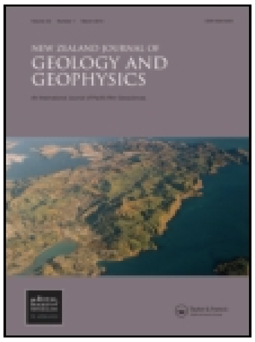

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The Marlborough Sounds is a large and spectacular network of rias or drowned valleys. The Sounds were formed by stream incision and dissection of uplifting rocks followed by subsidence and marine incursion into the valleys. The evolution of the Marlborough Sounds is examined using a combination of seismic-reflection lines from the offshore Wanganui Basin, topographic data and seafloor bathymetry. Drainage incision produced valleys and ridges in the Sounds that were part of a mountainous region which reached maximum altitudes of c. 2000 m and extended northwards across the basin to the Wanganui coast. Sedimentary strata as old as c. 5 Ma infill this palaeotopography in the basin, suggesting that topography in the Sounds formed primarily during the Miocene. This topography started to submerge in the Sounds at c. 1.5 Ma when the Wanganui Basin stepped southwards by about 50 km. At the present outer edge of the Sounds, the average rates of subsidence since this time have been low (c. 0.3 $mm\,a^{-1}$) and the resulting accommodation space in the valley system filled by sediments. As a consequence of sedimentation, the absolute altitude of valley floors remained approximately constant relative to a fixed earth datum. Thus, while subsidence was important for bringing strongly dissected topography close to sea level, isostatic sea-level rises are inferred not to have been responsible for submergence of the Sounds region. Instead, marine inundation may have been primarily driven by eustatic sea-level changes which resulted in ephemeral submergence during interglacial periods when sea levels were highest. The present coastline in the Marlborough Sounds formed c. 7 ka ago, and similar highstand sea-level configurations probably occurred about every 100 ka throughout the Late Quaternary.

Keywords: drowned valleys; eustatic sea-level changes; Marlborough Sounds; ria; subsidence; Wanganui Basin

Introduction

The Marlborough Sounds is a large network of rias comprising an intricate array of small inlets, coves and islands formed by drowning of a dendritic drainage system, (Fig. 1). It covers an area of c. 4000 km^2 and accounts for about 1/10 of New Zealand's total coastline length (i.e. c. 1500 km at 1:1,000,000 scale) (Fig. 1 & 2) (e.g. Crawford 1874; Jobberns 1935; Soons 1968; Cotton 1969; Singh 2001). Formation of the Sounds has been attributed to stream incision and dissection of uplifting rocks followed by marine incursion into the valleys. There is general acceptance that drowning of these valleys reflects a combination of regional subsidence associated with north-eastwards tilting of the Sounds and post-glacial sea-level rise (Buick 1900; Cotton 1913, 1955, 1969, 1974; Campbell & Johnston 1992; Singh 1994, 2001; Ota et al. 1995; Begg & Johnston 2000; Berryman & Hull 2003). These mechanisms seem equally valid today as they did c. 100 years ago when first proposed; however, few data have been presented to constrain the relative importance of isostatic and eustatic sea-level rises in the development of the Marlborough Sounds.

While the role of subsidence is not universally accepted (e.g. Esler 1984; Lauder 1987), most models require a component of isostatic sea-level rise to form the Marlborough Sounds (e.g. Cotton 1974; Gibb 1979; Begg & Johnston 2000; Singh 2001). Relatively recent studies support the view that subsidence is active (e.g. Singh 1994, 2001; Hayward et al. 2010a, Hayward et al. 2010b); however, the timing of its onset is not well constrained. The total amount and rates of subsidence in the Sounds are inferred to increase to the north-northeast in association with tilting in the same direction (Cotton 1913; Lauder 1970; Wellman 1979; Stern et al. 1992, 1993; Singh 1994, 2001; Ota et al. 1995; Berryman & Hull 2003). In addition to producing submergence of the dissected topography, tilting has been postulated to account for the abandonment or reversal of drainages previously flowing southwards into the Wairau Valley (Lauder 1970). Recent work on the ancestral Pelorus River in the Kaituna Valley however suggests that its abandonment may be due to erosion and breaching of a drainage divide coupled with aggradation of fluvial deposits rather than northeast tectonic back tilting of the river bed (Mortimer & Wopereis 1997; Craw et al. 2007). These recent discoveries raise questions about how much tilting has occurred in the Sounds region and what impact this, and the associated subsidence, has had on landscape evolution.

The primary purpose of this paper is to place constraints on the timing and amount of subsidence (and tilting) together with the timing of uplift and development of the incised valley system in the Sounds. Seismic-reflection lines

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Figure 1 Oblique aerial photograph looking south across the Marlborough Sounds. View to the south towards Picton and the Wairau Valley. Arrow indicates the mouth of Queen Charlotte Sound (photograph courtesy of DL Homer).

in the offshore Wanganui Basin (e.g. Fig. 3 for location) along with bathymetric and topographic data (Figs. 4–6) have been used to examine the geomorphic history of the Sounds since 5 Ma. These data provide key insights into the age of the landscape, the relative importance of isostatic (i.e. subsidence) and eustatic sea-level changes in the drowning of valleys and the longevity of the coastline we see today.

Geological setting

The Marlborough Sounds are located at the northern end of the South Island, New Zealand (Fig. 2). The palaeovalleys and ridges that make up the Sounds are mainly cut into basement which comprises Mesozoic greywackes and schists (Beck 1964; Vitaliano 1968; Mortimer 1993; Begg & Johnston 2000). The Sounds region is part of a tectonic block which is bounded to the south by the Wairau Fault (or Vernon Fault) and to the west by the Waimea–Flaxmore Fault System (Fig. 2B). The altitude of this block generally decreases towards the northeast where the Sounds give way to the open ocean of the offshore Wanganui Basin. This topographic gradient has led to the suggestion that the entire Sounds block is, or has been until recently, tilting towards the northeast (Cotton 1913, 1955, 1974; Fleming 1953; Wellman 1979; Singh 1994, 2001; Begg & Johnston 2000). Tilting of the Sounds block is supported by seismic-reflection lines which indicate that the top of basement rocks beneath the Wanganui Basin immediately northeast of the Sounds are also tilted to the northeast (Fig. 3) (Anderton 1981; Lewis et al. 1994; Uruski 1998; Lamarche et al. 2005; Proust et al. 2005). This tilting and the associated subsidence has been inferred to arise from high friction on the top of the subducting Pacific Plate (i.e. the subduction thrust) some 40–60 km beneath, which produces a downward pull and flexure of the overriding Australian Plate resulting in formation of the Wanganui Basin (Stern et al. 1992). Whatever the origin of the subsidence, northeast tilting of basin strata requires that million-year subsidence rates have been significantly higher in the Wanganui Basin than the adjacent Marlborough Sounds.

In the Marlborough Sounds the submerged floors of incised palaeovalleys are interspersed with ridges that have altitudes up to 1203 m (Fig. 2C). Marine inundation of the palaeovalley and ridge topography has produced many small inlets, coves and islands (Fig. 1 & 2). Hill-slope angles are typically 5–35° with the steeper slopes at, or close to, the angle of repose (Fig. 4 & 5) (Walls & Laffan 1986; New Zealand 1:50 000 Topographical maps NZMS 260 P26, Q26, P27 & Q27; Queen Charlotte Sounds bathymetry map NZ6153 1987). These slopes contrast with those of the main arterial valleys, which are relatively flat and typically have slopes of $<0.2°$ (e.g. Singh 1994; Mortimer & Wopereis 1997; Craw et al. 2007; New Zealand 1:50 000 Topographical map NZMS 260 P27; Queen Charlotte Sounds bathymetry map NZ6153 1987). The paleovalleys have been partially filled with sediment which, in the case of Queen Charlotte Sound, is estimated to be up to 400 m thick at the valley axis (e.g. Fig. 2D, 4). Because the inner Sounds are largely protected from open-ocean waves the rates of coastal erosion have, in most cases, been slow. In Fig. 5, for example, the horizontal erosion of the coastline at present sea level (i.e. since c. 7 ka) is c. 30 m averaged for four localities with an erosion rate of c. 0.4 m per 100 yrs (e.g. Fig. 5 insets). Although coastal wave-cut platforms have been inferred to exist both above (e.g. Esler 1984) and below (Gibb 1979; Singh 2001) present sea level, the evidence for these strand lines is equivocal. If present (and not buried by sediments or eroded by wave action), such strand lines may help constrain subsidence rates within the Sounds; swath bathymetry and high-resolution seismic reflection data may be required to detect submerged strand lines. One consequence of the limited coastal erosion and the apparent absence of strand lines is that the pre-submergence topography in the inner Sounds area has changed little since marine incursion.

