PALAEOGEOGRAPHY 31

PRELIMINARY RECONSTRUCTIONS FOR THE CRETACEOUS TO CAINOZOIC OF THE NEW ZEALAND – NEW CALEDONIA REGION

ANNE M. WALLEY & MALCOLM I. ROSS

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

ONSHORE SEDIMENTARY & PETROLEUM GEOLOGY

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by

Anne M. Walley and Malcolm I. Ross

BUREAU OF MINERAL RESOURCES
AND
PETROLEUM DIVISION OF THE
AUSTRALIAN MINERAL INDUSTRIES RESEARCH ASSOCIATION
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1. INTRODUCTION

Preliminary plate reconstructions for the Cretaceous to Cainozoic of the New Zealand - New Caledonia region (Figure 1) are presented in this report. The study forms part of the Bureau of Mineral Resources (BMR)/ Petroleum Division of the Australian Mineral Industries Research Association (APIRA) Phanerozoic History of Australia Project. These reconstructions will provide portions of the base maps for a series of palaeogeographic maps of the Indo-Australian Plate, for a number of Cretaceous and Cainozoic time intervals. The area to be discussed here lies between the Dampier Ridge and Lord Howe Rise in the west, the North Loyalty Basin in the north, the Kermadec Trench in the east and the Campbell Plateau in the south. New Zealand lies astride the Indo-Australian/Pacific Plate boundary, in the southeastern portion of the project study area. New Caledonia, which forms the northern part of the Norfolk Ridge, is situated near the northeastern edge of the Indo-Australian Plate. The Vanuatu - Fiji - Tonga region will be the subject of a separate report, and reconstructions for the latter area are currently undergoing revision (M. Bradshaw, BMR, personal communication, 1991).

Maps 1 to 12 display plate movements in the New Zealand - New Caledonia area from the Early Cretaceous (100 Ma) to the present day. The maps were prepared by compiling a data set of geological constraints on the plate tectonic development of this region. These parameters were then digitised and used to create a series of computer-based reconstructions, using the Macintosh program "Terra Mobilis". The geological parameters were compiled and interpreted by A. Walley, who is responsible for most of the text. The computer-generated reconstructions were created by M. Ross. The palaeomagnetic constraints for the model are based on the latest versions of a global plate tectonic database compiled by the International Union of Geodesy and Geophysics/International Union of Geological Sciences, during a Special Project of the International Commission on the Lithosphere (PALEOMAP; Scotese and others, 1988; Scotese, in preparation). The palaeomagnetic framework has also been taken from Ziegler and others (1982).

The present study is a new compilation of existing data and has drawn upon the work of many experts on this region, referred to in the following text. The geological history of New Zealand has been integrated with plate tectonic reconstructions by a number of researchers (e.g. Carter and Norris, 1976; Kamp, 1986a,b; and Korsch and Wellman, 1988). The Cretaceous - Cainozoic plate tectonic history of the New Caledonia region has been considered by Paris (1981), Launay and others (1982), Kroenke (1984), Brothers and Lillie (1988) and other scientists. This report highlights aspects of the geological history which are important for reconstructions of this region. Some of the points of disagreement between the various theories are also discussed. All localities are referred to below with respect to their present geographic positions.

The relative plate positions at 100 Ma have been used as a starting point for the reconstructions because, at about that time, there was a major change in tectonic regime in New Zealand (Bradshaw, 1989). From the Permian until the early Early Cretaceous, New Zealand was dominated by convergent margin tectonics. The collision of the youngest segments of the convergent margin with the remainder of New Zealand took place in the Early Cretaceous, ceasing at approximately 105 ± 5 Ma, in the NZ Motuan

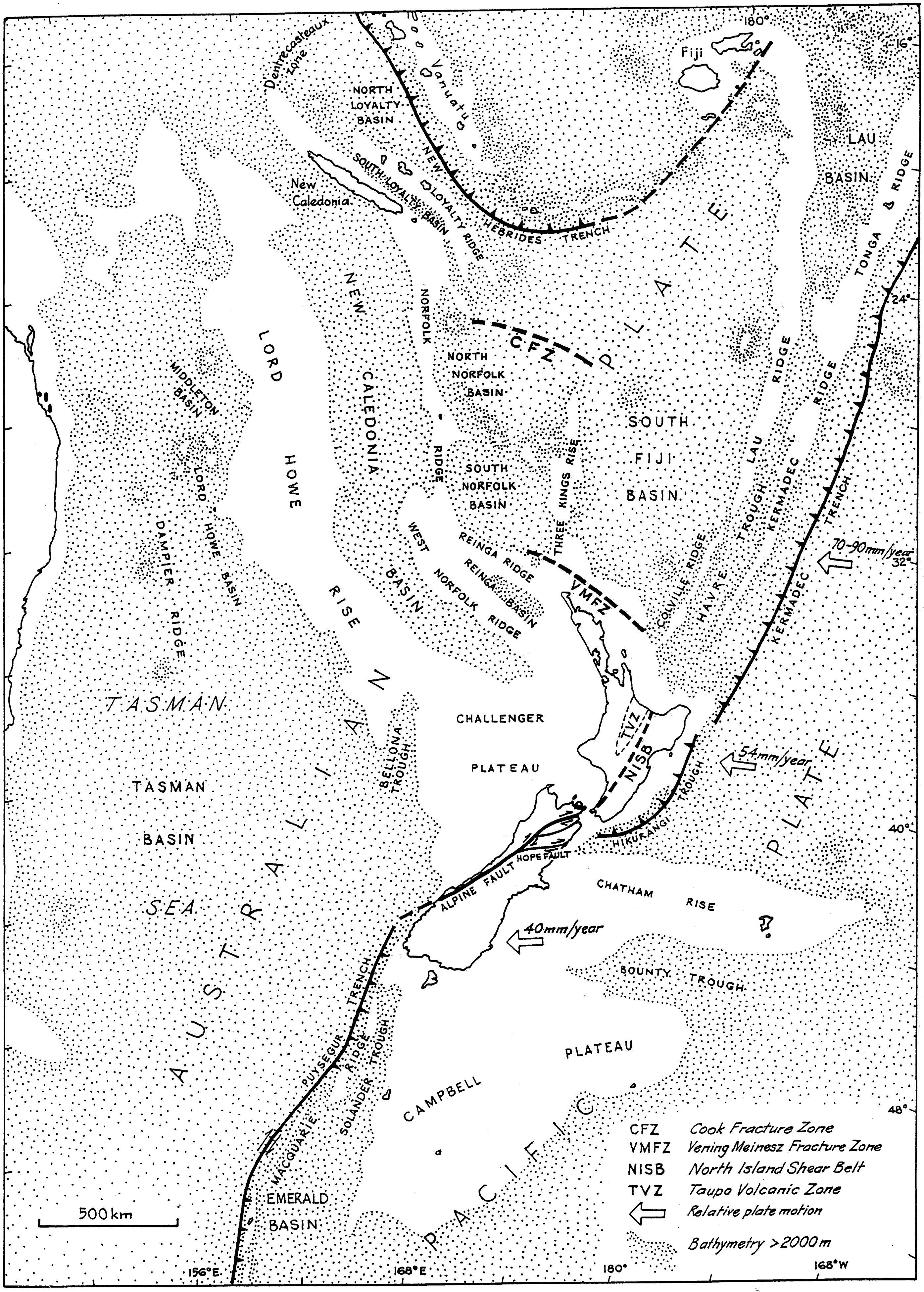


FIGURE 1: Plate tectonic setting of the New Zealand - New Caledonia region

Information compiled from: Circum-Pacific Map Project (1981), Launay et al. (1982), Cole (1984, 1986), Walcott (1984, 1987) and Pelletier (1990).

Stage (Bradshaw, 1989; Figure 2). Summary stratigraphic information prepared for this project indicates that in Eastern North Island this may have been at about 102 Ma (Walley, 1990). There was also a major change in tectonic regime in New Caledonia between the Early and Late Cretaceous, but the timing is less well constrained (see Paris, 1981).

From the late Early Cretaceous until the end of the Palaeogene, extension, followed by lithospheric cooling and subsidence, dominated the New Zealand region. New Caledonia also underwent extension, followed by regional subsidence until the Eocene, when there was oblique convergence of the Indo-Australian and Pacific Plates along the Norfolk Ridge. The convergent plate boundary moved east of New Caledonia after the Early Oligocene. The Indo-Australian/Pacific Plate boundary became established in New Zealand in the latest Oligocene/earliest Miocene, placing New Zealand once again in a convergent tectonic regime (oblique convergence), which has persisted throughout the Neogene (see Paris, 1981; Kroenke, 1984; Kamp, 1986a).

In the ensuing notes, a brief discussion of the method used for the reconstructions is followed by a description of each component of the region, with an emphasis on the geological constraints which affect the plate reconstructions. Some of the main problems involved in reconstructing this area are then summarised and an outline of the evolution of the region is given to accompany the maps. The report concludes with comments on implications for hydrocarbon exploration.

2. METHOD

The region has been subdivided into a number of components (Figure 3), which are thought to have moved relative to each other during the Cretaceous to Cainozoic. In view of the scale of the final map (1:10 000 000), only the main constituent parts of the region have been considered. The emphasis in this compilation is on the regional plate-wide picture and, therefore, calculations have not been made for the smaller-scale movements within the individual components. The present-day shape of the areas has thus been used throughout the reconstructions. As can be seen from the reconstructions, this has produced some anomalous overlap of components.

The term 'terrane' is not considered to be applicable to this region for the period under discussion (i.e. ~100 Ma to the present): the components are not 'fault-bounded entities' which 'demonstrate different and unrelated geologic histories' (Jones and others, 1983). Some of the components could be described as 'tectonic elements', bounded by faults or fault zones and demonstrating different, but related, histories. Other components were once contiguous, but became separated during sea-floor spreading.

Fault zones are summarised on the maps as single lines. Complex regions are broken into discrete elements that behave approximately rigidly. Oceanic crust appears as gaps between the components. The boundary between oceanic and non-oceanic crust (continental or volcanic arc material) is taken as the present-day shelf/slope break (steepest bathymetry), which is in most cases landward of the actual oceanic/non-oceanic boundary. This position is chosen to partially compensate for stretching of continental

