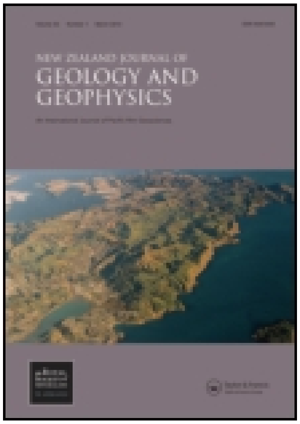

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Post-breakup stratigraphy of the Kaikoura Synthem (Cretaceous-Cenozoic), continental margin, southeastern New Zealand

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Abstract The stratigraphy and structure of the Kaikoura Synthem (Cretaceous–Cenozoic) is synthesised from available seismic records and well reports on the continental margin of southeastern South Island. Four seismic sequences are distinguished, corresponding to lithostratigraphic groups that can also be recognised nearby on land: Matakea Group (Cretaceous), Onekakara Group (late Cretaceous–Oligocene), Kekenodon Group (Late Oligocene–Miocene), and Otakou Group (Miocene–Recent). These sequences achieve maximum thickness within three sedimentary basins underlying the continental shelf (Canterbury and Foveaux Basins) and slope (Great South Basin).

The Great South Basin is separated from the Canterbury and Foveaux Basins across the Waipounamou Fault System, a northeasterly oriented zone of faults which controlled rifting and Matakea Group sedimentation along the western edge of a Cretaceous aulacogen now manifest as the Bounty Trough. The Canterbury and Foveaux Basins contain transgressive sequences (Onekakara Group) that were deposited in response to post-rifting thermal subsidence of the margin. By the mid Cenozoic, land areas were greatly reduced, and at peak transgression there was the development of a widespread Oligocene unconformity (Marshall Unconformity at the base of the Kekenodon Group). Subsidence continued until the Miocene, though punctuated by phases of mild faulting and volcanism in the Paleocene, Middle Eocene and Late Eocene–Oligocene. Regression commenced in the Miocene (Otakou Group), consequent upon uplift of the Southern Alps along the Alpine plate boundary in the west. Crustal deformation attained a climax in eastern Otago in the late Middle Miocene, with substantial volcanism and block faulting.

Keywords New Zealand; continental margin; passive margins; tectonics; Kaikoura Synthem; Canterbury Basin; Great South Basin; Matakea Group; Onekakara Group; Kekenodon Group; Otakou Group; Maori Bottom Group; new stratigraphic names

INTRODUCTION

Rifting between the New Zealand plateau and Antarctica–Australia began in the Cretaceous with the creation of the southern Tasman and Pacific Ocean basins. Spreading occurred along a mid-ocean ridge system which was active between c. 80 Ma ago (Anomaly 33) and 55 Ma ago (Anomaly 24). In the Late Eocene, the spreading ridge in the southern Tasman Ocean was truncated by the linking of an eastward-propogating Indian Ocean ridge and the established mid-Pacific spreading centre. Differential spreading on the Indian and Pacific Ocean segments of the newly continuous southern ocean ridge system then caused the formation of the modern boundary between the Indo-Australian and Pacific plates, now manifest as the Macquarie Ridge complex, Alpine transform fault, and Tonga–Kermadec subduction zone (Hayes & Ringis 1973; Molnar et al. 1975).

This sequence of tectonic events is well reflected in the regional Cretaceous–Cenozoic sedimentary sequences developed in South Island, New Zealand (Carter & Norris 1976; Norris et al. 1978; Kamp 1986), provided the effects of local events such as volcanism, or the controlling influence of basement blocks, are taken into account (Norris & Carter 1982).

With respect to the offshore, a large amount of oil company seismic data is now available from the continental margin southeast of South Island. Data includes that collected on reconnaissance surveys by Mobil (1972) and Gulf (1973), and on more

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detailed exploration surveys in North Otago by British Petroleum (BP) (1974) and in South Otago by Hunt International Petroleum Company (HIPCO) (1971, 1972, 1976). Recent detailed surveys of the North Otago shelf (British Petroleum, Shell and Todd (BPST) 1984) were not available on open file in time for this study.

Stratigraphic control is provided by four exploration holes in the southern Canterbury Basin (Wildig & Sweetman 1971; HIPCO 1978b; Wilson 1985) and five exploration holes in the Great South Basin (Holloway et al. 1982; Carter 1988).

In this paper, a summary is presented of seismic data from the eastern South Island continental shelf, particularly that adjacent to the Great South Basin and its seaward continuation, the Bounty Trough (Fig. 1, 2). Available well control (Fig. 3) is used to relate the offshore seismic stratigraphy to the well-known regional stratigraphy of nearby eastern South Island (Fig. 4 and Table 1). The group level terminology used, which was introduced informally by Carter (1977), is described in more detail in Appendix 1.

SEISMIC STRATIGRAPHY

The continental shelf and slope off Otago and South Canterbury is underlain by geology that is a continuation of that onland (Fig. 4). Apart from the effects of Miocene block faulting, particularly conspicuous off the Taieri River (Fig. 5, upper), and of Late Eocene and Late Miocene volcanic intrusions, conspicuous off Oamaru and Otago/Banks Peninsulas, respectively, the shelf is underlain by flat-lying to gently seawards dipping Cretaceous–Cenozoic sedimentary sequences (e.g., Fig. 5, lower).

The offshore seismic stratigraphy falls readily into four seismic sequences which compare well with lithostratigraphic groups recognised nearby onland (Carter 1977) (cf. Table 1 and Appendix 1). The most conspicuous reflector, apart from the basement unconformity, falls in about the middle of the sequence and is associated with the Early–Middle Oligocene Marshall Unconformity and the overlying greensands and limestones of the Kekenodon Group. Thus, the BP yellow (Dean & Hill 1976; Wilson 1985) and the SEAHUNT upper yellow (HIPCO 1976) reflectors are taken to correspond to the Marshall Unconformity. Since this unconformity marks perhaps the most important Cenozoic stratigraphic event in eastern New Zealand (Carter 1985), it has been used as a reference level in this analysis. In offshore situations, the unconformity coincides with reflector 3, which merges with reflector 4 beneath the upper slope and shelf (cf. Fig. 11, upper). Beneath reflectors 3–4 the transgressive sediments of Onekakara Group successively onlap westwards onto basement; above reflector 4, the eastward-progradational foresets of the Otakou Group are conspicuous. Some fault-angle depressions within the basement are infilled with obliquely stratified sediments interpreted as equivalents to the onland Late Cretaceous Matakea Group fanglomerates and coal measures.

The main reflectors mapped were therefore:

Reflector	Nature
4	Base of (clinoform) Otakou Group
3	Marshall Unconformity (Mid Oligocene)
2	SEAHUNT intra-Eocene horizon
1	SEAHUNT red reflector (near top Paleocene)
C	Top Cretaceous (= top Matakea Group)
Cr	Cretaceous (Matakea Group and equivalents)
B	Basement

THE LIMITS OF THE CANTERBURY AND GREAT SOUTH BASINS

Western and southern edges of the Canterbury Basin

The western edge of the Canterbury Basin follows broadly the eastern foothills of the Southern Alps (A in inset, Fig. 2), along which occur infaulted patches of thin Onekakara Group of marginal marine and shallow marine facies.

In North Otago, the probable paleoshoreline at maximum Onekakara transgression swings gradually from a northeasterly to a northwesterly orientation, concomitant with the sediments lapping onto the basement schist geanticline (Suggate et al. 1978). In the vicinity of Dunedin, the paleoshoreline is only a few tens of kilometres from the coast, extending southwest until it runs into the Murihiku Escarpment on the northern edge of the Southland Syncline (dotted line in Fig. 2).

The Canterbury Basin therefore narrows to the south, and the offshore data combined with the land geology suggest that a distinct Kaitangata Sub-basin, located between the Titri Fault and the Waipounamou Fault System (C, Fig. 2), marks the southern end of the Canterbury Basin. The thick sedimentary fill of the Kaitangata Sub-basin abuts abruptly to the south against a basement high, here named the Nuggets High (Fig. 6).

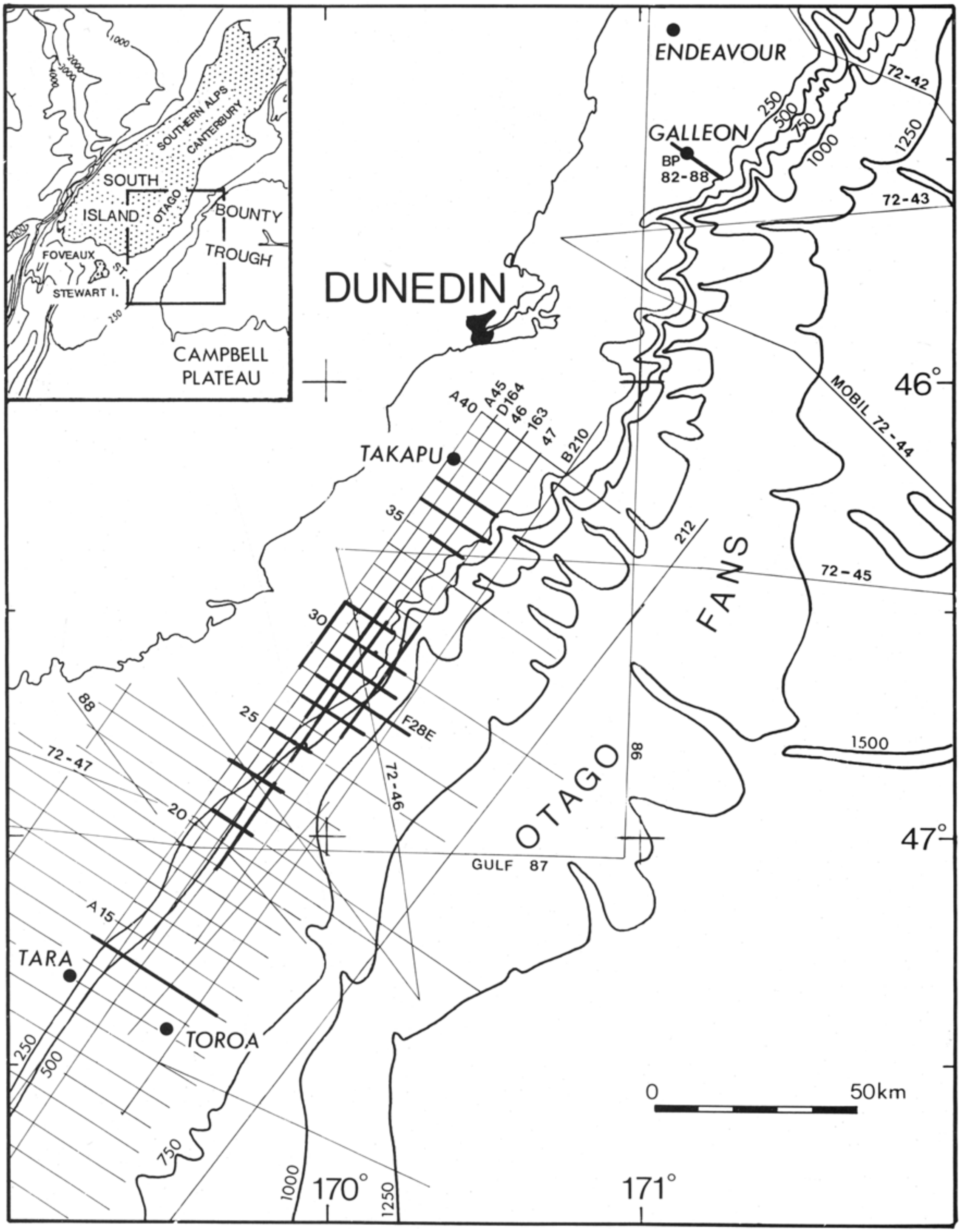


Fig. 1 Bathymetric and locality map, southeastern South Island, showing the location of available seismic cover and wildcat exploration wells. Heavy lines indicate the seismic profiles reproduced in this paper.