Data

Data are from two primary sources: topography/bathymetry in the Sounds and seismic-reflection lines in the offshore Wanganui Basin. Topography presented in Fig. 4, Fig. 5 and Fig. 6 were derived from the New Zealand 1:50 000 Topographical maps NZMS 260 P26, Q26, P27 & Q27 (20 m topographic contours), handheld GPS calibrated to mean sea level (± 5 m), bathymetry from Queen Charlotte Sounds bathymetry map NZ6153 1987 (± 1 m) and depth sound measurements (± 2 m).

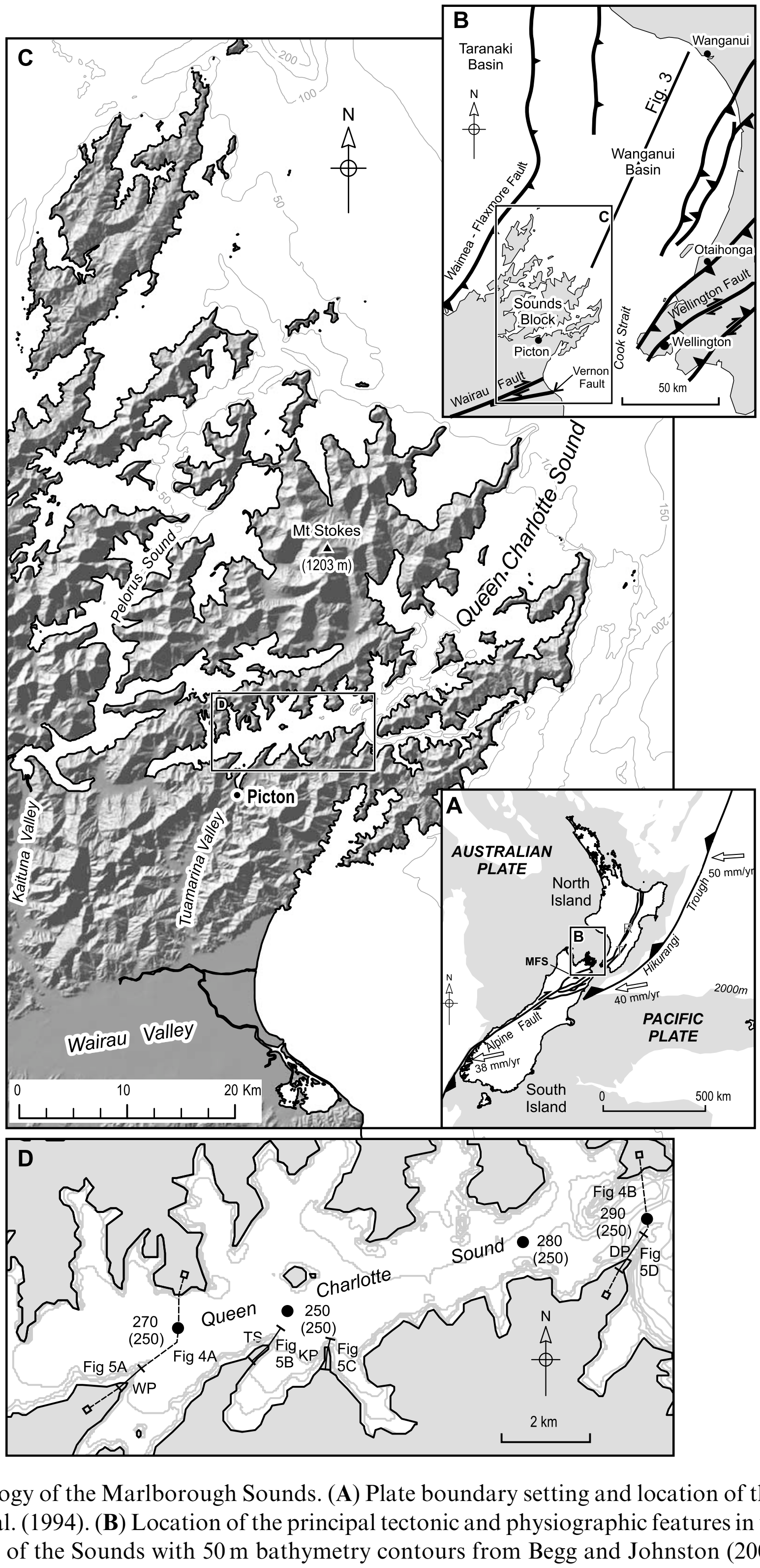

Figure 2 Location and morphology of the Marlborough Sounds. (**A**) Plate boundary setting and location of the Sounds in New Zealand. Plate motion vectors from DeMets et al. (1994). (**B**) Location of the principal tectonic and physiographic features in the region of the Sounds. (**C**) Sun shaded Digital Elevation Model of the Sounds with 50 m bathymetry contours from Begg and Johnston (2000). (**D**) Map of the inner Queen Charlotte Sound showing bathymetry at 10 m intervals (from NZ hydrographic map NZ6153 1987) and the locations of four topographic transects shown in Fig. 4A & B and Fig. 5 A–D (WP: Wedge Point; TS: The Snout; KP: Karaka Point; DP: Dieffenbach Point). Filled circles and numbers indicate the estimated depth in metres below sea level to the top of basement with the thickness of sediments (again in metres) shown in brackets.

