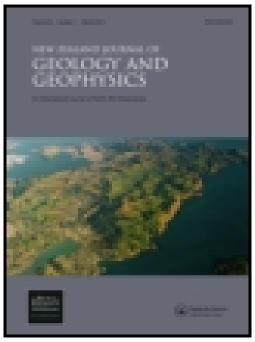

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Mount Stewart–Halcombe Anticline: a look inside a growing fold in the Manawatu region, New Zealand

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Abstract A seismic reflection profile across the c. 25 km long, NNE-trending Mount Stewart–Halcombe Anticline in the southeastern Wanganui Basin, along with reinterpretation of its stratigraphy, reveals details of the structure and development of the fold. Two reverse faults (I and II), 1 km apart, bound the eastern side of the anticline and dip at 60–65° beneath the anticline; a third reverse fault (III) dips 60° to the east towards the adjacent Feilding Anticline. The faults offset basement (Torlesse greywacke), Mangapanian, Nukumaruan, and lower Castlecliffian strata, but do not propagate through upper Castlecliffian – Haweran strata to the surface; this upper part of the sedimentary section is folded but not faulted. Progressive deformation of the sedimentary sequence, as well as differences in sedimentary thickness across the faults, indicates that the Mount Stewart–Halcombe Anticline has been growing from at least Mangapanian time (c. 3.1 Ma) through to the present. Topographic expression of the anticline, combined with seismic reflection data, shows that the anticline axis and its controlling faults curve from a northerly trend at Mount Stewart to an ENE trend 15 km farther south.

Correlations of horizons from the oil exploration well Santoft-1A to Mount Stewart, using pre-existing seismic data, as well as nearby occurrences of Castlecliffian sediments, demonstrate that the sedimentary sequence on Mount Stewart includes Castlecliffian strata, which had previously been thought to be absent. Based on correlations from Santoft-1A, we date the oldest sediments on the flanks of Mount Stewart as Mangapanian, whereas on the crest of Mount Stewart, at the location of the oil exploration well Young-1, onlap has cut out the Mangapanian, and Nukumaruan sediments lie on basement. "Upper Waitotaran" ages proposed by previous authors for the base of the sequence in Young-1 are therefore too old.

Fault I, the westernmost fault, appears to be the only fault of the three to be currently active. Average dip-slip rates over the period 2.6 to c. 0.6 Ma were between 0.1 and 0.2 mm/yr for faults I and II, whereas fault III was slightly slower at just under 0.1 mm/yr. Faults II and III have been inactive since c. 0.4 Ma, whereas fault I has moved faster over the period 0.2 Ma to the present, at c. 0.3 mm/yr. Based on a slip-rate of 0.3 mm/yr for fault I, and assuming 1–4 m of dip-slip displacement per earthquake, the return time for *M*6.5–7+ earthquakes on the Mount Stewart–Halcombe Anticline is at least several thousand years and may be longer than 10 000 years.

Keywords Mount Stewart–Halcombe Anticline; Manawatu; Wanganui Basin; seismic reflection; active faults; active folds; slip rate; Castlecliffian; seismic hazard

INTRODUCTION

Growing folds generated by unexposed active faults are recognised from many areas of the world (e.g., Harding 1976; Philip & Meghraoui 1983; Yeats 1986; Namson & Davis 1988), including New Zealand (e.g., Kennett 1964; Lamb &Vella 1987; Cape et al. 1990). In the Manawatu region of the Wanganui Basin, New Zealand, mapping and an early seismic reflection survey (Feldmeyer et al. 1943; Te Punga 1957) outlined a series of folds which were postulated to be fault controlled, though the faults did not appear to reach the surface. Onland, the folding occurs within the region between Marton in the west, up to the base of the Ruahine Ranges in the east, a zone some 40 km wide (Fig. 1) encompassing a significant portion of the Wanganui Basin.

Following initial mapping and seismic surveying in the Manawatu, two of the anticlines were drilled in 1942, the Mount Stewart–Halcombe Anticline with Young-1 and the Marton Anticline with Stantiall-1 (Superior Oil Company 1942; Feldmeyer et al. 1943). A third exploration well, Santoft-1A (Dunlap 1964), was drilled near the coast west of Bulls (Fig. 1). All three wells reached basement (Torlesse greywacke), but they did not contain significant quantities of oil or gas.

A seismic reflection survey was recorded by Bounty Oil in 1970 in the coastal region southwest of Mount Stewart, on either side of the Rangitikei River (Fig. 1; Bounty Oil 1970). Only a brief interpretation of the data was presented by Bounty Oil, and no attempt was made to identify geological horizons or correlate them across the numerous faults. However, the survey did further delineate the anticlinal structures, and basement is clear on most lines.

The geomorphology of the anticlines was described in detail by Te Punga (1957), who considered them to be very young features with high uplift rates, in the order of 8 mm/yr. Testing these high uplift rates, and the implied high earthquake hazard, was a primary goal of our study. For the Mount Stewart–Halcombe Anticline, Te Punga (1957) stated that folding could not have begun until after deposition of Haweran sediments, but he considered that an older period of faulting during Pliocene–Pleistocene time had caused

