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Collapse in a Quaternary shelf basin off East Cape, New Zealand: evidence for passage of a subducted seamount inboard of the Ruatoria giant avalanche

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Abstract The Ruatoria margin indentation and its associated giant avalanche off East Cape, New Zealand, have been inferred to result from margin instability following oblique subduction of a large seamount. The earlier studies hypothesise that a diachronous seamount-wake trough formed the northern part of the indentation, and collapse between the oblique trough and an oversteepened margin front formed the southern indentation and giant avalanche. If correct, then the impacting seamount must now be landward of the indentation. New seismic profiles, supported by multibeam bathymetry and core samples, from landward of the Ruatoria Indentation, provide support for the passage of a large seamount deep beneath the continental shelf.

The continental margin around the head of the indentation is underlain by Quaternary basins that are inferred to result from transpression associated with oblique plate convergence. One basin underlies the shelf landward of the indentation, its seaward edge having collapsed into the indentation. There, faults and a graben with gravitational collapse structures that are transverse to the northeast–southwest regional trends may be evidence of passage of a seamount. A tentative sequence stratigraphy, based on Quaternary unconformities and shelf-edge prograding units, suggests that the main phase of collapse occurred on the outer shelf before the penultimate, major, glacial sea-level lowering c. 155–135 000 yr ago. Depths to the post-last-glacial erosion surface indicate that the basin is subsiding rapidly at >4 m/ka. If a significant part of the subsidence relates to wake collapse behind a subducting seamount, then the seamount must now underlie the adjacent land. Onshore, doming hills, with coastal terraces indicating uplift of 2.6 m/ka, suggest that the seamount is now c. 10 km west of East Cape.

Keywords Hikurangi margin; New Zealand; Quaternary basin; subducted seamount; debris avalanche; submarine landslide; Raukumara Peninsula

INTRODUCTION

Ruatoria Indentation: the subducting seamount hypothesis

One of the most dramatic features of eastern New Zealand's convergent Hikurangi margin is the huge Ruatoria Indentation at the margin's steep northern end (Fig. 1). The indentation is upslope from a giant avalanche deposit (Fig. 1, 2) that extends nearly 50 km out across the flat northern Hikurangi Trough (Lewis et al. 1998). Despite the obvious inference that the indentation is a result of massive slope failure, its straight northern edge and a volume that is greater than the resulting avalanche deposit have prompted a suggestion that the indentation is a composite feature, rather than just an avalanche scar (Collot et al. 2001). The composite hypothesis proposes that the indentation formed by the combined effects of subducting seamount impact and massive avalanching of a destabilised margin. It infers that, firstly, multiple small failures occurring in the wake of a large, obliquely subducting seamount formed a trough obliquely across the margin between c. 2 and 0.2 m.y. ago. Following this, the destabilised triangle in the acute angle between the trough and an oversteepened margin front collapsed c. 170 ± 40 000 yr ago in avalanches that were two orders of magnitude bigger than the biggest slope failures on land (Lewis et al. 1999). The subducted seamount that is inferred to have been the primary cause of the Ruatoria Indentation must now necessarily be landward of the indentation. Despite the plausibility of the hypothesis, there is presently no corroborating evidence of a subducted seamount landward of the indentation. However, even deeply subducted seamounts can leave patterns of deformation that are evidence of their presence (or passage) landward of their wake trough (von Huene & Lallemand 1990; Lallemand et al. 1994; Dominguez et al. 1998a,b, 2000). This paper examines the continental shelf landward of the Ruatoria Indentation for evidence of a seamount, or passage of a seamount, beneath it.

Regional setting

The N35°E-trending Hikurangi margin is on the forearc or Kermadec Microplate at the edge of the Australian plate (Fig. 1) (Collot et al. 2001). It has the 12–15 km thick, oceanic, Hikurangi Plateau on the Pacific plate being subducted westwards beneath it (Fig. 1) (Davy 1992; Wood & Davy 1994; Mortimer & Parkinson 1996). The subducting

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plateau is heavily studded with volcanic seamounts, with many, including Gisborne and Mahia Seamounts (Fig. 1), aligned in ridges trending N150 ± 20°E (Collot et al. 1996). Between seamounts, the oceanic crust is draped by pelagic sediments up to c. 1 km thick (Wood & Davy 1994) and, approaching the northern Hikurangi margin deformation front, by a wedge of turbidites that is an additional 1 km thick (Lewis et al. 1998). Tectonic erosion by the seamount-studded subducting plate has narrowed and steeped the northern Hikurangi margin continental slope, in places to over 10° (Fig. 3) (Collot et al. 1996).

At the latitude of the Ruatoria Indentation, the Pacific plate and its seamounts are converging with the Australian plate at 45 mm/a in a direction of 267° (De Mets et al. 1994). Thus, there is obliquity of c. 40° between the convergence direction and the N127° orthogonal to the margin. However, backarc spreading in the Havre Trough/Taupo Volcanic Zone, besides increasing the rate of convergence between the Pacific plate and the Kermadec forearc to 54 mm/a, also reduces the obliquity of convergence to 30° (Collot et al. 2001). In addition, active deformation within the forearc may further modify the speed and angle of convergence at the leading edge.

Knowledge of the structure and stratigraphy of the margin adjacent to the Ruatoria Indentation has been based mainly on a limited number of reconnaissance seismic lines (Lewis & Pettinga 1993; Collot et al. 1996; Field et al. 1997; Lewis et al. 1997). These indicate that the northern Hikurangi margin's structure is significantly different from both the actively accreting margin to the south (Davey et al. 1986; Barnes & Mercier de Lepinay 1997) and from the uplifted oceanic Kermadec Ridge to the north (Collot & Davy 1998). It has previously been suggested that the similarly trending Kermadec and Hikurangi segments of the Tonga-Kermadec-Hikurangi subduction system may have developed with markedly different trends and rotated into line only in the last few million years (Cole & Lewis 1981; King 2000).

On the adjacent land, the geology of the Raukumara Peninsula is complex (Fig. 3). Its rugged landscape (Fig. 2) is deeply eroded and highly unstable (Field et al. 1997). Slide-sheets of oceanic Cretaceous–Oligocene sediments and seamount blocks, collectively known as the East Coast Allochthon (Fig. 3), were obducted from the NNE over passive margin sediments of similar ages in early Miocene times, motion of the slide-sheets being lubricated by Eocene smectites (Stoneley 1968; Ballance & Spörli 1979; Rait 1995). The East Coast Allochthon is covered, in places, by Neogene deposits that are up to nearly 5 km thick (Field et al. 1997; Mazengarb & Speden 2000). The allochthon and cover beds outcrop along the coast near the head of the Ruatoria Indentation, and there is no reason to suppose that either of these units stops at the coast, with both having been interpreted in offshore profiles (Field et al. 1997; Collot et al. 2001). Onshore, the rocks from Mesozoic basement upwards have been involved in Quaternary contractional tectonics and in extensional, gravitational collapse towards the Hikurangi Trough (Mazengarb & Speden 2000).

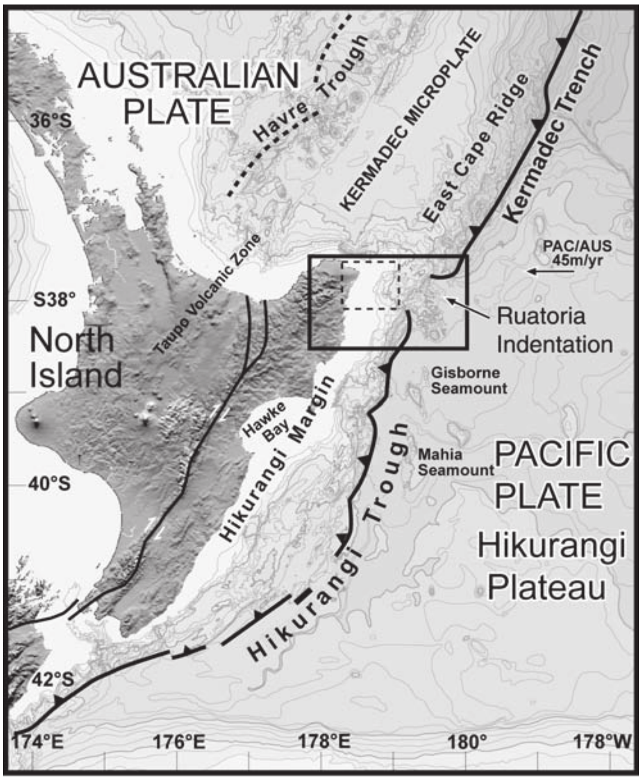


Fig. 1 Position of Ruatoria Indentation east of Raukumara Peninsula, North Island, New Zealand, in relation to the Pacific/Australian plate boundary (flagged line) and to major tectonic elements. Solid box shows the area illustrated in Fig. 2 and 3. Broken box shows the area covered by Fig. 4, 8, and 10).

