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Marshall Paraconformity: a mid-Oligocene record of inception of the Antarctic Circumpolar Current and coeval glacio-eustatic lowstand?

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The sedimentary fill of the Canterbury Basin, New Zealand, is the product of a long-term (80 Ma), tectonically controlled relative sea-level cycle with a megasequence geometry analogous to the sequence stratigraphic model of Vail (*Am. Assoc. Petrol. Geol. Stud. Geol. No. 27*, **1**, 1–10, 1987). The condensed section of the megasequence, resolvable in detail in outcrop and on seismic profiles, comprises a basin-wide pelagic to hemipelagic limestone interval. A regional mid-Oligocene unconformity, the Marshall Paraconformity, lies within the limestone interval onshore and correlates with hiatuses in at least two, and possibly three, offshore exploration wells and with a temporary lithological change from limestone to quartz sand at a fourth. Strontium isotopic age estimates confirm that a 2–4 Ma hiatus is associated with onshore outcrops of the Marshall Paraconformity (between ~32 and 29 Ma), which correlates with the opening of the Pacific sector of the Southern Ocean and the postulated mid-Oligocene sea-level fall of Haq *et al.* (*Science* **235**, 1156–1167, 1987; *Spec. Publ. Soc. Econ. Paleonotol. Mineral. No. 42*, 71–108, 1988). Lowering of base level, coupled with cooling and enhancement of current activity, may have caused the temporary cessation of limestone deposition and a regional hiatus. This hypothesis reconciles the apparently contradictory palaeogeographical evidence for a regional highstand. The Marshall Paraconformity may exemplify the signature by which similar glacio-eustatic events can be recognized in offshore platform facies.

Keywords: sequence stratigraphy; sea-level changes; Antarctic Circumpolar Current

The upper Eocene to lower Miocene sedimentary section in the Canterbury Basin, on the eastern margin of the South Island of New Zealand (*Figure 1*), is highly condensed. Within this interval, the Marshall Paraconformity is a regional mid-Oligocene unconformity that can be identified at numerous localities (Carter and Landis, 1972; Carter, 1985; Lewis, 1992). A probable equivalent surface also occurs in southern Australia (e.g. Abele *et al.*, 1976). The age of the unconformity coincides approximately with the hypothesized major mid-Oligocene (30 Ma) eustatic fall shown on the global cycle chart of Haq *et al.* (1987; 1988) (Hornibrook, 1987). Regional geological evidence has, however, generally been interpreted as requiring the condensed sediments associated with the Marshall Paraconformity to have been deposited during a period of maximum transgression and relative sea-level highstand in the New Zealand region (Carter, 1985). Evidence for subaerial exposure at the Marshall Paraconformity is localized (Lewis, 1992) and has been questioned (Carter, 1985). In addition, uncertainties remain regarding the age of the Marshall Paraconformity relative to the timing of the postulated eustatic fall (Hornibrook, 1987). To establish that the mid-Oligocene sea-level fall was a global event, the ambiguities in the evidence from New Zealand must be reconciled. We attempt to achieve this by integrating seismic profiles, drilling results from four exploration wells in the Canterbury Basin and new strontium isotopic age data.

Sediments above and below the Marshall Paraconformity constitute a condensed section that was

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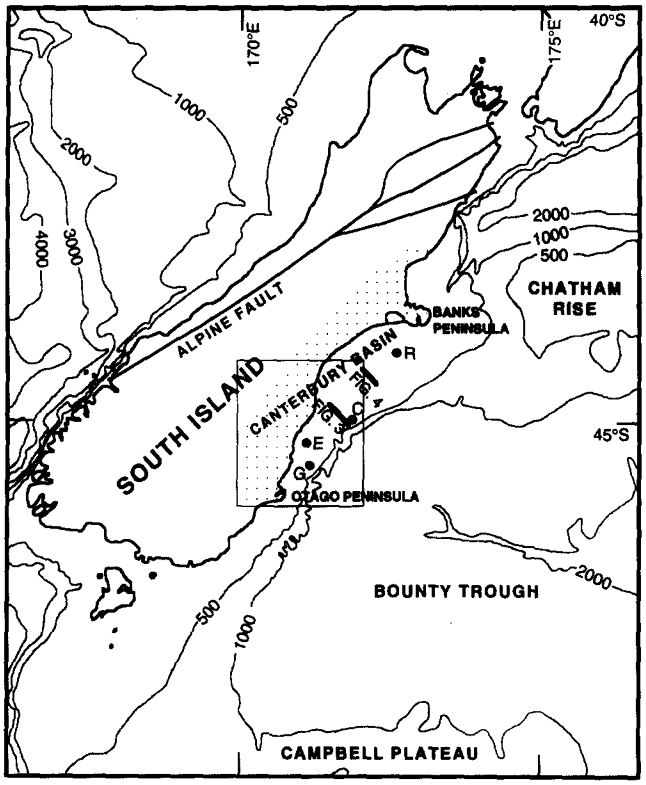

Figure 1 South Island of New Zealand showing Canterbury Basin (onshore part stippled), seismic lines CB-82-54 (*Figure 3*), CB-82-26 (*Figure 4*) and locations of exploration wells: G, Galleon; E, Endeavour; C, Clipper; and R, Resolution. Box shows location of map in *Figure 5*

defined from outcrop studies (Gate, 1957; Carter and Landis, 1972; Jenkins, 1971; 1987; 1993; Carter *et al.*, 1982; Hornibrook, 1966; 1987; Carter, 1985). Rather than being the product of a single, short (e.g. third-order) eustatic cycle, the condensed section developed in response to a long-term (80 Ma) tectonic cycle, on which are superimposed numerous higher frequency (third- and fourth-order) sequences (Loutit *et al.*, 1988; Fulthorpe, 1991). A multichannel seismic (MCS) grid from the offshore Canterbury Basin displays the depositional geometries associated with the long-term transgressive–regressive cycle. The resulting mega-sequence can be resolved seismically in considerable detail and provides a model for the development of the usually less well-resolved, condensed sections associated with maximum transgression within single third- or higher-order sequences.

Geological setting

The eastern margin of the South Island of New Zealand (*Figure 1*) is part of a continental fragment that includes the Campbell Plateau, Chatham Rise and Bounty Trough and which rifted from Antarctica beginning at about 80 Ma (Molnar *et al.*, 1975; Weissel *et al.*, 1977). The most extensive basement faulting and crustal thinning occurred seaward of the present day shelf edge. The Bounty Trough, a rifted basin which formed at a high angle to the strike of the margin, lies within this distal zone.

The Canterbury Basin is located at the landward edge of the continental fragment and underlies the present day Canterbury Plains and continental shelf (*Figures 1* and *2*). Despite its proximity to a major plate boundary, currently represented by the Alpine Fault, the Canterbury Basin has been an area of relative tectonic stability, characterized by subsidence since the Late Cretaceous rifting event. Subsidence has allowed an estimated 9.1 cm/ky of post-Oligocene sediment accumulation (uncorrected) at the Clipper exploration well near the modern shelf edge (Fulthorpe and Carter, 1989). The high rate of sediment accumulation and tectonically stable setting combine to make the Canterbury Basin an attractive location at which to test the concepts of sequence stratigraphy. Seismic profiles show little or no Cenozoic faulting apart from that associated with local igneous intrusions of Eocene to Oligocene and middle–late Miocene age (Milne *et al.*, 1975; Coombs *et al.*, 1986). The Banks and Otago peninsulas (*Figure 1*) are mid–late Miocene volcanic centres situated on basement uplifts with a relatively thin cover of post-rift sediments. Basin sediments also thin onshore and ultimately become involved in faulting associated with the development of the Southern Alps. The thickest sedimentary section, 6.5 km including basal rift-fill, lies approximately midway between the Banks and Otago peninsulas near the present day shelf edge (Browne and Field, 1988). The seismic character of the post-rift sediment varies laterally across the basin and vertically through the section and reflects the way in which the basin has filled in response to tectonics, rate of sediment supply and eustasy.

Post-rift stratigraphy of the Canterbury Basin: a Cretaceous–Cenozoic megacycle

The post-rift Cretaceous to Recent sedimentary history of the Canterbury Basin comprises a first-order, tectonically controlled, transgressive–regressive cycle. The sedimentary section can be divided into three distinct intervals during which contrasting, large-scale sedimentary processes operated. Transgression occurred during the Late Cretaceous and early Cenozoic and regression during the late Cenozoic (*Figure 2*). Maximum regional transgression occurred during the Oligocene, with the development of a basin-wide condensed interval in association with the Marshall Paraconformity (Carter, 1985). Three major groups (Onekakara, Kekenodon and Otakou) are recognized, which correspond to these three sedimentary phases. This nomenclature follows Carter (1977), Carter and Carter (1982) and Carter (1988) and was evolved to provide regionally applicable names for groups and formations. An alternative lithostratigraphy has been proposed by Field and Browne (1986).