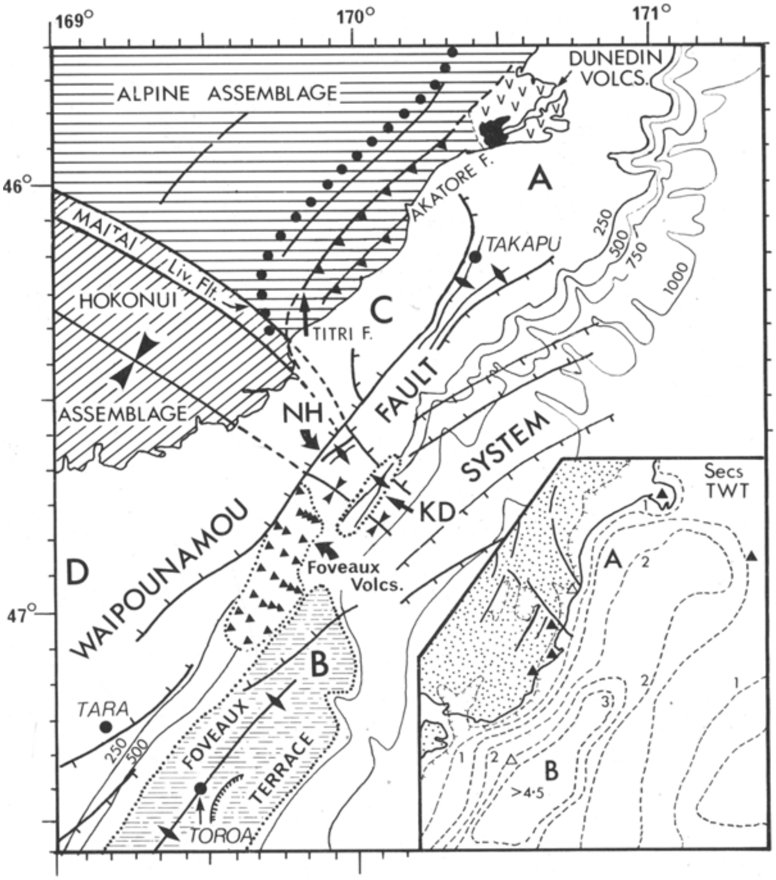


Fig. 2 Structural summary map of the continental shelf off southeastern South Island. Waipounamou Fault System is amended after Ebanks et al. (1979). *Inset:* Isopach map (in seconds of two-way-time) of Kaikoura Synthem sediments of eastern South Island; volcanic centres indicated by triangles (after Davey 1977; Katz 1980).
A = Canterbury Basin; B = Great South Basin; C = Kaitangata Sub-basin; D = Foveaux Basin; NH = Nuggets High; KD = Korora Dome. The heavy dotted line marks the approximate position of the mid-Cenozoic shoreline, at peak transgression.

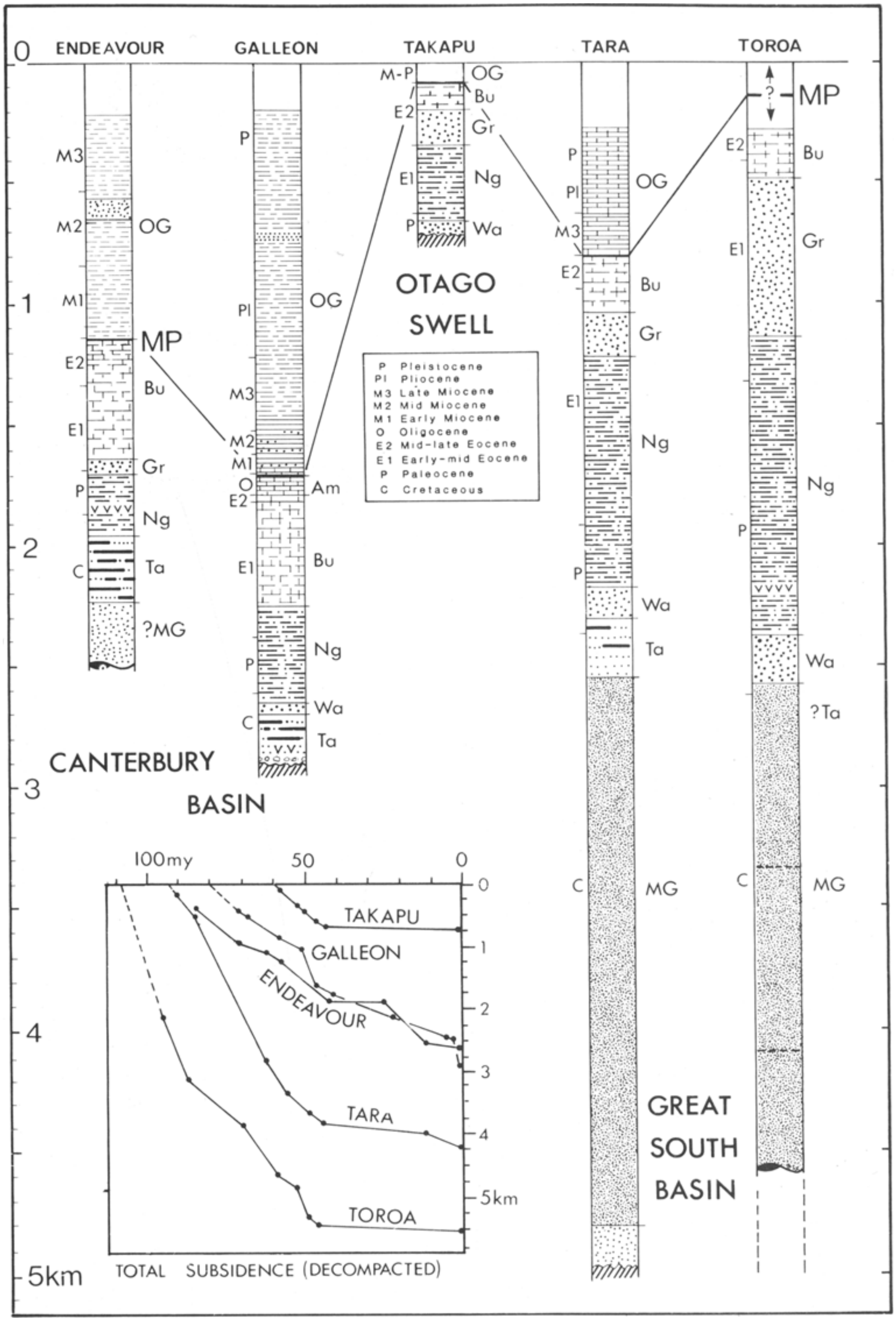
Table 1 Main seismic units recognised on the offshore southeastern New Zealand continental margin.

Unit	2-way travel time (s) Typical	Maximum	Maximum thickness (m) (assumed velocity in brackets)	
Otakou	0.9	c.1.8	2250	(2500 m/s)
Kekenodon	<0.1	<0.1	c.30	
Onekakara	1.2	c.2.0	3000	(3000 m/s)
Matakea	0.5	c.1.0	2100	(4200 m/s)

Relationship between the Canterbury and Great South Basins

Exploration wells in the Great South Basin penetrated a sedimentary sequence homotaxial with that of the Canterbury Basin, though the Great South Basin sequence is thicker, exceeding 8 km in its deepest parts (Holloway et al. 1982). The transgressive sedimentary facies of the Onekakara Group, in

Fig. 3 (*opposite*) Summary logs of available exploration well data from southeastern South Island. MP = Middle Oligocene Marshall Paraconformity.
Ages are indicated by letters to left of each column (key in inset box).
The lithostratigraphy is indicated on the right of each column, as follows: MG, Matakea Group; Ta, Taratu Coal Measures; Wa, Wangaloa Formation; Ng, Ngarara Formation; Gr, Green Island Sand; Bu, Burnside Mudstone; Am, Amuri Limestone; OG, Otakou Group.
Inset: Subsidence curves (corrected for compaction) for each well (method after Sclater & Christie 1980).



ENDEAVOUR
GALLEON
TAKAPU
TARA
TOROA
MP
OG
Bu
Gr
Ng
Ta
?MG
Am
Wa
?Ta
MG
OTAGO SWELL
CANTERBURY BASIN
GREAT SOUTH BASIN
P Pleistocene
Pl Pliocene
M3 Late Miocene
M2 Mid Miocene
M1 Early Miocene
O Oligocene
E2 Mid-late Eocene
E1 Early-mid Eocene
P Paleocene
C Cretaceous
0
1
2
3
4
5km
100my
50
TOTAL SUBSIDENCE (DECOMPACTED)

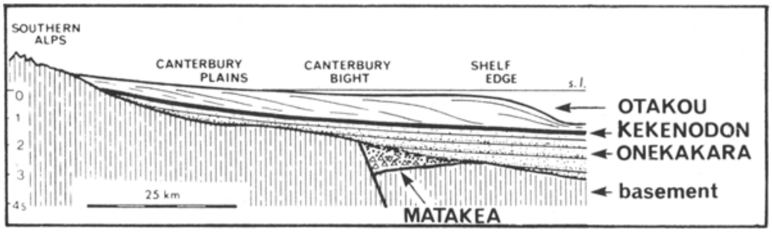


Fig. 4 Summary cross-section for the Kaikoura Synthem (Cretaceous–Cenozoic), Canterbury Basin (after Carter 1988).