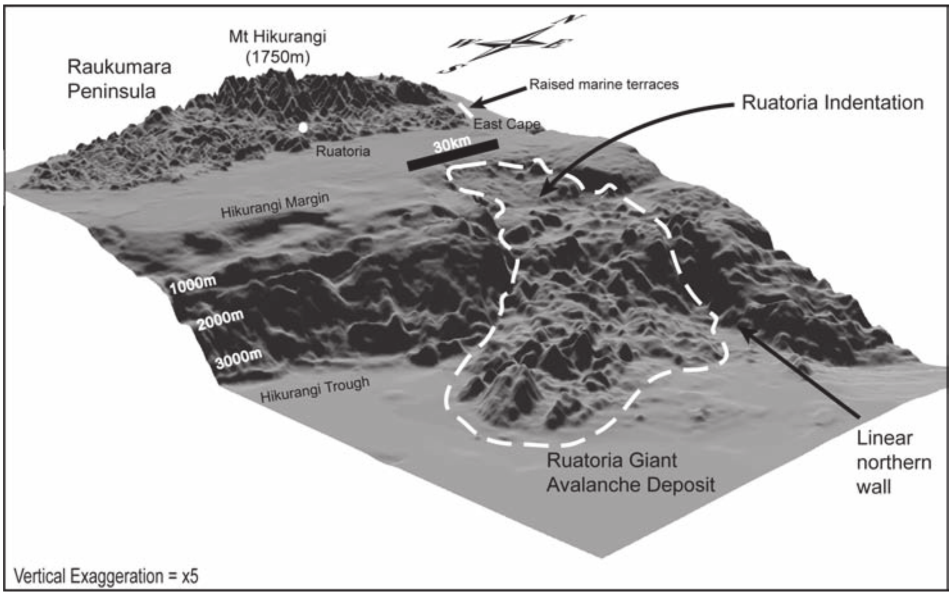
Nature and setting of the Ruatoria Indentation

First tentatively recognised from sparse echo soundings and seismic profiles as a huge slump scar (Lewis & Pettinga 1993), the Ruatoria Indentation is 65 km wide at its base along the edge of the 3600 m deep Hikurangi Trough. It tapers landward to 30 km where it incises the 140 m deep edge of the shelf, 65 km to landward (Fig. 2, 3). Its area is >3300 km^2. Swath mapping and seismic surveys, collected as part of the French/New Zealand GeodyNZ Project, confirmed the interpretation of massive slope failure (Collot et al. 1996). They also produced evidence that mass failure was not the only cause for the indentation.

The straight northern wall of the indentation (Fig. 3) is aligned in the direction of plate convergence between the Pacific plate and the Kermadec forearc or "Kermadec Microplate", as it is pushed and rotated at the leading edge of the Australian plate by opening of the backarc Havre Trough/Taupo Volcanic Zone (Fig. 1) (Collot et al. 2001). This aligned northern wall, together with rotational collapse structures in the adjacent indentation, prompted the suggestion that the northern part of the indentation is primarily a diachronous seamount impact trough (Collot et al. 2001). It is envisaged that, as the seamount subducts beneath the margin, it carries margin material with it in "shadow zones" in front and behind it, the resulting loss of material producing a tunnel effect and collapse in its wake (Ballance et al. 1989). This wake collapse left a 20–30 km wide trough obliquely across the margin (Collot et al. 2001).

In contrast, the southern wall of the indentation is highly irregular and it lies upslope from a seabed littered with displaced blocks many kilometres across (Fig. 2) . This indicates that the southern part of the indentation may be the headwall of the giant avalanche. Massive failure occurred, not only because oblique passage of the seamount had

Fig. 2 Oblique terrain model of the Ruatoria Indentation and Giant Avalanche deposit (solid box in Fig. 1). The indentation's linear northern wall is inferred to have formed as part of a subducting seamount's "impact scar" or "wake trough".



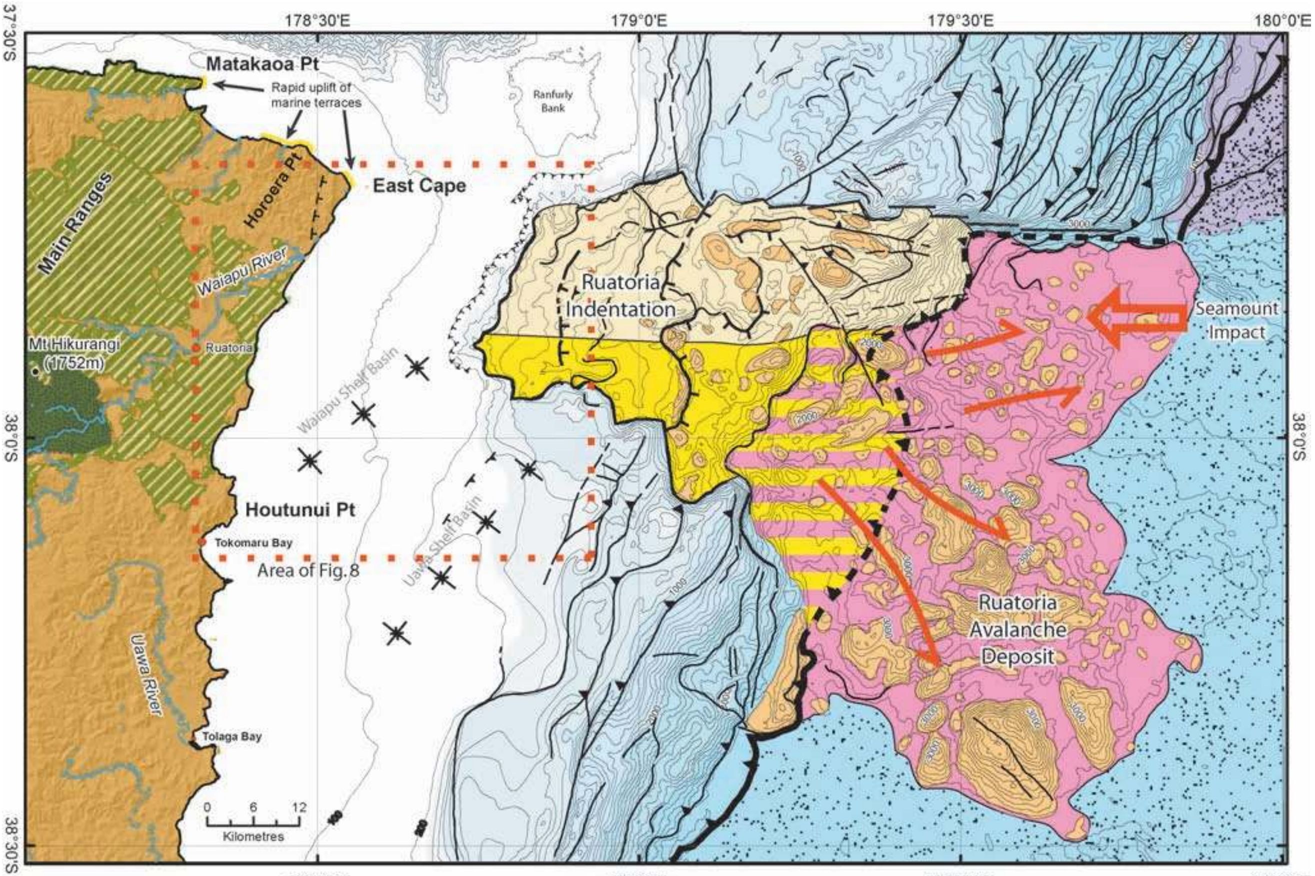


Fig. 3 Simplified geology and physiography of the Raukumara Peninsula and adjacent continental margin, based on Mazengarb & Speden (2000) and Collot et al. (2001). Onshore shows Mesozoic basement (dark green), East Coast Allochthon (green stripes), and Neogene/Quaternary cover (ochre). Last Interglacial and Holocene raised marine terraces from Gibb (1981). Offshore shows bathymetry with contours at 100 m intervals (shades of blue), Hikurangi Plateau (spotted), main avalanche deposits (pink), larger slide blocks (pale orange), indentation collapsed in wake of subducting seamount (pale yellow), head of avalanche (bright yellow), avalanche detachment surface buried by slide (yellow and pink stripes), main faults and folds (black), with pre-avalanche deformation front (thick broken line), route of impacting seamount (open red arrow), and motion of avalanche (one-sided red arrows). Area of Fig. 4, 8, and 10 shown by red broken box.

destabilised a triangle of margin between impact trough and a margin front (Fig. 3), but also because this margin was already potentially unstable due to: (1) oversteepening by "tectonic" erosion (Collot et al. 2001), (2) seaward tilting by uplift onshore, (3) potential remobilisation of old slide deposits, (4) lubrication by overpressured, fluid clays, and (5) rapid sediment loading from New Zealand's largest sediment-bearing river, the Waiapu River. The unstable triangle of margin, with a volume of >3400 km^3, collapsed catastrophically carrying huge blocks, up to 18 km across and 2 km thick, for nearly 50 km out across the flat floor of the Hikurangi Trough (Fig. 2, 3), with debris flow deposits extending up to 100 km beyond that (Collot et al. 2001). The result was a composite indentation, with the impacting seamount's nearly straight, old, diachronous northern edge, and the avalanche's ragged, much younger southern edge.

