Rift History of the Western Victoria Land Basin: A new Perspective Based on Integration of Cores with Seismic Reflection Data

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Abstract. The results of a stratigraphic study of the western Victoria Land Basin, Antarctica, are summarized. This analysis is based on all existing seismic reflection data integrated with lithological information from fully cored drillholes in the Cape Roberts area of western McMurdo Sound. A number of subsurface seismic reflectors were recognized in the Cape Roberts area and correlated to stratal interfaces previously recognized in the cores. These events were then traced regionally throughout the southern McMurdo Sound, and form the basis for a new seismic stratigraphic subdivision of the Cenozoic section. Key reflectors define boundaries of seismic stratigraphic units, each of which shows distinctive overall cross-sectional geometry and internal reflection character/facies. On this basis, we propose a new model for the evolution of the Victoria Land Basin, invoking five phases of tectonic activity and associated sediment accumulation patterns. 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 rather 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" and gave rise to a succession containing both young magmatic rocks and young faults and which thickens markedly into a central depocentre. The new framework allows recognition of thick, post-Early Miocene stratigraphic intervals as yet unsampled by stratigraphic drilling in McMurdo Sound.

Introduction

Despite a considerable history of geological and geophysical exploration, the tectonic history and basin evolution of the Victoria Land Basin (VLB) in the Ross Sea region of Antarctica are poorly understood. Various seismic reflection surveys have been carried out, over more than thirty years (Fig. 6.4-1), leading to several seismic stratigraphic frameworks and consequent interpretations of basin history, but until recently such models have been largely unconstrained by lithological data. This is because sedimentary strata of the VLB are only preserved below the water and ice of McMurdo Sound (Fig. 6.4-1) and do not crop out on land. In the late 1990s, core drilling by the Cape Roberts Project (Cape Roberts Science Team 1998, 1999, 2000) provided a complete lithological transect through the western VLB, allowing firm correlations between the extensive seismic data set and geological reality for the first time. Lithostratigraphic boundaries in Cape Roberts Project (CRP) cores have been correlated to events imaged by seismic reflection data in the immediate vicinity of the CRP drillholes by both CRP scientists (Henrys et al. 2000, 2001; Fielding et al. 2000, 2001) and by Hamilton et al. (2001). However, to date, no-one has attempted to correlate these events regionally throughout the seismic data set for the McMurdo Sound region (Fig. 6.4-1). Furthermore, problems with seismic data quality (in particular, the prominence of sea-floor multiples on seismic sections) have to date hampered a complete understanding of local cross-sectional basin geometry in the vicinity of Cape Roberts.

In this paper, we summarize the results of a comprehensive review of available seismic data. We utilize scientific results from CRP drillholes to constrain the timing and geological meaning of events recognized on seismic data, and use the resulting framework as the basis for a new geological model for the western VLB. We compare our framework with those published previously by others.

Methods

Seismic reflection data from all surveys carried out in McMurdo Sound (Fig. 6.4-1) were collated at the Institute of Geological and Nuclear Sciences (GNS) at Lower Hutt, New Zealand, and loaded onto a Unix workstation running Schlumberger Geoquest (©) interpretation software. Navigational data were used to correct some older lines to a linear distance scale. Seismic lines were then interpreted on a work-station, using cross-line functions to provide realistic four way and other stratigraphic ties. Paper prints were also interpreted independently to serve as a quality control mechanism. Seismic data quality is compromised in the area by the presence of a strong sea-floor multiple due to ice cover and associated "ringing" effects. Since the first multiple lies closer to the sea floor in shallower water, and since all holes drilled to date have been sited on shallow submerged ridges (notably CRP and CIROS holes), the data quality issue is (confoundingly) most acute over the ar-