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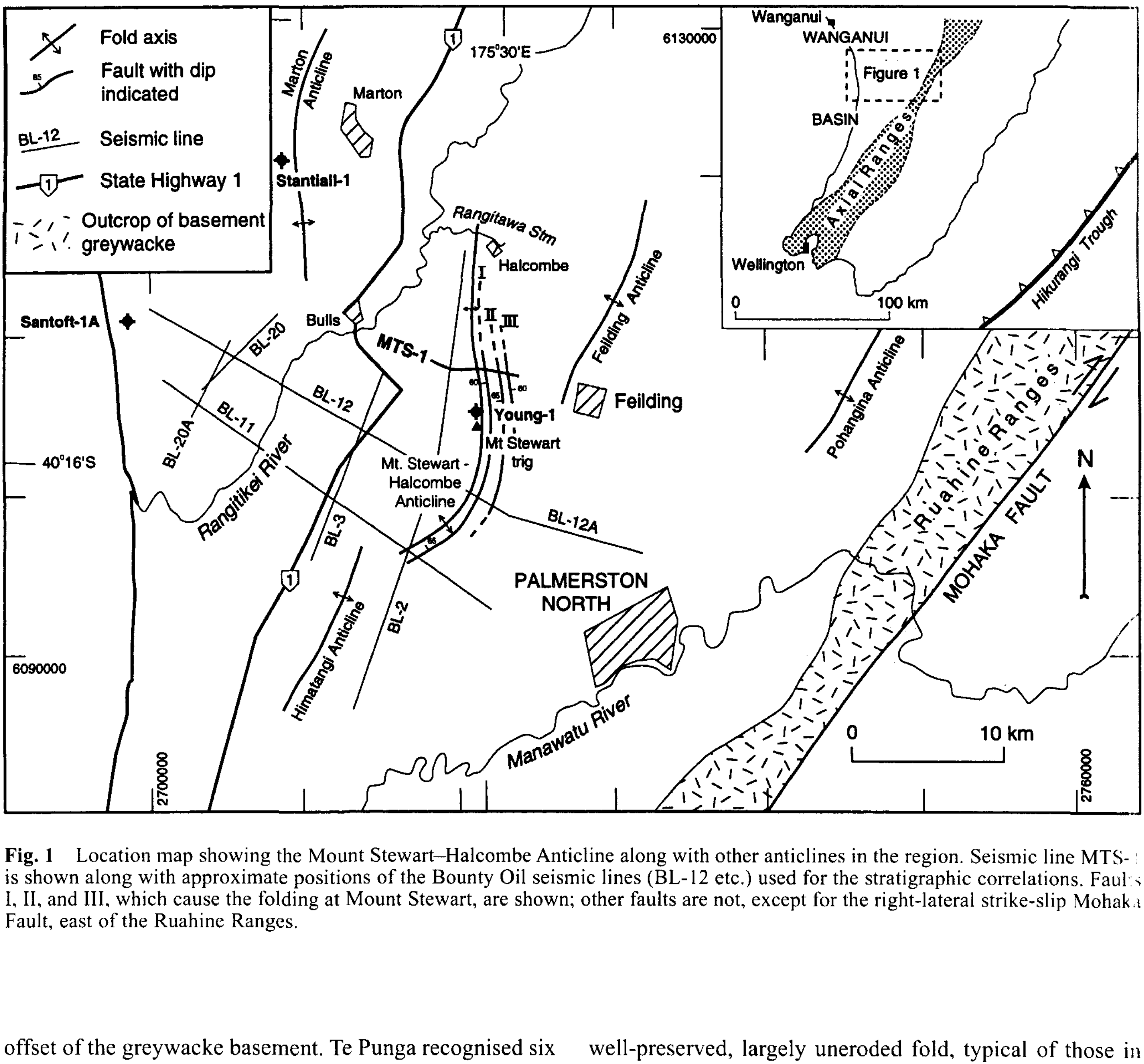


Fig. 1 Location map showing the Mount Stewart–Halcombe Anticline along with other anticlines in the region. Seismic line MTS-1 is shown along with approximate positions of the Bounty Oil seismic lines (BL-12 etc.) used for the stratigraphic correlations. Faults I, II, and III, which cause the folding at Mount Stewart, are shown; other faults are not, except for the right-lateral strike-slip Mohaka Fault, east of the Ruahine Ranges.

offset of the greywacke basement. Te Punga recognised six anticlines, and noted their asymmetry: the western limbs of the anticlines dip very gently, while the eastern limbs dip more steeply. Both Feldmeyer et al. (1943) and Te Punga (1957) inferred that the anticlines had cores of basement rocks. Superior Oil showed normal faults bounding the eastern sides of the anticlines in their cross-sections (Feldmeyer et al. 1943) and they considered that faulting had continued during sediment deposition. The anticlines were not evident on Hunt's (1980) residual gravity anomaly map of the Wanganui Basin. Hunt concluded that the anticlines could not be seen because they were either too small or too deep to show up as an anomaly on the scale of the map.

Anderton (1981) reinterpreted the Bounty Oil onshore dataset, as well as offshore seismic reflection data recorded by Bounty Oil, Mobil, and Esso in the late 1960s and early 1970s, in order to describe the structure and evolution of the Wanganui Basin. He considered that the anticlines were formed by growth faulting, and that the faults had been primarily active in the Pleistocene.

This paper presents the results of a seismic reflection profile across the Mount Stewart–Halcombe Anticline, a well-preserved, largely uneroded fold, typical of those in the region. Our seismic line was of much higher resolution than the 1970 Bounty Oil onshore data because of more modern acquisition and processing techniques, so the subsurface image is far more detailed than in the past. The main objective of our study was to document the style and growth of the Mount Stewart–Halcombe Anticline in order to clarify previous, often conflicting, ideas about the development of the folds. Outcrop is restricted to Castlecliffian–Recent strata, and the possible faults controlling the folds do not have surface traces, so the seismic reflection method is an ideal way to provide information on the structure.

We limit our discussion to the structure of the Mount Stewart–Halcombe Anticline itself, using the results from our seismic reflection profile (MTS-1) combined with the pre-existing onshore Bounty Oil seismic reflection data, some of which we have reinterpreted. Geomorphologically, the Mount Stewart–Halcombe Anticline is similar to many of the other active folds in the Manawatu area, and because of this similarity, we expect that the conclusions drawn from this study may be broadly applicable to other folds in the region.

ACQUISITION AND PROCESSING OF SEISMIC DATA

A seismic reflection profile (MTS-1), 5.8 km long, was recorded by the Institute of Geological and Nuclear Sciences across the Mount Stewart–Halcombe Anticline in February 1993 using the Institute's 48-channel Sercel 338HR recording system (Fig. 1). MTS-1 started on the western limb of the Mount Stewart–Halcombe Anticline, and was extended onto the western limb of the adjacent Feilding Anticline. The line intersects line BL-2 of the 1970 Bounty Oil survey (Fig. 1). The acquisition parameters are summarised in Table 1. Alternate shots were recorded into split-spread and off-end spread geometries, so that the offset range was 45–595 m. Towards the east end of the line, an extra shot was placed at the location of each off-end shot, and recorded into the split-spread in order to increase the coverage in the near-surface strata in the region where faulting was expected.

The data processing is summarised in Table 2. As is usual in processing onshore data, static corrections were important in improving the stack. Refraction statics were calculated and applied before velocity analysis, then several passes of residual statics were calculated and applied between subsequent velocity analyses.

The good results are largely attributed to a uniform near-surface layer which favoured seismic energy transmission. Examination of individual shot records showed that the near-surface layer had a fairly uniform *P*-wave velocity of 700–800 m/s and a thickness of 40–60 m. The base of this layer is probably the water-table in the area. We did not encounter a variable thickness, low velocity, weathered zone, which is often responsible for poor onshore seismic results because it absorbs and scatters seismic energy and creates static shift problems.

