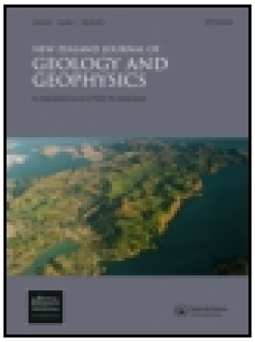

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Tilting of active folds and faults in the Manawatu region, New Zealand: evidence from surface drainage patterns

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Abstract We examine the drainage system on four anticlinal ridges in Manawatu that affect a mid-Quaternary (c. 300 000 yr old) marine horizon. The folds are all located above buried, west-dipping, reverse faults in the basement that are c. 15–20 km long and capable of generating earthquakes of c. M_W 6.5–7.0. The drainage systems allow us to distinguish a regional tectonic tilt from the normal plunge of an anticline axis towards its end. We estimate tilt rates of around 4×10^{-8} rad/yr towards the south averaged over the last c. 300 000 yr. The regional tilting is related to the development and southward migration of the Pliocene–Pleistocene depocentre in the offshore South Wanganui Basin.

Keywords geomorphology; drainage; faulting; active tectonics

INTRODUCTION

In regions of active tectonics, the landscape itself is often the most obvious guide to the existence of active structures, mainly because topography can be generated quickly compared with rates of erosion and deposition. As the landscape evolves due to modification of tectonically produced slopes by erosion, deposition, and the continued growth of structures, then drainage systems adapt to changes in surface slope. Drainage thus has the potential to record information about the evolution of folds and faults, and may be particularly useful for this purpose in areas such as emerging hanging walls or anticlines, where the environment is essentially erosional and syntectonic stratigraphic markers are absent (see, e.g., Keller et al. 1989; Jackson & Leeder 1994; Jackson et al. 1996).

In many parts of the world, growing anticlines have been recognised above active, earthquake-generating faults in the basement, which may or may not break the surface (e.g., King & Vita-Finzi 1981; Stein & King 1984; Yeats 1986a, b; Philip et al. 1992). This paper is concerned with the drainage systems on four growing anticlines situated above active buried reverse faults in the Manawatu region of the North Island, New Zealand. These folds all have lengths of 15–20 km and vertical uplift rates of <1 mm/yr. On all of them there is a clear relationship between the drainage systems and the underlying active faults. We show that the drainage has evolved in response to regional tilting on a scale larger than that of the faults. The drainage systems on the Manawatu anticlines thus contrast with those on the growing anticlinal ridges in, for example, central Otago (Jackson et al. 1996), where regional tilting has had little noticeable effect.

REGIONAL TECTONIC AND STRATIGRAPHIC SETTING

The Manawatu region of the Wanganui Basin in the North Island of New Zealand (Fig. 1) contains a series of anticlinal folds at the surface in the area between the Ruahine Range in the east and Wanganui in the west. In this paper we discuss four of these: at Marton, Mt Stewart-Halcombe, Feilding, and Pohangina (Fig. 1). All of them form clear, but subdued, ridges trending roughly N–S to NNE–SSW and rising only c. 100–200 m above the surrounding countryside. None of them is associated with significant faulting at the ground surface, but Te Punga (1957) realised the coincidence between the surface expression of these anticlines and the subsurface structure imaged by early seismic reflection surveys (Feldmeyer et al. 1943), and postulated that the anticlines occurred above active reverse faults at depth. Buried reverse faults have been imaged clearly in more recent seismic reflection data across the Mt Stewart-Halcombe Anticline (Melhuish et al. 1996), and the other anticlines are almost certainly underlain by similar faults.

The stratigraphy and subsurface structure of the region is discussed in detail by Melhuish et al. (1996), who reviewed the earlier work of Fleming (1953), Te Punga (1957), Anderton (1981), and various hydrocarbon exploration ventures. Surface outcrop is nearly everywhere restricted to Quaternary marine mudstones, sands, and gravels of Castlecliflian (<1.5 Ma) or much younger age. Various boreholes have penetrated 1000–2000 m of marine sediments that are all thought to be younger than 5 Ma and which overlie basement greywacke of Triassic–Jurassic age. All four anticlines discussed here deform mid-Quaternary sediments and marine surfaces that are probably younger than c. 0.5 Ma, while farther west, near Wanganui, folds visibly affect coastal terraces as young as 60 000 yr (Pillans 1990). The best studied anticline is that at Mt Stewart-Halcombe, which Melhuish et al. (1996) showed

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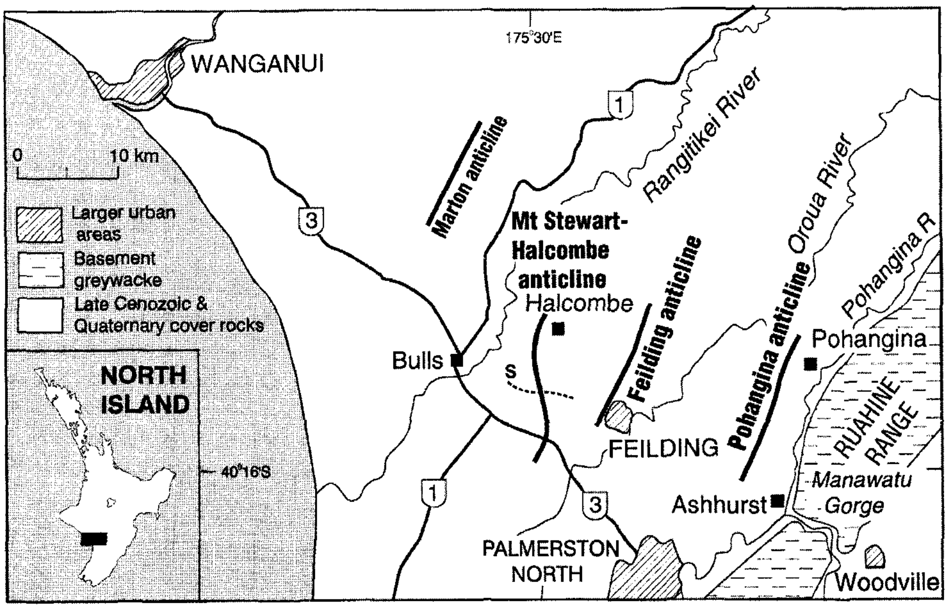