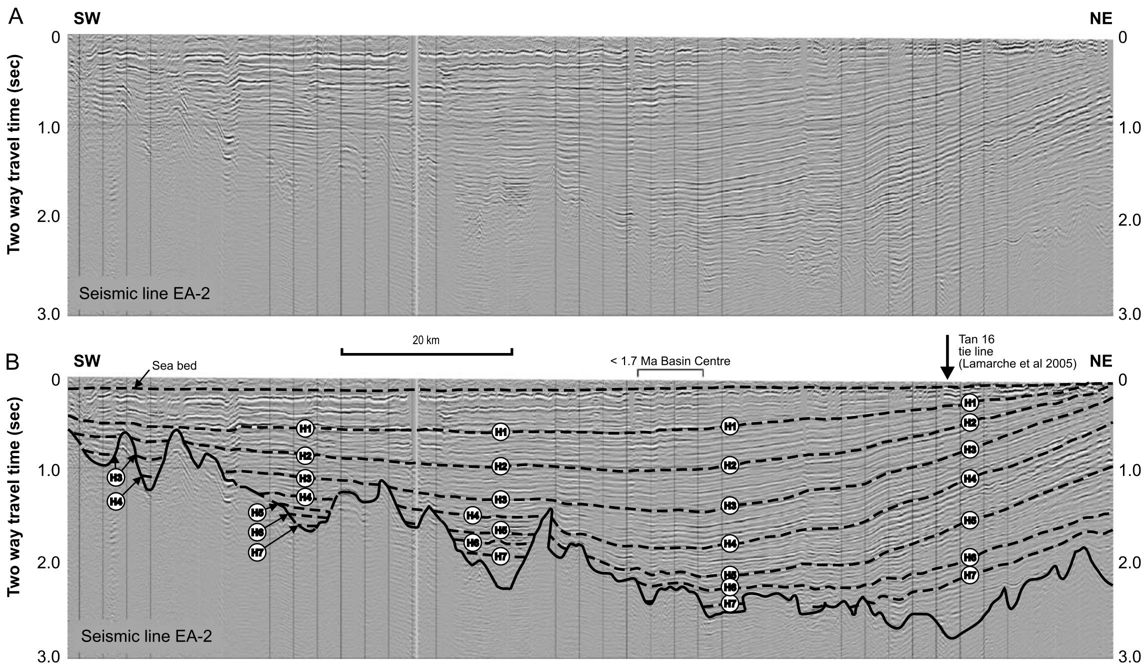

Figure 3 Seismic reflection profile (line EA-2) across the offshore Wanganui Basin. (**A**) Uninterpreted and (**B**) Interpreted. Eight seismic reflectors (H1–H7 and top basement) have been interpreted in the seismic line with the age and location of the H1–H7 reflectors from cross line Tan 16 of Lamarche et al. (2005). Mapped reflectors range in age from about 3.6 Ma to 120–260 ka and provide a record of basin and Marlborough Sounds evolution over this time period. See text for further discussion of seismic reflection data.

Multiple channel seismic reflection lines have been collected throughout the offshore Wanganui Basin region (Fig. 2B). These seismic lines were acquired by the petroleum industry during the 1970s and reprocessed in 1991 for TENEX, and are held on open file by New Zealand's Ministry of Economic Development (MED) (Fried 1992). Figure 3 illustrates a representative seismic-reflection line that trends north-northeast across most of the offshore Wanganui Basin. These seismic lines record basin reflectors to two-way travel time (TWTT) of up to c. 4 seconds. Seismic penetration is sufficient to image the full thickness of basin fill together with palaeotopography on the top of basement rocks. All of the available industry seismic lines, together with the Moho line (Davey 1987; Stern et al. 1992), were used to construct the top basement structure contour map in Fig. 7. Reflectors H1-H7 on Fig. 3B were located from cross-line Tan 16 of Lamarche et al. (2005). The ages of the reflectors used in this paper are primarily from Lamarche et al. (2005) and Proust et al. (2005). These ages are as follows: H1 120–260 ka, H2 620 $\pm$ 100 ka, H3 1000 $\pm$ 150 ka, H4 1750 $\pm$ 300 ka, H5 2400 $\pm$ 200 ka, H6 2600 $\pm$ 200 ka, H7 3000 $\pm$ 200 ka. For the purpose of constructing Fig. 8A additional ages of

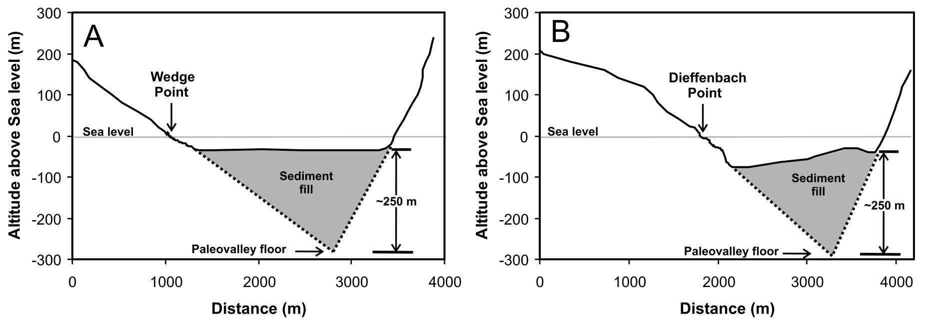

Figure 4 Cross-sections across (**A**) wedge and (**B**) Dieffenbach points showing topography, the estimated maximum depth to the palaeovalley floor and the thickness of sediment fill beneath the sea bed (see also Cotton 1955). The inferred V-shaped valley profiles are consistent with the form of many palaeovalleys observed in offshore seismic reflection profiles. Vertical exaggeration c. $\times$4.5. See main text for discussion of the topographic and bathymetry data.

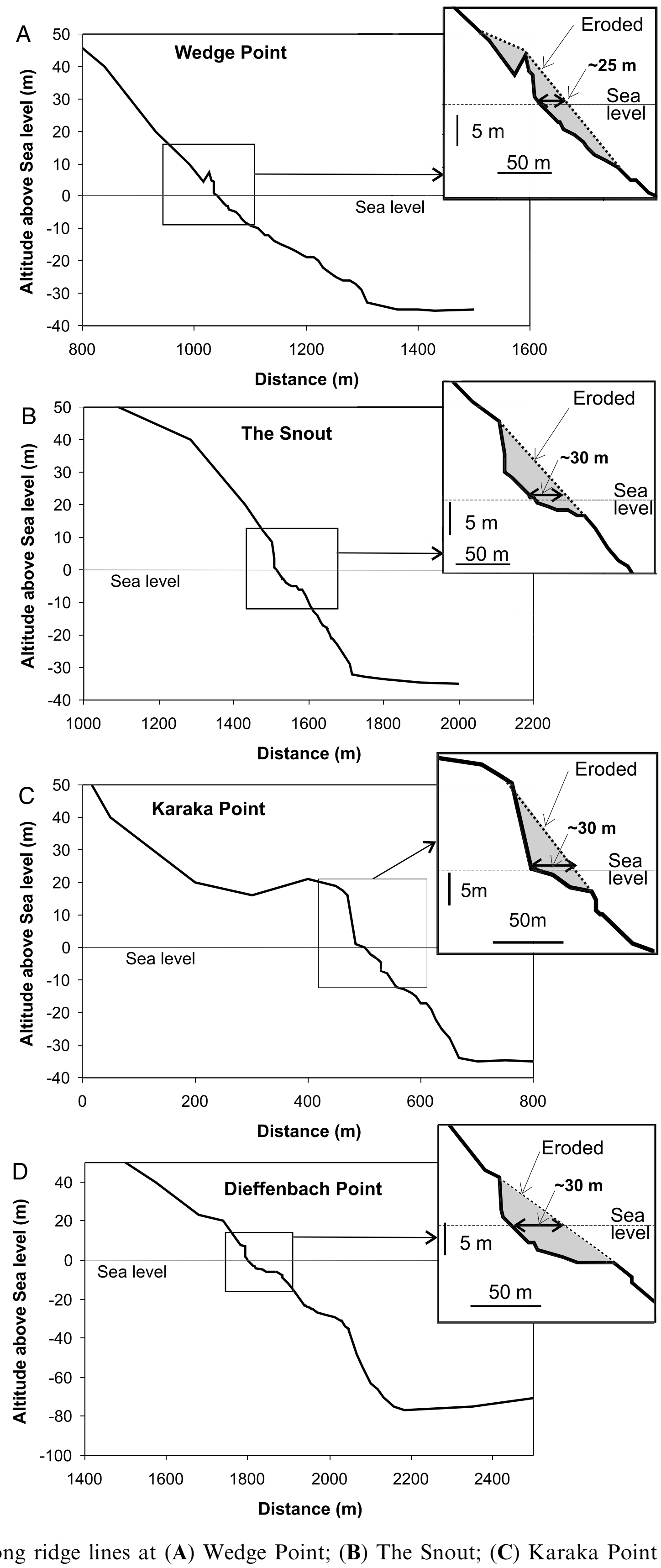

Figure 5 Topography profiles along ridge lines at (**A**) Wedge Point; (**B**) The Snout; (**C**) Karaka Point and (**D**) Dieffenbach Point. Insets constrain the amount of coastal erosion. See Fig. 2 for profile locations. Refer to main text for discussion of the topographic and bathymetry data.