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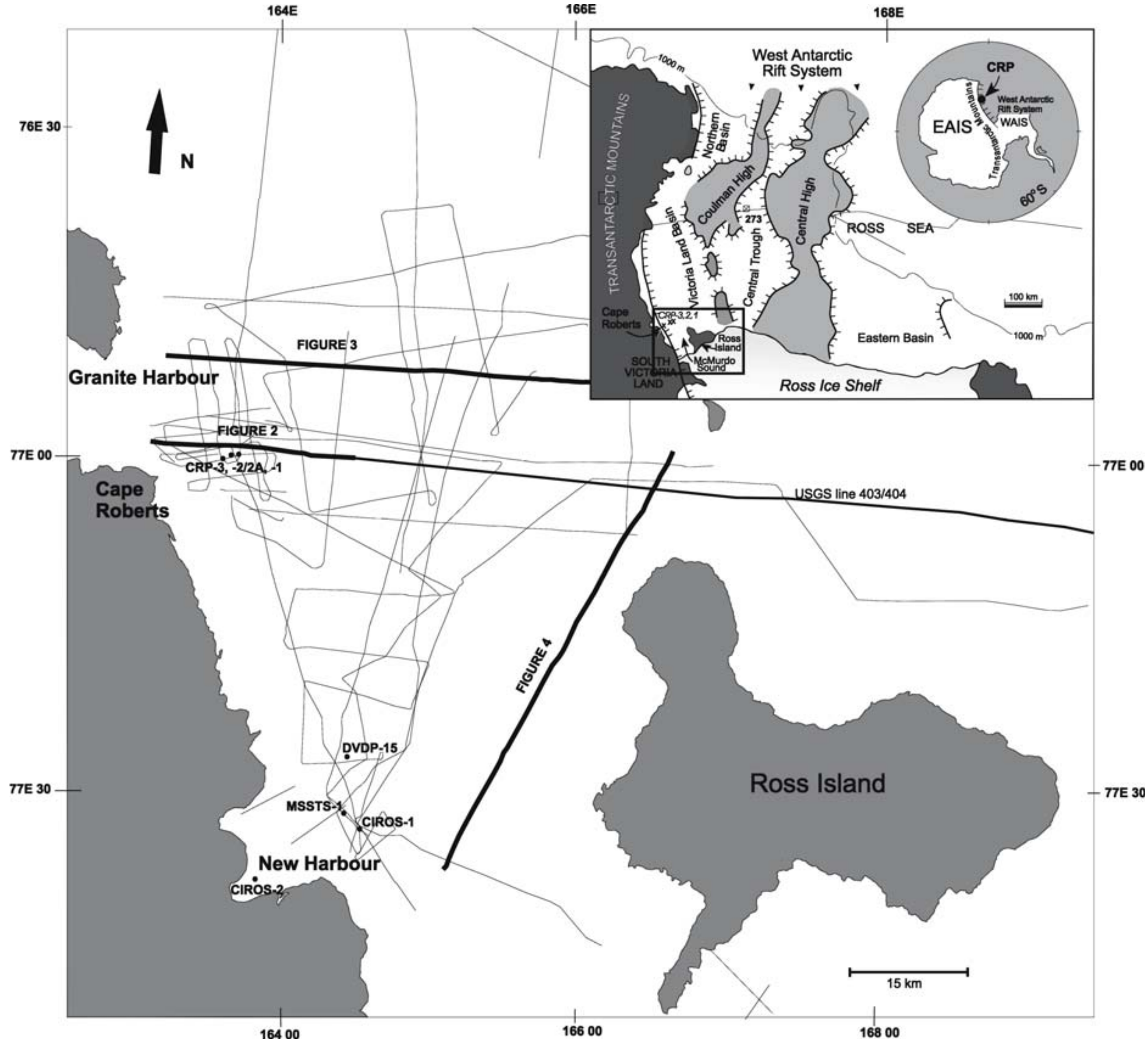

Fig. 6.4-1. Maps showing the regional context and structure of the Victoria Land Basin, the track lines of seismic reflection surveys and relevant drillhole locations. Note the positions of USGS seismic reflection line 403/404 (*bold section* illustrated as Fig. 6.4-2), line IT90a-75 (Fig. 6.4-3) and line IT90a-70 (Fig. 6.4-4)

eas of greatest interest. In order to circumvent this as far as possible, correlations from the Cape Roberts area to the New Harbor (CIROS) area were achieved by tracing events in one area eastward into deeper water, north-south along depositional strike and then westward up into shallow water again. Additionally, important new data on the deeper structure of the basin in the vicinity of Cape Roberts were generated by re-processing of USGS Line 403/404 (Cooper et al. 1987) at GNS to mitigate multiple effects. This line, and the tectonic interpretations that follow from it, are treated separately by Wilson et al. (submitted). In the present paper, a new seismic stratigraphic framework is presented, prominent seismic events are linked to lithostratigraphic horizons recognised in the CRP cores, and this framework is interpreted in terms of basin history.

Regional Geological Considerations

The VLB is broadly north-northwest-elongated, as defined by major bounding faults and horsts (Fig. 6.4-1). Depositional dip is east-northeastward in the western part of the basin, and has an opposite sense in the east. Thus, regional seismic lines such as USGS Line 403/404 (Cooper et al. 1987) show stratal thickening from both west and east into a central depocentre, analogous to the "steer's head" rift geometry of White and McKenzie (1988). The central depocentre is also a zone where the amplitudes of reflectors are attenuated and scattered, interpreted by various workers (e.g., Cooper et al. 1987) as concentrations of magmatic (intrusive and volcanic) rocks. Near the western margin of the basin (CIROS-1, CRP-1, -2/2A, -3), the VLB succession comprises a mostly homoclinal section ranging in age from latest Eocene (ca. 34 Ma) through to late Early Miocene (ca. 17 Ma), unconformably overlain by a generally thin Plio-Pleistocene section. The major angular discordance that separates these two packages has been referred to by many previous workers as the "Ross Sea Unconformity", although it is clear now that more than one major unconformity punctuates the section in some areas.