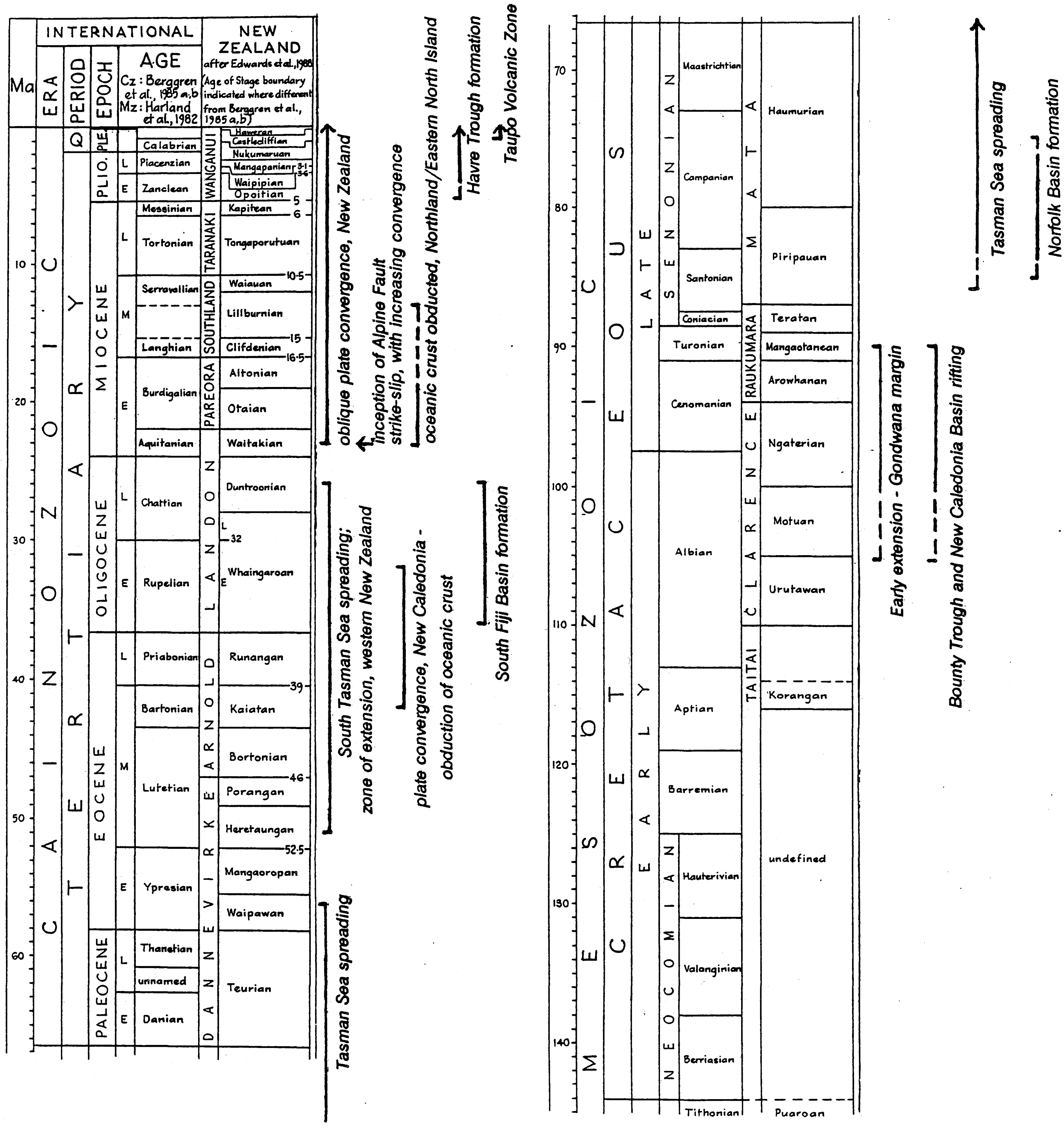
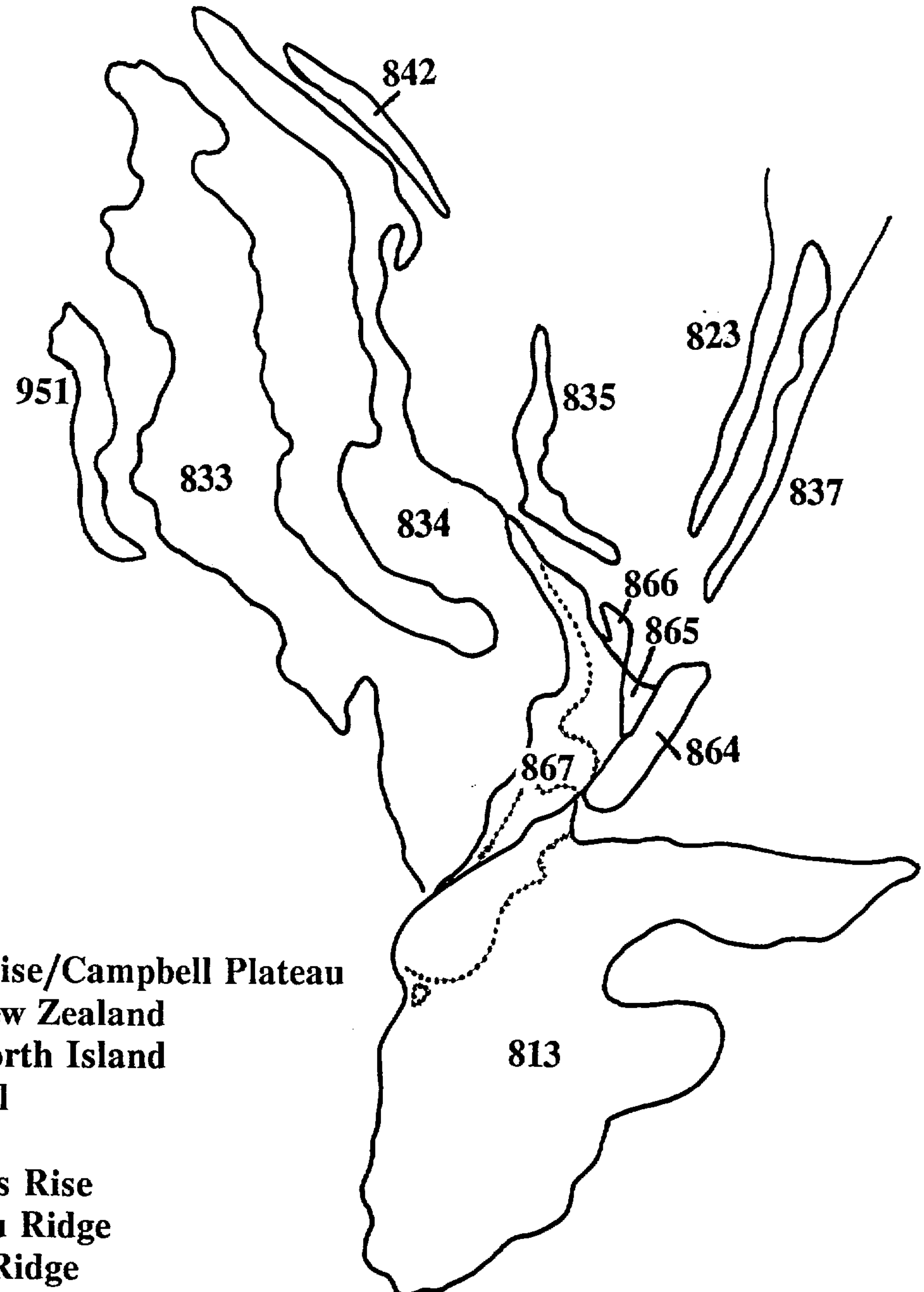


FIGURE 2: Cretaceous - Cainozoic timescale and main tectonic events



COMPONENTS

813: Chatham Rise/Campbell Plateau
867: Western New Zealand
864: Eastern North Island
866: Coromandel
865: Taupo
835: Three Kings Rise
823: Colville-Lau Ridge
837: Kermadec Ridge
833: Lord Howe Rise
951: Dampier Ridge
834: Norfolk Ridge
842: Loyalty Ridge

.... New Zealand coastline

FIGURE 3: Components of the New Zealand - New Caledonia region

crust that may have occurred during rifting.

Non-oceanic areas that have undergone compression during the time of concern will show as gaps when reconstructed to past positions; areas of extension will appear with overlap. Since oceanic material is not shown, oceanic basins can be restored to an approximately palinspastic pre-rift configuration simply by matching the conjugate shelf-slope breaks. Zones of seafloor spreading can be identified on the map by areas of non-oceanic crust which diverge with time. Subduction is shown by convergence between non-oceanic material.

Further information on the reconstruction method, including palaeomagnetic constraints within the plate model, is in Ross (in preparation).

3. COMPONENTS OF THE NEW ZEALAND - NEW CALEDONIA REGION

A brief description of each of the components is given below, together with an outline of the geological constraints on reconstruction of each part of the region. The pre-late Early Cretaceous sequence of the region (i.e. prior to ~100 Ma) is not referred to in the following notes.

3.1 New Zealand region

Localities referred to below are shown on Figures 1 and 4.

Component 813: Chatham Rise/Campbell Plateau

Component 813 includes the Chatham Rise and Campbell Plateau, Stewart Island and onshore South Island east of the Alpine Fault. Late Early or early Late Cretaceous to Recent sediments were deposited in this area, although there is an unconformity between the Cretaceous and the Mid-Eocene in much of the onshore southwest. There was Cretaceous to Pleistocene intra-plate volcanism in Canterbury-Otago and the Chatham Rise (see Field and others, 1989; Wood and others, 1989). The Bounty Trough, between the Chatham Rise and Campbell Plateau, opened in the late Early to early Late Cretaceous, but failed to spread (Anderton and others, 1982; Cook, 1989). Component 813 has moved relative to western New Zealand (western South Island), by both dextral strike-slip along the Alpine Fault and convergence normal to the Alpine Fault, since ~23 Ma (Walcott, 1979; Kamp, 1986a). Estimated amounts of movement along the Alpine Fault since its inception at ~23 Ma are: 480 km of dextral strike-slip and a total of 100 km of convergence (Wellman and Willett, 1942; Allis, 1986; Kamp, 1986a). Kamp (1991) now considers that strike-slip movement on the Alpine Fault may have commenced at ~25 Ma, correlating with a major plate reorganisation in the eastern Pacific. Prior to the mid-Neogene, movement on the Alpine Fault was predominantly strike-slip. Significant convergence began at approximately 10-15 Ma, with a larger amount occurring in the last 5 Ma (Norris and Koons, 1989; Norris and others, 1990).

The northern part of this component (Marlborough) marks the southern end of the

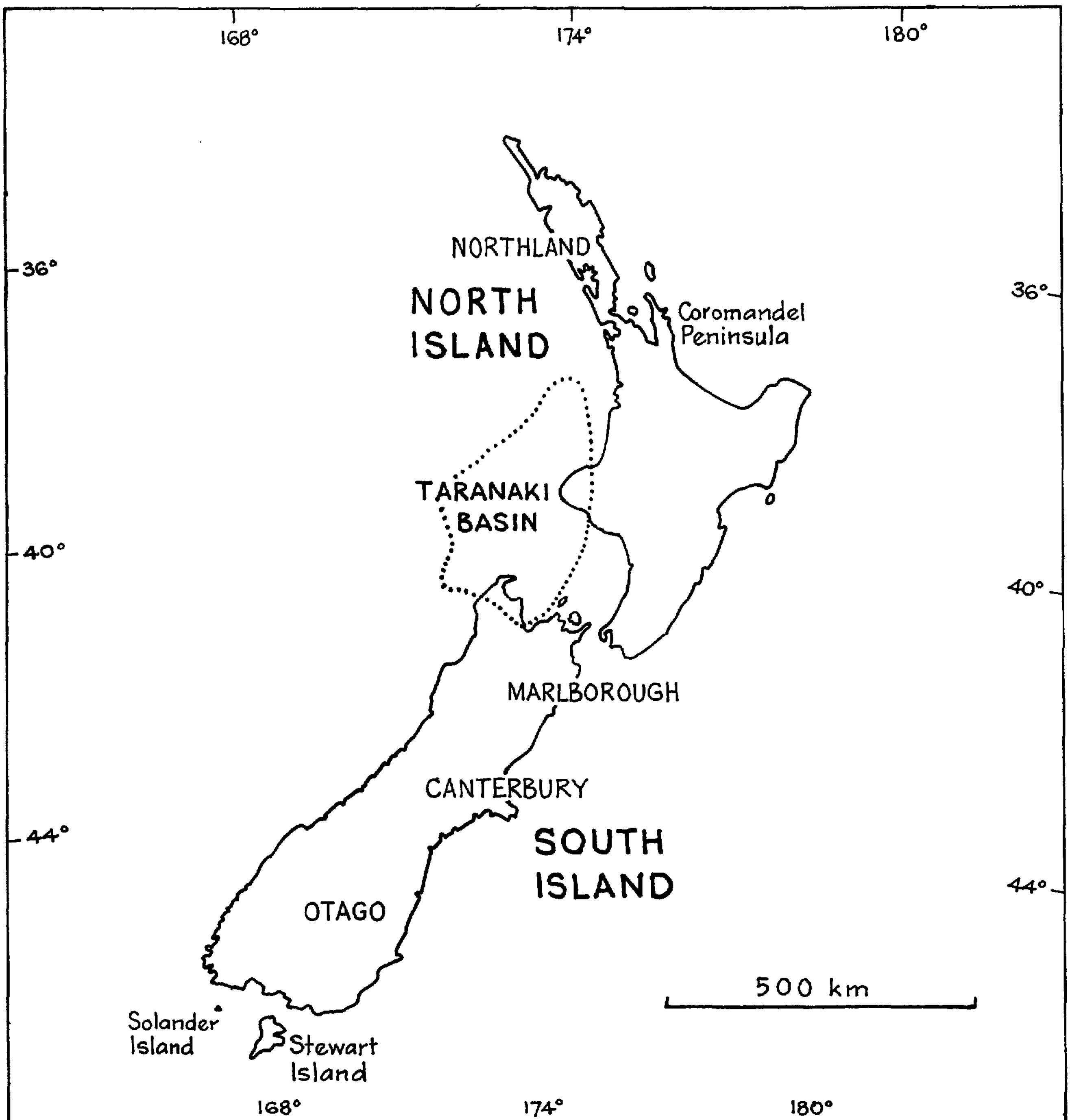


FIGURE 4: New Zealand - localities referred to in this report

Neogene subduction system (Hikurangi Trough; Figure 1). In this complex region, dextral transpression and rotation of large crustal blocks during the Neogene record the rotation of the edge of the subduction system to its present trend (Lamb and Bibby, 1989). There is some doubt about the position of Marlborough prior to the inception of the Neogene subduction system. M.G. Laird (DSIR, personal communication, 1991) points out that the Cretaceous sequences of Marlborough (north of the Hope Fault; Figure 1) and Eastern North Island are similar and may have been deposited in the same basin. The separation of these areas in the reconstructions presented here (see, for example, Maps 1 to 4) implies that this basin was extremely large. Late Cretaceous to Palaeogene units common to Marlborough and north Canterbury indicate the proximity of these two areas at that time, and Neogene dextral offset between Marlborough and Canterbury along the Hope Fault appears to be less than 20 km (see Field and others, 1989). The northern margin of the Chatham Rise may be a major fracture zone: a prominent lineament is visible on both topographic and free air gravity maps (see also Wood and others, 1989).

South of component 813, the present-day convergent plate boundary lies immediately west of the Macquarie Ridge (Figure 1), which is a fossil spreading centre. The ridge comprises oceanic lithosphere formed at a mid-ocean ridge, which was probably part of the mid-Eocene - Oligocene southeast Indian Ridge-extension spreading centre (Kamp, 1986a; see component 867 below, p. 13). Uplift of the ridge has occurred mainly since the Pliocene, during oblique compression on the plate boundary (Kamp, 1986b). Since the latest Oligocene/earliest Miocene formation of the plate boundary through New Zealand (Kamp, 1986a), the continuation of the plate boundary south of New Zealand has evolved as a steeply easterly-dipping subduction zone at the Puysegur Trench. Island arc-type volcanism is only very weakly developed (one calc-alkaline volcano on Solander Island), because of the small amount of underthrusting, most of which has occurred since 10 Ma (Kamp, 1986b).