The hypothesis requires that a subducted seamount lies buried somewhere deep beneath the margin landward of the Ruatoria Indentation headwall; a tentative reconstruction showed it beneath the adjacent continental shelf (Collot et al. 2001). There is presently no substantiating evidence for this "lost" seamount. Appropriate geophysical evidence is difficult to obtain from beneath a continental shelf that is close to obducted ophiolites (Brothers & Delaloye 1982) and where the subducted seamount is buried by 10–12 km of rock (Beanland 1995; Field et al. 1997; Reyners & McGinty 1999). However, besides producing wake troughs, even deeply buried subducting seamounts may dome up the margin above their existing position, with characteristic patterns of transverse splay faults above and ahead of their position (Lallemand et al. 1994; Dominguez et al. 1998a,b, 2000). Evidence of this deformation may remain to mark a seamount's passage beneath the margin (Dominguez et al. 1998b). In this study, we investigate the structure and seismic stratigraphy of the continental shelf at the head of the Ruatoria Indentation, with particular reference to any structures that may mark the passage of a seamount beneath it. We are deliberately looking for any evidence that may help to support or reject the composite hypothesis of the Ruatoria Indentation's origin.

METHODS

The primary dataset for this study is represented by the results of NIWA cruises 3044, TAN-0106, and TAN-0204. It includes a grid of 24-channel seismic profiles collected with a GI Airgun in 45/105 mode (Fig. 4,) together with piston cores, rock samples, and multibeam data collected with a hull-mounted Simrad EM300 swath-mapping system. It is supplemented by archived data collected on earlier scientific and oil industry surveys (Fig. 4). New seismic data were processed at NIWA using the GNS Globe Claritas processing package.

A limited programme of sandbox modelling was undertaken at the University of Montpellier to elucidate some of the processes of oblique seamount subduction. The systems used for these experiments are described by Dominguez et al. (2000). The subducting plate is simulated with a sheet of mylar film to which cones are fixed to represent seamounts. This is pulled slowly beneath a simulated margin that includes a fixed board representing the "rigid backstop" of Mesozoic basement and a prism of sand that equates to a "deformable backstop" of Cenozoic margin sediment. These are aligned obliquely to the direction that the film is pulled. In some cases, sand cover on the subducting mylar film is off-scraped to form an "accretionary prism" that simulates the imbricate-thrust lower margin of the northern Hikurangi margin. The small cones on the mylar film are pulled through the margin sediments as far as the rigid backstop, thus replicating some of the effects of oblique seamount subduction.

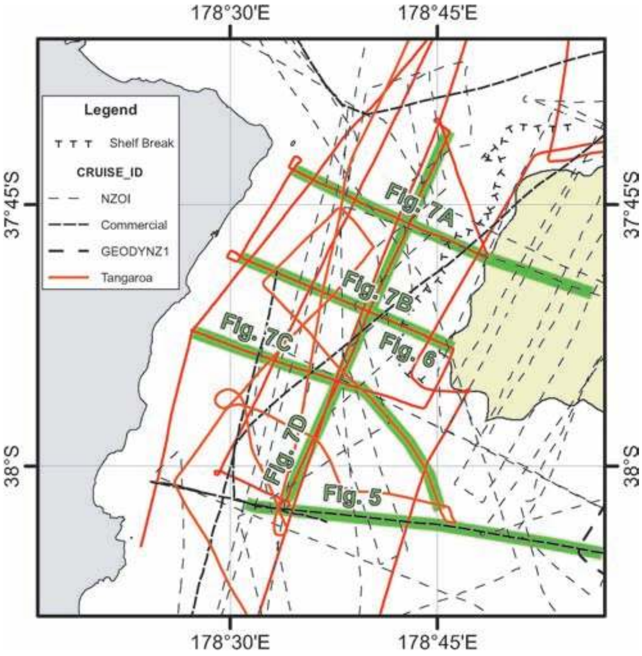


Fig. 4 Map of seismic tracks at the head of the Ruatoria Indentation (beige). Red tracks were collected for this and allied studies by RV *Tangaroa*. Thick green lines show segments illustrated in Fig. 5, 6, and 7.

UPPER MARGIN STRATIGRAPHY

Overall seismic stratigraphy

The basic stratigraphy of the northeastern Raukumara Peninsula (Fig. 3), which comprises (1) "basement" of indurated Mesozoic greywackes and autochthonous Paleogene strata, (2) early Miocene slide-sheets of the East Coast Allochthon, and (3) Neogene and Quaternary cover beds (Mazengarb & Speden 2000), can be extrapolated offshore in seismic profiles (Fig. 5) (Field et al. 1997; Collot et al. 2001). The top of subducting oceanic crust is locally correlated with a deep, strong reflector below the basement reflector. The East Coast Allochthon is correlated with a layer, up to c. 2 s two way travel time (twtt) (possibly c. 2 km) thick, that has few internal reflectors. Above this, well-bedded, broadly folded cover beds, which range up to c. 3 s twtt (probably 2.5–3 km) thick, are correlated with the onshore Neogene and Quaternary deposits. These broad stratigraphic divisions are supported by rock samples from the irregular southern wall of the indentation and from the avalanche deposits that originated from the southern wall (Collot et al. 2001). *In situ* samples containing Miocene and possible early Pliocene foraminifera appear to equate with the well-bedded units, whereas Oligocene and early Miocene faunas from near the top of a weakly bedded avalanche block may correlate with the inferred allochthonous units.

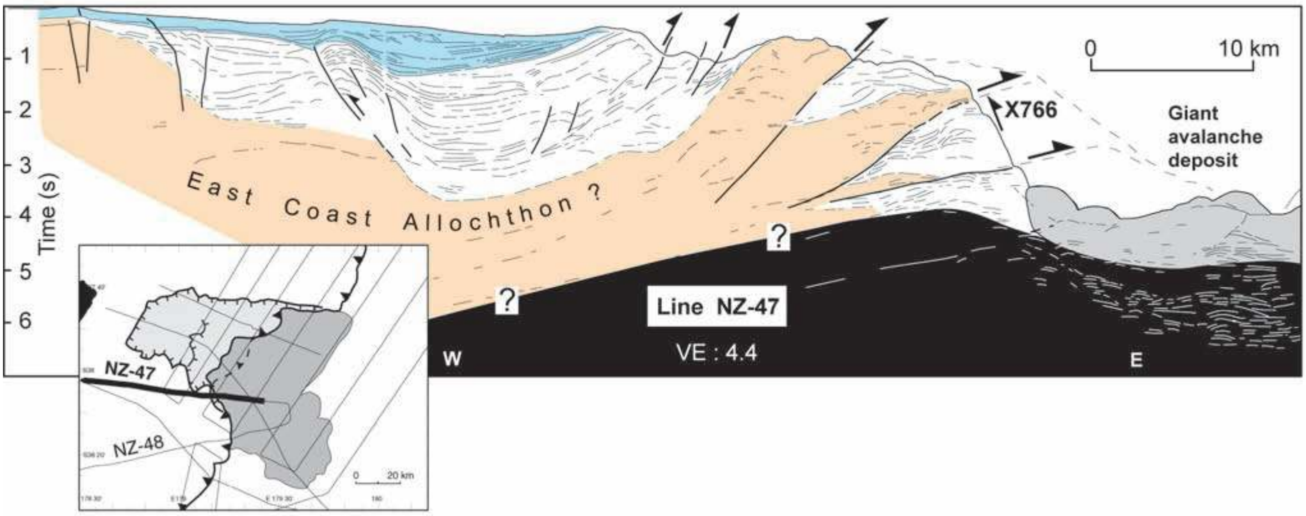


Fig. 5 Interpretation of Gulfrex line NZ-47 (vertical exaggeration ×4.4 at the seabed) showing regional stratigraphy, modified from Collot et al. (2001), with subducting Pacific plate (black), deformed East Coast Allochthon (pale orange), well-bedded Neogene sediments (white), and Quaternary unit with unconformities and prograding, shelf-edge deposits (blue). The original outer margin (broken line) has collapsed to form the Ruatoria Giant Avalanche deposit (grey). *Inset*: Position of line NZ-47 relative to indentation and avalanche deposit.

In the upper part of the well-bedded succession, a strongly reflective unconformity separates lower, parallel-bedded strata from upper beds with numerous, small, angular unconformities and prograding, shelf-edge units (Fig. 5). This strongly reflective unconformity may correlate with the widespread unconformity between Quaternary beds and Pliocene strata on the adjacent Raukumara Peninsula (Mazengarb & Speden 2000) and perhaps with a late Neogene unconformity with similar seismic character beneath the East Cape Ridge to the north (Gillies & Davey 1986; Field et al. 1997). The underlying, parallel-bedded strata may represent deposition in the tectonically more quiescent time between the early Miocene emplacement of the East Coast Allochthon and the Pliocene onset of more rapid deformation (Field et al. 1997).

Quaternary seismic stratigraphy

The upper unit with small angular unconformities is similar in appearance to upper units in Hawke Bay (Fig. 1), where tilted angular unconformities have been interpreted as sequence boundaries (Lewis 1971, 1973; Barnes et al. 2002). There, the sequences are inferred to represent cycles of onshore and offshore migration of shore-parallel zones of wave-planation and nearshore deposition, during Quaternary glacio-eustatic oscillations of sea level (Lewis 1971, 1973). Similar interpretations are now well established (Vail et al. 1977; Posamentier & Vail 1988), and they are adopted for this study. Just as in Hawke Bay, rapid rates of both tilting and deposition on the Ruatoria shelf ensure that the outer parts of sequences, seaward of the axis of no vertical motion, are well preserved and are well displayed on seismic sections (Fig. 5–7).

