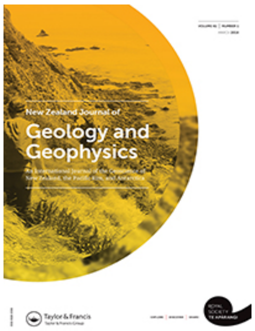

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RESEARCH ARTICLE

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Post-remagnetisation vertical axis rotation and tilting of the Murihiku Terrane (North Island, New Zealand)

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ABSTRACT
We collected palaeomagnetic sample sets from Murihiku Terrane, North Island to constrain its palaeolatitude during the Late Triassic–Jurassic. The majority of the sample host rocks were remagnetised. However, a few samples show a magnetic signal that possibly recorded a primary remanent magnetisation. These samples preliminarily indicate that Murihiku Terrane was located at c. 63°S during the Early Jurassic. The remagnetised samples reveal significant post-remagnetisation tectonic rotation and tilting of the host rocks. We estimated an 83 ± 5 Ma timing of remagnetisation by plotting the palaeolatitude data on the apparent polar wander path of northern Zealandia. Samples from southernmost sites have lower inclination, which we interpret as reflecting eastward post-remagnetisation tilt of this region by 20°. In addition, declination data indicate large-scale post-remagnetisation rotation of Port Waikato and Awakino Gorge areas. This study contributes to the ongoing debate on the age and tectonic origin of oroclines in New Zealand basement.

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Introduction

The New Zealand continent (Zealandia) separated from Gondwana during the Late Cretaceous following continental rifting and sea floor spreading in Tasman Sea and between Campbell Plateau and Marie Byrd Land (MacKinnon 1983; Haston and Luyendyk 1991; Mortimer 2004). The majority of basement on land in New Zealand, the so-called Eastern Province, consists of volcanic arc (Brook Street Terrane), ocean floor (Dun Mountain Terrane), forearc (Murihiku Terrane) and accretionary wedge elements (Torlesse complex), interpreted to have formed at one or more intra-oceanic subduction zones (Mortimer et al. 2014). This allochthonous assemblage is separated from Gondwana-derived units in western New Zealand (Northwest Nelson, Westland, Fiordland) by the Median Batholith (c. 375 and 110 Ma), which represents a long-lived magmatic arc along the Gondwana margin (Mortimer 2004).

The Murihiku Terrane, noted above is one of the Eastern Province elements, is structurally separate from adjacent terranes, forming a simple yet long syncline, known in the North Island as the Kawhia syncline and in the South Island as the Southland syncline. This terrane has long been regarded as a Triassic–Jurassic forearc basin based on its simple structure, its well-bedded and fossil-rich character and its volcanic arc provenance (Briggs et al. 2004).

Here, we present the results of a paleomagnetic study of rocks within the Kawhia syncline in an attempt to constrain the paleolatitude of the Murihiku Terrane during the Jurassic, and hence to assess the amount of probable Early Cretaceous convergence between it and Paleozoic terranes comprising eastern Gondwana. We are aware that previous paleomagnetic studies have concluded widespread remagnetisation of the Eastern Province basement of New Zealand (Haston and Luyendyk 1991), including within the Kawhia syncline (Oliver 1994; Kodama et al. 2007). Nevertheless, we hypothesise that the analysis of samples from different facies and localities within the Murihiku Terrane may identify some that retain a detrital remanent magnetisation from which the paleolatitude can be calculated. Even if the rocks drilled at all sampled sites turn out to be remagnetised, these paleomagnetic data may be useful to help constrain the post-remagnetisation tectonic history of the terrane.

Geological setting

The Murihiku Terrane mostly comprises Triassic to Upper Jurassic marine and non-marine sediments

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(Ballance and Campbell 1993) consisting mainly of volcaniclastic sandstone and siltstone with conglomerate in places and frequent tuff layers (Aita and Spörli 1992). These strata span c. 90 Ma and have thicknesses of up to 10 km or more (Coombs et al. 1992; Roser et al. 2002). Zeolite facies have formed through low-grade burial metamorphism (Coombs 1954; Ballance et al. 1980; Roser et al. 2002).

Petrographic and geochemical studies of Murihiku Terrane samples show that they derived from direct volcanic eruptive materials and mainly from erosion of a volcanic arc terrane (Roser et al. 2002; Briggs et al. 2004). The sediments and tuff accumulated within a forearc basin probably underlain by oceanic crust (Spörli 1987; Aita and Spörli 1992). However, an origin as an intra-arc or back-arc basin has also been suggested (Howell 1980; Coombs et al. 1992). A paleomagnetically determined paleolatitude for Murihiku basin strata would help constrain the intra-Panthalassa Ocean location where the volcanic arc may have formed.

A previous paleomagnetic study of Lower Jurassic Murihiku Terrane volcanic rocks in the Southland syncline suggested that the basin was located at a high paleolatitude, close to the eastern Gondwana margin (Grindley et al. 1980). The similarity between Triassic plant fossils in Murihiku Terrane strata and from nearby coastal regions of Gondwana has also been used to suggest that the origin of the Murihiku basin must have been close to the Gondwana margin (Retallack 1987). However, the presence of two synchronous magmatic/volcanic arcs of the Median Batholith and the Brook Street Terrane in particular, has been used to suggest that a subduction plate boundary must have existed between the intra-oceanic arc and Gondwana during the Permian prior to accumulation of sediments now exposed in the Murihiku Terrane (Bradshaw 1994; Mortimer 2004). Whether the Murihiku Terrane basin originated adjacent to or at a distance from the eastern Gondwana margin thus remains uncertain, but all tectonostratigraphic terranes were sutured along that margin by the end of the Early Cretaceous (Howell 1980).

At present, the Murihiku Terrane is exposed in both North and South Islands as a broad synclinorium. From south to north, the synclinorium consists of the Southland, Key Summit and Nelson synclines in the South Island and the Kawhia syncline in the North Island (Campbell et al. 2003). The Murihiku Terrane synclinorium is dextrally offset by c. 460 km along the Alpine Fault (e.g. Edbrooke et al. 2015). Regional strikes of Murihiku and other basement bends towards the Alpine Fault and form large oroclines on either side of this fault. The age of oroclinal bending within these terranes as well as its relation to Alpine Fault deformation remains uncertain. A widely held view is that Cenozoic plate motion within New Zealand was accommodated across the Alpine Fault as well as in a broad zone of deformation, leading to bending of basement terranes as a result of large-scale drag (Kamp 1987; Sutherland 1999; Mortimer 2014). An alternative view is that the basement terranes were bent pre-Cenozoic and that the curvature of the terranes remained unchanged in the Cenozoic because Neogene dextral displacement on Alpine Fault occurred in a very narrow zone (Lamb et al. 2016).

In the Kawhia syncline, the location of our paleomagnetic sampling, the Murihiku Terrane is exposed along the west coast of the central–western North Island between Port Waikato in the north and Awakino Gorge in the south as well as inland. The Kawhia syncline is c. 40 km wide and the strike of its fold axis varies from north–northeast in the south to north–northwest in the north (Figure 1). The age of Murihiku Terrane strata within the Kawhia syncline varies from Late Triassic (Norian) to Late Jurassic (Tithonian) (Roser et al. 2002).

Methods

Rock samples from Murihiku Terrane were obtained from three locations (Figure 1, Table 1) using a petrol-powered drill with a drill bit having an internal diameter of 25 mm. We always sampled over a sufficiently long interval (10–20 m) per site, enough to average out paleosecular variation (see A95 parameter in Table 2 and explanation below). The cores were oriented in the field using a Brunton magnetic compass with an inclinometer attached. Cores were cut into subsamples 22 mm long using a double-blade circular saw.