Cretaceous–Oligocene transgression. A relative rise in sea level accompanied post-rift subsidence. Transgression caused major reflections to onlap basement and produced a distinctive pattern of seismic reflections with shallow seaward dips and ramp-style sedimentary architecture below reflection Green (*Figure 3*). Onlap occurs against some of these reflections, indicating that they are sequence boundaries of the type described by Vail (1987) and Van Wagoner *et al.* (1988). Examples of onlap are scarce, however, and truncation was not observed because shallowly

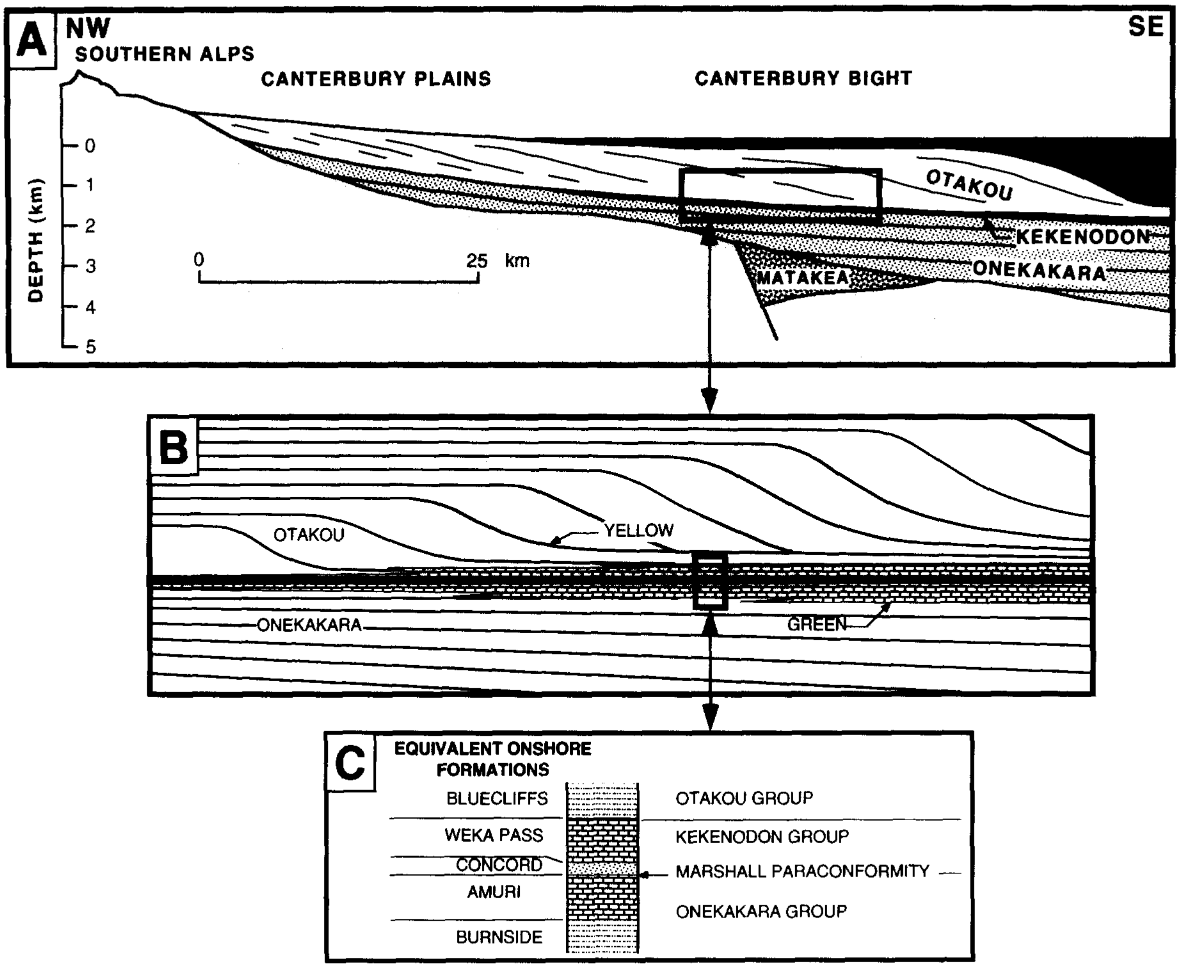

Figure 2 Schematic stratigraphy of the Canterbury Basin at various scales. (A) Large-scale, post-rift stratigraphy. Onekakara, Kekenodon and Otakou groups were deposited during regional transgressive, highstand and regressive phases, respectively. (B) Seismic-scale stratigraphy. Successive clinoforms generally prograde over older, toe of clinoform sediment, but current reworking produces downlap onto seismic reflection Yellow (*Figure 3*) in places. Limestones are shown as distal facies of upper transgressive Onekakara Group and lower regressive Otakou Group. Limestone facies boundaries are near-horizontal and are responsible for seismic reflection Green (*Figure 3*). (C) Outcrop-scale stratigraphy across the Marshall Paraconformity

dipping reflection geometries provide few resolvable reflection terminations. Sequence boundaries are continuous surfaces that can be traced across the seismic grid and suggest that transgression was episodic and that the post-rift trend of rising relative sea level was punctuated by periods of relative sea-level still-stand or lowering (Fulthorpe, 1991).

Oligocene highstand. The transgressive phase terminated during the Oligocene when flooding of the land mass was at a maximum (Fleming, 1962; Suggate *et al.*, 1978). Reduced terrigenous influx resulted in the deposition of pelagic limestone, the Amuri and Weka Pass formations (and equivalent units; cf. Carter, 1988), which outcrop extensively onshore (Speight and Wild, 1918; Morris, 1987). In most onland outcrops, a bioturbated glauconitic sand, the Concord Greensand Formation and equivalent units, occurs between the Amuri and Weka Pass limestones. In some areas, particularly North Canterbury (Field and Brown, 1989), the Concord Greensand grades laterally onto the base of the Weka Pass limestone, emphasizing its nature as a basal, condensed facies of the limestone. The base of the Concord Greensand Formation is commonly a burrowed omission surface which has been designated the Marshall Paraconformity (Carter and Landis, 1972) and marks the base of the Kekenodon Group (*Figure 2*).

Offshore exploration wells reveal that limestones were deposited over much of a broad, near-horizontal platform above the Cretaceous–Oligocene transgressive sediments (*Figure 2*). These limestones are probable equivalents of the onland Amuri and Weka Pass formations (Speight and Wild, 1918), though their ages vary across the platform. Existence of the mid-Cenozoic platform, which represented the mature stage of the ~80–35 Ma rift–drift cycle, greatly influenced the subsequent Neogene sedimentary evolution of the margin. Water depth during the period of limestone deposition is not known accurately, but is crucial to understanding the origins of the Marshall Paraconformity and, in particular, the role of eustasy. Faunal composition of limestones encountered in offshore exploration wells mostly indicate depths of outer shelf (100–200 m) to upper bathyal (200–600 m), with some evidence for slightly shallower environments above the Marshall Paraconformity than below (Wilding and Sweetman, 1971; Milne *et al.*, 1975; Wilson, 1985). Onshore outcrops indicate outer shelf to bathyal depths of deposition for the Amuri Limestone (Lewis, 1992).

Miocene–Recent regression. Miocene regression

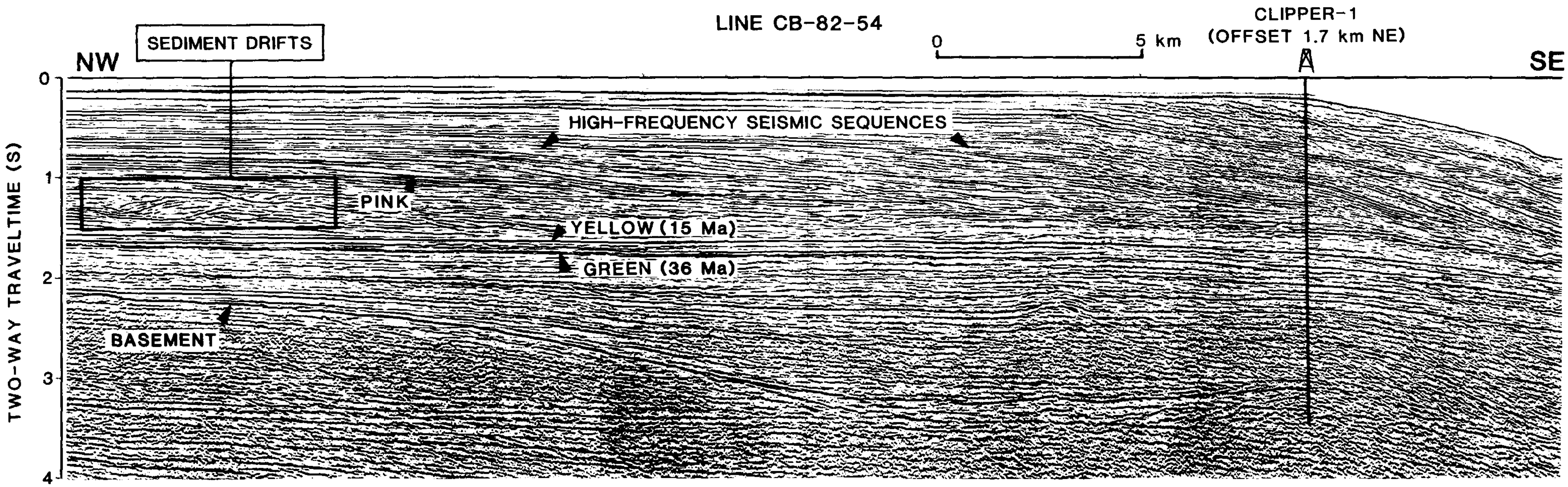

Figure 3 Multichannel seismic (60-fold) dip profile CB-82-54 (migrated) from the central part of Canterbury Basin (see *Figure 1* for location), showing regional seismic reflections Green, Yellow and Pink. Note prograding clinoforms of the Otakou Group above reflection Yellow, which form high-frequency sequences above Pink, and evidence for sediment drifts. Ages are approximate and were estimated by extrapolation to Clipper exploration well, offset 1.7 km from this profile

Miocene–Recent regression. Miocene regression occurred in response to an increase in the supply of sediment which accompanied the mid-Cenozoic development of strike-slip motion on the Alpine Fault (Norris *et al.*, 1978). The sediment influx was deposited as the clinoform Otakou Group (Carter and Carter, 1982) and has resulted in the eastward progradation of the shelf since the late Oligocene or early Miocene at rates of between 1.5 and 4.9 km/Ma. Offshore exploration wells Clipper (Hawkes and Mound, 1984), Galleon (Wilson, 1985) and Endeavour (Wilding and Sweetman, 1971) reveal sediments of the Otakou Group to be predominantly terrigenous siltstone with intermittent intervals of fine to very fine-grained sand and mud, whereas at Resolution the lithology is predominantly silty mudstone (Milne *et al.*, 1975). The Otakou Group offshore therefore exhibits similar lithology to the onland Bluecliffs Silt (Gair, 1959) and the equivalent Waikari Formation (Andrews, 1963). The presence of sediment drifts (*Figures 3* and *4*) provides evidence of strong current activity during deposition of the Otakou Group. Progradation, in part, resulted from the seaward accretion of successive sediment drifts in some areas of the basin (Fulthorpe and Carter, 1991).