In the southern part of an actively growing synclinal basin landward of the Ruatoria Indentation, between two and five sequences, typically separated by strongly reflective unconformities, are identified above the widespread regional unconformity (Fig. 6, 7). In the lower part of most sequences, onlap onto a basal erosion surface may indicate transgression of an outer shelf/upper slope sediment prism over a previously wave-planed surface (Fig. 7). These basal layers may typically represent coastal onlapping, of transgressive system tracts (Vail et al. 1991), which are inferred to correlate with rising glacio-eustatic sea levels. For the lower sequences, there is baselap, probably onlap, not only towards the coast but also around a southern outer shelf high (Fig. 7C). Tentative correlation suggests that only the top two or three sequences extend into the northern part of the basin (Fig. 7A,D), implying a change in the locus of subsidence in that direction. Most obviously overlying the top transgressive system tract, but also some earlier ones, there are parallel-bedded layers in a prism that is thickest on the mid shelf, typically with off-lapping, shelf-edge strata at the top of each sequence (Fig. 6, 7B). These are interpreted as the high-stand and regressive system tracts of the subsequent high and falling sea level. Beds at the shelf edge that prograde onto the upper slope (Fig. 6, 7A,B) are interpreted as low sea-level, shelf-edge system tracts. The erosion surfaces that extend landward from the top of each prograding unit on the outer shelf are inferred to indicate wave-planation during glacial maxima and the subsequent rising sea level. Channels that are incised many tens of metres below the level of the top erosion surface are interpreted as river channels cut during a period of lowered sea level (Fig. 7C).

Specific erosion surfaces and sequences identified in seismic sections have not been cored or dated. Although they are inferred to represent glacio-eustatic changes of sea level, correlations with well-established sea-level cycles become increasingly tenuous with age. The top unconformity (Fig. 6, 7) is confidently correlated with the last postglacial, transgression, ranging in age from c. 18 ka on the outer shelf to c. 6 ka near the shore. The sediment above it (shaded yellow in Fig. 6, 7) therefore represents Marine Isotope Stage MIS 1 and part of 2 (Martinson et al. 1987). The next extensive erosion surface beneath it could possibly correlate

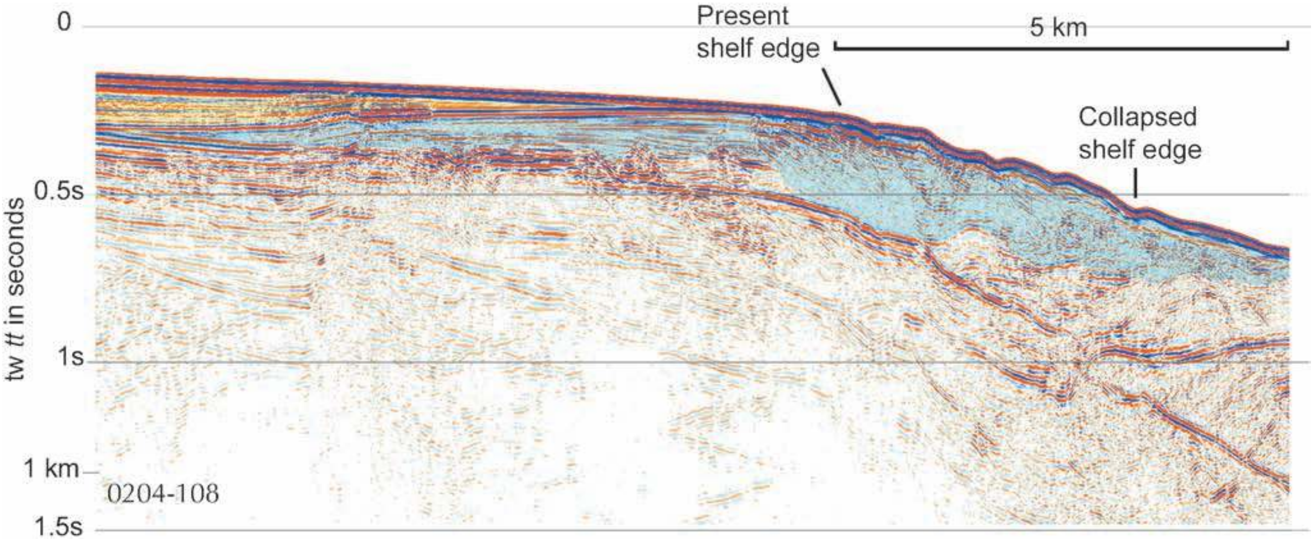


Fig. 6 Part of migrated line 0204-108 (interpreted in Fig. 7B) showing post-last-glacial age shelf prism (yellow overlay) and last glacial age, low sea level, shelf-edge system tracts (blue overlay) prograding into the head of the Ruatoria Indentation. Note landward dip of postglacial transgressive erosion surface between yellow and blue and collapse of prograding shelf-edge units (data collected for Waiapu shelf deposition study by L. Carter).

with transgression after the penultimate glacial age (MIS 6, 135–155 ka). The sequence between the top two unconformities would then include the last interglacial highstand and early last glacial regressive system tracts, MIS 3–5. A prism of prograding sediment that is thickest on the upper slope above older collapse structures and fossil shelf-breaks (Fig. 6, 7A,B) would, in this analysis, represent the deposits of the last glacial age, low sea level (MIS 2).

The postglacial sequence

The top wave-planed surface (Fig. 6, 7) truncates all earlier unconformities and extends across pre-Quaternary rocks on the inner shelf to the shore. It is inferred to represent the post-last-glacial, diachronous (18–6 ka), wave-planed surface. The MIS 1 and late MIS 2 sediments above this surface, which include both the basal, onlapping, transgressive system tract of the last postglacial sea-level rise and the Holocene high sea level system tract, ranges up to 150 ms (c. 112 m) thick on the mid shelf, off the Waiapu River mouth (Fig. 7B). Estimates of thickness of the post-last-glacial layer are mainly based on airgun profiles, because strong, seismically opaque reflectors in most high-resolution seismic profiles across the mid shelf make these records of limited value. Similar layers in similar stratigraphic positions elsewhere have been interpreted as gas-charged organic layers (Foster & Carter 1997; Lewis & Barnes 1999), perhaps derived from rapidly flooded coastal deposits (Pantin 1966; Lewis 1973).

UPPER MARGIN STRUCTURE

Contraction, extension, and strike-slip

Despite some uncertainties with the positioning of some older seismic tracks, and hence in correlation of some small structures, the major folds and faults around the head of the Ruatoria Indentation can be mapped (Fig. 8). These, in turn, can be related to regional oblique contraction and to slope failure on various scales.

The main active structural feature on the shelf at the head of the indentation is a broad, synclinal basin in well-bedded Neogene strata that has been progressively filled with Quaternary sediments (see Fig. 7). This is referred to here as the Waiapu shelf basin. A similar basin to the south, which is arranged en echelon to the Waiapu shelf basin along the outer shelf and upper slope near the southern edge of the indentation, is referred to as the Uawa shelf basin (Fig. 3, 8). The dip of beds on the flanks of each basin increases with age down through the Quaternary deposits and, in places, into the Neogene beds. This indicates that the present pattern of folding began, or accelerated significantly, in latest Neogene times and developed through the Quaternary. Both basins trend c. N45°E at an acute angle to the N20°E-trending coast and to the N35°E-trending margin. Farther south, a third basin, the Waipaoa shelf basin, has a similar trend to its Uawa and Waiapu counterparts at its northern end, its southern reach being aligned at N10° (Foster & Carter 1997).

The basins are at least partly controlled by contraction driven by the friction between overriding and subducting plates (Lewis & Pettinga 1993). The Uawa basin is defined by a series of thrust-bound anticlines on its seaward side (Fig. 3, 5) (Lewis et al. 1997). The seaward side of the Waiapu shelf basin is a broad anticline (Fig. 7C) that may be controlled by contractional back-thrusting at depth (Fig. 5) (Collot et al. 2001). The imbricate-thrust margin here is composed of a “deforming backstop” of pre-existing margin sediment, there being no accretionary prism of offscraped trench sediments as occurs in the south (Lewis & Pettinga 1993).

Circumstantial evidence exists for a component of dextral strike-slip in the saw-toothed plan of the northern wall of the indentation (Fig 3), strike-slip having been inferred on the margin to the north (Collot & Davy 1998) and to the south (Barnes et al. 1998). This motion may possibly continue in some of the mainly pre-late Quaternary faults on the landward side of the Waiapu shelf basin (Fig. 7A,B, 8).