Component 864: Eastern North Island

This component is characterised by a Cretaceous to Recent, largely marine, sedimentary sequence. From approximately 23 Ma onwards (see below), this area has comprised an accretionary prism and forearc basin, associated with the onset of west-dipping subduction along the eastern side of the North Island (Hikurangi Trough). The following geological evidence indicates that Eastern North Island lay near Northland prior to the onset of Cainozoic subduction in the New Zealand region: the Miocene-Pliocene accretionary prism is in Eastern North Island and the associated volcanic arc is in Northland/Coromandel. Moreover, an allochthon (including oceanic crust) was emplaced in both Northland and the northern end of Eastern North Island between ~23 Ma and ~19 Ma (Ballance and Spörli, 1979; Brothers and Delaloye, 1982; see component 835 below, p. 13).

Eastern North Island has gradually rotated clockwise to its present position due to dextral movement along the Vening Meinesz Fracture Zone (VMFZ) and North Island Shear Belt (NISB) (see below, Figure 1 and Cole, 1984). This movement was associated with the clockwise rotation of the subduction system to its present position. The precise timing of the dextral movement of Eastern North Island is controversial: the obduction of oceanic crust mentioned above is thought to have been triggered by movement on the VMFZ (Brothers and Delaloye, 1982), which was associated with the development of the modern convergent plate boundary in New Zealand at ~ 23 Ma. Possibly the clockwise shift in plate motion at this time led to the propagation of the VMFZ through North Island as the NISB. The ensuing supposition is that movement on the NISB began at ~23 Ma. For possible events associated with movement along the VMFZ, see component 835, below (p. 13).

Eastern North Island lay near Northland/Coromandel until the Pliocene and moved further clockwise, to its present position, during the opening of the Havre Trough and Taupo Volcanic Zone (see component 865 below). Seafloor spreading data and palaeomagnetic declination studies indicate that there has been rotation of the forearc region of Eastern North Island through 60° in the last 20 Ma; the rate of rotation has increased through time and at the present day it is 7° Ma^{-1} (Walcott, 1987). Rotation of Eastern North Island probably accelerated during the opening of the Havre Trough (between components 823 and 837), at ~4 (or 5) Ma. The Havre Trough is currently spreading at ~20 mm/year (Cole, 1986).

The western boundary of eastern North Island, the North Island Shear Belt, is a 100 km-wide mega shear zone (Kamp, 1987). The 480 km of Alpine Fault strike-slip movement in the South Island is thus represented in the North Island by a wide zone of distributed deformation. The accretionary process in Eastern North Island is widely believed to have partitioned the oblique-slip convergence into strike-slip dominated faults in the axial ranges (NISB) and dip-slip shortening along reverse faults in the accretionary wedge (see, e.g. Lewis, 1980; M. Rattenbury, BMR, personal communication, 1991). The reverse-dextral faults within the NISB have a combined displacement rate of 14-18 mm/year (dextral) and a reverse component of 4 mm/year (Lensen, 1975; Cole, 1984). Owing to the methodology used for the present reconstructions, the rotation of Eastern North Island is, however, shown as having occurred along one structural boundary.

Component 865: Taupo

The Taupo Volcanic Zone comprises the ensialic back-arc basin and volcanic arc associated with the present-day subduction zone. Extension began within this zone at ~1 Ma (Cole, 1986) and the rate of spreading is ~12 mm/year (Stern and Davey, 1989). In order to avoid excessive overlap on the reconstructions, this component is shown as opening on a pivot centred further south than the southernmost extent of the Taupo Volcanic Zone (compare Figures 1 and 3).

Component 866: Coromandel

The Coromandel Peninsula was the site of a volcanic arc during the Miocene, Pliocene and ?early Pleistocene: pre-Taupo Volcanic Zone volcanism occurred here from ~19 Ma to ~1.5 Ma. Between ~11.5 - ~5.6 Ma, the Coromandel Peninsula appears to have been the eastern bounding arc of the Hauraki inter-arc basin (Map 11; Skinner, 1986) between Northland and Coromandel. Component 866 is therefore shown as having moved clockwise during this period, associated with the extension of the Hauraki inter-arc basin.

Component 867: Western New Zealand

This is a composite component incorporating South Island west of the Alpine Fault and North Island west of Coromandel/Taupo/North Island Shear Belt. An Early Cretaceous to Recent sequence is present in the west (offshore and, locally, in western onshore areas). In the eastern part of this region, however, the Cretaceous to Mid-Eocene period is not represented. Within this component, there was Late Cretaceous to Eocene basaltic volcanism in the South Island, but late Cainozoic volcanic activity (arc and back-arc) has been confined to the North Island. There was a volcanic arc in western Northland from ~23 to ~16 Ma (see Hayward, 1979), slightly overlapping in age with the Coromandel volcanic arc.

The amount of anticlockwise rotation of the northwestern part of component 867 (in relation to the opening of the Havre Trough and Taupo back-arc basin) is thought to have been small (Ballance and others, 1982).

From the Mid-Eocene to the Oligocene, between magnetic anomalies 21 and 7, there was a zone of extension through the western part of this component, aligned with a spreading ridge in the South Tasman Sea and Emerald Basin (Kamp, 1986a). This zone may have been an orthogonal rift (Kamp, 1986a), an extensional transform margin, or a complex transform along which the style of movement varied (see King, in press; King and Thrasher, in press). There was apparently, therefore, some movement between this component and part of the Lord Howe Rise/Norfolk Ridge (833 and 834, respectively) during this period, but the amount of extension is quoted as only 'a few tens of km...' (Kamp, 1986a; Gray and Norton, 1988) and has not been shown on the reconstructions.

Component 835: Three Kings Rise

Three Kings Rise is probably a remnant arc, which has been variously interpreted as having formed above either a west-dipping (see Ballance and others, 1982) or east-dipping (see Kroenke and Dupont, 1982; Kroenke and Eade, 1982; Eade, 1988) subduction zone. Its age is controversial, but has been interpreted both as Cretaceous to Eocene (Launay and others, 1982) and Miocene (Ballance and others, 1982; Kroenke, 1984). In view of the presence of obducted oceanic crust on the Three Kings Rise, Korsch and Wellman (1988) view the entire rise as an allochthonous slide which was emplaced in the earliest Miocene, at about the same time as the emplacement of the Northland allochthon (see component 864, above).

A sample of andesite from the rise confirms the presence of volcanics of island arc affinity, and seismic interpretation suggests an arc above an east-dipping subduction zone (Kroenke and Dupont, 1982; Kroenke and Eade, 1982). The rise may have been an Oligocene arc, behind which (to the east) the South Fiji Basin opened (see below). In this scenario, Norfolk Basin seafloor would have been subducted under the rise from the west (Eade, 1988). The timing of the terminal obduction of (Norfolk Basin) oceanic crust over the southern half of the rise is uncertain, but probably occurred after formation of the South Fiji Basin (Kroenke and Dupont, 1982), at about the time of obduction of oceanic crust on to Northland (see 864, above). The ophiolites are thought to have originated by transform motion along the Vening Meinesz Fracture Zone

(VMFZ). Further movement along this zone in the Neogene may have been associated with the opening of the unnamed portion of ocean between Norfolk Basin and Three Kings Rise (the 'Transition Zone' of Launay and others, 1982). This oceanic area is of unknown age, but has, from seismic evidence, been inferred to be much younger than the Norfolk Basin and could be mid-Cainozoic (Eade, 1988). The opening of this ocean is shown on maps 10 to 12.

The South Fiji Basin opened in the Oligocene, from ~36 - 26 Ma (Malahoff and others, 1982). This spreading has been associated with movement along the VMFZ (see Cole, 1986; Kamp, 1986a). Any movement along the VMFZ at this time does not appear to have been linked to movement along a North Island Shear Belt (see discussion under 864 above, p. 11).

Component 823: Colville-Lau Ridge

The Colville-Lau Ridge is a remnant island arc. Lau Ridge sedimentary rocks are exclusively shallow marine. They are mainly Mid-Miocene and younger (Katz, 1986), but Late Eocene rocks have been recorded (Dupont, 1988) and may represent part of the earliest South Fiji Basin sequence. The main volcanism on the Lau Ridge occurred between 14 and 6 Ma (Cole, 1986; Katz, 1986), but may have begun at ~22 Ma (Kroenke, 1984, p. 118). The arc was associated with the west-dipping subduction zone north of New Zealand at that time (see Walcott, 1987), prior to the opening of the Havre Trough. The timing of the Havre Trough is discussed under 864, above.

The Lau Basin is a marginal basin with a complex history. There were two spreading centres, the central one of which propagated south at the expense of the eastern one. Most of the central and south Lau Basin formed at approximately the same time as the Havre Trough marginal basin, from 5 Ma to the present (Parson and others, 1990). After the opening of the Lau Basin, volcanism continued along the Lau Ridge until 2.8 Ma (Dupont, 1988).

Component 837: Kermadec Ridge

The Kermadec Ridge is an active island arc (joining the Tonga Ridge in the north) and is associated with the present-day subduction system. Until the opening of the Havre Trough in the Pliocene (i.e., ~5 Ma), this component and the Colville-Lau Ridge were contiguous. The pre-Pliocene stratigraphy has been determined on the Tonga Ridge, where the oldest rocks are Late Eocene and overlie an undated volcanic basement (see Katz, 1986; Dupont, 1988). As on the Lau Ridge, there are Miocene (here, Early Miocene; Dupont, 1988) and younger sediments and volcaniclastics.

The Kermadec Trench to the east of the arc marks the convergence (7-9cm/year; Pelletier, 1990), north of New Zealand, of the Pacific and Indo-Australian Plates.

3.2 New Caledonia region: New Caledonia/Norfolk Ridge and Lord Howe Rise

Components 833 and 951: Lord Howe Rise and Dampier Ridge

The Lord Howe Rise and Dampier Ridge are segments of continental crust which were detached from the Australian margin as a result of seafloor spreading, which commenced at ~86 Ma and formed the Tasman, Middleton and Lord Howe Basins (Shaw, 1978; Symonds and Willcox, 1989). There are pre-breakup Early Cretaceous graben structures on western Lord Howe Rise, which are thought to have developed within a transtensional zone on the eastern seaboard of Australia and to have become detached during seafloor spreading (Jongsma and Mutter, 1978; Falvey and Mutter, 1981; Symonds and Willcox, 1989). The seafloor magnetic anomaly pattern indicates that central Lord Howe Rise was near the Gippsland Basin during the Early Cretaceous (see Map 1) and both areas were probably arms of a three-branched rift or rift/wrench system (see Mutter and Jongsma, 1978; Willcox, 1984; Symonds and Willcox, 1989). In the north Tasman Sea, rifting and the earliest phase of seafloor spreading was centred on the Middleton and Lord Howe Basins. Spreading centres transferred from east to west of the proto-Dampier Ridge at about anomaly 31 - 32 time (by ~70 Ma), because of a sudden change in plate rotation path (Mutter and Jongsma, 1978; Shaw, 1978), thus separating the Dampier Ridge from mainland Australia. The basement of the Middleton and Lord Howe Basins may be extended continental, rather than oceanic, crust (B. Willcox, BMR, personal communication, 1991). The pattern of early rifting and seafloor spreading in the Tasman Sea is discussed in Mutter and Jongsma (1978) and Shaw (1978). As shown in Shaw (1978), several hundred kilometres of sinistral movement displaced the Lord Howe Rise with respect to Australia, between ~86 and ~56 Ma (when Tasman Sea spreading ceased). Late Cretaceous to Quaternary marine sediments have overlapped the early rift deposits. During the Neogene, there has been widespread intra-plate volcanism on the Rise, possibly related to northward drift over a mantle hot-spot (Vogt and Conolly, 1971).

The eastern flank of the Lord Howe Rise has been interpreted as the former continental margin of Australia-Antarctica (Willcox and others, 1980). However, the core of the Norfolk Ridge, located farther east, is probably also continental (Symonds and Willcox, 1989). There are early extensional structures in the New Caledonia Basin which correlate with similar structures within the Taranaki Basin (Figure 4). Thus, the New Caledonia Basin is thought to have opened prior to the opening of the Tasman Sea (see Wood, 1989; Wood and Uruski, 1989). Correlation with similar early rift structures in the New Zealand region (Walley, 1990) suggests the early extension was Albian-Cenomanian, between 105 Ma (max.) and ~90 Ma. Geophysical data indicate that there is thinned continental crust in the southern part of the New Caledonia Basin (Wood and Uruski, 1989; Uruski and Wood, 1991). The only Deep Sea Drilling hole in the New Caledonia Basin (DSDP 206; Burns and others, 1973) bottomed within Paleocene sediments and thus did not confirm the maximum age of the basin sequence.

The Challenger Plateau, at the southern end of Lord Howe Rise, is partially separated from the main part of the Lord Howe Rise by the Bellona Trough, which probably opened in conjunction with Tasman Sea rifting in the Late Cretaceous (Wood, 1989). The Challenger Plateau and Lord Howe Rise are treated as one component for the purpose of these reconstructions.