Seismic Data and Interpretation

The regional seismic reflection line USGS 403/404 passes within 2 km of the Cape Roberts Project drillholes (Fig. 6.4-1). Re-processing has revealed the deeper structure in this region necessary to allow interpretation of early Cenozoic basin formation. The westernmost portion of the re-processed line in the vicinity of Cape Roberts is shown in Fig. 6.4-2 (see Fig. 6.4-1 for location). The major features of the present sea-floor bathymetry are, from the coastline eastward, a narrow shelf adjacent to the coast, a north-south-linear trough with steep margins ("Cape Roberts Rift Basin" of Hamilton et al. 2001), a linear topographic high named the Roberts Ridge (on the western flank of which the CRP holes were sited: Fig. 6.4-2), and a ramp slope that descends from the crest of Roberts Ridge at ca. −50 m to the deepest part of McMurdo Sound (−700 to −800 m). Figure 6.4-2 shows a thick succession beneath Roberts Ridge that thickens and dips eastward and is apparently truncated westward against the margin of the "Cape Roberts Rift Basin" (CRRB). This trough is interpreted as being fault-bounded, and its fill is essentially flat-lying in contrast to the Roberts Ridge section. A further important structural feature evident from the re-processed data is a basement horst downdip from the drilling sites that appears to truncate the lower part of the coherent stratigraphy (below the yellow event: Fig. 6.4-2). A variety of shallow faults have also been interpreted, some directly above the basement horst and others closer to the CRRB.

The most consistently recognizable and persistent reflections in this and other lines were chosen as the basis for a seismic stratigraphic framework. Most of these are major seismic sequence boundaries, and correlate to important stratal interfaces identified independently in the CRP cores (Table 6.4-1). The basal navy blue event is interpreted as the basement unconformity. It is intersected in CRP-3, where it separates probable Devonian quartzose sandstones below from probable latest Eocene, lithic sandstones, conglomerates and breccias above. This event is truncated updip against the margin of the CRRB, can be tentatively interpreted at greater depth within that feature, and also terminates downdip against the afore-mentioned basement horst (Fig. 6.4-2). The overlying section, dominated in CRP-3 by conglomerates passing upward into predominantly sandstones with minor conglomerates, thickens into the area immediately updip of the basement horst and is confined by that feature. This interval corresponds to much of the 800+ m thick, sandstone-dominated latest Eocene to earliest Oligocene section penetrated in CRP-3, which becomes gradually more organized into depositional sequences upward, and becomes lithologically more diverse, with increasing proportions of mudrock and diamictite upward.

The next major seismic marker is the yellow event (Fig. 6.4-2, Table 6.4-1), which corresponds to a major stratal interface in CRP-2/2A (at 443 m below sea floor: m b.s.f.). This horizon separates sections confined by the early

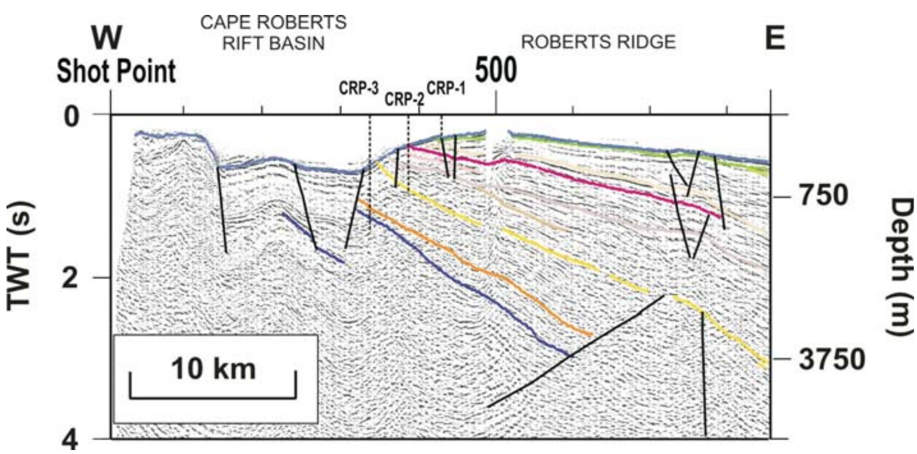

Fig. 6.4-2. Westernmost portion of seismic reflection line USGS 403/404 (re-processed to mitigate the masking effects of the sea-floor multiples), showing the projected positions of Cape Roberts Project drillholes (*CRP-1, -2/2A* and *-3*), and interpreted to show major faults and seismic events described in the text. *TWT:* Two Way Travel Time. See Table 6.4-1 for key to seismic reflector coding scheme. The tectonic phase 2 (early rift) spans the interval between the *navy blue* and *yellow* reflectors, Phase 3 (main rift) between the *yellow* and *purple-grey* reflectors, phase 4 (thermal subsidence) between the *purple-grey* and *green* reflectors and phase 5 (Terror Rift formation) is the thin interval above the *green* reflectors. The phase 5 section thickens markedly into the central depocentre of the VLB (see Fig. 6.4-3 and 6.4-4)

