 12. Total sediment thickness.　The sediment thicknesses in the Eastern Basin, Northern Basin, Central Trough, Central Basin and Central High Basin reach more than 5,000 m, 4,000 m, 4,000 m 3,000 m and 2,000 m, respectively. NB, the Northern Basin; HR, the Hallett Ridge; CB, the Central Basin; CT, the Central Trough; CH, the Central High; CMH, the Coulman High; CHB, the Central High Basin; VLB, the Victoria Land Basin; EB, the Eastern Basin. Contour interval is 1,000 m.

4.2.2 Combined Thickness of S1 and S2 (Late Cretaceous-late Early Oligocene)

S1 and S2 terminate against the basement highs and/or major faults and fill basement grabens and depressions, burying the graben-and-rift basement topography (Fig. 4). The combined thickness of S1 and S2 varies from less than 500 m in the Central High Basin to over 2,000 m in the Eastern Basin and Central Trough (Fig. 13).

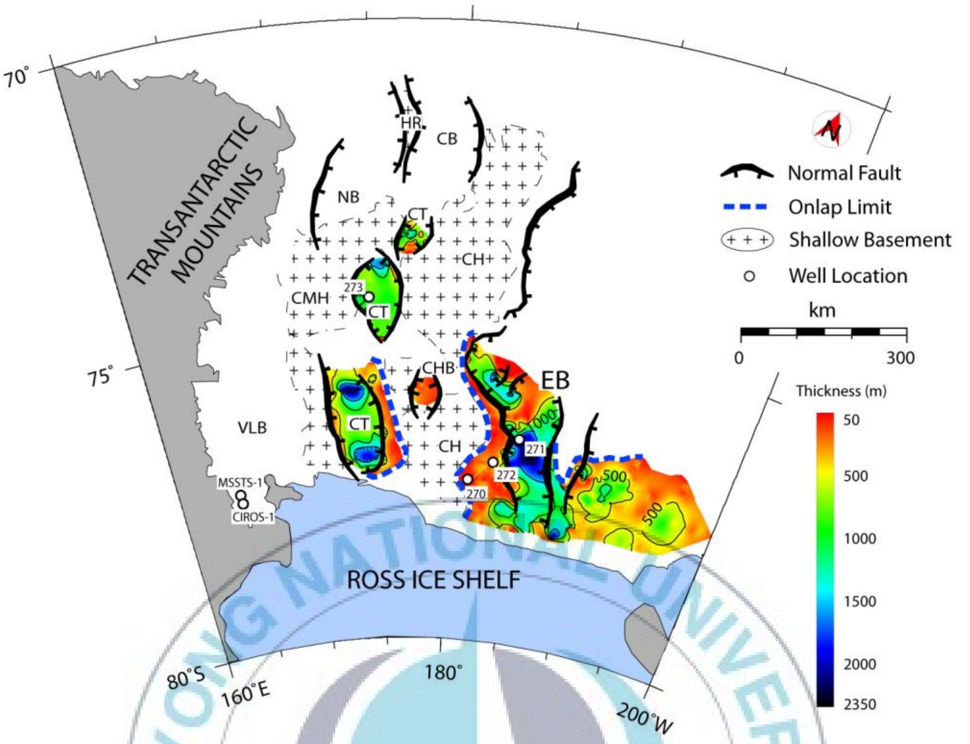

Figure 13. Combined thickness of S1 and S2 (Late Cretaceous-late Early Oligocene). NB, the Northern Basin; HR, the Hallett Ridge; CB, the Central Basin; CT, the Central Trough; CH, the Central High; CMH, the Coulman High; CHB, the Central High Basin; VLB, the Victoria Land Basin; EB, the Eastern Basin. Contour interval is 500 m.

4.2.3 Combined Thickness of S3 to S12 (late Early Oligocene-present)

The sedimentary unit above SB3 that includes S3 to S12 largely fills the area after the graben-and-rift basement topography was buried by S1 and S2 (Fig. 4). The thicknesses of this unit range from about 100 m over the basement highs and to more than 4,500 m in the Eastern Basin (Fig. 14). They reach more than 4,500 m, 2,500 m and 2,500 m in the Eastern Basin, Central Trough and Central High Basin, respectively.

