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Seismic stratigraphy and structural history of the Reinga Basin and its margins, southern Norfolk Ridge system

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Abstract The Reinga Basin northwest of the North Island of New Zealand was initially formed by crustal extension in Cretaceous time. Gravity models suggest up to 35–40% crustal thinning. The seismic stratigraphy of the basin is continuous with that of the offshore western North Island, where reflectors are well constrained by oil exploration data. In the Reinga Basin, there are two Cretaceous sequences above an older Mesozoic basement. The lower sequence is apparently terrestrial and may include both pre-rift and syn-rift subsequences; the upper is a rift-filling marine sequence. These are overlain by Paleocene and Eocene blanket sequences that were laid down during a period of relative tectonic quiescence consistent with cooling subsidence, continued submergence, a northeast-facing continental shelf, and absence of a significant active plate boundary. A strong regional reflector, caused by a combined unconformity and Oligocene condensed sequence, separates the Paleogene and Neogene sequences.

The Neogene sequences record sedimentary infill from several source directions, not only from the New Zealand landmass, but from the north and west as well. Near the Northland coast, sediment accumulated in clastic wedges and ponded sub-basins from the Miocene to the present day. Along the flanking ridges to the northwest, similar deposition occurred in the Early and Middle Miocene but changed in the Late Miocene to sedimentation in drifts flanked by scours. This change reflects the end of tectonism, a diminishing clastic sediment supply, and the establishment of a throughgoing oceanic current regime as the marginal ridges submerged. This pattern of sedimentation persists today.

Post-Cretaceous volcanism occurred in two parts of the basin. In the central southeastern part, volcanic bodies in the ?Oligocene to Early Miocene sequences could be a northwestern extension of the Northland volcanic arc. In the western part, small intrusive and extrusive bodies appear to be of Pliocene intraplate origin.

Compression (or transpression) had an important role in developing the basin's present form. Miocene compressional structures—asymmetric anticlines, reverse faults, everted basins, and pop-ups—are present everywhere but at the southeastern end. The present marginal ridges have structurally complex origins. The Reinga Ridge which forms the northeastern margin is a transform boundary with the Norfolk backarc basin. Deformation thought to be caused by the action of the transform is recorded in folded and faulted Cretaceous–Paleogene sequences and syntectonic Early and Middle Miocene sequences along its length. The southwestern margin of the basin is a double ridge comprising the Wanganella Ridge, an early Middle to early Late Miocene, compressional uplift, and the older, eroded West Norfolk Ridge, which contains Cretaceous half-grabens. The northern half of the Wanganella Ridge is an everted ?Oligocene to Early Miocene aulacogen in which slivers of basement rock were thrust up along with the sedimentary fill, whereas the southern half is an uplifted block of folded sedimentary rocks of probable Cretaceous or older age.

Paleogeographic reconstructions show that Oligocene uplift of the Norfolk Ridge and Miocene uplift of the Reinga Ridge could have provided a means for terrestrial biota of New Caledonian affinities to spread into New Zealand.

The total sediment thickness in the Reinga Basin is estimated to be 3.5–5.5 km. Potential source, seal and reservoir rocks are present, and there is an abundance of suitable structures. The potential for petroleum occurrences in the basin is good.

Keywords seismic stratigraphy; gravity; tectonism; land bridges; petroleum potential; New Zealand; Reinga Basin; Norfolk Ridge

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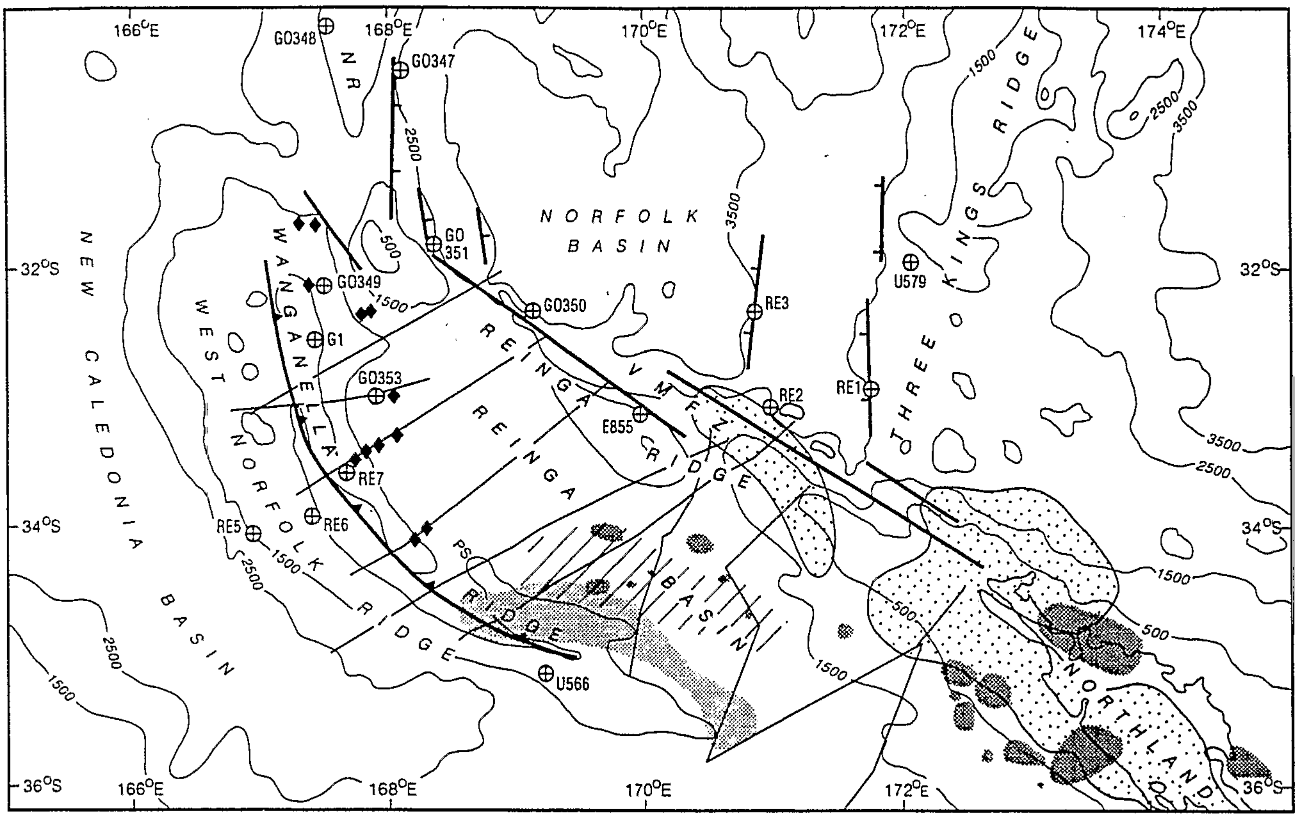

Fig. 1 Location and morphostructural elements of the Reinga Basin. Heavy lines = generalised major Neogene fault systems. Light stipple = known limit of Northland Allochthon. Dark shaded circles = ?Oligocene–Miocene volcanoes. Those near Northland were identified in previous studies (Herzer 1995); the group in the centre of the basin were identified in this study. Volcanoes of the Three Kings Ridge arc are not shown. Hatching = area of occluded zone. Medium shading = area of folded zone. NR = Norfolk Ridge. PS = Petrel Spur. VMFZ = Vening Meinesz Fracture Zone. ◆ = interpreted Pliocene igneous bodies. ⊕ = dredge locations. Because of space, the labels of dredge stations of cruise RE9302 are shortened here to RE. In the text and Table 1 they are given in full. Regional seismic profiles of Fig. 5–9 are shown (see Fig. 2 for labels).

INTRODUCTION

The Reinga Basin is a long, sediment-filled trough extending c. 500 km northwest of the North Island of New Zealand. The basin is bounded to the northeast by the Reinga Ridge and the Northland peninsula, and to the southwest by a pair of parallel ridges—the Wanganella Ridge and West Norfolk Ridge (WNR) (Fig. 1). It is almost closed at its northwestern end where the Reinga, Norfolk, and Wanganella Ridges meet but opens southeastwards into the New Caledonia Basin. The Pacific side of the Reinga Ridge is the present continental margin, formed by the Vening Meinesz Fracture Zone (VMFZ), a transform fault that separates the Reinga Basin from the Norfolk back-arc basin and Three Kings remnant arc (Mascle et al. 1994; Herzer & Mascle 1996).

The Reinga Basin has never been the object of a focused study. Those basins west of New Zealand that have been studied have been found to be rift basins (e.g., Bishop 1992; Isaac et al. 1994; Kamp 1986; Nathan et al. 1986; Uruski & Wood 1991; Laird 1993; Wood 1994) formed during the New Zealand–Australia breakup of Gondwana, and the opening of the Tasman Sea from mid-Cretaceous to Early Eocene time (Shaw 1978; Veevers & Li 1991). Previous geophysical studies indicate that attenuated continental crust underlies the greater region. Long offset seismic refraction surveys record a depth to the mantle of c. 15 km under the New Caledonia Basin, 20 km under the Lord Howe Rise and Norfolk Ridge (Shor et al. 1971), and c. 25 km beneath the Northland peninsula (Stern et al. 1987). Marine gravity studies reveal similar crustal thicknesses under the other major ridges and reduced thicknesses of 15–20 km under the basins (Uruski & Wood 1991; Wood 1991; Zhu & Symonds 1994). Evidence for Cretaceous ductile deformation due to northeast extension is found in core complexes in the western and northern South Island dated as 114 ± 18 Ma and 109.6 ± 1.7 Ma (Tulloch & Kimbrough 1989; Muir et al. 1994). Granite-derived, mainly terrestrial deposits of similar age fill rifts in the western South and North Islands (Laird 1993; Shell, BP & Todd 1986).

Tectonic deformation of the Reinga Basin was noted by Davey (1977) and discussed by Eade (1988) who attributed compressional structures in the Reinga and New Caledonia Basins and uplift of the West Norfolk and Wanganella Ridges to the Eocene compression that led finally to obduction of the New Caledonia ophiolite in the Early Oligocene. In Eade's model the Wanganella Ridge is portrayed as a large southwest-directed thrust. Although the case for Eocene compression in New Caledonia is well documented (e.g., Parrot & Dugas 1980; Regnier 1988; Aitchison et al. 1995), there is no evidence of contemporaneous compression in nearby northern New Zealand (Isaac et al. 1994).

Recent studies, based on new seismic reflection, swath bathymetric, and geological data, demonstrate that some of the deformation in the Reinga Basin coincided with the

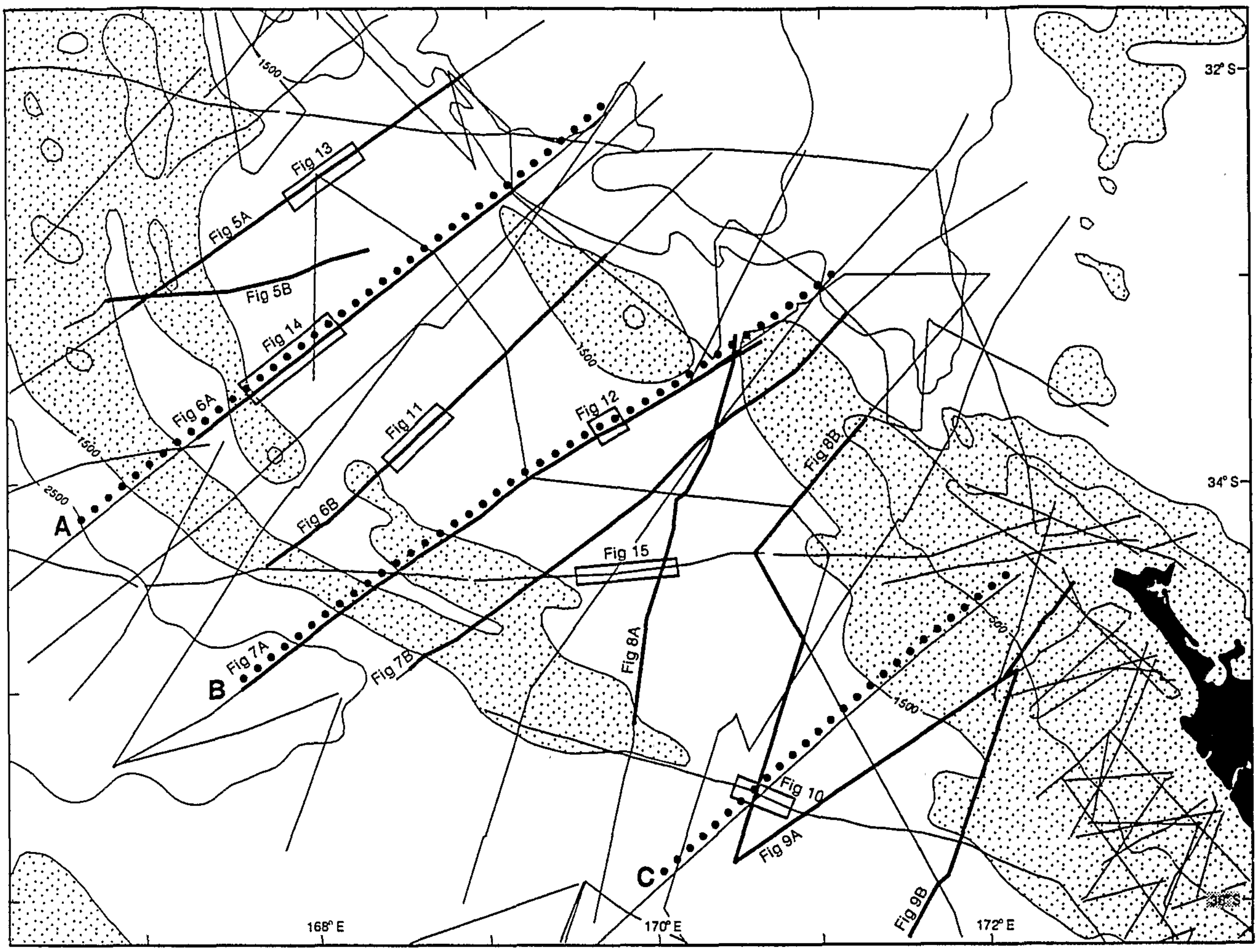

Fig. 2 Total seismic reflection profile coverage. Thick lines = regional profiles shown as line drawings. Heavy dotted lines = locations of gravity profiles shown in Fig. 4. Boxes = locations of illustrated seismic profiles.

opening of the Norfolk backarc basin in the Early Miocene (Mascle et al. 1994; Herzer & Mascle 1996; Mortimer et al. in press). The Reinga Ridge, which actually consists of a chain of left-stepping, en echelon structural blocks, developed during this time by transpressive deformation as the Three Kings Ridge migrated southeastward along the Vening Meinesz transform. These events were heralded in the latest Oligocene to earliest Miocene (Waitakian) by the obduction of the Northland Allochthon (Ballance & Spörli 1979) onto the continental margin occupied by the present-day southeastern Reinga Ridge and Northland peninsula.

Arc volcanism was active in the Early Miocene on and around the Northland peninsula and Three Kings Ridge (Hayward 1993; Herzer 1995; Mortimer et al. in press). The Northland volcanic arc has been well studied, but its extent to the northwest and its association, if any, with the Three Kings Ridge volcanic arc have never been determined. The subduction zone for both arcs lay somewhere to the northeast.

METHOD

Before 1993, c. 5000 km of 1970's-vintage single and multichannel seismic reflection data existed in the Reinga Basin region (excluding the continental shelf). In 1993 this coverage was almost doubled with 2000 km of single channel, seismic reflection data by the Institute of Geological & Nuclear Sciences (IGNS) (RE lines, Cruise RE9302, *RV Akademik M.A. Lavrentyev*), 700 km of 96-channel data by the Australian Geological Survey Organisation (AGSO) (Marshall et al. 1994) (RS lines, Cruise RS114, *RV Rig Seismic*), and 1200 km of 6-channel data by the French Centre National de la Recherche Scientifique (CNRS) (Mascle et al. 1994) and AGSO, respectively (TN and TS lines, Cruises TRANSNOR and TASMANTE, *RV l'Atalante)*. The resulting grid comprises 14 transverse lines and adequate longitudinal lines to tie them (Fig. 2). Gravity and magnetic data were recorded along all of the new seismic lines.

All the available seismic lines were interpreted, applying a uniform seismic stratigraphy based on that of the New Zealand continental shelf (Fig. 3). Seismic interval velocities from Isaac et al. (1994) (derived in Herzer (1992) from RMS velocity spectra) were used to compute the thicknesses of sequences.