Laboratory analyses were carried out at the paleomagnetic laboratory, Fort Hoofddijk, at Utrecht University, the Netherlands. The natural remanent magnetisation of samples was measured on a 2G DC-SQUID magnetometer and further investigated using thermal as well as alternating field (AF) stepwise demagnetisation. Thermal demagnetisation was carried out using successively higher temperatures (in °C): 20, 100, 150, 180, 210, 240, 270, 300, 330, 360, 390, 420, 450, 480, 500, 520, 540, 560 and 580. During AF demagnetisation we used the following field strengths (in mT): 0, 4, 8, 12, 16, 20, 25, 30, 35, 40, 45, 50, 60, 70, (80, 90, 100). Thermomagnetic analyses to determine the nature of magnetic carriers were performed on representative samples for each locality using a horizontal translation-type Curie balance with cycling applied magnetic field, usually 150–300 mT (Mullender et al. 1993). We used (finely crushed) bulk material, usually 50–80 mg. A number of heating–cooling cycles was applied to detect magneto-mineralogical alterations during heating. We used the following temperature scheme (in °C): 20–150, 100–250, 150–350, 250–400, 350–500 and 400–700.

Statistical analysis and interpretation were performed using the online, platform independent portal: www.paleomagnetism.org (Koymans et al. 2016). Demagnetisation diagrams are plotted as orthogonal vector diagrams (Zijderveld 1967). Interpretation of

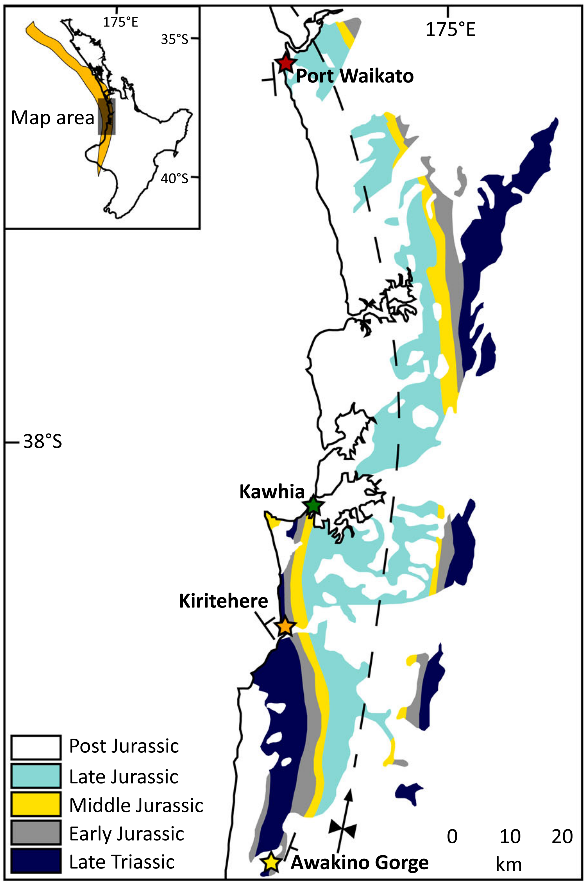

Figure 1. Simplified geological map of Murihiku Terrane exposed within Kawhia syncline (based on Edbrooke 2001, 2005). Note the change in strike of the fold axis (dashed line) of the syncline from north–northeast in the south to north–northwest in the north. Stars indicate sample localities. Inset, Map of North Island showing the distribution of Murihiku Terrane (orange colour) (based on Mortimer 2004).

demagnetisation diagrams was performed by determining a characteristic remanent magnetisation (ChRM) for components decaying towards the origin. We determined great circles if we found no clear ChRM decaying towards the origin because of a pervasive (low temperature or low coercive) overprint causing overlapping blocking temperatures or coercivity. Lines (ChRM, denoted as 'setpoints') and planes (great circles) were determined following an eigenvector approach (Kirschvink 1980). If we have both setpoints and great circles in a site, we use the method of McFadden and McElhinny (1988) to determine great circle solutions. We applied a 45° cut-off to the virtual geomagnetic pole (VGP) distribution of a set of directions (following Johnson et al. 2008; Deenen et al. 2011). This is an arbitrary fixed angle cut-off meant to remove outliers due to excursions or transitional directions, or to remove outliers due to (assumed, possible) errors in sampling and orientation measurement. Mean directions were determined using Fisher (1953), whereas directional statistics were derived from the corresponding VGP distribution (Deenen et al. 2011), and errors in declination (ΔD_x) and inclination (ΔI_x) were calculated from the cone of confidence (A95) of the mean VGP following Butler (1992). We applied the reliability criteria of Deenen et al. (2011) by determining A95 of the VGP distribution, and calculate the N-dependent values of $A95_{min}$ and $A95_{max}$ (recalculated by Deenen et al. 2014). Values plotting within this envelope can be explained by paleosecular variation. Values of $A95 > A95_{max}$ may indicate additional sources of scatter, while values of $A95 < A95_{min}$ represent low dispersion (high *k*-values, as with lavas) and cannot reliably represent paleosecular variation. To test the primary origin of the ChRM and if the data permit, we perform field tests. The fold test follows an eigenvector approach (Tauxe and Watson 1994) or the reversal test using the coordinate bootstrap test (Tauxe et al. 2010). The results are compared with the expected directions for a reference locality from the Global Apparent Polar Wander Path of Torsvik et al. (2012). All methods used (and more) are available at www.paleomagnetism.org. In the online supplementary information, we provide all the demagnetisation results and interpretations as a *.dir* file that can be easily imported into www.paleomagnetism.org. Similarly, all statistical results are provided as *a .pmag* file.

Location descriptions

Awakino Gorge

The southernmost area we sampled was a road section exposed in Awakino Gorge (AG), (Figure 1, Table 1).

Table 1. Information about GPS location of the site, measured bedding plane (strike/dip) and their age plus reference and the number of demagnetised samples per site.

		GPS coordinates					No. of samples demagnetised	
Site	Strike/Dip	Latitude (N)	Longitude (E)	Age (stage)	Age (Ma)	Reference	Th.	AF
AG1	302/63	−38.6739	174.6876	Middle Rhaetian	207–204	Hay (1967)	5	12
AG2	026/70	−38.6737	174.7108	Middle Toarcian	181–176	Hay (1967)	7	22
AG3	022/54	−38.6270	174.7309	Bajocian	170–168	Hay (1967)	5	28
AG4	021/60	−38.6370	174.7275	Bajocian	170–168	Hay (1967)	3	10
KI1	327/33	−38.3268	174.7041	Lower Rhaetian	209–207	Kear (1960)	8	26
KI2	328/37	−38.3168	174.7108	Upper Rhaetian	204–201	Kear (1960)	5	17
KI3	310/29	−38.3201	174.7075	Middle Rhaetian	207–204	Kear (1960)	3	14
KI4	336/29	−38.3201	174.7075	Middle Rhaetian	207–204	Kear (1960)	3	13
KI5	323/29	−38.3201	174.7075	Middle Rhaetian	207–204	Kear (1960)	6	26
PW1	175/36	−37.3993	174.7108	Late Tithonian	147–145	Challinor (2001)	8	40

Table 2. Geomagnetic directions per site.