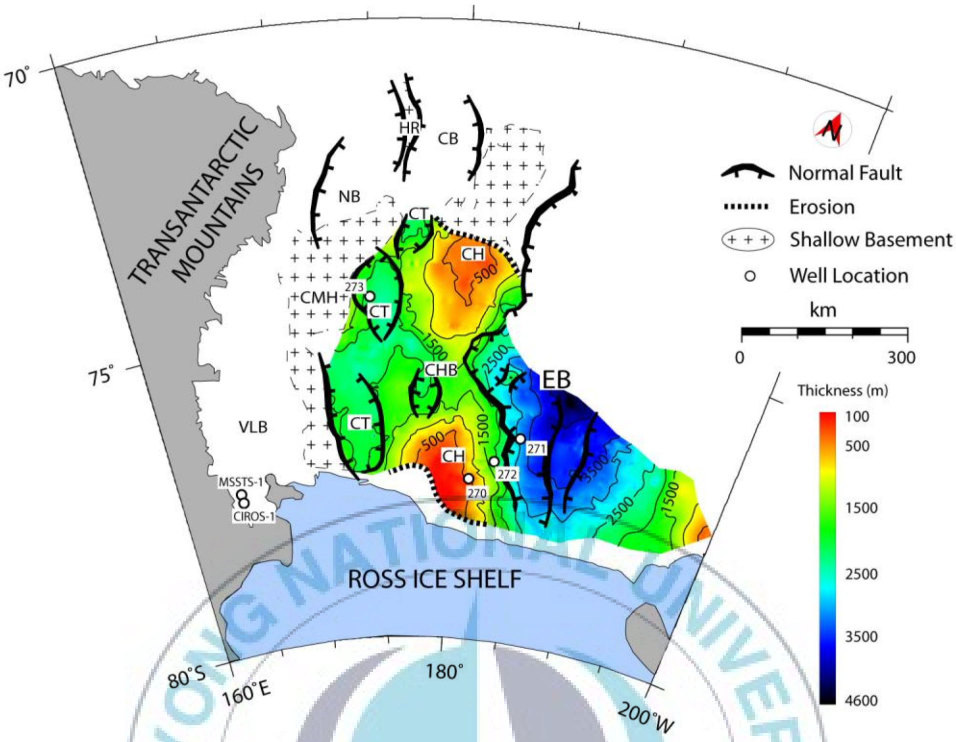

Figure 14. Combined thickness of S3 to S12 (late Early Oligocene-present). NB, the Northern Basin; HR, the Hallett Ridge; CB, the Central Basin; CT, the Central Trough; CH, the Central High; CMH, the Coulman High; CHB, the Central High Basin; VLB, the Victoria Land Basin; EB, the Eastern Basin. Contour interval is 500 m.

4.2.4 Thickness of S7 (middle-late Early Miocene)

S7 is seen in the Eastern Basin, Central High Basin and two southern depocenters of the Central Trough (Fig. 15). Seismic reflections in S7 are characterized by low to high and variable amplitude, good continuity over much of the mapped area in the Central Trough and Central High Basin. Clinoforms are seen locally in the inner shelf; these clinoforms prograded about 120 km northward (Fig. 16). On the other hand, the progradation (ca. 60 km) of shelf margin along the southern margin of the Eastern Basin appears to be widespread (Fig. 17). The thicknesses of S7 range from less than 100 m over basement highs to over 1,300 m in the continental margin of the Eastern Basin.

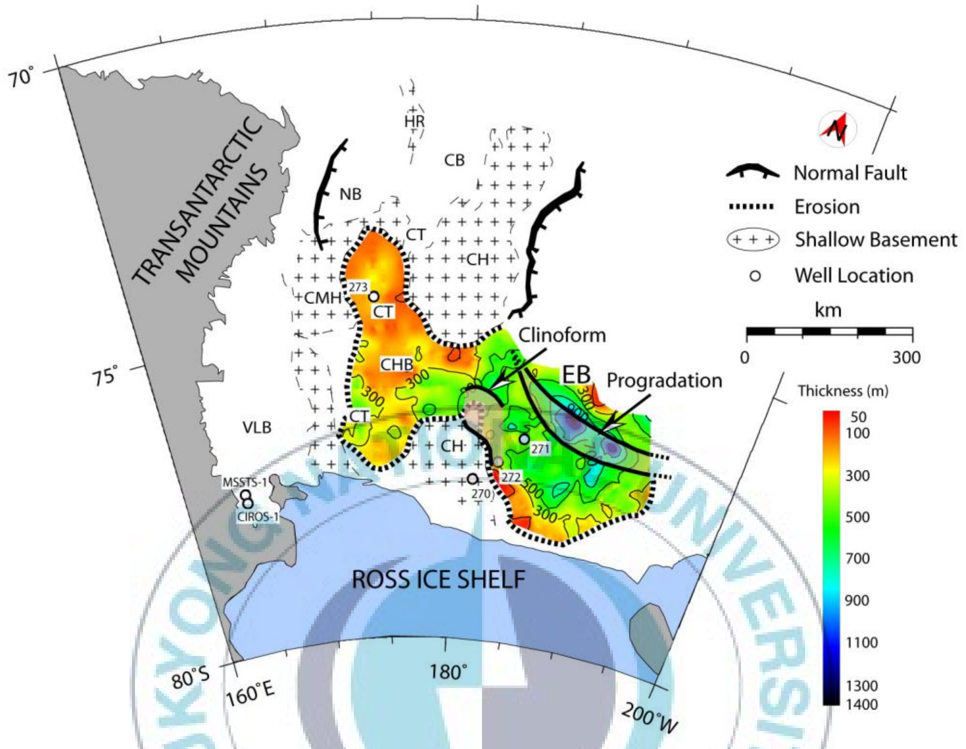

Figure 15. Thickness of S7 (middle-late Early Miocene). Distances of progradation in the upper shelf and the shelf margin are 120 km and 60 km, respectively. NB, the Northern Basin; HR, the Hallett Ridge; CB, the Central Basin; CT, the Central Trough; CH, the Central High; CMH, the Coulman High; CHB, the Central High Basin; VLB, the Victoria Land Basin; EB, the Eastern Basin. Contour interval is 200 m.