Six dredge hauls were taken on Cruise RE9302, bringing the total number of dredge stations around the Reinga Basin region useful for this study to 15 (Fig. 1). Sedimentary rocks from IGNS, Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM), and National

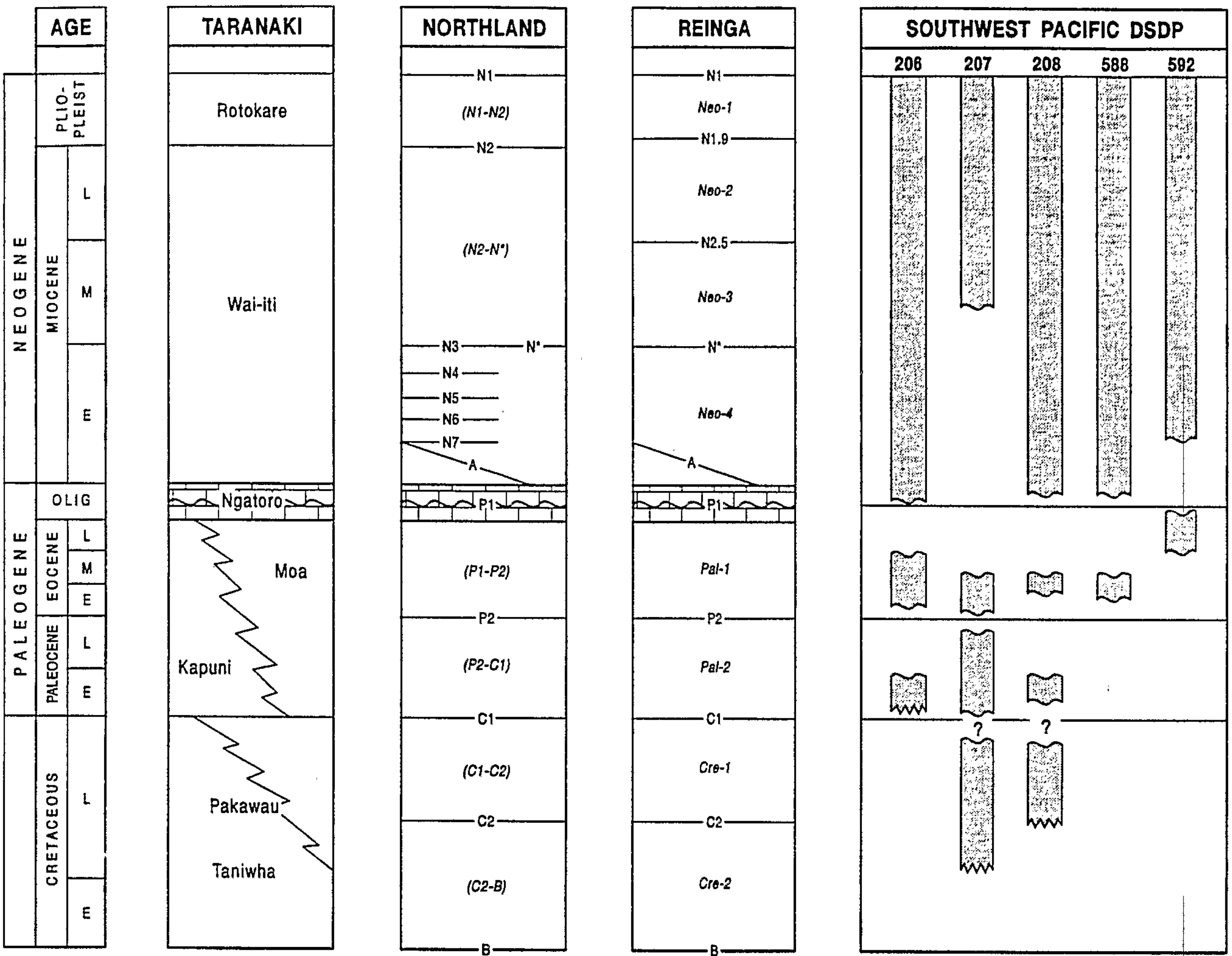

Fig. 3 Stratigraphic correlation diagram. The Taranaki column is based on Thrasher (1988) and King & Thrasher (1996). The Northland column is from Isaac et al. (1994) and Herzer (1995). The Southwest Pacific DSDP columns are from Jenkins & Srinivasan (1986). The Reinga column is developed in this paper, largely from the Northland column. Main seismic reflectors between N1 and B in the Northland and Reinga columns are correlated with seismic reflectors defining supersequence boundaries recognised in wells in the Taranaki Basin. The apparent correlation of some major reflectors with important hiatuses in the deep-sea sedimentary record is seen in the last box.

Institute of Water and Atmospheric Research (NIWA) collections were analysed to constrain seismic sequence ages, ascertain sequence lithologies, and provide control for vertical tectonic histories (Table 1). Faunal and floral zones were correlated with the latest New Zealand and Australian timescales (Morgans et al. in press; Young & Laurie 1996), which are based on that of Berggren et al. (1995). Igneous rocks from these collections (including dredge stations not shown here) were analysed by Mortimer et al. (in press) and their results are used here where appropriate.

Two-dimensional gravity models along seismic lines crossing the basin (Fig. 4) were derived using an adaptation of the method of Talwani (1973). The northwestern section A (Zhu & Symonds 1994) is a previously published model based on marine gravity and seismic line RS114-04 (Fig. 2).

Section B uses a composite of seismic lines P-706 (acquired by *MV Petrel* in 1971) and RE-5. Marine gravity was available only for the short line segment RE-5; for the remainder (P-706), satellite gravity (Davy 1995) was used. The model for section B uses the method of Zhu & Symonds (1994), which utilises assumed lateral as well as vertical variations in crustal density to achieve a best fit. Multiple bodies were used to refine the model and attempt to differentiate different terranes along the section.

The southeastern section C was modelled along marine gravity and seismic line TS94 (acquired by *RV l'Atalante* in 1994) using a simple crustal model with no lateral variations in crustal density. A water layer and two sedimentary layers interpreted from seismic reflection data (seafloor to top Paleogene and top Paleogene to basement), were used to define shallow structure and constrain the gravity models. Depths to the mantle were then derived assuming local isostatic equilibrium relative to the oceanic Tasman Basin which lies to the west of the area. No attempt was made to model high-frequency anomalies caused by shallow buried igneous bodies, except where these are seen on the seismic profile.

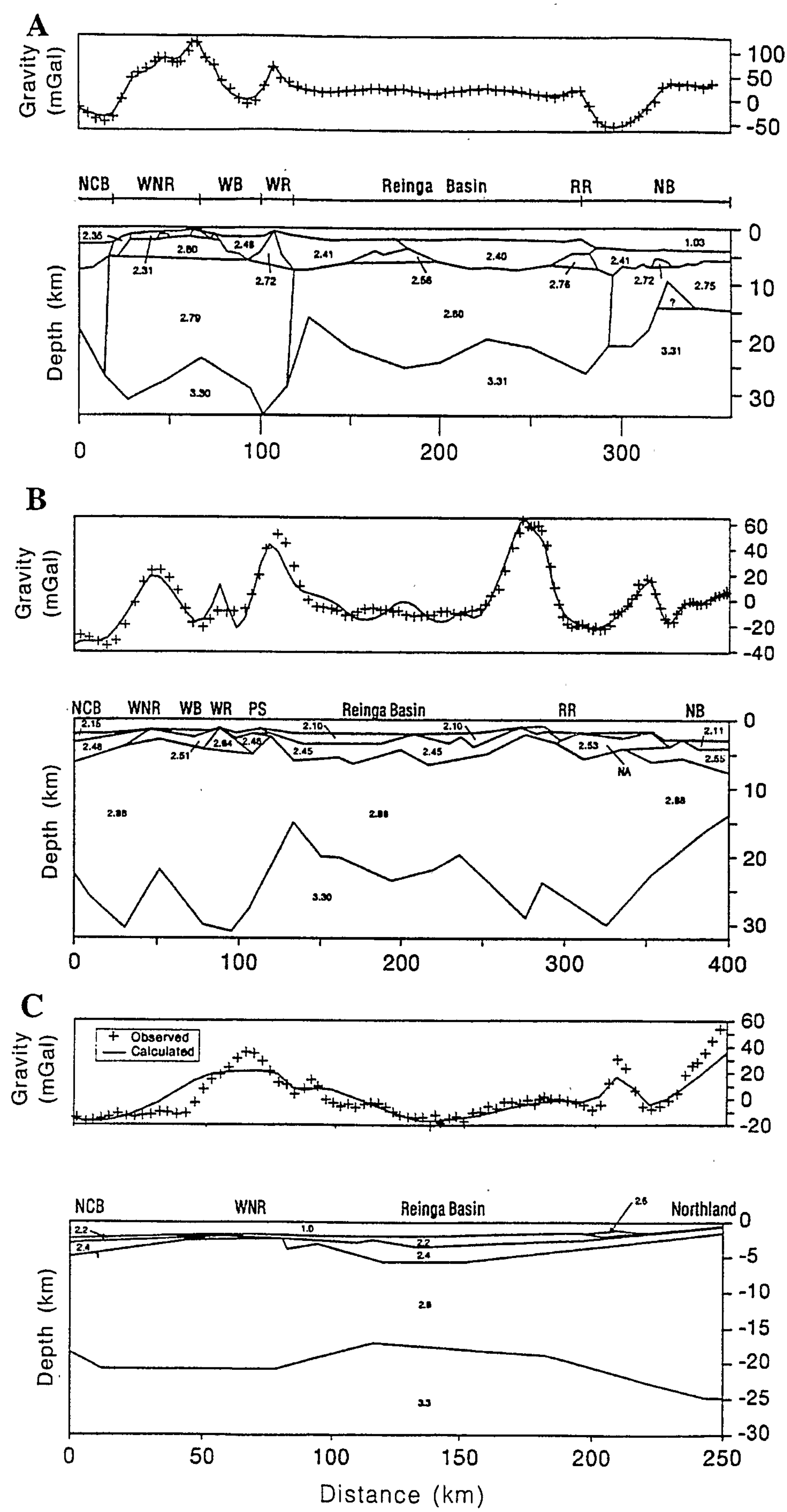

Fig. 4 Interpreted gravity profiles across the Reinga Basin. + = observed anomaly. Solid line = modelled anomaly. Body densities are in Mg/m^3. See Fig. 2 for locations. NB, Norfolk Basin; NCB, New Caledonia Basin; PS, Petrel Spur; RR, Reinga Ridge; WB, Wanganella Basin; WNR, West Norfolk Ridge; WR, Wanganella Ridge.

Table 1 Dredged sedimentary rocks from the greater Reinga Basin region. Maximum age ranges are given; most likely age is underlined. Where more than one age and environment are given for the same sample, the rock consists of multiple parts. nd = no determination due to insufficient fossil material; nf = barren; E = Early; M = Middle; L = Late; e = early; m = middle; l = late; vE = very Early. Where a dredge station appears in Fig. 1 but not in this table, no sedimentary rocks were found. (D-dinoflagellates; F-foraminifers; N-nanofossils; P-pollen/spores; R-radiolarians; underlined letter = diagnostic group).

Sample no.	NZ Fossil Record no.	Latitude	Longitude	Depth	Fossil group examined	NZ stage	Age	Lithology and environment
E-855	(SE33169/f1)	33°10′S	169°56′E	742 m	F	nf		sandy limestone
G-1	(SE32167/f1)	32°35′S	167°23′E	138 m	F	Pl - ?S	lE.Mio-?M.Mio	algal ball, shallow photic zone, sheltered
GO347D-a	(SE30168/f1)	30°28.5′S	168°05.4′E	1840–2300 m	F,R	nd (aggl. forams)		calcareous mudstone
GO347D-b	(SE30168/f2)	30°28.5′S	168°05.4′E	1840–2300 m	F	Lw-Po	vL.Olig-E.Mio	bioclastic lithic limestone, leached (moldic porosity) shallow marine, photic zone
GO347D-c	(SE30168/f3)	30°28.5′S	168°05.4′E	1840–2300 m	F	Lw-Po	vL.Olig-E.Mio	bioclastic lithic limestone, shallow marine, photic zone
					F	Wo-Wq	Plio-Rec	ooze-filled solution cavities or borings, bathyal
GO348D-b	(SE30167/f2)	30°07.2′S	167°29.8′E	900–1400 m	F	Lw	vL.Olig-vE.Mio	coquina with volcanic lithics, shallow open marine, photic zone to >100 m
GO348D-c	(SE30167/f3)	30°07.2′S	167°29.8′E	900–1400 m	F	Lw	vL.Olig-vE.Mio	limestone, shallow open marine photic zone
		30°07.2′S	167°29.8′E	900–1400 m	F	Wo	E.Plio	ooze-filled solution cavities or borings, bathyal
		30°07.2′S	167°29.8′E	900–1400 m	F	Sl-Wq	M.Mio-Rec	ooze-filled solution cavities or borings, bathyal
		30°07.2′S	167°29.8′E	900–1400 m	F	Tk	lL.Mio	ooze-filled solution cavities or borings, bathyal
		30°07.2′S	167°29.8′E	900–1400 m	F	Wo-Wq	E.Plio-Rec	ooze-filled solution cavities or borings, bathyal
GO349D-a	(SE32167/f2)	32°09.5′S	167°28.5′E	1000–2000 m	F,R	nd (aggl. forams)		fine argillaceous limestone
GO349D-b	(SE32167/f3)	32°09.5′S	167°28.5′E	1000–2000 m	F,R	nd		limestone breccia
GO349D-c	(SE32167/f4)	32°09.5′S	167°28.5′E	1000–2000 m	F,R	nd		laminated argillaceous limestone
GO349D-d	(SE32167/f5)	32°09.5′S	167°28.5′E	1000–2000 m	F,R	nd		laminated grey calcareous mudstone
GO349D-e	(SE32167/f6)	32°09.5′S	167°28.5′E	1000–2000 m	F	nf		altered calcareous volcanic sandstone
GO350D-5	(SE32169/f1)	32°21.8′S	169°08.5′E	1600–3400 m	F	lDt-Dw-Ab	L.Pal-E.Eo-M.Eo	?argillaceous limestone, cataclasite, planktonic
GO351D-a	(SE31168/f1)	31°52.9′S	168°17.2′E	900–2500 m	F,D,R	lMp -eMh	mL.Cret	black shale, marine
GO351D-b	(SE31168/f2)	31°52.9′S	168°17.2′E	900–2500 m	F,R	nd		siliceous grey mudstone
GO351D-c	(SE31168/f3)	31°52.9′S	168°17.2′E	900–2500 m	F,R	nd (Chondrites)		siliceous grey mudstone
GO351D-d	(SE31168/f4)	31°52.9′S	168°17.2′E	900–2500 m	F,R	Ab-lAk-eAr-Ar	lM.Eo-L.Eo	very siliceous grey mudstone, marine
GO351D-e	(SE31168/f5)	31°52.9′S	168°17.2′E	900–2500 m	F,R	nd		laminated fine argillaceous limestone
GO351D-f	(SE31168/f6)	31°52.9′S	168°17.2′E	900–2500 m	F	Dp-Ab-?Ar	M.-?L.Eo	calcareous mudstone breccia, polymict, bathyal >1000 m (age and depth of matrix fauna only)
GO351D-g	(SE31168/f7)	31°52.9′S	168°17.2′E	900–2500 m	F	Dp-Ab	M.Eo	mudstone breccia, bathyal >1000 m (age and depth of matrix fauna only)
RE9302-1-1	(SE33171/f3)	33°00.66′S	171°42.42′E	2500–2700 m	F,N	?Lw-Pl	?vL.Olig-E.Mio	calcareous volcanic sandstone, shoal
RE9302-1-4	(SE33171/f2)	33°00.66′S	171°42.42′E	2500–2700 m	F,N	nd, ?mPl-?eSl	?lE.-?eM.Mio	lapilli tuff, lower bathyal, rapidly deposited
RE9302-2-1	(SE33170/f3)	33°07.59′S	170°54.85′E	1875–1950 m	F,R	Mh	lL.Cret.	siliceous mudstone (Whangai), probably mid-bathyal or deeper
RE9302-2-2	(SE33170/f1)	33°07.59′S	170°54.85′E	1875–1950 m	F	?D	?Pal-?M.Eo	fine grained calcareous rock, probably oceanic deep bathyal
					F	Wn	L.Plio	ooze infilling of cracks
RE9302-2-5	(SE33170/f5)	33°07.59′S	170°54.85′E	1875–1950 m	D,R	Mh	lL.Cret	siliceous mudstone cataclasite, marine
					F	Wn	L.Plio	ooze pocket in crack near surface, oceanic, deep bathyal
RE9302-2-6	(SE33170/f4)	33°07.59′S	170°54.85′E	1875–1950 m	F,N	lPo-mPl	mE.Mio	micrite infilling cracks in basalt, oceanic bathyal, calm
RE9302-3-6	(SE32170/f2)	32°22.06′S	170°52.04′E	3680–4160 m	F	lSl-Sw	mM.-lM.Mio	calcareous ooze chalk, bathyal >1000 m
RE9302-3-7	(SE32170/f3)	32°22.06′S	170°52.04′E	3680–4160 m	F	Sw-eTt	lM.Mio-eL.Mio	calcareous ooze, deep bathyal

RE9302-3-8	(SE32170/f4)	32°22.06′S	170°52.04′E	3680–4160 m	F	?Sc-Sw	?e-lM.Mio	calcareous ooze chalk, deep bathyal
RE9302-5-2	(SE34166/f1)	34°00.65′S	166°57.5′E	1270-2250 m	P	Ra-Rm-Rt	eL.Cret	coal measures, carbonaceous mudstone, lower coastal plain
RE9302-6-1	(SE33167/f2)	33°54.43′S	167°22.89′E	700-735 m	F	Lw -ePl	vL.Olig-E.Mio	bioclastic bryozoan limestone, bored, and replaced by foraminiferal limestone, bathyal (age and depth ranges common to both limestones)
RE9302-7-2	(SE33167/f3)	33°33.65′S	167°39.32′E	650-900 m	F	Lw-Po-Pl	vL.Olig-mE.Mio	foraminiferal limestone, bathyal
U566-1	(SE35169/f1)	35°05′S	169°10′E	979 m	F	lPo-ePl	mE.Mio	foraminiferal ooze, oceanic, bathyal
U566-2	(SE35169/f3)	35°05′S	169°10′E	979 m	F	lSl-Sw-eTt	lM.-eL.Mio	foraminiferal ooze, oceanic, bathyal
U566-3	(SE35169/f2)	35°05′S	169°10′E	979 m	F	?Lw-Pl	?vL.Olig-lE.Mio	bioclastic, bryozoan limestone, oceanic, shoal
U579	(SE31171/f1)	31°51.5′S	171°57.6′E	2109 m	E,N	nd	late Paleogene? Olig?	calcareous fine sandstone, oceanic, bathyal or deeper

FRAMEWORK

Basement geology

The nature of the rocks making up the basement under the Reinga Basin can be inferred from the geology of the New Zealand landmass, regional geophysical patterns, and rare dredge samples from submarine outcrops. In the western North Island and northern South Island the basement is composed of successive terranes accreted to a western province of cratonic rocks. Adjacent to the Western Province is the Median Tectonic Zone (MTZ), which includes granitoid plutonic units and early Mesozoic arc volcanics of the Brook Street Terrane. Terranes following the MTZ in sequence from west to east are Triassic–Early Cretaceous Murihiku forearc sandstone and mudstone, Dun Mountain–Maitai ultramafic and related rocks, and Permian–Jurassic Waipapa greywacke, argillite, and minor basalt.