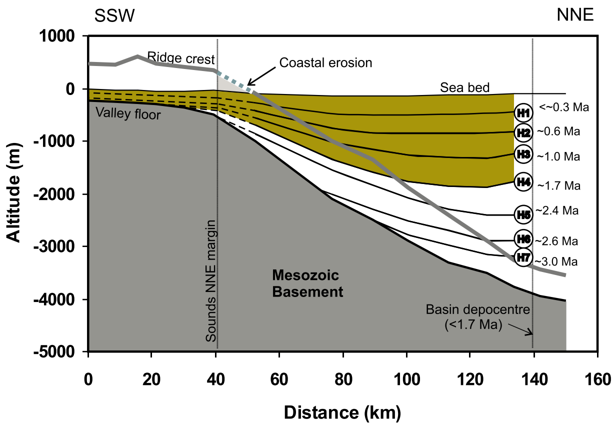

Figure 6 Profile constructed along the axis of Queen Charlotte Sound and its offshore extension in the Wanganui Basin. Locations of dated horizons estimated from seismic reflection data (e.g. Fig. 3) and are dashed where they have been projected SSW from the basin into the Sounds. See text for further discussion of the derivation and age of these horizons. Light grey polygon indicates strata inferred to have been deposited after the onset of Sounds subsidence. The depths to the top basement in the Sounds valleys are maxima estimated using the technique outlined in Fig. 4; uncertainties of up to about ±150 m on these depths are possible but do not significantly modify the shape of the top basement profile or the conclusions drawn from it. The altitude of the ridge crest has been averaged between the ridges on either side of Queen Charlotte Sound (using Topographical maps NZMS 260 Q26, P27 & Q27) and the Queen Charlotte palaeovalley offshore (using data from Fig. 7). The dashed ridge line immediately north of the outer margin of the Sounds shows the section of the ridges eroded by coastal processes.

1350 ± 300 and 3600 ± 400 ka have been assigned to reflectors midway between H3 and H4 and on top basement, respectively. Interval velocities from Lamarche et al. (2005) were used for depth conversions in Fig. 7 & 8. For further information on the industry seismic lines in the offshore Wanganui Basin, refer to Anderton (1981), Fried (1992) and Uruski (1998).

Age and formation of topography

In Marlborough Sounds the valley and ridge topography is inferred to have developed through a combination of uplift and drainage incision of mainly Mesozoic schist and greywacke basement rocks (Begg & Johnston 2000). This basement topography can be traced to the north where it is buried by up to 4 km of sedimentary strata deposited in the Wanganui Basin (Anderton 1981; Holt & Stern 1994; Lewis et al. 1994; Lamarche et al. 2005; Proust et al. 2005). Dating of these basin strata and analysis of their geometries provides key information about the timing and evolution of drainage incision into basement rocks in the Sounds.

Wanganui Basin fill and irregular palaeotopography on top basement are illustrated by the seismic-reflection line in Fig. 3 (see also Fig. 5 of Holt & Stern 1994). The irregular geometry of the top basement surface is interpreted to have formed due to drainage incision prior to subsidence, basin formation and sediment deposition (Anderton 1981; Lewis et al. 1994; Proust et al. 2005). Relief on the top basement reaches a maximum of about 1600 m beneath the basin. Basement is mantled by sedimentary strata which, based on outcrop and drillhole data in the Wanganui area, are inferred to primarily comprise shallow marine deposits (e.g. Fleming 1953; Begg & Mazengarb 1996; Kamp et al. 2004; Naish et al. 2005). In the offshore basin these deposits onlap basement as it rises towards the Sounds in the south-southwest. Due to this onlap, the age of strata resting directly on basement becomes younger towards the Sounds from 3–5 Ma in the northeast to ≤1.7 Ma at the present outer margin of the Sounds (e.g. Fig. 3 & 6). The oldest sedimentary rocks in the basin resting on (and infilling) basement topography are c. 5 Ma and occur west of Wanganui and Fig. 3 (Proust et al. 2005). These ages indicate that the onset of marine incursion, and probably also basin subsidence, varied throughout the basin. Basin formation commenced at c. 5 Ma; prior to this time much of the Wanganui Basin was probably above sea level and experiencing uplift and drainage incision.

A key question is whether palaeotopography beneath the Wanganui Basin formed in association with topography in the Marlborough Sounds. To examine the relations between the geometries of the basement erosional surface in the two areas, a structure contour map has been constructed for this surface from seismic-reflection lines across the offshore Wanganui Basin (Fig. 7). The structural contour map in Fig. 7 was produced by correlating palaeovalleys and ridges between 2D seismic-reflection lines in much the same way as faults or folds are correlated. Due to the wide spacing of seismic lines (c. 5–15 km) the resulting map only shows the locations of first-order palaeovalleys and ridges; many smaller (<c. 500 m amplitude) basement highs and lows are visible in seismic lines and suggest that, in detail, structure contours on top basement in the basin are likely to exhibit a complexity similar to that of the coastline in the Sounds. The general shape and values of the structure contours in Fig. 7 are similar to those previously presented (e.g. Anderton 1981; Lewis et al. 1994; Uruski 1998; Lamarche et al. 2005), and may differ slightly due to differences in the time–depth relations used for depth conversion and the contouring strategy.

Marlborough Sounds topography and palaeotopography preserved beneath the Wanganui Basin are inferred to be part of the same valley and ridge system. The largest palaeovalleys and ridges in Fig. 7 generally trend north-northeast and are the northern continuations of the main drowned valleys and emergent ridges in the Sounds. Three primary palaeovalleys can, for example, be traced 70–90 km northwards from the Sounds. These palaeovalleys, which were previously identified and referred to as submarine