Gravitational, normal faulting occurs extensively in the upper Ruatoria Indentation (Collot et al. 2001), and it appears

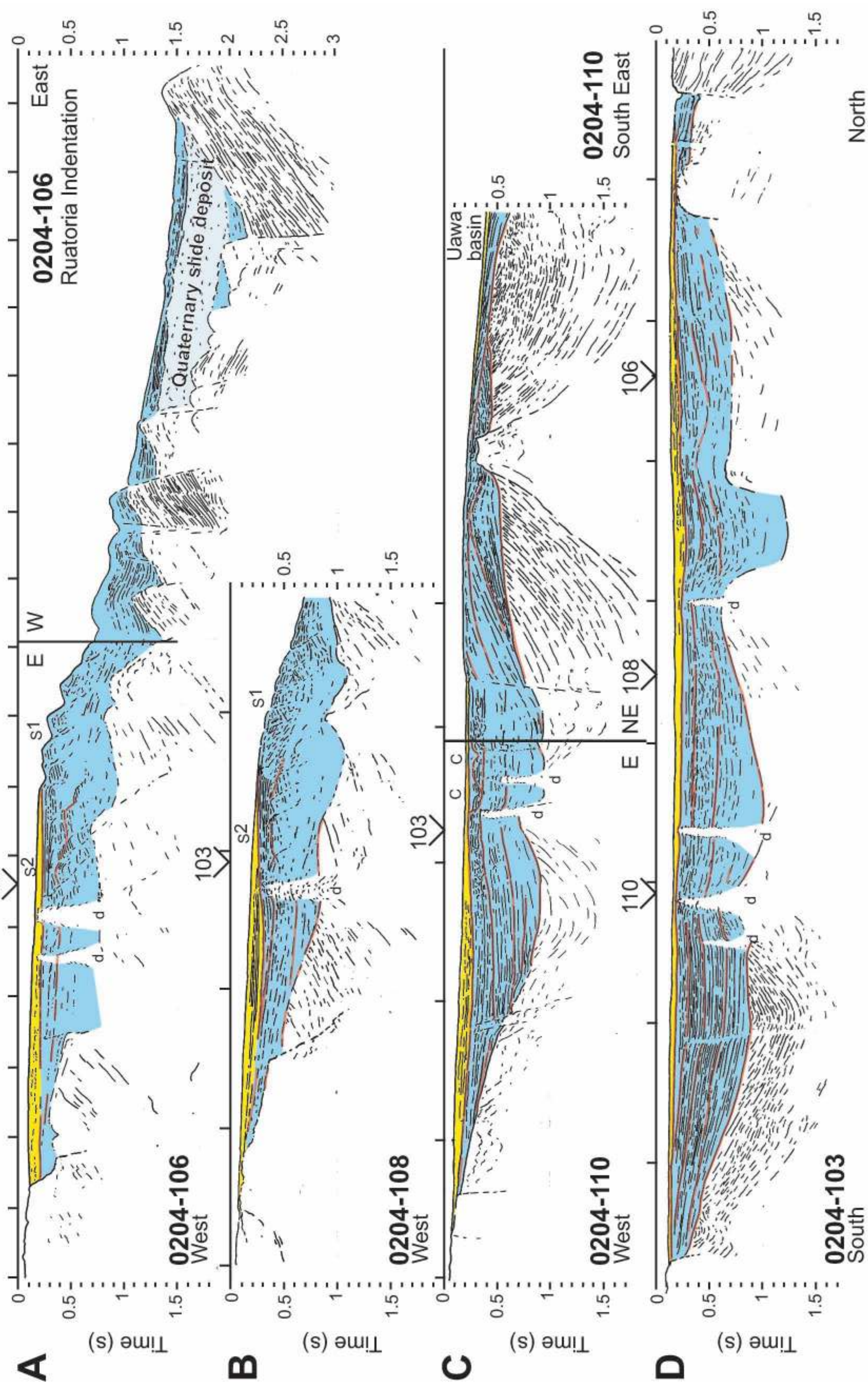


Fig. 7 Interpretations of seismic lines west–east (A,B,C) and south–north (D) across the Waiapu shelf basin and head of the Ruatoria Indentation (positions shown in Fig. 4), showing seismic stratigraphy of inferred Pleistocene (blue) and postglacial (yellow) strata lying unconformably on folded and faulted Neogene strata (white). Sequence boundaries are shown with red overlay. s1 and s2 indicate positions of late last glacial and older shelf-edge slumping, respectively; d shows positions of diapiric intrusions; c indicates positions of buried channels. Original of right half of line 7B is shown in Fig. 6 (data collected for Waiapu shelf deposition study by L. Carter).

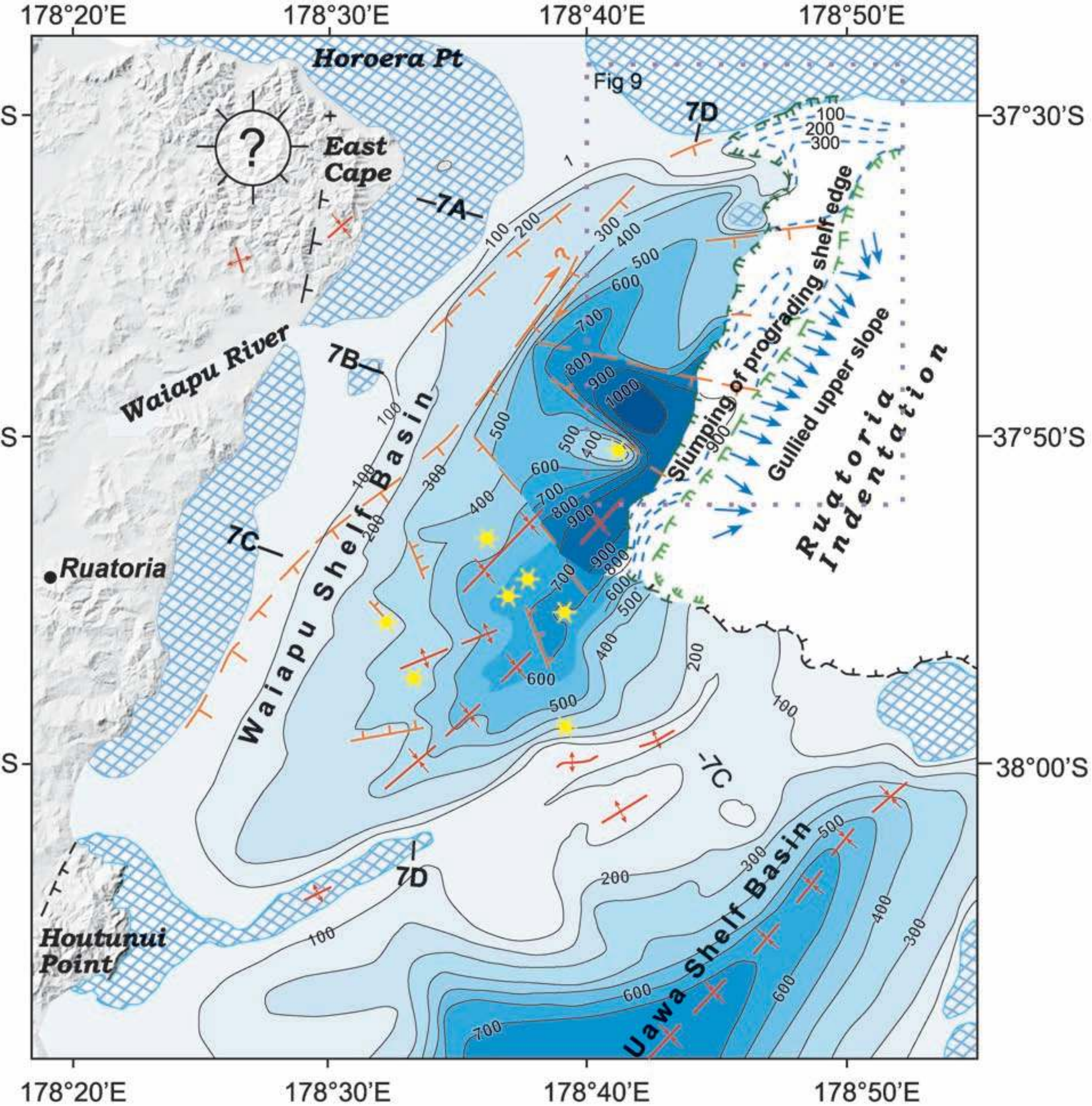


Fig. 8 Structure of the Ruatoria Shelf showing total thickness in metres (assuming sound velocity in sediment of 1600 m/s) of Quaternary sediments. Pre-Quaternary outcrops shown cross-hatched. Main Quaternary structural trends in red. Major faults, mainly in Neogene strata, in orange. Larger diapiric intrusions yellow. Shelf edge and downdropped glacial-age shelf edge shown, respectively, by dark green and light green broken ticked lines. Possible position of subducting seamount shown by black question mark in area of rapid onshore uplift near Horoera Point.

to continue beneath the Waiapu shelf basin to landward (Fig. 7A). Several faults that strike transverse to the regional trends in the northern Waiapu shelf basin (Fig. 8) have considerable vertical, apparently normal offsets (Fig. 7D); two of them define the edges of a graben that is transverse to the margin and other regional trends.