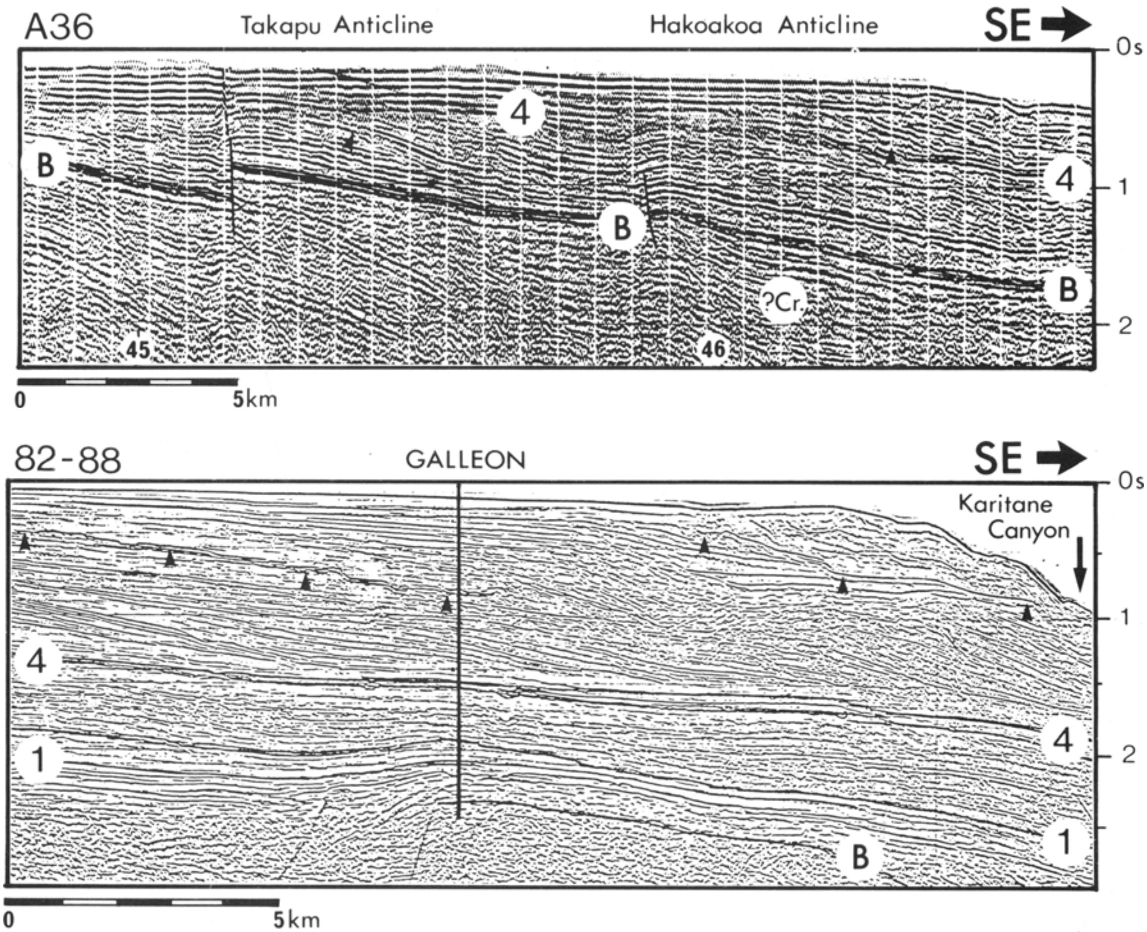
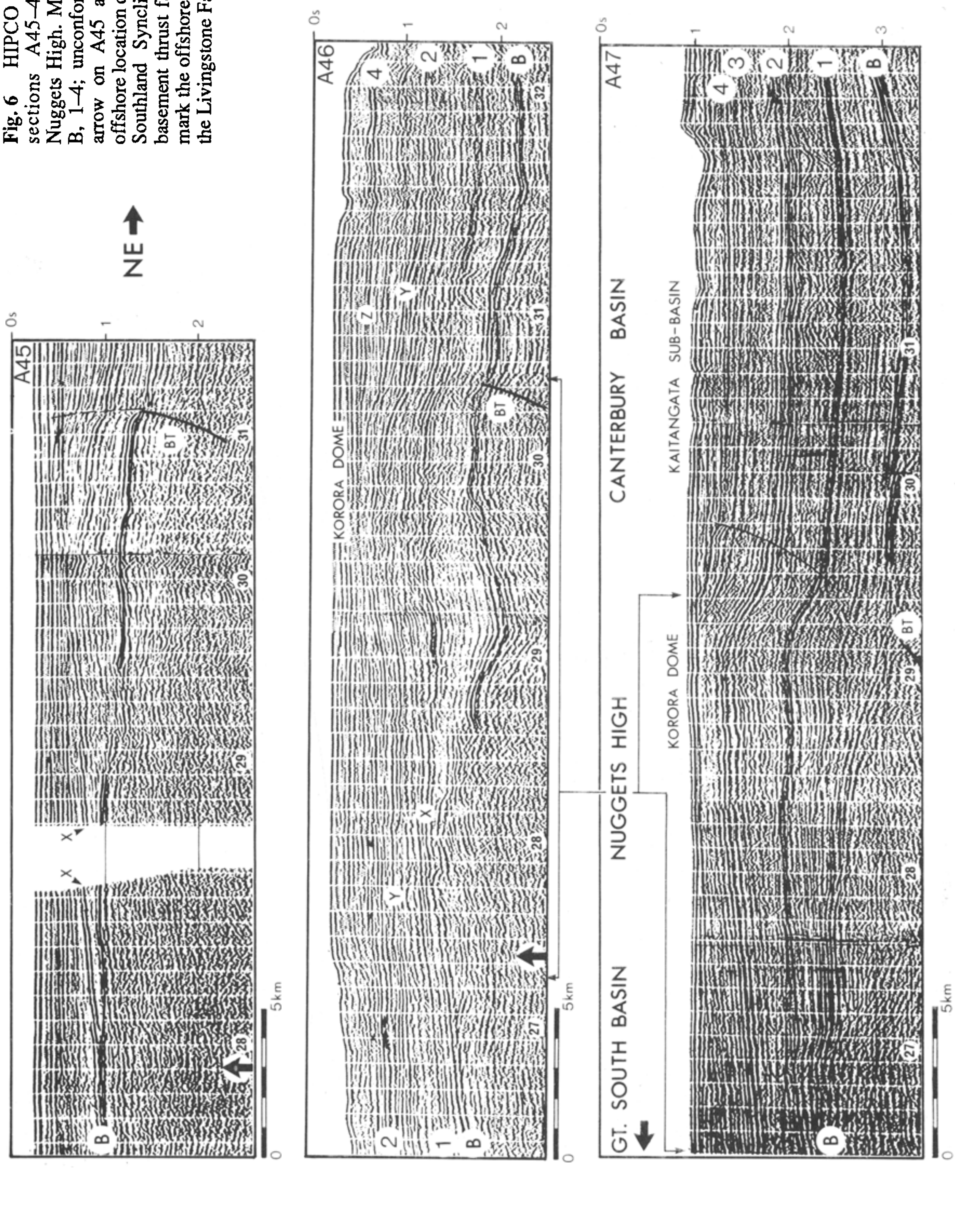


Fig. 5 Typical northwest–southeast profiles through the eastern Otago shelf, south of Dunedin (A36) and north (82–88, migrated profile).
Arrows: A36, indicate position of unconformities present on seaward flanks of Takapu and Hakoakoa Anticlines (see text for full explanation); 82–88, indicate prominent erosional surfaces within foresets of the Otakou Group, which mark earlier positions of the upper slope channels and canyons. Cr indicates Cretaceous sediment.

particular, are closely similar between the two basins (Fig. 3) (cf. Carter 1988).

On the inner shelf, the two basins are separated by the Nuggets High (Fig. 6, 7) which marks the seaward continuation of basement trends onshore (cf. Fig. 2). The high is 15–20 km wide and, at its simplest (Fig. 7), comprises a tilted fault-block, with a steeper scarp towards the northeast which may

Fig. 6 HIPCO deep seismic sections A45–47 across the Nuggets High. Main reflectors = B, 1–4; unconformities = X–Z; arrow on A45 and A46 = the offshore location of the axis of the Southland Synclinorium; BT = basement thrust fault which may mark the offshore continuation of the Livingstone Fault.



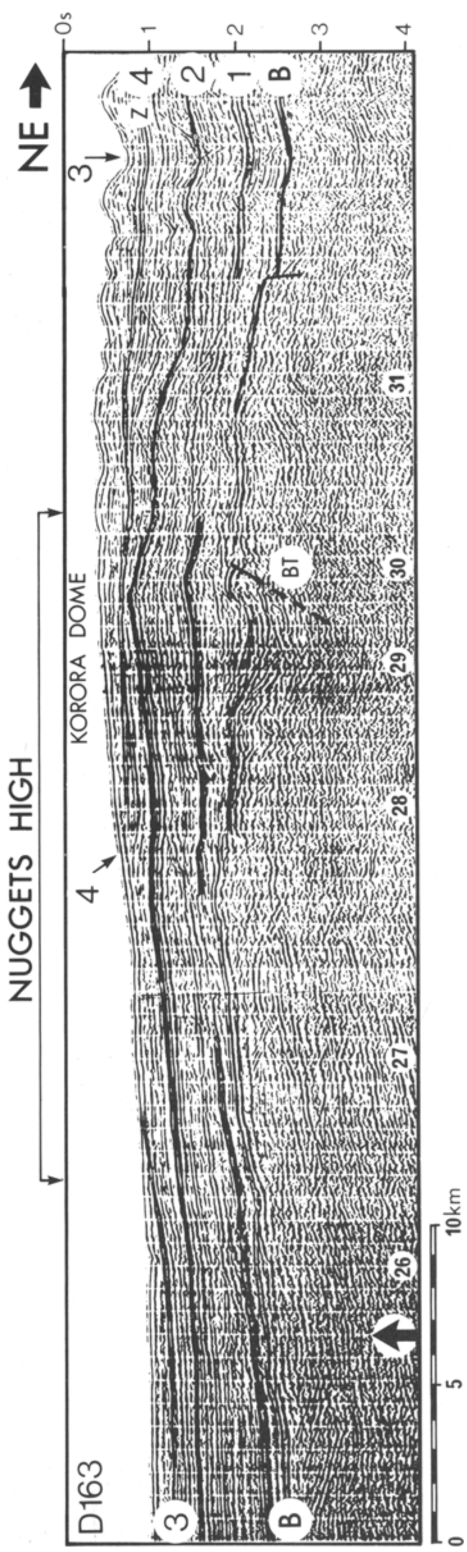


Fig. 7 HIPCO deep seismic section D163 across the Nuggets High. BT = basement thrust fault; arrow = axis of Southland Synclinorium; main reflectors = B, 1–4. (Ignore multiple reflection at c.1 s and line-crossing 31).

mark the offshore extension of the Livingstone–Macpherson Fault System (e.g., Cawood 1986) (cf. Fig. 2). The associated Korora Dome, situated adjacent to the northern side of the high, has formed in response to reverse faulting in the basement; reverse faulting of Kaitangata Sub-basin sediments on the northern limb of the structure is also visible in some profiles (Fig. 6, A47).

Beds of the lower part of the succession lap onto the Nuggets High from both the north and south (Fig. 6). At the southern end of the Canterbury Basin, the Kaitangata Sub-basin comprises a thick sequence (two-way travel time 2s), largely of Cretaceous–Eocene age, which accumulated in a complex graben bounded to the southwest by the Nuggets High and to the northwest by the Titri Fault (McKellar 1966). In contrast, the Onekakara-equivalent sediments of the Great South Basin lap more gradually onto the gently southward sloping face of the Nuggets High from the south.

Neogene sediments (Otakou Group) of the Otago shelf and fan complex encroach the high from the north, but only a thin cover of Neogene sediment exists on the inner shelf (Fig. 6, A45). The high therefore plunges seawards across the shelf, resulting in the continuity of lower and lower stratigraphic horizons between the Canterbury and Great South Basins. The basins merge under the outer shelf and slope.

The Nuggets High has had a complex history, influencing sedimentation from at least the Cretaceous onwards. The faults bounding the Southland Syncline and the high were active before and during the accumulation of the Matakea Group, because Cretaceous sediment is cut out against both fault-blocks on the inner and middle shelf (Fig. 6, A45, A46). Growth of the Korora Dome postdates the Cretaceous Matakea Group and predates the Miocene Otakou Group, because the fold incorporates sediment between the basement and reflector 3 of Late Eocene to Mid-Oligocene age (Fig. 6, A47). The presence of at least two low-angle unconformities within the folded Cretaceous-Paleogene sequence (labelled X and Y on Fig. 6) together with a third unconformity (Z) at the top of the folded sequence, and another recorded nearby onland within the Matakea Group (between Henley Breccia and the Kaitangata Coal Measures: Harrington 1958), suggests that the fold grew spasmodically throughout the Late Cretaceous and Paleogene. The geometry of the fold, and associated faults, is consistent with draping over the basement Nuggets High, resulting from northerly directed

high-angle, reverse faulting on the basement fault, which therefore must have reversed its Cretaceous direction of movement (cf. Mutch & Wilson 1952). Phases of movement are inferred during the Paleocene (unconformity X; Korora-I), Mid Eocene (unconformity Y), and Late Eocene–Oligocene (unconformity Z; Korora-II). The Paleocene phase of movement was accentuated on the inner shelf (Fig. 6, cf. profiles A45 and A47).

Isopach maps of total sediment thickness off the Otago coast (Davey 1977; Katz 1980) show that the thickest sequences in the Great South Basin are located near latitude 47°S. However, sequences several kilometres thick continue on the northeasterly trend of the basin axis as far north as Oamaru (45°30′S) (Fig. 2, inset). This isopach trend is due to the thicker post-Oligocene sediment associated with submarine fans in the head of the Bounty Trough (Carter & Carter, unpub.) rather than the thick Late Cretaceous–Paleogene sediment seen in the Great South Basin itself.

The Waipounamou Fault System

The boundary between the Great South Basin proper and its flexural shoulder runs northeast approximately along the line of the modern shelf edge (Fig. 2). Several previous authors, starting with Menard (1964), have postulated a major fault in this position in order to explain the difference in topographic level between the continental crust of the Campbell Plateau and the main South Island landmass. This suggestion was taken up by Cullen (1967, 1970), who proposed that the fault, named the Waipounamou Fault and interpreted as a right-lateral transcurrent feature, stretched across the New Zealand plateau from the Solander Trough to the Bounty Trough. Summerhayes (1969) adopted a similar interpretation, but suggested that the fault might have major vertical, rather than transcurrent, throw.

The detailed seismic data collected by the SEAHUNT group provide, for the first time, accurate information regarding the position and nature of the Waipounamou Fault (HIPCO 1971, 1972, 1976; Holloway et al. 1982). This information confirms the existence of a major system of northeasterly trending fractures along the general line of the Waipounamou Fault. Rather than forming a single continuous feature, the faults are arranged en echelon to form what is here termed, after Cullen (1967, 1970), the Waipounamou Fault System (Fig. 2).