Fig. 1 Location map of the Manawatu anticlines. Thick black lines are the anticline axes. The location of the seismic line described by Melhuish et al. (1996) is marked S.

has been actively growing from at least Mangapanian time (c. 3.1 Ma) through to the present. The other three folds studied here are likely to have similar histories.

COMMON CHARACTERISTICS OF THE ANTICLINES

The four anticlines have many features in common. All of them are asymmetric, with gentle slopes (typically c. 2°) to the west and steeper slopes on the east. We interpret this asymmetry to reflect the likely westward dip of the underlying reverse faults, as seen in the seismic reflection survey of Melhuish et al. (1996). A prominent geomorphological characteristic of the anticlines is the preservation of a continuous marine surface across each fold, especially on the gentle westward flanks. On each fold this surface, or its remnant, is recognisable as planar interfluves between a regular system of parallel streams that dissects the flanks of the rising anticline (Fig. 2). The preserved marine horizon is a bedding surface of mid-Quaternary age and must have originally been subhorizontal. We do not know whether it is the same marine surface preserved on all four anticlines, but that on the Feilding Anticline (and that on the adjacent Mt Stewart-Halcombe Anticline) is thought to be c. 300 000 yr old and to have formed during the Brunswick Interglacial. This age correlation is based on the presence of Griffins Road Tephra, with an estimated age of c. 300 000–340 000 yr (Bussell & Pillans 1992; Berger et al. 1992; Pillans 1994), within the top of the marine sequence that is warped into the Feilding Anticline (grid ref. NZMS 260 S23/259065; A. Palmer pers. comm. 1996), within the dune sands that immediately overlie the marine sediments of the Feilding Anticline (T23/310145), and within the coverbeds of alluvial gravels that also overlie the marine sediments (S23/302193; A. Palmer pers. comm. 1996).

The preservation of a recognisable surface on each anticline allows structural contours to be drawn that reveal the present shape of the fold (Fig. 3). Each fold shows the same general features: (1) a drainage divide that is close to the southeastern (steep) limb of the anticline and almost coincident with the axis of the anticline deduced from the structural contours; (2) a fold axis (and drainage divide) that plunges to the south; and (3) a system of parallel streams on the western (gentle) limb of the fold that are oblique to the structural contours.

The obliquity of the stream systems to the structural contours is a particularly important feature which requires some early comment. If the parallel stream systems developed in response to the growing anticlines (i.e., were "consequent" streams) they would be expected to flow down the steepest slope, perpendicular to the structural contours (as was seen everywhere, e.g., in central Otago, by Jackson et al. 1996). The streams on the Manawatu anticlines do not do this. There are two possible explanations: either the stream systems were there already ("antecedent") and have maintained their original courses through the growing anticlines; or the streams originated as genuine consequent drainage, but the anticlines have been tilted to the south.

There are three reasons why we believe the stream systems are consequent on the anticlines. (1) The streams are approximately perpendicular to the drainage divides and anticline axes. If they were antecedent, this would have to be coincidence. (2) There are, in general, no air gaps or dry valleys along the anticline axes that would suggest a stream system that predated the uplift of the ridges. (3) Some of the anticlines show radial stream patterns around their ends, which is a clear sign of consequent drainage. In addition to these three reasons, there are clear signs in the morphology and capture patterns of the streams themselves (which we discuss later) that the region has been tilted to the south.

The features described above are not all displayed with equal clarity on each anticline, and each one has undergone erosion to a varying extent. We will now briefly describe the essential features of each fold before discussing their tectonic significance. In many respects, the Feilding Anticline is the best preserved, and so we discuss it in the most detail.

Pohangina Anticline

This is the easternmost and highest of the four folds we discuss (Fig. 3A), and is also the most dissected by the