The terrane sequence from the Western Province to Murihiku is present under the continental shelf off Taranaki (Mortimer et al. 1997), and the terranes from Murihiku to Waipapa (Spörli 1978, but see Black 1994) are present in the northwestern North Island. In the Northland peninsula, all but the Waipapa Terrane are completely covered by Paleogene sedimentary rocks and sedimentary and ophiolitic nappes of the Northland Allochthon. In the extreme north of the peninsula, Waipapa rocks are replaced by another terrane—the Mt Camel—composed of Late Cretaceous spilites, silicic tuffs, and greywackes (Hay 1975; Isaac et al. 1994).

Magnetic anomalies form linear patterns parallel to bathymetric and coastal trends and are inferred to reflect major basement rocks in the region (Eade 1988; Davy 1992; Mortimer et al. in press). The whole West Norfolk Ridge and parts of the Wanganella Ridge are strongly positively magnetic due to the presence of rocks of the Brook Street Terrane and Median Tectonic Zone (Mortimer et al. in press), whereas a characteristic linear magnetic anomaly which runs the length of the Northland peninsula is apparently due to the presence of the Dun Mountain–Maitai ultramafic belt (Hatherton & Sibson 1970). As the Murihiku Terrane is normally found between the Brook Street and Dun Mountain–Maitai Terranes, Murihiku rocks should be the principal component of the basement under the southeastern part of the Reinga Basin.

The basement under the northwestern part of the basin is less certain because little is known of the crust under the Reinga Ridge. Although Waipapa rocks appear offshore on the Reinga Ridge northwest of Northland (Mortimer et al. in press), almost the whole southeastern half of the ridge is covered by the Northland Allochthon (Herzer & Mascle 1996). The northwestern half is buried by sedimentary strata; however, cataclastic, metasomatised basalts and felsic igneous rocks of uncertain affinity outcrop on a scarp at its northwestern end (Mortimer et al. in press). There are magnetic anomalies on the Reinga Ridge, but the pattern is not very clear and is strongly influenced to the southeast by the ophiolites and the Early Miocene volcanic arc of Northland. The more deep-seated anomalies along the ridge could be caused by Mt Camel volcanics, Dun Mountain ultramafics, or rift-related basalts (Mortimer et al. in press). The basement under the northwestern part of the basin is most likely Murihiku but could include Waipapa.

Gravity and crustal structure

The West Norfolk Ridge, Wanganella Basin, Wanganella Ridge, Reinga Basin, and Reinga Ridge to Northland peninsula high are the main structural elements of the study area. The gravity models are consistent with a mean crustal density under all these elements of 2.8 Mg/m^3, the global average for continental crust (Christensen & Mooney 1995). Continental affinity of the crust is confirmed by the composition of rocks outcropping on the basement ridges (Mortimer et al. in press).

The gravity models and seismic profiles demonstrate that the crust under the Reinga Basin is c. 15–20 km thick, whereas that under the flanking West Norfolk/Wanganella, Northland, and Reinga Ridges is 20–30 km thick (i.e. crustal thinning by up to c. 35–40% in the basin relative to the flanking ridges and the Northland peninsula). Without a dramatic and implausible lateral density variation under the Reinga Basin, mantle upwelling caused by crustal thinning is necessary for the models to fit the observed data. A modelled double root under the Reinga Ridge (under RR on the section B model) coincides with a left step in the major faults of the Vening Meinesz Fracture Zone (Fig. 1). Seismic character (see Herzer & Mascle 1996, fig. 11) and the gravity model inversion of section B support the existence of a relatively high density 2.53–2.55 Mg/m^3 body on the northeastern half of the step-over, which is interpreted as the Northland Allochthon. All three models require the presence of high-density rocks within the West Norfolk Ridge, although none adequately explains the cause of the large positive anomaly.

Seismic stratigraphy

Seismic sequences

The Northland continental shelf and slope at the southeastern end of the Reinga Basin is covered by good quality, industry, seismic reflection data. Offshore Northland (34–37°S, 172–175°E) has no wells useful for seismic stratigraphy so the stratigraphy is tied to petroleum wells farther south off the Taranaki coast (37–41°S, 172–175°E). Taranaki seismic stratigraphy (Thrasher 1988) thus underpins the Northland seismic stratigraphy (Herzer 1992; Isaac et al. 1994), which in turn can be extended into the main part of the Reinga Basin. Because of the great distance from controlling wells, the seismic stratigraphy of the Reinga Basin must be regarded with suitable caution. Briefly the Northland seismic sequences and their confining reflectors (paired alphanumerics, e.g., C1–C2, below and in Fig. 3) define the following mid-Cretaceous to Recent geological history for the western Northland shelf. As described by Isaac et al. (1994), the history begins with mid-Cretaceous rifting, but Gage & Kurata (1996) present a case for an Early and mid-Cretaceous, pre-rift, Pacific-facing sedimentary margin. Such a basin might have extended the length of the Reinga Basin, but our seismic data are not good enough to differentiate the basal sequences critical for this interpretation, and there are no drillholes to test the theory. The concept is nevertheless incorporated in the following summary.

Pre-rifting and early rifting: Early Cretaceous deposition of a widespread passive margin sequence of unknown lithology, followed by mid-Cretaceous (c. 100 ± 10 Ma) rifting and deposition of terrestrial deposits and coal measures among widely spaced extensional fault ridges (sequence C2-B, characterised by a bright reflector package).

Late rifting: Later Cretaceous (Piripauan–Haumurian) extensional faulting (offsetting the earlier Cretaceous sequences) and submergence with deposition of a seismically bland, marine, graben-filling and regional clastic sequence, including shelf sands, bathyal muds, and redeposited greensands (sequence C1–C2).

Basin subsidence and passive margin: Paleocene–Late Oligocene passive margin with deposition of thin paralic to bathyal clastic and calcareous sediments (sequences P2–C1 and P1–P2). Some deltaic progradation towards the west (basinward). Erosion to base level, culminating in regional limestone deposition (represented by reflector P1).

Foreland subsidence: Late Oligocene rapid foreland subsidence; initiation of a subduction zone to the northeast. Change from shelf and shallow bathyal to deep-water carbonates.

Obduction and active arc phase: Latest Oligocene – earliest Miocene (Waitakian) obduction of Northland Allochthon from the northeast (sequence A); Northland arc volcanism with deposition of mainly volcaniclastics throughout the Early Miocene (subsequences within sequence N*–P1).

Passive margin: Clastic infill (westward progradation) during the Middle and Late Miocene (sequence N2–N*) and Pliocene–Pleistocene (sequence N1–N2).

We have mapped the following regional reflectors in the Reinga Basin, tying them where possible to the stratigraphy of the western Northland continental shelf (Isaac et al. 1994) (Fig. 3).

Reflector N1.9 was tied to the Northland reflectors a few seismic wavelets above N2, which is thought to be near the top of the Miocene sequence. It is generally recognisable as one of many closely spaced medium amplitude reflectors in a packet surrounded by low-amplitude reflectors. Some correlation jumps are necessary where the reflector packet is cut by seafloor erosion.

Reflector N2.5 was not differentiated in the mapping of the Northland continental shelf. In the Reinga Basin it occurs approximately midway between the near-top Miocene N1.9 and top of Early Miocene N* reflectors and is assumed to be approximately the top of the Middle Miocene. It is generally recognisable by character throughout the Reinga Basin, associated with a packet of closely spaced reflectors.

Reflector N* is the uppermost in a packet of Early Miocene volcaniclastic subsequences off Northland (Herzer 1995). From Northland the reflector extends throughout the Reinga Basin as a recognisable, single, strong event at the top of a mainly ponded sequence that rarely exhibits any progradational facies. However, the reflector loses its distinctive signature and becomes difficult to distinguish in a basin that lies along the northeastern side of the Wanganella Ridge, which we have named the East Wanganella Sub-basin (EWS) (described later).

Reflector P1 is an easily recognised high-amplitude regional marker that is tied without difficulty to wells in the Taranaki Basin, where it was mapped as a velocity inversion at the base of the Oligocene carbonate sequence. A major hiatus in the Southwest Pacific deep-sea stratigraphic record (Jenkins & Srinivasan 1986) (Fig. 3) coincides with this carbonate sequence, which occurs throughout much of New Zealand as a regional paraconformity and condensed limestone/greensand complex spanning the Oligocene (e.g., Carter 1985; Fulthorpe et al. 1996). In onshore Northland and offshore Taranaki Basin, the entire Oligocene sequence is generally <100 m thick. In offshore Northland, reflector P1 was considered to encompass the Oligocene condensed sequence and paraconformity (Herzer 1992; Isaac et al. 1994). Following this example we chose to confine the Oligocene sequence in the Reinga Basin to one or two seismic wavelets about the P1 reflector (<100 m) while recognising that locally it may be thicker. Some correlation jumps across structures are required to follow the reflector around the Reinga Basin.

Reflector P2 is traced with confidence from offshore Northland, where it was placed near the top of the Paleocene, based on correlation with wells in northern Taranaki Basin (Isaac et al. 1994). We believe that it correlates with a regional hiatus of this age in the Southwest Pacific deep-sea drilling record (Jenkins & Srinivasan 1986) and with a regional black shale marker—the Waipawa Black Shale (Killops et al. 1996) in New Zealand. The reflector is a continuous, high-amplitude marker in the southeastern half of the Reinga Basin, where it generally occurs a fairly uniform distance below reflector P1. However, it is rarely as strong as P1. To trace it into the northwestern part of the basin, correlation jumps based on position and seismic signature were necessary.

Reflector C1 is mapped in offshore Northland and Taranaki as the top of the Cretaceous sequence. It is a high-amplitude reflector relative to the weakly reflective sequences above and below it, but is often not seen on profiles with poor seismic penetration. It was mapped with confidence in the southeastern part of the Reinga Basin close to petroleum industry seismic lines. However, it appears only intermittently on the shallow penetration seismic tie line down the axis of the basin, making its identification in the northwest speculative.

Reflector C2 is the top of a unit of very high amplitude reflectors off Northland which has been interpreted as a terrestrial sequence. The reflections are so strong as to often mask the older Mesozoic basement beneath. This character is preserved throughout the Reinga Basin where it was not everywhere possible to distinguish between basement and C2.

Reflector B, the top of the Paleozoic and Mesozoic basement terranes, is clearly distinguishable on the ridges flanking the Reinga Basin and on buried highs within the basin, especially on multifold data. It is otherwise often masked by reflector C2 or by poor seismic penetration.

The following regional reflector-bound sequences are discussed in this study. They are illustrated in 10 sequential regional seismic reflection cross-sections (Fig. 5–9): **Neo-1**, mainly Pliocene–Pleistocene (N1–N1.9); **Neo-2**, mainly Late Miocene (N1.9–N2.5); **Neo-3**, mainly Middle Miocene (N2.5–N*); **Neo-4**, Early Miocene and possibly some Late Oligocene (N*–P1); **Pal-1**, Eocene and possibly some Early Oligocene (P1–P2); **Pal-2**, Paleocene (P2–C1); **Cre-1**, Late Cretaceous rift and post-rift marine (C1–C2); **Cre-2**, mid-Cretaceous pre-rift and rift terrestrial (C2–B).

Three other seismic units have only a local extent in the basin (Fig. 1). They are the Northland Allochthon, ?Oligocene–Miocene volcanics, and igneous features near the Wanganella Ridge. In addition, two zones of unusual seismic reflections occur in the south: a zone of thick folded rocks under the southern Wanganella and West Norfolk Ridges (identified as F on seismic profiles), and a zone of poor seismic penetration below the Neogene sequences to the north of it (identified as OC "occluded" on seismic profiles). There is some uncertainty about whether to place unit F (discussed later) beneath reflector B or reflector C2.

Geometry, facies, and significance of seismic units

Cretaceous sequences Cre-2 and Cre-1: The base of the Cretaceous–Cenozoic section throughout most of the basin is found in tilted normal fault blocks (e.g., eastern half of Fig. 10). In some profiles these blocks involve only the basement, with sequence Cre-2 infilling the grabens (Fig. 9A, southwest side of profile [RE-17]) or lapping onto highs (Fig. 6A [RS114-04]), but in most profiles sequence Cre-2 itself is offset, with sequence Cre-1 filling the grabens (Fig. 6A, 9B [RS114-04, RE-18]). The same two-phase rifting affected the Reinga Basin in the Late Cretaceous as affected the Northland and Taranaki regions. Half grabens filled with sequence Cre-2 extend right across the West Norfolk Ridge (e.g., P706, Fig. 7A). The block-faulted structure extends northwest to the foot of the Reinga Ridge, but cannot be traced across it due to later deformation by the Vening Meinesz transform and obscuring by the Northland Allochthon.

Reflector C1 is very poorly constrained. C2 is a strong reflector but it is in many places difficult to distinguish from basement. As a consequence, neither the maximum thickness of Cretaceous sedimentary rocks nor the Cretaceous basin geometry can be determined. We estimate that the combined Cretaceous sequences reach a thickness of 1–2 s two-way time (TWT), equivalent to a sediment thickness of 1.6–4 km, assuming seismic velocities are the same as those of comparable rocks in offshore Northland (Herzer 1992; Isaac et al. 1994).

Both terrestrial and marine Cretaceous rocks have been dredged in the region around the Reinga Basin (Fig. 1). Granite-sourced coal measures of early Late Cretaceous (most likely Mangaotanean, Turonian, 90–88 Ma) age were obtained from a sequence overlying acoustic basement on the West Norfolk Ridge (station RE-5), and a pyritiferous, marine black shale of late Late Cretaceous (Haumurian) age was obtained from the Norfolk Ridge near the northern end of the basin (station GO351) (Table 1; samples RE9302-5-2, and GO351-D-a). It is likely that these rock types extend into the Reinga Basin. Eocene sedimentary breccia dredged at station GO351 contained clasts of unfossiliferous, pale grey to white siliceous and calcareous mudstones. Similar siliceous mudstone of Haumurian age was dredged at station RE-2 (Fig. 1) on the scarp of the Vening Meinesz Fracture Zone (at the eastern margin of the basin) (samples RE9302-2-1 and -5; Table 1); the samples were sheared and shattered. The pale-coloured mudstones are correlated with the Whangai Formation, a regionally extensive marine mudstone in New Zealand and with equivalents throughout the Southwest Pacific (Moore 1988).