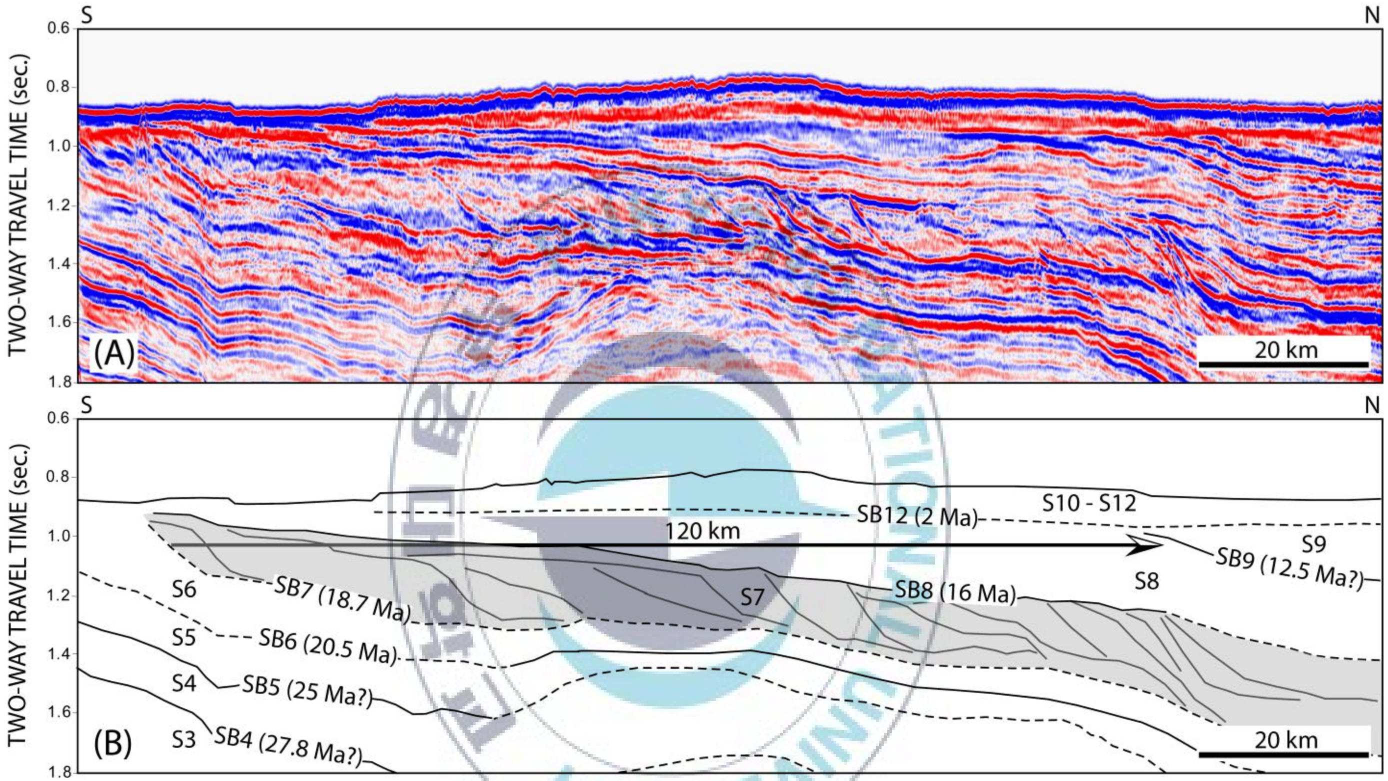

Figure 16. (A) Seismic profile crossing the Eastern Basin in S-N direction. (B) Interpretation of (A). It exhibits northward progradational clinoforms in S7; the distance of progradation is about 120 km. See Fig. 3 for location.