Waiapu shelf basin

The developing Waiapu shelf basin, centred between the head of the indentation and the mouth of the Waiapu River, is c. 25 km wide and 50 km long (Fig. 8). It contains up to 1 km thickness of syn-depositional Quaternary sediments (based on an estimated average sound velocity in Quaternary sediments of 1.6 km/s). It extends northwards as far as an anticlinal ridge of pre-Quaternary rocks that projects offshore from outcrops of late Miocene–Pliocene rocks at East Cape (Fig. 3, 8). A sample of calcareous mudstone (Tan0204/12A) from the anticlinal ridge (Fig. 9) is tentatively dated as Pliocene in age, on the basis of its spore and pollen content (Stratigraphic Solutions Ltd, Waikanae, pers. comm.). In the south, the basin extends to another anticline trending obliquely offshore from Houtunui Point (Fig. 8). This southern anticline is also in well-bedded Neogene strata, its core locally having the reflection-free signature of the East Coast Allochthon (Fig. 7C), which outcrops near Houtunui Point (Fig. 3). This anticline was extensively wave-planed before deposition of Quaternary units

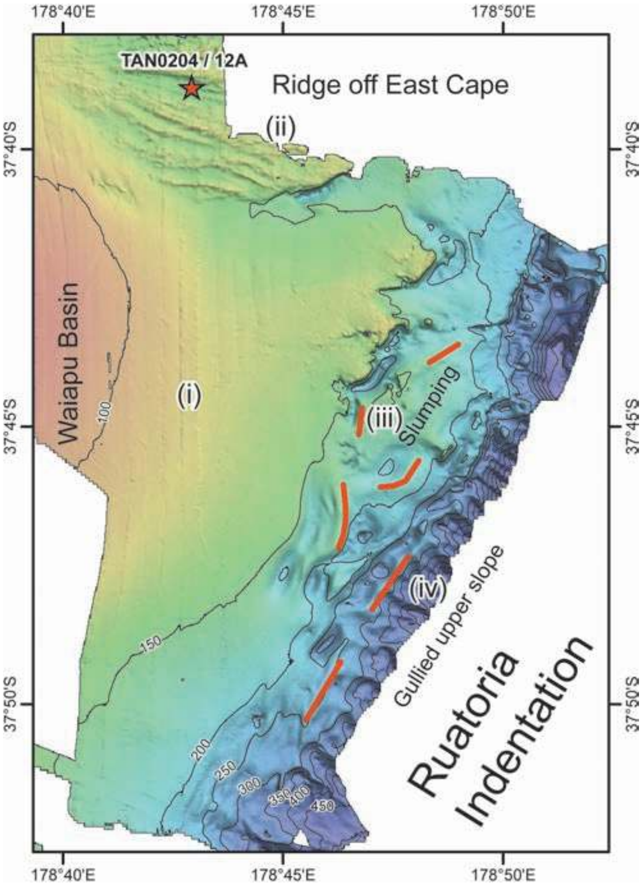


Fig. 9 Multibeam swath map of the outer shelf at the head of the Ruatoria Indentation (position shown in Fig. 10) illustrating (i) smooth surface of postglacial shelf sediments in the west, (ii) outcropping ridges of Pliocene strata in the north, (iii) enclosed basins trending subparallel with shelf edge in collapsed shelf-edge strata, and (iv) gullies in glacial age slope strata below c. 300 m deep. Red star shows position of Pliocene calcareous mudstone sample TAN0204/12A (data collected for study of Waiapu shelf deposition by L. Carter).

(Fig. 7C). The Waiapu shelf basin is bounded to the west by a coastal platform, probably cut into the East Coast Allochthon and Miocene cover beds that outcrop in coastal cliffs (Fig. 3). To the east, the northern basin is truncated by the 400 m high, east-facing head-scarp of the Ruatoria Indentation (Fig. 7A,B, 8). The Waiapu shelf basin is probably the primary Quaternary depocentre of the Waiapu River (Fig. 3).

The structure of the Waiapu shelf basin is significantly different at its northern and southern ends. The southern half, which is mostly south of the Ruatoria Indentation, is a relatively simple, growing synclinal basin, with up to c. 1 km thickness of Quaternary sediment unconformably overlying folded, possibly back-thrust, Neogene strata (Fig. 5, 7C,D, 8). The northern half, which is immediately landward of the Ruatoria Indentation, contains only the top few Quaternary sequences, although these are locally up to 1 km thick, infilling basins in block-faulted and transverse faulted Neogene strata (Fig. 7A,B, 8). Although the large-scale block faulting that continues under the Waiapu shelf basin predates the last few Quaternary sequences, there is extensive, smaller scale collapse of prograding shelf-edge deposits of inferred MIS 3 age along the head of the indentation (Fig. 7A,B).

Uawa shelf basin

Southeast of the anticline off Houtunui Point, there is an en echelon synclinal basin of syn-depositional Quaternary strata, the Uawa shelf basin, which has the same general trend at the Waiapu shelf basin, and a maximum basin-fill thickness of c. 800 m. Its northern end extends obliquely across the upper slope to within 10 km of the southern wall of the Ruatoria Indentation. Extrapolated southwestwards, its southern end intersects the coast near the Uawa River mouth, Tologa Bay (Fig. 3). This basin probably represents the shelf depocentre of the Uawa River. The basin may represent a structural continuation of a broad, late Neogene, “forearc”, synclinal basin onshore to the southwest (Mazengarb & Speden 2000). The thrusts that uplift its seaward side are typical of this imbricate-thrust margin.

Transverse faults in the northern Waiapu shelf basin

Despite the questionable navigational quality of early seismic surveys, faults striking E-W to NE-SW, some with significant vertical throw, can be correlated between profiles obliquely across the shelf in the northern Waiapu shelf basin. These faults displace Neogene rocks and mainly, but not completely, predate the Quaternary cover of the last few glacio-eustatic sequences. (Fig. 7D, 8). These faults are transverse to the main structural features of the region and define a graben with c. 1 km of Quaternary fill. Similarly trending structures are rare in the southern Waiapu shelf basin and are not recognised in the Uawa shelf basin.

Subsidence in the northern Waiapu shelf basin

As well as the transverse structures, the northern Waiapu shelf basin is noteworthy for what appears to be a landward continuation of the gravitational block faulting of Neogene rocks at the head of the Ruatoria Indentation (Fig. 7A). In some cases, the seaward-dipping normal faults that define 2–4 km wide blocks continue up into the overlying late Quaternary shelf-edge sequences that have prograded out over them. However, the main phase of block faulting seems to predate the top few Quaternary sequences and is, therefore, probably at least several hundred thousand years old beneath the outer shelf.

Wave-like structures, with a “wave-length” of 0.5–1 km in the prograding shelf-edge deposits (Fig. 6, 7A,B), are interpreted as small-scale collapse structures, since they exhibit none of the changes of bed thickness that characterise sediment waves (cf. Lewis & Pantin 2002). The location at the edge of a steep slope and trends subparallel with the shelf-edge (Fig. 9) are in agreement with such an interpretation. In some cases, this shelf-edge collapse may be related to the continuing motion of deeper faults that are rotating the Neogene blocks. However, in most cases, the small-scale structures in the Quaternary strata reflect only collapse of prograding clinoforms deposited during low sea level. Such strata were probably deposited very rapidly at a time when sediment fluxes were perhaps double those of high-stand system tracts (Carter et al. 2002). Thus, they may have been inherently metastable and particularly subject to failure during earthquake or wave-induced stress. There appear to be at least two phases of shelf-edge failure, one affecting the seabed and the sediments of the last glacial age (MIS 2), and an earlier phase affecting prograding sediments of the penultimate glacial age (MIS 6).