Paleogene sequences Pal-1 and Pal-2: The Paleogene sequences blanket the region, lapping onto or thinning over

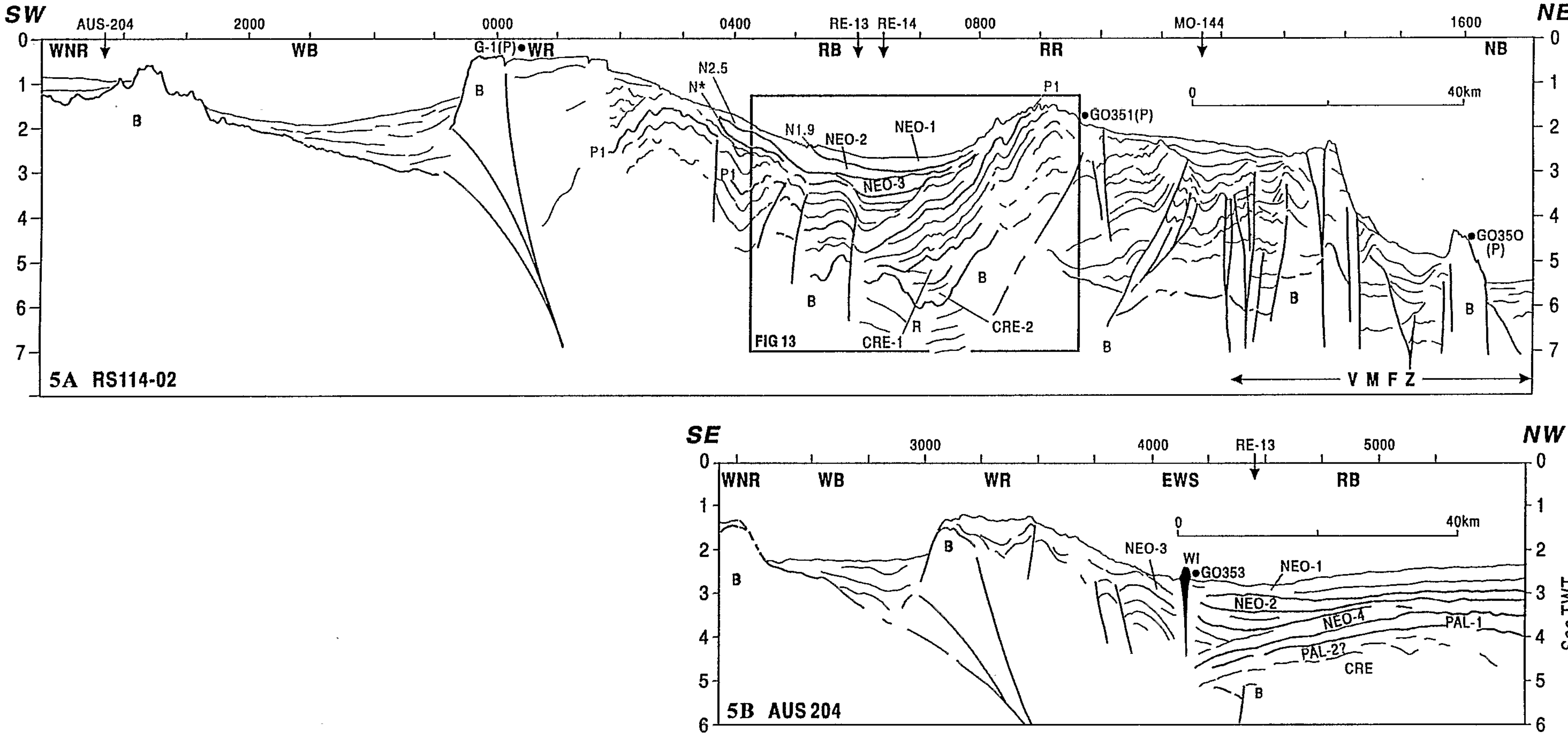

Fig. 5 Line drawings of seismic profiles RS114-02 (Fig. 5A) and AUS-204 (Fig. 5B). Red lines are sequence bounding reflectors correlated to Northland continental shelf reflectors. Where red lines are absent there is inadequate seismic tie or resolution to identify sequence boundaries. In 5A, sequence Neo-4 is the whole complex region between Neo-3 and reflector P1. East- and west-verging reverse-faults and folding are within the East Wanganella Sub-basin (EWS) in 5B. RB, Reinga Basin; VMFZ, faults belonging to Vening Meinesz Fracture Zone; WI, Wanganella igneous body; • = dredge location; (P) signifies that the dredge site is nearby and is projected along-strike to this location. See Fig. 4 for explanation of other abbreviations. The reverse fault under the Wanganella Ridge is never imaged in seismic profiles but is inferred from the other compressional features associated with the ridge. Box shows location of Fig. 13.

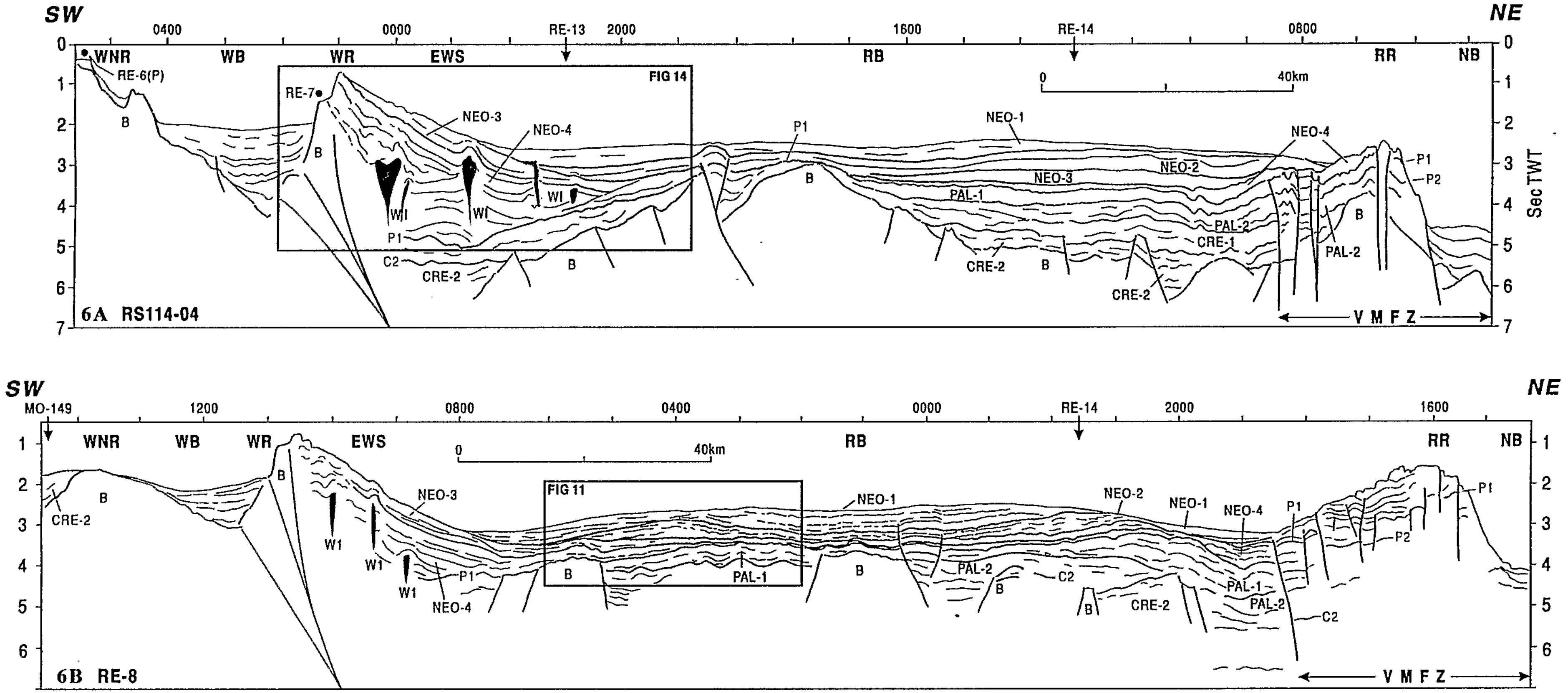

Fig. 6 Line drawings of seismic profiles RS114-04 (Fig. 6A) and RE-8 (Fig. 6B). See Fig. 4 and 5 for explanation of abbreviations. The thick wedge of sediment between Neo-3 and reflector P1 in the EWS is all sequence Neo-4. Reflector C1 and sequence Cre-1 are not distinguishable on line RE-8. Boxes show locations of Fig. 14 and 11.

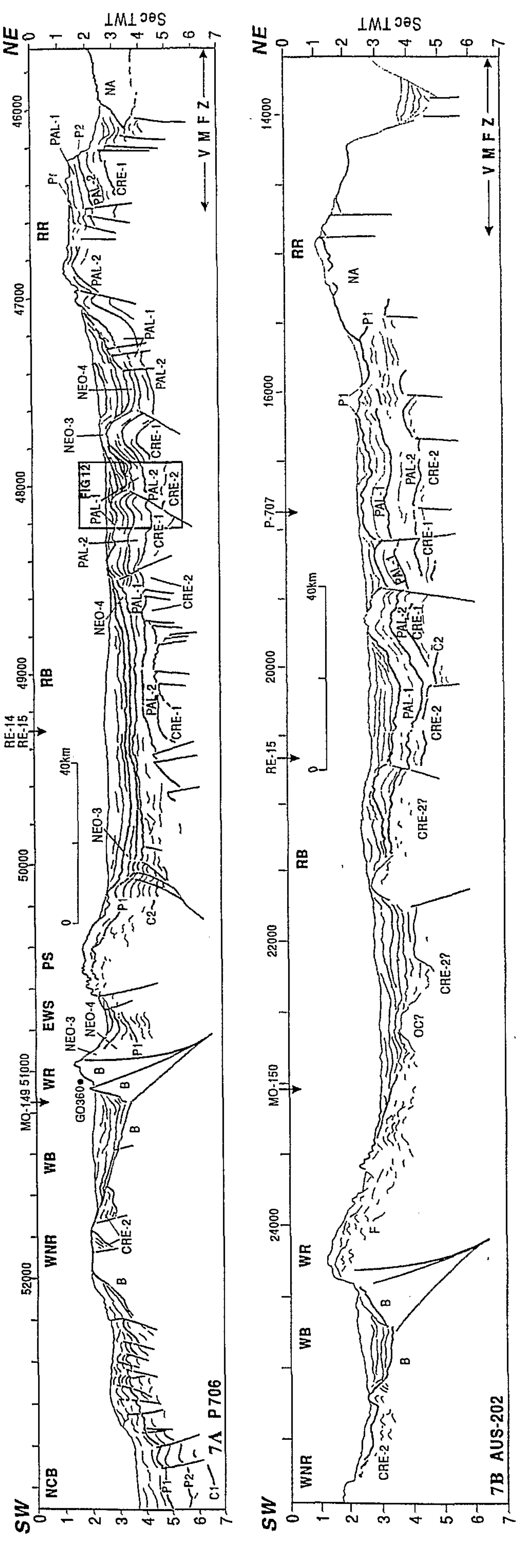

Fig. 7 Line drawings of seismic profiles P-706 (Fig. 7A) and AUS-202 (Fig. 7B). NCB = New Caledonia Basin; F = rocks of folded zone; OC = occluded zone?; PS = Petrel Spur; NA = Northland Allochthon. See Fig. 4 and 5 for explanation of other abbreviations. Box shows location of Fig. 12. In profile P-706 Neogene sequences above Neo-3 have not been differentiated; in AUS-202 no Neogene sequences have been differentiated.

highs (Fig. 6A, 8A, 9B [RS114-04, P-707, RE-18]). Rarely, they appear to abut the sides of basement horst blocks, suggesting that there was local Paleogene extensional faulting (Fig. 6B, 8B [RE-9, RE-16/2/3]). Seismic detail at these deeper levels is insufficient to resolve the contact relationship; hence, it is possible that the Paleogene strata passively infilled remaining Cretaceous grabens. These sequences have been deformed by Neogene folding, reverse faulting, basin eversion, pop-ups, and wrench faulting (seen on most profiles northwest of RE-17).

The combined Paleogene sequences are of fairly uniform thickness over the southeastern part of the basin (east of 170.5°E), thinning or pinching out only over the West Norfolk Ridge and Northland peninsula (Fig. 8B, 9A, B [RE-16–RE-18]). In the northwestern part of the basin, they generally thin or pinch out on a central basement high and on older rocks on the southwestern margin but they thicken northeastwards in the direction of the present continental margin where they are truncated by the Vening Meinesz Fracture Zone (Fig. 6 to 8A [RS114-04–P-707]).

The sequences have been dredged on the nearby Norfolk Ridge and on the fault scarps of the Reinga Ridge (GO350, GO351 and RE-2; Fig. 1) (GO350D-5, GO351D and RE9302-2-2; Table 1). The dredge hauls consisted of siliceous mudstones and fine-grained argillaceous limestones, and breccias of unfossiliferous calcareous mudstone with Eocene matrix ages. Similar but unfossiliferous calcareous rock types dredged at the western end of the Reinga Basin (GO349) may also be from these sequences.

Neo-4: Sequence Neo-4, the lateral equivalent of the Early Miocene Northland arc volcaniclastic aprons that occur to the southeast, extends discontinuously for the length of the Reinga Basin. Its thickness is highly variable, generally <250 ms TWT or c. <400 m. It is ponded in regional lows and in structural basins such as Neogene synclines (Fig. 11–13), and thins or pinches out over residual basement-cored highs (Fig. 6A, B, 8B, 9A, B [RS114-04, RE-8, RE-16/2/3, RE-17, RE-18]). It is especially thick in the East Wanganella Sub-basin (EWS), which has since been dramatically everted. In this former structural trough, which appears to have been a half graben, it thickens to as much as 2.5 s TWT (c. 4 km) (Fig. 5A, 6A, B, possibly 7B and 8A [RS-114-02, RS-114-04, RE-8, Aus-202, P-707] and 14). It also thickens locally syntectonically into the Reinga Ridge and the deformed northwestern extremity of the basin (Fig. 6B, 8B, 5A [RE-8, RE-16/2/3, RS114-02]). Given the wide potential age range of reflector P1, there could be significant Oligocene sediment in the thicker of these deposits. Although the deposition of the sequence was controlled by structure, the sequence was itself deformed in the Neogene (e.g., Fig. 5A, 6A, B, 7A, 8B, 13 [RS114-02, -04, RE-8, P-706, RE-16/2/3]). It is tilted on the flanks of the uplifted Wanganella and Reinga

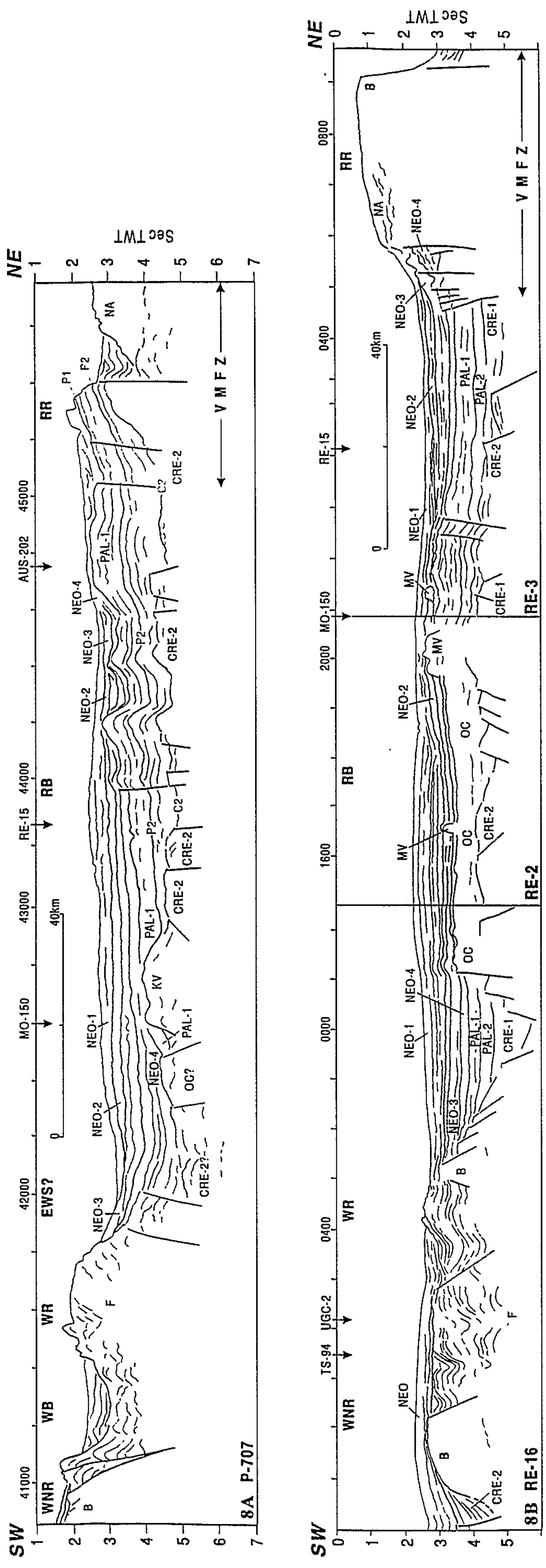

Fig. 8 Line drawings of seismic profiles P-707 (Fig. 8A) and RE-16/2/3 (Fig. 8B). F = rocks of folded zone; KV = possible Cretaceous volcano in Cre-2 sequence; MV = ?Oligocene–Early Miocene volcanic bodies; NA = Northland Allochthon; OC = occluded zone. See Fig. 4 and 5 for explanation of other abbreviations. Reflector C1 and sequence Cre-1 are not distinguishable on line P-707. The folds from 0300 to 0500 on line RE-16, which appear to be younger than those from 0500 to 0800, are considered to be part of the Wanganella Ridge structure. The occluded zone on profile 8B stretches from 2300 on RE-16 to 2030 on RE-2.