Site	Ns	Na	D	ΔD_x	I	ΔI_x	K	$A95_{min}$	A95	$A95_{max}$	λ
Geographic coordinates											
AG1	17	16	130.3	12.3	−63.8	6.8	19.5	4.0	8.6	14.3	−45.5
AG2	29	21	103.4	5.6	−49.7	5.4	44.6	3.6	4.8	12.0	−30.5
AG3	34	31	98.3	8.4	−62.4	5.0	19.2	3.0	6.0	9.4	−43.8
AG4	13	13	81.0	9.0	−55.0	7.2	33.4	4.3	7.3	16.3	−35.5
AG all	93	79	101.9	5.0	−58.5	3.5	17.7	2.1	3.9	5.2	−39.2
AG E20	**85**	**77**	**121.0**	**12.0**	**−77.0**	**2.9**	**11.4**	**2.1**	**5.0**	**5.3**	**−65.3**
AG2*	8	8	301.3	5.4	5.8	10.7	106.6	5.2	5.4	22.1	2.9
AG2* E20	8	8	304.1	6.2	22.7	10.9	83.3	5.2	6.1	22.1	11.8
KI1	33	30	37.3	18.1	−78.6	3.7	16.6	3.1	6.7	9.6	−68.0
KI2	22	20	60.5	11.3	−70.0	4.5	25.4	3.6	6.6	12.4	−54.0
KI3	17	17	356.2	12.5	−74.0	3.8	34.1	3.9	6.2	13.8	−60.1
KI4	16	15	17.3	10.7	−71.7	3.8	43.6	4.1	5.9	14.9	−56.5
KI5	32	30	14.9	8.1	−69.9	3.3	30.6	3.1	4.8	9.6	−53.1
KI all	**121**	**116**	**26.8**	**6.9**	**−74.4**	**2.0**	**16.3**	**1.8**	**3.4**	**4.1**	**−60.7**
PW1	**48**	**44**	**346.2**	**9.5**	**−74.1**	**2.9**	**22.2**	**2.6**	**4.7**	**7.6**	**−60.3**
Tectonic coordinates											
AG1	17	17	184.9	8.1	−36.4	13.4	21.5	3.9	7.9	13.8	−13.9
AG2	29	21	311.8	7.9	−58.7	5.5	28.0	3.6	6.4	12.0	−39.4
AG3	34	32	305.9	8.0	−61.2	5.0	19.6	3.0	5.9	9.2	−42.3
AG4	13	13	322.9	10.7	−57.2	7.9	25.2	4.3	8.4	16.3	−37.8
AG all	93	65	310.5	4.9	−59.7	3.3	23.7	2.3	3.7	5.9	−40.5
AG E20	N/A										
AG2*	8	8	316.8	27.0	74.9	7.5	20.6	5.2	12.5	22.1	61.6
AG2* E20	**8**	**8**	**308.3**	**27.6**	**75.2**	**7.5**	**20.6**	**5.2**	**12.5**	**22.1**	**62.1**
KI1	33	33	247.0	10.8	−67.1	5.1	13.9	3.0	7.0	9.1	−49.9
KI2	22	22	237.9	13.0	−70.4	5.0	18.1	3.5	7.5	11.7	−54.6
KI3	17	17	253.3	8.5	−69.6	3.5	50.2	3.9	5.1	13.8	−53.4
KI4	16	15	286.3	8.4	−63.6	3.6	55.4	4.1	5.2	14.9	−51.8
KI5	32	29	276.3	8.4	−71.7	3.0	34.7	3.1	4.6	9.8	−56.5
KI all	121	119	257.3	5.5	−70.3	2.1	17.6	1.8	3.2	4.0	−54.3
PW1	48	48	61.0	4.9	−54.6	4.0	27.0	2.6	4.0	7.2	−35.1

Ns=total number of measured samples, Na=number of samples after 45° cut-off
Declination/inclination (D, I), their respective errors (ΔD_x, ΔI_x) and paleolatitude (λ) in degrees
AG2 includes samples taken at AG2, excluding AG2*, which is the sample set that has a deviating magnetic signal and is listed separately. Values given in bold are used for our paleomagnetic analysis and interpretation. AG E20 refers to the Awakino Gorge sample set corrected for the 20° eastward dip.

The oldest rocks (Site AG1) we drilled are of Middle Rhaetian age (207–204 Ma, Otapirian New Zealand Stage) followed upwards by Middle Toarcian Site AG2 (181–176 Ma, upper Ururoan to lower Te Temaikian New Zealand Stage) and then Bajocian Sites AG3 and AG4 (170–168 Ma, mid-Temaikian New Zealand Stage) (Hay 1967). Stage boundary ages are based on the geological time scale of Gradstein et al. (2012). The 94 samples collected include both sandstone and siltstone (mudstone) facies. Cores from AG1 are mostly quite weathered. At AG2, some cores comprise very fine bluish-grey siltstone and some comprise sandstone. Cores from AG3 comprise bluish-grey siltstone of which the top 0.5 cm is weathered to a brownish colour. The cores taken from AG4 are from two turbidite units comprising silty sandstone.

Kiritehere

Some 87 cores were collected from five sites at Kiritehere Beach (KI) (Figure 1, Table 1), these sites being accessible only during low tide. One drill site (KI1) is located on the shore platform south of Rararimu Stream, and the four other sites (KI2–5) lie on the shore platform north of this stream. The cores comprise bluish-grey siltstone that was easy to drill. The age of the cores obtained from Kiritehere range from lowermost Rhaetian (209–207 Ma, Otapirian New Zealand stage, Site KI1) to Middle Rhaetian (207–204 Ma, Site KI3-5) and Upper Rhaetian (204–201 Ma, Site KI2) (Kear 1960). After cutting, 116 specimens were available for paleomagnetic analysis.

Port Waikato

The most northerly area sampled within the Kawhia syncline was along the rocky coast immediately south of Port Waikato (PW), which is mainly accessible during low tide. This section comprises central parts of the Kawhia syncline and some of the youngest beds preserved within it (Late Tithonian, c. 147–145 Ma; Puaroan New Zealand Stage) (Challinor 2001) (Figure 1, Table 1). At Port Waikato, the sedimentary succession comprises Coleman Conglomerate (a formational unit), which consists of siltstone, sandstone and minor conglomerate (Challinor 2001). The 24 cores we drilled comprise mainly silty sandstone, yielding 48 specimens for paleomagnetic analysis.

Results

Magnetic carriers

We carried out thermomagnetic analyses on selected samples at each locality and present representative examples in Figure 3. From Awakino Gorge, sample

AG1.2 (Figure 2A) shows magnetisation that has an almost reversible decrease until 580 °C (Figure 2A), indicating magnetite as the main magnetic carrier. At temperatures above 350 °C, however, there is a slight decrease in the cooling curves, which suggests some contribution of maghemite that inverts to hematite at c. 350 °C (Dankers 1978). The final cooling curve is lower on the figure indicating that at least part of the magnetite/maghemite has been oxidised. Sample AG3.5 (Figure 2B) shows similar behaviour, but above 420 °C there is a small increase followed by a higher cooling curve. This indicates the new formation of magnetite from (a small amount of) pyrite that inverts to magnetite at temperatures above 390–420 °C, which subsequently oxidises to maghemite and finally to haematite, causing the increase and subsequent decrease in magnetisation (Passier et al. 2001). This is visible in thermomagnetic curves. In thermal demagnetization, the newly formed magnetite may produce spurious demagnetisation behaviour at higher temperatures. Samples from Kiritehere show a significant increase in magnetisation above c. 420 °C, which is caused by the transformation of pyrite into magnetite. The newly formed magnetite is subsequently demagnetised at temperatures above 500 °C. In sample KI1.21 (Figure 2C) there is again a slight loss of magnetisation in the cooling curves after heating to 350 °C, indicating the presence of maghemite. The final cooling curve is lower, meaning that the available maghemite and magnetite have been oxidised. In sample KI2.10 (Figure 2D), the newly formed magnetite from pyrite is (nearly) fully demagnetised. There