STRATIGRAPHY

Original correlations of units between the wells Young-1, Stantiall-1, and Santoft-1A in the Wanganui Basin relied on identifying units of similar lithology and age (e.g., Feldmeyer et al. 1943; Fleming 1953; Cope 1966). As noted by Anderton (1981), the method is not reliable because of sparse microfossil assemblages and lateral facies changes across the basin. Instead of relying on poorly constrained, pre-existing well correlations, we used some of the Bounty Oil seismic lines (Fig. 1; Bounty Oil 1970) to correlate between Santoft-1A and Young-1. This method eliminates much of the uncertainty in tracing units from one area to another. These correlations provide the basis for our definition of the stratigraphy as shown in Fig. 2. Our stratigraphy is similar to that implied by Anderton's (1981) isopach maps, and differs from other interpretations that infer no Castlecliffian sediments in the Mount Stewart area (Feldmeyer et al. 1943; Fleming 1953; Cope 1966). Anderton's (1981, fig. 19) isopach map indicates c. 1000 m of Castlecliffian-age sediment on Mount Stewart, contradicting his fig. 3 showing no Castlecliffian in Young-1.

We accept the stratigraphy for Santoft-1A as described by Dunlap (1964), but divide his Waitotaran Stage in the well into the now-accepted Waipipian and Mangapanian Stages. The top of the Waipipian is defined by the last occurrence of the microfossil *Cibicides molestus* (Edwards et al. 1988; Hornibrook et al. 1989). We therefore take the level in Santoft-1A at which *C. molestus* was last noted by Dunlap (1964) as the top of the Waipipian. The Mangapanian–Nukumaruan boundary was located in Santoft-1A by Dunlap at the last appearance of *Notorotalia kingmai*. This was recorded at a position c. 70 m above a prominent greywacke conglomerate and shellbed, which we consider is a possible correlative of the Hautawa Shellbed, defined to be the base of the Nukumaruan (Fleming 1953). We expect a good reflection from this bed, and we have therefore taken the shelly conglomerate to mark the base of the Nukumaruan for seismic correlation purposes. The base of the Castlecliffian is defined as Butler's Shell Conglomerate at Wanganui (Fleming 1953; Beu et al. 1987), and Pakihikura Pumice in the Rangitikei River area (Te Punga 1952). The age of the Pakihikura Pumice has recently been revised to 1.63 Ma (Alloway et al. 1993), so that the age of the base of the Castlecliffian is older than the 1.2 Ma stated by Edwards et al. (1988). A pumiceous sand at 645 m depth in Santoft-1A was considered to be the Pakihikura Pumice by Dunlap (1964), and therefore the base of the Castlecliffian appears to be located in the well.

The sequence in Young-1 is thinner than in Santoft-1A, and the original dating of Young-1 (Feldmeyer et al. 1943) suggested it was the younger section which was missing (Fig. 2). Feldmeyer et al. (1943) considered the section to consist of Waitotaran sediments lying on basement greywacke, passing up into Nukumaruan strata which were unconformably overlain by Haweran sediments. Superior

Table 1 Seismic acquisition parameters.

Source	Powergel, 320 g
Spread geometry	Symmetric split spread and off-end
Shot spacing	20 m
Geophones	28 Hz OYO, 6 geophones per string
Group interval	10 m
Geo. interval	2 m
Near offset	45 m
Far offset	595 m
Nominal fold	12 and 18
Low cut filter	10 Hz
Recording instrument	Sercel 338HR 48 channel
Sample rate	1 ms
Record length	4 s

Table 2 Processing sequence.

- Demultiplex field tapes
- Resample to 2 ms
- Geometry and CDPs inserted into headers
- Remove noisy traces
- Zero-phase deconvolution
- Time-varying frequency domain filter
- Frequency-wavenumber domain filter, cutoff 11 ms/trace
- 400 ms AGC as trace balance before stack
- Height datum 140 m, replacement velocity 1800 m/s
- Refraction static corrections
- CDP sort
- Velocities from CVS
- Residual statics
- Stack with maximum fold 21
- Post-stack frequency filter
- Post-stack coherency filter