Individual faults of the Waipounamou system have vertical throws up to 4 km, downthrown to the southeast, and were the controlling features on Cretaceous sedimentation in the Great South Basin (Fig. 8). Many other similar faults occur further southeast within the basin, bounding basement horsts and grabens. These intrabasinal faults generally exhibit lesser throw and more easterly trend than those of the Waipounamou system.

The Waipounamou Fault System constitutes the northwestern margin of the Great South Basin. Early basin-fill sediments form the thick sequences of the "Central Graben" of HIPCO (Holloway et al. 1982), and lap-up to the northwest against the boundary faults. Younger sediments of the Cretaceous–Paleogene transgression overstep the Waipounamou Fault System to form the Foveaux and Canterbury Basins (Fig. 2, inset).

The Waipounamou Fault System can be traced from at least latitude 49°S to latitude 45°50′S offshore from Dunedin. As such, the fault system forms the western side of the Cretaceous aulacogen within which the Great South Basin sequence accumulated (cf. Dixon & Parke 1983); consequently the fault system likely terminates in the head of the Bounty Trough as hypothesised by Cullen (1970).

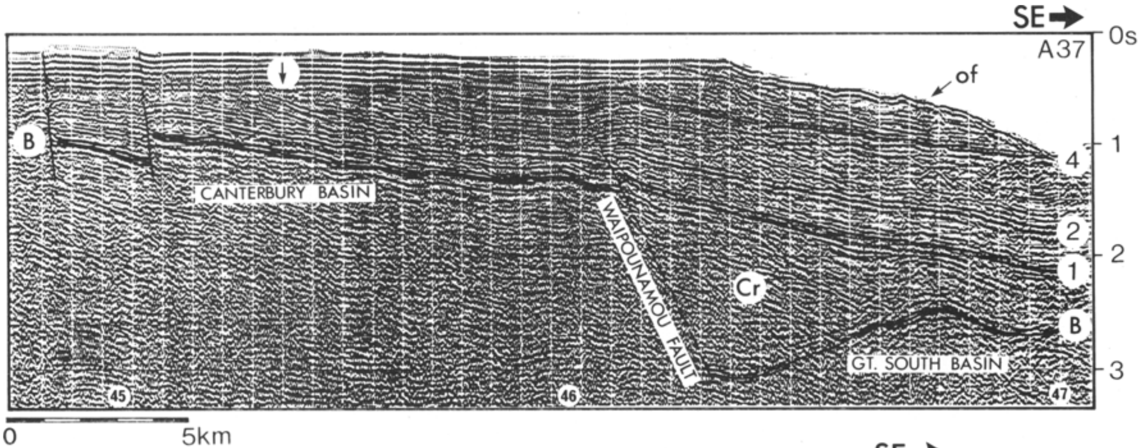
Holloway et al. (1982) have argued for two discrete phases of movement on the Waipounamou Fault System. The phase of extensional tectonics responsible for the formation of the Great South Basin was concentrated in the Early–mid Cretaceous, and had effectively ceased by the end of the Cretaceous. Some time during the middle Cenozoic, however, reactivation occurred, causing gentle uplift, folding, and faulting. This later phase was believed by Holloway et al. (1982, p. 55) to reflect transcurrent movement on Waipounamou faults.

GEOLOGY OF THE NORTHWESTERN MARGIN OF THE GREAT SOUTH BASIN

Seismic stratigraphy

The axis of the Great South Basin trends southwest–northeast beneath the edge of the continental shelf and upper slope. The basin comprises a large half-graben, bounded to the northwest by the Waipounamou Fault System, and contains a fill of Cretaceous–Cenozoic sediment up to 8 km thick (Sandford 1980; Holloway et al. 1982; Carter 1988). Post-Eocene sediment is only thinly developed, comprising a pelagic drape in the east and an eastwards advancing foresetted shelf wedge in the west.

Two well-developed reflectors in the upper part of the Paleogene sequence can be traced regionally,



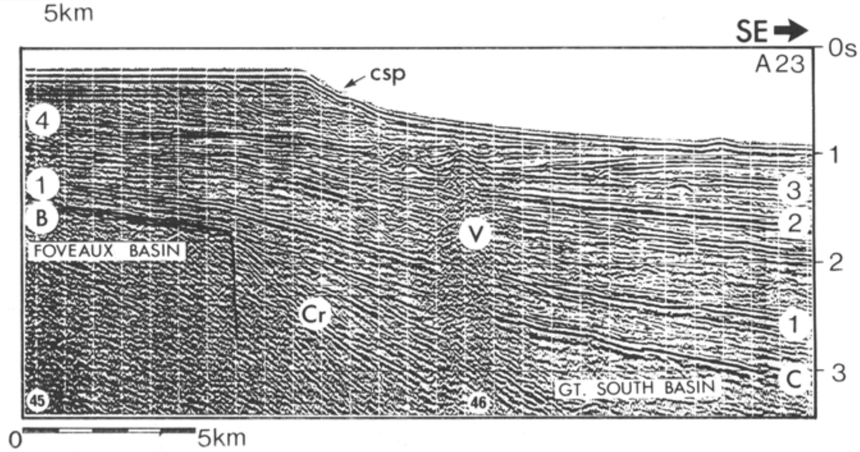


Fig. 8 Typical deep seismic sections across the Waipounamou Fault System. Note the presence of a prograding part of the Otago fan system in the northerly profile (A37, of), compared with simple clinoform slope progradation, with minor slumping, further south (A23, csp). Main reflectors = B, C, 1–4. Arrow on A37 indicates conspicuous intra-Onekakara unconformity at 0.8 s on the seaward flank of the Hakoakoa Anticline.

since they overlap the boundary faults and pass into the Foveaux and Canterbury Basins (Fig. 8). Reflector 1 (equivalent to SEAHUNT's red reflector) occurs near the Paleocene–Eocene boundary in sediments of marginal marine character. Reflector 2 (equivalent to a SEAHUNT intra-Eocene reflector) falls near the top of the Middle Eocene at a stratigraphic level about equivalent to that of the Green Island Formation of the onland Canterbury Basin sequence. Two further reflectors are recognised also: reflector 3, at the Marshall Unconformity (represented offshore by a low-angle, onlap unconformity); and reflector 4 at the base of the regressing Miocene shelf sediments. Reflectors 3 and 4 converge landwards, and merge into one reflector (labelled 4) landwards of about the modern shelf edge.

The relationship between these reflectors, the shelf edge, the Waipounamou Fault System, and the top of basement is illustrated in Fig. 3 and 8. The Foveaux and Canterbury Basins comprise the shoreward continuation of the Great South Basin, and result from overlap of sediment after filling of the axial depocentre was complete. Marine transgression across this shelf-margin was controlled by post-rifting thermal subsidence of the underlying, stretched lithosphere (Fig. 3, inset) (cf. McKenzie 1978).

Foveaux volcanic sediments

A previously undescribed province of igneous intrusion and volcanism occurs along the shelf edge due east of Foveaux Strait (Fig. 8, 9), over an area

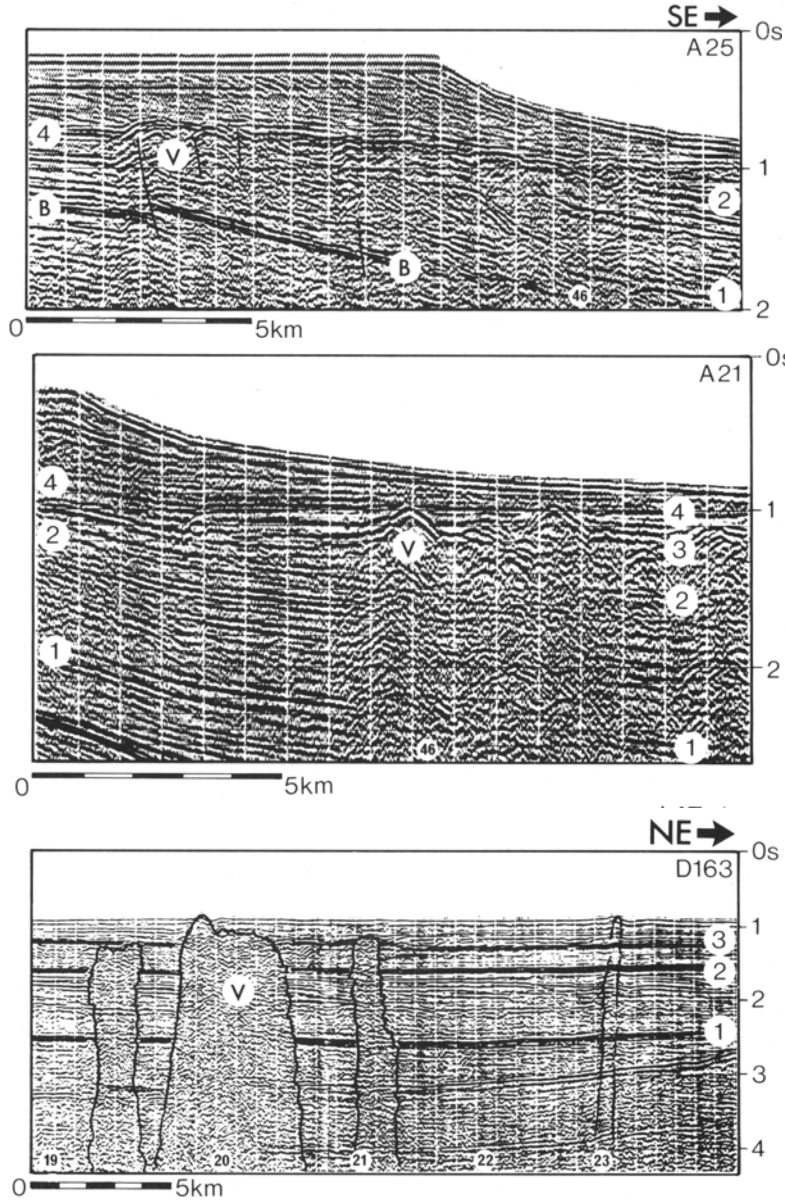


Fig. 9 HIPCO profiles A25, A21 and D163 through the Foveaux volcanic sediments (V). Reflectors = B, 1–4.

about 20 × 50 km. Though some of the volcanics are exposed on the modern seafloor, no dredge samples are available to confirm their identification. Interpretations of the age and significance of the province are therefore based solely on the seismic data.

The Foveaux volcanic sediments show the following characteristics (Fig. 8, 9) :

(1) They intrude Onekakara Group equivalent sediments, clearly cutting or masking reflectors 1 and 2. Therefore they must be younger than Middle Eocene (Porangan).

(2) They occur as individual intrusions or edifices a few kilometres wide, or as groups. Typically, the volcanic bodies have hummocky tops with relief of up to c. 150 m (0.2 s), forming a locally strengthened reflector 3.