Component 834: Norfolk Ridge (including New Caledonia)

The Norfolk Ridge is a block of continental crust between the oceanic Norfolk and New Caledonia Basins. Prior to the opening of the New Caledonia Basin (see above) the ridge lay adjacent to the Lord Howe Rise. New Caledonia forms the northern end of the Norfolk Ridge. The earliest Cretaceous units exposed in New Caledonia (Coniacian; Figure 2) are ?fault-controlled conglomerates possibly correlative with the pre-breakup rifting elsewhere on western Norfolk Ridge (see Symonds and Willcox, 1989; Wood and Uruski, 1989) and in the New Caledonia Basin. When the Tasman Sea opened, extension in the New Caledonia Basin probably ceased. East-dipping subduction is then thought to have begun along the western side of the Norfolk Ridge and subduction appears to have continued here until the Eocene (Launay and others, 1982). There were small back-arc basins in New Caledonia from the Cretaceous until the Eocene (Paris, 1981; Launay and others, 1982), but there appears to be no other supporting evidence for subduction along western Norfolk Ridge until the Mid-Eocene, when there was a dramatic change in sedimentation, with the development of probable forearc trench slope deposition along western New Caledonia (see Paris, 1981).

Weak magnetic anomalies in the Norfolk Basin suggest it opened in the Late Cretaceous (from ~85 - 75 Ma; Launay and others, 1982; Eade, 1988). It may have developed as a back-arc basin (to the east of the Norfolk Ridge arc?), accompanied by transform faulting on Cook and Vening Meinesz Fracture Zones (see Launay and others, 1982 and Figure 1); however, this is speculative. Other researchers have suggested the Norfolk Basin opened in the Miocene, as a back-arc basin to an arc along the Three Kings Rise (Ballance and others, 1982), but there is no evidence for a Miocene age. Norfolk Basin oceanic crust was obducted onto Northland in the earliest Miocene (see component 864, above), thus contradicting a Miocene age.

Through the middle of, and along the length of, New Caledonia, there is a major structure which underwent strike-slip movement in the Rangitata Orogeny (latest Jurassic to early Late Cretaceous). However, both the sense and amount of movement are unclear and have not therefore been accounted for in the present reconstructions. This fault zone also controlled the palaeogeography from the Late Cretaceous until the mid-Eocene, but tectonism was predominantly vertical (Paris, 1981; Maurizot and others, 1985) and thus the reconstructions are not appreciably affected.

Convergence increased on the northwestern sector of the plate boundary in the Mid-Eocene, correlative with a change in Pacific plate motion from northwards to westwards (see Wells, 1989). From the Late Eocene until the Early Oligocene (~42 - ~32 Ma) there was oblique plate convergence in New Caledonia, with high pressure metamorphism in the northern part of New Caledonia and obduction of newly-formed oceanic crust from the North Loyalty Basin. This event is well-dated from the occurrence of fossiliferous sediments which overlapped the emplaced peridotite and incorporated eroded peridotite fragments (Paris, 1981; Brothers and Lillie, 1988). The marine basin referred to above was also deformed at this time. This convergent event also caused deformation in the New Caledonia Basin, forming ridges within the basin (the Fairway-West Norfolk and Wanganella Ridges) not shown at the scale of these reconstructions (Eade, 1988).

Component 842: Loyalty Ridge (and Loyalty Basin)

The Loyalty Ridge existed as a sea floor rise prior to the Late Eocene (Katz, 1986). There was alkali-basalt volcanism on this ridge from ~13 - 9 Ma, but an additional radiometric date of 29 ± 4 Ma indicates volcanism probably began earlier (Paris, 1981; Katz, 1986). The earlier volcanism appears to have been coeval with formation of the South Fiji Basin. During the opening of this basin, the Loyalty Ridge and Three Kings Rise could have comprised one arc (see continuity of trends on Maps 7 and 8). The arcuate trend was disrupted by events in the earliest Miocene (see component 835: Three Kings Rise, p. 13).

Kroenke (1984) has related the Miocene volcanism to southeast-dipping subduction along the Loyalty Ridge, but there does not appear to be any supporting evidence for a subduction zone. As the Lau Ridge was also an active island arc at this time (14 - 6 Ma; see notes above), Ballance and others (1982) argued that there were two major arcs in the New Zealand region in the Mid- to Late Miocene: a Loyalty - Three Kings Rise - Coromandel arc and a Colville-Lau arc, both associated with west-dipping subduction zones. This is speculative and dependent upon the age of the Three Kings Rise arc, evidence for subduction polarity, and whether Loyalty Ridge volcanism was arc-related. Alternatively, the Colville-Lau arc may have continued through Coromandel, whereas the Miocene volcanism on the Loyalty Ridge may have been intraplate.

Both the North and South Loyalty Basins are Eocene. The present northern boundary of the North Loyalty Basin is the d'Entrecasteaux Zone. However, as noted below, in the Eocene this basin and the d'Entrecasteaux Zone may have formed one larger basin. The North Loyalty Basin opened between 52 and 42 Ma (magnetic anomalies 23 to 18; Weissel and others, 1982). The South Loyalty Basin may have formed earlier, in conjunction with the North Norfolk Basin, as part of a larger basin (Eade, 1988), but there is no supporting evidence. At the present day, the Loyalty Ridge is colliding with the New Hebrides arc (Daniel and others, 1990).

The d'Entrecasteaux Zone, north of the Norfolk Ridge, was the site of a marginal basin in the Eocene, between ~56 and ~36 Ma (dated tholeiitic basalt; Lapouille, 1982; Maillet and others, 1982). This basin was possibly contiguous with the North Loyalty Basin at that time. From the end of the Eocene to the earliest Oligocene, the zone was probably the arcuate northerly continuation of the plate boundary discussed above (Daniel and Katz, 1981). The zone was affected by extension in the Mid-Miocene (15 Ma onwards), during which it attained its present morphology (Maillet and others, 1982). During the past 8 Ma, the d'Entrecasteaux Zone has undergone oblique subduction due to its collision with the central part of the New Hebrides island arc. The collision zone moves 2.5 cm/year northward along the trench (Collot and Fisher, 1990).

4. RECONSTRUCTIONS: SUMMARY OF PROBLEMS

It is clear that an accurate reconstruction of the region is subject to resolution of several geological uncertainties. There are many different existing interpretations. At this stage, it is useful to summarise some of the issues which need to be considered.

Early Cretaceous: Albian - Cenomanian (~105 - 90 Ma)

There is evidence for early extension in a number of areas (Western New Zealand, the Chatham Rise, western and eastern Lord Howe Rise and the New Caledonia Basin). In New Zealand, the beginning of extension is well dated from stratigraphy, a widespread late Albian unconformity and intrusions preceding graben formation (see, for example, Laird, 1981; Nathan and others, 1986; Bradshaw, 1989 and Tulloch and Kimbrough, 1989). The grabens or half-grabens within the Lord Howe Rise - New Caledonia Basin area are not precisely dated, but presumed to be Early Cretaceous (definitely pre-Maastrichtian), based on overlying post-break-up sequences, coeval Early Cretaceous volcanics on the Lord Howe Rise, and regional correlation.

These rift structures provide the earliest evidence for break-up of the Gondwana margin. From seismic interpretation, a transtensional component appears to have been involved on both western Lord Howe Rise and along western New Zealand (see, for example, Mutter and Jongsma, 1978; Shaw, 1978; Whitworth and others, 1985; Thrasher, 1989 and Tulloch and Kimbrough, 1989). How were these areas linked?

The pre-drift position of the Lord Howe Rise is tightly constrained by the seafloor magnetic anomaly pattern in the Tasman Sea. The pre-drift shape and position of New Zealand, however, are a contentious issue dependent upon a number of complex factors, including the age and amount of offset along the Alpine Fault plate boundary. The consensus is presented above (p. 9), but there is no complete agreement among New Zealand researchers. Another factor which influences determination of the pre-drift shape of New Zealand is the recurved arc trend of Palaeozoic to Mesozoic basement rocks, and the timing of its development. This is analysed in Kamp (1986b, 1987) and Korsch and Wellman (1988).

Thus, there is good evidence for Early Cretaceous extension, but incomplete evidence for the pattern of extension and timing.

Late Cretaceous - Early Eocene (~86 - 57 Ma)

The opening of the Tasman Sea and Southern Ocean (between ~86 and ~57 Ma) is constrained by seafloor magnetic anomalies and supporting Deep Sea Drilling information. Known sedimentary sequences throughout New Zealand, the Lord Howe Rise and Norfolk Ridge (New Caledonia) reflect the initial extensional regime, progressing to lithospheric cooling and ensuing regional subsidence (with quiescent sedimentation). A subduction zone has been proposed along northwestern Norfolk Ridge during this period (see p. 16), but there appears to be little evidence. Where the Norfolk Ridge convergent boundary is supposed to have been farther south is most unclear. There is no evidence for any plate boundary in the New Zealand region throughout the Paleocene and Early Eocene.

Mid-Eocene to Oligocene (~51 - 26 Ma)

A series of rift basins indicate that there was a zone of renewed extension along the western side of New Zealand, but there is disagreement on the style of this extension (see component 867, above, p. 13).

The South Fiji Basin opened at this time (~36 - 26 Ma; see p. 14) and is generally considered to have been a back-arc basin. However, where was the arc? Was this along the Three Kings Rise, or the Colville-Lau Ridge (where there was a Miocene arc)?

What was the link between the New Zealand situation and the Three Kings Rise/South Fiji Basin? The Vening Meinesz Fracture Zone separates the two areas. What type of structure was it at that time?

From the late Eocene to Early Oligocene (~42 - 32 Ma), there was an obliquely convergent plate boundary along the northern Norfolk Ridge (see p. 16). What was the link between the plate boundary in New Caledonia and the complex plate boundary situation in the New Zealand region? Was the Cook Fracture Zone (Figure 1) an active feature at this time?

Thus, there was extension in the New Zealand region, and convergence in New Caledonia, but the style of extension is uncertain, and there are many questions as to how these various areas were linked together.

Oligocene/Miocene boundary (~23 Ma)

A major change took place in the New Zealand region at this time. There was a transition from an extensional to a compressional regime, and the former 'rift' or transform system was disrupted. This event is marked by an unconformity and change in rate and type of sedimentation throughout much of New Zealand in the earliest Miocene. This is discussed by Kamp (1986a) and is apparent on the New Zealand correlation chart compiled for this project (Walley, 1990). From this evidence, the inception of the modern convergent plate boundary through New Zealand is thought to have been at this time - ~23 Ma (see p. 9). The plate boundary in the South Island is the Alpine Fault and, east of North Island, a subduction zone. Eastern North Island (where the accretionary prism developed) is thought to have formerly been close to Northland and to have gradually rotated dextrally along a broad shear zone to its present position, during clockwise movement of the subduction system in the Neogene. But the amount of movement, the timing, or whether these blocks did move relative to each other in this fashion, are all controversial. What was the configuration of the subduction system in the Miocene - assuming the continuation of the plate boundary to the north lay along the Colville-Lau Ridge?

How was the movement of Eastern North Island linked to movement along the Vening Meinesz Fracture Zone (see p. 11)?

Farther north, the plate boundary was now removed from New Caledonia, to the east. An active arc is thought to have developed along the Loyalty Ridge (see p. 17), but where was the subduction zone?

These are examples of some of the issues involved in trying to reconstruct this region. There was a transition, over time, from a dominantly extensional to a dominantly compressional regime. However, there are problems involved in trying to determine timing and type of movements.

5. EVOLUTION OF NEW ZEALAND - NEW CALEDONIA REGION: A BRIEF OUTLINE

Maps 1 to 12 show our best estimate of a reconstruction history for this region. The dot pattern highlights the main components discussed in this report, and the solid black shades the present shapes of onshore New Zealand and New Caledonia.

100 - 90 Ma: late Early to early Late Cretaceous (Maps 1, 2)

New Zealand, the Lord Howe Rise and Norfolk Ridge were close to Australia/Antarctica. Early rifting at the Gondwana margin began, and the Bounty Trough and New Caledonia Basin are considered to have opened at this time.

80 - 70 Ma: Late Cretaceous (Maps 3, 4)

The Tasman Sea and Southern Ocean began to open. The New Caledonia Basin and Bounty Trough 'rifts' 'failed' and east-dipping subduction may have commenced along the western side of north Norfolk Ridge, but the evidence is arguable. Back-arc basins developed in New Caledonia and to the east of the Norfolk Ridge (for example, the Norfolk Basin).

60 Ma: Late Paleocene (Map 5)

Spreading in the Tasman Sea and Southern Ocean was now almost complete. There may have continued to be a subduction zone along northwest Norfolk Ridge, but there was quiescence in the New Zealand region throughout this period. Was there a plate boundary in Antarctica?

50 - 40 Ma: Mid to Late Eocene (Maps 6, 7)

There is firmer evidence for an east-dipping subduction zone along the Norfolk Ridge, during which back-arc basins northeast of New Caledonia opened between the Early and late Middle Eocene. From the late Middle Eocene to Early Oligocene, convergence increased, the configuration of this plate boundary may have changed, marginal basins northeast of New Caledonia were 'closed' and newly-formed oceanic crust was obducted from the northeast on to New Caledonia.

A transform margin (or rift system) developed along the western side of New Zealand, with limited extension propagating from a spreading ridge in the South Tasman Sea.

30 Ma: Mid-Oligocene (Map 8)

The convergent plate boundary moved away from New Caledonia to the North Solomons. The transform margin (or rift system) was still present through western New Zealand. The South Fiji Basin began to open as a back-arc basin to an arc along either the Three Kings Rise or the Colville-Lau Ridge.

20 Ma: Early Miocene (Map 9)

Spreading in the South Fiji Basin and along the South Tasman Sea spreading ridge ceased at about 26 Ma. At about 23 Ma, the plate boundary began to propagate through New Zealand as a convergent boundary.