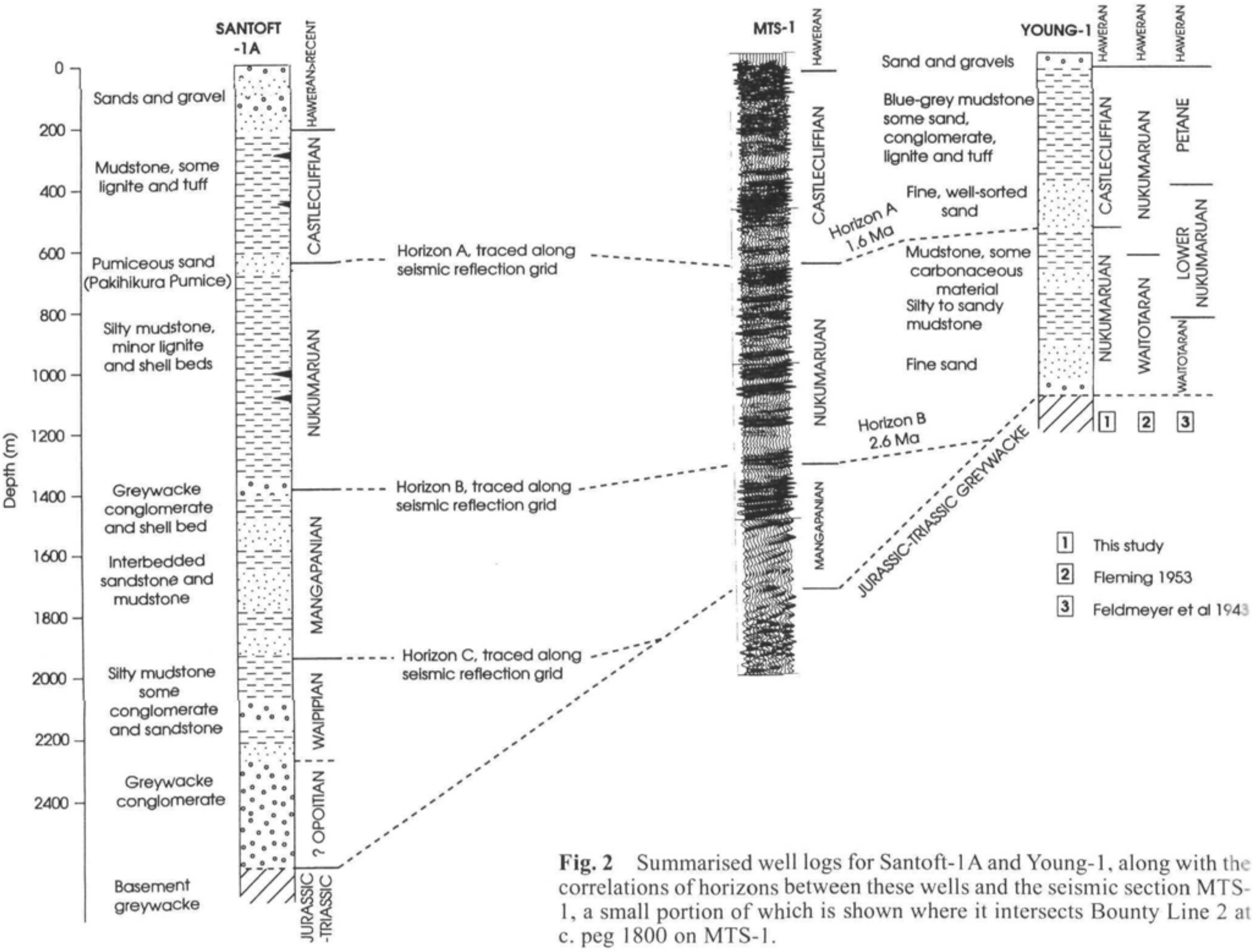


Fig. 2 Summarised well logs for Santoft-1A and Young-1, along with the correlations of horizons between these wells and the seismic section MTS-1, a small portion of which is shown where it intersects Bounty Line 2 at c. peg 1800 on MTS-1.

Oil (1942) and Feldmeyer et al. (1943) noted that microfossils were generally sparse throughout the sequence, and many of their age determinations appear to be based on lithological correlations with outcrop in other areas of the basin. Two lines of evidence utilising the Bounty seismic reflection data suggest that the original dating may have overestimated the age of the sediments in Young-1, probably because of incorrect lithological correlations due to lateral facies variation.

Bounty line 12 (BL-12) passes close to Santoft-1A, and the sequence in the well can be projected onto the seismic line by performing a depth to time conversion using velocities from the sonic log for the well (Dunlap 1964). The base of the Castlecliffian (Pakihikura Pumice; 645 m depth) corresponds to a two-way-time (TWT) of 0.7 s at the well, and a prominent horizon at this time on BL-12 is taken to be the equivalent. In the following discussion, we refer to this horizon as horizon A, as it appears to be the same as Anderton's (1981) horizon A. Horizon A can be traced with confidence across a grid of seismic lines onto Bounty line 2 (BL-2), which intersects MTS-1, and the horizon lies at c. 0.8 s TWT (c. 800 m depth) beneath peg 1800 on MTS-1. This implies that a considerable thickness of Castlecliffian strata is present in the Mount Stewart area.

The second line of evidence comes from outcrop of the Castlecliffian sequence in the Rangitikei River. The northern end of BL-2 nearly reaches Rangitawa Stream, in which sediments of uppermost Castlecliffian to Haweran age are exposed (Bussel 1984) and comprise the top of the section through Nukumaruan, Castlecliffian, and Haweran strata along the Rangitikei River (Te Punga 1952). The thickness of sediments between the Pakihikura Pumice (basal Castlecliffian, 1.6 Ma) and Rangitawa fossil beds (early Haweran) is c. 850 m (Alloway et al. 1993). Unless there is a large fault separating the river section and the northern end of BL-2, the Pakihikura Pumice should lie at c. 0.9 s TWT on the northern end of BL-2, and should also be present on MTS-1, and this result agrees with the seismic correlations from Santoft-1A, described above. There is no evidence for such a large fault which, being necessarily a young feature to have cut out all of the Castlecliffian section, would be expected to have some sort of geomorphic expression.

On the crest of the Feilding Anticline, macrofossils which were recovered from a depth of 80 m in a drillhole were Castlecliffian in age (Te Punga 1957). The presence of Castlecliffian strata at this location further suggests that they should lie beneath Mount Stewart.

Two other horizons were traced from Santoft-1A across the grid of Bounty Oil data to the Mount Stewart area. Both the base of Nukumaruan strata (horizon B) and the base of Mangapanian strata (horizon C) were traced onto MTS-1, and occur at 1.4 and 1.6 s TWT, respectively, at the intersection of MTS-1 and BL-2. Horizon C, which is the least well constrained, is approximately coincident with the base of the sedimentary section at this point. Both horizons pinch out against the basement surface as it slopes up to the south towards the topographic high of Mount Stewart, so that sediments at the highest point of the anticline are all younger than base Nukumaruan. We assume that individual horizons are synchronous between Santoft-1A and the Mount Stewart–Halcombe Anticline, although this is not certain. The absence of Mangapanian strata on the high point of the Mount Stewart–Halcombe Anticline indicates that previous interpretations of Waitotaran sediments in the lower part of Young-1 (Feldmeyer et al. 1943; Fleming 1953) were incorrect, and that microfossils on which that age was based were either unreliable or reworked.

The absolute ages of the sediments are particularly important in the calculation of deformation rates. Following the ages proposed by Alloway et al. (1993), Edwards et al. (1988), and Beu (pers. comm.), we define six "time" horizons: horizon A (base Castlecliffian, 1.6 Ma), horizon B (base Nukumaruan, 2.6 Ma), and horizon C (base Mangapanian, c. 3.1 Ma) are defined by correlations from Santoft-1A. Horizon H (taken to be the base of the Haweran) is located on MTS-1 by correlating from Young-1 and by its position at an unconformity on MTS-1. The base of the Haweran Stage is defined as the top of oxygen isotope stage 11 (Beu et al. 1987) and is assigned an age of 0.4 Ma by Edwards et al. (1988). The Haweran sediments in the vicinity of MTS-1 range in age from 0.4 Ma up to possibly 0.1 Ma (oxygen isotope stage 5; Beu et al. 1987) and are capped by loess (Cowie 1964). The ages of an additional three horizons (A1, 1.2 Ma; A2, 0.94 Ma; and A3, 0.57 Ma) have been estimated by linear interpolation between the ages of horizons A and H (1.6 and 0.4 Ma), assuming a complete section and constant sedimentation rate between these horizons beneath peg 4900 (the lowest part of the fold). If the section is not complete at this point, the interpolated horizon ages will be slightly too young.