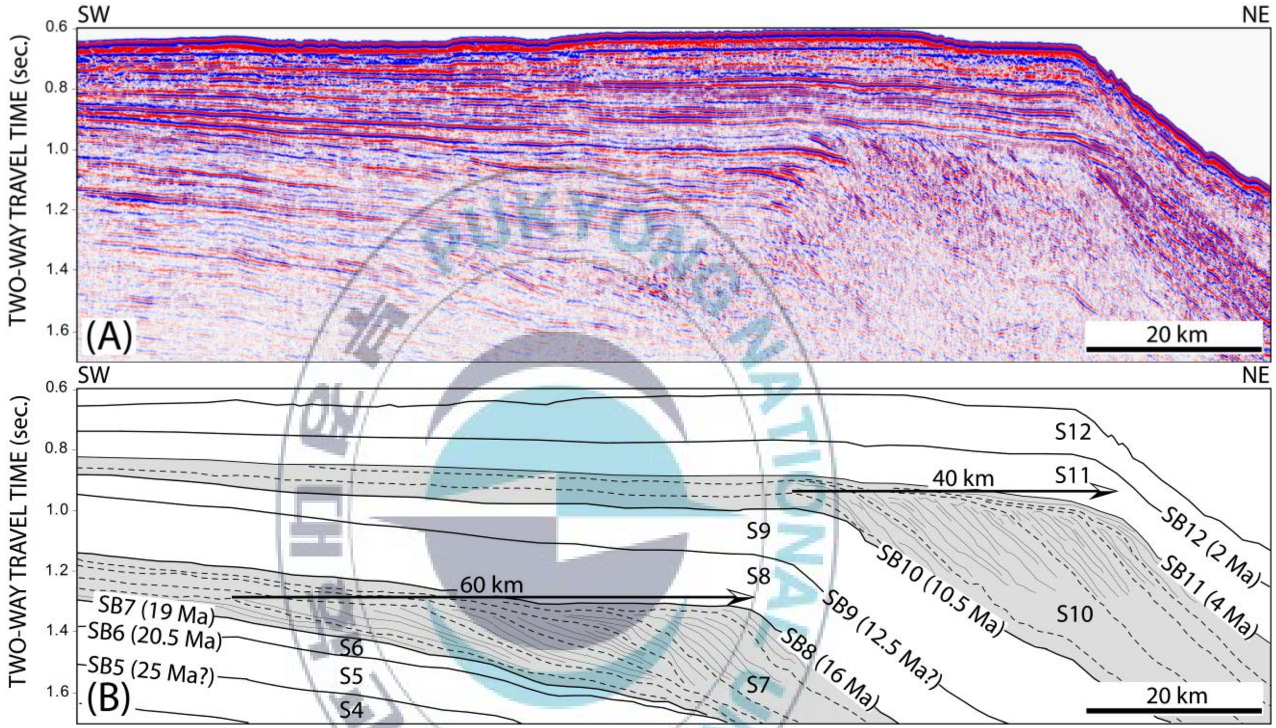

Figure 17. (A) Part of the seismic profile in Figure 5. (B) Interpretation of (A). Progradation of the shelf margin along the southern margin of the Eastern Basin is seen in S7 and S10. (1) middle-late Early Miocene and (2) Late Miocene-Early Pliocene. Progradation distances of S7 and S10 are about 60 km and 40 km, respectively. See Fig. 3 for location.

4.2.5 Thickness of S10 (late Middle Miocene-Early Pliocene)

S10 is seen in the southern Eastern Basin (Fig. 18). It is about 50 m thick in the shelf and over 2,000 m thick along the shelf margin, characterized by clinoform packages with steep forest and eroded topset beds (Figs. 17, 19). The distance of progradation is about 40 km. Seismic reflections within S10 are similar to those of S7 but tend to be more continuous and of higher amplitude (Fig. 17).

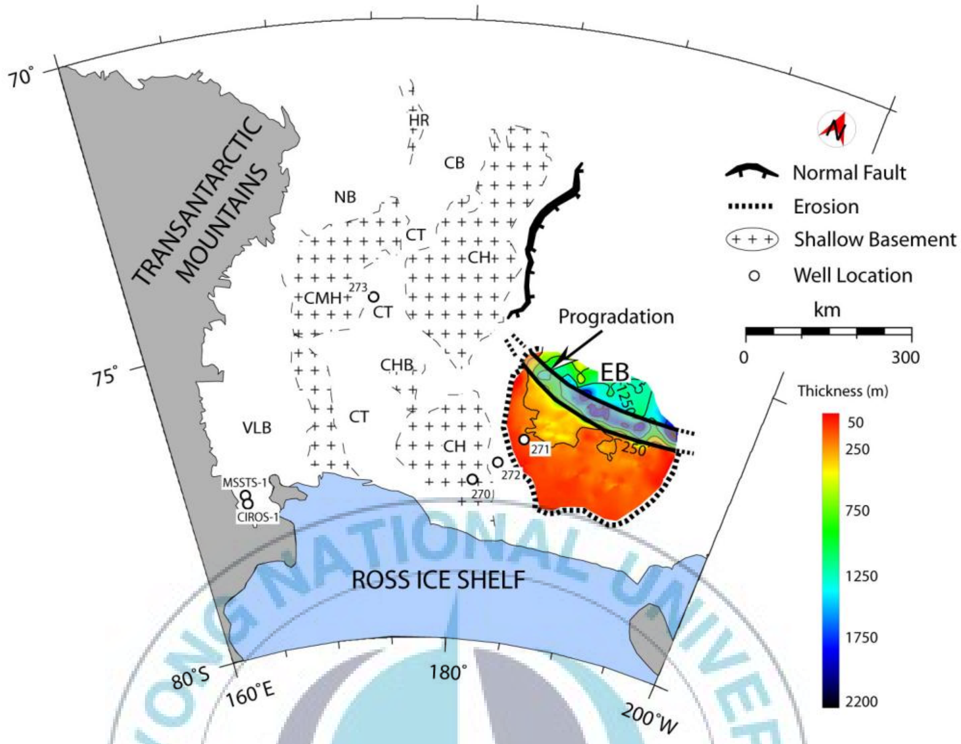

Figure 18. Thickness of S10 (late Middle Miocene-Early Pliocene). Distance of the shelf-margin progradation is about 40 km. NB, the Northern Basin; HR, the Hallett Ridge; CB, the Central Basin; CT, the Central Trough; CH, the Central High; CMH, the Coulman High; CHB, the Central High Basin; VLB, the Victoria Land Basin; EB, the Eastern Basin. Contour interval is 500 m.