There was transform motion along the Vening Meinesz Fracture Zone (Figure 1), and this dextral movement was associated with the commencement of dextral shear between the two halves of North Island. This is the expression of relative plate motion through the North Island. These movements were in turn associated with Neogene clockwise rotation of the subduction system.

Farther south, the plate boundary became a zone of dextral transcurrent movement: the inception of the Alpine Fault. Immediately south of the Alpine Fault, an east-dipping subduction system developed along the line of the future Macquarie Ridge.

10 Ma: Late Miocene (Map 10)

A further change in the rotation path of the Pacific Plate (Stock and Molnar, 1982) triggered oblique compression along the Alpine Fault at this time, and this also caused commencement of uplift of the Macquarie Ridge. The two 'halves' of South Island were now closer together.

5 Ma: Early Pliocene (Map 11)

The subduction system (including eastern North Island) and associated arc rotated further clockwise. The Hauraki inter-arc basin (between Northland and Coromandel) had opened by now. The Havre Trough started to open and the active arc moved eastwards to the Kermadec Ridge. The rotation of the subduction system led to an increasing obliquity of compression on the Alpine Fault.

In the far north, the Loyalty Ridge began to collide with the New Hebrides arc at about 8 Ma, due to commencement of clockwise rotation of that arc.

0 Ma: present day (Map 12)

From ~1 Ma, the Kermadec arc propagated through North Island as the Taupo arc.

The Taupo back-arc basin opened at about that time and is still extending. Dextral transpression along the Alpine Fault brought the two 'halves' of South Island to their present position.

6. IMPLICATIONS FOR HYDROCARBON POTENTIAL

In conclusion, some of the implications which the plate tectonic development of the region has for hydrocarbon potential will be briefly mentioned.

The fault-controlled Early Cretaceous basins, in the New Zealand and Lord Howe Rise region, have a thick largely non-marine fill (including coal measures), reflecting deposition at southerly latitudes. Some of these units may be correlatives of the Strzelecki Group in the Gippsland Basin (New Zealand was much nearer Australia than it is now). Moreover, these early-rift sequences in the Taranaki Basin are thought to be both source rocks and potential reservoirs (see Thrasher, 1989; King, in press). Failed rifts such as the New Caledonia Basin and Bounty Trough are also prospective areas.

New Zealand and New Caledonia underwent a similar evolution in the Cretaceous and Paleocene. In the Paleocene, for example, there was extensive shale deposition in both eastern North Island and New Caledonia. This Paleocene shale is one of New Zealand's richest potential source rocks (see Moore, 1989). The source rock for oil and gas found in Eocene flysch in two exploration wells in onshore New Caledonia in the 1950s (Paris, 1981) could possibly be Paleocene.

The structural style and regional extent of the zone of Eocene - Oligocene basins through, and immediately offshore of, western New Zealand, are also of potential hydrocarbon interest.

There was inversion of Palaeogene basins, particularly west of the plate boundary zone, during the propagation of the convergent plate boundary through New Zealand in the Neogene (Figure 5). These inversion structures are important hydrocarbon traps. Conversely, the transpressive regime has also initiated new basins - for example, the rapid and continuing subsidence of the South Wanganui Basin, which started at the beginning of the Pliocene.

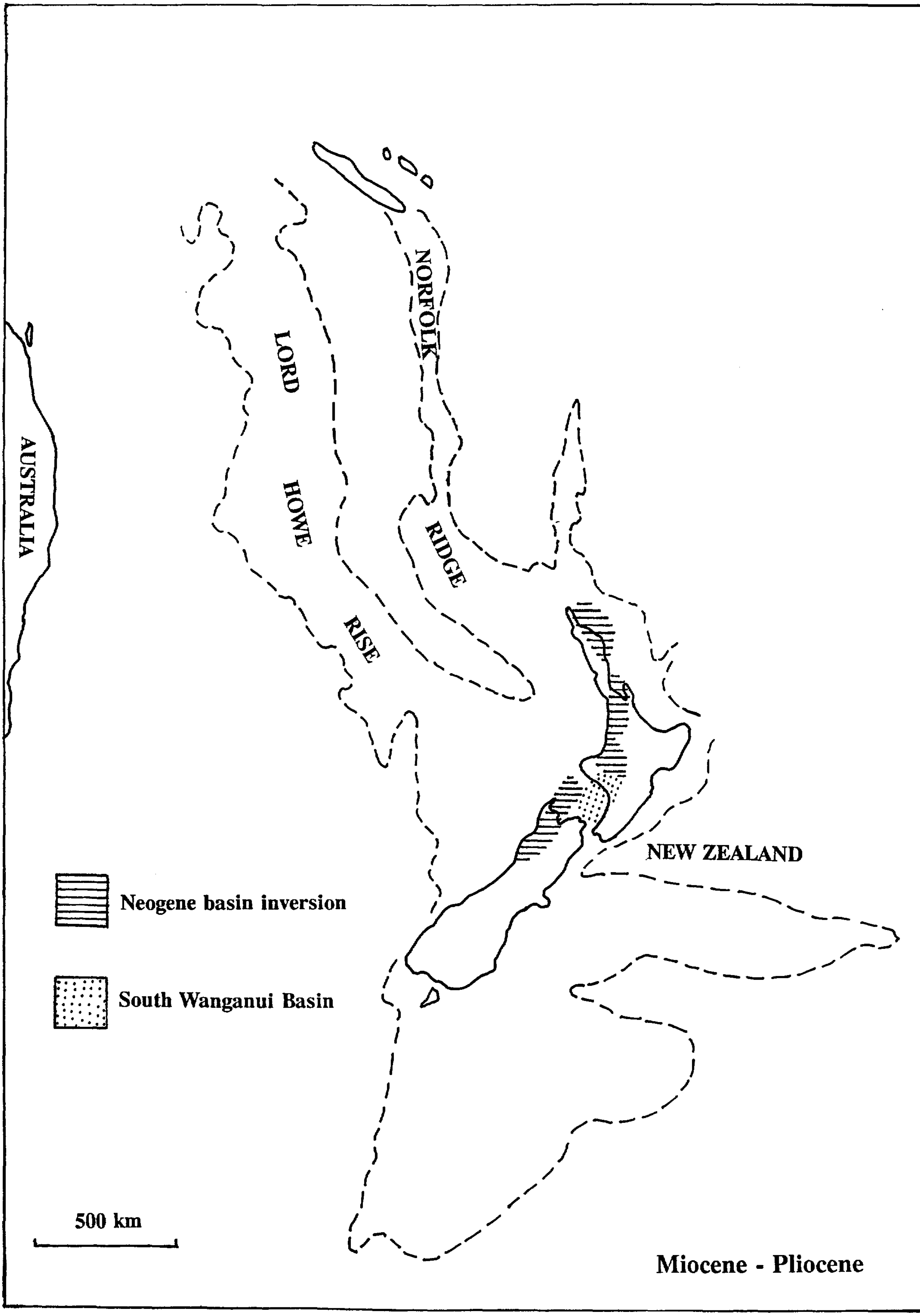


FIGURE 5: Neogene basin inversion, New Zealand

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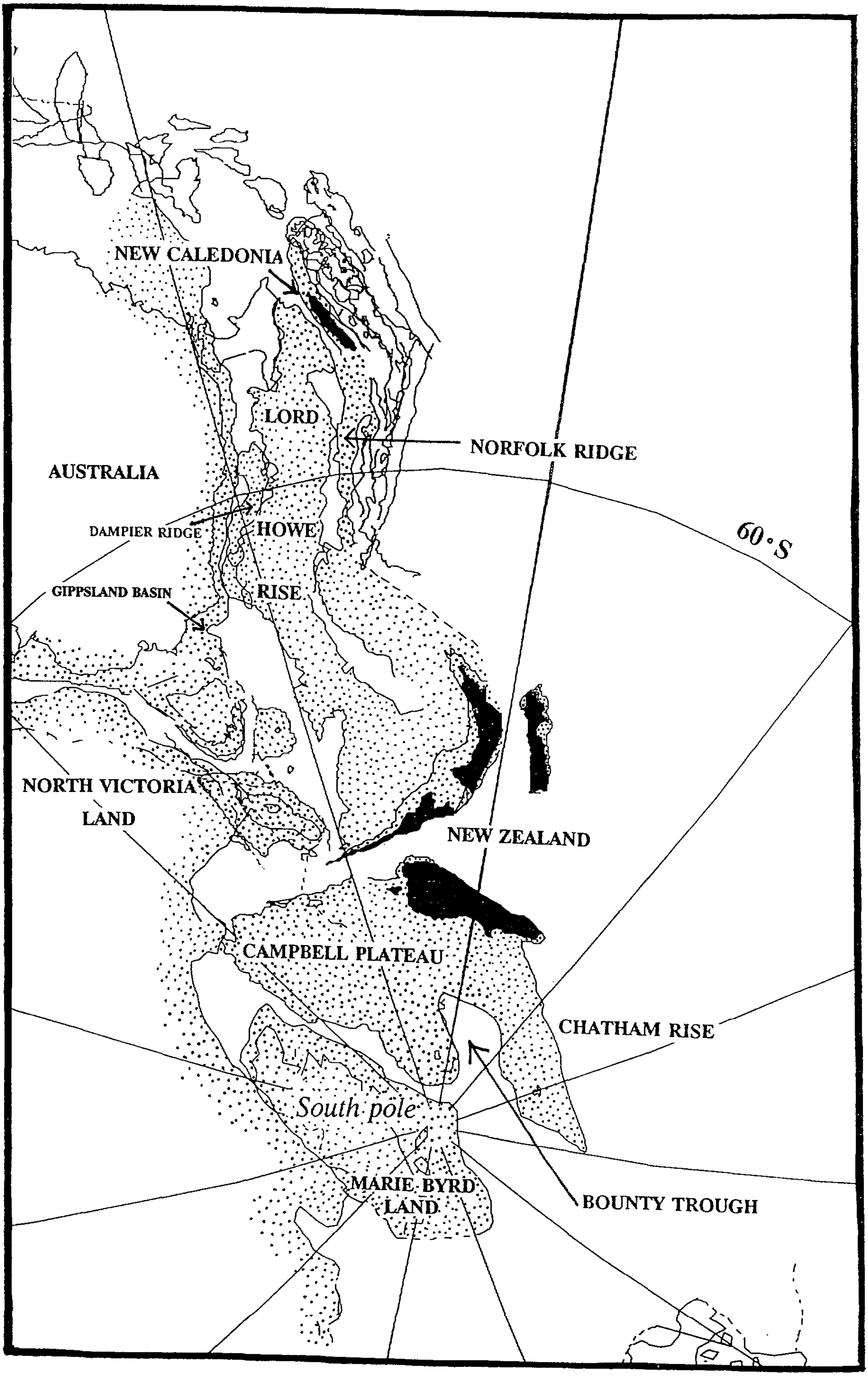
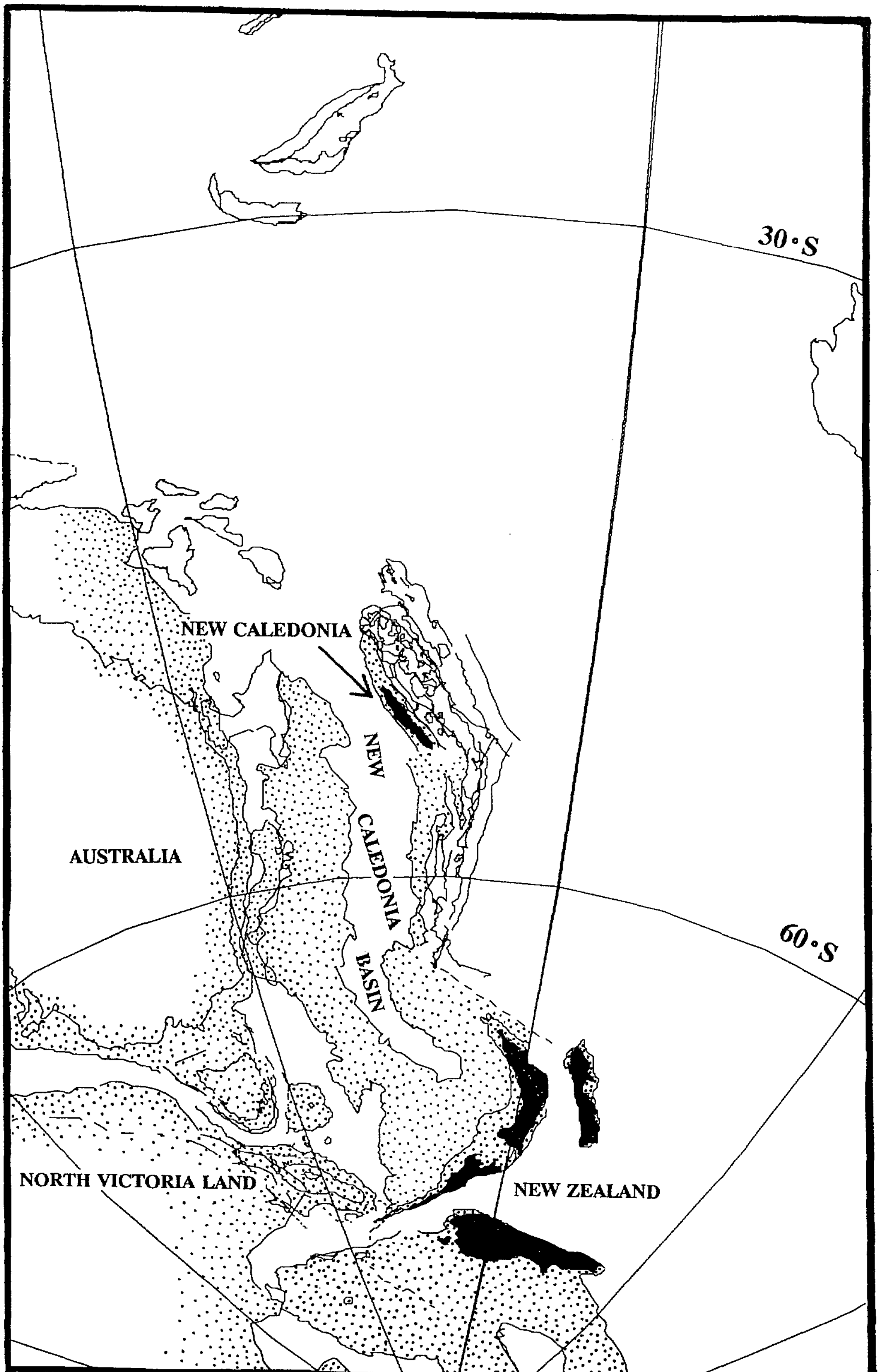
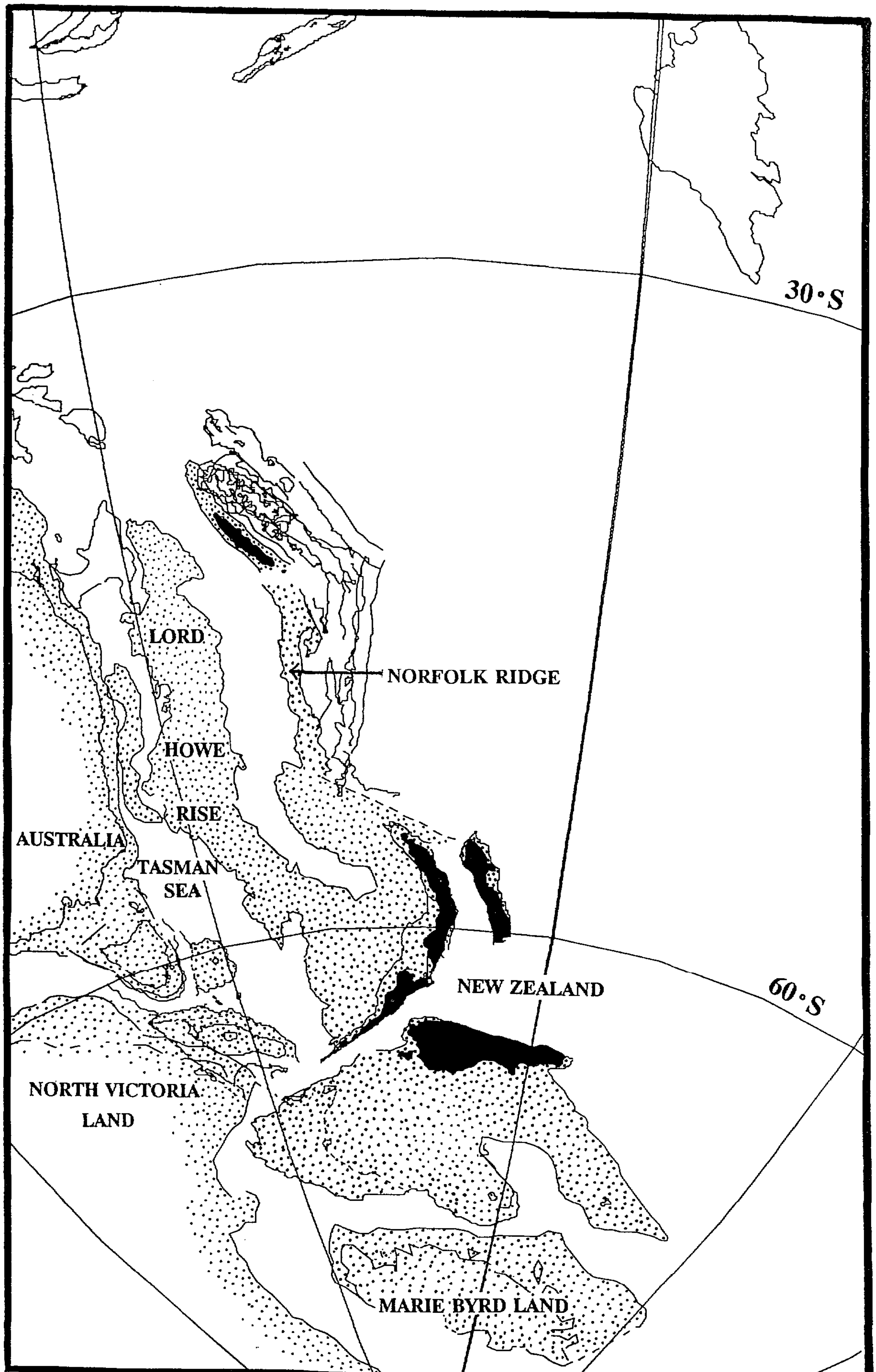