Ridges, and folded in several Reinga Basin anticlines and pop-ups.

Early Miocene rocks were dredged from many ridge and scarp locations in the region (Table 1, Fig. 1). Late Oligocene rocks (other than Waitakian), however, appear to be rare. The rocks are mainly limestones in which shoal and photic zone fauna are common while lithic fragments are rare. Shallow water and a nearby volcanic source supplying rounded lithic clasts are indicated for the flat-topped Norfolk Ridge between 30° and 31°S in the Late Oligocene to Early Miocene (samples GO347D-b and c, GO348D-b and c; Table 1). Coleman & Veevers (1971) reported Early Miocene (likely late Early – early Middle Miocene), shallow-water, lithic-free limestone on Philip Island near 29°S. Shallow water without a nearby clastic sediment source is indicated for the flat-topped southern West Norfolk Ridge in the Early Miocene (sample U566-3; Table 1), and a change from higher to lower energy is indicated for the flat top of the central West Norfolk Ridge (dredge RE-6, sample RE9302-6-1; Table 1) by infilling and burial of bored or solution-pitted bioclastic bryozoan limestone with bathyal foraminiferal ooze. Bathyal foraminiferal limestone dredged from the scarp of the jagged central Wanganella Ridge is of latest Oligocene – Early Miocene age (dredge RE-7, sample RE9302-7-2; Table 1), whereas an algal ball which must have formed in the photic zone, found at dredge station G-1 on the flat top of the northern Wanganella Ridge (Table 1), was dated as late Early–Middle Miocene on the basis of enclosed forams. Although the sample evidence is sparse and must be regarded with caution, it implies (1) that the flat-topped West Norfolk and Norfolk Ridges were partly awash and supplying a limited amount of clastic sediment in the Early Miocene but they might have been larger clastic sources before that, and (2) that the northern part of the Wanganella Ridge was uplifted to sea level by Middle Miocene time, considerably earlier than the rest of the ridge (see Neo-2 below).

Early Miocene subaerial or near sea level volcanism is indicated on the Three Kings Ridge where a shoal microfauna (dredge RE-1, sample RE9302-1-1; Table 1) was found in dredged volcaniclastic sandstone associated with wave-worn calc-alkaline volcanic pebbles Ar-Ar dated at 20–21 Ma (Mortimer et al. in press). Thus, a northern volcaniclastic and possibly epiclastic sediment source could have fed the Reinga Basin during this period.

?Oligocene–Miocene volcanics: Scattered volcanic extrusives and igneous intrusions with magnetic anomalies occur in the lower Miocene and possibly Oligocene section throughout much of the southeastern two-thirds of the basin (Fig. 1). Those near the

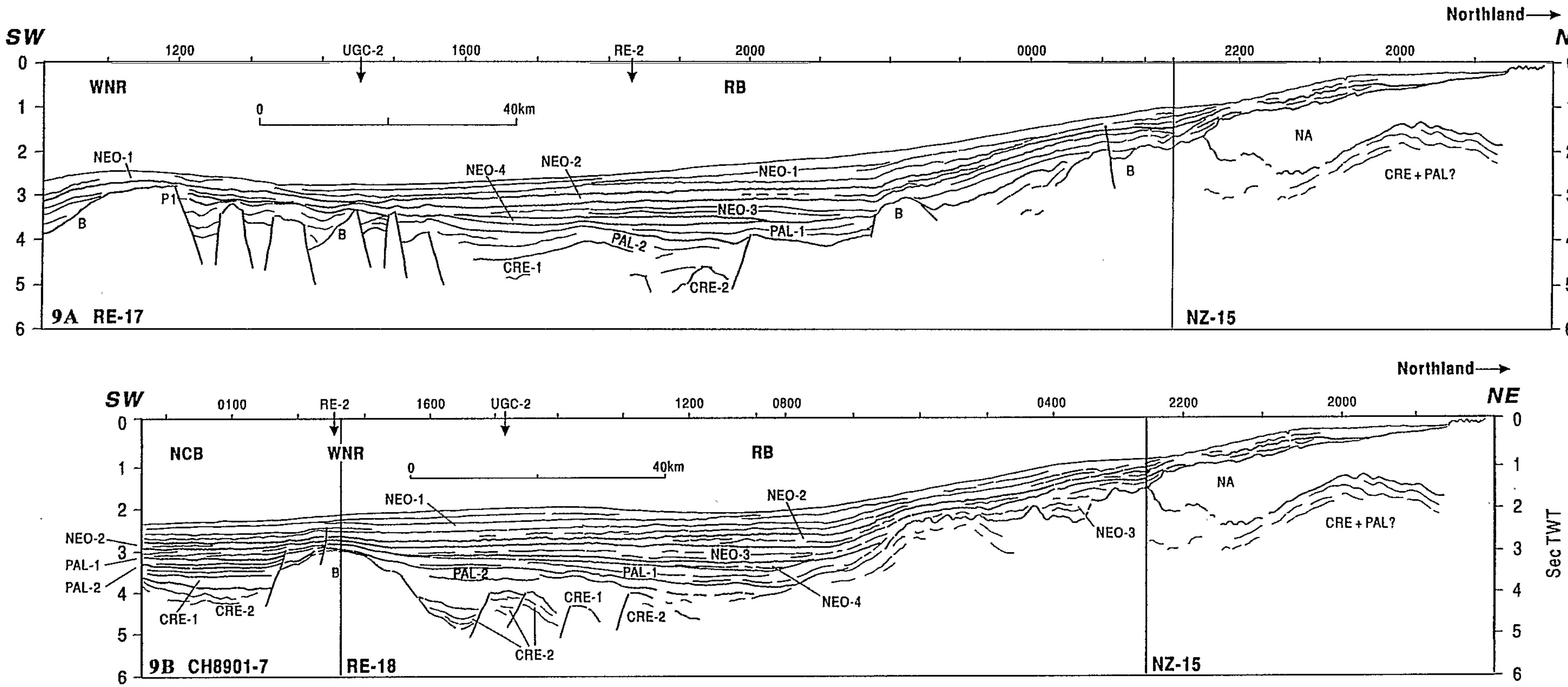

Fig. 9 Line drawings of seismic profiles RE-17/NZ-15 (Fig. 9A) and RE-18/NZ-15 (Fig. 9B). NA = Northland Allochthon. Profile NZ-15 (Australian Gulf Oil 1973). See Fig. 4 and 5 for explanation of abbreviations.

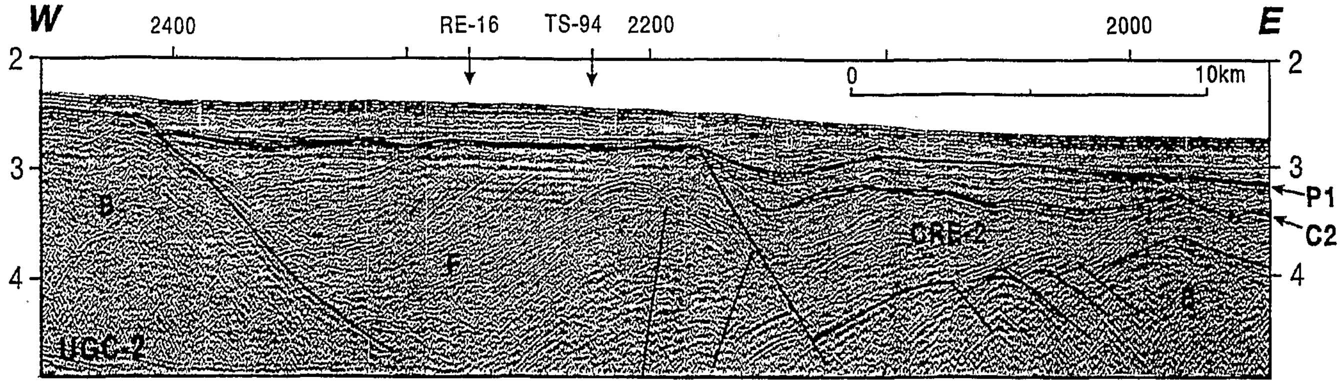

Fig. 10 [UGC-2]. Folded sedimentary unit of zone F and its apparently close relationship with mid-Cretaceous block-faulted sequence Cre-2 considered to be of mainly terrestrial origin. An alternative origin for unit F is to be part of pre-mid-Cretaceous basement as Murihiku Terrane. Offset unconformities show minor Paleogene and Neogene movement on the main normal faults. Basement block (B) at left forms the core of the West Norfolk Ridge. Profile UGC-2 (United Geophysical 1970).

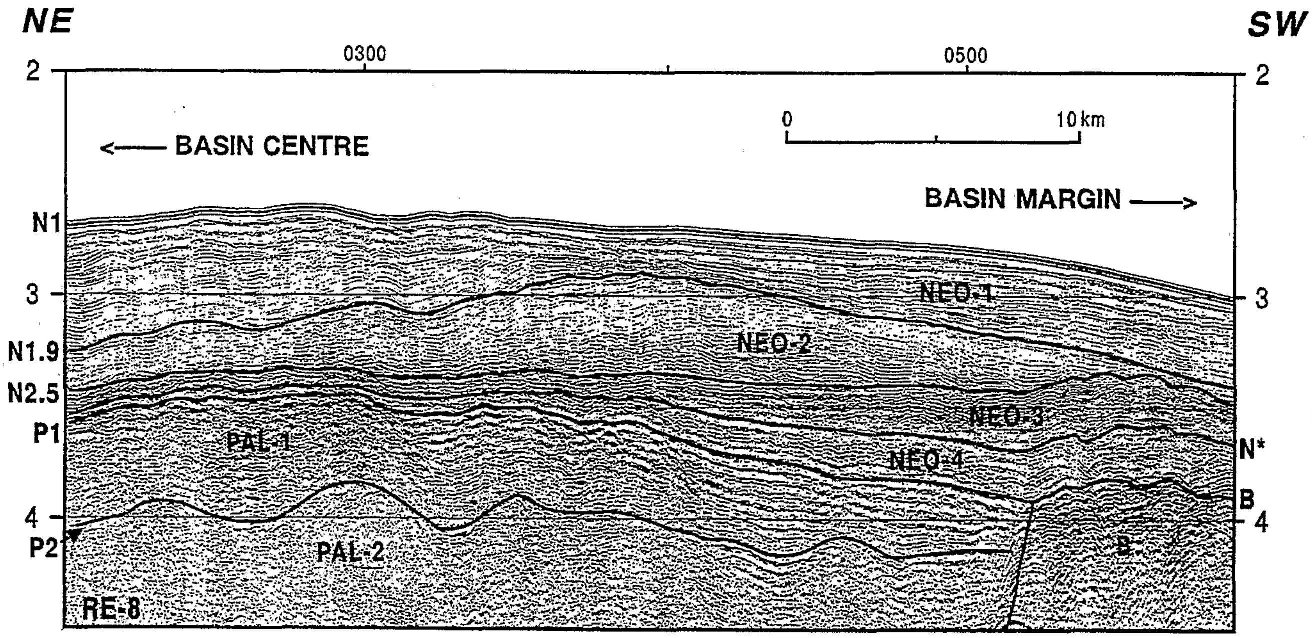

Fig. 11 [RE-8]. Seismic profile near the southwestern flank of Reinga Basin. Early and mid-Miocene sequences Neo-4 and Neo-3 fill lows and thin over highs, demonstrating their probable clastic (turbidite) origins. Late Miocene sequence Neo-2 is in the form of a drift or dune that built northeastwards towards the basin centre (left), while an erosional or nondepositional trough developed to the southwest along the basin margin (right). Pliocene–Pleistocene sequence Neo-1 has continued the basinward growth of the drift, but accumulated sediment on the backslope demonstrates that the current became non-erosive.

coast of Northland are adequately delineated by the existing seismic grid, but in the Reinga Basin the seismic grid is so wide that volcanic bodies were crossed only at random. There nevertheless appears to be a cluster midway along the axis of the basin.

Some volcanoes in the cluster have an apparently conical shape and a central chaotic to flanking downlapping reflector pattern (Fig. 15); others are wide, low bodies with chaotic reflectors (cf. the offshore Kaipara volcano in Herzer 1995, fig. 5b). Where distinguishable, the reflectors of the volcanic aprons occur within the Neo-4 sequence and downlap onto the P1 reflector. However, this level of detail usually cannot be seen due to the poor resolution of the seismic data. Most of the volcanic bodies occur just above or below the P1 reflector and in the Neo-4 sequence. Intrusions have been identified from offsets of overlying reflectors (at 2345 and 0100 in Fig. 15) which affect the Neo-4 to lower Neo-3 sequences. Thus, while most of the volcanoes appear to be Early Miocene, igneous activity might have extended from Oligocene to early Middle Miocene.

The location and stratigraphic age of these volcanic features suggest that they could be part of the Northland volcanic arc. If so, then the arc extended in a curve north to 34°S and west to 169.5°E. This affinity, though likely, is by no means certain. Uruski & Wood (1991) have identified major volcanic bodies of Early Miocene age in seismic

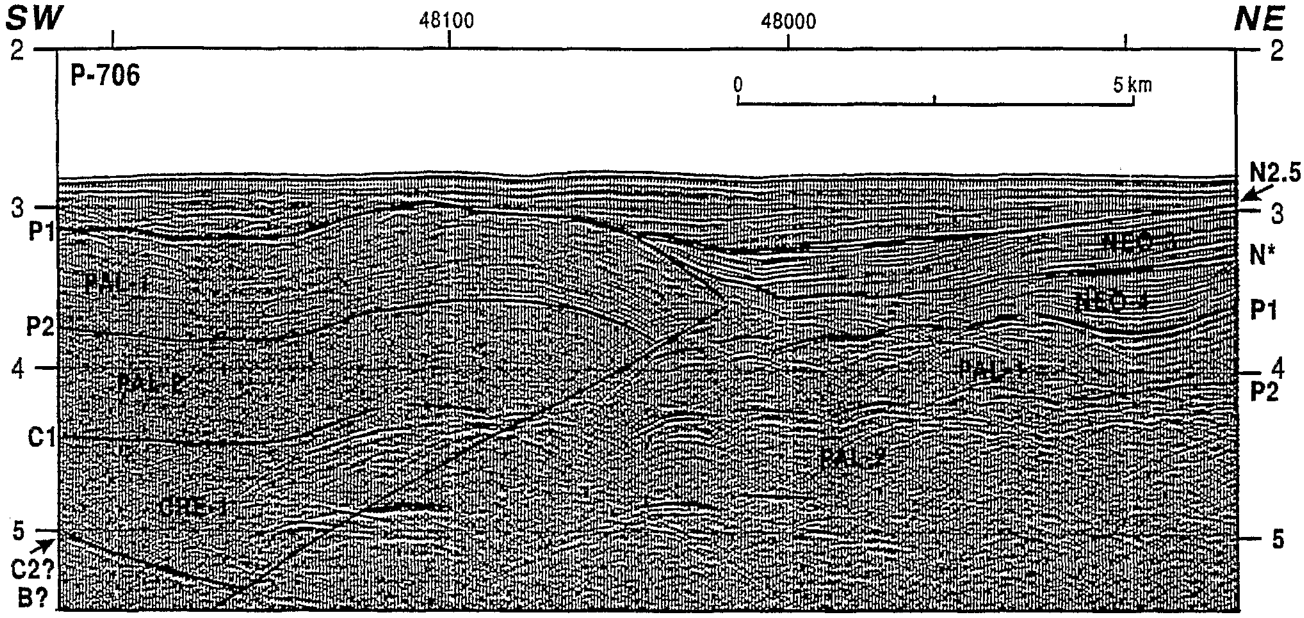

Fig. 12 [P-706]. Detail of a fold developed over a thrust fault, a reversed normal fault on the edge of an everted Cretaceous half-graben, in the middle of the Reinga Basin. The onlap relationships of sequences Neo-4, Neo-3, and the lower part of Neo-2 (not distinguished here from Neo-1), and the erosion of the top of the anticline, show that the fold grew from Early to early Late Miocene, corresponding to the periods of transpression on the Vening Meinesz transform and later uplift of the Wanganella Ridge. The early Neogene sequences are tilted by another larger thrust-fault/fold structure out of view to the right. Seismic profile Petrel-706 (Shell Internationale Petroleum Maatschappij 1971).