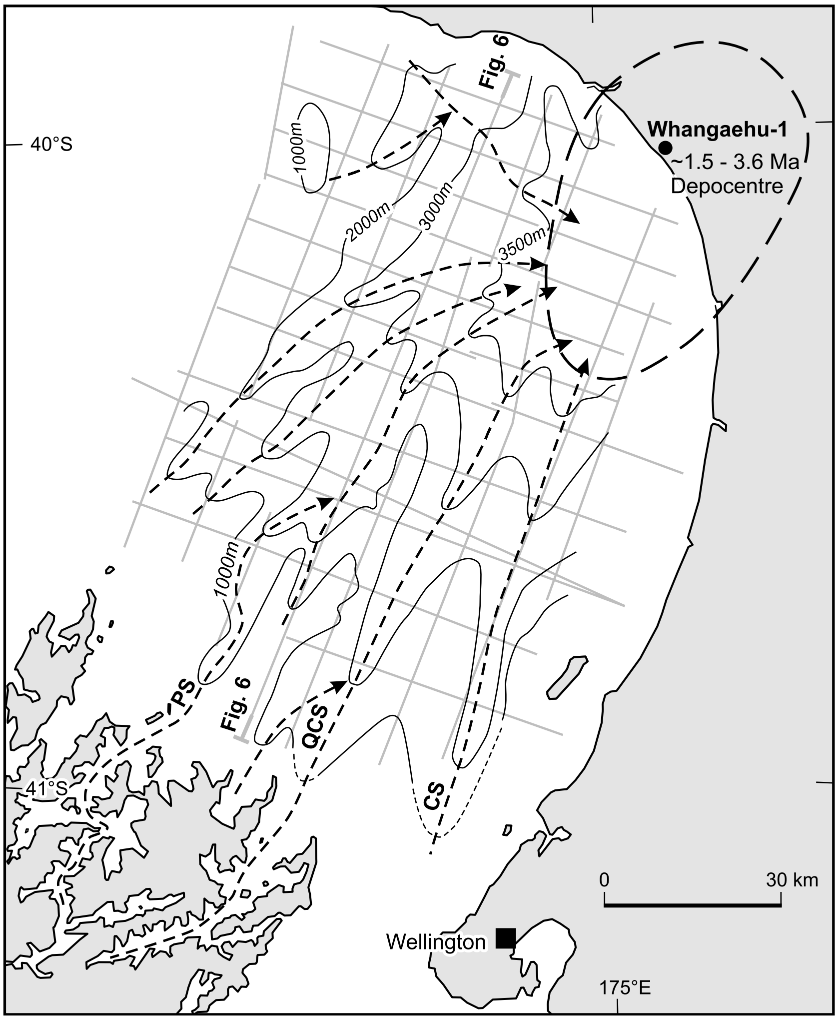

Figure 7 Structure contour map showing the depth (in metres below sea level) to the top of basement beneath the offshore Wanganui Basin. Contour map constructed using the interpreted depth of top basement as imaged in seismic-reflection lines, the locations of which are shown by the light grey lines. Intermediate length dashed lines define the axes of palaeovalleys incised into basement with arrows indicating the inferred palaeoflow direction. PS, QCS and CS show the locations of palaeovalleys inferred to be the north-northeast continuations of Pelorus Sound, Queen Charlotte Sound and Cook Strait, respectively. Filled circle shows the location of the Whangaehu-1 well. Line comprising long dashes defines the approximate location of the Wanganui Basin depocentre between c. 1.5 and 3.6 Ma.

canyons by Winslow (1968), are here referred to as PS, QCS and CS and are inferred to be the northern continuations of Pelorus Sound, Queen Charlotte Sound and Cook Strait, respectively (Fig. 7). It is therefore suggested that the Sounds topography formed at the same time as the palaeotopography beneath the basin and at least partly predates the onset of basin formation at c. 5 Ma. The trend of the main palaeovalleys together with the inferred position of the coast at c. 5 Ma (Fig. 9) suggest that, during the Miocene, sediment was eroded from the northern South Island (including the Sounds) and transported towards the north-northeast at least c. 100 km across what is now the offshore Wanganui Basin.

How much modification the topography of the Sounds has undergone since the onset of basin formation at c. 5 Ma has important implications for the age of this topography. The maximum amplitude (i.e. c. 1500 m) and hill slopes (i.e. c. 5–35°) of palaeotopography beneath the basin are similar to those of top basement in the Sounds. This observation is supported by the near-constant altitude difference of about 1000 m between the ridge crests and the valley axis along the Queen Charlotte Sound valley system (Fig. 6). Apart from c. 10 km of coastal erosion of the ridge crests immediately northeast of the Sounds, there is no discernable difference in basement relief across the present outer margin of the Sounds (Fig. 6). Similarities in the amplitude of the topography of the eroded basement in the Sounds and beneath Wanganui Basin are consistent with the notion that the first-order topography in both regions is part of the same system and may not have changed substantially in amplitude (e.g. <400 m) or orientation in the past 5 Ma. For this to be true ongoing hill-slope erosion, as indicated by regolith failures during high-intensity rain storms and the formation of small deltas at many stream mouths (e.g. Cotton 1913; Laffan et al. 1989), must not have occurred at sufficiently high rates to substantially modify the amplitudes, hill-slope angles or orientations of the main valleys and ridges in the Sounds.

The longevity of the Marlborough Sounds main valleys and ridges is consistent with the widespread deep weathering and oxidation of basement rocks throughout the inner Sounds (e.g. Nicol 1988; Mortimer & Little 1998). The depth of bedrock weathering and the thickness of the overlying soil are inversely related to altitude suggesting increased erosion (and decreased deposition) on higher altitude slopes (Walls & Laffan 1986; Laffan et al. 1989). Coastal outcrops in the inner Sounds are strongly weathered, despite the fact that in places they were probably greater than 20 m below the ground surface prior to Holocene coastal erosion (Fig. 5 insets), indicating that the thickness of strongly weathered basement rocks often exceeds 20 m. The low rates of erosion suggested by the strong weathering of basement rocks and the absence of a change in the topography on the top basement surface across the outer margin of the Sounds are consistent with the view that the Sounds were probably not a significant source of the <5 Ma sediments deposited in the offshore Wanganui Basin.

The available seismic reflection data suggest that the Marlborough Sounds area was, prior to c. 5 Ma, part of uplifted ranges that extended at least as far as the North Island coastline to the north and east (Fig. 9A). As these palaeo-ranges formed due to erosion with little or no recorded deposition, they are inferred to be terrestrial with maximum altitudes of up to c. 2000 m (see Fig. 9 caption for further explanation of altitude estimates). The timing of the onset of the formation of this topography is not known precisely. The topography must post-date the deposition of mainly Early Oligocene marine strata which are preserved in small fault-bounded slivers near Picton and Otaihanga (see Fig. 2B & C) (Grant-Taylor 1978; Nicol & Campbell 1990; Begg & Mazengarb 1996; Begg & Johnston 2000). These slivers indicate that Oligocene rocks within the Taranaki Basin once extended over a much wider area including the Wanganui Basin, Marlborough Sounds and Wellington region. Near Picton the Oligocene strata were the basal remnants of a sedimentary sequence >4 km thick (Grant-Taylor 1978; Nicol & Campbell 1990). Given that time would have been required to deposit these sediments, it is inferred that the uplift and incision required to produce the Sounds topography probably initiated during the Miocene (Nicol & Campbell 1990). This uplift may have resulted partly from reverse displacement on the Waimea–Flaxmore Fault System (part of the Taranaki Fault System) which bounds the western margin of the Marlborough Sounds block (Fig. 9A). Reverse displacement on the Taranaki Fault System accelerated during the Early Miocene (e.g.

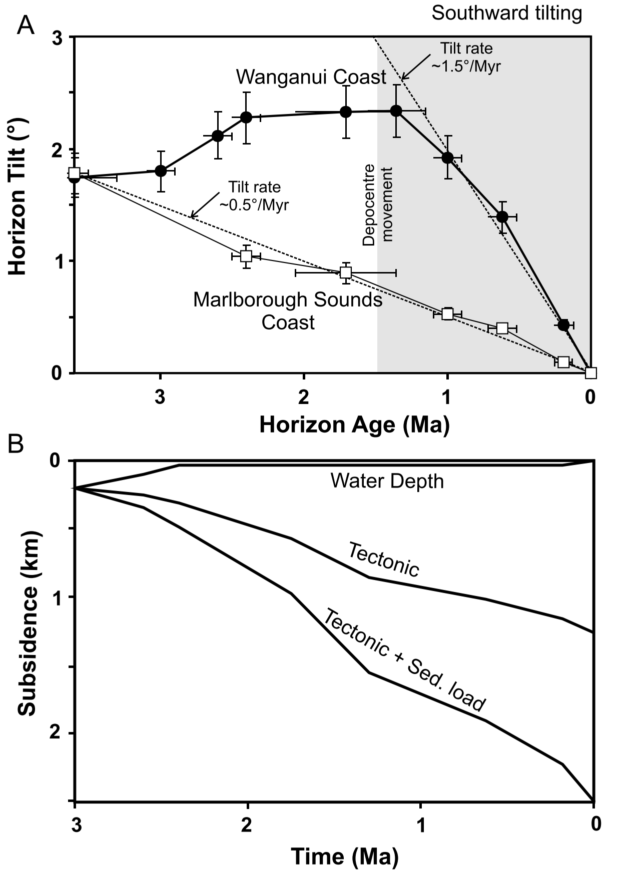

Figure 8 (**A**) Graph showing tilt versus horizon age for horizons mapped in Fig. 3. Wanganui coast tilts (filled circles) have been measured between the Tan 16 cross line and the north-northeast end of the seismic line in Fig. 3. Marlborough Sounds tilts (unfilled squares) were measured between the c. 1.5 Ma basin axis and the south-southwest end of the seismic line in Fig. 3. Interval velocities of Lamarche et al. (2005) were used to measure the tilts in the section, while horizon ages and their uncertainties are also primarily from Lamarche et al. (2005). Refer to text for further discussion of seismic line and interpretation of the graph. (**B**) Graph showing the rock subsidence (tectonic plus sediment loading) and tectonic subsidence at the post 1.7 Ma basin depocentre since 3 Ma. Components of subsidence due to tectonics and sediment loading were calculated using equations from Steckler and Watts (1978) using GNS Geohistory software written by Phil Scadden.