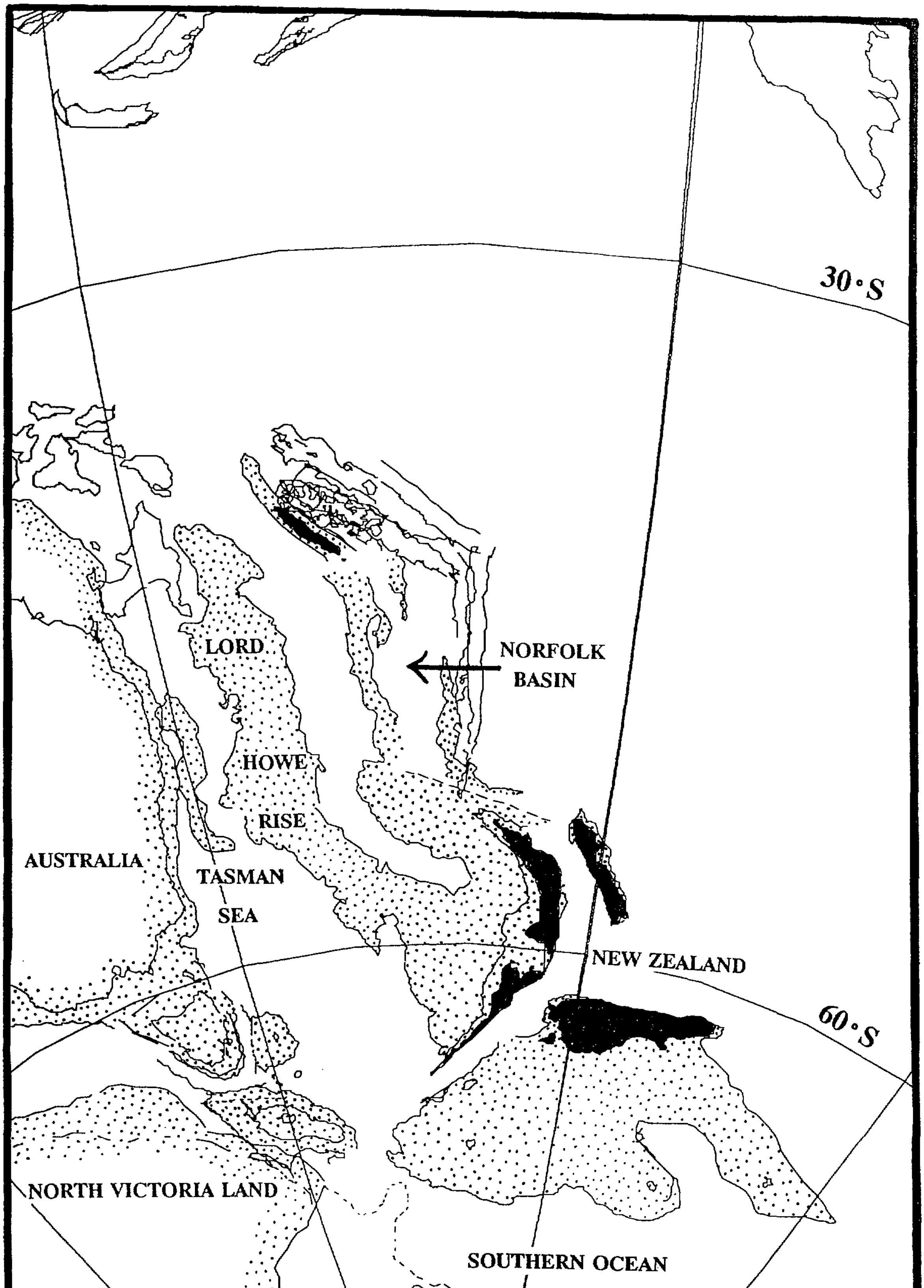
MAP 1 100 Ma: Early Cretaceous (late Albian)



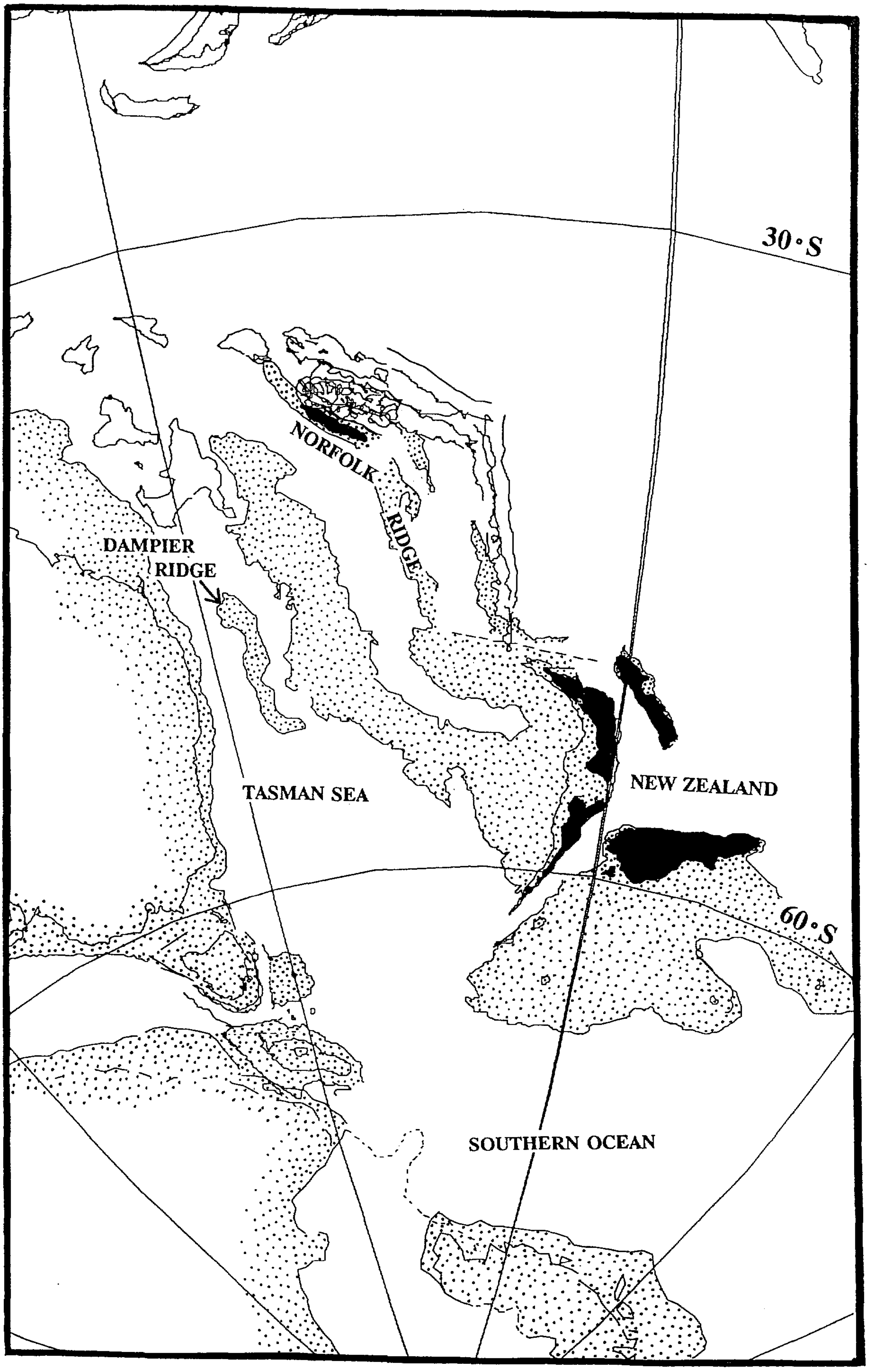
MAP 2 90 Ma: Late Cretaceous (Turonian)