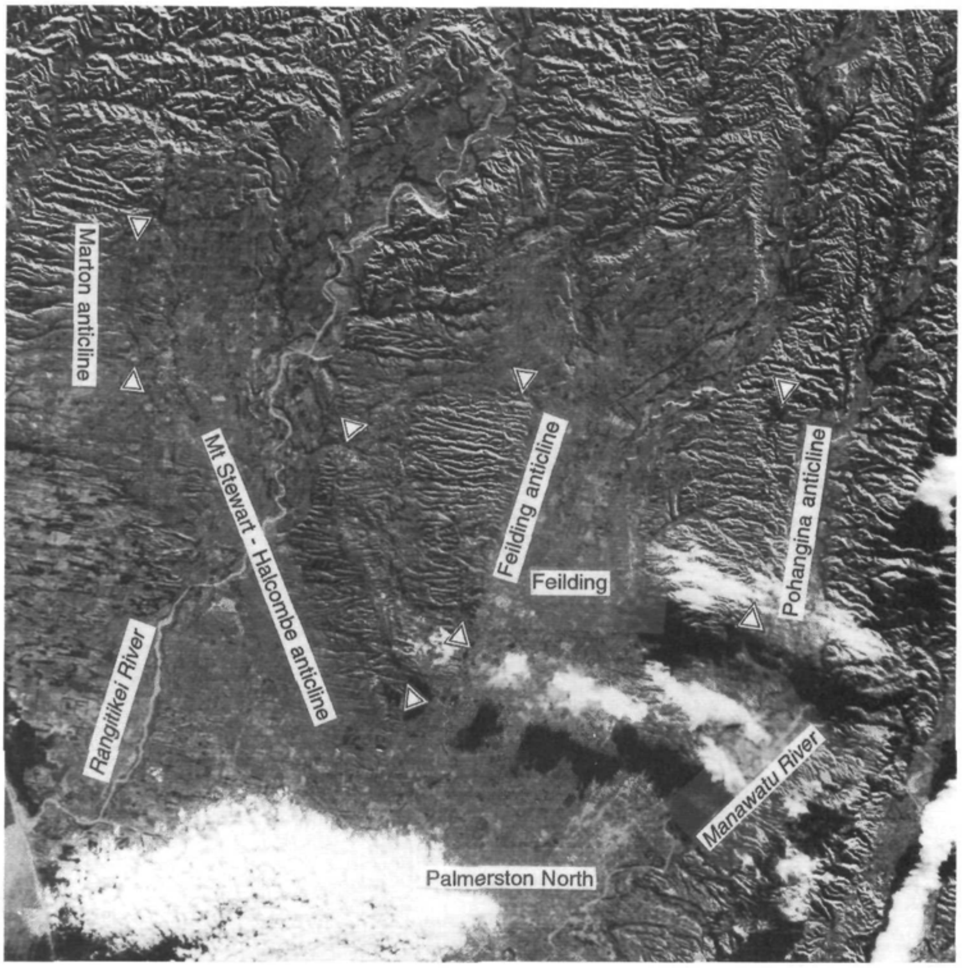


Fig. 2 LANDSAT thematic mapper image of the Manawatu anticlines. Arrows mark the positions of the anticline axes. Note the parallel stream systems, with the planar interfluves between them, on the gently dipping western slopes of the ridges.

drainage. The asymmetry of the drainage system reflects the fold shape, which has a gentle west slope of 2–4° parallel to the underlying bedding, but much steeper dips (up to 60°) on its eastern limb. Streams on both flanks have eroded headwards to produce a drainage divide that is sinuous in places, but the absence of air gaps along the anticline crest suggests that the drainage system was not antecedent. Clear planar interfluves are visible, particularly at the southern end. Towards the northern end, the interfluves are much dissected and remain only as remnant outliers. The southern end of the anticline may also have the remains of a radial drainage pattern, though this has been modified by Stony Creek and the Manawatu River flood plain. The folded marine sediments that form the planar interfluves on the Pohangina Anticline are probably c. 300 000 yr old (Berryman & Cowan 1993).

Feilding Anticline

The drainage divide

The Feilding Anticline has the best preserved planar interfluves, especially on its western flank (Fig. 2). The crest of the anticline and its asymmetry are well defined by the height of the interfluve surface (Fig. 3B). The streams on the steep eastern flank have eroded headwards of the ridge crest in a number of places, particularly near Feilding itself, where the course of Makino Stream is very close to the axis of the anticline (Fig. 4A). In this region, the east-flowing streams had their courses steepened as the Makino Stream eroded the eastern flank of the growing ridge, allowing them to erode headwards and capture some of the streams that originally drained west. One such stream is followed by the North Island Main Trunk Railway along Lethridge Road (Fig. 4A). The air gaps produced by this capture all lie west of the anticline axis. The drainage pattern at the southern end of the anticline is disturbed by the Makino and Mangaone West Streams, and no radial pattern (if it ever existed) is now visible.

For a few kilometres north of the 213 m trig point (Fig. 3B), the western fork of the Makino Stream has also eroded the eastern flank of the anticline, causing the east-flowing streams to erode westward and capture the headwaters of west-flowing streams (Fig. 4B, C). In this region there are only isolated remnants of the original interfluve surface on the eastern flank of the anticline.

Asymmetry of the stream systems

The interfluves on the western limb of the anticline are all part of the same original marine surface of c. 300 000 yr old, which is easily recognisable over the whole length of the fold. In many places this western limb shows a consistent asymmetry to its stream channels and capture patterns, first noticed by Te Punga (1957). To illustrate this we made two traverses parallel to the strike of the anticline axis (Fig. 4B), measuring the elevation of the ground surface using