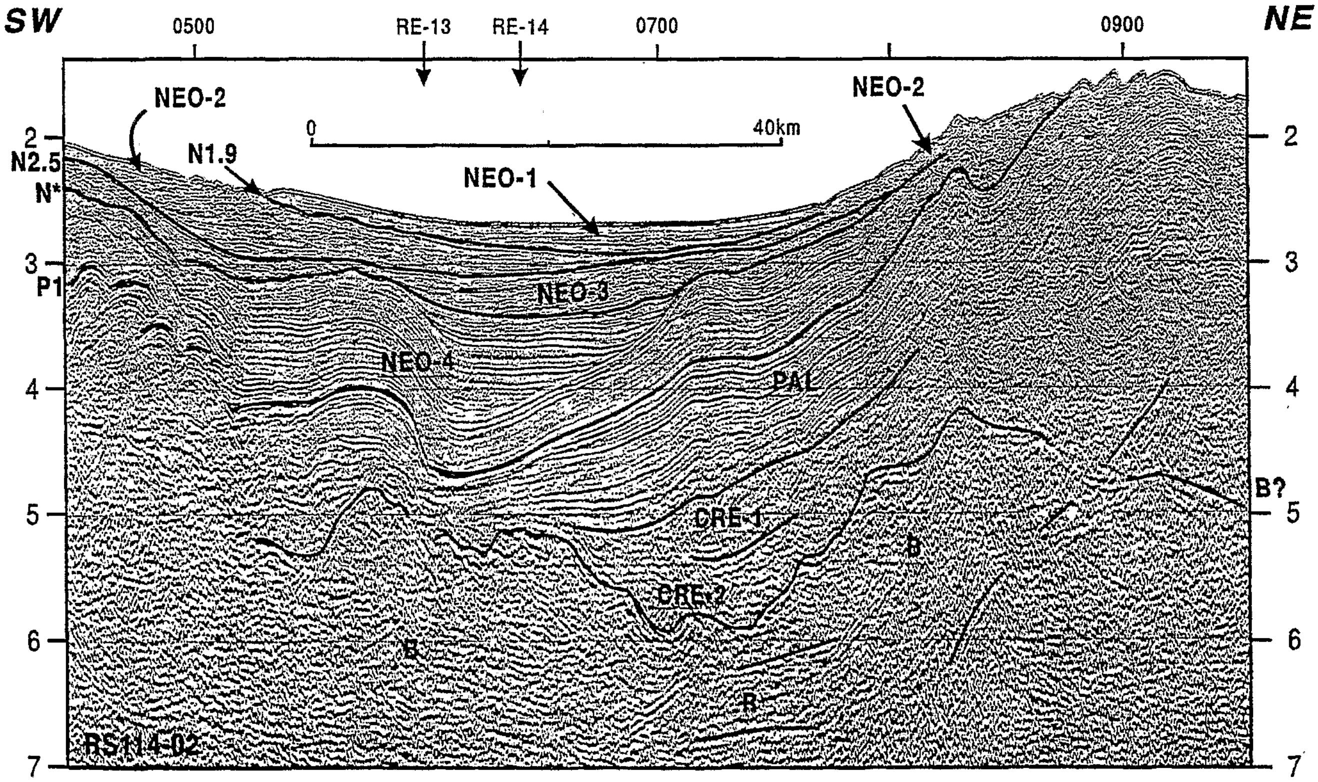

Fig. 13 [RS114-02]. Seismic detail of part of the northern extremity of the Reinga Basin. Reflectors (R) within basement (B) between about 0600 and 0800 could indicate the presence of either Murihiku sedimentary rocks or of sequence Cre-2 deeper than where we have drawn it. Some of the complex deformation where the Wanganella Ridge (out of view at left) approaches the Vening Meinesz transform (out of view at right) is seen here. Thinning of lower Neo-4 strata towards the Reinga Ridge near 0800 indicates very early Miocene activity on the Vening Meinesz Fracture Zone. Southwestward tilting and folding of the lower Neo-4 sequence (northeast of 0600) and strong onlap of upper Neo-4 strata in the basin axis then records very rapid uplift of the Reinga Ridge due to the main wrenching phase on the Vening Meinesz Fracture Zone (Herzer & Mascle 1996). The anticlines and reverse faults on the southwestern side of the Reinga Basin (at left), which formed during uplift of the Wanganella Ridge, did not begin to form until late in Neo-4 sequence time and continued into Neo-3 sequence time (i.e. late Early to early Middle Miocene). The subsequent shifts of Neo-3 to Neo-1 depocentres reflect much less dynamic changes of basin and ridge configurations after that.

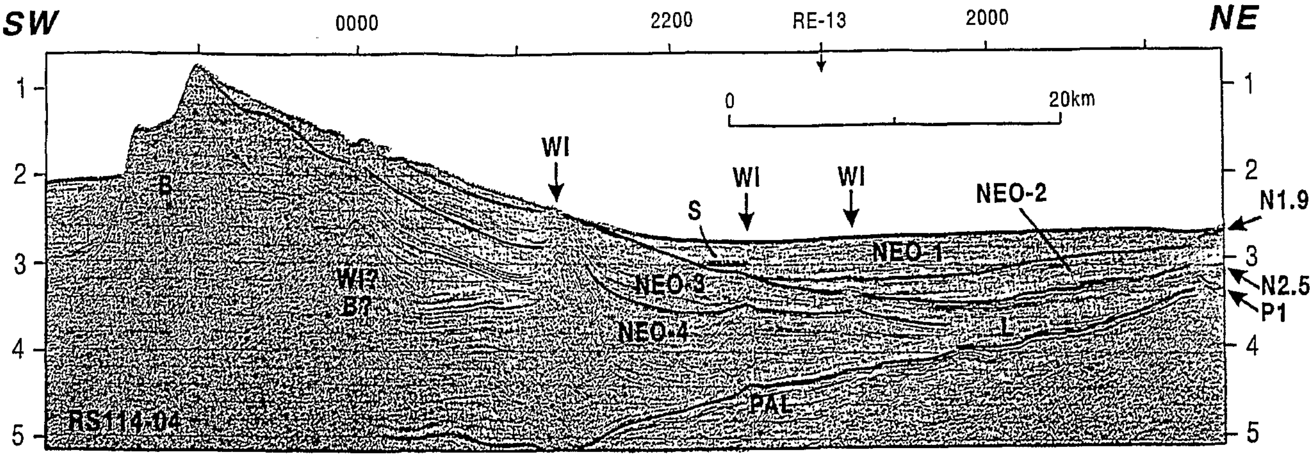

Fig. 14 [RS114-04]. Seismic reflection detail of the Wanganella Ridge and East Wanganella Sub-basin. The strong divergence of two main sedimentary packages in the Neo-4 sequence indicates two pulses of rapid subsidence probably controlled by a major listric normal fault located under the present ridge with a basin hinge line near the right-hand side of the profile. The lens of sediment (L) at right above the strong southwest-dipping P1 reflector suggests that subsidence began sometime after the development of P1 (in the very late Oligocene or very early Miocene?). Lens L is of local extent only and we include it in Neo-4. Subsidence had probably halted before the Middle Miocene as sequence Neo-3 does not have the dramatic wedge shape of Neo-4. Rather, passive onlapping of untilted sequences Neo-2 and Neo-1 on reflector N2.5 shows that rapid eversion took place at the end of Neo-3 (middle Miocene) deposition. Substantial basement slivers (B) were thrust up during the basin eversion. The distinction between basement and sedimentary sequences is complicated by several Pliocene intrusive bodies (WI, under vertical arrows). The bodies appear to include both vertical and horizontal shapes. A short horizontal body 300 ms below the seabed under S could be a flow or thin sill.

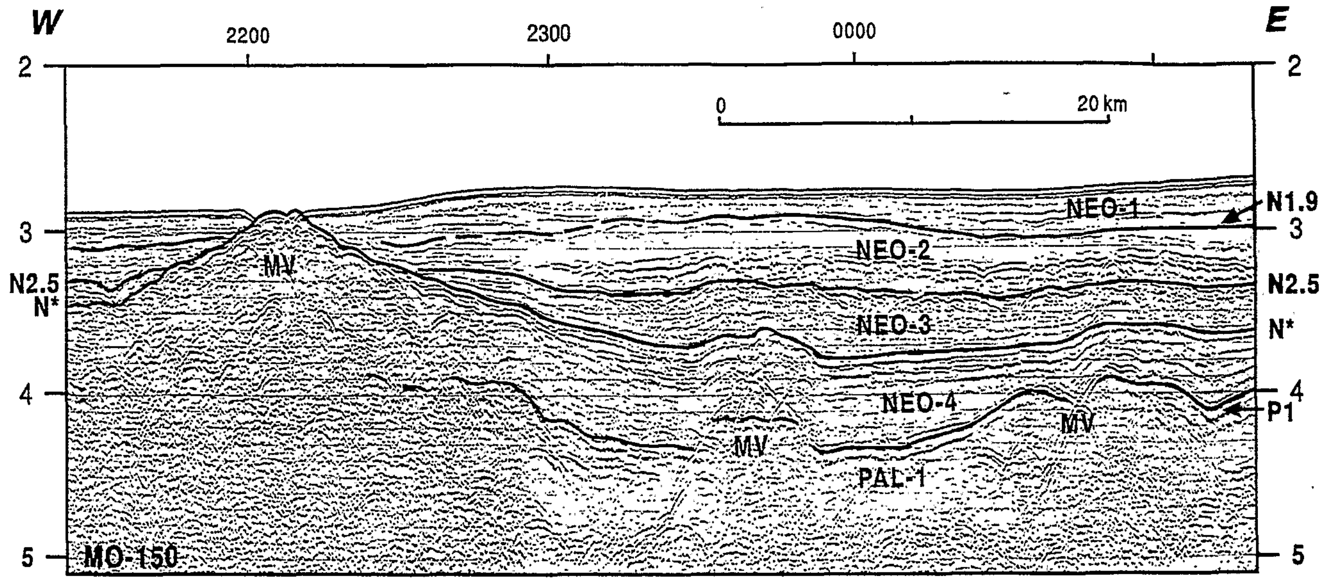

Fig. 15 [MO-150]. Volcanic bodies (MV) of Late Oligocene to Early Miocene age (buried features with positive relief). The edifice at left is a volcano that postdated the P1 surface (that can still be seen faintly beneath it with velocity pull-up). Onlapping upper Neo-4 reflectors at about 2300 show that it had ceased its activity before the end of the Early Miocene. At centre, a probable intrusion of Early or Middle Miocene age offsets Neo-4 and Neo-3 strata. The complex body at right could be a combination of late Oligocene extrusive and Early Miocene intrusive products since it combines both onlap and reflector offsets in Neo-4. These volcanics obscure the seismic record beneath them. A change from sediment ponding (turbidite deposition) in sequences Neo-4 and Neo-3 to a more hemipelagic drift style of sedimentation in sequences Neo-2 and Neo-1 is evident. Profile MO-150 (Mobil International 1979).

profiles in the New Caledonia Basin and others of possible Late Eocene – Early Miocene age on the Challenger Plateau to the south.

Neo-3: The deposition of sequence Neo-3, of mainly Middle Miocene age, was also controlled by structure. It is a regional blanket, usually 200–300 ms TWT (250–400 m) thick. It thickens into a wedge off Northland (Fig. 8B, 9A, B [RE-3, RE-17, RE-18]), fills regional lows (Fig. 6A, 8A, 9A, 11 [RS114-04, P-707, RE-17, RE-8]), thins or pinches out over pre-existing highs (Fig. 6A, 9B, 15 [RS114-04, RE-18, MO-150]) and young folds (Fig. 5A, 7A, 8A, 12, 13 [RS114-02, P-706, P-707]), and locally either thickens towards or pinches out on the Reinga Ridge (Fig. 6A, 7A, 8B [RS114-04, P-706, RE-3]). It thickens also into the East Wanganella Sub-basin but attains only 500–800 ms TWT (Fig. 6A, B, 14 [RS114-04, RE-8]). The sequence was subject to the same synsedimentary tectonism as Neo-4.

Few shallow-water rocks containing fauna of Middle Miocene age were dredged other than the algal ball of (G1) on northern Wanganella Ridge (Table 1). The possible early Middle Miocene upper age limit of the foraminifers in the shallow-water volcaniclastic sandstone (RE9302-1-1) from the Three Kings Ridge (dredge RE-1) suggests that this ridge might have continued as a source of sediment during this period.

Neo-2: In contrast to the Early and Middle Miocene sequences, sequence Neo-2 of mainly Late Miocene age is a nontectonic basin infill. It is generally of uniform 100–150 ms TWT (120–180 m) thickness in the central southeastern part of the Reinga Basin, but it thickens to 500 ms (600 m) in the Northland clastic wedge and pinches out on young structural highs (Fig. 8B, 9 [RE-16/2/3, RE-17, RE-18]). It onlaps tilted sedimentary sequences of the East Wanganella Sub-basin (Fig. 6A, 8A, 14 [RS114-04, P-707]), which implies that the Wanganella Ridge was uplifted about the end of the Middle Miocene. In the central northwestern part of the Reinga Basin the sequence thickens locally into depositional/erosional mounds up to 500 ms TWT (600 m) thick, resembling very broad dunes (Fig. 6B, 11 [RE-8]), is absent locally in erosional or nondepositional troughs along the basin margins, and is locally thick in the basin axis where it tends to reverse the basin profile (Fig. 6 [RS114-04, RE-8]). These features resemble those described by Wood (1992) from equivalent strata on the Challenger Plateau. We interpret the deposits in the southeastern Reinga Basin as clastic and those in the northwest as pelagic or hemipelagic sediment drifts, distributed and eroded by ocean currents that were concentrated around the margins of the basin.

No significant rocks of this age have been dredged (Table 1).

Neo-1: Sequence Neo-1 of mainly Pliocene–Pleistocene age repeats the pattern of Neo-2 in that it is a passive infill as much as 800 ms TWT (760 m) thick on the prograding continental slope off northern Northland (Fig. 9 [RE-17, RE-18]), and a broad swell of pelagic/hemipelagic drift sediment up to 1 s TWT (990 m) thick in the Reinga Basin axis, with erosion or reduced deposition along the margins, particularly in the northwestern half of the basin (Fig. 6, 8, 11 [RS114-04, RE-8, P-707, RE-16/2]).

The only Pliocene material of importance obtained in dredge hauls were bathyal ooze infillings of bored or solution-pitted shallow-water limestones (GO347D-c, GO348D-c) which document late Neogene subsidence of the Norfolk Ridge (Table 1, Fig. 1). There are several generations of borings or solution cavities in GO348D-c which may have taken place at different times. The faunas are consistent with the notion that the Early Miocene limestone on the Norfolk Ridge was exposed to erosion or strong currents until late in the Miocene, that it was submerged to bathyal depths by the early Pliocene, and that depths have not changed a great deal since that time. A similar late Middle to early Late Miocene hiatus in the Papuan Basin and on the Marion Plateau off northeastern Australia (Chaproniere & Pigram 1993) suggests that a South Pacific-wide event might be superimposed on the tectonic events that affected the ridges around the Reinga Basin.

Northland Allochthon: The Northland Allochthon is confined to the southeastern Reinga Ridge and Northland peninsula (Fig. 1). It is an easily recognisable lens c. 1.5 s TWT (2.5 km) thick of chaotic reflectors, the base of which sits stratigraphically and structurally no higher than the level of reflector P1 (Herzer & Isaac 1992; Isaac et al. 1994) (Fig. 7B [Aus-202]). It is onlapped and overlain by Neogene sequences (Fig. 9 [NZ-15]). The terminus and underlying contact are often unclear. For instance, on multichannel seismic profile NZ-15 (Fig. 9) off the Northland coast, where the base of the allochthon can be seen, we can only infer, with the existing data, what unit underlies it. Parallel reflectors beneath it are gently folded, much like the characteristic open folds of the Murihiku Terrane. The rocks of other basement terranes are too deformed to have such a seismic signature. However, the folding of the reflectors mimics the shape of the underside of the allochthon, a relationship one would not expect from the Murihiku which was folded in the Mesozoic. Near Northland, the allochthon and its substrate are thought to have been folded after its emplacement, and the higher parts of its upper surface planed off (Isaac et al. 1994). This suggests that the reflectors beneath the allochthon are part of the Cretaceous–Paleogene sequence. The timing of this folding is not precisely known. It predates the Late Miocene because undeformed sequences Neo-1 and Neo-2 onlap the planed top of the allochthon (Fig. 9; Isaac et al. 1994 fig. 8.9). The relationships of sequences Neo-4, Neo-3, and the allochthon in Fig. 9A, B suggest that the planation postdates the Early Miocene and might have occurred in the Middle Miocene when there was significant sediment progradation seaward of the allochthon. Thus, the folding could have taken place in the Early or Middle Miocene.

Wanganella igneous bodies: There is a field of shallow intrusions and extrusions near the Wanganella Ridge in the northwestern part of the Reinga Basin (Fig. 1). These features are seen in the thick, tilted wedge of Miocene sedimentary rocks in the everted East Wanganella Sub-basin where they fold the strata and locally disrupt the seabed (Fig. 6, 14 [RS114-04, RE-8]). Also visible at the seabed on multibeam bathymetry north of the seismic lines are small conical peaks, but the data coverage is not close enough to link them definitely to the bodies seen in the seismic profiles. On the few seismic lines available, the bodies appear to decrease in size and penetration or amplitude away from the ridge, which suggests a causal relationship with the ridge. Reflectors can be traced without real offset beneath the bodies on multifold seismic profiles (Fig. 14 [RS114-04]). Thus, the bodies appear like diapirs or detached anticlines. However, there is evidence that their origin is igneous. On profile RS114-04 (Fig. 14) there is a short horizontal reflector in the Pliocene–Pleistocene sequence (Neo-1) resembling a sill or flow above a zone of slight upwarp and disruption of reflectors. A small peak on the seafloor on profile Aus-204 (Fig. 5B), which appears to belong to one of the diapiric bodies, was dredged (GO353), and late Pliocene intraplate alkaline basalts and hyaloclastites were recovered there (Monzier & Vallot 1983; Mortimer et al. in press). Some hyaloclastites were also recovered at dredge site GO349 on a prominent peak 100 km to the north of GO353.