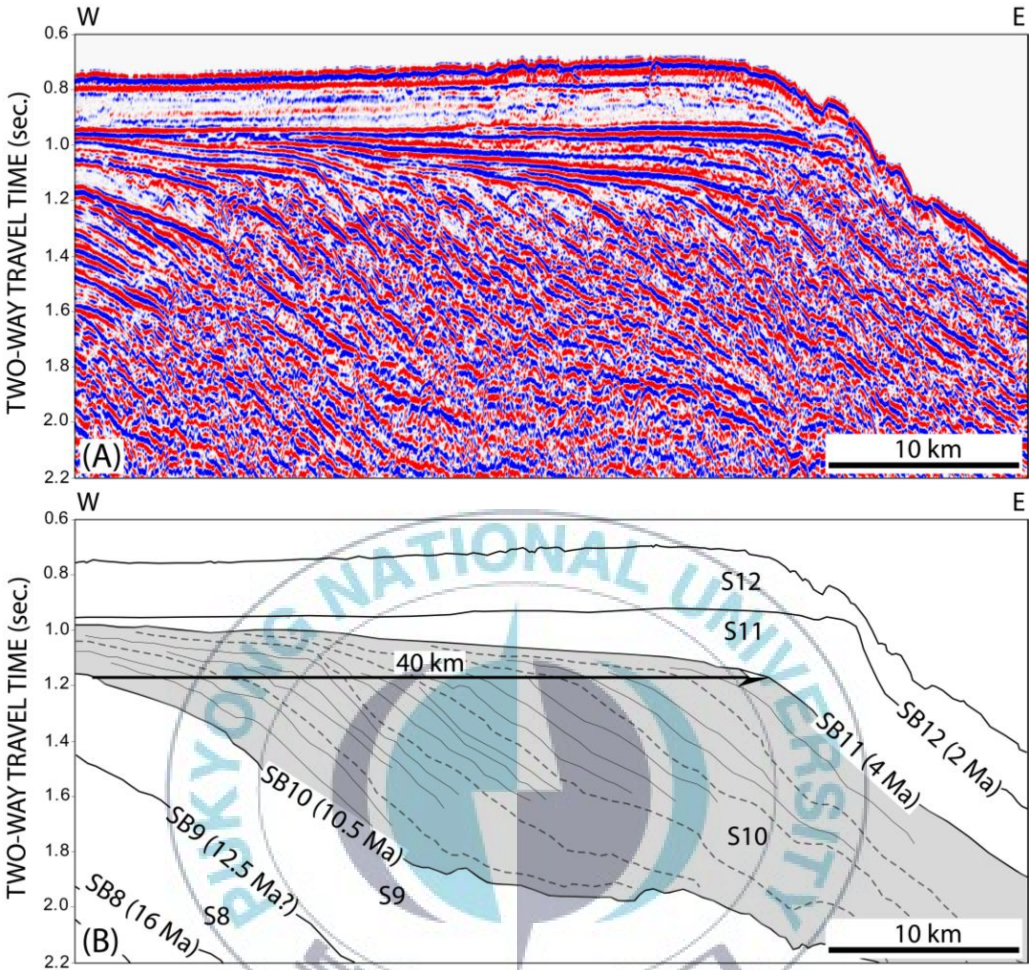

Figure 19. (A) Part of the seismic profile in Figure 4. (B) Interpretation of (A). The shelf-margin progradation in S10 is characterized by steep foreset and eroded topset beds, typical of till deltas. The distance of progradation is about 40 km. See Fig. 3 for location

4.3 Cross-Section Restoration

To better understand the structural evolution of the area, a representative cross-section (Fig. 20), was depth-converted and restored using 2DMove® (version 5.1) (Fig. 21). The cross section traverses the Central High Basin, Central High, Central Trough and part of the Coulman High in E-W direction (Fig. 20). The normal faults in the basement formed mainly during the initial stage of the rifting and extension (Late Cretaceous); the extension rate was about 4.3% in the Central Trough. Mild extension (0.4%) continued in the Central High and Central High Basin in the Late Oligocene. The postrift subsidence was interrupted by an uplift sometime in the late Early Miocene.