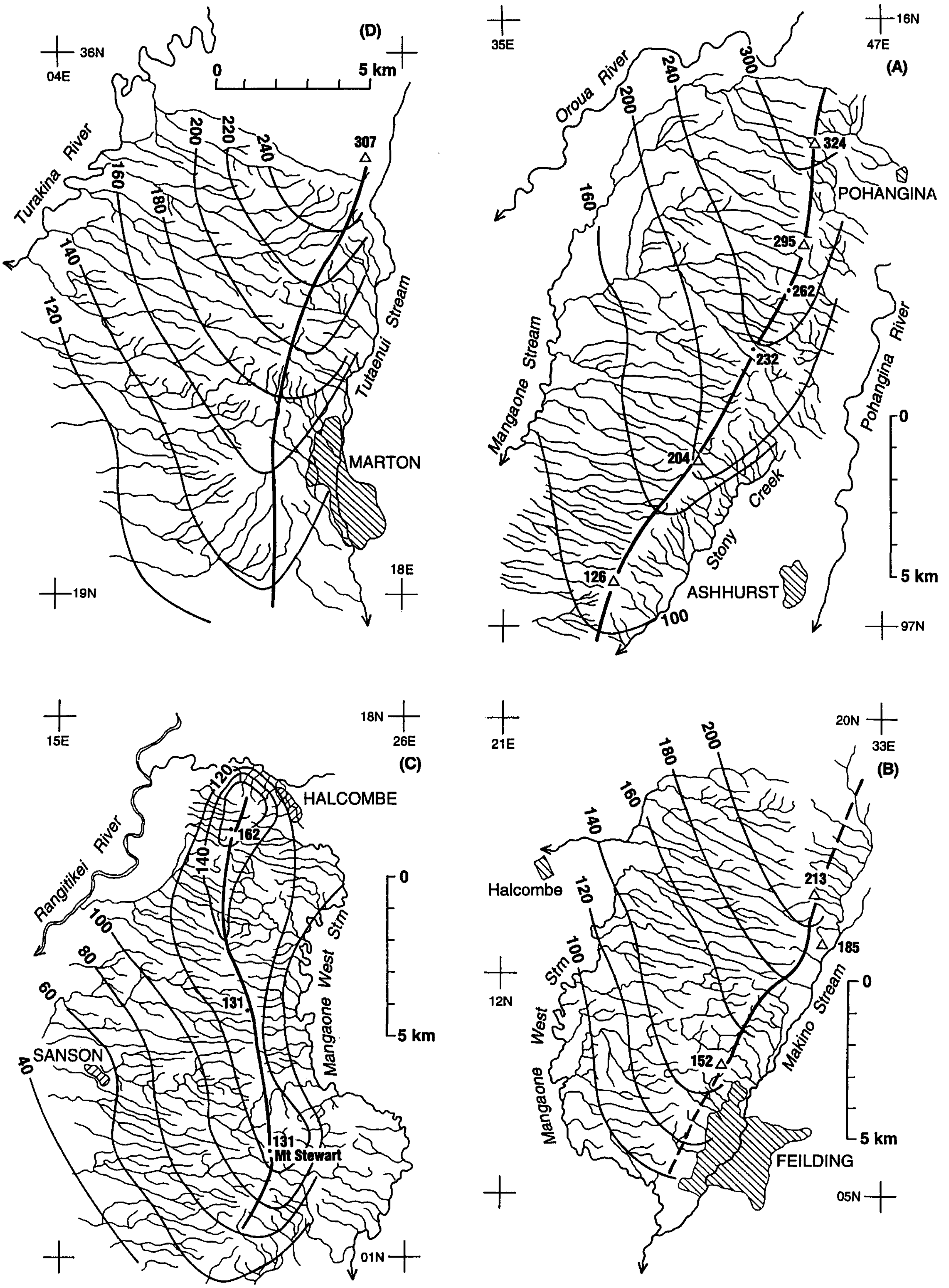


Fig. 3 Drainage summary maps of (A) Pohangina, (B) Feilding, (C) Mt Stewart-Halcombe, and (D) Marton Anticlines. Structural contours are drawn on the marine surface that forms the planar interfluve surfaces, with heights in metres. The solid black lines are the approximate traces of the anticline axes, with spot heights also in metres. The drainage divides originally followed the anticline axes but in places have been modified by subsequent stream capture.

differential GPS (Global Positioning System). The traverses are shown in Fig. 5A, in which the correlation of the interfluve height is clearly recognisable. Detailed plan views (map and air photograph in Fig. 4B, C) show that the main streams nearly all have smaller parallel streams feeding into them from the northern side, whereas the southern side of the main stream valley is usually straight and continuous. This pattern comes about from a process which Cotton (1942) called "abstraction", which is common in a system of parallel incising streams (Fig. 6). As the streams cut into the landscape, irregularities in the rates of incision will lead to one stream capturing its parallel neighbour, so as to give a fork-like stream pattern upstream and a "beheaded" stream downstream. However, on the Feilding Anticline this has not happened randomly, but is nearly everywhere consistently in one direction, with streams being captured by a parallel stream to the south. The asymmetry occurs because the small tributaries perpendicular to the main streams erode more vigorously on the northern side of valleys than on the south. Thus, a cross-section through the streams has an asymmetric sawtooth-like shape, with the steepest slope and deepest valley on the southern side and the remnants of captured parallel stream valleys forming shallower valleys or terraces on the northern side (see the detailed cross-section in Fig. 5B and the view in Fig. 7). This asymmetry is noticeable in the capture patterns on all four anticlines, but is best developed at the northern end of the one at Feilding.

Tilting

We attribute the asymmetry of the stream system, in both plan view and cross-section, to a tilting of the whole anticline to the south, steepening the northern side of the valleys and making the southern sides less steep. We presume also that this tilting is responsible for the obliquity of the parallel streams to the structural contours on the interfluve surface. If the stream system is genuinely consequent on the fold development, it must have started with the streams flowing down the maximum slope, which would have been perpendicular to the fold axis, as is still seen today. During subsequent tilting to the south, the stream systems have managed to maintain their original courses, but have undergone an asymmetry in their capture and cross-sections.