Holt & Stern 1994; King & Thrasher 1996; Stagpoole & Nicol 2008) and may have triggered inversion of the Oligocene basin together with a change from marine to terrestrial environments. This resulted in erosion and fluvial dissection of the Marlborough Sounds to Wanganui Basin region. Similarly, c. 4–5 Ma cessation of movement on the Taranaki Fault System at the latitude of the offshore Wanganui Basin may have been partly responsible for the onset of subsidence and submergence of the offshore Wanganui Basin at this time (Stagpoole & Nicol 2008). (Note, Plio-Pleistocene folding of strata above the Taranaki

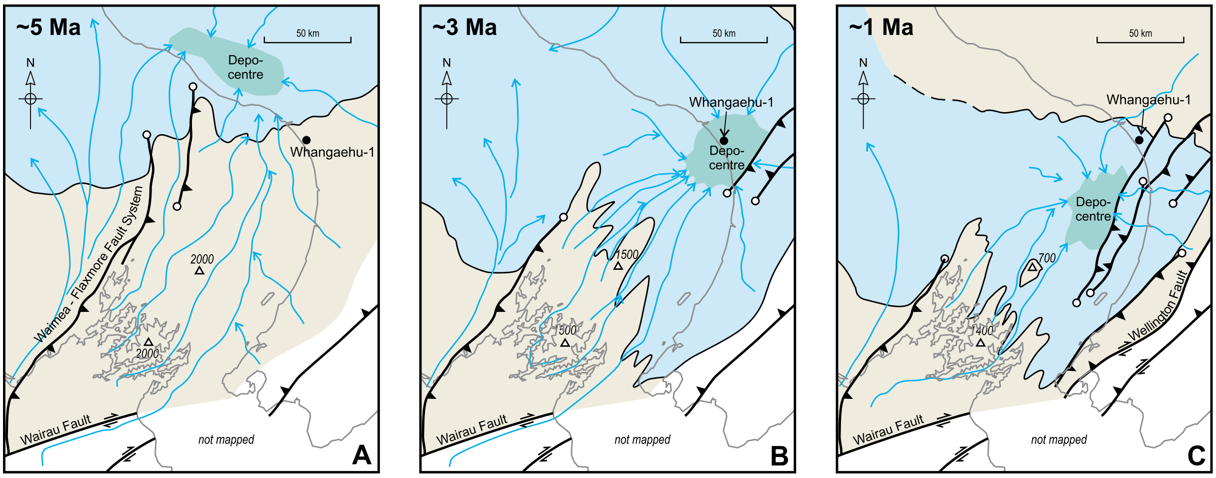

Figure 9 Palaeogeographic reconstructions of the offshore Wanganui Basin and Marlborough Sounds at c. 5, 3 and 1 Ma; marine (blue fill), terrestrial (light green fill), inferred palaeocoastline (thin black lines), present coastline (grey lines) and drainage (blue lines; arrowheads indicate flow direction). Palaeogeography maps only apply to the regions north and west of the Wairau and Wellington faults where the Plio-Pleistocene strains were low. Diagrams include palaeogeographic data from Anderton (1981), King & Thrasher (1996), Begg & Mazengarb (1996), Kamp et al. (2004) and Proust et al. (2005). Triangles indicate the location of summit heights (in metres) estimated using the present topography on top basement and assuming that the initial gradient on the floor of the Queen Charlotte palaeovalley was 0.1° (i.e. consistent with present river gradients in the region). Active faults are indicated by thick black lines with open circles showing the locations of their tips.

Fault [e.g. Proust et al. 2005] can be entirely accounted for by differential compaction across the basement high in the hanging wall of the fault and need not require post-4-Ma fault displacement).

Timing of subsidence

Sedimentation in the Wanganui Basin offers the prospect of deciphering the subsidence, tilting and sedimentation history of the Marlborough Sounds. In particular, these data provide insights into the timing of onset of Sounds subsidence and the rates of these processes. Sedimentary strata in the Wanganui Basin reveal a two-stage basin subsidence history. In the first stage, between the H4 (c. 1.7 Ma) and top basement (c. 3–4 Ma) seismic reflectors in Fig. 3, the basin depocentre straddled the North Island coastline 90–150 km north-northeast of the Sounds (Fig. 9B). At this basin depocentre, mudstone-dominated strata were deposited within c. 470 m of basement in the Whangaehu-1 well in upper bathyal palaeo-water depths of 200–600 m (Ian R Brown Associates 1996). The altitude change from terrestrial ranges to bathyal marine environments by far exceeds eustatic sea-level fluctuations (i.e. up to 120 m) and requires significant rock subsidence (e.g. $>$200–500 m). Near Wanganui at the basin depocentre this initial period of subsidence is inferred to have commenced no later than c. 4 Ma. Along the southern margin of the basin the coastline geometry during highstand sea levels at c. 3 Ma may have been similar to the present Sounds coastline and c. 50 km north of its current location (Fig. 9B). Subsequent sedimentation in the basin was associated with a shallowing of the palaeo-water depths to $\leq$50m between c. 3 and 4 Ma (Ian R Brown Associates 1996) and produced onlap onto basement of the H4 (c. 1.7 Ma) and older reflectors, mostly within 20 km of the southern margin of the basin (Fig. 3 & 6). These reflectors are discontinuous and suggest that prior to c. 1.7 Ma, sedimentation had only partially filled basement palaeovalleys in the basin.

The second stage of basin development post H4 (c. 1.7 Ma) is marked by a c. 50 km southward shift in the depocentre at c. 1.5 Ma (compare Fig. 9B & C). The southward migration in the Wanganui Basin depocentre has been widely reported (e.g. Anderton 1981; Stern et al. 1992, 1993; Kamp et al. 2004; Proust et al. 2005). Inspection of Fig. 3 suggests that this migration was achieved by a step rather than slow and progressive migration of the depocentre. The units below the H4 (c. 1.7 Ma) reflector appear to thicken towards the north-eastern end of the seismic section, while units above the H4 reflector thicken towards a basin depocentre 50 km from the northeast end of the seismic line (Fig. 3).

The onset of uplift of the Wanganui coast and associated southwards tilting of reflectors at the northern end of the seismic-reflection line in Fig. 3 provide a means of constraining the timing of the basin depocentre shift more precisely than is possible from visual inspection of Fig. 3. Tilting of up to 2.5° (of strata between the Tan 16 cross line and the northern end of the seismic line in Fig. 3) is shown by the top curve in Fig. 8A which indicates an onset of southwards tilting and a southwards shift in the depocentre location at c. 1.5 Ma. This southwards tilting produced uplift and erosion of Plio-Pleistocene strata which are exposed along the Wanganui coast and have been extensively studied (e.g. Fleming 1953; Naish et al. 2005). This new basin centre location persisted for at least 1 Ma until formation of the H1 reflector, or younger. The timing of the shift in basin centre is not marked by a change in the northwards tilting of the strata approaching the Marlborough Sounds (between the marked basin centre and the southern end of the line in Fig. 3; lower curve Fig. 8A). Mapping of basin strata indicates that the southern limit of the H4 reflector is approximately positioned at the present-day outer margin of the Marlborough Sounds, suggesting that this was approximately the southern limit of the basin at c. 1.7 Ma and that the Sounds area probably remained above sea level until at least this time (Fig. 3 & 9). The onset of sedimentation within the Sounds may signify encroachment of basin sedimentation into the Sounds and appears to approximately coincide with the timing of the shift in basin depocentre. It is therefore inferred that the southwards shift in basin depocentre also resulted in a southwards step in the southern margin of the basin. The commencement of basin sedimentation in the Sounds may have resulted from an increase in the rates of subsidence in the Sounds and could signal the onset of their submergence at c. 1.5 Ma. This estimate for the onset of subsidence is intermediate between the 0.5 Ma and 2–3 Ma proposed by Singh (2001) and Cotton (1974), respectively.