RESULTS AND INTERPRETATIONS

Figure 3 shows both stacked and migrated versions of MTS-1, and our interpretation is shown on the migrated section (Fig. 3B). The very reflective sedimentary sequence is gently folded across the Mount Stewart–Halcombe Anticline, and strong diffractions arise from faulting of the sequence on the eastern side of the profile. The faults offset basement and extend up through the sedimentary section. There is an abrupt transition from the highly reflective sedimentary sequence to largely unreflective basement, although the basement/sediment interface does not produce a distinct reflection. The interpretation of basement on the western side of the section is confirmed by the location of basement at 1100 m depth in Young-1, which is located c. 4 km south of MTS-1.

The sedimentary sequence is folded into a broad, gently asymmetric anticline whose eastern limb dips more steeply than the western limb. For example, west of the anticline crest, horizon A dips at c. 6° west; east of the crest, the same horizon dips at c. 22° east. To the east of the anticlinal crest, three reverse faults offset basement and the overlying sedimentary sequence. Fault I dips at c. 60° west, fault II dips c. 65° west, and fault III dips c. 60° east, towards the Feilding Anticline. The fault dips are well constrained to c. 2 s TWT from reflection terminations, but their dip at greater depths is speculative. The faults appear to be planar, without splays or branches, unlike typical "flower structures" which are associated with strike-slip faults (Sylvester 1988, and references cited therein). Faults I and II control the folding of the Mount Stewart–Halcombe Anticline, while fault III, which has an opposing dip, may be a back-thrust associated with the fault that is presumed to lie beneath the adjacent asymmetric (east limb steeper) Feilding Anticline.

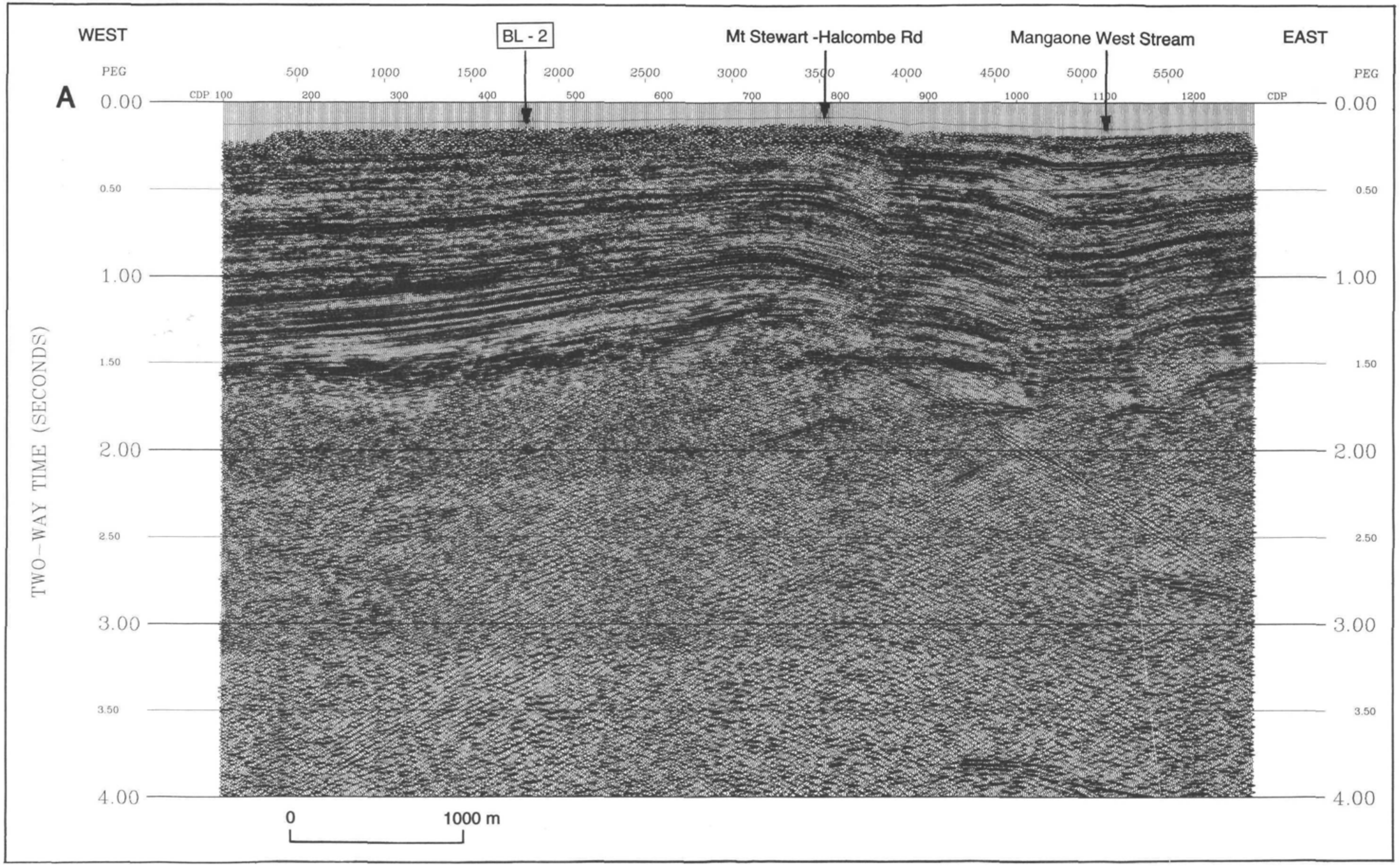
Displacement progressively decreases up the section on each of the faults, and the near-surface beds are not broken, although they are usually folded. The dip of the reflections immediately west of the anticline crest increases with age. Reflections high in the sequence dip parallel to the topographic surface at c. 1–2° west, whereas deeper reflections dip west at c. 8°. The entire sequence therefore thins eastward towards the anticline crest. For most of the sequence, the thinning occurs without obvious development of unconformities, or onlapping features.

Towards the top of the sedimentary sequence (above horizon A2), more marked unconformities occur. The most prominent of these is at horizon H, and progressively more of the Castlecliffian section is missing here as the crest of the anticline is approached from the west. The development of prominent unconformities in the shallow part of the sedimentary sequence may relate to the change from general basin subsidence to regional uplift (which Alloway et al. 1993 date at c. 0.9 Ma). Apparently, as the region was no longer subsiding, the continued folding intermittently brought parts of the fold above wave-base, and it was thus subject to erosion. Around 40 m of Haweran sediments were deposited across the entire Mount Stewart area before continuing regional uplift combined with folding created the present-day topography.

These patterns of progressive fault displacement and thinning onto the fold crest are typical of growth faulting, where the fault has been active throughout deposition of the sedimentary sequence (Bally 1983). The gradual thickness changes suggest that the anticline grew steadily throughout deposition of the sedimentary sequence during Nukumaruan and Castlecliffian time, and the displacement rates calculated for the faults support this (see below).