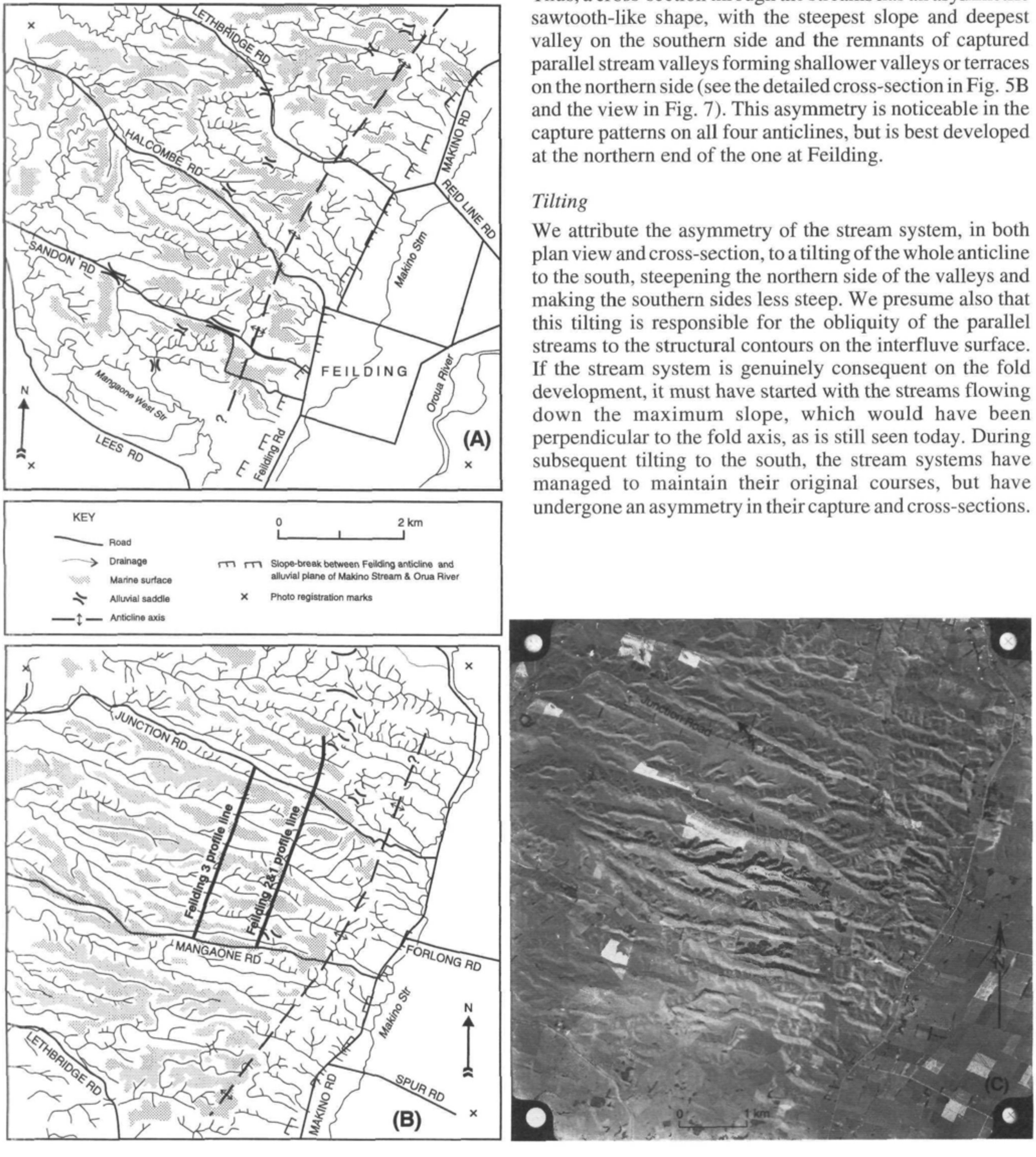


Fig. 4 Detailed maps and airphoto of Feilding anticline: (A) south part; (B and C) north part. The arrow in (C) shows the location of the view in Fig. 7.