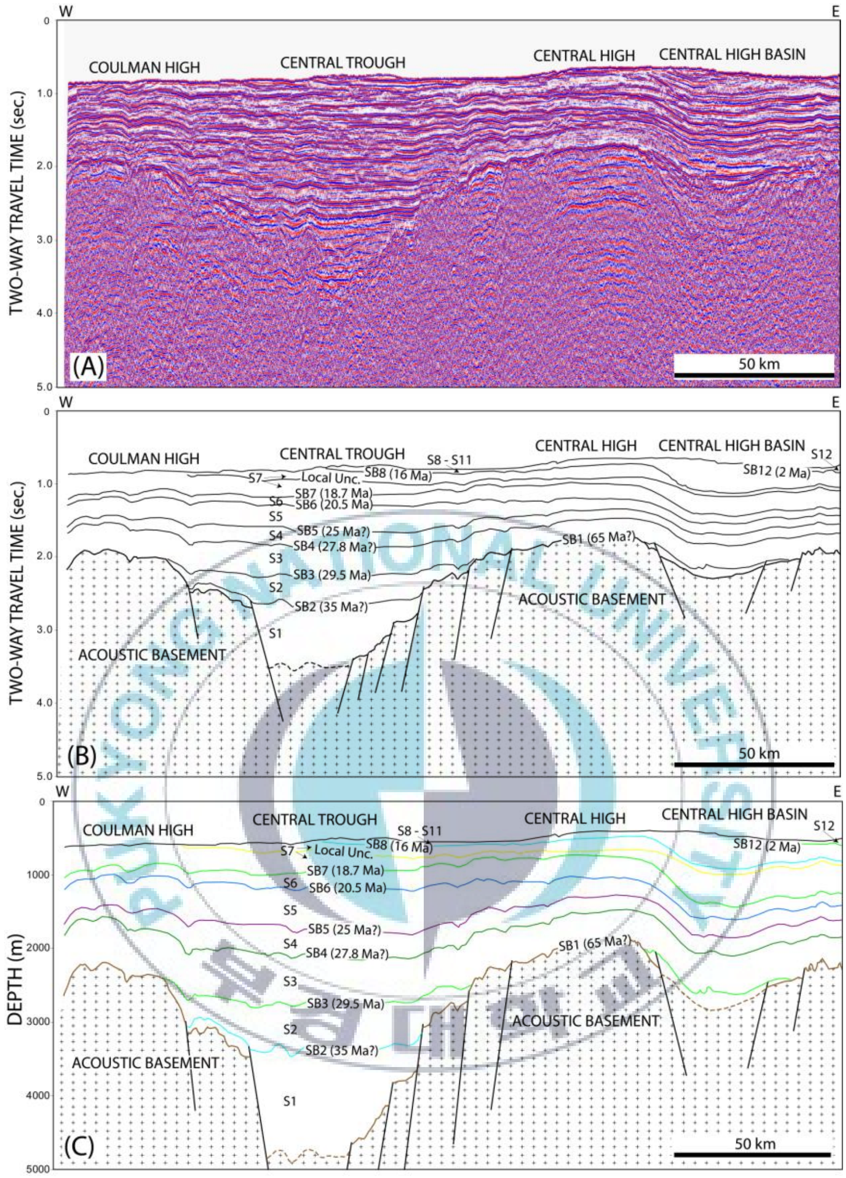

Figure 20. (A) E-W seismic profile crossing the Central High Basin, Central High, Central Trough and part of the Coulman High in E-W direction. (B) Interpretation of (A). (C) Depth model of (A). See Fig. 3 for location.

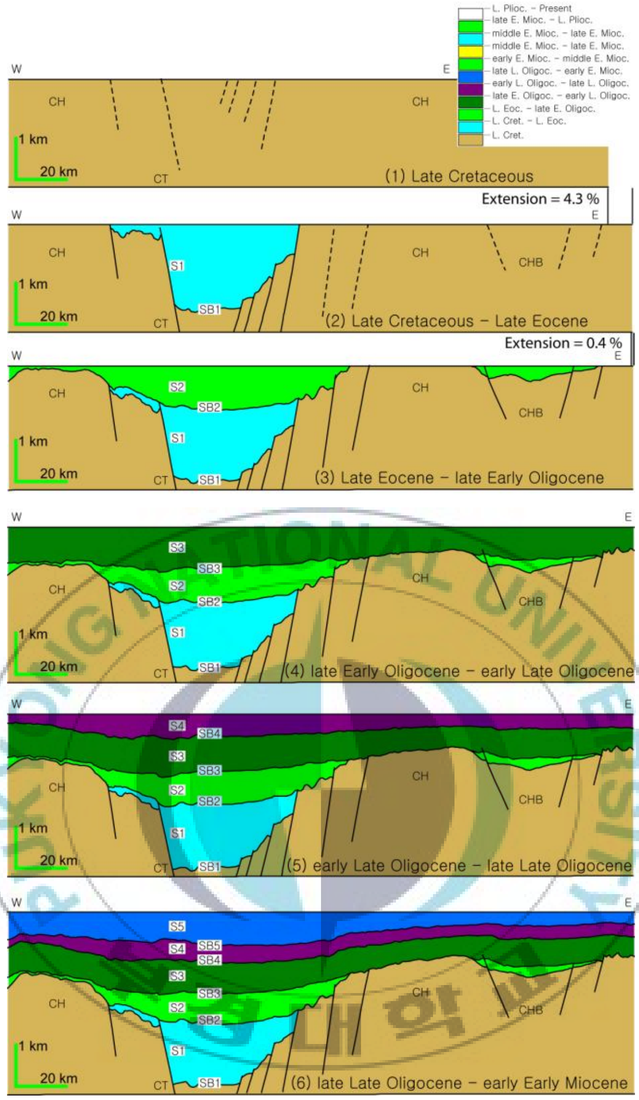

Figure 21. Restoration of the depth model in Fig. 8C, using 2DMove®. Basins and structures formed in two different stages of extension. The basement graben formed in two rifting phases separated by SB2. The subsidence-dominant postrift phase was interrupted by uplift in the Middle Miocene.