The graph in Fig. 4 shows the dip-slip displacement rate for each fault through time. The horizon displacements were measured from a depth-converted seismic section and were assumed to represent the dip-slip component of movement across the faults. Many of the horizons are deformed by both folding and faulting, though the shallower horizons are folded only. The folding has been incorporated into our estimate of dip-slip displacement. For fault I, dip-slip displacements range from c. 320 m for horizon B to 80 m for horizon H; fault II has c. 410 m dip-slip displacement across horizon B, down to 60 m across horizon A3; and fault III has c. 140 m offset across horizon B and only 20 m across horizon A3.

Over the period 2.6 to c. 0.6 Ma, faults I and II have slip rates of between 0.1 and 0.2 mm/yr, with fault III being slightly slower at just under 0.1 mm/yr. The combined slip rate of faults I and II is c. 0.3 mm/yr. The beginning of fault activity is not constrained, but all the faults were active during the Mangapanian through to the Castlecliffian. Faults II and III displace horizon A3, but do not displace horizon H. Activity on these faults had therefore ceased by 0.4 Ma. In the period 0.6–0.4 Ma, fault II appears to have been moving considerably more rapidly (at c. 0.6 mm/yr) than it


A
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BL - 2
Mt Stewart -Halcombe Rd
Mangaone West Stream
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CDP 100
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TWO-WAY TIME (SECONDS)
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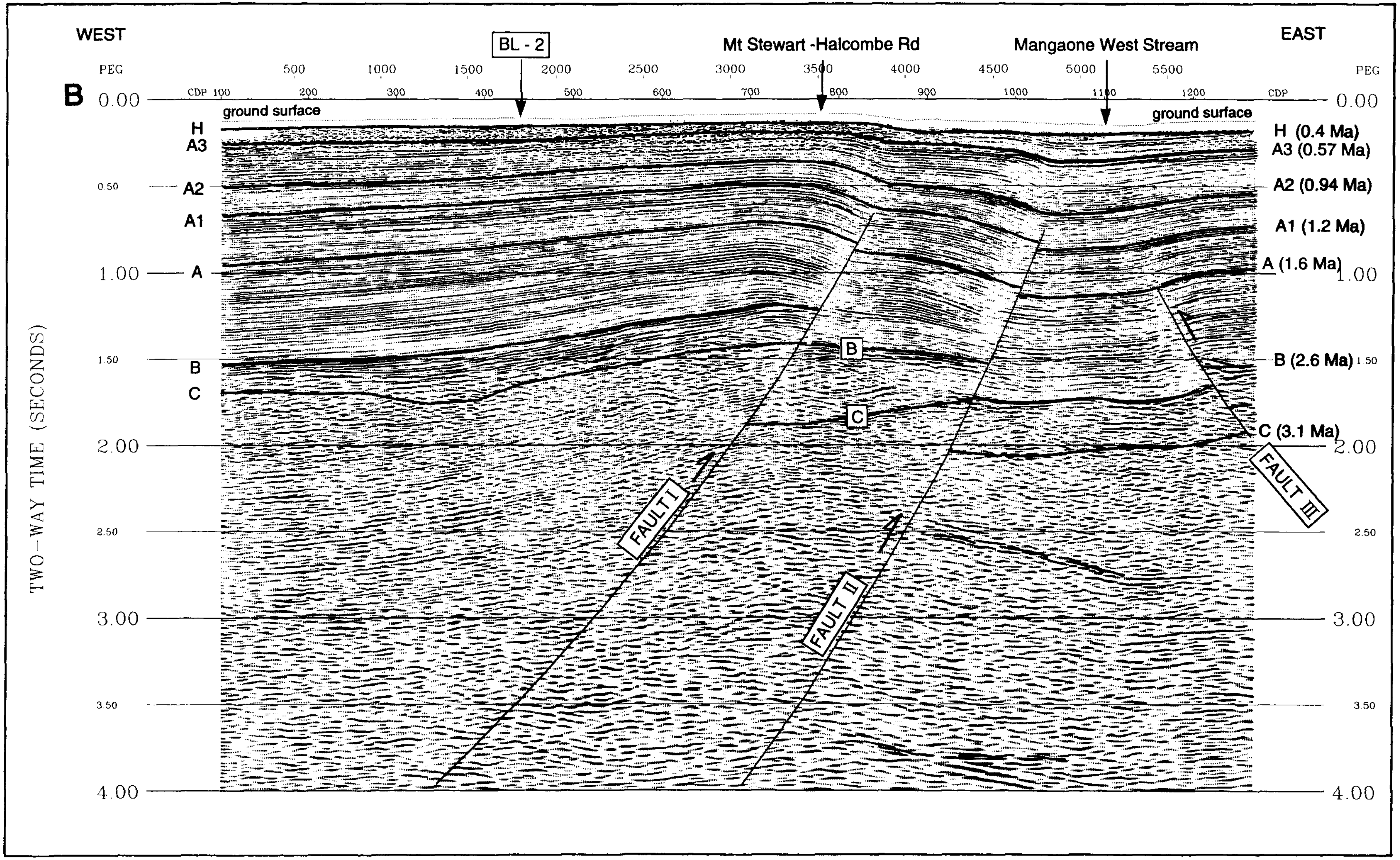

Fig. 3A *(top)* Final stacked section of the seismic line MTS-1, which crosses the Mount Stewart–Halcombe Anticline. **Fig. 3B** *(bottom)* MTS-1 migrated section, with interpretation. Horizons and their ages (in Ma) are indicated at the side of the section. Two zones of reflections at c. 2.5 and 4 s TWT east of fault II are dashed, and are probably from out of the plane of the section.