Rates of tilting, subsidence and sedimentation

Subsidence and north-eastwards tilting of the Sounds block are considered by many to be critical for the partial submergence and development of the Marlborough Sounds (Cotton 1913, 1955, 1969, 1974; Campbell & Johnston 1992; Singh 1994, 2001; Begg & Johnston 2000). Few constraints are, however, available for the rates of these processes and the role that they have played in the present submergence of ancestral valleys in the Sounds. Seismic-reflection data are here used to constrain the rates of tilting, subsidence and sedimentation along the north-eastern margin of the Sounds over the last c. 0.12–3 Ma (Fig. 8).

A striking feature of the curves in Fig. 8A is that the tilt and associated tilt rates approximately perpendicular to the north-northeast and south-southeast margins of the offshore Wanganui Basin are universally low (tilts $<2.5^\circ$ and tilt rates $<1.5^\circ$ per Ma). The tilt rates are particularly low to the south of the depocentres and approaching the Marlborough Sounds, where they average c. 0.5° per Ma (lower curve of open squares in Fig. 8A) and the 4 km of basin depth is achieved because tilting in a north-northeast direction occurs over large distances of up to c. 120 km. The c. 0.5° per Ma tilt rate for the Wanganui Basin may provide a maximum for the Marlborough Sounds region because it incorporates subsidence that was, at least partly, induced by sediment loading.

To illustrate this point the graph in Fig. 8B shows total rock subsidence (sediment loading + tectonic) and tectonic subsidence at the post 1.7 Ma basin centre. Sediment loading was calculated using Airy Isostacy (Steckler & Watts 1978) and accounts for about half of the total subsidence (see also Stern et al. 1993). In the Sounds, however, sediment is limited to thin (<400 m thick; Fig. 4) narrow strips in palaeovalleys which produce minimal sediment loading and associated subsidence. In the absence of significant sediment loading, tilting and tilt rates in the Sounds are likely to be lower than those in the Wanganui Basin; this conclusion is supported by the dramatic decrease in the tilt of top basement between the basin and the Sounds (Fig. 6). Subtraction of Wanganui Basin tilting due to sediment loading (c. 0.25° per Ma) from the total tilting (c. 0.5° per Ma) suggests average tilt rates towards the north-northeast could be as low as c. 0.25° per Ma at the outer edge of the Sounds over the last 3.5 Ma. These tilt rates (i.e. c. 0.25° per Ma) are significantly lower that the 3.9° per Ma and 1.1° per Ma estimated in Pelorus Sound for c. 14 ka and c. 135 ka horizons, respectively (Singh 2001). These differences could partly reflect uncertainties in the rate estimates. For example, the high rates of tilting for the past c. 135 ka are strongly dependent on the inferred depositional tilt which, based on present seabed bathymetry in the Sounds, could have varied over the range 0–0.2° and would result in a range of tilt rates of 0–7° per Ma.

The low million-year tilt rates, which are consistent (within the uncertainties) with a lack of evidence for tilting since c. 6.5 ka (Hayward et al. 2010a), do not appear to be high enough to significantly affect landscape evolution over shorter timescales (e.g. <100 ka). In the Kaituna Valley, for example, the long-term tilt rates calculated here (i.e. $<0.25^\circ$ per Ma) would, if applied for the past 10 ka, produce <1m uplift along the entire length of the valley. Uplift this small is unlikely to defeat the flow of rivers and streams which, in New Zealand, often incised tens of metres during the Holocene (e.g. Bull 1991; Nicol & Campbell 2001; Litchfield & Berryman 2006). These results add weight to the suggestions of Mortimer & Wopereis (1997) and Craw et al. (2007) that processes other than tectonic tilting were responsible for drainage reversal in the Kaituna Valley. Similarly, the very low tilt rates bring into question the inferred role of tectonic tilting in, and occurrence of, drainage reversal postulated by Lauder (1970).

Tilting of the Sounds Block and Wanganui Basin requires decreasing total subsidence towards the Marlborough Sounds south-southwest of the basin depocentre. With the exception of the initial period of rapid subsidence, perhaps between 4 and 5 Ma, subsidence rates in the basin were approximately matched by sedimentation rates (e.g. Naish et al. 2005). At the deepest part of the Wanganui Basin, 4 km of sediment were deposited in c. 4 Ma suggesting average subsidence and sedimentation rates of about 1 mm a^{-1}. Similarly, at the basin centre post 1.7 Ma the average subsidence and sedimentation rates since this time were c. 1.2 mm a^{-1}. Along the present outer north-northeast edge of the Marlborough Sounds, the rates of subsidence and the thickness of basin-fill sediments are significantly lower than at the basin depocentres.

At the entrance to Queen Charlotte Sound, for example, the estimated depth of seismic reflectors suggests that sediment-fill in the valley floor which the Sound occupies has a thickness of c. 500 m (e.g. Fig. 6; Cotton 1955). The age of the strata resting directly on basement at this location is estimated to be c. 1.5 Ma (e.g. Fig. 6). If the top of basement at this location was close to sea level at 1.5 Ma, then the average subsidence rate since this time was c. 0.3 mm a^{-1} and comparable to average sedimentation rates over the same time interval. This sedimentation rate is similar to the c. 0.3 mm a^{-1} average after the H2 horizon (c. 620 ka) calculated using an estimated sediment thickness of c. 200 m from Fig. 6. Given the north-northeast tilting of the Sounds Block (and the southern Wanganui Basin) it is expected that subsidence rates will decrease from the outer to inner Sounds, perhaps reaching zero close to the head of Pelorus Sound (e.g. Wellman 1979; Singh 2001).

The long-term ($>$c. 620 ka) subsidence in the Sounds is therefore inferred to be $<$0.3 mm a^{-1}. This subsidence rate is lower than the c. 1 mm a^{-1} estimated in Pelorus Sound since c. 12 ka (Singh 1994, 2001) and the c. 0.5–1.0 mm a^{-1} preferred by Hayward et al. (2010a), Hayward et al. (2010b) over much of the Sounds during the last c. 6.5 ka. The apparent disparity between these short ($\leq$12 ka) and long-term ($\geq$620 ka) data may indicate temporal variations in subsidence rates on timescales of tens–hundreds of ka as has been observed for other geomorphic and tectonic processes (e.g. Gardner et al. 1987).

Water loading of the lithosphere associated with post-glacial sea-level rise provides one mechanism that could have produced up to 20% acceleration of subsidence rates during the Holocene (compared to the long-term average) at the present outer margin of the Sounds (Hutton & Syvitski 2008). The high Holocene rates of subsidence may also be interpreted to signal a late Quaternary southwards shift in Wanganui Basin subsidence as appears to have occurred at c. 1.5 Ma and has been postulated by Singh (2001) during the past c. 135 ka. The late Quaternary southwards migration hypothesis cannot however be independently tested with the observed rates and, given the estimated c. $\pm$0.2–0.4 mm a^{-1} uncertainties on subsidence rates, may not be required to account for the available data.

Given the available seismic and topographic data it is suggested that the accommodation space created by subsidence in the Wanganui Basin and the Marlborough Sounds was largely filled with sediment. In the Sounds these sediments include gravels (Cotton 1913; Esler 1984; Singh 1994, 2001; Mortimer & Wopereis 1997; Begg & Johnston 2000; Craw et al. 2007; Hayward et al. 2010a), which may indicate that gravel-bearing rivers occupied valleys between marine incursions. Episodic gravel deposition is likely to have been rapid and to have assisted in the infilling of accommodation space created in the valleys by subsidence. If this accommodation space was largely infilled with sediment, then while isostatic sea-level rise is critical for lowering deeply dissected topography to sea level it does not ultimately produce submergence of the Sounds.