(3) The top of the volcanics, and reflector 3, may be (a) buried beneath the regressive shelf wedge, particularly towards the west, when the surface

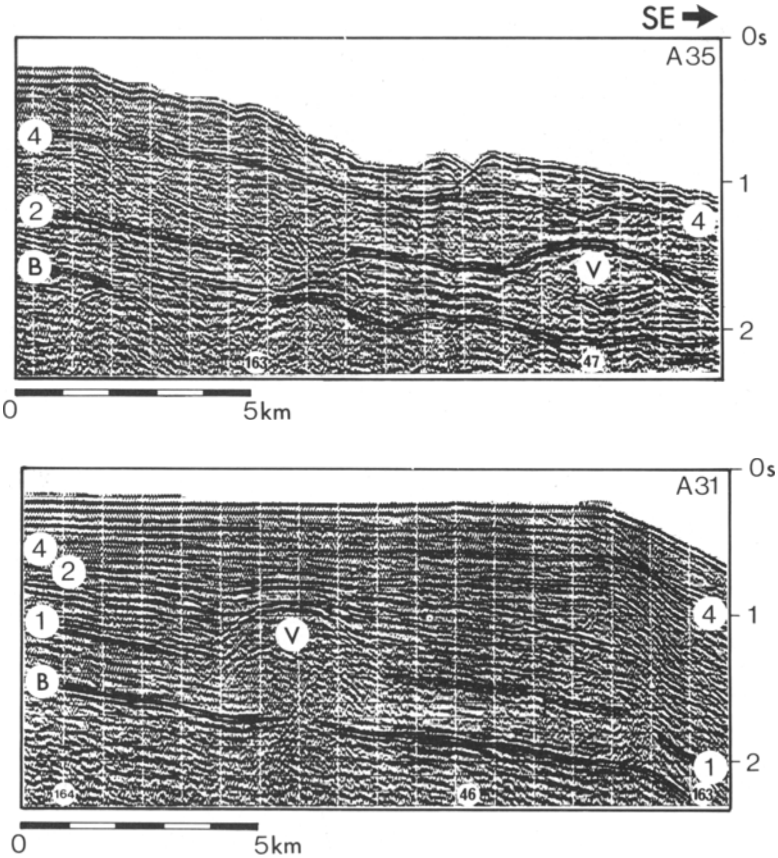


Fig. 10 Isolated ?volcanic bodies (V) of Paleogene age, north of the main area of occurrence of the Foveaux volcanic sediments (HIPCO profiles A35, A31). Reflectors = B, 1–4.

becomes coincident with reflector 4 (Fig. 9, A25); (b) separated from reflector 4 by a draped lens of mid-Cenozoic sediment, particularly towards the east (Fig. 9, A21); or (c) exposed at the seafloor where sedimentation has been insufficient to bury the volcanic pinnacles (Fig. 9, D163). These relations show that some of the intrusions reached the contemporary seafloor, forming volcanic edifices which have since been variously modified by submarine erosion and/or buried by younger sediment.

The volcanics were probably emplaced in the Late Eocene–Oligocene, which was a time of widespread submarine volcanism over the New Zealand plateau (Schofield 1951; Suggate et al. 1978). Other isolated strong reflectors suggestive of igneous sills or dikes occur north of the volcanics, particularly beneath the outer shelf and slope north of the Nuggets High (Fig. 10). These occurrences are slightly lower in the stratigraphic sequence and may be of Middle Eocene age.

Late Middle Miocene tectonism

A pattern of Late Miocene block-faulting and folding similar to that which occurs onshore is evident on the Otago continental shelf. Two subparallel reverse faults, upthrown to the east, occur about 30 km seawards of the Akatore Fault (Fig. 2, 5). In each fault the upthrown basement block has produced an asymmetric, shorewards-facing anticline in the overlying Cretaceous–Cenozoic sediments. The faults and associated anticlines can be traced for c. 50 km.

The most inshore structure, the Takapu Anticline, has been the site of an exploration well (HIPCO 1978b). The *Takapu*-1 well encountered the Marshall Unconformity 120 m below the seabed, then traversed a thin sequence of Onekakara Group to terminate in schist basement at –759 m (Fig. 3). A single sample of Caversham Sandstone (lower Otakou Group) was collected from above the paraconformity, confirming that the folding postdates the Early Miocene. However, seismic line A36 (Fig. 5) shows (1)

clinoform Otakou Group sediment downlapping onto the seaward limb of the Hakoakoa Anticline; and (2) angular discrepancy within the Onekakara Group sediments on the seaward limb of the Takapau Anticline (arrowed). These facts suggest that, like the Nuggets High, the Takapu and Hakoakoa structures formed in response to reactivation along basement faults. The faults were last active during the late Middle Miocene (cf. the reverse faulting of this age associated with the nearby Dunedin volcano; Benson 1968). However, at least one earlier phase of folding occurred, probably in the Late Eocene and possibly the same Korora-II phase already inferred for the Korora Dome.

Korora Dome

Further south, adjacent to the northern edge of the Great South Basin, similar reverse-fault bounded anticlines underlie a seafloor bulge associated with the Korora Dome (Fig. 6, 11). The northern end of this dome coincides with the seaward continuation of the thrust fault (Livingstone–Macpherson suture) bounding the northern side of the Nuggets High, and falls between lines A30 and A29 of Fig. 11.

Korora Dome is northeasterly oriented and about 20 km long and 8 km wide. The major anticlinal fold comprising the northern end of the swell bifurcates into two gentle, broad anticlines further south. As for the Takapu and Hakoakoa structures (and for the northeastward dipping flank of the dome itself), the major phase of folding took place along a northeast axis as a response to reverse faulting of the basement, and involves the entire Onekakara Group. The upper (Late Eocene) parts of the folded sequence are eroded off the flanks and top of the dome, the northern crest of which exposes, at the seafloor, sediments at and just below the level of reflector 3. Small lenses of sediment younger than reflector 3 lap onto the sides of the high, and, on the landward side, are themselves overlain by reflector 4 sediments and its superposed shelf wedge (Fig. 11, especially A28).

Because the Korora structure lies under the lower continental slope, it possesses little sediment cover and displays well the relationship between deeper, off-shelf sediment drapes and the inferred Eocene–Oligocene unconformity that caps the folded sequence. The terrigenous sediment wedge derived from the East Otago canyon-fan complex laps onto the Korora swell from the north (Fig. 7, sediments above unconformity Z), confirming that the last phase of movement on the structure (Korora-II) took place prior to the late Neogene, probably during the Late Eocene–Early Oligocene.

Toroa Anticline

Further south and just seawards of the edge of the continental shelf occurs a gentle 30 km wide anticline on which was drilled the *Toroa*-1 exploration well (Fig. 2, 3, 12).

Toroa Anticline, like the anticlines further north, is a relatively young feature and formed in response to Cenozoic reactivation of basement faults. Because the structure occurs above the thickest part of the Great South Basin, the details of the deeply buried basement faults are not clear. Holloway et al. (1982) mapped them as of high-angle reverse nature, and interpreted a seafloor irregularity on the eastern side of the anticline as evidence for Recent minor fault displacement.

The seafloor feature on the eastern flank of the Toroa structure is better interpreted as a seafloor mass-failure rather than a Recent fault. Scrutiny of the available seismic cover suggests that a thin layer of Oligocene–Miocene sediment progressively onlapped the high from the seaward side, later failing by slumping (Fig. 12). Also, none of the deep-seated faults associated with the Toroa Anticline continue into strata higher than Upper Eocene. The only faults that cut younger sediments are small, superficial structures that are probably associated with incipient slumping.

Ebanks et al. (1979, p. 100) interpreted the Toroa structure as "formed over the basinward lip of a tilted fault block during the Mio–Pliocene Kaikoura orogeny". Holloway et al. (1982, p. 55) preferred to interpret the anticline as forming in response to a phase of dextral strike-slip faulting that affected the northwestern flank of the Great South Basin in post-Oligocene time. Thus, in terms of the known regional timing of phases of folding, both groups of authors apparently adopt a Late Miocene (Kaikoura) age for the deformation, despite their differing interpretations regarding its style.

A Late Miocene age cannot be disproved from the available data, but an Eocene–Oligocene age is more probable, for the following reasons.

1. The Toroa structure differs in size, style, and area of occurrence from the smaller folds associated with basement reverse faulting of the eastern Otago late Middle Miocene phase of tectonism. I agree with Holloway et al. (1982) that the fold is similar in style to those produced in strike-slip terrains, and note that the Waipounamou Fault System could have been subjected to strain of this type during the Late Eocene–Oligocene plate adjustments in the

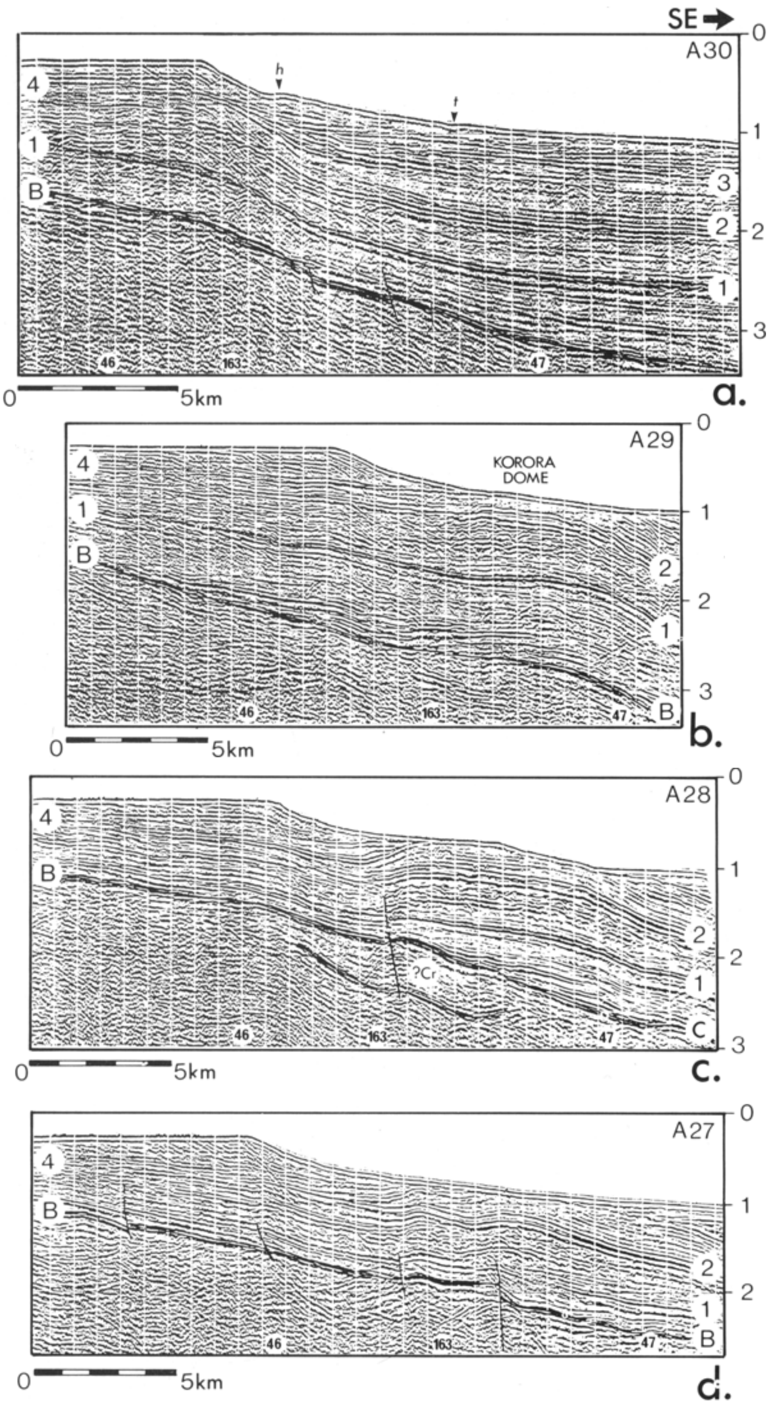


Fig. 11 Successive deep seismic profiles across the Korora Dome and Nuggets High; reflectors = B, 1–4. **(a)** Profile A30 just north of the Korora Dome; note the relatively thick cover sequence of the Kaitangata Sub-basin, with landwards overlap of post-reflector 3 offshore pelagic facies (h, t = head and toe of slump-mass on slope). **(b)** Profile A29 through northern end of Korora Dome; note the thick Cretaceous–Eocene sequence of the Kaitangata Sub-basin. **(c)** Profile A28 through the centre of the Korora structure; note that folded Eocene strata are exposed at the seafloor, and are onlapped from landwards and seawards by post-Eocene sediment. **(d)** Profile A27 through the southern end of the Korora structure, above the Nuggets High; note the great thinning of the sediments below reflector 1 (Paleocene), and that the Korora structure has graded into a double anticline, consequent upon reverse faulting in the basement.