Nature of the Marshall Paraconformity

The detailed lithostratigraphy of the mid-Cenozoic limestone interval is best revealed in outcrup (*Figure 5*), where the Amuri Formation is a bioturbated, foraminiferal coccolith chalk (Suggate *et al.*, 1978; Morris, 1987). It is overlain by the thin Concord Greensand Formation (generally less than 2 m thick), a micritic, glauconitic sand with little terrigenous sediment (Carter, 1985; 1988). The greensand is intensely bioturbated and its base is a burrowed omission surface (Marshall Paraconformity). In most outcrops, the Concord Greensand Formation grades into the overlying Weka Pass Limestone Formation, a micritic calcarenite, often glauconitic, with an abundant brachiopod–echinoderm–pectinid macrofauna and rich planktonic microfauna (Carter, 1988). The Weka Pass Limestone is strongly bioturbated throughout, but in many locations also contains large-scale crossbedding (Ward and Lewis, 1975; Carter, 1988). Faunal and textural evidence is consistent with a shallower water depositional environment above the Marshall Paraconformity than below. The textural evidence includes increased quartz grain size and coarse skewness of the quartz grain size distribution, consistent with the winnowing of fines, above the paraconformity (J. Wilson, unpublished data).

Lewis (1992) reported dissolution features, interpreted as evidence for subaerial exposure, at some onshore outcrops of the Marshall Paraconformity in North Canterbury. Such evidence does not, however, occur at most outcrops of the unconformity and Lewis (1992) inferred that subaerial exposure was restricted to local palaeotopographic highs produced by folding. The Eocene–Oamaru guyot is a long-known example of a high that led to an extended hiatus associated with the development of the Marshall Paraconformity. There, lower Miocene Gee Greensand rests directly on the cemented, phosphatized top of the lower Oligocene Totara Limestone and a hiatus of ~10 Ma is indicated (Gage, 1957). More recently, Field and Browne (1989) have presented evidence that the Oamaru region formed part of a larger, coast-parallel high, the Endeavour High, against which Oligocene units are cut out, consistent with the high first becoming active in the Late Eocene to early Oligocene. The main effect of the Endeavour High on the Marshall Paraconformity was therefore to extend the hiatus across the top of the High, as at the Endeavour exploration well discussed further in the following.

Although many of the features described by Lewis (1992) may represent solution features, their age of formation is not well constrained. For example, spectacular karsting has long been known to occur at the top of the Weka Pass limestone down to the level of the Marshall Paraconformity, but the age of formation of these features post-dates deposition and is probably Pliocene (Willett, 1946). Furthermore, in many onshore locations, some of which were interpreted as palaeotopographic lows by Lewis (1992), evidence for subaerial exposure at the unconformity is lacking and the hiatus is inferred to be non-depositional, rather than erosional (Carter, 1985; Lewis, 1992). Unless all evidence of subaerial exposure was eroded during the subsequent relative sea-level rise (which is indeed commonly the case in, for example, Pleistocene sequences; Abbott and Carter, 1994), water depths greater than the magnitude of the mid-Oligocene eustatic fall are indicated at such locations. The existence of non-terrigenous glauconitic and phosphatic sediments immediately overlying the Marshall Paraconformity is consistent with relatively deep water post-unconformity conditions (Carter, 1985; Lewis, 1992).

Offshore seismic profiles over a wide region reveal little evidence of folding or topographic highs that existed during the Oligocene. Closed structures affecting mid-Tertiary sediments do, however, exist at the Endeavour and Resolution exploration wells. The timing of uplift at Endeavour is uncertain (Wilding and Sweetman, 1971) and its influence on the formation of the unconformity cannot be ruled out. At Resolution, however, uplift has been ascribed to a middle Miocene igneous intrusion (12±2 Ma) and lower Oligocene and lower Miocene rocks pass over the structure without thickness change (Milne *et al.*, 1975).

Decompaction of seismically interpreted palaeoshelf sediment prisms, preserved in the prograding Otakou Group overlying the mid-Cenozoic platform, yields an estimate of the height of the middle Miocene (~15 Ma) palaeoshelf above the platform of the order of 650 m in the central part of the offshore Canterbury Basin. Making the conservative assumption that such palaeoshelves were at sea level, 650 m is an estimate of the minimum middle Miocene water depth over the mid-Cenozoic platform. Subsidence of the transgressed continental margin platform would have continued during the late Oligocene and early Miocene. Assuming lithospheric stretching during rifting in the Canterbury Basin by a factor $\beta=1.5$ (a very high value for a such an inboard location on the rifted margin) and sediment fill to sea level (conservative), 400 m of subsidence is predicted by the rifting model of McKenzie (1978) for the interval between 30 and 15 Ma (50 and 65 Ma post-rift). Subtracting this amount from the middle Miocene geometric depth estimate of 650 m

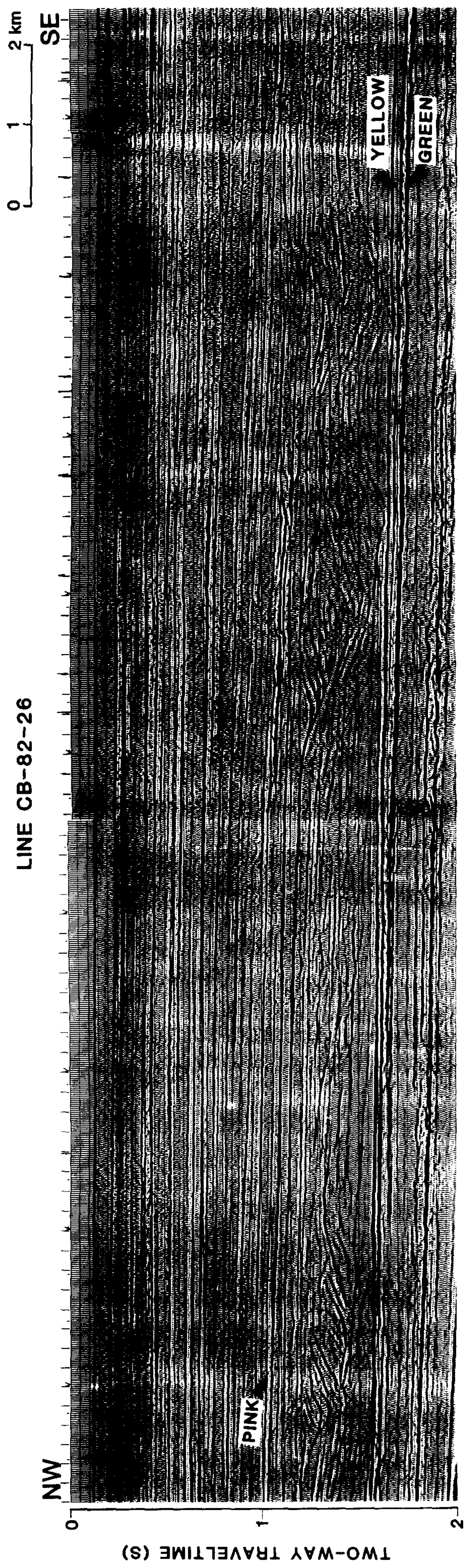

Figure 4 Multichannel seismic (60-fold) dip profile CB-82-26 (migrated) showing current-deposited sediment drifts between 1 s and reflection Yellow (~15 Ma). See *Figure 1* for location