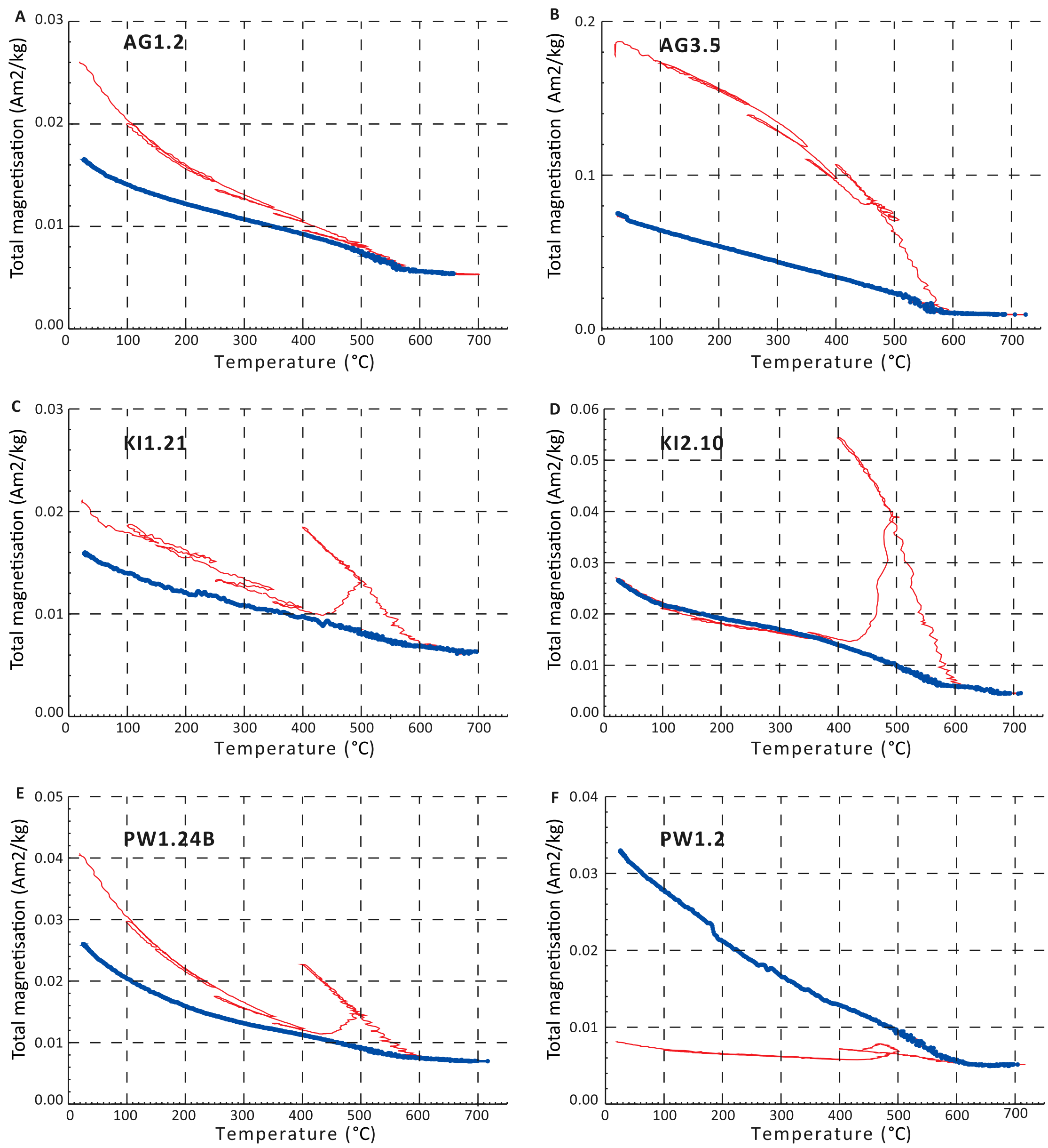

Figure 2. Representative thermomagnetic curves from a Curie balance using a cycling field between 50 and 300 mT (Mullender et al. 1993). Heating is applied to a maximum temperature of 700 °C in a number of heating–cooling cycles (thin red lines) with the final cooling curve as a thick blue line. Samples are from Awakino Gorge (AG), Kiritehere (KI) and Port Waikato (PW). We used crushed bulk material (typically 50–80 mg). Interpretations are described in the text.

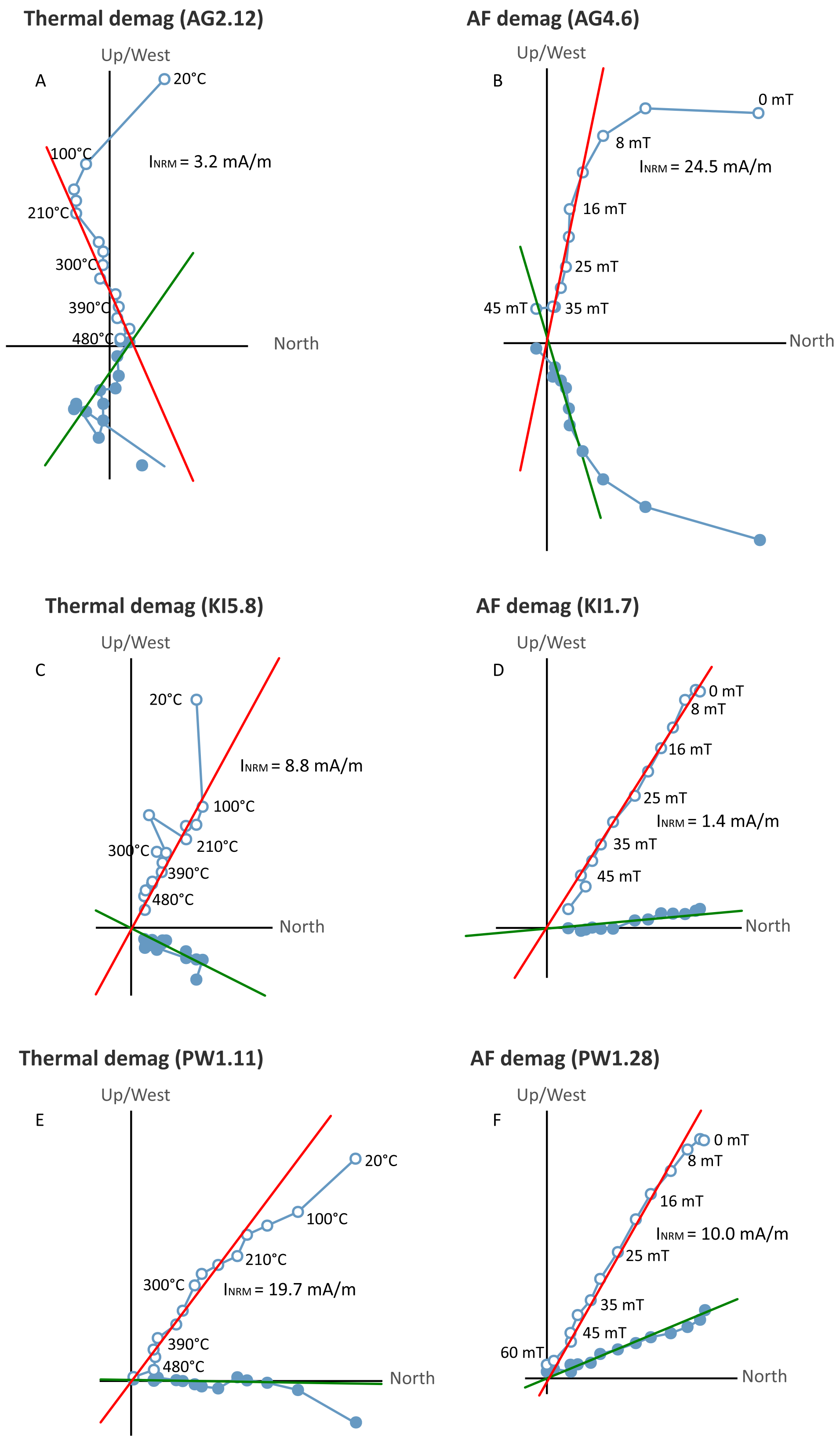

Figure 3. Representative examples of demagnetisation diagrams (Zijderveld 1967) in geographic coordinates from our three sample localities (AG, KI and PW). I_{NRM} indicates the initial natural remanent magnetisation, closed (open) symbols are projections on the horizontal (vertical) plane, and the respective projections (green, red lines) denote the interpreted characteristic remanent magnetisation (ChRM). Numbers refer to temperature (°C) or AF field (mT) steps. The initial natural remanent magnetisation intensities (I_{NRM}) are given in mA/m.

is no notable contribution of maghemite considering the final cooling curve, which is only marginally higher than the heating curves, meaning that there are some traces left of the newly formed magnetite.

Samples from Port Waikato generally show behaviour similar to those of Kiritehere (PW1.24B, Figure 2E). In sample PW1.2 (Figure 2F) there is a different behaviour; above 450 °C some new magnetite is formed but it is again demagnetised at c. 500 °C. Yet the final cooling curve is significantly higher than the heating curves, and new magnetic material is probably formed at temperatures up to 700 °C. This is possibly magnetite, judged from the breakdown of clay minerals at the highest temperature reached (700 °C).