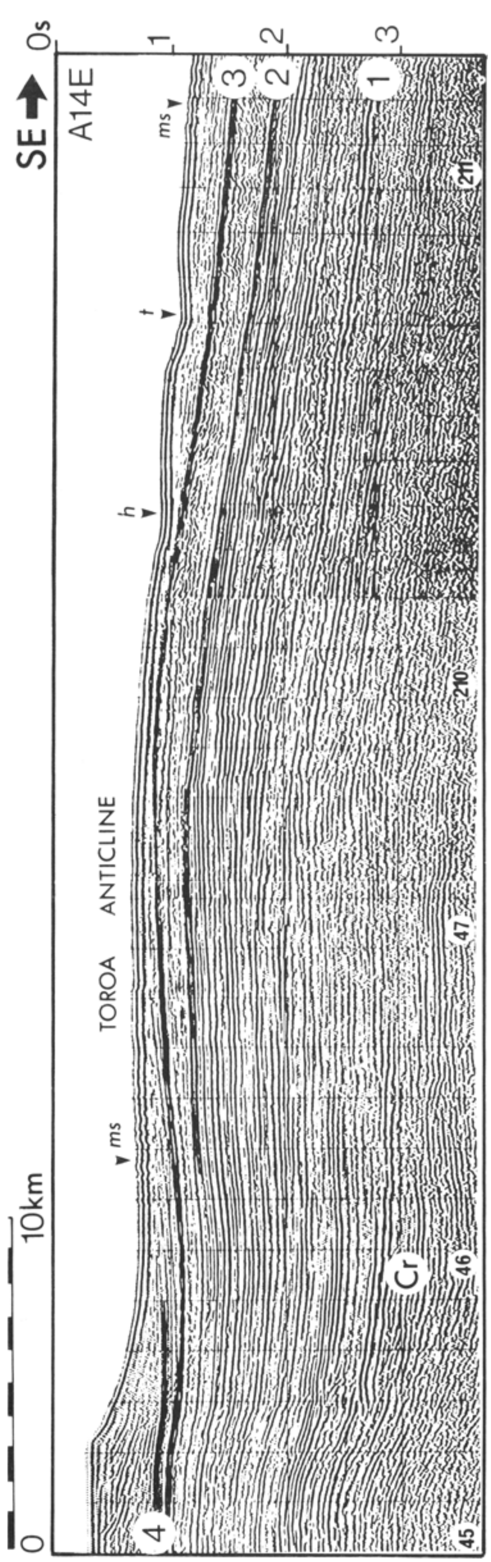


Fig. 12 Northwest–southeast profile through the Foveaux shelf-edge and the Toroa Anticline; note the folded Cretaceous–Late Eocene sequence, capped by the Marshall Unconformity (reflector 3) and onlapped from the east by post-MP biopelagic sediments and from the west by clinoform shelf calcarenites. (h, t = head and toe of large slide-mass on the eastern side of the anticline; ms = areas of minor seafloor slumping).

region. Similar "inversion-of-relief" folds were produced during mid-Cenozoic deformation adjacent to the Alpine Fault on the West Coast of the South Island (Gage 1949).

2. The Foveaux volcanism, and faulting/folding described above for the Nuggets High and the Takapu Anticline, provide independent evidence for structural instability prior to that of the late Middle Miocene.
3. The youngest horizon affected by the folding is reflector 3, which is probably the offshore manifestation of the Marshall Unconformity and therefore of Oligocene age. The eastern flank of the Toroa Anticline is quite clearly onlapped from the east (oceanwards) by post-reflector 3 sediments (Fig. 12). Well control demonstrates that these sediments are of Oligocene age where they have their thickest accumulation, about 70 km SSE of Toroa. Depending upon the rate of landwards overlap, sediment as old as Middle–Late Oligocene could overlap the Marshall Unconformity on the Toroa Anticline, which must then be Late Eocene–Early Oligocene in age.

The timing of the Toroa phase of folding has important implications for the maturation and migration of hydrocarbons.

The regressive shelf prism and offshore plateau drape

The late Middle Miocene Kaikoura phase of volcanism, reverse faulting, and associated folding was followed by largely quiescent conditions in southeastern South Island.

The Foveaux Basin sequence is capped by only a thin cover of regressive shelf sediments derived from the west. The offshore portions of this shelf wedge, penetrated by the *Tara*-1 well (Fig. 3), comprise 700 m of shelly, bryozoan-foram chalks of outer shelf and upper slope facies and Late Pliocene and Pleistocene age (Mangapanian–Nukumaruan). The short, irregular foreset reflectors mark earlier positions of the prograding slope and pass seawards into long uniform reflectors which drape the sediment-impoverished seafloor further east (Fig. 11, 12). Despite being a cold-temperate bioclastic carbonate platform, the edge of the Foveaux shelf is prograding seawards at rates of 3 km/Ma, associated with vertical sediment accretion at the *Tara* wellsite of 24 cm/ka (Table 2).

The regressive shelf wedge capping the Foveaux Basin is continuous, at least at the modern seafloor,

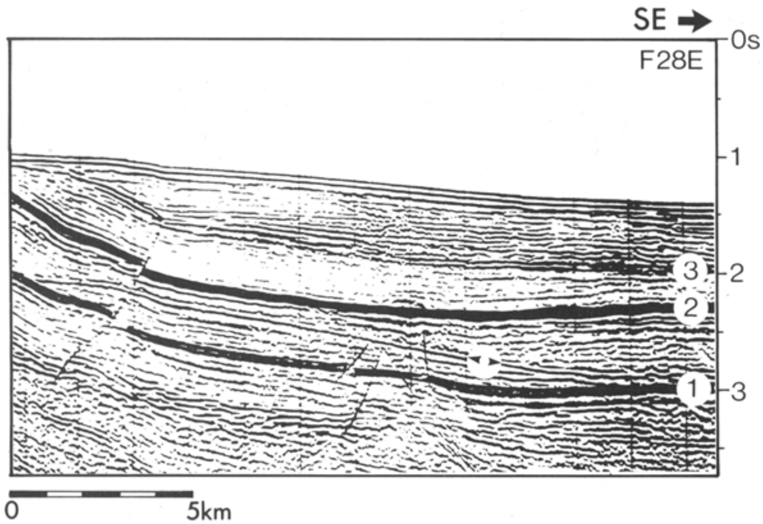


Fig. 13 Detail of profile F28E, showing successive onlap of post-reflector 3 (Oligocene) sediments onto the southeastern flank of the Korora Dome. Ignore the multiple reflection (arrowed).

Table 2 Shelf-edge progradation rates and post-Oligocene sedimentation rates, Otago–Canterbury shelf. Rates assume regression started at 25 Ma B.P. in the Early Miocene.

Location	Width (km)	Rate (km/Ma)
Shelf progradation rates		
Shelf off Rangitata River	122	4.9
Shelf through *Endeavour* well	68	2.7
Shelf through *Galleon* well	48	1.9
Shelf off Palmerston	37	1.5
Shelf through *Takapu* well	55	2.2
Shelf through *Tara* well	74	3.0

Vertical sediment accumulation rates	Thickness (km)	Duration (Ma)	Rate (cm/ka)
Endeavour well transect			
Slope foresets	0.7	6(Pl–Sw)	12
Shelf topsets	0.45	12(Tt–Rec)	3.7
Galleon well transect			
Slope foresets	1.25	8(Sw–Wo)	16
Shelf topsets	0.4	4(Wo–Rec)	10
Takapu wellsite	0.1	7(Po–Sw)	1.4
Tara wellsite			
Average value (?mostly foresets)	0.49	2(Wm–Rec)	24.5

with that of the Canterbury Basin further north. The wedge is thinnest in the region of the Nuggets High. The base of the wedge, recognised as seismic reflector 4, is generally coincident with the Marshall Unconformity (reflector 3) across the shelf. Further east, on the slope and western parts of the Campbell Plateau, reflectors 3 and 4 diverge. Pelagic drape above the reflector 3 successively onlaps landward (Fig. 12, 13), whereas the westerly derived clinoforms above reflector 4 downlap seawards (Fig. 8, 9, 12), implying that both reflectors mark low-angle unconformities.

On the continental slope, sediments above reflector 3 thicken seawards, a consequence of the successive landwards overstepping by the main Campbell Plateau pelagic sediment drape. Thus offshore, reflector 3 (as the Marshall Unconformity) separates Oligocene–Miocene pelagic drape from similar biopelagic sediment at the top of the Late Eocene transgessive sequence. These Late Eocene–Early Oligocene chalks mark the offshore phase of the Onekakara Group, as seen, for example, in the *Kawau*-1 and *Hoiho*-1 exploration wells (HIPCO 1977, 1978a; Carter 1988).

The Otago–Canterbury continental shelf (including adjacent coastal plain) varies in width from about 37 km, just north of Dunedin, to 122 km offshore from the mid-Canterbury Plains. The shelf is underlain throughout by Otakou Group clinoforms, regression commencing about 25 Ma ago in the Early Miocene. Rates of seaward progradation of the shelf-edge therefore range between 1.5 and 4.9 km/Ma (Table 2). Wellsite information from *Endeavour* and *Galleon* (Fig. 1, 3) indicates that vertical accumulation of slope clinoforms (mostly siltstone) takes place at 12–15 cm/ka. Topset accumulation is markedly slower and lessens landward of the shelf edge, with *Endeavour* having a rate of 3.75 cm/ka and *Galleon* 10 cm/ka. Thus it appears that massive shelf bypassing is taking place

for finer grained sediment. Wave and current regimes must be such that constant winnowing of terrigenous mud occurs on the outer shelf, thus reducing topset accumulation rates and accentuating the bioclastic component of topset sediments. The further inshore a site is located, the more effective will be wave and storm-driven resuspension (cf. Carter & Herzer 1979), and hence the lower the topset sedimentation rate. Even lower topset sedimentation rates occur where the shelf has been subjected to recent uplift, for instance the 1.4 cm/ka rate at Takapu (Table 2).

REGIONAL IMPLICATIONS

Subsidence models

Subsidence curves for the five available offshore exploration wells in the region studied are presented as an inset to Fig. 3, calculated following the method outlined by Sclater & Christie (1980). The subsidence curves point to an origin of rifting in the Late Cretaceous, between about 110 and 90 Ma ago, in accordance with regional models of the development of the Kaikoura Synthem. Sedimentation commenced later in wells which are situated landwards of the basin-margin fault zone, in accordance with flexural subsidence of the rift shoulder during post-rift cooling.

The pattern of subsidence is not that of a single, simple cooling curve, as reported for several other sedimentary basins (e.g., Steckler & Watts 1978; Keen 1979; Sclater & Christie 1980). Though subsidence decreases through time for all wells, the pattern is suggestive of two superposed heat-decay curves, commencing in the Late Cretaceous (c. 100 Ma ago) and Late Eocene (c. 60 Ma ago), respectively. There is widespread evidence of Late Eocene volcanism in the New Zealand region. Occurrences include the Oamaru volcano (Gage 1957), the Cookson and other volcanics of North Canterbury (Schofield 1951), part of the Kekerione Group of the Chatham Islands (Suggate et al. 1978), and the Lalitha Pinnacle and associated volcanics on the Lord Howe Rise (Kennett et al. 1985). Whereas the earlier phase of subsidence clearly relates to initial rifting of the eastern New Zealand margin, the rejuvenation of subsidence seen in most wells in the Late Eocene may rather reflect a second deformation and heating event that is manifested also by volcanic sequences of that age.

The period between 40 and 20 Ma ago, during which all wells except *Galleon* show a plateau in their overall subsidence, coincides with nondeposition at the Marshall Unconformity.

Plate tectonic models

The relationship between local geology and regional plate tectonic models for southern New Zealand has been discussed by Carter & Norris (1976), Norris et al. (1978), and Kamp (1986). The conclusions of this paper are consistent with the major premises of these earlier models:

(1) Rifting of the Tasman and Southern Oceans in the Late Cretaceous; formation of the Bounty and Great South Basin aulacogens; rapid sedimentation on thinned, heated, block-faulted lithosphere (Matakea Group).

(2) Relaxation of the thermal anomaly in the lower lithosphere, with flexural subsidence of the adjacent rift-shoulders and marine transgression; subsidence rates decrease up until the Late Eocene (Onekakara Group).