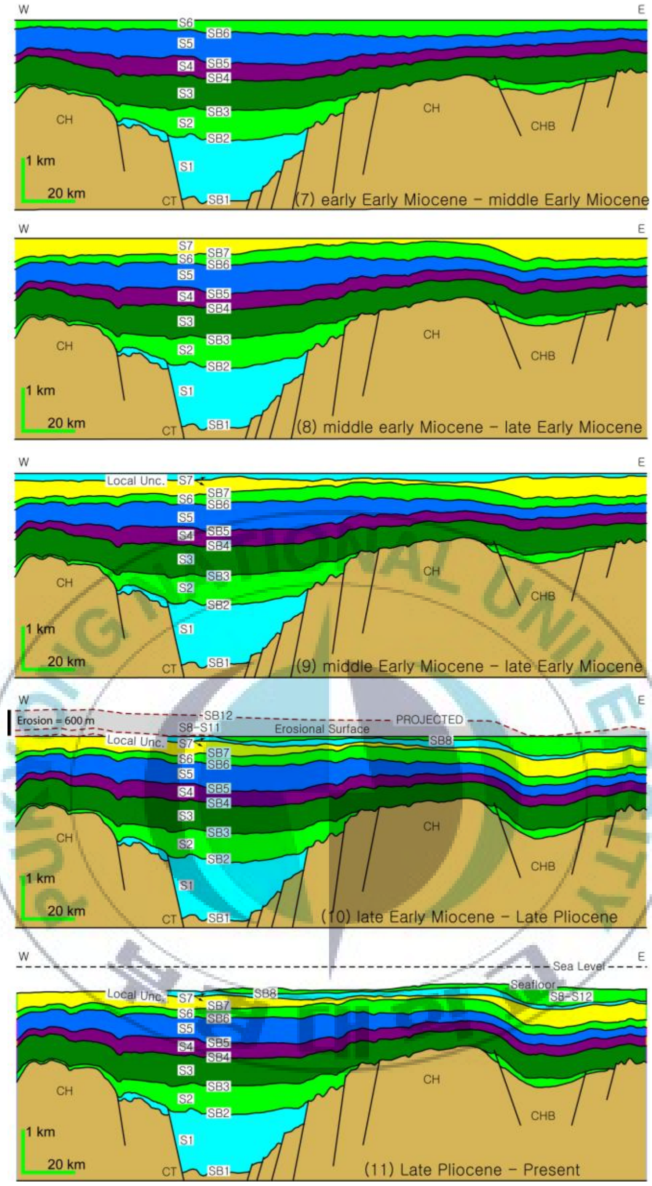

Figure 21. Continued.

5. Discussion

5.1 Rifting to Regional Subsidence

S1 and S2 (Late Cretaceous-late Early Oligocene) are interpreted as synrift sediments as they almost completely filled the basement grabens and half grabens, formed during the initial rifting and extension in the area (Figs. 4, 5). SB2, dividing S1 and S2, suggests two phases of rifting. Decesari (2006) also recognized two synrift packages below the Oligocene sediments across the Ross Sea from seismic reflection data. The initial rifting and extension in the Central Trough started in the Late Cretaceous and the estimated E-W extension is about 10 km (4.3 %). This initial extension may be related to the onset of seafloor spreading between Antarctica, New Zealand and Australia in the Late Cretaceous (Cooper et al., 1987; Behrendt et al., 1991; Richard et al., 1994; Fritzgerald, 2002).

The postrift phase was dominated by subsidence; however, the cross-section restoration indicates uplift (~ 600 m) in the late Early Miocene in the Central High. The erosion of uplifted sediments resulted in SB11/RSU-2 which forms a prominent angular unconformity (Fig. 5). SB11/RSU-2 has been interpreted to be related to a major glaciation (Hinz and Block, 1984; Larter and Barker, 1989; Anderson, 1991; Cooper et al., 1991a; De Santis et al., 1995; 1999;

Brancolini et al., 1995). The cross-section restoration suggests that the timing of the local uplift coincides with the major glaciation. Thus, the erosion that formed SB11 may have been caused by either glaciation and/or subaerial exposure. Bart (2003) also argued that the West Antarctic land areas were significantly higher than today.

5.2 Glacial History

Sedimentary sequences that appear to have recorded the history of grounded ice sheets in the Eastern Basin include: (1) S7 (middle-late Early Miocene) or RSS-4 of ANTOSTRAT (1995) and Brancolini et al. (1995) and (2) S10 (Late Miocene-Early Pliocene) or RSS-6 or ANTOSTRAT (1995) and Brancolini et al. (1995). Chow and Bart (2003) suggested at least five shelf-wide ice grounding events in the Ross Sea during the Middle Miocene. Bart (2003) also reported that at least two WAIS grounding events occurred in the Ross Sea during the early Middle Miocene. Major grounded ice sheet development also occurred in the Late Miocene-Early Pliocene (Hinz and Block, 1984; Larter and Barker, 1989; Anderson, 1991; Cooper et al., 1991a; De Santis et al., 1995; 1999; Brancolini et al., 1995), largely coinciding with the progradation of S10. The high-velocity and low-porosity sediments immediately above S10/RSU-2 may suggest a major advance of the WAIS on the continental shelf of the Ross Sea (Accaino et al., 2005).