Demagnetisation behaviour and paleomagnetic directions

Samples from Awakino Gorge that were thermally demagnetised generally show the removal of a low-temperature or low-coercive component, followed by a remanent magnetisation component that is stable and decays linearly to the origin above 180–210 °C or above 12 mT. This component is completely removed in most samples at 500 °C (Figure 3A), or at c. 60 mT (Figure 3B), which we interpret as the ChRM.

Mean paleomagnetic directions for all sites are listed in Table 2. ChRMs interpreted from Awakino Gorge samples show variation in mean declination from 81.0° (AG4) to 130.3° (AG1) (Table 2). In geographic coordinates, mean inclinations vary between −49.7° (AG2) and −63.8° (AG1) (Table 2). When all AG sites are grouped together, 14 of 93 directions are rejected by the 45° cut-off (Figure 4A,B). All samples indicate normal polarity and give a mean direction with D = 101.9 ± 5.0° and I = −58.5 ± 3.5° (where D = declination, I = inclination). After tilt correction, the mean direction is D = 310.5 ± 4.9°; I = −59.7 ± 3.3° (Figure 4A,B, Table 2).

Remarkably, eight samples form a separate cluster with very low inclinations before bedding tilt correction (see yellow symbols, Figure 4). These samples were all taken at Toarcian site AG2. These samples do not show characteristic differences in composition compared to the other samples taken at AG2. Two of these samples were thermally demagnetised and both have a stable natural remanent magnetisation component between 300 and 500 °C. The stable natural remanent magnetisation component during AF demagnetisation is obtained between 30 and 60 mT (Figure 5). The mean *in situ* direction of these samples (AG2*) is D = 301.3 ± 5.4° and I = 5.8 ± 10.7°, and a tilt-corrected direction D= 316.8 ± 27.0° and I =74.9 ± 7.5° (Table 2).

Thermal demagnetisation behaviour in Kiritehere samples generally shows a stable natural magnetisation component between 300 and 500 °C, and occasionally between 180 and 500 °C (Figure 3C). AF demagnetisation diagrams show linear trends and the magnetisation component is generally removed at 60–80 mT (Figure 3D).

Because of the relatively small stratigraphic range from which the sites (KI1–5) were taken at Kiritehere, directions from all 116 measured specimens were grouped and treated as a single set for statistical analysis (Figure 4C,D, Table 2). Only five samples are rejected by the 45° cut-off. All sites indicate normal polarity and give a direction D = 26.8 ± 6.9° and I = −74.4 ± 2.0°, and a tilt-corrected direction D= 257.3 ± 5.5°; I = −70.3 ± 2.1°.

The Port Waikato samples show very consistent behaviour, with linear decay for both thermal and AF demagnetisation above 180–210 °C and 10–12 mT, respectively (Figure 3E,F). The stable remanent magnetisation component is removed at 480–510 °C or at 60–80 mT. The 48 specimens from Port Waikato yield a mean direction D = 346.2 ± 9.5° and I = −74.1 ± 2.9°, and a tilt-corrected direction D = 61.0 ± 4.9° and I = −54.6 ± 4.0° (Figure 4E,F, Table 2). Four samples are rejected by the 45° cut-off and, again, all samples indicate normal polarity.

All sites have an A95 value between $A95_{min}$ and $A95_{max}$ (Table 2), which suggests that the scatter in the individual datasets can be simply explained by paleosecular variation (Deenen et al. 2011),

Fold test

We performed a fold test for all three localities, following the eigenvector bootstrap approach of Tauxe and Watson (1994) in www.paleomagnetism.org. The eight samples of AG2* that form a separate cluster (Figure 4A,B) are not taken into account in the Awakino Gorge fold test in the absence of significant bedding tilt differences. The remaining Awakino Gorge directions clearly fail the fold test, with highest clustering around 0% unfolding, ranging [−8%, +6%] at the 95% level (Figure 6A).

The fold test performed on Kiritehere samples shows a less straightforward result, and highest clustering is found around an unfolding percentage of 44%, ranging [15–73%] (Figure 6B). This may be the result of remagnetisation during folding, but it may also be the result of a new phase of folding after a first post-folding remagnetisation occurred (Tauxe and Watson 1994). Therefore, the data fail the fold test and tectonically corrected directions for Kiritehere sample sites cannot be used for tectonic analysis.

The Port Waikato samples were all taken at one site at an outcrop with a very constant bedding orientation and consequently a fold test cannot be performed on the directions of the Port Waikato locality.

Discussion

The most striking result from our paleomagnetic analysis is the almost exclusively normal polarity held within samples from all three localities, despite the large stratigraphic age range (c. 209–145 Ma) sampled. During accumulation of Murihiku sediments, many polarity reversals took place (Gradstein et al. 2012). Therefore, the almost complete absence of samples with reversed

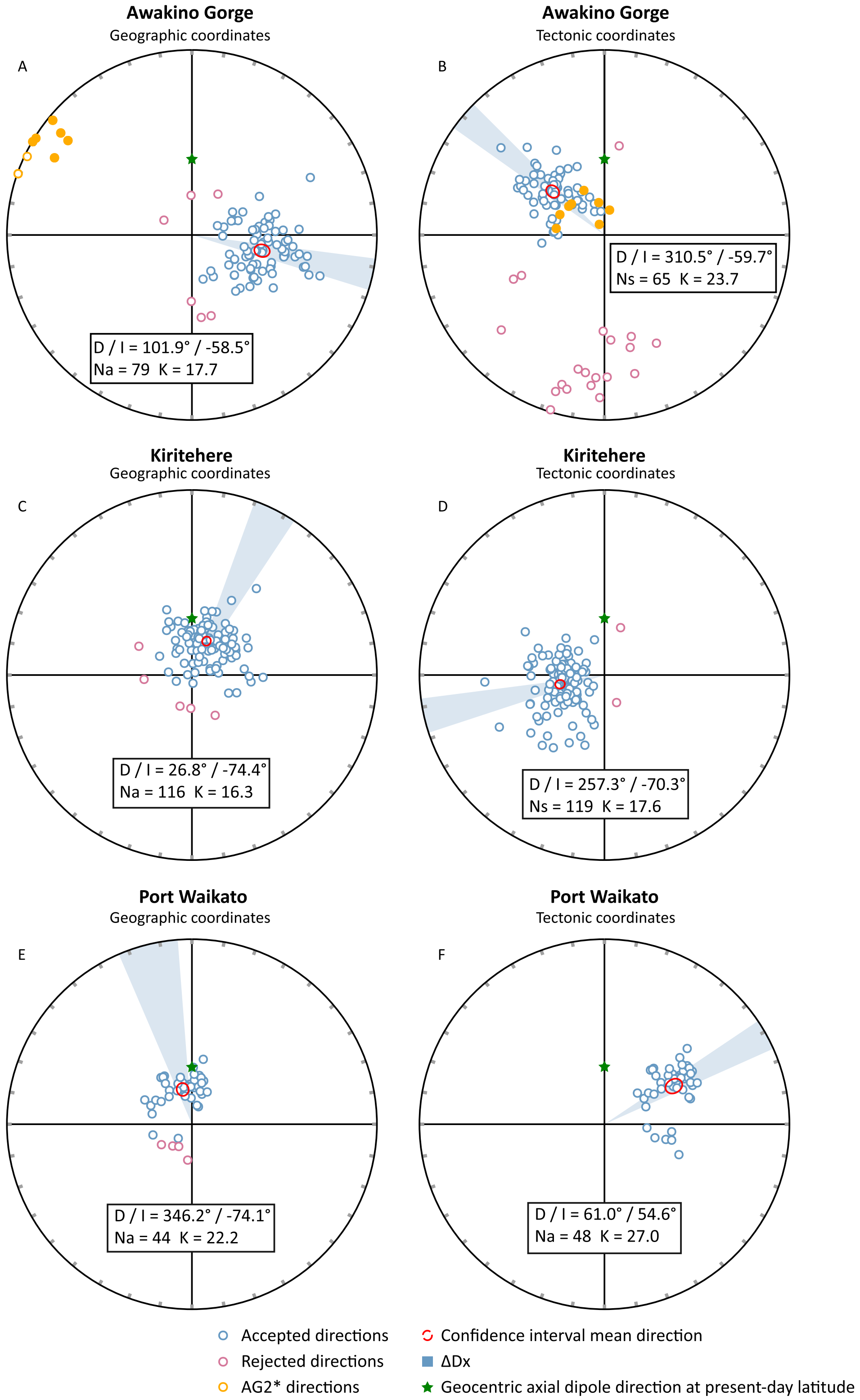

Figure 4. Equal area projections of characteristic remanent magnetisation (ChRM) directions per site. Closed (open) circles indicate lower (upper) hemisphere projection. Boxes give the mean with D/I as declination/inclination, K is the precision parameter of the VGP distribution, Na is the number of accepted samples accepted by the 45° cut-off.