Occluded zone: A zone in which pre-Neogene sequences cannot be distinguished or resolved due to poor seismic resolution (Fig. 7B, 8 [Aus-202, P-707, RE-16/2]) extends diagonally (west-northwestwards) from a central basin position at 171°E to near a ridge that we have named the Petrel Spur adjacent to the Wanganella Ridge at 169°E (Fig. 1). The cause of the occlusion is not immediately obvious. However, most of the ?Oligocene–Miocene volcanic bodies occur within the occluded zone. They mask immediately underlying reflectors (Fig. 15 [MO-150]), a relationship which suggests that volcanic products could possibly be the cause of the more widespread seismic occlusion.

Folded zone: The folded zone, informally designated F, may comprise different groups of sequences in different places. Rocks in this zone have never been sampled. They underlie c. 250 km of the southeastern Wanganella Ridge, extending a short distance into the West Norfolk Ridge and Reinga Basin (Fig. 1). Their base is not seen. The greatest recorded thickness is 2 s TWT, probably amounting to several kilometres.

At the southeastern end of the Wanganella and West Norfolk Ridges (east of 169°45′E) the zone consists of a distinctive folded unit which is well displayed on the better seismic profiles (Fig. 8B, 10 [RE-16 and UGC-2]). Here the unit is bounded to the southwest by the footwall of a very large, reflector-free basement block that forms the core of the West Norfolk Ridge. Both the folded unit and the basement are bevelled by a strong subhorizontal unconformity. The unit is faulted to eastward and replaced by unfolded half-graben fill of sequence Cre-2.

In profile UGC-2 (Fig. 10) both the folded sedimentary unit F and nonfolded sequence Cre-2 are clearly older than the Paleogene sequence which onlaps them, but their relationship to each other is not clear. On profile RE-16 (Fig. 8B), which intersects UGC-2, a young anticline that breaks the seabed near 0400, and a basement horst near 0300, are interposed between the deformed and clearly planed-off folded unit (F) and the flat-lying basin-fill sequences. Whereas the gentle anticline might be part of the older folded unit, it was folded after the unconformity was formed, and its strata could well belong to the Cretaceous–Tertiary sequences northeast of the horst. The anticline is on the trend of the Wanganella Ridge and probably related to it.

The sharp southwestern contact of the folded unit with the faulted flank of the basement core of the West Norfolk Ridge (Fig. 8A, B, 10 [P-707, RE-16, UGC-2]) suggests either that the unit is part of sequence Cre-2, deposited at a major Cretaceous rift shoulder in a complex listric growth fault structure, or that it is an older folded sedimentary sequence. The style of folding and the reflector character of this unit are reminiscent of the supposedly pre-rift Seismic Unit IIA on the Chatham Rise, for which no onland equivalent has been found (Wood et al. 1989). Another alternative is that the folded unit is Murihiku Terrane, the only likely basement terrane with gentle enough deformation to be potentially seen on seismic profiles. The fault contact with Brook Street or MTZ rocks could be in this case the terrane boundary.

Elsewhere, the relationship of rocks in the folded zone to the Reinga Basin sequences and their contact with Norfolk Ridge basement are not well resolved in our data. This obscurity seems to be caused in part by deformation associated with uplift of the Wanganella Ridge, and partly by other factors. In profiles Aus-202 and P-707 west of 170° (Fig. 7B, 8A), the folded zone appears to merge basinwards with a poorly defined and noisy unit that might be Cre-2 or younger. Orderly Paleogene and higher Cretaceous reflectors do not appear until much farther to the northeast in the basin, and their relationship to the noisy unit is not clear. We include this noisy unit in the occluded zone, and the question of structural relationships with the folded zone is left unresolved.

Northwest of about 169°E, between Aus-202 and P-706, the folded sedimentary core (F) of the Wanganella Ridge is replaced by uplifted seismically opaque igneous and metavolcanic MTZ and Brook Street Terrane basement (Dredge GO360; Mortimer et al. in press) (Fig. 7); the folded zone is not seen again. Deformed sedimentary rocks are still evident nearby though, for example in a pop-up that forms the Petrel Spur, but this deformation is obviously young, clearly affecting the Cretaceous–Tertiary sequence, and perhaps contemporaneous with the formation of the anticline in Fig. 8B [RE-16].

TECTONISM AND BASIN EVOLUTION

The Reinga Basin has a polyphase tectonic history. The earliest deformational phase might have been associated with the early folding in the southeastern folded zone. If the zone is composed of Murihiku Terrane, then its folding history predates the extension in the basin. However, if the zone represents a younger unit, it could record mid-Cretaceous multiple listric faulting and roll-over at the southern rift shoulder of the basin.

Extension and rifting with deposition of probable terrestrial sediments in grabens and wide lowlands, as in offshore western Northland, probably began throughout the Reinga and New Caledonia Basin regions in the mid Cretaceous (Fig. 16A). Fossil evidence from the deltaic Taniwha Formation of the Taranaki Basin (Shell BP & Todd 1986; Thrasher 1992) and the carbonaceous nonmarine facies of Dredge RE-5 on the West Norfolk Ridge (Herzer et al. in prep.) suggest that this phase continued through at least the first half of the Late Cretaceous (Ngaterian–Mangaotanean (100–89 Ma). Acritarchs and test-filling pyrite in the otherwise terrestrial rocks in Dredge RE-5 show that the sea was not far away towards the end of this early stage, probably in the New Caledonia Basin. Very low thermal maturity of the Dredge RE-5 coal measures indicates only shallow burial (Herzer et al. in prep.), suggesting that the West Norfolk Ridge remained a positive topographic feature throughout its history. According to the reconstructions of Isaac et al. (1994), the Northland peninsula area was a landmass throughout this period, shedding sediments both northeast onto the open Pacific margin and southwest into terrestrial rift basins. Gage & Kurata's (1996) model proposes that Northland began as a submerged Pacific-facing continental shelf and was uplifted during this period. There is no information for the rest of the northeastern margin of the Reinga Basin so we cannot determine marine versus terrestrial influence from the northeast.

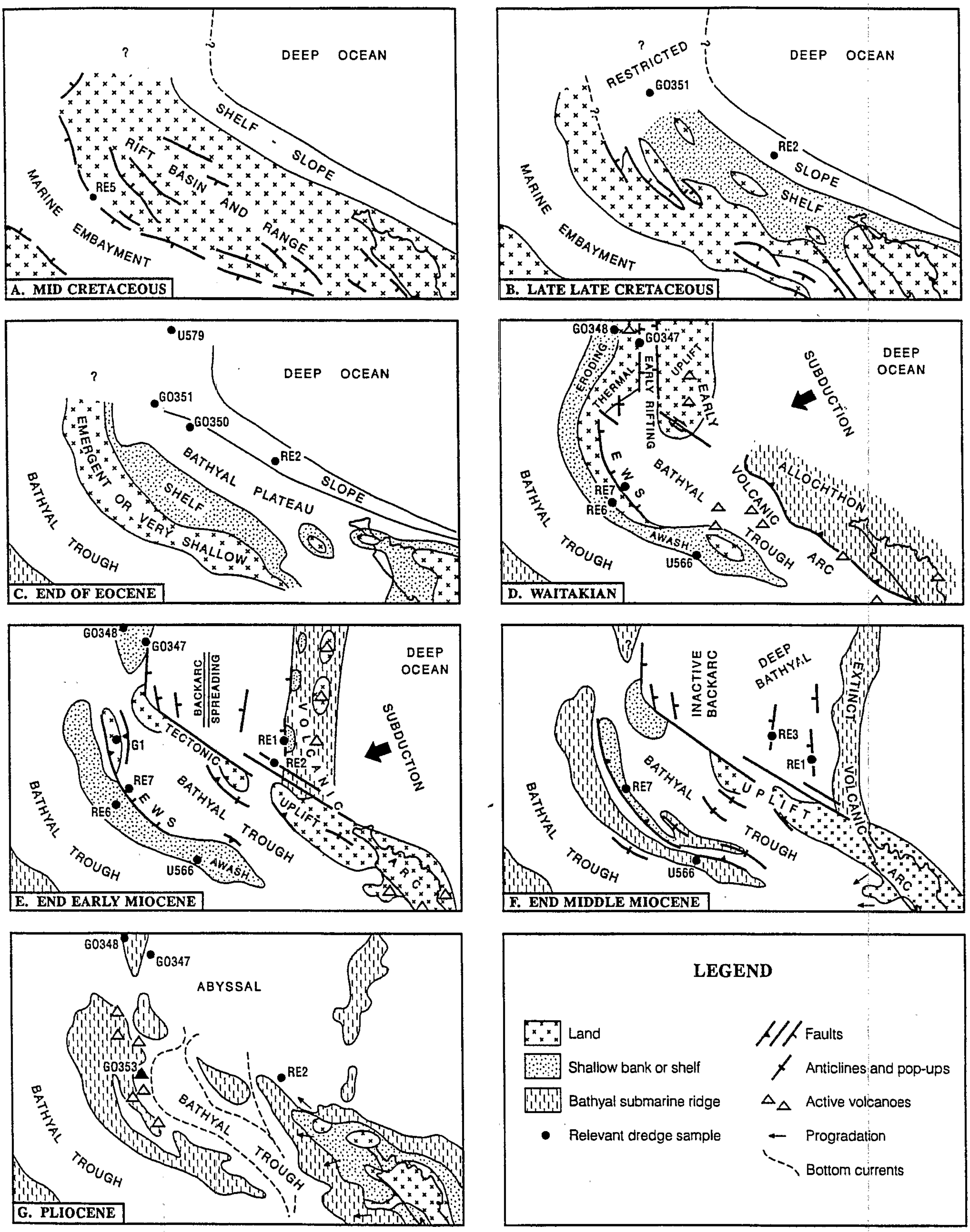

Fig. 16 Paleogeographic/paleotectonic maps of the Reinga Basin region.

The second phase of rifting, which affected the Taranaki and Northland regions in the late Late Cretaceous (Piripauan–Haumurian) (Isaac et al. 1994; King 1996), apparently affected the Reinga Basin as well, as evidenced by the offsets of sequence Cre-2. This phase appears to have involved widespread subsidence and marine incursion (Fig. 16B). The Northland peninsula was still a landmass (Isaac et al. 1994; Gage & Kurata 1996), and regional onlap patterns (Fig. 8B, 9A [RE-16, RE-17]) suggest that a wide area including the West Norfolk Ridge remained exposed on the southwestern side of the basin. Active grabens cut bays and channels into the landmass, probably creating effective sediment traps. There is no evidence in the seismic profiles that a ridge existed in the present location of the Reinga Ridge. Greensand turbidites and bathyal mudstones were deposited on the Pacific side of northern Northland (now exposed in the Northland Allochthon) (Isaac et al. 1994). Together, these suggest that there was a northeast-facing continental shelf with a low sediment supply. The black shale (dredge sample GO531-D-a) suggests that circulation well to the northwest was restricted.

Passive margin sedimentation occurred throughout most of the Paleogene, probably as a response to thermal contraction and subsidence. However, it appears to have been punctuated by episodes of local extensional faulting. In a few central parts of the Reinga Basin there was renewed extension on Cretaceous normal faults, whereas around the margins extension was not marked. The record in the southeast (the Northland margin) is one of erosion of the Northland landmass eventually to base level, very minor reactivation of normal faults in the Paleocene, minor normal faulting in the Late Eocene (a few tens to a hundred or so metres), and subsidence to shallow bathyal depths (Isaac et al. 1994). Delta-fed sedimentation gave way to more calcareous and glauconitic facies. On the southwestern side of the basin, where not deformed by later events, the record is one of continued gradual regional onlap onto a high in the present location of the Wanganella and West Norfolk Ridges, as in the Late Cretaceous (Fig. 8B, 9A, B [RE-16, RE-17, RE-18] and Fig. 16C). In the northwestern half of the basin the Paleogene sea extended as far west as the present-day Wanganella Ridge and lapped around small, isolated, central basin highs. There is no indication of a northeastern basin margin at the Reinga Ridge; the sequences generally thicken and extend without interruption across the ridge, suggesting an unrestricted, northerly facing continental shelf. The sedimentary facies of the samples from dredges (GO350, GO351, RE-2 (RE9302-2) and U579; Table 1) are consistent with deep water and distant or small sediment sources. The southwestern high was finally reduced to about the present limits of the combined West Norfolk and Wanganella Ridges, either as a low-lying landmass or shallow bank.

In the Eocene, during the time that the Reinga Basin and the northern New Zealand region underwent gradual thermal subsidence and mild extension, south of New Zealand and the Tasman Sea, the northwest–southeast-spreading Southeast Indian Ridge was propagating northward into the Campbell Plateau (Sutherland 1995; Wood et al. 1996), while far to the north, in the region of present-day New Caledonia, there was a convergent margin which culminated in the Late Eocene overthrusting of the New Caledonia ophiolite nappe (Parrot & Dugas 1980; Regnier 1988; Aitchison et al. 1995). The kinematics—spreading in the south, convergence in the north, and little deformation between—suggest an Eocene stage pole not far from the North Island and the Reinga Basin, which is consistent with that of Sutherland (1995).

In the Oligocene, the Norfolk Basin did not exist yet, and the progenitor crust of the Three Kings Ridge lay near 169°E, more than 150 km west of its present position (Herzer & Mascle 1996). Subduction from the north must have started along the northern margin of the Reinga Basin in the Late Oligocene in order for the Northland volcanic arc to appear in the earliest Miocene. Likewise, eastward subduction under the Three Kings Ridge must have been occurring in the Late Oligocene for shoshonitic volcaniclastics to be deposited on the Norfolk Ridge north of the Reinga Basin at 26.3 ± 0.1 Ma (Mortimer et al. in press).

Thermal maturity studies on the Late Cretaceous black shale sample GO351D-a collected from the Norfolk Ridge, and evidence from seismic profiles, indicate that there was much deeper erosion of the southern Norfolk Ridge than of the Reinga Ridge (Herzer et al. in prep.). It was estimated that several kilometres of thermal uplift and erosion took place along the Norfolk Ridge (the future axis of rifting of the Norfolk Basin), probably in the Oligocene in tandem with early subduction. By contrast, lithic limestones, deposited in the photic zone at dredge sites GO348 and GO347 in the Waitakian and Early Miocene, respectively, followed by equally shallow, non-lithic limestones in the later Early Miocene at Philip Island (Coleman & Veevers 1971), then by bathyal hardground limestone deposits in the Late Miocene and Pliocene, testify that by the end of the Early Miocene, this uplift and any arc volcanoes on it had been largely reduced to sea level.

It is difficult to determine the Oligocene history of the Reinga Basin because we cannot establish an Oligocene sedimentary sequence thick enough to tell a story. The Oligocene record is thin in the western North Island and patchy in the Southwest Pacific. With so little control it is possible that some of the Reinga Basin deformation assigned to the Early Miocene below could have begun in the Oligocene.

In the very late Oligocene and very early Miocene (Waitakian) much of the Northland and Taranaki regions rapidly subsided from shelf to bathyal depths. This was quickly followed (still in the Waitakian) by obduction of the allochthon from the northeast over Northland and the southeastern part of the present-day Reinga Ridge, which together would have been the northeastern continental margin (Fig. 16D). Coeval with obduction were early eruptions of the Northland volcanic arc. Early wrench stresses might have been felt at the same time to the northwest, as rifting in the future Norfolk Basin caused the Three Kings crust to begin decoupling from Reinga Basin crust. The East Wanganella Sub-basin also began to subside and fill as a large half-graben. Analogue modelling by Benes & Scott (1995) predicts that a rift, obliquely intersecting an ocean-continent crustal interface, such as the northern New Zealand margin, will propagate into the continental crust at an even more oblique angle, accompanied by strike-slip faulting along the interface. The combination of Norfolk Basin, East Wanganella Sub-basin, and early Vening Meinesz Fracture Zone seems to form a rift-rift-fault triple junction in which the East Wanganella Sub-basin is an asymmetric aulacogen. The model helps to explain the unusual orientation of the aulacogen, but the fault system may also have been guided by the structural trend of the basement terranes.