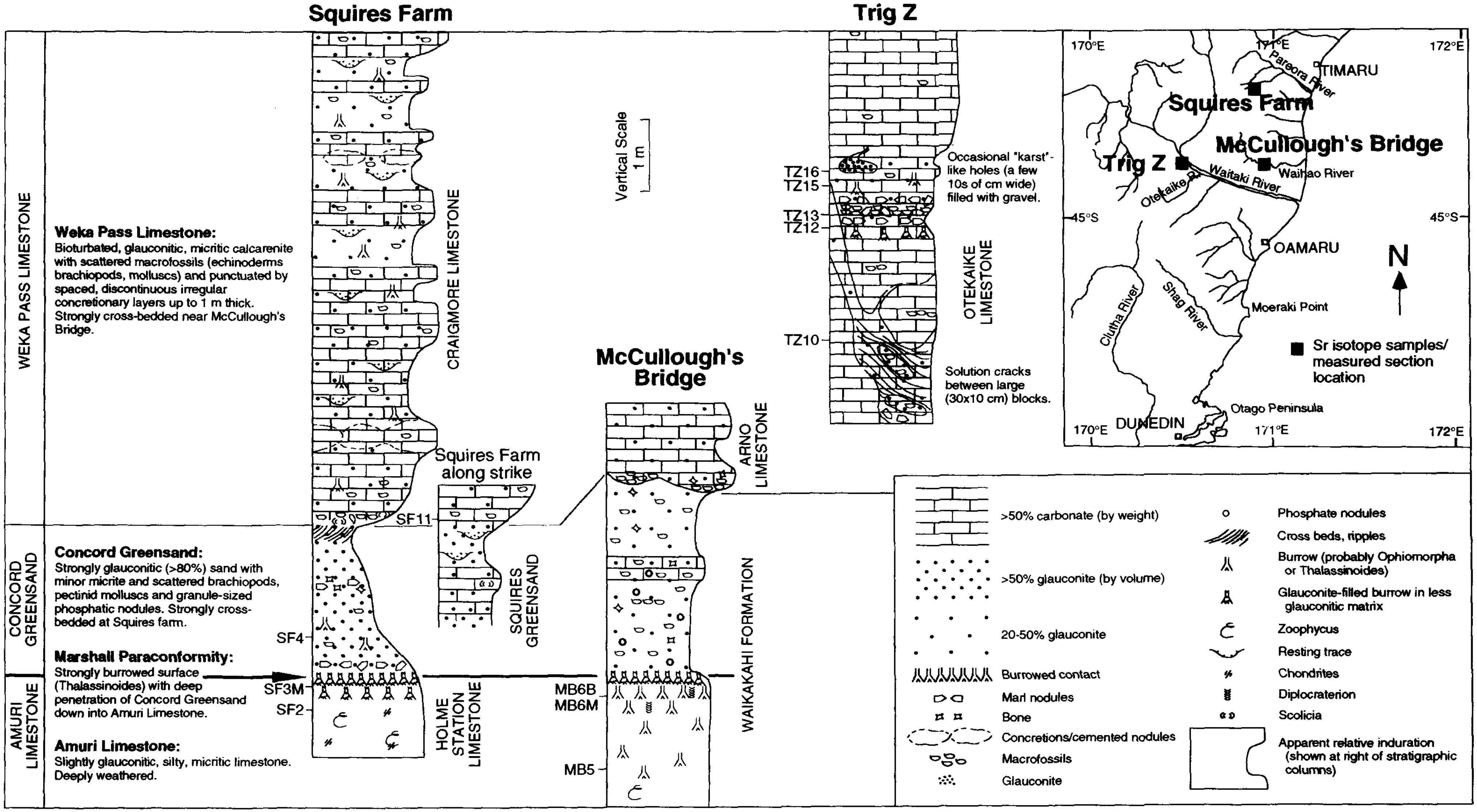

Figure 5 Measured stratigraphic sections in the vicinity of the Marshall Paraconformity at Squires Farm, McCullough's Bridge and Trig Z (J. Williams, unpublished data). Location shown on map inset. Local formation names synonymous with the regional Weka Pass Limestone, Concord Greensand and Amuri Limestone formations (Carter, 1988) are given alongside stratigraphic columns. SF4, MB6B, etc., are locations of samples taken for strontium isotope analysis. In highly burrowed intervals, suffices B and M refer to samples taken from burrow and matrix, respectively

results in a minimum water depth estimate of 250 m for the central part of the Canterbury Basin platform during the mid-Oligocene (30 Ma), in agreement with the outer shelf to bathyal palaeoenvironment indicated by limestone faunal compositions and greater than the probable magnitude of the mid-Oligocene eustatic fall (e.g. Haq *et al.*, 1987; 1988).

Any explanation of the origin of the Marshall Paraconformity must therefore take into account the likelihood that water depths across much of the seismically defined mid-Cenozoic platform, as well as at many onshore outcrops of the Marshall Paraconformity, were sufficient to prevent any mid-Oligocene eustatic fall from exposing the Amuri Limestone to subaerial erosion. This, together with concerns about the age of the Marshall Paraconformity relative to the timing of the proposed mid-Oligocene eustatic fall of Haq *et al.* (1987; 1988), has made it difficult to achieve consensus on a link between the Marshall Paraconformity and the mid-Oligocene eustatic fall (Carter, 1985; Hornibrook, 1987; Lewis, 1992).

Seismic structure of the megasequence

The geometry of the sedimentary fill of the Canterbury Basin, as revealed on MCS profiles (*Figure 3*), is analogous to that of the sequence stratigraphic model of Vail (1987), Van Wagoner *et al.* (1987; 1988), Posamentier *et al.* (1988), Posamentier and Vail (1988) and Vail *et al.* (1991). Both are the results of relative sea-level cycles, albeit of different periods. The Canterbury Basin fill developed in response to a long-term tectonic cycle which encompasses numerous higher frequency, inferred eustatic, sequences (Loutit *et al.*, 1988; Browne and Field, 1988; Fulthorpe and Carter, 1989; Fulthorpe, 1991). Because the Canterbury Basin megasequence has been resolved seismically in considerable detail, it can be used to illustrate the development of the more common, but generally thinner and less well resolved, third- and higher-order sequences on which the Haq *et al.* (1987; 1988) curve is based. In particular, the megasequence illustrates well the geometry of the mid-cycle condensed section. Loutit *et al.* (1988) referred to this interval in the Canterbury Basin as a composite condensed section, which they inferred to be the product of several third-order eustatic cycles.

By analogy with the sequence stratigraphic model, the Cretaceous–Oligocene transgressive section (Onekakara Group) is equivalent to the transgressive systems tract (TST) and was deposited during the relative sea-level rise that accompanied post-rift subsidence (*Figure 2*). The Oligocene Kekenodon Group approximates the condensed interval, deposited as the supply of terrigenous sediment was restricted near relative sea-level highstand and maximum transgression. The early Miocene to Recent regressive section (Otakou Group) is equivalent to the highstand system tract (HST), deposited as the rate of relative sea-level rise decreased and the rate of sediment supply increased, causing progradation.

Seismic resolution of the megasequence condensed section

Seismic profiles from the centre of the Canterbury Basin (*Figure 3*) illustrate that downlap of HST clinoforms occurs at progressively higher stratigraphic levels in the basinward direction because of the progradation of successive clinoforms over previously deposited toe-of-clinoform sediment. The toe-of-clinoform sediment blanket represents the continuation of the condensed section into the basal HST. At the landward ends of dip profiles, prograding offlapping reflections downlap into a regional reflection, labelled Green by oil industry interpreters. However, the point of downlap (i.e. the break in slope at the junction between any clinoform and its contemporaneous toe-of-slope sediment) rises offshore. For example, Yellow,a prominent reflection above Green over much of the basin, is of wide extent and is itself a downlap surface (DLS) for higher reflections over part of the basin. Further offshore still, downlap occurs onto horizons above Yellow (*Figure 3*). There is, therefore, generally no single, regional stratigraphic surface of downlap (*Figure 6A*). This confirms the result of Rudolph *et al.* (1989), whose seismic modelling showed that a single DLS is commonly an oversimplification, the result of acoustic interference where foreslope beds thin below seismic resolution at clinoform toes (see also Thorne, 1992).

Seismic profiles from the Canterbury Basin also indicate, however, that a regional DLS, which represents a stratigraphic discontinuity, can occur under special circumstances. This requires that toe-of-clinoform sediment is removed or reworked in advance of the prograding clinoforms (*Figure 6B*). Such a situation existed in some areas of the Canterbury Basin, where current activity scoured a platform to the level of horizon Yellow and deposited the overlying sediment in large drifts (Fulthorpe and Carter, 1991) (*Figures 3* and *4*). Downlap in this region therefore occurs onto a single omission surface which might be regionally identifiable in outcrop.

Correlation with lithostratigraphy. Offshore wells through the seismically defined, sequence stratigraphic condensed interval penetrated a limestone interval that is the age and/or facies equivalent of the Amuri, Concord and Weka Pass formations and which contrasts strongly with overlying and underlying terrigenous sediments. The base of this basin-wide limestone

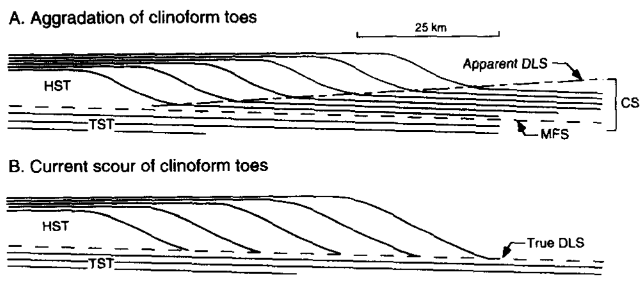

Figure 6 (A) DLS as an artifact of limited seismic resolution of aggrading toe-of-clinoform sediment. Site of apparent downlap rises offshore. (B) Special case of current scour of clinoform toes producing a true DLS. DLS, Downlap surface; MFS, maximum flooding surface; CS, condensed section; TST, transgressive systems tract; HST, highstand systems tract

interval is marked by a significant sonic velocity shift at the Resolution, Galleon and Endeavour exploration wells and correlates approximately with seismic reflection Green (*Figure 3*), providing additional confirmation that the limestone interval in the upper part of the transgressive sequence (Onekakara Group) is part of the condensed interval of the Canterbury Basin megasequence. Green horizon can be traced throughout almost the entire seismic grid. It is sub-horizontal, with only a slight seaward dip (*Figure 3*). Pelagic to hemipelagic carbonate deposition therefore occurred simultaneously across a broad, near-horizontal platform on top of the Cretaceous–Palaeogene terrigenous transgressive section. The upper and lower boundaries of the limestone interval are facies boundaries (*Figure 2*; Carter, 1988), but the platform depositional geometry resulted in facies boundaries being virtually horizontal, and consequently bedding-parallel. Correlation of reflection Green with a facies boundary does not therefore conflict with the seismic sequence stratigraphic principle that reflections are time horizons (*Figure 2*). The limestone interval is thickest (150 m) at the most basinward exploration well (Clipper) and, in general, thins landward. As discussed earlier, the condensed section in the sequence stratigraphic model (Loutit *et al.*, 1988; Baum and Vail, 1988) includes the uppermost sediment of the TST and the distal toe-of-clinoform sediment of the overlying HST, unless the latter has been removed by current activity. In the Canterbury Basin, the Amuri Limestone, Marshall Paraconformity/Concord Greensand and Weka Pass Limestone, deposited during the Oligocene to early Miocene, comprise the core of the megasequence condensed section.