Table 6.4-1. Key to seismic reflector coding scheme

Cooper et al. 1987	Brancolini et al. 1995	Bartek et al. 1996	Hamilton et al. 2001	Henrys et al. 2000, 2001; Fielding et al. 2000, 2001	This paper	Rift phase
V1	RSU 1-3 RSS 5-8 (Middle Miocene in DSDP273) RSU 4 (Lower Miocene in DSDP 273) RSS 4	A-H	?	Thin intervals only sampled	(Pliocene or Pleistocene in MSSTS/CIROS/CRP)	5
	RSU 4a				Refl. h (dark green)	
V2	RSS 3	I J K	? ? ?	Not sampled		
	RSU 5	L-M	?		Refl. h1 (light green)	4
V3	RSS 2	N O P	? ? ?	Not sampled		
	~RSU 6	P/Q			w1 (beige) 17 Ma ~ top CRP section	
			V3			
		R	90 mbsf CRP-2/2A	?Refl. "a" 52 mbsf CRP-2/2A	w1b (crimson) 19 Ma	
			V4a	Q		
			307 mbsf CRP-2/2A	Refl. "b" 91 mbsf CRP-2/2A	w1a (pink) 21 Ma	
V4		S	V4b	R	(d) = top thick sequences 23.7 Ma	
				Refl. "e" ("d") 186 (130) mbsf CRP-2/2A	w2 (e) (brown + purple-grey)	
				S		3
			443 mbsf CRP-2/2A	Refl. "i" 307 mbsf CRP-2/2A	Base thick sequences 24.1 Ma	
	RSS 1	T	V5a ?	T		
V5			330 mbsf CRP-3	Refl. "l" 443 mbsf CRP-2/2A	w3 (yellow) 29 Ma	
			V5b+V5c ?	U		2
				Refl. "p" 95 mbsf CRP-3		
				V		
				Refl. "r" 225 mbsf CRP-3		
				W		
				Refl. "u" 444 mbsf CRP-3		
					w4 (orange)	
				X	w5 (red) 34 Ma	
				Basement 823 mbsf CRP-3	Basement (navy blue)	
V6		("volcanics")	V6			1
V7		("basement")	V7			

horst-graben topography from overlying strata that are not confined by this structure. Above the yellow event, the section thickens downdip into a more distal depocentre to the east (Fig. 6.4-2). In the CRP cores, this section is sandstone-dominated but lithologically more heterogeneous, including numerous diamictite intervals, and can be divided into depositional sequences bounded by erosion surfaces that are interpreted to record glacial advance/retreat cycles with associated changes in relative sea-level (Fielding et al. 1998, 2000, 2001; Naish et al. 2001). This interval is of Lower Oligocene to basal Lower Miocene age. In addition to the numerous sequence-bounding unconformities, many of which can be recognized as persistent seismic reflectors (Fielding et al. 2000), a major, angular unconformity is mapped at the purple-grey reflector, which truncates the brown reflector (Fig. 6.4-2). This unconformity forms the top of the eastward-thickening stratal wedge mentioned above.

Above this unconformity, the section is more tabular in cross-sectional geometry. The overlying interval corresponds to the upper part of the Lower Miocene section in CRP-2/2A and the section penetrated by CRP-1, which lithologically is composed of highly top-truncated and incomplete depositional sequences otherwise similar to those below with abundant diamictites. The uppermost Miocene horizon penetrated by CRP-1 corresponds to the beige (light brown) event (Fig. 6.4-2), dated at ca. 17 Ma from microfossils. However, up to several hundred metres of additional (as yet unsampled) section clearly concordant with this event is evident from the seismic data. Above this is a prominent unconformity surface coded light green (Fig. 6.4-2). This surface separates the more or less tabular-stratified section below from a section above that thickens more prominently into VLB depocentres (Fig. 6.4-2). A further major stratal interface (coded dark green: Fig. 6.4-2, Table 6.4-1) occurs near the top of the CRP section, and is a prominent, angular unconformity overlain across the Roberts Ridge by only a thin (1–2 cycles thick) section which in CRP is of Pleistocene and Pliocene age. This section also thickens spectacularly eastward. The major (dark green) unconformity in CRP separates lithified strata of Lower Miocene (17 Ma) age from largely unconsolidated, diamictite-dominated Pliocene and Pleistocene strata.

The post-CRP section is better illustrated by seismic profiles that extend into the deep water depocentre of the present McMurdo Sound. Figure 6.4-3 shows part of seismic profile IT90a-75 (near-trace, single channel section), which runs parallel to, and north of the USGS 403/404 line (Fig. 6.4-1). The northward extension of the CRRB and Roberts Ridge are evident near the west end of the transect, as is the Eocene-Miocene section described above (note the location of the beige reflector denoting the top-CRP Miocene horizon). Unlike Fig. 6.4-2, however, Fig. 6.4-3 shows a massive post-17 Ma section (up to 1.5 seconds Two-Way Travel Time [TWT], conservatively