polarity, with the possible exception of AG2*, implies widespread remagnetisation. The negative fold test of Awakino Gorge demonstrates that the remanent magnetisation signal was acquired after folding of the succession. The outcome of the fold test performed on Kiritehere data demonstrates that these samples do not carry their original (or at least pre-folding) magnetisation, but the exact timing of the magnetisation relative to the deformation history is more difficult to assess. Therefore, we conclude that most of the sample host rocks have been remagnetised. As a result, the bulk of our data cannot help constrain the Mesozoic paleolatitude of the Murihiku Terrane. However, as the paleomagnetic directions do not correspond to a recent

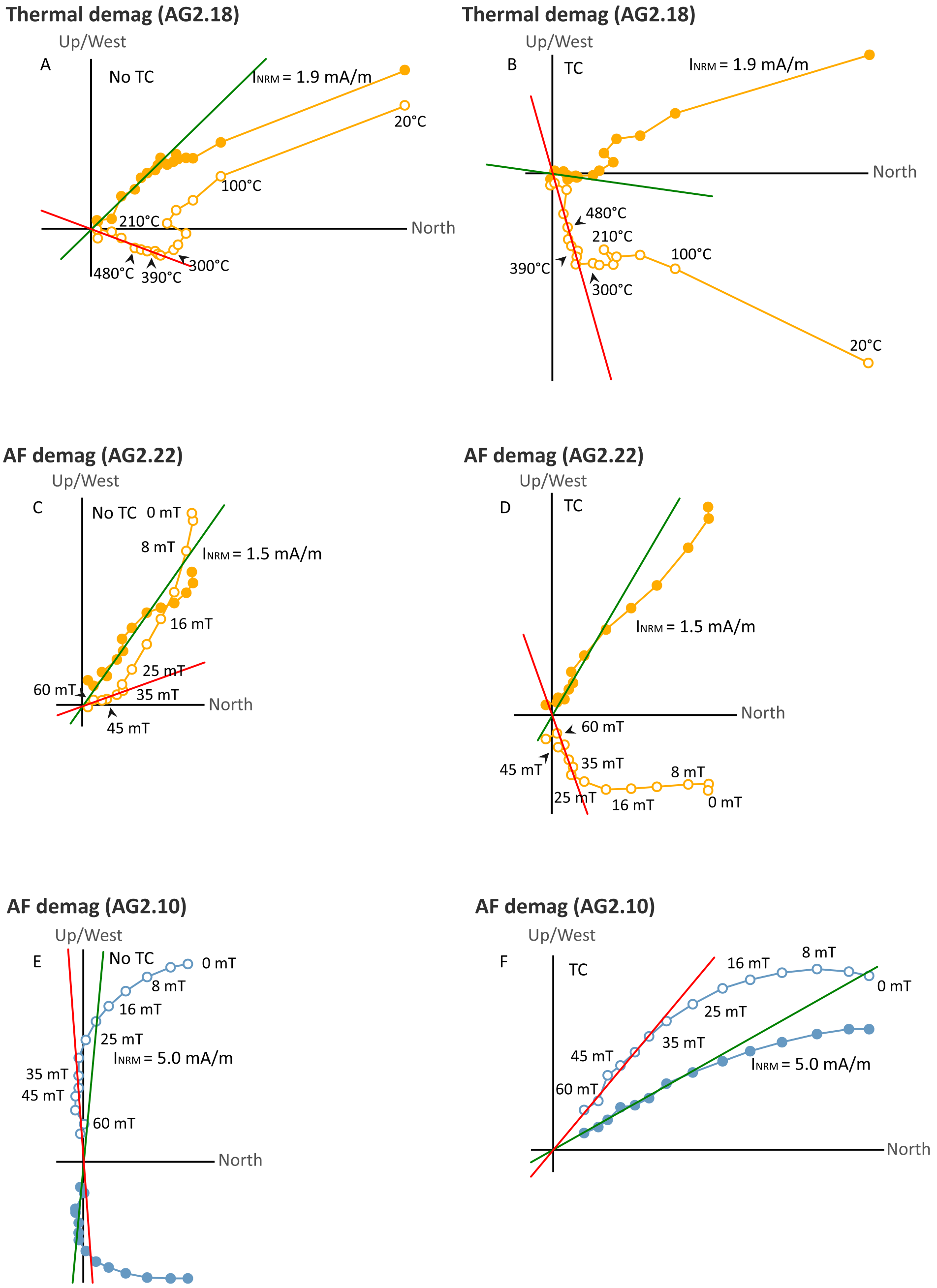

Figure 5. Examples of demagnetisation diagrams in both geographic (no TC, left column) and tectonic (TC, right column) coordinates for samples from sites AG2* (yellow) and AG2 (blue). For symbols, refer to caption to Figure 3.

geocentric axial dipole (GAD) direction (Figure 4), we explore their value in identifying a tectonic signal since remagnetisation. This implies that we need an estimate of the age of remagnetisation. The meaning of the small set of directions in AG2* that show a different paleomagnetic result are also discussed.

Remagnetisation event

The occurrence of widespread remagnetisation in New Zealand has been demonstrated previously by Haston and Luyendyk (1991), Oliver (1994) and Kodama et al. (2007). The age and origin of the remagnetisation event remains unclear, but is of importance for understanding New Zealand's tectonic history. Some suggestions of the age and origin have been made, but none has been conclusive. Haston and Luyendyk (1991) undertook a paleomagnetic study of samples from the Waipapa Terrane and compared their computed paleomagnetic pole (69.7°S, 150.7°E) to a synthetic apparent polar wander path of New Zealand. They concluded that the remagnetisation event most likely occurred between 12 Ma and 58 Ma. They prefer a 25 Ma age of remagnetisation, caused by a major change in the tectonic regime. The change in tectonic regime has been associated with: (i) emplacement of ophiolites across northern Northland Peninsula at that time (Ballance and Spörli 1979), (ii) inception of subduction along the Hikurangi margin (e.g. Cole and Lewis 1981; Kamp 1999) and (iii) initiation of

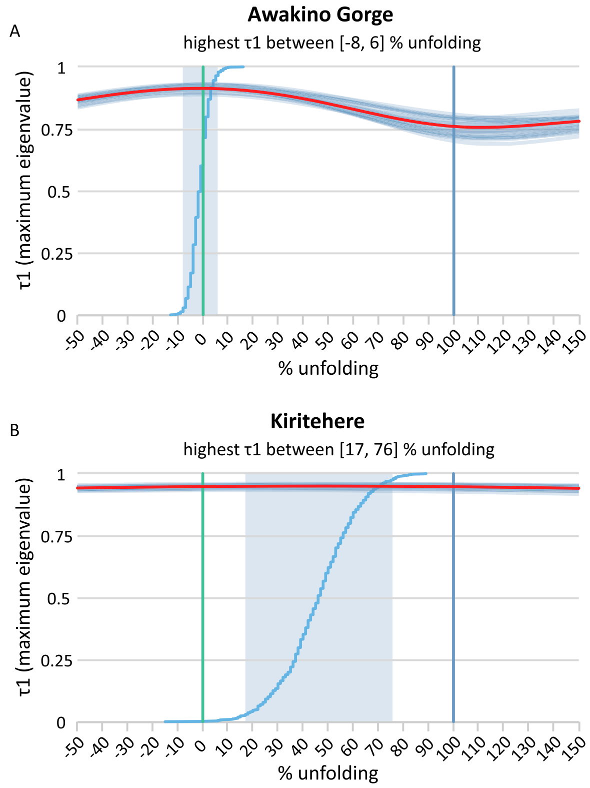

Figure 6. Results of the eigenvector bootstrap (Nb = 1000) fold test according to Tauxe and Watson (1994) performed on the Awakino (A) and Kiritehere (B) data sets. Shaded area shows the cumulative distribution function of the maximum unfolding at the 95% bootstrap confidence level. The first 25 bootstraps are shown.