Age of the Marshall Paraconformity

The long-standing problem of dating the Marshall Paraconformity accurately has resulted from three factors (Carter, 1985). Firstly, most New Zealand Oligocene sequences, including specifically the type section of the late Oligocene Duntroonian Stage, are developed in condensed sedimentary facies. Thus the local biostratigraphy has been poorly discriminatory for this period. Secondly, dating has relied heavily on microfossil determinations from strata that are heavily burrowed and in which reworked species are common (cf. Hornibrook, 1966). Thirdly, very few of the papers that discuss the micropalaeontological age of the paraconformity contain adequate descriptions of the physical stratigraphy and sedimentology of the samples collected.

Despite these problems, the published microfaunal evidence has consistently indicated a mid-Oligocene age for the Marshall Paraconformity. In terms of local New Zealand biostratigraphy, once allowance is made for reworked specimens, virtually all the dated samples from above the paraconformity are Duntroonian (post-*Globigerina angiporoides* Zone, i.e. post-~32 Ma; Hornbrook, 1966; 1987; Jenkins, 1971; Findlay, 1980). Isolated occurrences of *G. angiporoides* or other early Oligocene microfossils in sediments above the paraconformity (Hornibrook, 1966; Jenkins, 1971; Hornibrook, 1985, also quoted in Field and Browne, 1989) are almost certainly reworked. It is therefore well established that most of the late early Oligocene *Chiloguembelina cubensis* Zone and the lower parts of the *G. euapertura* Zone are missing from New Zealand sections at the position of the Marshall Paraconformity. Hornibrook (1987) summarized the microfaunal evidence as indicating a mid-Oligocene gap of about 4 Ma across the unconformity, with 'the top *G. antiporoides* datum ... somewhere in the Marshall Paraconformity' (written personal communication to R. M. Carter, 1993).

The youngest sediments below the paraconformity are lower Whaingaroan (Waghorn, 1981; Hornibrook, 1966). The end of the early Whaingaroan is at 32 Ma (early Oligocene) in the time-scale of Edwards *et al.* (1988). The oldest overlying sediments may be upper Whaingaroan and the minimum hiatus across the Marshall Paraconformity indicated by biostratigraphy is of the order of 2 Ma (Jenkins, 1987) to 4 Ma (Hornibrook, 1987). The Marshall Paraconformity apparently everywhere encompasses a core 2–4 Ma hiatus of mid-Oligocene age. However, the total time gap represented across the paraconformity may locally range up to 15 Ma. For instance, some sections have sediments as old as Eocene beneath the paraconformity (e.g. Dunedin, offshore well Endeavour), whereas offshore the oldest dated sediments overlying the unconformity are as young as early Miocene. Such extended hiatuses formed in response to local effects such as gentle warping, or sediment starvation, and their existence does not affect the validity of the Marshall Paraconformity as a regionally important feature.

Strontium isotopic ages

Previous estimates of the age of the Marshall Paraconformity have relied on biostratigraphic data. We have attempted to date the Marshall Paraconformity more precisely using age estimates based on strontium isotope values (*Table 1*; *Figure 5*). Two of the locations are outcrops of the Marshall Paraconformity: Squires Farm, the type section (Carter *et al.*, 1982), and McCullough's Bridge. A third location, Trig Z, originally thought to be an outcrop of the Marshall Paraconformity, is indicated by strontium isotopic ages to be a younger surface without a measurable hiatus (*Table 1*).

Strontium isotope data were generated on mixed foraminiferal taxa following the procedures outlined in Miller *et al.* (1988). Mixed species of foraminifera were cleaned in distilled water and dissolved in 1.5 N HCl. Standard ion-exchange techniques were used to separate strontium, which was analysed on a VG Sector mass spectrometer at Rutgers University. The internal precision on the Sector is approximately ± 0.000007 (mean for the 12 samples in this study) and the external precision is between ± 0.000020 and ± 0.000030 or better (Miller *et al.*, 1991a; Oslick *et al.*, 1994). At the time that we analysed the New Zealand samples, NBS 987 was routinely measured as 0.710250 normalized to $^{86}Sr/^{88}Sr$ of 0.1194 (Miller *et al.*, 1988) and values are reported as $^{87}Sr/^{86}Sr$ ratios (*Table 1*). We measured Recent marine carbonates as 0.709185 and 0.709195 on the giant clam EN-1, an informal Sr isotope standard; this allowed conversion of the data to the $\delta_{seawater}$ notation of Hess *et al.* (1986).

Age estimates were obtained using the empirical

Table 1 Strontium isotopic ages

Squires Farm				McCullough's Bridge				Trig Z			
Sample	$^{87}Sr/^{86}Sr$	Internal error	Age BKF85 (CK92)	Sample	$^{87}Sr/^{86}Sr$	Internal error	Age BKF85 (CK92)	Sample	$^{87}Sr/^{86}Sr$	Internal error	Age BKF85 (CK92)
SF11	0.708240	±0.000013	24.6 (24.5)					TZ16	0.708261	±0.000004	24.0 (24.1)
SF4	0.708088	±0.000008	29.0 (27.5)					TZ15	0.708258	±0.000004	24.1 (24.2)
								---------Unconformity?---------			
		-------------------Marshall Paraconformity-------------------						TZ13	0.708298	±0.000006	23.0 (23.4)
SF3M	0.707971	±0.000010	32.4 (30.7)	MB6B	0.708031	±0.000010	30.6 (28.6)	TZ12	0.708256	±0.000006	24.2 (24.2)
SF2	0.707954	±0.000006	32.9 (31.2)	MB5	0.707989	±0.000006	31.8 (30.3)	TZ10	0.708253	±0.000008	24.3 (24.3)
				MB6M	0.707955	±0.000004	32.8 (31.2)				

BKF85 ages were estimated from Sr isotope values using the following regression (Miller *et al.*, 1988): Age (Ma) = 20 392.79 − 28 758.84 ($^{87}Sr/^{86}Sr$), valid from 23 to 38 Ma. BKF85 is used for all correlations in this paper.
CK92 ages are also reported. They were estimated using the following regressions (Oslick *et al.*, 1994); Age (Ma) = 13 803.52 − 19 455.25 ($^{87}Sr/^{86}Sr$), valid from 23.2 to 28.0 Ma; Age (Ma) = 19 374.21 − 27 322.40 ($^{87}Sr/^{86}Sr$), valid from 23.2 to 28.0 Ma.
Note: in highly burrowed intervals, suffix B indicates a sample taken from a filled burrow and suffix M indicates a sample from surrounding matrix.

Oligocene age-strontium isotope calibration of Miller *et al.* (1988), which is calibrated to the geomagnetic polarity time scale (GPTS) and biostratigraphic ages of Berggren *et al.* (1985b; referred to as BKF85) for the Oligocene (*Table 1*). We recalibrated the inferred eustatic curve of Haq *et al.* (1987; 1988) to the GPTS of Berggren *et al.* (1985a; 1985b) based on their reported biostratigraphy and thus achieved a reasonably consistent chronology between the Haq *et al.* (1987; 1988) and New Zealand records (*Figure 7*). The GPTS has recently been revised (Cande and Kent, 1992; referred to as CK92); however, biostratigraphic ages have not been fully recalibrated to the new GPTS. Thus we used BKF85 in our comparisons (*Figure 7*). We also report (*Table 1*) Sr isotopic ages to CK92 using the equations of Oslick *et al.* (1994). However, note that these ages are younger than those of BKF85 and Haq *et al.* (1987) due to differences in the age calibration.

At the Squires Farm type section (*Figure 5*), strontium isotopic age estimates indicate that the hiatus across the Marshall Paraconformity is 3–4 Ma (from ~32.4 to 29 Ma). Samples from McCullough's Bridge were all from below the unconformity. Two samples (MB6M and MB5) indicate that the underlying surface is approximately the same age as at Squires Farm (31.8 Ma). One sample (MB6B) indicates a younger age (30.6 Ma), but was collected from a burrow that contains younger material and was, therefore, expected to yield an intermediate age (*Table 1*).