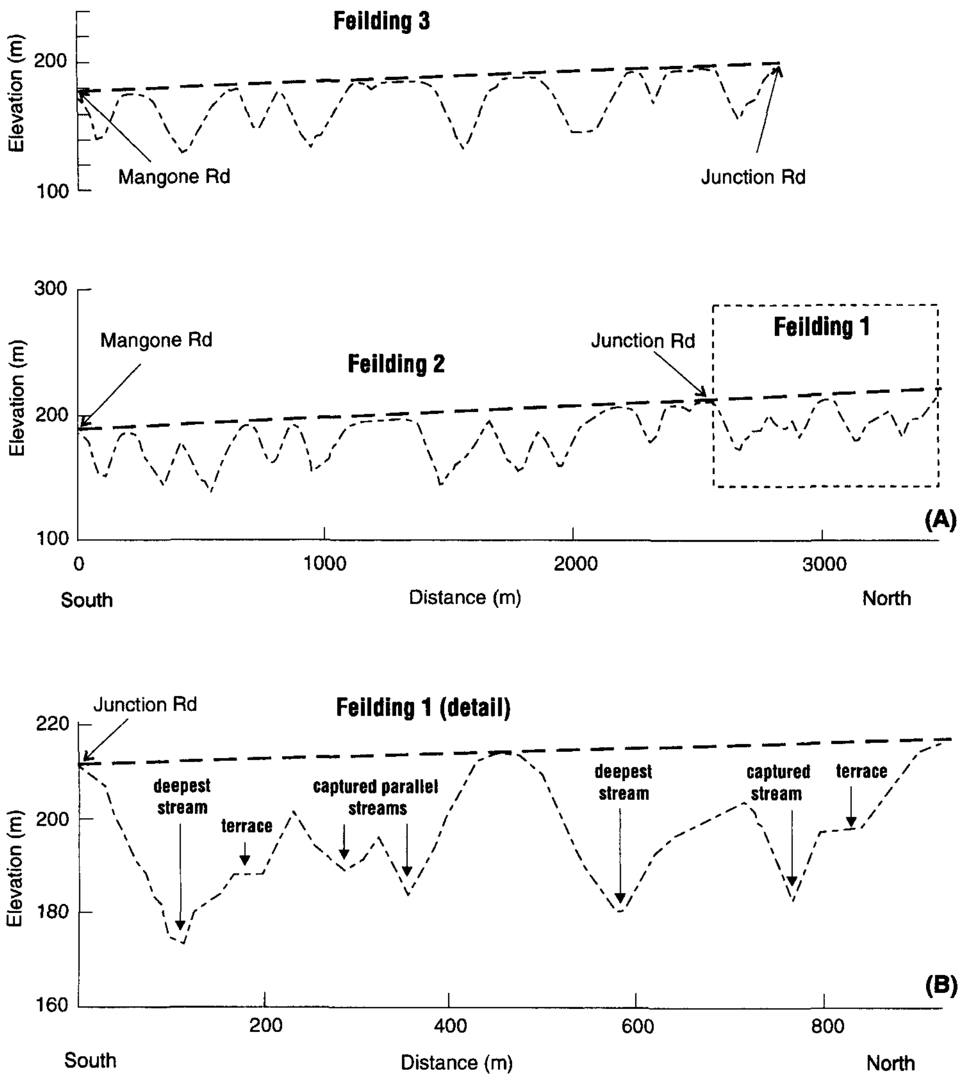


Fig. 5 Two topographic profiles perpendicular to the drainage on the northwestern flank of the Feilding Anticline (see Fig. 4B for location), measured by differential GPS: (A) two long traverses (Feilding 2 and 3); (B) close up (Feilding 1, north of Junction Road).

Mount Stewart-Halcombe Anticline

A seismic reflection line across the central part of the Mt Stewart-Halcombe Anticline (5 km north of Mt Stewart) revealed two buried, west-dipping reverse faults, c. 1000 m apart, that project to the surface beneath the steep eastern limb of the fold, though their tips only reach to c. 1000 m below the surface (see Melhuish et al. 1996, fig. 3). A smaller, also buried, reverse fault is located in the footwall of the other two and dips east: it appears to have no correlation with the topography. Only the westernmost of the two west-dipping faults is thought to be now active, and the other two faults have been inactive since c. 0.4 Ma. Melhuish et al. (1996) concluded that the fold has grown from at least 3.1 Ma through to the present, and that the underlying active fault is moving at an average rate of c. 0.3 mm/yr.

The most striking feature of the Mt Stewart-Halcombe Anticline is its sigmoidal shape, well defined by the drainage divide which is preserved as a continuous interfluve surface with almost no air gaps. It is the best preserved and least dissected divide of the four anticlines we discuss. At the northern end, the flood plain of the Rangitikei River has eroded the northwestern flank of the anticline, steepening the streams on the western flank. About 1 km south of the Halcombe 162 m spot height, a stream flowing west has captured the headwaters of one that originally flowed east, leaving behind the only obvious air gap on the drainage divide (see also Te Punga 1957). The lack of original air gaps, and the clear radial drainage patterns at the northern and southern ends of the ridge, are consistent with consequent (rather than antecedent) drainage.

The origin of the sigmoidal shape of the fold axis is not clear. It is the shape expected if the ridge is actually underlain by two buried, en-echelon fault segments in a left-stepping pattern. It is possible that the two parallel faults detected in the seismic reflection profile of Melhuish et al. (1996) are two such en-echelon segments, with the seismic line crossing the region of their overlap. Against this interpretation is the clear evidence for two west-dipping faults in a parallel, older seismic line c. 5 km south of Mt Stewart (see Melhuish et al. 1996). However, it is not certain that the two faults are the same in each profile, and the eastern fault in the southern profile could be the southern end of the fault underlying the Feilding Anticline immediately to the east.

The western flank of the fold, particularly in its central part, shows the same asymmetry of parallel stream capture that is so clear on the Feilding Anticline, with streams generally capturing parallel valleys to the north. We presume that these features, together with the obliquity of the streams

Fig. 6 Sketches to show the evolution of the parallel stream systems on the gently dipping western slope of the Feilding Anticline. The views are normal to anticline axis, from the west. The ridge crest is at the top. In (A) the parallel streams are incising but at different rates. In (B) streams 2 and 4 have captured streams 1 and 3 in several places, leaving behind high, dry, or beheaded stream courses, marked S. In the absence of tilting, this capture would be random, with streams capturing those on both sides. However, in this case, tilting of the ridge crest (up on the left, down on the right) has led to an asymmetry of the capture pattern, with streams 2 and 4 capturing streams on the left but not on the right.