arc volcanism (e.g. Mortimer et al. 2010). Remagnetisation in the Waipapa Terrane may be due to fluid migration associated with those events. Oliver (1994) undertook a paleomagnetic study of rocks from the Kawhia and Marokopa areas within the Murihiku Terrane north of Kiritehere. He acquired exclusively normal polarity magnetic directions, in agreement with our findings. He obtained a paleomagnetic pole from the remagnetised directions (57.2°S, 163.2°E), which is consistent with the c. 80–90 Ma position predicted by the apparent polar wander path of Australia, as well as a Cretaceous pole determined for Marie Byrd Land (West Antarctica) by Grindley and Oliver (1983). Oliver (1994) thus suggested that remagnetisation took place around 85 Ma, possibly linked to onset of Tasman Sea spreading around that time (Weissel et al. 1977; Weissel and Hayes 1977; Gaina et al. 1998). Kodama et al. (2007) concluded that remagnetisation must have occurred no later than Late Paleocene–Eocene, since they argued for a primary magnetic signal in Late Paleocene–Eocene sedimentary rocks in Kaiwhata Stream.

The timing of folding of the Kawhia syncline and its parasitic smaller-scale folds, has been constrained from thermal history modelling of apatite fission track data obtained from samples collected from the Port Waikato area (Kamp and Liddell 2000). These data indicate cooling of 110–120 °C along the eastern limb of the syncline by c. 100 Ma, indicating that folding occurred during the early Cretaceous.

Furthermore, the remagnetisation of strata within the Kawhia syncline probably occurred before uplift and erosion of the Kawhia syncline succession, which accompanied or followed deformation of the succession. This can be reasoned from the requirement that remagnetisation is thought to require burial temperatures higher than those in the near subsurface following the bulk of the erosion. The timing of uplift and erosion of Murihiku Terrane is constrained stratigraphically to lie between: (i) the latest Jurassic, which is the age of the Huriwai Group, forming the youngest strata involved in the syncline and hence giving a maximum age when peak burial heating was experienced by the strata; and (ii) the Late Eocene, which is the age of the overlying Te Kuiti Group (Nelson 1978; Edbrooke 2005; Kamp et al. 2014). From this, we conclude that remagnetisation most probably occurred after 100 Ma and before 40 Ma.

We confined the estimated age of remagnetisation further by plotting our obtained geomagnetic directions on the apparent polar wander path of New Zealand. To this end, we calculated the Global Apparent Polar Wander Path of Torsvik et al. (2012) in the coordinates of New Zealand north of the Alpine Fault (northern Zealandia), using the Euler rotations provided in the plate reconstruction of Müller et al. (2016). We used the thereto designed tool at www.paleomagnetism.org as described in Li et al. (2017). Comparison between the paleolatitudes of reference location (38.359°S, 174.802°E) calculated from the directions in geographic coordinates for both Port Waikato and Kiritehere and the predicted Apparent Polar Wander Path for northern Zealandia, suggests an age of remagnetisation of 80 ± 8 Ma (Figure 7, black bar on horizontal axis). Because all our samples carry a normal polarity signal, resetting of the magnetic signal must have taken place during a normal polarity interval. Based on the 80 ± 8 Ma fit, remagnetisation then likely occurred during the Cretaceous Normal Superchron (126–83.6 Ma), or possibly during younger chrons such as 33n (79.9–74.3 Ma) (Gradstein et al. 2012). Because of its shallower inclination (I = −58.2°) compared with our other sites, the corresponding paleolatitude of Awakino Gorge differs considerably from those of Port Waikato and Kiritehere, and would be close to the present-day latitude of New Zealand (Figure 7). This could indicate that the remagnetisation is a relatively young (Eocene) to very recent field overprint. However, if the samples of Awakino Gorge were overprinted by a recent field, a declination of 0° would be expected, which is not observed (Figure 4). We consider a possible explanation for this discrepancy below.

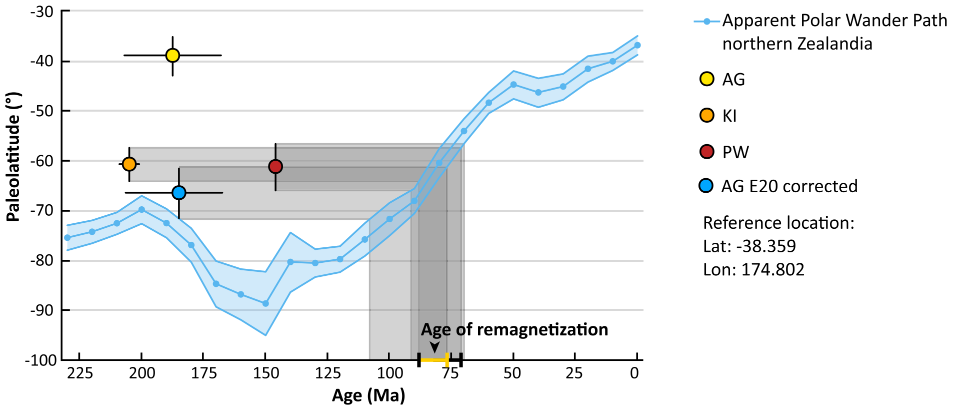

Figure 7. Diagram of the paleolatitudes (geographic coordinates) of sampling localities AG, KI, PW and the AG locality corrected for a 20° dip towards the east vs. the Apparent Polar Wander Path (APWP) of northern Zealandia. From the uncertainties in paleolatitude we deduce an age of remagnetisation of c. 83 ± 5 Ma. The paleolatitude of Awakino Gorge significantly deviates from the paleolatitudes of Kiritehere and Port Waikato, but becomes very similar after the E-dip correction.

We note that an c. 80 Ma age of remagnetisation coincides with the early stages of seafloor spreading in the Tasman Sea (Gaina et al. 1998), as previously noted by Oliver (1994). Additionally, remagnetisation may be related to the end of subduction along the Gondwana margin of New Zealand. The timing of the end of subduction is subject to debate and is generally thought to have occurred around 105–100 Ma (Bradshaw 1989; Luyendyk 1995; Davy et al. 2008; Matthews et al. 2012), but ages around 85 Ma have been proposed (Mazengarb and Harris 1994; Kamp and Liddell 2000; Vry et al. 2004), for example based on zircon fission track analysis of the youngest rocks in the toe of the Torlesse Complex (Kamp 1999, 2000).

Post-remagnetisation tectonics affecting the Awakino Gorge area?

Given the evidence above for pervasive and widespread remagnetisation in the Kawhia syncline, as well as by previous studies in the North Island and Marlborough, South Island (Haston and Luyendyk 1991; Oliver 1994; Kodama et al. 2007), it is remarkable that *in situ* directions for samples from Awakino Gorge differ significantly from those obtained from the Port Waikato and Kiritehere sections. As we have already identified, if the *in situ* direction in AG samples is an overprint direction, it must have been acquired sometime between the Eocene and present day (Figure 7). This is very unlikely, however, given the large difference of > 100° between the GAD declination and the declination observed at Awakino Gorge (Figure 4). We therefore seek an alternative explanation for the lower inclination and the declination of Awakino Gorge data.

An inferred Late Cretaceous overprint would yield an observed inclination of around −74° at the reference location (38.359°S, 174.802°E), identical within error to the values reported here for the Port Waikato and Kiritehere sample sites (Table 2). Because the average observed inclination for the Awakino Gorge samples is −58.2 ± 3.6°, the sample host strata have been subject to inclination lowering of c. 15°.