The strontium isotopic data confirm that the Marshall Paraconformity at these localities spans the boundary between the early and late Oligocene, placed at 30 Ma on the time-scale of Berggren *et al.* (1985b) and Haq *et al.* (1987; 1988), 32 Ma on that of Edwards *et al.* (1988) and 29.3 Ma on that of Harland *et al.* (1990). The Marshall Paraconformity onshore therefore closely coincides with the postulated mid-Oligocene sea-level fall of Haq *et al.* (1987; 1988), as illustrated on *Figure 7*. The hiatus is also consistent, within the uncertainty of the strontium isotopic measurements (conservatively ±0.9 Ma in the Oligocene; Miller *et al.*, 1988), with an older age for the mid-Oligocene event of 32.2 Ma (*Figure 7*), determined by Miller *et al.* (1993) at the base of the Chickasawhay Formation in Alabama, which is correlated with the TB1.1 sequence boundary of Haq *et al.* (1987; 1988; see also Baum and Vail, 1988).

Age estimates from offshore exploration wells

Biostratigraphy provides age control for lithological units in the vicinity of the Marshall Paraconformity encountered in the four offshore exploration wells drilled in the Canterbury Basin (*Figures 1* and *7*). As the data are based on well cuttings, the ages are necessarily less well constrained than biostratigraphic and strontium isotopic ages from samples from onshore outcrops. The following discussion is based on well completion reports: Endeavour (Wilding and Sweetman, 1971), Resolution (Milne *et al.*, 1975), Clipper (Hawkes and Mound, 1984) and Galleon (Wilson, 1985). An Oligocene unconformity was recognized at Endeavour and Resolution and may also be present in Galleon and Clipper.

The New Zealand time-scale in *Figure 7* is that of Edwards *et al.* (1988) and well stratigraphies are shown relative to that time-scale. Edwards *et al.* (1988) linked their time-scale to that of Berggren *et al.* (1985a; 1985b), but altered some of the latter's stage boundary ages to make many New Zealand and international stage boundaries coeval. Of particular importance to this paper, Edwards *et al.* (1988) noted that the last occurrence of *Chiloguembelina*, placed at the base of the Chattian at 30 Ma in Chron C10 by Berggren *et al.* (1985b), is an unreliable bioevent for dating in New Zealand. The last occurrence of *G. angiporoides*, well defined in New Zealand and coincident with the early–late Whaingaroan boundary, was selected by Edwards *et al.* (1988) as the early/late Oligocene boundary. Berggren *et al.* (1985b) assigned an age of 32 Ma (Chron 11) to this bioevent and Edwards *et al.* (1988) adopted this age as that of their early/late Oligocene boundary.

Figure 7 displays the original Berggren *et al.* (1985a; 1985b) time-scale (unmodified by Edwards *et al.*, 1988) because the strontium isotopic age data are based on that time-scale. In addition, as noted previously, the inferred eustatic curve of Haq *et al.* (1987; 1988) has been adjusted to fit Berggren *et al.* (1985a; 1985b). Well stratigraphies are, however, related to New Zealand stage boundaries of Edwards *et al.* (1988). Well hiatuses are centred on the early–late Whaingaroan boundary (32 Ma) and do not plot at the early–late Oligocene boundary on the unmodified Berggren *et al.* (1985a; 1985b) time-scale (30 Ma). The correlation of well hiatuses to ~32 Ma is, however,

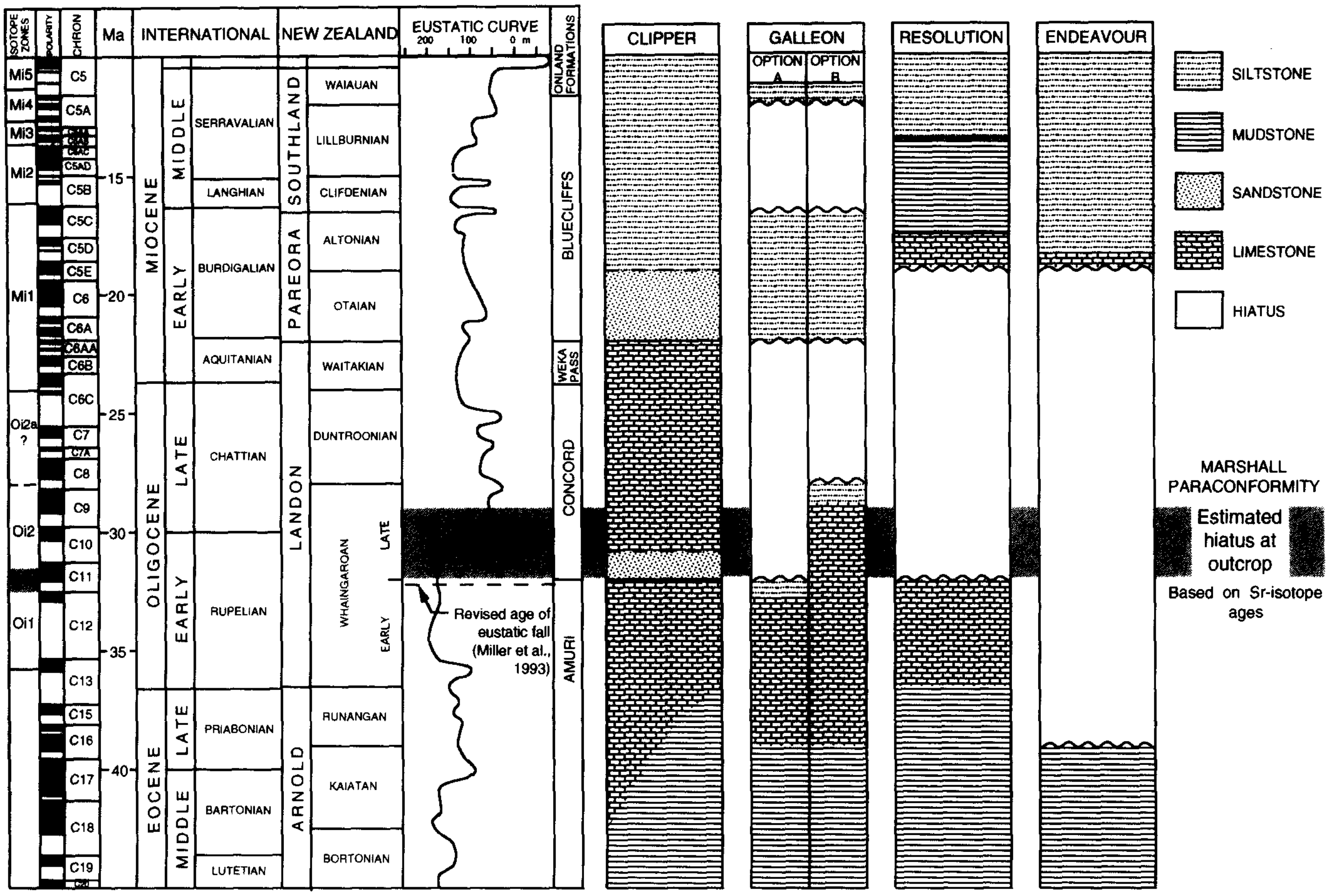

Figure 7 Simplified stratigraphy of offshore exploration wells Clipper, Galleon, Resolution and Endeavour. Also shown is the minimum hiatus (31.8–29.0 Ma) represented by the Marshall Paraconformity, derived by combining Sr isotope ages from its Squires Farm type section and McCullough's Bridge, excluding burrow sample MB6B. Oxygen isotopic zones are from Miller *et al.* (1991b). Magnetostratigraphy and international time-scale are those of Berggren *et al.* (1985a; 1985b) and the eustatic curve of Haq *et al.* (1988) has been adjusted to that time-scale. Note that the ages of the time-scale have been revised by Cande and Kent (1992), but this does not affect the comparisons made here (see text). The Haq *et al.* (1988) curve shows the mid-Oligocene eustatic fall at 30 Ma. A broken line on the eustatic curve at 32.2 Ma represents an older age for the mid-Oligocene event, determined by Miller *et al.* (1993) at the base of the Chickasawhay Formation in Alabama, which is correlated with the TB1.1 sequence boundary of Haq *et al.* (1988; see also Baum and Vail, 1988). The New Zealand time-scale is that of Edwards *et al.* (1988) and well stratigraphies and onshore formations are shown relative to that time-scale. Note that Edwards *et al.* (1988) correlated numerous New Zealand stage boundaries directly with international stage boundaries, but their age assignments differed from those of Berggren *et al.* (1985a; 1985b). In particular, Edwards *et al.* (1988) correlated the early–late Whaingaroan boundary with the early–late Oligocene boundary, which they set at 32.0 Ma. Berggren *et al.* (1985b), however, placed the early–late Oligocene boundary at 30 Ma. Use of the Berggren *et al.* (1985a; 1985b) and Edwards *et al.* (1988) time-scales side by side results in offset stage boundaries. See text for further discussion

consistent with the strontium isotopic age estimates of the hiatus at outcrop (between ~32 and 29 Ma at Squires Farm; *Table 1*) and with the revised age of Miller *et al.* (1993) for the mid-Oligocene event (32.2 Ma).

Endeavour encountered the oldest pre-unconformity surface of the exploration wells. Sediments are Kaiatan (not younger than late Eocene, ~39 Ma) mudstones of 'outer neritic' origin. A 15 m thick limestone unit, lithologically similar to the Weka Pass Formation, but younger, overlies the unconformity; its environment of deposition was interpreted as 'outer to middle neritic'. The longest hiatus is that at Endeavour, where Runangan to Otaian (uppermost upper Eocene–lower lower Miocene) sediments are absent. The duration of the haitus was ~20 Ma (*Figure 7*).