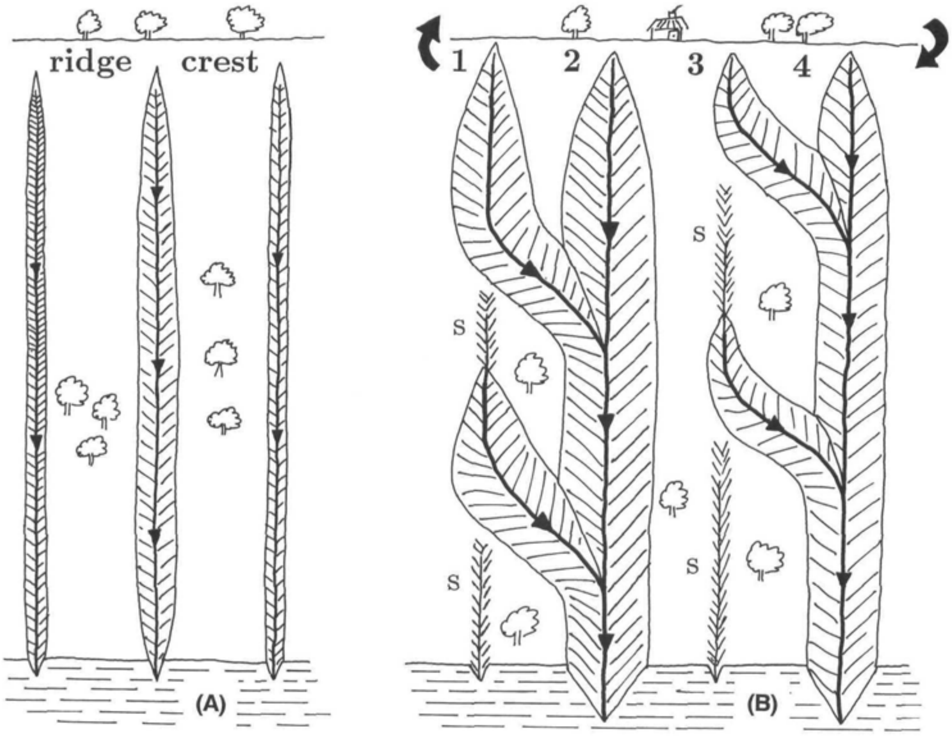
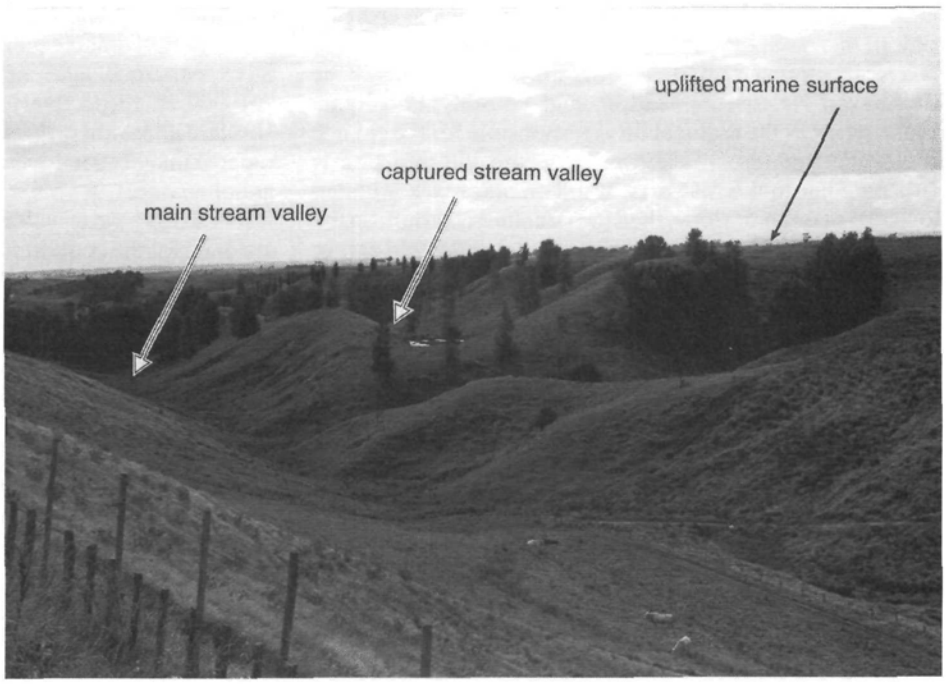


Fig. 7 View from S23/285160 looking west (downstream) along the valley north of Junction Road. The main stream valley has a single steep slope on the south (left). The north side of this valley has a stepped slope, with the remains of a parallel, abandoned valley higher than the main stream valley floor. The abandoned valley now contains a reservoir (centre picture), and its headwaters were captured by the stream entering from the north (right). The uplifted marine surface forms the flat interfluves between the main streams on the anticline. Compare this view with the cross-section in Fig. 5B.



to the structural contours, are all caused by a regional tilting towards the south. In the central part of the fold, the southward plunge of the anticline axis itself is markedly less than on the other folds (see Discussion), perhaps because the fold is underlain by two en-echelon faults.

Marton Anticline

The Marton Anticline is a broad, subdued fold with well-preserved planar interfluve surfaces, especially in the south, immediately west of Marton. As on the other anticlines, the long, parallel stream system on the western flank is oblique to the structural contours on the planar interfluve surface yet approximately perpendicular to the fold axis. A radial drainage pattern is preserved at the southern end.

DISCUSSION

The four anticlines not only share similar drainage characteristics but also are all of approximately the same scale. Longitudinal streams, parallel to the fold axes, have to some extent eroded the flanks of all of them, especially on their steeper sides. Making an allowance for this erosion, they all have a width of c. 10 km, which is to be expected from reverse faults that penetrate the upper 10 km of the seismogenic upper crust. The lengths of the fold axes, and thus of the underlying faults, are in the region of 15–20 km, and they are therefore capable of moving in earthquakes of c. M_W 6.5–7.0 in size (see Melhuish et al. 1996).

There is little in the geomorphology to distinguish the relative ages of the folds. Although there are signs that the Pohangina Anticline is the most dissected, and the Marton fold perhaps the least, this could be due to their relative proximity to powerful longitudinal streams, or to their relative amplitude, or to their relative rates of growth rather than to their relative age. From the likely age of the preserved planar interfluve surface of c. 300 000 yr on the Pohangina, Feilding, and Mt Stewart-Halcombe Anticlines, we know they have been active since at least that time. We can also tell that the Mt Stewart-Halcombe Fault has been sufficiently active in the last 300 000 yr to divert the drainage off the western flank of the Feilding Anticline south into the Mangaone West Stream (Fig. 3B, C), rather than allow it to cross the drainage divide of the adjacent Mt Stewart-Halcombe ridge, which has no air gaps. This is, of course, a small part of the fault's active history, which began over 3 m.y. ago (Melhuish et al. 1996).