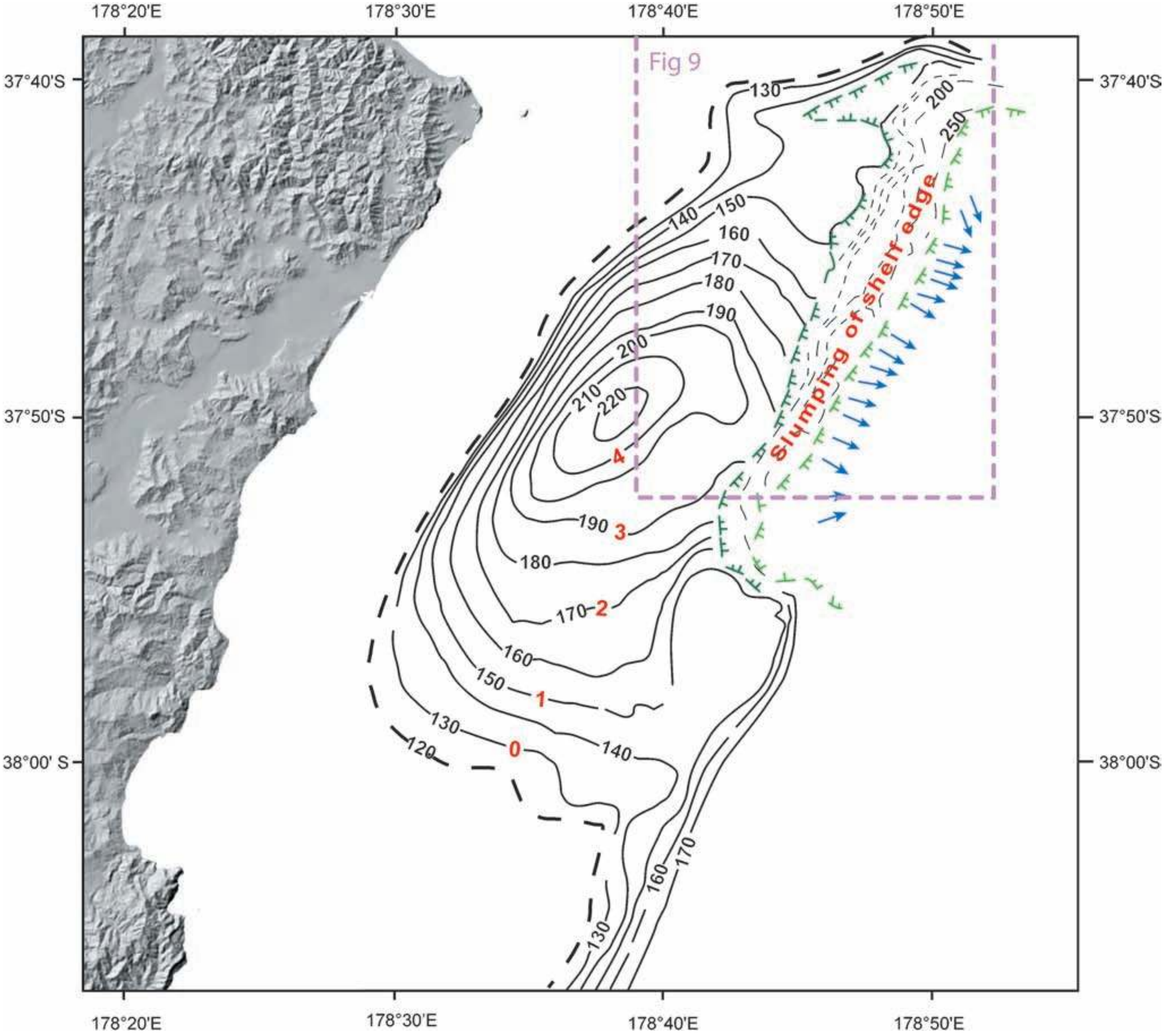


Fig. 10 Contours of depth in metres below present sea level (assuming velocity of sound of 1.5 m/s) to the top (postglacial) erosion-progradational surface formed mainly when sea level was c. 120 m below present. Depths below c. 130 m may be indicative of subsidence of the northern Waiapu shelf basin in about the last 20 000 yr, with rates of subsidence in m/ka (mm/a) in red. Slope failure on the outer shelf has lowered the glacial-age shelf edge (light green broken flagged line) to >250 m below present sea level and to >100 m below the present shelf edge (dark green broken flagged line). Positions of slope gullies (see Fig. 9) shown by blue arrows.

Post-last-glacial subsidence of the Waiapu shelf basin

The post-last-glacial shelf sediment prism is >150 ms (c. 112 m) thick beneath the 100 m isobath off the Waiapu River (Fig. 7B). This is an extreme thickness, but even more surprising is that the transgressive erosion surface underlying this prism is over 220 m below present sea level (Fig. 10). This is nearly 100 m deeper than the maximum lowering of sea level of the last glacial maximum and perhaps 80–90 m deeper than the wave-cut platform and top of prograding clinoforms of the last glacial maximum. This suggests subsidence of about this amount in the last 18–20 000 yr, equating to a subsidence rate of >4 m/ka (Fig. 10).

Farther offshore, the prograding, low sea-level shelf edge has slumped into the head of the Ruatoria Indentation, and is now 250–350 m deep (Fig. 6, 9). This is 100–200 m below the level of the adjacent, stable shelf-edge sediments, suggesting gravitational failure of a similar magnitude in addition to the rapid basin subsidence.

Diapiric intrusions

The Waiapu shelf basin is extensively intruded by vertical columns of deformed reflectors that are interpreted as diapiric intrusions (Fig. 7, 8). None of the columns appears to reach the seabed, although some stop at the base of the post-last-glacial sequence, or within it (Fig. 7). In some cases, they occur above a fault or anticline. In the absence of any additional local data, the intrusions may be inferred to be presently inactive seeps of either hydrocarbon-rich fluids (Lewis & Marshall 1996), or intrusions of Paleogene smectites (Nelson & Healy 1984; Field et al. 1997), or both.

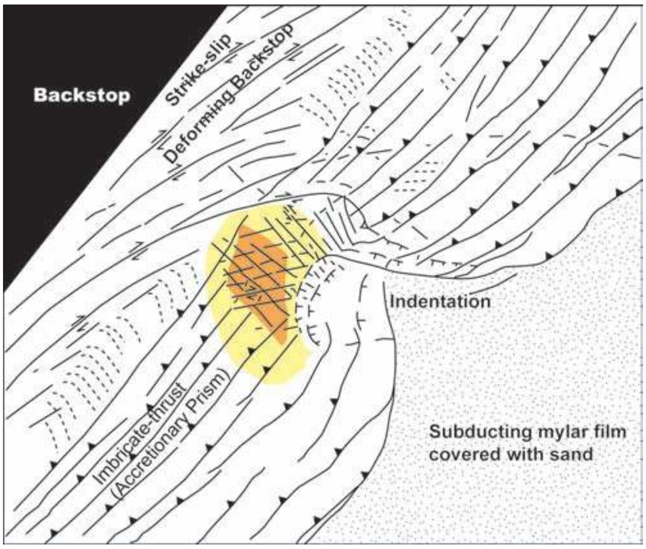


Fig. 11 Sketch of sand-box model of oblique seamount subduction showing lozenge-shaped "seamount" (orange) subducted beneath an imbricate-thrust (in this case frontal accreted) margin with partitioning of dextral strike-slip deformation occurring in a more rigid, but deforming backstop. Adjacent areas domed and fractured by subducted "seamount" (yellow) (University of Montpellier experiment NZ4).

MODELLING OBLIQUE SEAMOUNT SUBDUCTION

Sandbox experiments conducted at the University of Montpellier illustrate the effects of oblique subduction of a seamount analogous to that inferred to occur beneath the Ruatoria Indentation. Most of the models included significant accretion, so that some of the observed effects may not be directly applicable to the Ruatoria margin where accretion is minimal. Nevertheless, there are many analogies with the Ruatoria margin, where a backstop of Neogene slope strata, rather than offscraped trench sediments, has been deformed by imbricate thrusting in response to subduction.

An experiment (NZ4) designed specifically to simulate aspects of subduction at the Ruatoria margin was conducted with a deformable backstop, 40° obliquity, moderate basal friction (simulating abundant small seamounts), and a large, lozenge-shaped block to simulate a seamount similar in size and shape to the nearby Mahia and Gisborne seamounts (Fig. 1, 11). Although subduction beneath the margin by the lozenge-shaped "seamount" was limited by modelling restrictions, it produced a "margin" indentation with many similarities to the Ruatoria feature, including a trough with margin collapse in the wake of the seamount and a straight wall parallel to the direction of convergence (Fig. 11). At the head of the indentation, the "margin" domed upwards over the "seamount", with small faults transverse to the orientation of the margin. At least one of the faults curved around to link with a strike-slip fault in the deforming backstop.

Sandbox modelling of oblique seamount subduction beneath the Ryukyu margin (Dominguez et al. 1998a) shows many of the same features. In the latter case, strain partitioning with major strike-slip motion on the upper margin has carried the lower margin over the path of the seamount, so that the position of the seamount is no longer directly in line with the trough produced in the wake of the seamount but dextrally offset from it.

DEVELOPMENT OF THE RUATORIA SHELF

Effects of oblique subduction of the volcano-studded Pacific plate

The tectonic structures at the head of the Ruatoria Indentation are varied and appear contradictory. There is both contractional thrusting and extensional normal faulting, as well as possible dextral strike-slip motion. All can be related in different ways to oblique subduction of volcano-studded oceanic crust beneath a relatively young continental margin. The imbricate-thrusting, including landward-verging backthrusts, results primarily from intraplate friction that drags slivers of lower margin beneath the upper margin (Collot et al. 1996). This appears to be a factor in the growth of the seaward-bounding ridges of the Waiapu and Uawa shelf basins.

Elsewhere along the Hikurangi margin, the effects of oblique convergence are partitioned between predominantly imbricate thrusting on the lower margin and predominantly dextral strike-slip on the upper margin (Barnes et al. 1998). Modelling has shown how the dextral strike-slip component on the upper margin results in the formation of en echelon basins oblique to regional trends on the southern Hikurangi margin (Martinez 1999). The en echelon Waiapu and Uawa shelf basins have the same oblique trends and may similarly be a result of upper margin transpression.

The block faulting that appears to continue from the Ruatoria Indentation beneath the shelf of the northern Waiapu shelf basin is interpreted to reflect gravitational failure. Although gravity tectonics occur widely both onshore and offshore in the region, gravity failure beneath the northern Waiapu shelf basin is in a very restricted zone that continues in the direction of plate convergence landward from the Ruatoria Indentation. In the indentation, the gravitational failure has been attributed to slumping in the wake of a large subducting seamount (Collot et al. 2001). The slump features observed farther landward beneath the shelf may be attributed to the same mechanism.