The pre-unconformity surface at Resolution is lower Whaingaroan (early Oligocene; *G. angiporoides* Zone), no younger than ~32 Ma. The limestone below the unconformity is the same age and facies as the onshore Amuri Formation and has an inferred environment of deposition of 'outer shelf or beyond'. The overlying limestone is again similar to, but younger than, the Weka Pass Formation, and was assigned an environment of deposition of 'at least outer shelf'. The total thickness of the two limestones is 41 m. Upper Whaingaroan to Otaian (upper Oligocene to lower lower Miocene) sediments are absent and the duration of the hiatus was at least 13 Ma (*Figure 7*). The unconformity at Resolution is also marked by a distinct positive peak on the gamma ray log.

At Galleon, a 60 m thick limestone, probably largely equivalent to the Amuri Formation, occurs near the stratigraphic level of the Marshall Paraconformity. Its environment of deposition was interpreted as 'outer shelf to upper bathyal'. Wilson (1985) identified an unconformity with a late Oligocene to early Miocene hiatus overlain by siltstone of Otaian (early Miocene) age with an interpreted depositional environment of mid- to outer shelf. Wilson (1985) indicated a possible late Oligocene correlation for the sediment (including the top of the limestone unit) underlying this unconformity. However, the ages given for this sediment are Zone NP24 or older and no younger than Zone P21. The boundary between the early and late Oligocene and, therefore, the mid-Oligocene sea-level fall, lie within Zones NP24 and P21 on the BKF85 timescale. The base of Zone NP24 should be in Chron C11 (31.2–32.5 Ma), based on unpublished studies by M.-P. Aubry (see Miller *et al.*, 1993). The sediment underlying the unconformity identified by Wilson (1985) could therefore be wholly lower Oligocene and may be as old as 32 Ma. Two alternative interpretations of Galleon biostratigraphy are presented in *Figure 7*. In Option A (left-hand side of Galleon statigraphic column, *Figure 7*), the pre-unconformity surface has been placed at the boundary between the early and late Whaingaroan. This is consistent with the biostratigraphy and with the unconformity representing the Marshall Paraconformity. The top of the limestone then lies ~15 m below the unconformity (*Figure 7*), which lies wholly within the overlying siltstone, with no obvious Weka Pass equivalent limestone deposition. The siltstone above and below the unconformity is, however, very calcareous and grades to silty limestone in places. According to this interpretation, the hiatus at Galleon is ~10 Ma. Option B (right-hand side of Galleon stratigraphic column, *Figure 7*) accepts that the upper part of the limestone could be upper Oligocene (and represent Concord or perhaps Weka Pass equivalent deposition). The Marshall Paraconformity would then lie within the limestone interval, as at other wells and onshore outcrops, but any associated hiatus has not been resolved from microfaunal examination of cuttings.

No Oligocene hiatus has been reported from the Clipper well, though this may again be due to the low biostratigraphic resolution attainable based on the examination of cuttings. Alternatively, the Oligocene section at Clipper may represent a correlative conformity. Age-equivalent limestones to the Amuri, Concord and Weka Pass formations were encountered, with a maximum combined thickness of 150 m. A 9 m thick, very-fine-grained sand was placed at the base of the upper Whaingaroan section by oil industry biostratigraphers and corresponds to the location of the unconformity at other wells and onshore. Detailed biostratigraphic data and palaeobathymetric estimates from this well were not made available for independent review.

Discussion

Origin of the Marshall Paraconformity

Omission surfaces are characteristic of condensed sections in general, as are glauconitic sediments (Loutit *et al.*, 1988), and both features are common in pericontinental chalks (Kennedy and Garrison, 1975). The upper part of the Amuri Limestone, beneath the Marshall Paraconformity, in some places contains additional burrowed omission surfaces (Begg, 1973; Carter, 1985) and Gage (1988) also noted several discontinuities in the locally condensed Oligocene–Miocene section. Carter and Landis (1982), Lewis and Belliss (1984) and Jenkins (1987) have presented evidence for the presence of additional unconformities associated with the upper Oligocene Kekenodon Group sediments that occur above the Marshall Paraconformity. However, none of these surfaces has yet been shown to have the regional extent and significance of the Marshall Paraconformity (Hornibrook, 1987). Rather, they seem to represent local accentuations of the condensed sedimentation regime that characterizes the whole Kekenodon Group. The suggestion by Jenkins (1987) that a second unconformity with a hiatus of ~5 Ma lies at the Kokoamu–Otekaike (= Concord–Weka Pass) contact in the Waitaki valley and at DSDP Site 593 was not supported by Hornibrook (1987). Data presented here show that not all bored surfaces represent measurable hiatuses (e.g. surface within Otekaike Limestone dated at Trig Z, *Figure 5*, *Table 1*). The Marshall Paraconformity is unique because of the distinctive character of the surface itself and of the overlying Concord Formation, its regional distribution and the consistent age of the ~32–29 Ma core hiatus that occurs at the surface.

The interval occupied by the Amuri, Concord and Weka Pass formations has long been interpreted as reflecting extreme restriction of terrigenous input resulting from maximum flooding of the land mass during the Oligocene to early Miocene regional relative highstand (Schofield, 1951). This interpretation is supported by analogy with the sequence stratigraphic model, discussed earlier, whereby the limestones represent the core of the megasequence condensed section. The interpretation has, however, never satisfactorily accounted in detail for the Marshall Paraconformity and, in particular, for the change in facies that occurs across it (Hornibrook, 1987). We consider in the following whether the prolonged, but temporary, interruption in carbonate deposition might indeed have been caused by an event or events external to the tectonic megacycle that generated the condensed section.

Evolution of the Antarctic Circumpolar Current system

Carter and Landis (1972) originally interpreted the Marshall Paraconformity, and the overlying Kekenodon Group, as being caused by regional plate tectonic events. In particular, the early Oligocene (~30–33 Ma) separation of Australia and Antarctica allowed the development for the first time of the proto-Antarctic Circumpolar Current (Jenkins 1974; 1993; Kennett *et al.*, 1975; Kennett, 1977; Jenkins and Srinivasan, 1986; Kennett and von der Borch, 1986), through the sluice between Australia and Antarctica. The New Zealand Plateau at this time lay directly to the east of the sluice (Molnar *et al.*, 1975; Lawver *et al.*, 1992) and was thereby subjected to the full impact of an evolving, strong, eastward-flowing current system, which then swung north-eastward into the Pacific Basin. Abundant evidence, summarized in Carter (1985), attests to the current-influenced nature of sediments immediately above the Marshall Paraconformity. It therefore seems likely that much of the erosion and non-deposition that accompanied the development of the paraconformity was caused by the nascent Antarctic Circumpolar Current system, perhaps associated with the global change from an ocean with warm saline deep water formed at low latitudes and dominated by halothermal circulation to a thermohaline system with cold deep water formed at high latitudes (Kennett and Stott, 1990).

On the east side of the Pacific, the opening of the Drake Passage was tectonically complex, but shallow flow was probably established by the early Oligocene (Lawver *et al.*, 1992) with deep water circulation following by the earliest Miocene (Barker and Burrell, 1982). The opening of a deep Drake Passage, and a widening southern ocean caused by New Zealand's continued northward movement, may have resulted in deep southern water of the Oligocene Indian–Pacific ocean system changing path from a north-easterly route into the Pacific to pass directly eastward, largely to the south of New Zealand, as a fully fledged Antarctic Circumpolar Current system. On the New Zealand plateau, this would have resulted in a lessening of current activity.

Relating the origin of the Marshall Paraconformity and the overlying Kekenodon Group to the inception of the Antarctic Circumpolar Current system does not preclude the involvement of a major sea-level event. Rifting between Australia and Antarctica was the final precursor to the thermal isolation of Antarctica and to the development of Antarctic glaciation. There is long-standing and increasingly strong evidence for a late Eocene to early Oligocene commencement of Antarctic glaciation (e.g. Devereux, 1967; Shackleton and Kennett, 1975; Barrett *et al.*, 1989; Barron *et al.*, 1991; Hambrey and Barrett, 1993) and the development of an ice-cap must inevitably have been accompanied by a eustatic sea-level fall (cf. Miller *et al.*, 1991b).

Global evidence for mid-Oligocene sea-level lowstands

Miller *et al.* (1991b) summarized the available oxygen isotope data relevant to Oligocene sea-level falls. Marked positive isotopic excursions occurred at 35.8 (Oil), 31.5–32.5 (Oi2) and possibly 28.0 Ma (Oi2a). Miller *et al.* (1991b) noted that the timing of the Oi2 oxygen isotopic event is poorly constrained and that more isotopic data (particularly from western equatorial planktonic foraminifera) were needed to confirm that this event resulted from ice-volume increase. Isotopic evidence for a glacio-eustatic low at Oi2 is, however, supported by results of Antarctic drilling, which has demonstrated definite mid-Oligocene, and perhaps late Eocene, glacially derived sediment (Barrett *et al.*, 1989; Barron *et al.*, 1989; 1991). Miller *et al.* (1991b) therefore concluded that the Oi2 event marked a glacio-eustatic low and correlated it with the 30 Ma (TB1.1) sequence boundary of Haq *et al.* (1987; 1988), ascribing the age discrepancy to mid-Oligocene biostratigraphic correlation problems. Miller *et al.* (1993), however, precisely dated the mid-Oligocene TB1.1 unconformity in Alabama; the event is there associated with a distinct unconformity at the base of the Chickasawhay Limestone (Baum and Vail, 1988) which is correlated with latest Chron C11r (32.2 Ma; Miller *et al.*, 1993). The age of the Marshall Paraconformity at its Squires Farm type locality and McCullough's Bridge (between ~32 and 29 Ma; *Table 1*) correlates well with both the Oi2 event and the mid-Oligocene (TB1.1) sequence boundary.