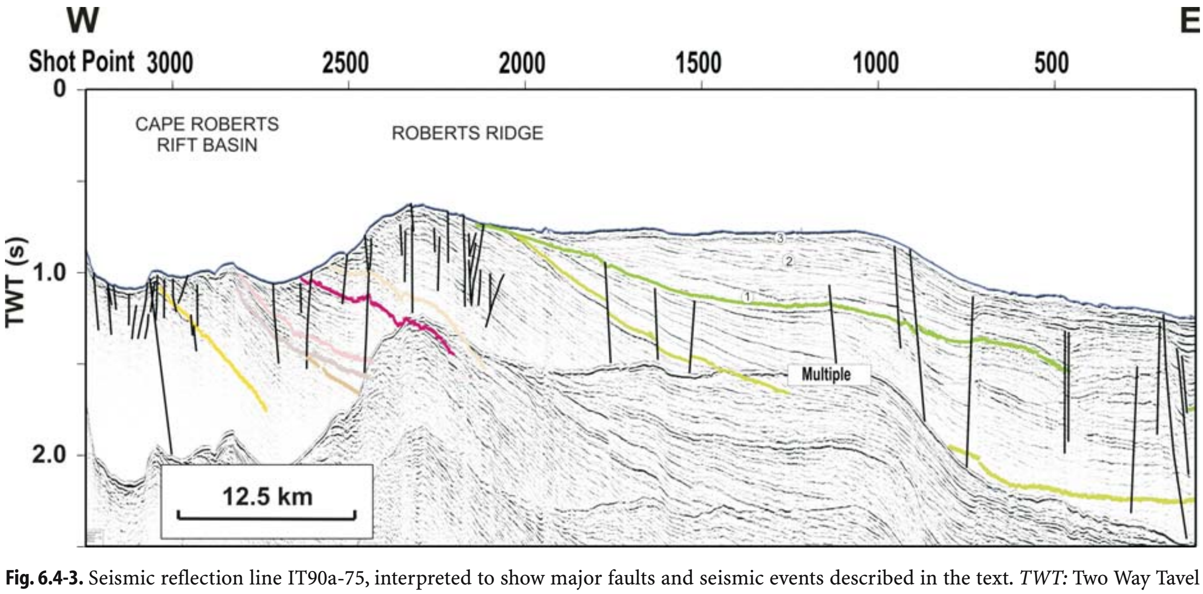

Fig. 6.4-3. Seismic reflection line IT90a-75, interpreted to show major faults and seismic events described in the text. *TWT:* Two Way Tavel Time. See Table 6.4-1 for key to seismic reflector coding scheme. Tectonic phase 2 (early rift) is that interval below the *yellow* reflector (not very clearly imaged), phase 3 (main rift) between the *yellow* and *purple-grey* reflectors, phase 4 (thermal subsidence) between the *purple-grey* and *light green* reflectors, and phase 5 (Terror Rift formation is above the *light green* reflector. The top of the Oligocene-Miocene section cored in the Cape Roberts holes is approximated by the *beige* (*light brown*) reflector, which intersects the sea floor at shot point ca. 2600. Note the dramatic thickening of the phase 5 section eastward into the VLB depocentre, the major angular unconformity represented by the *dark green* reflector, and the development of various seismic facies in the section above the unconformity (including 1. a reflection-free lens-shaped interval directly overlying the unconformity, interpreted as a lowstand slope wedge; 2. shelf-edge clinoforms overlying this wedge that form a pronounced progradational sequence set, and 3. a near-surface interval of parallel, concordant reflectors)