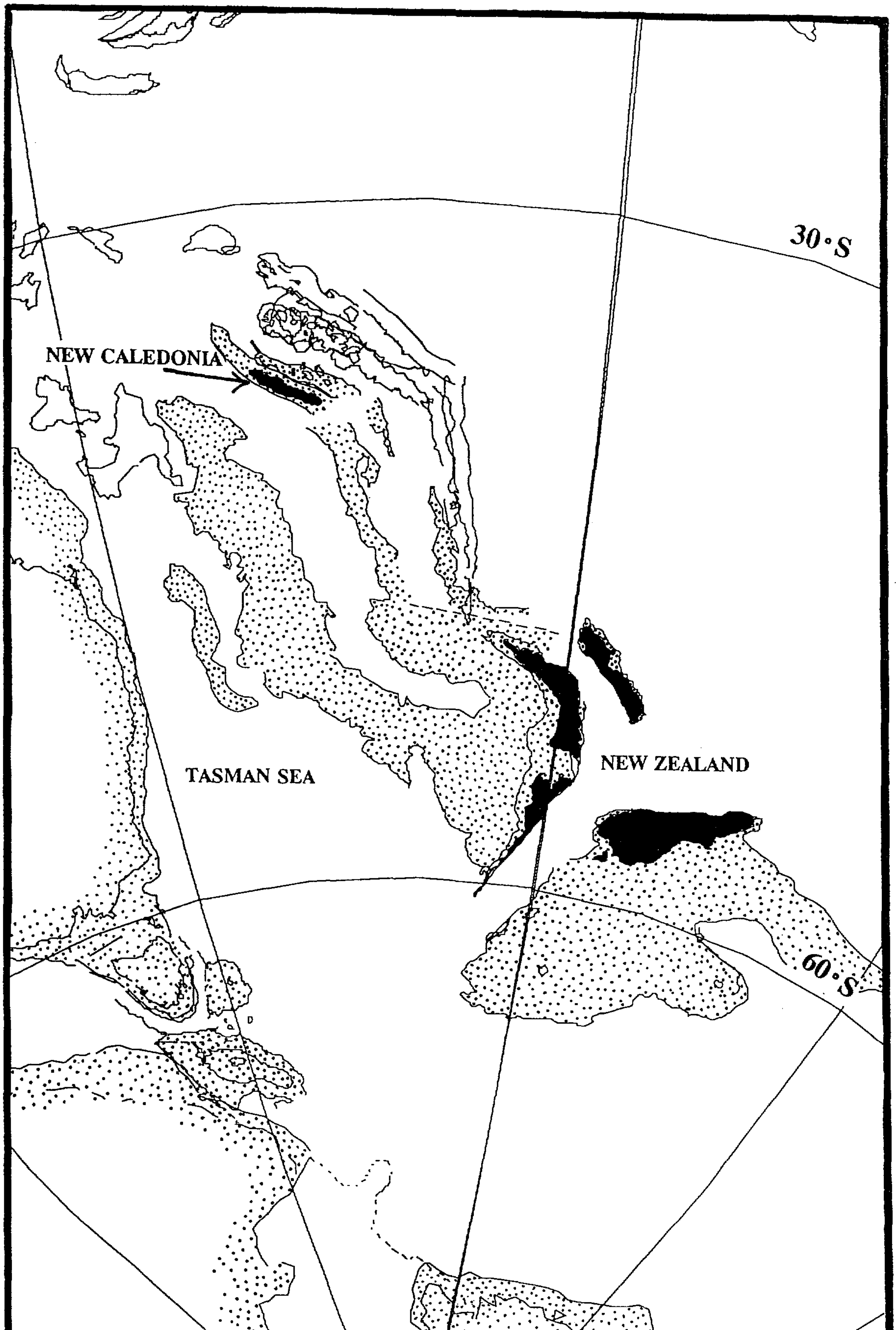
MAP 3 80 Ma: Late Cretaceous (early Campanian)



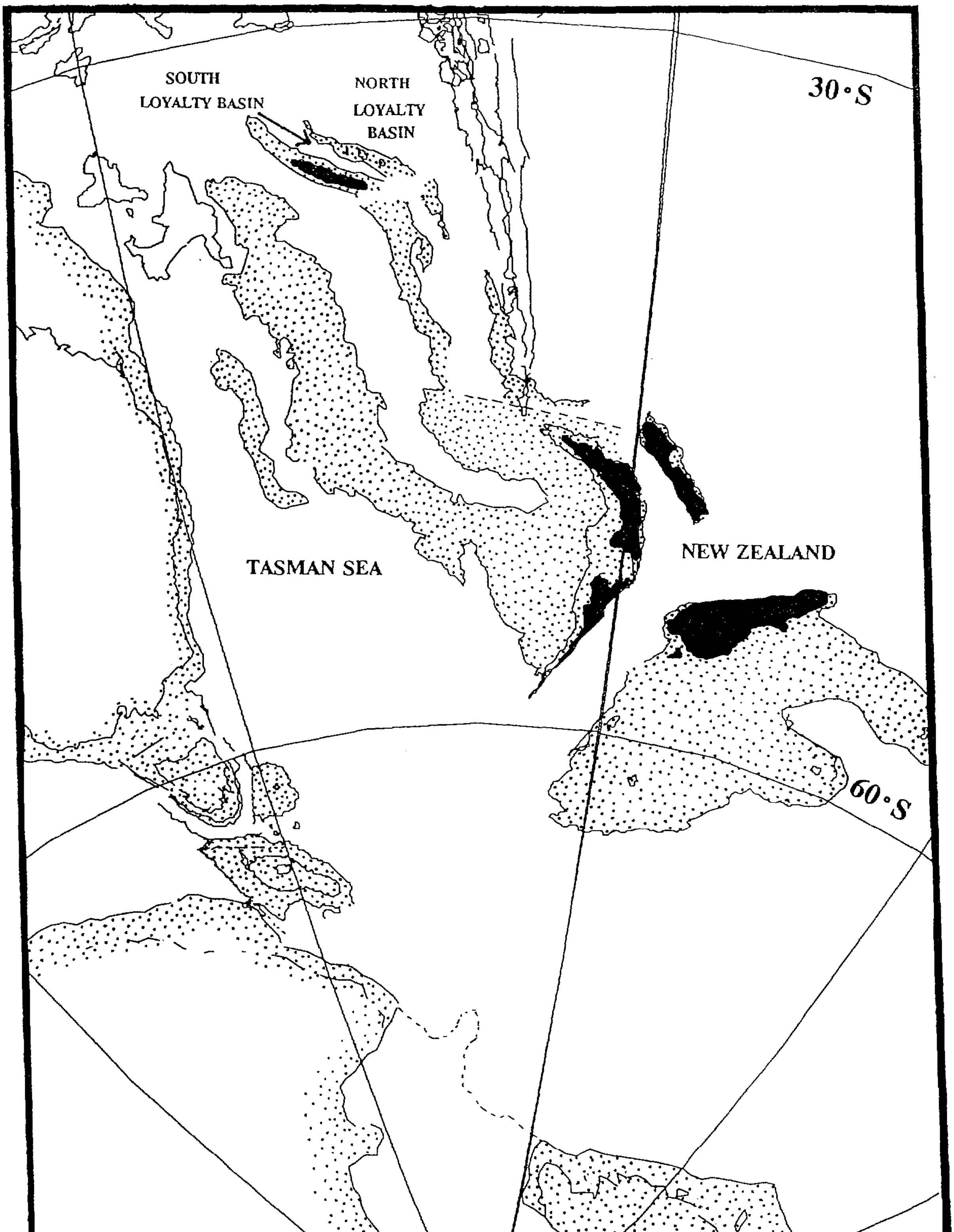
MAP 4 70 Ma: Late Cretaceous (Maastrichtian)