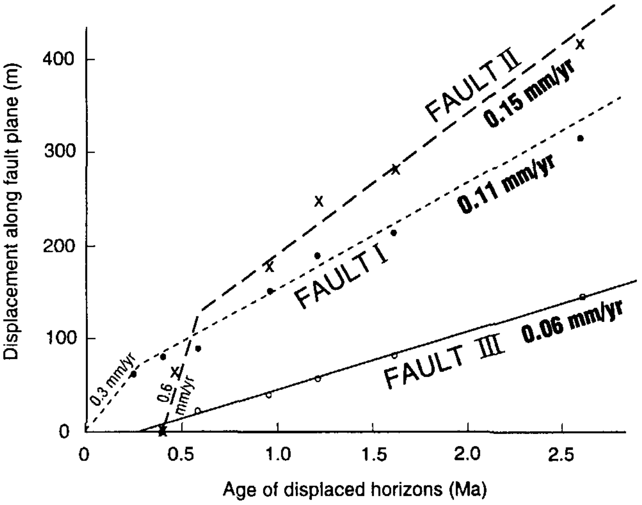

Fig. 4 Graph of dip-slip rates for faults I, II, and III at the eastern side of the Mount Stewart–Halcombe Anticline.

was earlier on. Fault I folds both horizon H and the topographic surface, demonstrating its continuing activity. The displacement rate of fault I appears to have increased in the period from 0.2 Ma to the present to nearly 0.3 mm/yr, which is the same as the combined rate of faults I and II for the period 2.6–0.6 Ma. The dip-slip displacement rates of 0.1–0.3 mm/yr for the reverse faults at Mount Stewart are similar to rates calculated by Pillans (1990) for normal faults in the western part of Wanganui Basin.

The main component of error in the slip rate calculations comes from uncertainties in the ages of the horizons. The horizon ages at MTS-1 depend on their identification and age in Santoft-1A being correct, and on their accurate location on MTS-1 following their correlation from Santoft-1A. Horizon C was excluded from the slip-rate calculations, as we considered it too uncertain in age. If the total mislocation of horizons A and B on MTS-1 is on the order of 0.2 s TWT, then their ages may be incorrect by c. 250 ka. We consider this figure to be a maximum. Lesser errors such as in the depth conversion of the data do not alter the rates significantly. Although there are uncertainties in the slip rate calculations, our data provide a general estimate of the rate of movement on the faults beneath the Mount Stewart–Halcombe Anticline.

The amount of shortening along each of horizons B, A, and A2 was measured from the west end of MTS-1 to the syncline between faults II and III. The horizontal shortening rate across the Mount Stewart–Halcombe Anticline is c. 0.1 mm/yr for each of the measured horizons, indicating a uniform shortening rate over the last 2.6 m.y. Unpublished strain results (D. Darby pers. comm.) in the Manawatu region are very low (insignificantly different from zero at the 95% confidence level), and are in line with the very low slip and shortening rates calculated in this study for the Mount Stewart–Halcombe Anticline.

Deep reflections

Two distinct bands of reflections are imaged at c. 3 and 4 s TWT on the eastern part of MTS-1, between pegs 3800 and 5800 (Fig. 3). The reflections dip towards the east, in contrast to the very gentle westwards tilt of reflections down to 1.5 s TWT in the overlying section, and are coherent over at least 1.5 km. True-amplitude processing of the section shows that the amplitudes of the deep reflections are much less than those of the reflective section above 2 s TWT. The recorded times correspond to approximate depths of 4–6 km.

There are two possibilities for the origin of the deep reflections. Either they arise from a feature located beneath the seismic line, or they are from out of the plane of the section, and are energy backscattered from a subsurface feature such as a fault plane. Reflections generated at an acoustic impedance contrast within the earth beneath the seismic line could arise either from sedimentary bedding or from structural features, such as shear zones within the greywacke basement.

Although we do not have adequate seismic coverage to resolve the three-dimensional structure of the area, we consider an out-of-plane origin likely. Reflections of similar appearance, apparently from within basement, have been noted in datasets from Taranaki and have been interpreted as out-of-plane reflections (G. Thrasher pers. comm.). Apart from the two bands of deep reflections, the character of the seismic section below 2 s TWT on the eastern part of the line is very like that of the basement positively identified to the west.

In their description of the seismic reflection survey recorded by Superior Oil, Feldmeyer et al. (1943) noted reflections from depths of 14 000–17 000 ft (c. 4–5 km) immediately east of the Mount Stewart–Halcombe and Feilding Anticlines, and also near the Marton Anticline. They implied that the deep reflections were over a limited distance only, within "1.5 to 3 miles" of the anticline crests, but did not speculate as to their origin.

DISCUSSION

The faulting revealed on the seismic line MTS-1 clarifies the structural history of the Mount Stewart–Halcombe Anticline. The high (8 mm/yr) uplift rates postulated by Te Punga (1957) on the basis of folding commencing in Haweran time are shown to be incorrect, as folding has been going on for at least 3 m.y. Anderton (1981) considered most of the activity on the faults to have occurred in the Pleistocene. However, there is no discernible change in rate between the upper Pliocene and Pleistocene; rather, growth of the anticline has been going on fairly steadily since the Mangapanian.

Anderton (1981) suggested that the faults at the east side of the Wanganui Basin were strike-slip in character, because he interpreted rapid changes in throw (high-angle normal to high-angle reverse) along some of the faults, and because of the way the faults bifurcate. Faults I, II, and III associated with the Mount Stewart–Halcombe Anticline have been active since at least Mangapanian time (3.1 Ma). In the region between faults I and II, the sedimentary sequence thickens towards fault I for sediments below horizon A (1.6 Ma), but it thickens in the opposite sense (i.e., towards fault II) for sediments above horizon A. We put forward two possible explanations for this change. (*1*) Before 1.6 Ma, fault I had a significant component of strike-slip movement, and this displacement juxtaposed different portions of the basin's sedimentary sequence across the fault. Post-1.6 Ma, the faulting style changed to be predominantly dip-slip. (2) Before 1.6 Ma, fault I may have been exposed at the seafloor, so that the sediments on the downthrown (east) side of the fault would have been overridden and would have tended to thicken towards fault I. Post-1.6 Ma, fault I caused folding of the seafloor, but did not break through to the surface, and the sediments thinned up onto the growing fold, which was cored by the (now blind) fault.

If these faults were part of a dominantly strike-slip structure, say with a strike-slip to dip-slip ratio of faulting of >3, then we suspect that 1.6 m.y. would be sufficient time for the faults to develop into a through-going surface rupture structure. As the faults do not now reach the surface, we consider that there has not been a significant amount of strike-slip displacement across the Mount Stewart–Halcombe Anticline over the last 1.6 m.y. We cannot discount the possibility that faults I, II, and/or III may at present be oblique-slip faults, perhaps with as much strike-slip displacement as dip-slip.

The topographic expression of the Mount Stewart–Halcombe Anticline extends 9 km to the north of MTS-1 and 6 km to the south. Using Bounty lines 11 and 12 (BL-11 and BL-12), the structure can be traced in the subsurface an additional 10 km towards the south (Fig. 1), so that the anticline is at least 25 km in length. There is no information on the fold in the region north of Halcombe or south of BL-11. The absence of topographic expression of the fold to the south may be because the ground surface is younger in this area than at Mount Stewart, and is not old enough for folding to have significantly affected the topographic surface. The depth to basement at the anticline crest is fairly uniform all the way along, being on the order of 1 s TWT (c. 1 km depth).