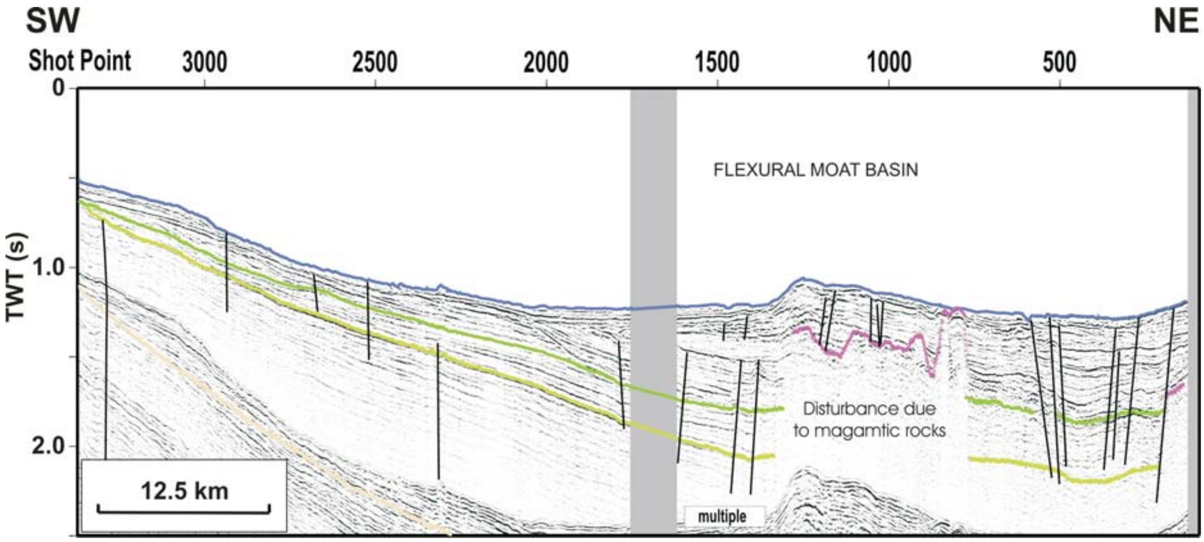

Fig. 6.4-4. Seismic reflection line IT90a-70, interpreted to show major faults and seismic events described in the text. See Table 6.4-1 for key to seismic reflector coding scheme. The *beige reflector*, representing the top of the Oligocene-Miocene section in CRP-1 to -3, lies somewhat below the first sea-floor multiple, the boundary between phase 4 (thermal subsidence) and phase 5 (Terror Rift formation lies at the *light green* reflector, and the major angular unconformity is represented by the *dark green* reflector. The line passes into a deep-water, flexural moat basin associated with the construction of the Ross Island volcanic edifices towards the northeast, and the top of an interpreted zone of magmatic rocks is denoted by the *purple* reflector. A series of further, post-*dark green* event unconformities likely caused by flexural loading is evident in the shallow subsurface between shot points 1 800–2 000

at least 1 500 m of section above the beige reflector: Fig. 6.4-3) preserved east of Roberts Ridge. The lower part of this section (at least 500 ms TWT) is concordant with the beige reflector and is of tabular cross-sectional geometry, suggesting that it forms part of the same succession as the upper CRP interval. Overlying this interval is an eastward-thickening wedge defined at its base by the light green event, and punctuated in the middle by the dark green angular unconformity. A further 300–400 ms of post-unconformity section is evident from this transect, suggesting significant post-Early Miocene sediment accumulation in the depocentre. This interval preserves spectacular examples of various seismic facies, including acoustically transparent wedges of strata on palaeo-slopes (lowstand wedges), and large-scale clinoform sets some of which define distinct shelf-slope breaks (Fig. 6.4-3).

The Neogene section is also clearly imaged by the northeast-trending line IT90a-70 (near-trace, single channel section: Fig. 6.4-4), which shows thickening of the post-beige interval into the deep water axial zone of the VLB, post-dark green unconformities that appear to be related to the formation of a flexural moat basin around Ross Island, and disruption of the seismic data by subsurface magmatic rocks in this region. The major Neogene reflectors were traced from the southwest end of Line IT90a-70 updip via line PD90-46 (see Barrett et al. 1995; Bartek et al. 1996) for illustrations and interpretations of this line) into the vicinity of CIROS-1 and MSSTS-1 (Fig. 6.4-1).

Integrated Stratigraphic Framework

The seismic stratigraphy described above and illustrated in Fig. 6.4-2 through 6.4-4 forms the basis for an interpretation of the evolution of the western VLB in the vicinity of Cape Roberts. Intervals between successive key horizons define seismic stratigraphic units, and changes in the cross-sectional geometry of these units are used to define Basin-Forming Phases 1 to 5 (Table 6.4-1). The following is a summary of the five interpreted phases of tectonic activity together with relevant geological information obtained from drillholes.

1. Regional Uplift and Erosion: Early Cenozoic (Pre-34 Ma)

Evidence from Apatite Fission Track Analysis (Fitzgerald 1992; Fitzgerald and Baldwin 1997) suggests that the Transantarctic Mountains underwent a period of major uplift during the early Cenozoic (55–45 Ma). Furthermore, clasts of granite and metamorphic rocks characteristic of the basement complex in the region west of McMurdo Sound are conspicuous throughout the Cenozoic section of CRP-3, down to immediately above the basal unconformity. The implications of these data are that substantial topography must have existed in the hinterland to the immediate west of CRP holes prior to any sediment delivery into the VLB, and that the topography had by this time excised at least down to the nonconformity with Lower Palaeozoic basement. The only stratigraphic record of this phase of activity is a thin breccia of ?Devonian sandstone clasts directly overlying the basement unconformity in CRP-3. The basement unconformity is defined by the navy blue seismic reflector in this study (Table 6.4-1). The eastward dip of the overlying VLB section in seismic lines also suggests that there was little if any down-to-the-basin normal faulting along the Transantarctic Mountain front during accumulation of the latest Eocene to Early Miocene rift succession.

2. Early Rift: Latest Eocene to Early Oligocene (34–29 Ma)

This package is defined in seismic data as the interval between the navy blue (basement) and yellow reflectors. Recognition of this basal, early rift package was facilitated by the reprocessing of USGS Line 403/404. Downdip of the Roberts Ridge, the interval overlying the basement unconformity is confined to structural lows (grabens) bounded by upstanding blocks (horsts), in a manner typical of early rift topography. Within the westernmost infra-basin, the cross-sectional geometry is an eastward-thickening wedge hinged on the western side. While such a structural and stratigraphic architecture is only visible in updip portions of this and some other lines, we suggest that the same architecture characterizes much if not all of the basin. The yellow event that defines the top of the package is the first reflector that is not confined by the early rift topography but rather is continuous over the tops of horsts into the deeper parts of the basin (eastward).