The northern wall of the indentation, which has been inferred to form partly by strike-slip between the subducting seamount and the overlying margin (Collot et al. 2001), may continue onto the shelf as the northern edge of the Waiapu shelf basin. Like the inner part of the indentation (Fig. 3), this northern edge of the basin is offset northwards with respect to the northern wall of the indentation and rotated closer to the Pacific-Australian plate convergence direction. If these two features are related, then the offset and change in strike might be explained by a significant component of margin-parallel, dextral strike-slip motion on the upper margin, which necessarily alters both the speed and direction of convergence between seamount and overriding plate. The other transverse faults beneath the northern Waiapu shelf basin are, like the slumping, restricted to the area landward of the indentation and may also be related to passage of a seamount. Transverse faults have been noted ahead of the relict indentations on the Costa Rica margin (Dominguez et al. 1998b), but the ones beneath the Waiapu shelf basin are now buried by rapid sedimentation and deformed by wake slumping.

Fluid seeps—the lubricant

The columns of diffuse reflectors in the Waiapu shelf basin that are interpreted as diapiric intrusions indicate high fluid pore pressures. Dewatering and gas generation from subduction of trench-fill sediments probably contributes to high fluid pressures and fluid seeps that occur widely along the Hikurangi margin (Kvenvolden 1988; Lewis & Marshall 1996; Lowry et al. 1998). Onshore along the eastern Raukumara Peninsula, fluids seeps are widespread (Reyners & McGinty 1999) and are inferred to remobilise smectite clays (Mazengarb 1998), lubricate faults, and contribute to the eruption of mud volcanoes (Stoneley 1962; Ridd 1970; Nelson & Healy 1984; Mazengarb & Speden 2000). If high fluid pressures occur widely beneath the margin at the head of the Ruatoria Indentation, as is suggested by the abundance of diapers in seismic profiles, they will drastically reduce the shear strength of sediments (Hampton et al. 1996; Papatheodorou et al. 1996) and contribute to gravitational collapse on the margin.

Gas, in particular, reduces the stability of dip slopes. Along much of the Hikurangi margin, methane clathrate (gas hydrate) infills sediment pore spaces beneath the mid and lower slope to produce strong, bottom-following seismic reflectors (Katz 1981, 1982; Henry et al. 2003). Clathrates are highly unstable, being particularly susceptible to small changes of temperature and pressure in the 400–1000 m water depth range. They may be particularly sensitive to an increase in the temperature of intermediate water at the end of glacial ages (Kennett et al. 2000, 2002), which is inferred to have occurred off eastern North Island with resurgence of subtropical inflow after the last glacial maximum (Nelson et al. 2000; Carter et al. 2002). Dissociating clathrates can release large quantities of free methane gas, thus drastically reducing the shear strength of overlying sediments and, in some cases, triggering large-scale slope failures (Hampton et al. 1996; Lerche & Bagirov 1998). It was noted that some of the diapirs in the Waiapu shelf basin appear to immediately predate the post-last-glacial transgressive layer. Although they are landward of the primary zone of clathrate instability, release of pressure on the nearby slope may have been sufficient to trigger release beneath the adjacent shelf, and perhaps to contribute to instability of the already unstable shelf edge at the end of the last two glacial ages.

Passage of a seamount beneath the shelf

Since the block-faulting beneath the northern Waiapu shelf basin is a direct, lateral continuation of similar collapse in the northern indentation, it is inferred to have the same origin in the wake of a subducting seamount. The only difference is that Waiapu shelf basin collapse has been buried by rapid outgrowth of late Quaternary shelf deposits derived mainly from the Waiapu River, which is New Zealand's largest river in terms of sediment transport (Hicks & Shankar 2003). Thus, the gravitational collapse beneath the northern Waiapu shelf basin suggests passage of a seamount beneath the present continental shelf and offers support for the hypothesis that subduction of a large seamount is a primary cause of the Ruatoria Indentation. If correct, then it implies that the main phase of collapse occurred before the last few glacio-eustatic cycles, at least on the outer shelf. However, the very rapid subsidence of the post-last-glacial erosional surface beneath the mid shelf of the northern Waiapu shelf basin, may not be entirely associated with transpressional basin development. Part of this subsidence may possibly be attributable to continuing gravitational collapse in the wake of a subducted seamount.

The transverse faults in the northern Waiapu shelf basin may represent additional support for our interpretation. Although a splay or grid of transverse faults forms above and in front of a subducting seamount (Fig. 11), some may survive long after the seamount has been subducted farther beneath the margin (Dominguez et al. 1998b, 2000). However, the Waiapu shelf structures are not well defined, which might be commensurate with the summit of the subducting seamount being necessarily 10 km or more deep beneath the continental shelf (Beanland 1995; Ansell & Bannister 1996; Field et al. 1997) and with subsequent gravitational collapse and burial. Accordingly, this aspect of our interpretation is tentative.

Where is the subducted seamount now?

If the gravitational collapse and continuing rapid subsidence in the northern Waiapu shelf basin occurred in the wake of a subducting seamount, then the seamount must necessarily now be somewhere landward of this. That is, it must be beneath the adjacent land, in the vicinity of East Cape. To date, a subducted seamount has not been identified in this area using geophysical data. Magnetic and thermal anomalies suggest a subducted seamount to the south (Hunt & Glover 1995), but these anomalies are probably too far south to represent a seamount that passed beneath the northern Waiapu shelf basin. Similar geophysical anomalies might be difficult to detect onshore near East Cape, where ophiolites have been obducted immediately to the west (Fig. 3).

How far inland might the seamount be? There is evidence of a Quaternary margin-parallel, normal fault 3–4 km inland from East Cape (Mazengarb & Speden 2000), which, although its age is uncertain, might also be related to collapse in the wake of a seamount. If so, then this would imply that the seamount is now landward of this.

Subducting seamounts can dome up the surface even when they are very deeply buried. In Vanuatu, a subducting seamount is inferred to be rapidly doming up Malekula Island, which lies inboard of a large margin indentation (Collot & Fisher 1989). The evidence for this is derived from raised beach terraces that demonstrate rates of uplift of >1 m/ka near the centre of the dome. There are similarly well-preserved raised last interglacial and Holocene marine terraces on the coast northwest of East Cape (Fig. 3, 8) (Gibb 1981). The maximum measured rate of uplift is 2.6 m/ka at Horoera Point c. 8 km northwest of East Cape, falling to 0.9 m/ka at East Cape and to 0.4 m/ka at Matakaoa Point c. 25 km farther west (Fig. 3) (Gibb 1981). Matakaoa Point is directly in line with the trend of high Raukumara Ranges (Fig. 2, 3) and might be expected to be rising more rapidly than the coast to the southeast. Thus, it is tempting to suggest that the rapid uplift at Horoera Point marks the present position of the subducted seamount. If it does, then applying a rate of plate convergence of 45–50 km/m.y. suggests that its summit passed beneath what is now the outer shelf c. 0.5 m.y. ago and beneath the present position of the coastline over 150 000 yr ago. This accords with the observation that the collapsed margin has subsided and been buried during the last few glacio-eustatic cycles on the outer shelf, with onlap towards the present coast.

The rapid uplift along the coastline near Horoera Point represents observations only in one plane. The centre of doming may be either south or north of the coastline. However, incised, hilly country immediately south of Horoera Point (Fig. 2, 8) may represent the central area of rapid uplift. Such a location is landward of the northern wall of the indentation, rather than directly in line with the wake trough across the slope and buried beneath the shelf. This is compatible with a suggestion of dextral strike-slip movement on the upper margin so that, in effect, the lower margin migrates southwards over the path of the seamount. This situation, where the seamount is offset from the lateral continuation of its wake trough because of upper margin strike-slip motion, is well demonstrated in similar oblique subduction of a seamount off Taiwan (Dominguez et al. 1998a). It must be stressed that this interpretation is tentative, but the scope of this project precludes any additional fieldwork that might validate or negate these possibilities. This we leave for others.

CONCLUSIONS

1. The basic stratigraphy of the northern Raukumara Peninsula, including the East Coast Allochthon, Neogene cover beds, and Quaternary basin fill, can be extrapolated offshore beneath the adjacent upper continental margin.
2. A rapidly subsiding Quaternary basin, the Waiapu shelf basin, underlies the continental shelf at the head of the Ruatoria Indentation and extends southward from it. A similar basin, the Uawa shelf basin, is forming in an en echelon position on the shelf and upper slope to the south. These basins are inferred to be a product of transpression associated with oblique subduction.
3. Large rotational slumps at the head of the Ruatoria Indentation extend landwards beneath the northern part of the Waiapu shelf basin.
4. Faults extend across the shelf, transverse to other structural features, in the northern Waiapu shelf basin, landward of the head of the Ruatoria Indentation.
5. Depths to the post-last-glacial erosion surface suggest subsidence of >4 m/ka in the Waiapu shelf basin.
6. Collapse and transverse structures in the northern Waiapu shelf basin may be interpreted as circumstantial evidence for the passage of a large seamount beneath continental shelf landward of the head of the Ruatoria Indentation and support for the hypothesis that the Ruatoria Indentation was formed primarily by collapse in the wake of an obliquely subducting seamount.
7. Rapid subsidence offshore contrasts with rapid uplift of coastal terraces and coastal hills west of East Cape; this rapid uplift is a long way east of the rapidly rising main ranges. Such uplift is tentatively suggested to reflect the present position of the subducting seamount.

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