At the eastern end of BL-12, we interpret two faults to be the southward continuations of faults I and II on MTS-1, c. 8 km to the north (Fig. 1). The faults are similarly spaced on the two lines, and apparently have similar dips to those on MTS-1, although interpretation of the poorer quality Bounty Oil data is somewhat equivocal, and the fault dips are not well constrained. At least one fault is visible on the next line to the south (BL-11), but we cannot resolve whether there are one or two fault strands because of the poor data quality. The intersections of the faults and anticline axis with the lines MTS-1, BL-12, and BL-11 show that the fold axis and main controlling fault curve southwards from a northerly trend at Mount Stewart to a more northeasterly trend over a distance of c. 15 km. This fault trend is shown fairly accurately on the structural contour map from the Superior Oil seismic survey (Feldmeyer et al. 1943; Te Punga 1957).

The Feilding Anticline lies immediately east of the Mount Stewart–Halcombe Anticline. It has a similar topographic expression to the Mount Stewart–Halcombe Anticline, and is shown by Te Punga (1957) to be fault bounded. Bounty lines BL-12 and BL-12A extend across the southern projection of the Mount Stewart–Halcombe Anticline and the Feilding Anticline. Except for the two closely spaced faults which we interpret as the extensions of faults I and II of the Mount Stewart–Halcombe Anticline, there is no faulting on the eastern end of BL-12 or on BL-12A. This implies that the fault at the eastern side of the Feilding Anticline has either joined up with faults I and/or II, or has died out before reaching BL-12 and BL-12A. The possibility that the fault passes to the east of BL-12A is discounted because it requires an abrupt and large change in strike of the fault, which is unlikely.

The detail of folding and faulting revealed by the excellent quality of line MTS-1 combined with the lesser quality Bounty data shows that the maps presented by Anderton (1981) are an over-simplification of the geology. Anderton showed a single, practically straight trace for the fault, which he called Rauoterangi Fault, adjacent to (and east of) Mount Stewart. Our work demonstrates that there are two faults (I and II) bounding the Mount Stewart–Halcombe Anticline, both of which are curved in plan view. Anderton showed no faults between Rauoterangi Fault and the Ruahine Range and considered this area to be a large, persistent fault-angle depression. Based on the geomorphic similarity of the Mount Stewart–Halcombe and Feilding Anticlines, we would suggest that the Feilding Anticline is bounded by at least one reverse fault on its eastern side (as shown by Te Punga 1957), and there is probably a fault beneath the Pohangina Anticline as well. The area between Mount Stewart and the Ruahine Range is therefore more complicated than Anderton suggested.

Seismic hazard implications

Buried active faults, often expressed at the ground surface as growing folds, are increasingly being recognised as potential sources for damaging earthquakes (e.g., Stein & Yeats 1989). Perhaps the best, historical, New Zealand example of such an earthquake is the 1968 Inangahua earthquake: a *M*w 7.1 event associated with at least 4 m of reverse slip at depth, but little, if any, primary fault rupture at the ground surface (Anderson et al. 1994). Our study of the Mount Stewart–Halcombe Anticline allows us to place some general constraints on the seismic hazard posed by this growing fold. Faults I and II that bound the eastern side of the Mount Stewart–Halcombe Anticline have dip-slip rates of between 0.1 and 0.2 mm/yr before c. 0.6 Ma. Fault II has been inactive since 0.4 Ma, whereas activity on fault I has continued at a similar or slightly greater rate than before. The anticline has a length of at least 25 km; however, the depths to which the faults extend are not known. By way of analogy with the Inangahua earthquake, 4 m of reverse slip accumulating at a rate of 0.3 mm/yr (the dip-slip rate for fault I over the last 0.2 m.y.) would imply a recurrence interval of 13 ka for M 7+ earthquakes (magnitude estimates are based on a rupture length of 20–25 km; a rupture width of 15–25 km, but not exceeding the rupture length; and a rigidity of 3×10^{10} N/m^2). We consider 4 m of slip at depth a maximum estimate for single-event displacement, for with any larger value we would expect to see evidence of surface fault rupture. It is also reasonable to consider the possibility that the faults that bound the Mount Stewart–Halcombe Anticline rupture in earthquakes with less slip than 4 m. For example, 1–2 m of slip at depth, instead of 4 m, would imply a recurrence interval of 3–7 ka for M 6.5–7 earthquakes. Though certainly not rigorous, these calculations indicate that the return time for $M > 6.5$ earthquakes on the Mount Stewart–Halcombe Anticline is at least several thousand years and may be longer than 10 000 years. The timing of the most recent earthquake on the Mount Stewart–Halcombe Anticline is not known.

CONCLUSIONS

The Mount Stewart–Halcombe Anticline is an asymmetric fold controlled by two reverse faults, and has been growing since at least Mangapanian time (c. 3.1 Ma). The two faults, I and II, dip at 60–65° west, and appear to have predominantly dip-slip displacement on planar fault planes. A third, nearby, fault (III) dips at 60° east, and may be a backthrust associated with the adjacent Feilding Anticline.

The anticline is at least 25 km in length and continues as a subsurface feature to the south of its area of topographic expression between Mount Stewart and Halcombe. The anticlinal axis and its controlling faults curve from a northerly trend at the location of the seismic line MTS-1 to a more ENE trend farther south.

Correlations using seismic reflection data between the well Santoft-1A and Mount Stewart have demonstrated the presence of Castlecliffian sediments on Mount Stewart, where they were thought previously to have been absent. The sedimentary sequence in the Mount Stewart area is between Mangapanian and Recent in age, with a complete section inferred to be present in the lowest part of the fold, on the downthrown side of fault II. Some of the upper Castlecliffian section has been eroded from the upthrown (western) side of the faults.

The dip-slip displacement rate was between 0.1 and 0.2 mm/yr on each of the three faults during the period 2.6–0.6 Ma. All three faults have been active throughout Mangapanian, Nukumaruan, and Castlecliffian time, but only fault I has been active through Haweran to the present, and its displacement rate over this time was greater, at c. 0.3 mm/yr, than for the earlier period. A lower limit for the onset of faulting is not able to be made, because the oldest sediments preserved are Mangapanian.

An estimate for the return time of damaging earthquakes (*M* 6.5–7+) resulting from movement of fault I ranges between several thousand years to > 10 000 years, depending primarily on the assumed amount of co-seismic dis–placement.

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