In the Early Miocene the Norfolk Basin was opening by northwest–southeast extension (Herzer & Mascle 1995; Mortimer et al. in press). Extension also continued in western Reinga Basin in the form of extreme subsidence of the East Wanganella Sub-basin, indicating that decoupling was not yet fully achieved along the Vening Meinesz Fracture Zone. Transpression along the Vening Meinesz Fracture Zone led to folding, reverse and wrench faulting, and the beginning of uplift of the northwestern Reinga Ridge. Parts of the allochthon were also uplifted, and by the end of the Early Miocene the whole Northland peninsula was exposed (Isaac et al. 1994). How much of this southwestern uplift was due to transpression and how much was due to subduction from the northeast is not known. The East Wanganella Sub-basin and local depocentres of the northern and northeastern Reinga Basin were filled with sediments from many sources, which would have included the West Norfolk Ridge (whose planation predated the uplift of the Wanganella Ridge), the region of the Norfolk Ridge, uplifted parts of the newly evolving Reinga Ridge, the northwestern part of the Northland Allochthon, and the volcanic arc.

The Northland and Three Kings volcanic arcs were active in the Early Miocene, maintained by subduction from the northeast. If the ?Oligocene–Miocene volcanics of the Reinga Basin are part of the Northland volcanic arc, as seems likely, they would have completed the connection of the Northland arc to the pre-spreading position of the Three Kings arc near 169°E, making one continuous volcanic arc (Fig. 16D).

In the late Early Miocene or Middle Miocene, the northern end of the East Wanganella Sub-basin must have been uplifted to sea level and wave-planed (allowing the algal ball of station G-1 to form) (Fig. 16E), by which time the adjacent northern West Norfolk Ridge was apparently below sea level. Was subsidence of the northern West Norfolk Ridge and Wanganella Basin linked to overthrusting by the nascent northern Wanganella Ridge? What was the relationship of this deformation to the wrenching on the Vening Meinesz Fracture Zone? Westerly dipping reverse faults in the northern extremity of the Reinga Basin, which contributed to the uplift of the northern Wanganella Ridge, show great syndepositional offsets of the Early Miocene sequence, tailing off in the Middle Miocene sequence (between 0430 and 0600 on RS114-02, Fig. 5A, 13), while planed-off syndepositional folds under the northernmost Wanganella Basin (seismic profile MO-145 [Mobil International 1979] not shown) predate the Wanganella Ridge thrust and are probably Waitakian. The timing coincided with the main wrench and transform phase along the nearby Vening Meinesz Fracture Zone (Herzer & Mascle 1996, and below), which strongly suggests a connection.

In the Middle Miocene the depocentres were chiefly along the sides of the Reinga Basin, as they were in the Early Miocene. The Northland volcanic arc had ceased to be active and the Northland peninsula, which emerged in the Early Miocene, was supplying clastic allochthon-derived sediment to a continental shelf and slope prograding into the Reinga Basin (Fig. 16F). On the southwestern side of the Reinga Basin, sedimentation was much reduced in the East Wanganella Sub-basin (Fig. 6A, B, 14 [RS114-04, RE-8]), reflecting the end of subsidence but continued submergent conditions (except in the newly uplifted northern part).

Synsedimentary deformation continued along the Vening Meinesz Fracture Zone, however, causing the Middle Miocene sequence to locally thicken towards or pinch out on the Reinga Ridge, and to locally be folded by or pinch out against growing folds and faults. Uplift of the Reinga Ridge continued. Together these suggest that the Norfolk Basin continued to spread.

About the end of the Middle Miocene (Fig. 16F), there was a compressional event which caused the remainder of the East Wanganella Sub-basin to evert, apparently by reversal of the deep-seated listric normal fault that is presumed to have formed its western wall. The uplifted mass became the Wanganella Ridge, which failed to reach sea level except in the extreme northwest where it was already high standing due to proximity to the Vening Meinesz Fracture Zone. The degree and style of deformation of the ridge changes from the northwest to the southeast. In the northwest, fault reversal carried with it substantial slivers of the pre-Cretaceous basement, recovered in Dredge RE-7 (Mortimer et al. in press), as well as tilting the Miocene basin fill (Fig. 5B, 6A, B, 7A [Aus-204, RS114-04, RE-8, P-706]). In the southeast, folded sedimentary rocks of zone F and the Cretaceous–Paleogene sequences were uplifted; reverse faulting was more diffuse, spreading into pop-up structures that either incorporated the ridge itself (Fig. 8A [P-707]) or developed beside it to form the Petrel Spur (Fig. 7A [P-706]). The major Wanganella Ridge structure eventually dies out southeastwards into the young anticline near 0400 on profile RE-16 (Fig. 8B).

Coeval compression was felt widely within the Reinga Basin, manifested as pop-ups, continued growth of some folds, and local uplift of the Reinga Ridge near the Vening Meinesz Fracture Zone. These features are absent east of 171°E, unless the folds under the Northland Allochthon off Northland are related; 171°E also happens to be the eastern limit of Wanganella Ridge deformation, which suggests a common stress regime.

Overall, from the Waitakian to the Middle Miocene, there was a southeastward migration of compression in the Reinga Basin region, which might record the migration of the Three Kings Ridge. However, the compressional event at the end of the Middle Miocene seems too widespread to have been due simply to transpression on the Vening Meinesz Fracture Zone. It might have been related in some way to whatever regional event caused the end of spreading in the Norfolk Basin, and might have been even more widespread than the Reinga Basin. Compressional features which are undated but appear to be of the same approximate age are seen west of the West Norfolk Ridge as well (Fig. 7A [P-706]), and others, not yet studied, are found on both sides of the southern New Caledonia Basin and even on the adjacent Lord Howe Rise. Compression of similar orientation and of Neogene age formed southwest-verging folds and thrusts at the foot of the southwestern New Caledonia continental slope (Rigolot & Pelletier 1988; Rigolot 1989).

In the Late Miocene the style of regional sedimentation in the Reinga Basin changed. There was no further synsedimentary deformation, so presumably tectonism had ceased. Although progradation continued off Northland, elsewhere the sedimentation was confined to the basin axis, pinching out towards static basin margins, which suggests that the emergent parts of the flanking Reinga and Wanganella Ridges subsided below sea level and were no longer sediment sources. With submergence would have come the establishment of constricted oceanic circulation pathways between the Tasman Sea basin and Pacific back-arc basins to the north. The tops of these young ridges became areas of erosion or nondeposition. The flow was probably concentrated in helicoidal currents along their flanks causing erosion or nondeposition in troughs along the basin-margin and build-up of dunes or drifts in the Neo-

2 sequence within the basin (Fig. 6B, 11 [RE-8]).

This tectonic quiescence and corresponding sedimentation style persisted through the Pliocene (Fig. 16G), adding to the sediment wedge off Northland and to the drifts filling the basin. Paleontological evidence shows that, by the Pliocene, all the ridges in the region of the Reinga Basin except the Northland peninsula had subsided to bathyal depths. With deepening of the ridges would have come less constricted water flow, which would account for the change to a more widespread depositional and less erosive style in the Neo-1 drift sequence (Fig. 6B, 11 [RE-8]).

Intrusive and extrusive activity occurred in the Pliocene on a small scale in a belt immediately east of the Wanganella Ridge. The close spatial association of the igneous bodies with the unusual Wanganella Ridge and East Wanganella Sub-basin structure suggest a causal relationship. However, the intraplate basalt composition of at least one peak, the northerly direction of the trend, and the later timing suggest that the belt is more likely to be a hot-spot trace as seen elsewhere on the Norfolk Ridge structure (Rigolot 1988).

LAND BRIDGES

Much of the terrestrial biota of New Zealand is related to the original connection to Gondwanaland in the Cretaceous, but there are post-Cretaceous immigrant species in New Zealand that cannot be explained without periodic land bridges or at least island chains to neighbouring landmasses. The Norfolk and Three Kings Ridges, and the Lord Howe Rise, are most commonly looked upon for such bridges, but there have been few useful offshore data to test these. Our results provide a basis for a tentative land-bridge history between New Zealand and New Caledonia.

The paleogeographic maps suggest that during the mid-Cretaceous rifting, land connecting New Zealand to New Caledonia via the Norfolk Ridge was probably separated early from the Lord Howe Rise by the New Caledonia Basin (Fig. 16A). By the late Late Cretaceous, this land bridge was much reduced in size and possibly cut into a chain of long islands separated by short stretches of water (Fig. 16B). By the end of the Eocene, it is possible that a viable bridge no longer existed for species that could not disperse by air or sea (Fig. 16C).

However, there is evidence (Herzer et al. in prep.) that at least the southern end of the Norfolk Ridge underwent several kilometres of uplift in the Oligocene, and was exposed to erosion. If, as seems most likely, the mechanism was thermal expansion before backarc rifting, the uplift would have taken place along virtually the whole length of the Norfolk Ridge, possibly extending from the New Caledonia landmass to as far south as 32°S, but not as far as New Zealand (Fig. 16D). The early Three Kings Ridge, which lay adjacent to the Norfolk Ridge, might also have been a part of this landmass.

The link to New Zealand was completed by Early Miocene transform tectonism which extended an island chain along the newly rising Reinga Ridge towards Northland. This new uplift was matched by submergence of the Norfolk and West Norfolk Ridges, which would have severed the link between New Caledonia and these newly formed islands. Thus, terrestrial biota, with Paleogene roots in the New Caledonia region, could have reached New Zealand in the Early and Middle Miocene by successively colonising the Norfolk and then the Reinga Ridges. Parts of the Three Kings Ridge, too, were at sea level in the Early Miocene, during its eruptive phase, but these may have amounted to no more than small islands. The Three Kings Ridge migrated away from the Norfolk Ridge in the Early Miocene to a position off the end of the Northland peninsula and eventually subsided to bathyal depths (Table 1, sample RE9302-1-1, dredge RE-1); whether or not it could have ferried species to New Zealand is not known.

PETROLEUM POTENTIAL

The Reinga Basin lies seaward of the petroleum-producing Taranaki and prospective Northland regions. Plentiful studies in the Taranaki region identify mainly Cretaceous and Paleogene coal measures and possibly marine shales as source rocks (Killops et al. 1994). The continuity of Taranaki and Northland seismic sequences into the farthest reaches of the Reinga Basin, and the occurrence of coal measure and marine organic shale facies in dredges RE-5 (RE9302-5) and GO351D, respectively, indicates that similar source facies are likely to be common. Both the coal measures and the marine shale indicate that organic material capable of generating hydrocarbons under the right conditions should exist in the basin (Herzer et al. in prep.). There are also plant beds in the Murihiku Terrane sedimentary rocks, which probably underlie much of the basin, and these too could be a potential hydrocarbon source.

The most common reservoir rocks are likely to be terrestrial and paralic sandstone facies of the Cretaceous sequences. Similar facies might be expected in Paleogene sequences regionally onlapping the southwestern margin and the Northland margin, and locally onlapping residual fault-block highs. The primary reservoir characteristics of the Neogene marine sequences are unknown, but turbidite sands are likely in areas where sedimentation rates were high (i.e. off Northland, along the Reinga Ridge, and in the East Wanganella Sub-basin). Early Miocene turbidites will contain a significant volcaniclastic component which could degrade reservoir quality. Limestones and other carbonate-rich facies are probably common at all stratigraphic levels in areas that were distant from clastic and volcanic sediment sources (i.e. in the basin and on submarine banks). The Miocene episodes of faulting and folding could have induced fracture porosity and permeability in the carbonates.

Appropriate facies to produce effective seals are likely to be common in the form of marine and coal-measure mudstones, marine shales, limestones, and altered volcaniclastics. Potential traps are evident on all the seismic sections: anticlines, faults, drapes, unconformities, onlaps, probable lateral facies changes, and combinations of these.

Maturity will depend on the depth of burial and the geothermal history, both of which are largely unknown. With the exception of multichannel lines RS-114-02 and -04, metamorphic or igneous basement has not been adequately imaged and mapped in the deeper parts of the basin because of the limited penetration of most of the seismic systems used. In general, however, at least 2.5–3.5 s TWT of sediment (c. 3–4.5 km assuming an average velocity of 2.5 km/s) is present in the thicker sections; and in the northwest where sub-basement reflectors are seen (Fig. 5A), this figure increases to 4.5 s (a further 1.5 km, assuming a higher velocity of 3.5 km/s for deeply buried rocks). The

Late Cretaceous marine shale (GO351D-a) recovered from a degraded Miocene fault scarp in the extreme northwest of the area contained extractable hydrocarbons of maturity equivalent to a vitrinite reflectance of Ro 0.6% (Herzer et al. in prep.). Thermal modelling, using the properties of the rocks recovered from dredges RE-5 (RE9302-5) and GO351D, and other New Zealand source rocks, suggests that hydrocarbon generation and expulsion should have occurred in many parts of the basin (Herzer et al. in prep.).

CONCLUSIONS

The gravity models and seismic profiles demonstrate that the foundation of the sediment-filled Reinga Basin is attenuated continental crust c. 15–20 km thick. The flanking West Norfolk/Wanganella, Northland, and Reinga Ridges are high-standing blocks of crust 20–30 km thick. The West Norfolk Ridge is an igneous/metamorphic basement block with a generally flat erosion surface and varying amounts of sedimentary cover, mainly in half-grabens. It is buried beneath young sediments at the New Zealand end. The Wanganella Ridge, by contrast, is cored by both igneous and sedimentary rocks. It has a rugged unplaned top, except in the far northwest near the Vening Meinesz Fracture Zone, and it commonly stands higher than the West Norfolk Ridge, a fact which argues either that it was uplifted after West Norfolk Ridge planation or, less likely, that the West Norfolk Ridge stood higher then subsided differentially. The Wanganella Basin between these two ridges is partly filled with an undeformed asymmetric wedge of sediment that onlaps both ridges and is considered younger than both. The Reinga Ridge is mainly a complexly faulted and uplifted piece of the Reinga Basin, complete with the same thick sedimentary sequence. It is a major basement ridge only in the southeast where it passes into the Northland continental shelf.

The Reinga Basin was initially formed by crustal extension in the Cretaceous. Two Cretaceous rift-filling phases produced terrestrial and marine sequences, respectively. These were followed by cooling subsidence and further submergence in the Paleocene and Eocene that produced wide regional blanket sequences. This period of relative tectonic quiescence was punctuated by at least one minor episode of renewed extension, most likely in the Eocene. The Oligocene sedimentary record in northern New Zealand and the Southwest Pacific is very abbreviated, being characterised by a major unconformity and/or condensed sequence. The same appears to have been true for the Reinga Basin where the same strong regional reflector associated with the hiatus in New Zealand is a widespread marker. Although the reflector appears mainly to define a thin paraconformable sequence, locally (along the basin margins) it might be the base or top of a measurably thick Oligocene section.

In the Early and Middle Miocene, clastic sediment infill dominated in the basin, with sediments coming from a number of possible sources, including emergent ridges to the north and west, the Northland Allochthon, and the volcanic arc. Clastic sediment progradation has apparently been continuous off the Northland coast from the Miocene to the present, but the ridges to the northwest had almost all submerged by the end of the Miocene, ending the sediment supply there. Their submergence must have allowed pathways for oceanic circulation between Tasman and Pacific water masses to develop and deepen, because Late Miocene and later sedimentation far from the Northland landmass was dominated by drifts and scours. In the Late Miocene these currents must have been particularly erosive, producing scoured or nondepositional troughs along the flanks of ridges and lateral buildup of dunes or drifts in the basin. With deeper submergence in the Pliocene–Pleistocene, scouring diminished and drift sedimentation became more evenly distributed across the basin.

The buried volcanic features identified in this study in the southeastern part of the basin are possibly a northwestern extension of the Northland volcanic arc. Most of these bodies occur on the mid-Cenozoic regional reflector or in the Lower Miocene sequence. However, several extrusive bodies lie directly under the reflector and could have been active in the Late Oligocene. The Northland arc was probably continuous with the Three Kings Ridge arc in the Late Oligocene – Early Miocene before the ridge had begun to migrate eastwards with the opening of the Norfolk Basin.

Compression in the Early and Middle Miocene modified the extensional and passive geometry of the basin. Asymmetric anticlines, reverse faults, everted basins, and pop-ups are found in all but the southeastern end of the basin. This Neogene deformation is most visible in the marginal ridges which are structurally complex. The Reinga Ridge is a transform boundary with the Norfolk backarc basin. Transpressional deformation, thought to be caused by wrench faulting in the development of the transform, is recorded in folded and faulted Cretaceous–Paleogene sequences and in syntectonic Early and Middle Miocene sequences along its length. The Wanganella Ridge appears to be younger—a mainly early Middle to early Late Miocene, reverse-faulted uplift. To the northwest it is composed of an everted Late ?Oligocene to Early Miocene aulacogen in which basement slivers were upthrust as well. To the southeast it is a more diffuse structure cored by folded sedimentary rocks. Its association with the rather passive, eroded West Norfolk Ridge, which it appears to partly override, is still poorly understood. The latter ridge locally shows mild compression on its western flank.

Pliocene intrusive and extrusive bodies occur in an approximately northeast-trending belt east of the Wanganella Ridge in the northwestern part of the Reinga Basin. Their closeness to the ridge suggests a tectonic origin, but their much later emplacement and alkaline composition favour a hot-spot origin.

Uplift of the Norfolk Ridge in the Oligocene, and of the Reinga Ridge in the Miocene, may have provided a means for terrestrial biota to move from the New Caledonia region to New Zealand.

The Reinga Basin has all the attributes required for petroleum generation, migration, and entrapment.

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