Eustatic sea-level changes

The question remains why have the Marlborough Sounds formed? Eustatic sea-level changes have long been considered important for the formation of the Marlborough Sounds (e.g. Cotton 1955, 1969, 1974; Campbell & Johnston 1992; Singh 1994, 2001; Ota et al. 1995; Begg & Johnston 2000; Berryman & Hull 2003). The importance of eustatic sea-level changes increases, however, if sedimentation rates approximately matched subsidence rates in the Sounds over the past 1.5 Ma. In these circumstances marine inundation of the Sounds would be generally restricted to interglacial periods when the rise in sea level associated with deglaciation outpaced average sedimentation rates by up to two orders of magnitude (e.g. c. 20 mm a^{-1} compared to $<$0.3 mm a^{-1}). The role of eustatic sea-level changes in the formation of the Sounds is illustrated in Fig. 10 which shows eustatic fluctuations in sea level of up to c. 120 m since 130 ka (Pillans et al. 1998). This eustatic sea-level curve was constructed using the oxygen isotope record from deep-sea core V19-30 in the east-equatorial Pacific and is comparable to many sea-level reconstructions prepared globally. For the past

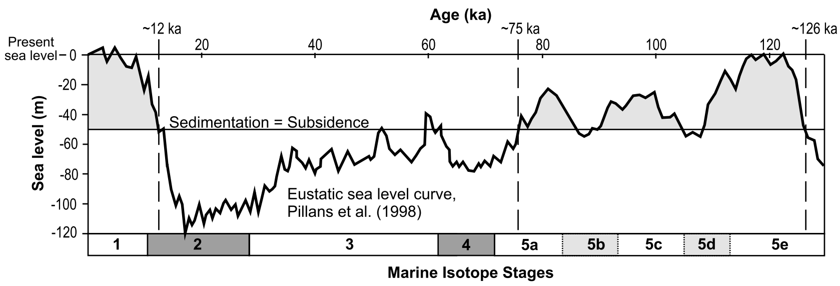

Figure 10 Eustatic sea-level curve since 130 ka (oxygen isotope stage boundaries are indicated at the base of the graph) from Pillans et al. (1998). If sedimentation and subsidence rates are equal, the absolute altitude of valley floors (relative to a fixed earth model) does not change and the Sounds will be mostly emergent and partly submerged at sea levels lower and higher than -50 m, respectively. The timing and magnitude of marine incursions into the Sounds are indicated by the grey polygons which fill the sea-level curve down to values of -50 m.

c. 800 ka these curves are broadly characterised by c.100 ka time intervals of gradual decrease in sea level followed by a rapid (over c. 10 ka) rise of c. 120 m (Fig. 10). Smaller amplitude sea-level fluctuations can produce departures in sea level of 20–30 m from the general trend of the curve. However, of greatest importance is the fact that eustatic fluctuations in sea level exceed the water depth in the Sounds, which is generally <50 m, by at least a factor of two and it is these changes (and possibly also the associated water loading of the lithosphere) that submerge the Sounds.

The influence of eustatic sea-level fluctuations on inundation of the Sounds is illustrated in Fig. 10 with reference to a sea level 50 m below the present. This value has been selected because a 50 m drop in present sea level would result in the Sounds being mainly emergent. In the case where subsidence and sedimentation rates in the Sounds are equal, the absolute altitude of the top of the sediment fill in palaeovalleys remains approximately fixed (i.e. relative to a fixed Earth datum rather than a fluctuating sea level). (Note that the present analysis excludes the influence of water loading which does not impact on the first-order conclusions outlined below.) In these circumstances, if sea level were to drop by 50 m or more below present values, the Sounds would become a series of large relatively flat-floored terrestrial river valleys. For lesser drops in sea level the Sounds would be variably inundated by the sea.

The timing and magnitude of these inundations are indicated by the grey polygons which fill the sea-level curve down to values of –50 m. These grey polygons illustrate three important points about the formation of the Sounds. First, the most recent incursion of the sea into the Sounds probably commenced at c. 12 ka and reached its current spatial extent and water depth by c. 7 ka. The relatively short period of geological time that the present coastline has been in position may help explain why coastal erosion in the Sounds is relatively minor (i.e. 30 m with an average rate of c. 0.4 m per 100 years since 7 ka). Second, between c. 12 and c. 75 ka valley floors were probably mainly above sea level and occupied by streams; the Sounds as we know them today did not exist. Third, between c. 75 and c. 126 ka, Sounds topography experienced varying degrees of inundation. The present incursion of sea into the Sounds is the greatest during the past c. 110 ka, with sea incursion to a level similar to the present at c. 120 ka (Fig. 10).

Discussion and conclusions

The Marlborough Sounds include some of New Zealand's most tortuous coastline which developed by partial drowning of the dendritic drainage to form a network of rias. The development of the Sounds required stream incision and dissection of uplifted rocks followed by subsidence and marine incursion into the valley systems. The primary valley and ridge systems in the Sounds are inferred to have mainly formed during the Miocene (>5 Ma). The antiquity of the Marlborough Sounds topography is consistent with the interpretation that the K-Surface in the Wellington region may be millions of years old (Cotton 1957). There is widespread recognition, however, that the mountains of Ruahine and Tararua Ranges in the central New Zealand are Pleistocene in age (Wellman 1948; Ghani 1978; Beu et al. 1981; Shane et al. 1996). One interpretation that can be placed on the existing data is that the age of the landscape varies by millions of years between different regions of New Zealand and is strongly influenced by the timing and magnitude of rock uplift. In areas like the Sounds for example, where indurated basement rocks appear not to have experienced significant deformation and uplift since 5 Ma, the primary topography may be relatively old (e.g. Miocene). How widespread in New Zealand these older landscapes are is a key question that requires further examination.

Marine inundation of New Zealand occurred widely in response to global sea-level rise since 20 ka (e.g. Gibb 1979, 1986; Pillans et al. 1998). In addition to this rise in sea level, subsidence is considered to be an important factor in the formation of the Sounds (Cotton 1913, 1955, 1969, 1974; Lauder 1970; Wellman 1979; Stern et al. 1992, 1993; Singh 1994, 2001; Begg & Johnston 2000); however, few data have previously been presented to constrain the amount and timing of the vertical movements responsible for the generation of the Marlborough Sounds landscape. The available data indicate that Sounds topography may have started to subside below sea level at c. 1.5 Ma when the Wanganui Basin stepped southwards by c. 50 km. The average rates of subsidence and tilting of the Sounds over the last c. 1.5 Ma have been low ($<0.3\,\mathrm{mm\,a^{-1}}$ and 0.25° per Ma). The accommodation space created by subsidence appears to have been filled in the valley system by sediments suggesting that, while subsidence was important for bringing strongly dissected topography to sea level, it was not the key driver for submergence and formation of the Sounds.

Instead, marine inundation of the Sounds is primarily controlled by eustatic sea-level rises which occur at rates of up to several orders of magnitude higher than the average rates of sedimentation and subsidence (e.g. c. $20\,\mathrm{mm\,a^{-1}}$ versus c. $0.3\,\mathrm{mm\,a^{-1}}$). The Marlborough Sounds are ephemeral and started to form at c. 12 ka with the present coastline established by c. 7 ka. Prior to c. 12 ka the Sounds was probably mostly above sea level until c. 75 ka and below sea level to varying degrees between c. 75 and 126 ka. The configuration of the present coastline is likely to have occurred approximately every 100 ka during the Late Quaternary.

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