An important aspect of the drainage on these anticlines is that it allows us to distinguish regional tilting from the ordinary plunging of an anticline axis towards the end of a fold. In this case, the plunge at the end of a fold is revealed by a radial drainage pattern (e.g., at the southern ends of the Mt Stewart-Halcombe, Marton, and possibly Pohangina folds), whereas the regional tilt is responsible for the change in elevation of the anticline ridge where the drainage is perpendicular to the fold axis. If the drainage was initiated down the maximum slope, then the structure contours on the interfluve surfaces must have been parallel to the fold axis in its central part, and so we can use the current slope of the axis to estimate the tilt in that direction over 300 000 yr (Table 1). A check on the internal consistency of this argument is given by the obliquity of the structural contours to the streams flowing perpendicular to the fold axis. If the angle between the streams and the structural contours is θ, then the relationship between the tilt of the fold axis (t) and the dip of the interfluve surface in the downdip direction (d) *is*: $\tan t = \tan d \cos \theta$. Thus, from the measured slopes of the fold axes and interfluve dip surfaces, a predicted value of θ can be compared with the observed value. These values are also shown in Table 1 (except for the Mt Stewart-Halcombe fold, whose sigmoidal shape precludes an unequivocal estimate of θ), and differ by less than 3° for the Pohangina and Feilding Anticlines. This test is less conclusive for the Marton Anticline, where the more curved structural contours allow a range of 40–50° for the observed angle θ.

We conclude that, on three of the four anticlines, the estimated tilts are similar. The anomaly is the Mt Stewart-Halcombe fold, which has an apparently very low tilt in its central part, possibly because it really overlies two en-echelon buried faults which form a saddle where they overlap.

The regional tilting is presumably related to the evolution of the South Wanganui Basin, which has been a subsiding and southward-moving depocentre offshore throughout the Pliocene–Pleistocene (e.g., Stern et al. 1992). As the depocentre has moved south, the coastal region has become uplifted (e.g., Pillans 1983, 1990), so that the 300 000 yr marine surface near Feilding and Pohangina is now at an elevation of 300 m or more. Our tilt rates in Table 1 can be compared with those derived using the estimated tilts of the nearby Rangitikei River terraces (Milne 1973a, b) and the revised ages of the terraces reported in Pillans (1994). Milne noticed that the higher (and older) the terraces, the more steeply were they inclined downstream. By assuming that the terraces were formed on the same gradient as the course of the modern Rangitikei River, he estimated tilts of the Burnard and Aldworth terraces of 9.3×10^{-3} rad and 1.44×10^{-2} rad, respectively. The Burnard and Aldworth terraces bracket in age the marine surface that defines the top of the Mt Stewart-Halcombe, Feilding, and Pohangina Anticlines, and have estimated ages of 240 000–280 000 and 340 000–350 000 yr, respectively (Pillans 1994). Tilt rates for the Burnard and Aldworth terraces, in the downstream direction (approximately southwest, and so in the same direction as the anticline axes), are 3.6×10^{-8} rad/yr and 4.2×10^{-8} rad/yr, respectively; these values are indistinguishable from our estimate for the anticline axes of $3\text{–}4 \times 10^{-8}$ rad/yr (Table 1).

A crude estimate of the longer term tilt rate can be obtained from the dip of the base-Pliocene reflector (c. 4 Ma) offshore in the South Wanganui Basin (Stern et al. 1992), which reaches a depth of 4000 m over a distance of 100 km. If we assume that these beds were deposited horizontally, we derive an average tilt rate of c. 1.0×10^{-8} rad/yr over 4 m.y. This, too, is similar in magnitude to our shorter term estimates, but is likely to be too low, as it represents an average over the whole northern half of the basin, whereas in cross-section the basin is sigmoidal rather than planar in shape (Stern et al. 1992), and tilt rates are probably steeper in the region of the coastline, near the hinge.

Table 1 Estimated tilting and tilt rates of the Manawatu anticlines. ΔH is the change in height along the central part of the ridge axis (in metres) over a distance L (km). This is shown as a tilt (in degrees and radians) and as a tilt rate (radians/year) assuming it occurred over 300 000 yr in the direction of the fold axis. Predicted and observed values of the obliquity (θ) of the streams to the structural contours are not given for the Mt Stewart-Halcombe fold (†), because of its sigmoidal shape.

	ΔH (m)	L (km)	Tilt		Tilt rate (rad/yr)	Obliquity, θ		Direction of tilt
			Degrees	Radians		Predicted	Observed	
Pohangina	198	16.0	0.71°	12.4×10^{-3}	4.1×10^{-8}	52°	53°	200°
Feilding	61	6.3	0.55°	9.7×10^{-3}	3.2×10^{-8}	53°	50°	205°
Mt Stewart-Halcombe	31	10.0	0.18°	3.1×10^{-3}	1.1 × 10-8	†	†	180°
Marton	100	12.0	0.48°	8.3×10^{-3}	2.8×10^{-8}	48°	40–50°	190°

CONCLUSIONS

Drainage systems on the Manawatu anticlines show simple patterns that are consequent on the growth of the folds yet are no longer perpendicular to the structural contours on the anticline flanks. This unusual situation has arisen because of a regional tilting related to the evolution of the South Wanganui Basin, which has been insufficient to change the originally consequent stream courses, though it strongly affects the asymmetry of their valleys and capture patterns. We can use the slope of the fold axes in their central parts to estimate a tilt rate of c. 4×10^{-8} rad/yr in those directions averaged over c. 300 000 yr. This value is similar to that estimated from the Rangitikei River terraces and of the same order of magnitude as the longer term tilt rates in the South Wanganui Basin.

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