The Oi2 isotopic event involves an increase in $\delta^{18}O$ of up to 1‰ (Miller *et al.*, 1991b). This is consistent with maximum sea-level falls of 90 m (using a Pleistocene calibration of 0.11‰/10 m; Fairbanks and Matthews, 1978) or 180 m (using the pre-Pleistocene calibration of 0.055‰/10 m; Miller *et al.*, 1987). Miller *et al.* (1991b), however, regarded the pre-Pleistocene calibration as an extreme upper bound and stated that Oligocene glacio-eustatic falls were probably close to those estimated using the Pleistocene calibration. In either instance, the fall would have been of insufficient magnitude to have resulted in subaerial exposure of the mid-Oligocene carbonate platform of the offshore Canterbury Basin, given the previous 250 m water depth estimate.

The Marshall Paraconformity revisited

Loutit *et al.* (1988) suggested that the 30 Ma sea-level fall was one of the components, together with tectonic effects, responsible for the termination of the condensed interval in the Canterbury Basin. However, the new ages obtained for the Marshall Paraconformity, and discussed earlier, indicate that the postulated sea-level event occurred centrally within the period of deposition of the condensed interval, and specifically within the hiatus represented by the Marshall Paraconformity (between ~32 and 29 Ma). The influence of a sea-level fall on coastal and shallow shelf deposition has formed the basis for the sequence stratigraphic model of terrigenous shelf facies (e.g. van Wagoner *et al.*, 1988; Posamentier *et al.*, 1988). The Canterbury Basin may provide an example of the effects of a glacio-eustatic fall on a deeper water carbonate facies.

Evidence for subaerial exposure of the paraconformity surface (Lewis, 1992) provides the most direct link between the mid-Oligocene eustatic fall and the Marshall Paraconformity. Such evidence has been seen as equivocal, however (Carter, 1985; Gage, 1988). Furthermore, reported occurrences of karsting and other evidence of subaerial exposure (Lewis and Bellis, 1984; Lewis 1992) are restricted in occurrence to the inshore part of the basin and may largely result from local tectonic movements associated with early Oligocene volcanism (Schofield, 1951; McLennan and Bradshaw, 1984) or with the inception of the Alpine plate boundary (Carter, 1985; Lewis, 1992). Any mid-Oligocene sea-level fall, therefore, did not result in regional subaerial exposure of the Amuri and equivalent formations and of the entire Marshall Paraconformity. Assuming a global fall of ~90 m (the best estimate of Miller *et al.*, 1991b; see earlier), this would require that, over much of the basin, the water depth at the time of deposition of the top of the Amuri limestone was significantly greater than 100 m, perhaps 200 m or more. This is likely. The nannofossil chalk facies of the Amuri Formation certainly accumulated outside any contemporaneous shore-connected terrigenous sediment prism and was, therefore, at least deeper than about 50 m and could represent any outer shelf to slope depth down to the carbonate compensation depth. Simple subsidence arguments discussed here suggest an extreme minimum estimated water depth of ~250 m across much of the offshore mid-Cenozoic platform.

The available seismic data indicate little or no erosion of the Amuri Formation offshore. In addition, strontium isotopic age estimates of the surface underlying onshore outcrops of the Marshall Paraconformity are close to the global age estimated for the mid-Oligocene sea-level fall, and therefore consistent with not only a temporal link between that event and the formation of the unconformity, but also with minimal erosion at those locations. The less precise ages of the sediment underlying the hiatus in the offshore wells also allow a temporal tie to the sea-level event, except at Endeavour. There, the age of the lower surface of the unconformity precedes the sea-level fall by up to 8 Ma (*Figure 7*). The indications are, therefore, that the hiatus associated with the Marshall Paraconformity is primarily the result of non-deposition, rather than erosion, over much of the Canterbury Basin, especially if the glacio-eustatic event was at 32.2 Ma as outlined earlier. Local erosion, subaerial or submarine, may have occurred at Endeavour, which is consistent with its situation on a palaeobathymetric high on Green horizon (Wilding and Sweetman, 1971), later included as part of a regional Endeavour High by Field and Browne (1989).

Current activity influenced sedimentation across much of the Canterbury Basin during the late Oligocene and Neogene. The current effects include large-scale cross-bedding in the Weka Pass Formation limestone (Ward and Lewis, 1975) and the formation of large offshore sediment drifts during progradation of the Neogene shelf sediment prism (Fulthorpe and Carter, 1991). The mid-Oligocene Oi2 sea-level fall has been associated with an Antarctic glacial episode (Miller *et al.*, 1985; 1991b; Barrett *et al.*, 1989) and with initiation of the proto-Antarctic Circumpolar Current. These events, in addition to lowering sea level, would have led to a period of enhanced flow of cold deep water (e.g. Shackleton and Kennett, 1975) with concomitant oceanic plankton changes (Jenkins, 1974; 1987; 1993; Jenkins and Srinivasan, 1986), which may have prevented the accumulation of sediment over much of the Canterbury Basin. In some settings, for example at Clipper, deposition continued, but pelagic carbonates were temporarily replaced by very fine-grained quartz sand. Further landward, the immediate post-unconformity sediment was glauconotic sand of the Concord Formation. Deposition of current-reworked carbonates resumed as climatic conditions ameliorated, sea level rose and current intensities decreased. The greater duration of the hiatus at offshore wells Endeavour and Resolution than at the onshore outcrop at Squires Farm and the Clipper and perhaps Galleon wells may be related either to subaerial or submarine erosion of local uplifts or to variations in the intensity and duration of current activity across the mid-Cenozoic platform.

Starved surfaces are usually inferred to represent sea-level rises (which displace the terrigenous source landward), as previously assumed for the Marshall Paraconformity. The overall limestone condensed interval in the Canterbury Basin megacycle, as the product of a tectonically induced transgression, fits this model. If the Marshall Paraconformity was a highstand-related omission surface and a normal element of the regional condensed section, it would imply that the mid-Oligocene glacio-eustatic event had no discernible effect in the Canterbury Basin. The close correlation between the Marshall Paraconformity and the postulated glacio-eustatic fall, however, and the demonstrated intensity of current activity on this margin, is strongly suggestive of a link with glacio-eustasy. We conclude, therefore, that for deep ramp margins at intermediate latitudes, and during periods characterized by glacio-eustasy, major sea-level falls may be marked by a stratigraphic signature of (1) paraconformity and (2) intensified current activity.

Conclusions

Seismic profiles confirm earlier interpretations of the first-order sedimentary geometry of the Canterbury Basin as the product of a long-term (80 Ma) relative sea-level cycle and show that the geometry is analogous to that of the sequence stratigraphic model. The sea-level cycle responsible for the Canterbury Basin megasequence was, however, the result of long-term changes in the rate of tectonic subsidence and regional sediment supply and not eustasy.

The scale of the Canterbury Basin megasequence has enabled detailed seismic resolution of its condensed section, which suggests that the downlap surface may be a seismic artifact of the thinning below seismic resolution of the toe-of-slope sediment in the HST. A true downlap surface, which is also a stratigraphic discontinuity, is possible if the toe-of-slope sediment is removed or reworked by currents in advance of the prograding HST, as has occurred in some areas of the Canterbury Basin during parts of the Neogene.

The Amuri and Weka Pass formations are revealed by seismic profiles, together with outcrops and exploration wells, to lie within the megasequence condensed section. Hiatuses in at least two and possibly three of the exploration wells, although of longer duration, correlate with the onshore Marshall Paraconformity. At the fourth well (Clipper), an abrupt lithological change from limestone to quartz sand correlates with the unconformity. Strontium isotopic age estimates from onshore outcrops of the Marshall Paraconformity confirm that it marks a short, 2–4 Ma hiatus between ~32 and 29 Ma, which encompasses the mid-Oligocene sea-level low of Haq *et al.* (1987; 1988) and the Oi2 oxygen isotope event of Miller *et al.* (1991).

The Marshall Paraconformity and overlying Concord and Weka Pass formations over much of the Canterbury Basin represent a temporary cessation of sedimentation between ~32 and 29 Ma followed by a change in facies of limestone deposition. Conflict between local evidence for regional highstand and global evidence for a mid-Oligocene eustatic fall can be resolved if the origin of the Marshall Paraconformity was independent of that of the regional condensed interval within which it lies. Age and lithological data are consistent with the Marshall Paraconformity and the associated temporary break in limestone deposition having been caused by the mid-Oligocene glacio-eustatic fall and related oceanographic processes. The hiatus was primarily non-depositional, rather than erosional, over much of the basin and was not formed by lowering of base level alone. Cooling and increased current intensities may have restricted the deposition of carbonates during the mid-Oligocene glacio-eustatic event. Terrigenous and glauconitic sediments were the first to be deposited following this episode, with carbonate deposition resuming, perhaps in shallower water than previously, as conditions ameliorated.

If this hypothesis for the formation of the Marshall Paraconformity is correct, the Marshall Paraconformity is a southern hemisphere record of the mid-Oligocene event and would provide strong evidence of that event's global significance. To address this fully, depositional mechanisms, in particular the onset and history of current activity, must be defined more precisely and additional age control obtained within the Canterbury Basin, perhaps by means of scientific ocean drilling.

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