The progradational clinoforms with truncated top surfaces seen locally in the upper shelf area of S7 are likely to have formed beneath grounded ice, suggesting the growth of the WAIS in the Early Miocene, earlier than the previously reported. These locally-developed clinoforms are very similar to the till deltas formed beneath the advancing ice sheet on the shelf, illustrated in the conceptual model of ice-sheet erosion and deposition on the Antarctic by Bart (2003) (Fig. 22A). The limited occurrence of these clinoforms may suggest local growth of ice which may have developed along a valley or in a lake, controlled by the topography.

The progradation of S7 and S10 along the shelf margin was probably due to the shelf-wide ice sheet that caused subglacial erosion of till deltas and underlying strata on the shelf and deposition of till deltas on the outer shelf and slope (Fig. 22B). The progradation was followed by aggradation, suggesting subsidence and/or relative rise of sea level or retreat of the ice sheet (Fig. 22C).

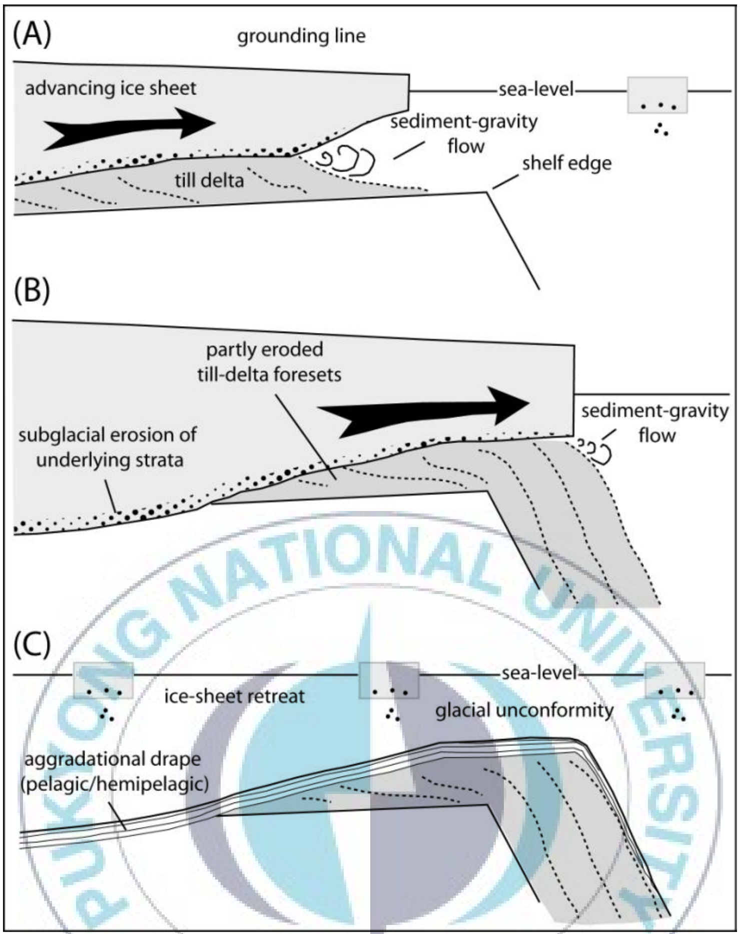

Figure 22. Conceptual model of ice-sheet erosion and deposition on the Antarctic outer continental shelf during a glacial/interglacial cycle. (A) Initial advance of the ice sheet from land onto inner shelf and deposition of a till delta at the grounding zone. (B) Subglacial erosion of till delta and underlying strata on the inner shelf and deposition of till delta on outer continental shelf. (C) Rapid ice-sheet retreat from the continental shelf and aggradation of open marine hemipelagics/pelagics. Modified from Bart (2003).

6. SUMMARY AND CONCLUSIONS

● The top of the acoustic basement and eleven regional unconformities were mapped from the public-domain multi-channel seismic reflection data.

● The basement structure reveals the main structural features in the area: the Northern Basin, Hallett Ridge, Central Basin, Central Trough, Coulman High, Central High, Central High Basin, and Eastern Basin.

● Basement faults are dominantly oriented N-S, parallel to the regional structural trend of the area and the basins form mostly on the basement grabens.

● The basins and troughs show a typical rift-basin development: faulted basement and synrift and postrift sedimentation separated by an unconformity.

● The synrift phase can be divided into early and late synrift phases.

● The postrift subsidence was interrupted by uplift in the late Early Miocene.

● The locally developed clinoforms with truncated topsets in the upper shelf area of S7 probably suggest the onset of ice growth in the Ross Sea in the middle to late Early Miocene, earlier than previously reported.

● The extensive shelf-margin progradation in S10 along the southern margin of the Eastern Basin is probably due to the growth of the WAIS into the area.

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To my family …

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