This graben-confined interval comprises the entire Cenozoic section of CRP-3 (823 m b.s.f. upward) and up to 443 m b.s.f. in CRP-2/2A, an aggregated thickness of ca. 1 000 m on Roberts Ridge. A subsidence model for the CRP cores based on a variety of chronostratigraphic data shows that this interval coincides with a period of very rapid subsidence (Wilson et al. submitted). Lithologically, the lower part of the interval comprises conglomerates and breccias up to boulder grade, progressively becoming interbedded with higher proportions of sandstone, but only minor mudrocks. This basal section has been interpreted as the product of subaerial to ultimately subaqueous base-of-slope fans or aprons, passing upward into a shallow marine environment characterised by oversupply of coarse sediment (Cape Roberts Science Team 2000). This interval, up to ca. 300 m b.s.f. in CRP-3, shows little or no cyclical vertical stacking of lithofacies that might be interpreted in terms of sequence stratigraphy. The upper half of the interval, spanning 300–0 m b.s.f. in CRP-3 and 623–443 m b.s.f. in CRP-2/2A, shows a progressive decrease in gravel grade facies and a concomitant increase in mudrocks (Cape Roberts Science Team 1999). The stratigraphically lowest diamictites also occur in this interval, increasing in abundance upward. These patterns are interpreted to record a progressive decline in the rate of sediment supply to the still rapidly subsiding graben, with sediment accumulation in a variety of shelfal water depths. The development of cyclical facies stacking patterns has been interpreted in terms of cycles of relative sea-level change under conditions of varying sediment supply and accommodation, and under the increasing influence of glacial advance and retreat across the shelf (Fielding et al. 2000).

3. Main Rift: Oligocene (29–24 Ma)

This package is defined from seismic data in the western VLB as an eastward-thickening wedge unconfined by the early horst-and-graben topography (Fielding et al. 2000; Wilson et al. submitted). The interval is bounded at its base by the yellow reflector and at its top by the purple-grey event (Table 6.4-1). The cross-sectional architecture is interpreted to reflect a lateral shift in the locus of subsidence eastward towards a more basin-central depocentre, and thus to record the main phase of rifting in the VLB.

This interval corresponds to 443–186 m b.s.f. in CRP-2/2A. Although according to the most recent seismic interpretation, the purple-grey event corresponds to the base of sequence 9 in CRP-2/2A at 186 m b.s.f. (Henrys et al. 2000), the top of the eastward-thickening stratal wedge may in fact correspond to the top of sequence 9 at 130 m b.s.f., which marks the top of the package of three, thick sequences and an upward change to much thinner, more truncated sequences (Fielding et al. 2000). The corresponding "reflector d", however, cannot be traced regionally and so in this analysis, the upper boundary of the Main Rift Phase is taken at the purple-grey reflector. Subsidence modeling (Wilson et al. submitted) shows that in CRP holes this interval was accumulated during a regime of variable subsidence, generally less rapid than the underlying Early Rift. This interval as a whole is lithologically diverse, with abundant mudrocks, sandstones and diamictites. Lithologies are cyclically stacked, allowing interpretation in terms of sequence stratigraphy (Fielding et al. 2000). The package of three unusually thick and complete sequences at the top of the interval, which Naish et al. (2001) have correlated to Milankovitch band cycles, evidently reflects a discrete (<450 ka) interval of accelerated subsidence. These patterns are interpreted to record sediment accumulation under varying subsidence and sedimentation rates in shallow glacimarine environments influenced by repeated glacial advance-retreat cycles and associated changes in relative sea-level.

4. Thermal Subsidence: Early Miocene (24–Younger Than 17 Ma)

This package is defined from seismic data as ranging from the purple-grey to the light green reflectors (Table 6.4-1). In cross-section, it has a more sheet-like tabular geometry than the underlying unit, and can be traced across the VLB with only a modest thickening into the central depocentre. This geometry is interpreted to reflect a period of passive, thermal subsidence that is a natural consequence of crustal extension. The angular unconformity noted at the purple-grey reflector could record a "rift-drift" unconformity such as is commonly found in other rift fill successions.

The thermal subsidence phase spans the upper part of the CRP section and a significant thickness of overlying, as yet undrilled, section. This interval coincides with a markedly slower subsidence rate, consistent with the above interpretation. Lithologically, the sampled part of the interval comprises generally thin, condensed glacimarine sequences dominated by diamictites formed during the retreat phase of glacial advance-retreat cycles. The Early Miocene section of CRP-2/2A also contains a composite basaltic fallout tephra interval deposited in a shallow marine setting at 21.44 Ma (Cape Roberts Science Team 1999).