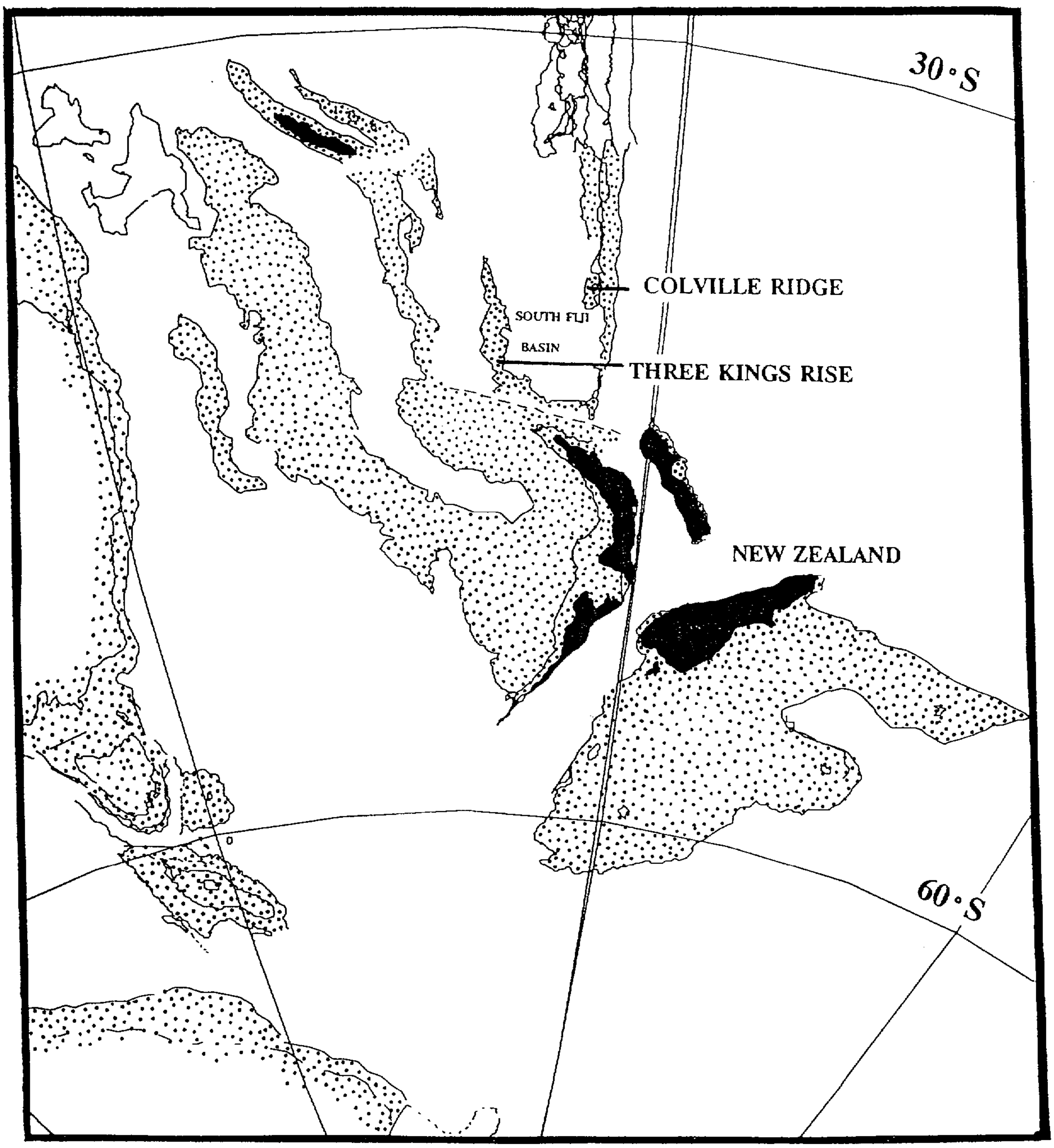
MAP 5 60 Ma: Late Paleocene



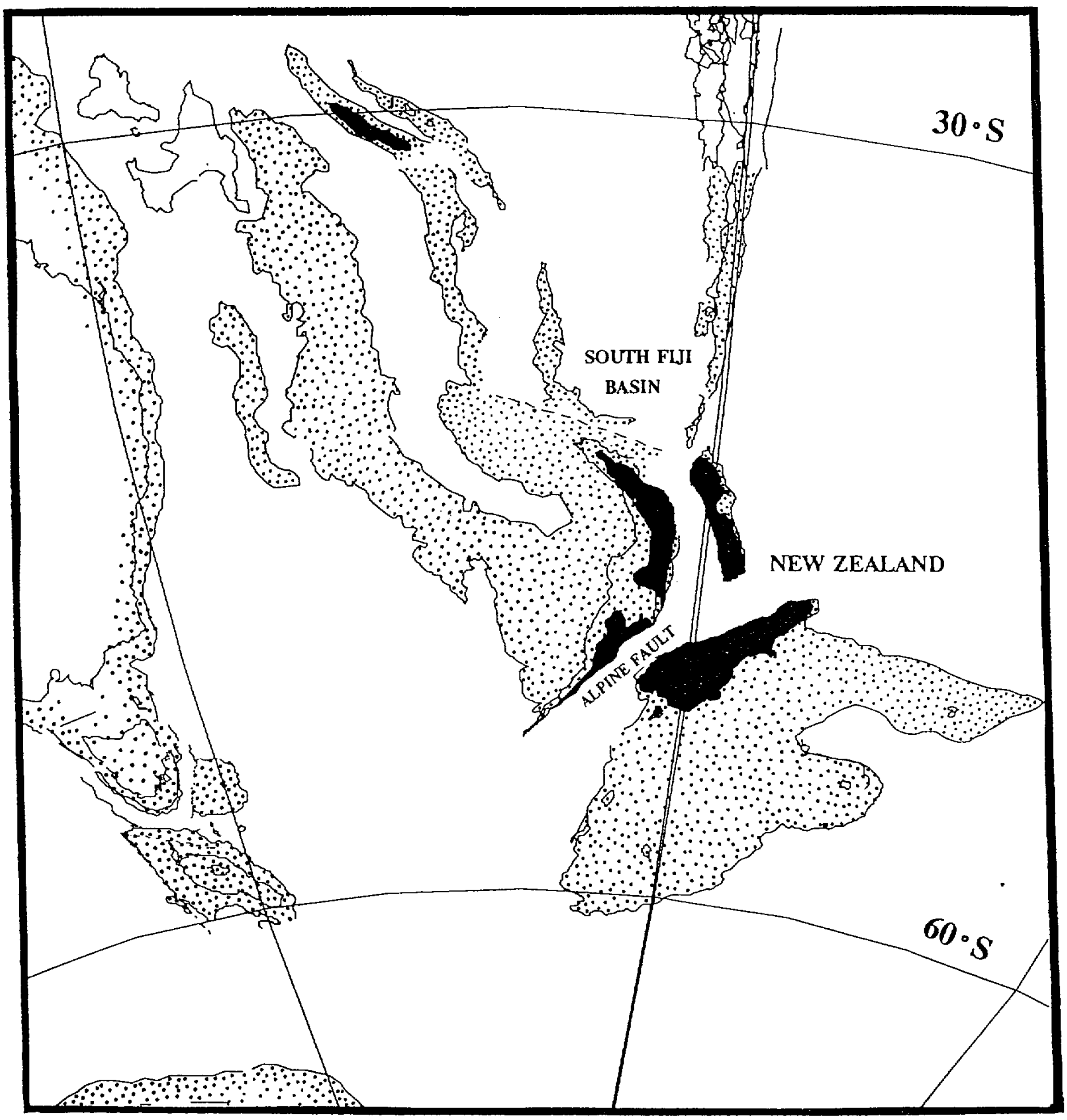
MAP 6 50 Ma: Mid-Eocene



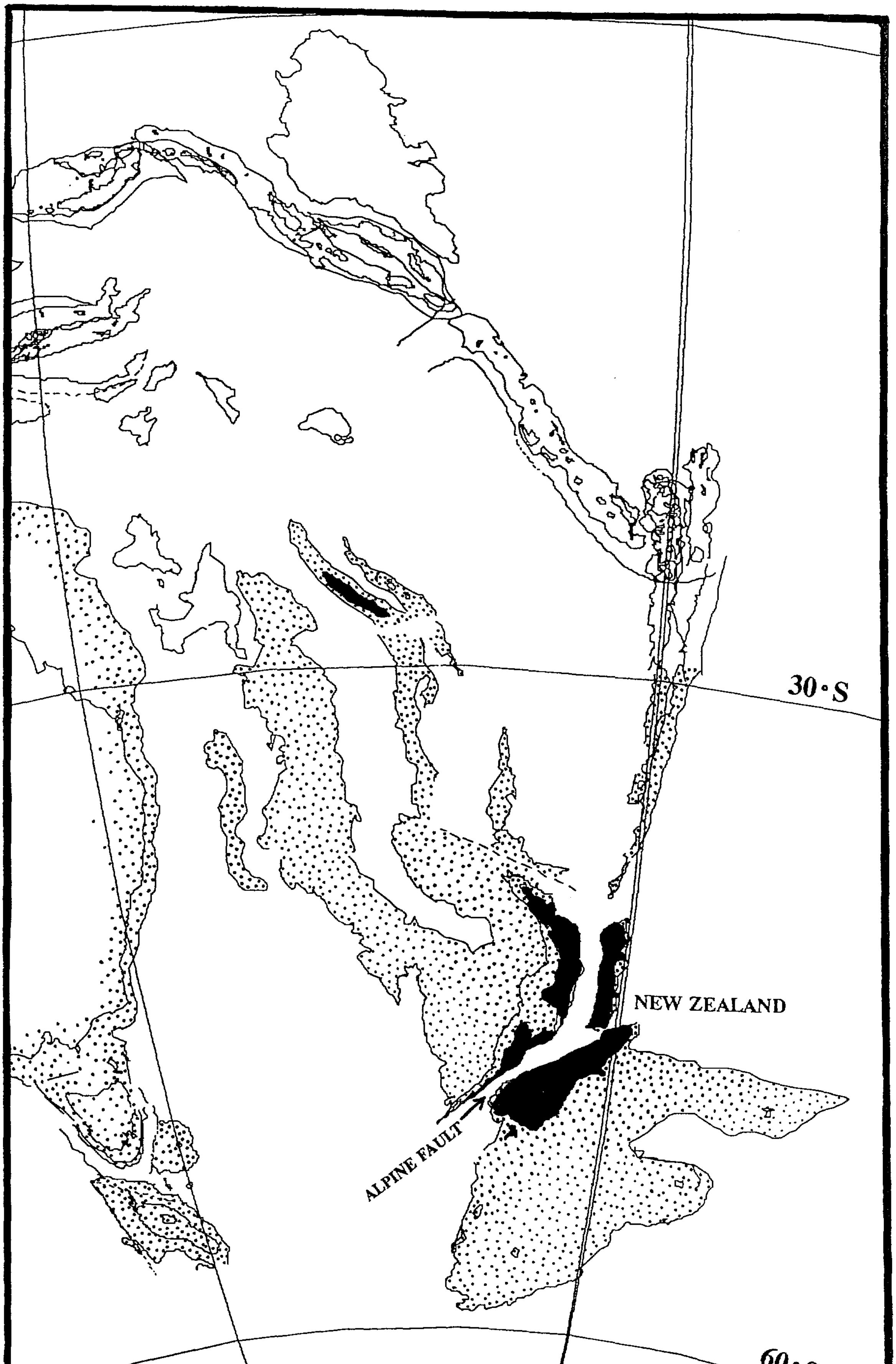
MAP 7 40 Ma: Late Eocene



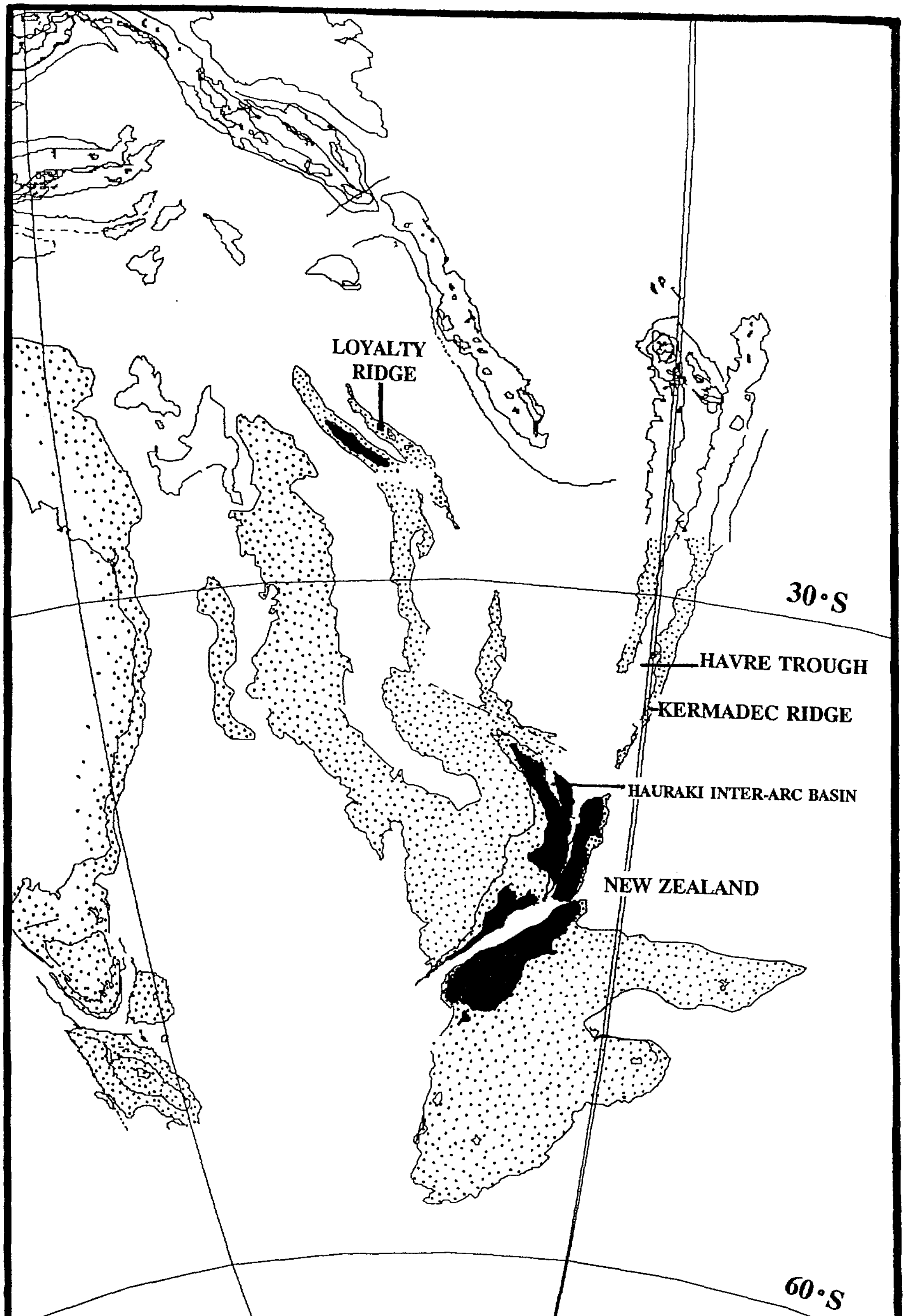
MAP 8 30 Ma: Mid-Oligocene



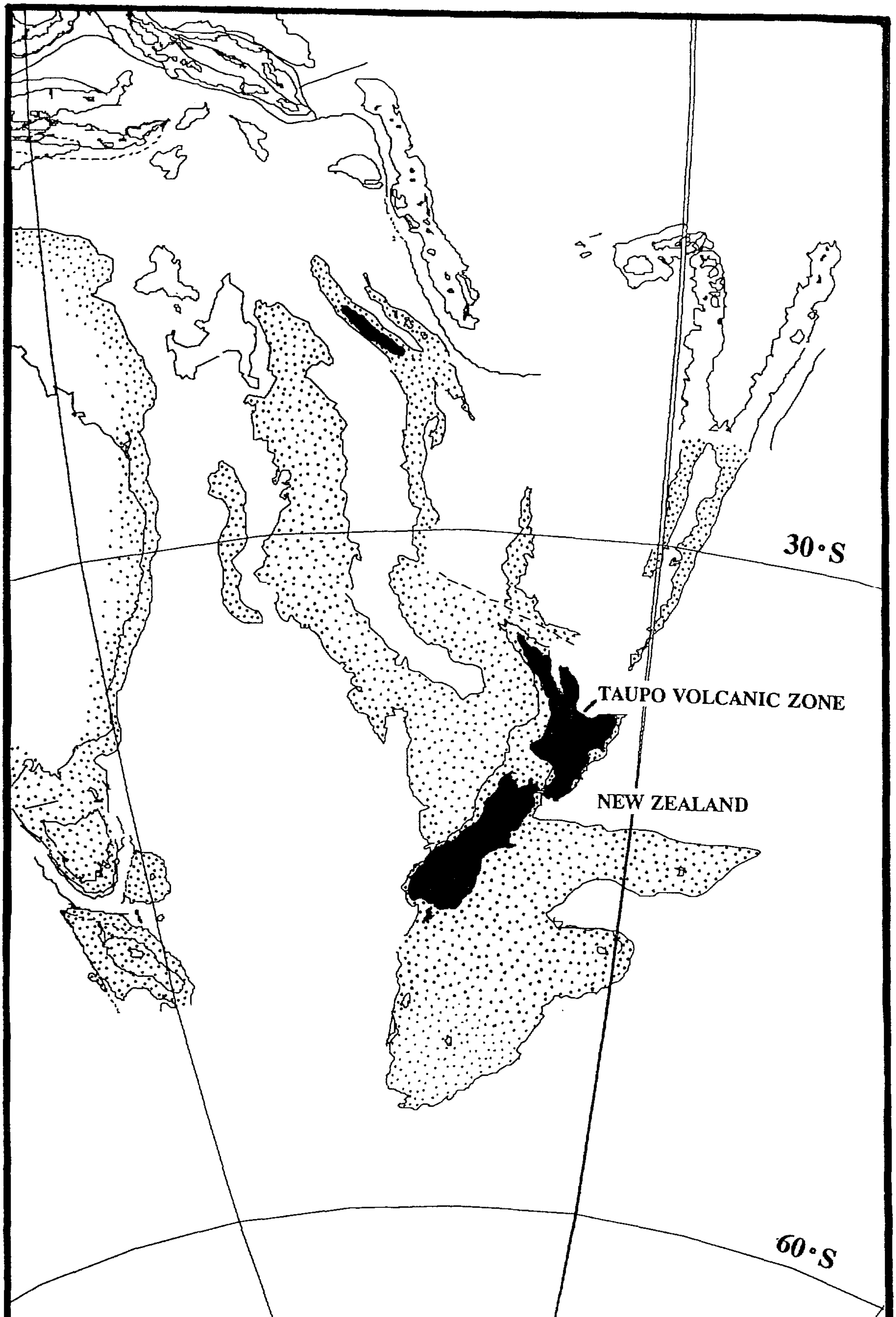
MAP 9 20 Ma: Early Miocene



MAP 10 10 Ma: Late Miocene



MAP 11 5 Ma: Early Pliocene



MAP 12 0 Ma: present day