(3) Late Eocene propogation of the Australia–Antarctic spreading ridge from the Indian Ocean to the southern Tasman Ocean, cutting off the Tasman spreading ridge and linking with the mid-Pacific rise; associated rifting in western New Zealand and widespread submarine volcanism (Foveaux-Oamaru-Canterbury volcanics) and faulting on reactivated basement faults (e.g., Nuggets High); increased subsidence rates, leading to peak submergence of the New Zealand plateau in the Middle Oligocene and development of the Marshall Unconformity.

(4) Transcurrent movement on the new Alpine Fault plate boundary through New Zealand, due to the Indo-Australian plate moving north at a faster rate than the Pacific plate; accompanying uplift of mountain belts in western South Island along transpressive segments of the fault, shedding copious sediment eastwards to the Canterbury Basin (minor transcurrent movement on fault-systems subparallel to the regional strain, e.g., the Waipounamou Fault System, with production of the Toroa and other anticlines); accompanied and followed by Otakou Group Otago–Canterbury shelf regression.

(5) Major change in pole of spreading in late Middle Miocene (c.10 Ma ago), leading to increased component of thrusting across the Alpine Fault with concomitant uplift, crustal instability, and increased sediment supply (volcanism at Otago and Banks Peninsula, associated reverse faulting on reactivated basement faults, and deposition of Maori Bottom Group gravels).

PETROLEUM PROSPECTS

Exploration in the offshore Canterbury Basin was considerably dampened by the results of the *Resolution*-1 exploration well, located south of Banks Peninsula (BP 1975). Dean & Hill (1976), summarising the available exploration results, argued that eastward-moving waters within gravel aquifers flushed hydrocarbons from the sequence. Furthermore, the sequence is only marginally mature (R_0-max = 0.6 at 2475 m in *Resolution*-1 and 3080 m, a little above basement in *Endeavour*-1).

Although these arguments may apply to large areas of the nearshore Canterbury Basin, they are not valid where thicker sequences occur in regions protected from aquifer flushing. These occurrences include fault-bounded grabens on the shelf, and, more importantly, the thicker sequences that occur near the shelf-break, above and beyond the line of the Waipounaumou Fault System (cf. Dean & Hill 1976; Herzer 1981). Furthermore, regional heat flow and, hence, maturity, will have varied markedly near the known occurrences of Eocene–Oligocene or Late Miocene intrusives (cf. Norris 1981). The recent discovery of noncommercial gas-condensate in *Galleon*-1 (190 STB/D condensate and 2.2 mmSCF/D gas through a 1/4 inch choke; Wilson 1985) confirms that the Canterbury Basin is prospective.

The knowledge that the Canterbury (and Foveaux) Basin represents the landward overlap of the Great South Basin is significant also, because of the favourable hydrocarbon prospects that occur in the Great South Basin (Ebanks et al. 1979; Sandford 1980; Holloway et al. 1982). Given the terrestrial organic provenance and, therefore, gas-prone nature of most New Zealand source rocks, the occurrence of oil-prone sources above the main gas reservoirs in the *Kawau*-1a well in the Great South Basin is of special importance (Ebanks et al. 1979), as is the up-dip migration from the basin axis implied by the oil seep at Leask Bay, Stewart Island (Cook 1982).

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APPENDIX 1

Stratigraphic nomenclature of the Kaikoura Synthem, eastern South Island, New Zealand

HIGH LEVEL CLASSIFICATION

New Zealand's geological history is represented by three major rock groupings, each separated by regional and generally angular unconformities. In recognition of this, Carter et al. (1974) introduced the terms Tuhua, Rangitata, and Kaikoura Sequence in description of the respective sets of unconformity-bounded strata, following the earlier example of Sloss et al. (1949) and the recommendations in International Subcommission on Stratigraphic Classification (ISSC) (1971).

Chang (1975), in a comprehensive discussion of unconformity-bounded units, recommended that the term "synthem" be used for them instead of "sequence". Since Chang's recommendation has now been adopted internationally (ISSC 1987), the correct designation of the three major New Zealand rock groupings is Tuhua, Rangitata, and Kaikoura Synthems.

LITHOSTRATIGRAPHIC SUBDIVISIONS OF THE KAIKOURA SYNTHEM

Previous usage

The widely scattered nature of stratigraphic studies in eastern South Island has not encouraged the use of a regional lithostratigraphy, not least because the local "stage" classification has usurped many of the functions that would be served more properly by an adequate lithostratigraphy (cf. Grantz 1969).

Many investigators have proposed suites of lithostratigraphic names for use in geographically small parts of the Canterbury Basin, such that by the mid 1970s more than 120 names had been proposed for a suite of transgressive-regressive lithofacies that can be mapped adequately using about 14 regional formations (cf. Fig. 14). Unfortunately, rather than consolidating this situation by gathering existing formations into meaningful groups based upon sedimentary genesis, recent workers have continued to add new lithostratigraphic names apace (e.g., Gage 1970; Ward & Lewis 1975; Warren & Speden 1978; Browne & Field 1985).

A five-group classification

It has been established since the nineteenth century that the Kaikoura Synthem in the Canterbury Basin comprises a grand transgressive-regressive cycle of Cretaceous–Recent age (e.g., Hutton 1874). Since the advent of plate tectonic theory in the late 1960s, the major components of this sedimentary cycle have been related to regional tectonic, sedimentary, and oceanographic controls (e.g., Carter & Landis 1972; Carter & Norris 1976; Norris et al. 1978; Carter & Carter 1982, 1987; Kamp 1986; Kamp & Fitzgerald 1987) leading to the informal proposal of a five-group subdivision of the Kaikoura Synthem (Carter 1977) (cf. Fig. 14, 15). These five groups are readily recognised offshore as well as on land, and therefcre form a convenient framework within which to discuss the geologic evolution of the southeastern New Zealand margin.

Following a suggestion by a referee of the main paper, the five groups and a number of constituent formations are defined formally in this appendix.

MATAKEA GROUP

NAME: After an abandoned term that included the Horse Range breccias of the lower Shag Valley (Hutton 1885).

TYPE: Comprising the Henley Breccia and Kaitangata Coal Measures of Harrington (1958).

OTHER UNITS: Horse Range Breccia, Kyeburn Formation (Bishop & Laird 1976).

DESCRIPTION: Terrestrial breccia-conglomerate, conglomerate, and immature sand, shale, and coal.

AGE: Mid–Late Cretaceous.

INTERPRETATION: Synorogenic and immediately postorogenic fanglomerate and fluvial sediment deposited in basement grabens during initial rifting of the continental margin.

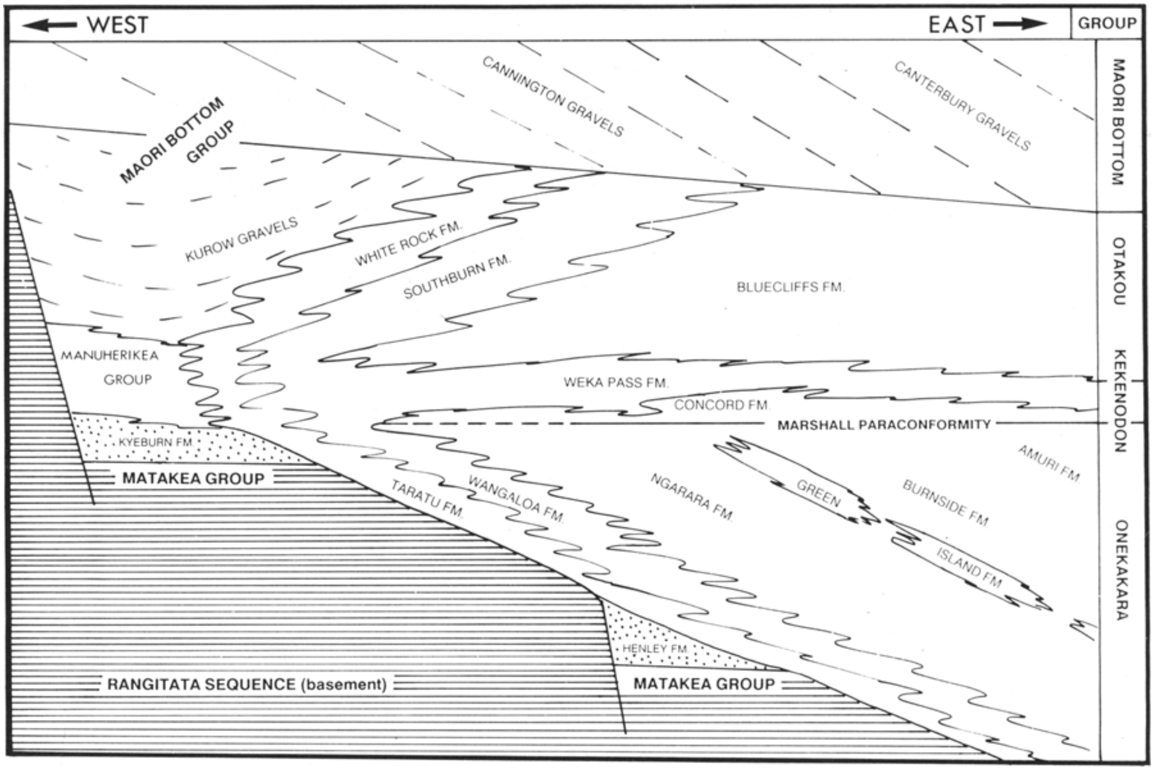

Fig. 14 Schematic east–west cross-section through Kaikoura Synthem, North Otago–South Canterbury (after Carter 1977).

ONEKAKARA GROUP

NAME: After the earliest name used in description of Canterbury Basin sediments, by Mantell (1850).

TYPE: Sediment represented between 3026 and1828 m BRT in the *Galleon*-1 exploration well (Wilson 1985). Another excellent reference section is that in *Clipper*-1 between 4584 m and the Marshall Unconformity at c.2233 m BRT (BPST 1984b).

OTHER UNITS: Encompassing the successive Taratu, Wangaloa, Ngarara, Green Island, Burnside, and Amuri Formations (and their equivalents) of the onshore sequence, as discussed further below (cf. Fig. 15).

DESCRIPTION: Coastal plain coal measures followed by shallow marine and often glauconitic sandstone-siltstone-shale, marl, and biopelagic chalk.

AGE: Late Cretaceous–Early Oligocene.

INTERPRETATION: Paralic and shallow shelf and ramp sediments deposited during a Late Cretaceous–Oligocene marine transgression (Fig. 16), caused by flexural subsidence of the eastern New Zealand margin during post-rift cooling.

KEKENODON GROUP

NAME: After the toothed whale collected from beds at this horizon at Wharekuri by McKay (1882).

TYPE: Comprising the Squires Greensand and Craigmore Limestone of the Pareora district (Gair 1959). The section at Squires Farm also comprises the type locality for the Marshall Unconformity (appendix in Carter et al. 1982), which falls at the base of the Kekenodon Group.

OTHER UNITS: Local greensand and limestone beds which occur immediately above the Marshall Unconformity, named occurrences of which are synonyms of the Concord Greensand and Weka Pass Limestone, respectively (cf. Fig. 15). The thinness of the group makes its recognition difficult offshore, but it is present at depths of 2201–2233 m BRT in *Clipper*-1 (BPST 1984b) and may be represented also at 1815–1828 m BRT in the *Galleon*-1 well (Wilson 1985).

DESCRIPTION: Blanket-like terrigenoclastic-poor greensand and glauconitic calcarenite, often with large-scale cross bedding (e.g., Ward & Lewis 1975) and a calcitic brachiopod-echinoderm-pectinid macrofauna.

AGE: Late Oligocene–Early Miocene.