5. Terror Rift Formation: ?Late Miocene to ?Present (Younger Than 17 Ma–?)

This package is defined on seismic data as the interval from the light green reflector to the sea floor (Table 6.4-1). In cross-section, the interval thickens from both east and west into the central depocentre. Strong interference patterns in the depocentre region (e.g., Fig. 6.4-4) indicate the presence of significant magmatic rocks in this interval, coinciding with the McMurdo Volcanic Group. The package can be divided into two sub-sections: *(a)* an interval characterized by broadly homoclinal reflectors that thicken passively into the depocentre, and *(b)* a diverse array of seismic stratigraphic units that overlie a major, regional, angular unconformity (dark green event: Table 6.4-1). This upper unit also contains several additional, less prominent unconformities. This interval is largely unsampled by drilling, but near-surface intersections in CIROS-1, -2, MSSTS-1 and CRP holes indicate Pliocene and Pleistocene ages for at least the upper parts. In addition to the evidence of young magmatic activity, a large number of shallow faults and basins are evident from seismic data. This succession as a whole is correlated to the formation of the Terror Rift (Cooper et al. 1987) by transtensional deformation (Wilson 1995; Salvini et al. 1997), over a period that is poorly constrained. Included in this period of activity is the "Cape Roberts Rift Basin" of Hamilton et al. (2001), which from its location landward (i.e., updip) of the Cape Roberts rift succession and its expression as a basin on the present sea-floor, is here considered likely to have formed subsequent to accumulation of the CRP section.

The older, largely homoclinal package suggests that Terror Rift formation developed initially via passive subsidence in the north-south axial zone of the Victoria Land Basin (Cooper et al. 1987). This phase was terminated by a structural upheaval that formed the major angular unconformity noted above. The degree of angularity on the unconformity increases dramatically westward towards the western margin of the VLB, suggesting that it may be associated with a young phase of uplift in the Transantarctic Mountains. The dramatic thickening of post-unconformity section basinward (eastward) in seismic data may also record sediment derivation and dispersal from the rejuvenated Transantarctic Mountains into the Terror Rift depocentre. We have traced the dark green (unconformity) event updip into the site of drillhole MSSTS-1 at ca. 35 m b.s.f., close to a horizon that separates Lower Miocene from Lower Pliocene strata (D. Harwood, pers. comm. 2004). Three seismic stratigraphic units have been recognized in the post-unconformity section, the boundaries between them not necessarily being single horizons. The lowest of these units is a package containing a variety of seismic facies, notably concordant reflections, acoustically bland wedges (?lowstand wedges: Fig. 6.4-3) and clinoform sets, all of which dip towards the depocentre. The second package is dominated by large-scale clinoform sets (Fig. 6.4-3), the flat tops of some of which appear to define palaeo-shelf edges. The upper package comprises mainly tabular, concordant reflections that are dominantly flat-lying (Fig. 6.4-3). This facies (though not necessarily this seismic stratigraphic unit) is most prevalent in the condensed section of shallow-water areas adjacent to drillholes, where the Plio-Pleistocene section has been drilled. Further unconformities are also evident within the post-dark green interval in some seismic lines. This is particularly the case in the deep-water "moat" around the modern volcanic construct of Ross Island. Here, post-dark green unconformities may be the product of flexural loading imposed by the construction of the Ross Island volcanic edifices (Fig. 6.4-4). If this interpretation is correct, then the <4.6 Ma ages from Ross Island magmatic rocks (Kyle 1990) may provide further constraints on these uppermost units.

Discussion and Conclusions

Since the original study of Cooper et al. (1987), subsequent seismic stratigraphic analyses of the McMurdo sound region have divided the section in much greater detail (e.g., Brancolini et al. 1995; Bartek et al. 1996; Henrys et al. 2000, 2001; Hamilton et al. 2001). The present analysis is based on the premise that a detailed (tens of meters vertical scale) seismic stratigraphic framework cannot be sustained across the large area of McMurdo Sound with the quality and quantity of data available. Rather, we have picked distinct, regionally traceable horizons that correspond to significant and recognizable changes in cross-sectional geometry, and have used these as the basis for our framework. Thus, each of the key horizons nominated in this study can be interpreted as recording some change in the tectonic development of the basin. Having completed this analysis, we subsequently discovered that our seismic stratigraphic units, and consequent basin-forming phases, correlate quite well with the original seismic stratigraphic analysis of Cooper et al. (1987). We also note substantial differences in the correlations between seismic reflectors and CRP made by Hamilton et al. (2001) and those made in this study (see Table 6.4-1). By comparing our correlations between the lithostratigraphy in CRP holes and the seismic stratigraphic scheme of Bartek et al. (1996) with the correlations proposed in Hamilton et al. (2001), we believe the correlation of Hamilton et al. (2001) of seismic unit boundaries with CRP cores to be too deep in all cases. It is also worthy of note that the entire pre-Pliocene section drilled in the Cape Roberts Project is contained within a single seismic stratigraphic unit (RSS 1) in the scheme of Brancolini et al. (1995).

This analysis has also shown that significant stratigraphic intervals remain largely or entirely unsampled by drilling (e.g., Fig. 6.4-3 and 6.4-4). Notable among these are the upper part of the homoclinal section overlying CRP holes (Lower Miocene and younger in age) and much of the Terror Rift succession, which in depocentres must reach 1–2 km in thickness (Table 6.4-1). These as yet unknown successions represent potential targets for future scientific drilling endeavours in the region.

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