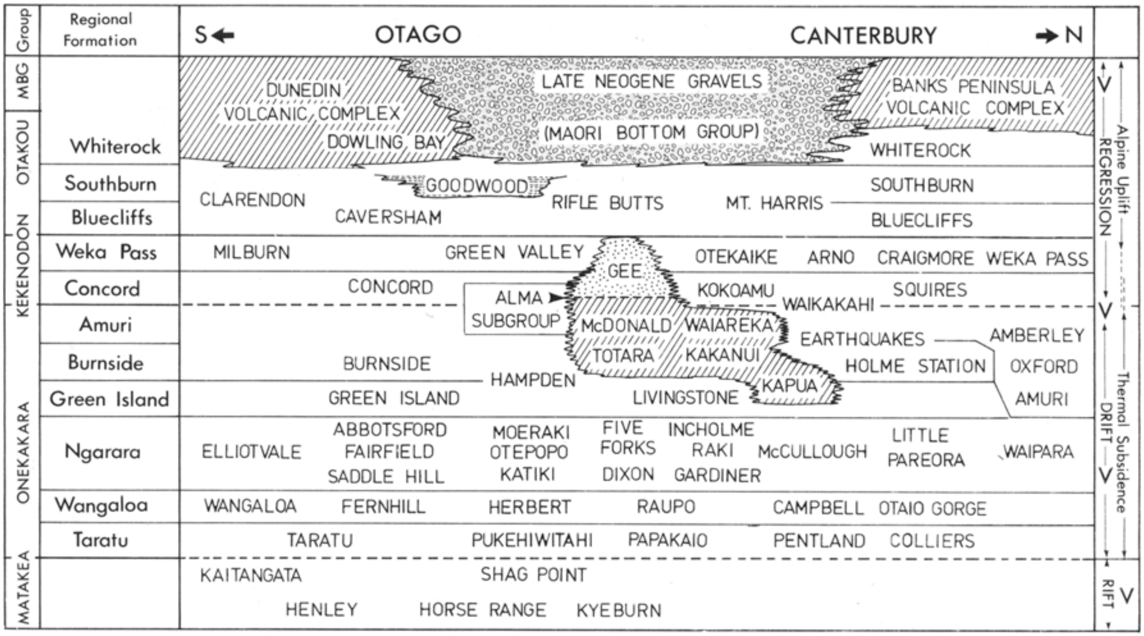

Fig. 15 Summary of a five-group lithostratigraphy for sediments of the Canterbury Basin. Though the formation and member level names in the main body of the figure are viewed as synonyms of the regional formations, they can nonetheless be used for local mapping where necessary.

INTERPRETATION: The Marshall Unconformity, which is a paraconformity in most outcrops, represents an extended pause in sedimentation coincident with peak Kaikoura transgression in the Middle Oligocene. The Kekenodon Group comprises detritus deposited on a shallow oceanic platform swept by erosive bottom currents.

OTAKOU GROUP

NAME: After a Maori settlement on Otago Peninsula, at the suggestion of Professor D. S. Coombs.

SYNONYM: Conway Group (Carter 1977), based on Hector's (1884) name for the widespread east coast "Grey Marls". Abandoned in favour of Otakou Group by Carter & Carter (1982) after the use of Conway Group in a different sense by Warren & Speden (1978).

TYPE: Sediment represented between 2201 m BRT and the seabed in the *Clipper*-1 exploration well, which includes a basal 61 m of sandstone similar to the onshore Caversham Sandstone (BPST 1984b). The same interval is also well represented between 1815 m BRT and the seabed in the *Galleon*-1 exploration well (Wilson 1985). (It is possible some or all of the interval 1815–1828 m BRT, tentatively included above in the Kekenodon Group, should rather be treated as basal Otakou Group.)

OTHER UNITS: Encompassing the successive Bluecliffs, Southburn, and White Rock Formations of the Pareora district (Gair 1959) and their equivalents elsewhere (cf. Fig. 14).

DESCRIPTION: Terrigenoclastic, noncalcareous silt and sand with offshore to intertidal marine faunas, overlain by coastal fluvial and coal measure sequences. Locally, an erosional unconformity may occur between the Otakou Group and underlying strata.

AGE: Early Miocene–Recent.

INTERPRETATION: Otakou Group represents a continental shelf and slope wedge which prograded eastwards as it was fed with sediment from the Southern Alps from the Early Miocene onwards.

MAORI BOTTOM GROUP

NAME: After an old miners term, first used by McKay (1894).

TYPE: Comprising the Kurow, Cannington, and Canterbury Gravels (Marwick 1935; Gair 1959; Wilson 1963).

OTHER UNITS: Encompasses all postmarine piedmont gravels of the Canterbury Plains, including those deposited in contiguous intermontane depressions to the west.

DESCRIPTION: Nonmarine breccia-conglomerate, conglomerate, and related fluvial sand-shale sequences, including loess.

AGE: Miocene–Recent.

INTERPRETATION: Transform plate boundary activity commenced in western South Island during the Late

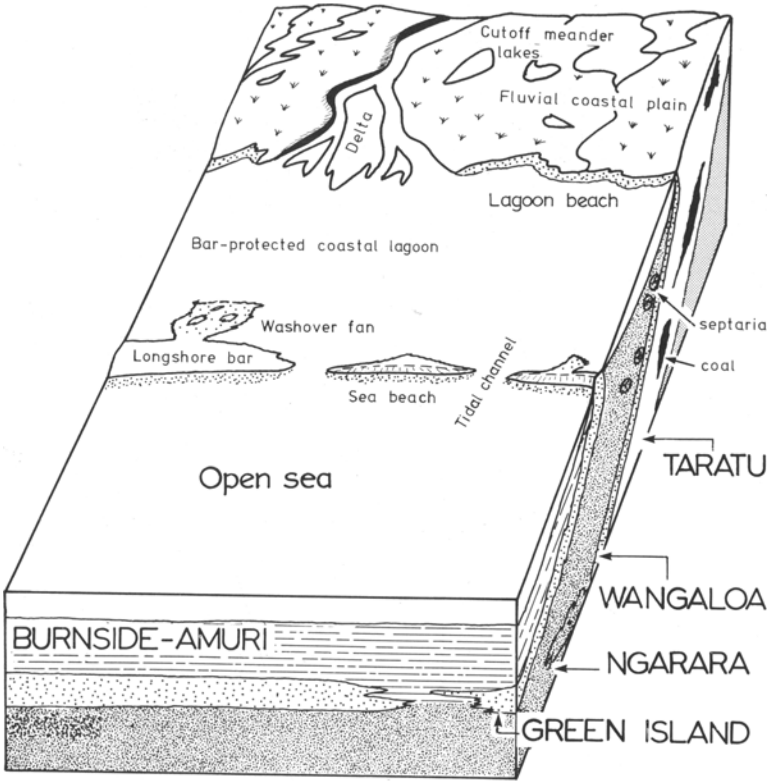

Fig. 16 Paleoenvironmental interpretation for the regional formations of Onekakara Group.

Oligocene–Early Miocene. Rising mountains shed copious quantitities of coarse-grained molasse from the Miocene onwards, with finer grained sediment being bypassed eastwards for deposition in the Otakou Group shelf wedge.

Constituent regional formations

The Late Cretaceous–Early Oligocene epeiric marine transgression took place across a basement that was approaching peneplanation. Homotaxial Onekakara Group sedimentary sequences were therefore deposited over wide areas. At least six superposed lithofacies- assemblages can be traced from North Canterbury to the Great South Basin (Norris et al. 1978; Carter 1988) and therefore deserve recognition as regional formations. Similarly, two regional lithofacies occur within the Kekenodon Group and three lithofacies characterise the regressive Otakou Group (Fig. 14, 15).

In choosing names for regional application, the following general principles have been applied: (1) historical precedence; (2) suitability, in the sense that the name as originally or currently defined should correspond with one of the regional lithofacies; (3) achieving a wide geographical spread throughout the Canterbury Basin; and (4) resurrection of obsolete terms rather than proposal of new names.

The following names are recommended, with synonyms as shown on Fig. 15. Most formation names are current in particular parts of the Canterbury Basin, and their type localities are therefore already established.

ONEKAKARA GROUP

TARATU FORMATION

The basal Onekakara unit, comprising quartzose coal measures that accumulated on an eastward-facing coastal plain.

WANGALOA FORMATION

Well-sorted marine intertidal sandstone, commonly with *Ophiomorpha* burrows, invertebrate shellbeds, and glauconite.

NGARARA FORMATION (after Hutton 1874)

(Type section here nominated as encompassing the types of the Katiki, Otepopo, Moeraki, and Kurinui Formations, coastal North Otago—Paterson 1941; Brown in Fleming 1959. Where convenient, the names of the constituent parts of Ngarara Formation, formerly formations themselves, may be treated as members.) A complexly variable assemblage of nearshore lagoonal, estuarine, and deltaic sediments, predominantly mudstone, siltstone–fine sandstone, and greensand. Sediments are often carbonaceous, micaceous, glauconitic, concretionary, and/or bioturbated.

The top of the Ngarara Formation is readily recognised as the base of the Green Island Formation in sections where that formation occurs (e.g., at Dunedin and Castle Hill Basin—Benson 1969; Gage 1970). In the absence o

the Green Island Formation (e.g., Pareora district; Gair 1959), the top of the Ngarara is placed at the level at which the sediment becomes appreciably calcareous (cf. Burnside Formation).

GREEN ISLAND FORMATION

Well-sorted sand, often with mineralogy exotic to its immediate basement, and corresponding to longshore sandbars that demarcated the Ngarara lithofacies to the east.

BURNSIDE FORMATION

Blue-grey calcareous siltstone and mudstone, sometimes glauconitic, with open marine invertebrate faunas. Sometimes rich also in biopelagic siliceous microfossils.

AMURI FORMATION

Oceanic, biopelagic chalk which represents the deepest and most offshore facies of the early Kaikoura transgression.

KEKENODON GROUP

CONCORD GREENSAND FORMATION

Terrigenoclastic-poor, micritic greensand often with a rich calcitic invertebrate macrofauna. The basal greensand is generally intensely bioturbated, penetrates into borings/burrows in underlying strata at the Marshall Unconformity, and in many places contains phosphatised shell or sediment fragments.

WEKA PASS LIMESTONE FORMATION

Micritic calcarenite, often glauconitic and with abundant calcitic macrofauna and planktic microfauna. Generally bioturbated throughout, despite which large-scale planar or cross-bedding is commonly preserved, accentuated by rubbly, nodular concretionary layers.

OTAKOU GROUP

BLUECLIFFS FORMATION

Poorly sorted, bioturbated, terrigenoclastic, muddy silt and fine sand with offshore to shallow shelf marine faunas.

SOUTHBURN FORMATION

Well-sorted sand with abundant sedimentary structures and subtidal to intertidal marine faunas.

WHITE ROCK FORMATION

Lithologically variable sand, mud and coal as characteristic of coastal plain coal measures.

Local variations to the regional lithostratigraphic pattern

The uniform and steady nature of early Kaikoura marine transgression (Fig. 16) makes the constituent formations of the Onekakarara and Kekenodon Groups mappable over an onshore and offshore area >100 000 km^2. Major variations on the homotaxial theme occur only around sites of active submarine volcanism, as known in North Otago and North Canterbury during the Late Eocene (e.g., Gage 1957, 1970), and at Otago and Banks Peninsulas during the late Middle Miocene (e.g., Coombs 1965). Such local variations are readily accommodated by treating the units associated with a particular volcanic centre as a subgroup (e.g., Alma Subgroup for the Oamaru centre; Fig. 15), or as a complex (e.g., Dunedin Volcanic Complex of Coombs 1965).

In contrast, the Matakea and Maori Bottom Groups are synorogenic. Though the groups are recognisable regionally, their local occurrence is generally constrained within fault-angle depressions, and recognition of regional formations is therefore not appropriate. Similar tectonic control of local depocentres also affected the marine Otakou Group in North Canterbury–Marlborough from about the Middle Miocene, but despite this the regional Otakou formations can in general still be recognised at the northern end of the Canterbury Basin.

The residual New Zealand landmass during the mid Cenozoic

In spite of marine transgression from both east and west, the Central Otago region remained the locus of nonmarine sedimentation throughout Kaikoura time. As described by McKay (1894) and Park (1910), widespread sand, shale, and lignite measures are largely of lacustrine origin, and accumulated contemporaneously with the Kekenodon and lower Otakou Groups of the east coast.

The term Manuherikia Group, after Hector (1884) and Park (1910), serves as a convenient term for the pre-orogenic mid-Cenozoic nonmarine sediments of Central Otago (cf. Douglas 1987).