The western limb of the syncline in the Awakino Gorge area has been accentuated by Late Oligocene and Early Miocene reverse displacement on the Manganui Fault (Kamp et al. 2004). Because this fault lies to the west of the Awakino Gorge paleomagnetic sampling sites, it probably increased the eastward dip of the beds we sampled by 20° as they lie in the hanging wall of the fault. This post-remagnetisation deformation may have contributed to the inclination shallowing of the magnetisation in these rocks compared with those at the Kiritehere and Port Waikato sample sites.

Because the 20° eastward tilting occurred after remagnetisation, we have to apply a 000/20 bedding tilt correction to our data from Awakino Gorge. This leads to I = −77 ± 2.9° and D = 121.0 ± 12.0° (for full parameters see Table 2). The newly obtained inclination is far more consistent with the data of Kiritehere and Port Waikato. We can now also use the Awakino Gorge data to obtain the age of remagnetisation, which is now constrained to 83 ± 5 Ma (Figure 7, yellow bar on horizontal axis).

Rotation of Murihiku Terrane

Another interesting feature is that the declination of the Kiritehere data set corresponds well to the 80 Ma declination of New Zealand, whereas the declinations of both Port Waikato and Awakino Gorge deviate (Figure 8). This suggests that parts of Murihiku Terrane have been rotated since the widespread remagnetisation. Because our Kiritehere data record a

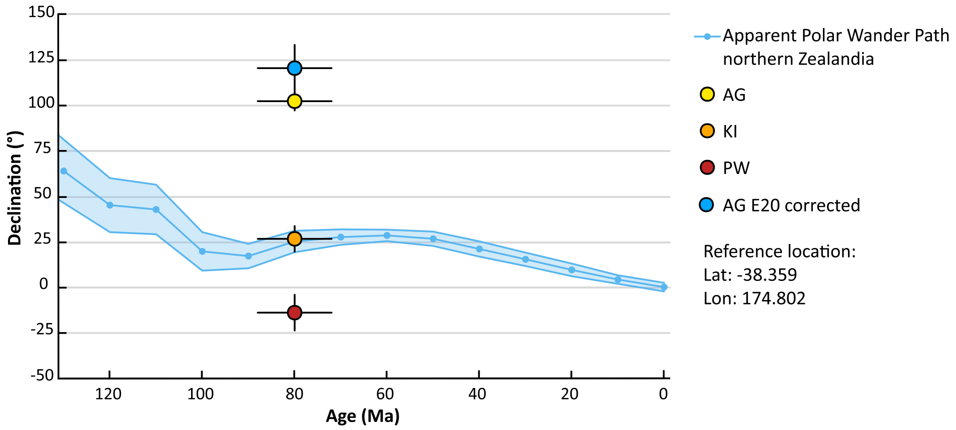

Figure 8. Diagram of declinations (geographic coordinates) of our sampling sites and the Apparent Polar Wander Path (APWP) of northern Zealandia. The declination of Kiritehere fits well with our inferred age of remagnetisation of 83 ± 5 Ma, but declinations of Port Waikato and Awakino Gorge deviate, indicating respectively 39.4 ± 9.5° counterclockwise and 77.3 ± 5.0° (uncorrected for 20° eastward dip) and 95.8 ± 12.0° (corrected for 20° eastward dip) clockwise rotations for these areas.

declination very similar to the declination of New Zealand at 80 Ma, it suggests that this part of the Murihiku Terrane has not been rotated relative to New Zealand since remagnetisation. Other paleomagnetic studies of Murihiku Terrane strata in the Kawhia area north of Kiritehere also suggested that the Murihiku Terrane did not experience significant amounts of vertical axis rotation since remagnetisation (Oliver 1994; Kodama et al. 2007) (Figure 9).

By contrast, our results suggest that the basement in Awakino Gorge rotated about 77.3 ± 5.0° clockwise, whereas the basement in the Port Waikato area has rotated c. 39.4 ± 9.5° counterclockwise since remagnetisation (Figure 9). After correcting the site data from Awakino Gorge for the 20° eastward dip, the rotation of the basement succession in Awakino Gorge increases to c. 95.8 ± 12.0°.

Previous paleomagnetic studies do indicate large-scale Neogene clockwise rotation along the Hikurangi margin, related to deformation considered to be associated with active subduction to the east of New Zealand (Wright and Walcott 1986; Rowan et al. 2005; Lamb 2011). These rotations may have affected the southern part of the Murihiku Terrane (i.e. Awakino Gorge) as well. However, previous paleomagnetic studies carried out on Oligocene calcareous siltstone (Whaingaroa Formation) exposed at the entrance to Bexley Station in Awakino Gorge (Lamb 2011, figure 4), record clockwise rotations up to 30° that had ceased by the Early Miocene (Mumme and Walcott 1985, cited in Lamb 2011). No paleomagnetic evidence exists for later rotations in this area.

We propose that rotation of the Murihiku Terrane in the Kawhia syncline is not directly related to modern Australia–Pacific plate boundary zone deformation. Clockwise rotation in the Awakino Gorge area is thought to have ceased before the c. 30–25 Ma inception of the Alpine Fault (Kamp 1986; Lamb 2011), and it would also fail to explain the counterclockwise rotation at Port Waikato. We suggest that the observed rotation may have been related to Cretaceous bending of basement terranes expressed in the New Zealand orocline, the origin of which remains unknown. The timing of bending is also subject to debate. Essentially, there are three scenarios regarding the age of the New

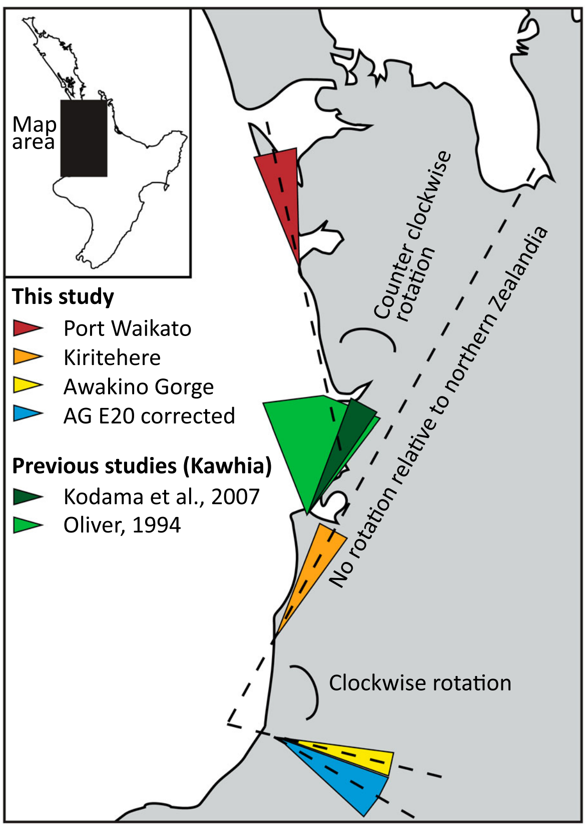

Figure 9. Map showing declinations of our sites and those of Oliver (1994) and Kodama et al. (2007) with respective confidence parashutes (ΔD_x). Declinations of Oliver (1994) and Kodama et al. (2007) have been acquired by recalculating their published data using www.paleomagnetism.org

Zealand orocline (Bradshaw et al. 1996, see also Lamb et al. 2016): (i) oroclinal bending is older than Late Cretaceous; (ii) large-scale bending occurred exclusively during the Cenozoic; and (iii) the basement terranes of New Zealand were partially bent before the Cenozoic, but a substantial amount of rotation occurred during the Cenozoic.

Our results suggest that considerable rotation occurred since the Late Cretaceous (83 ± 5 Ma), which would argue against the first option given above. Because we cannot rule out the possibility of partially bent terranes before c. 83 Ma, suggestions (ii) and (iii) are both considered possible. There is no paleomagnetic evidence for any rotations that occurred in this area since the Miocene, therefore the bulk of bending occurred between 83 ± 5 Ma and c. 20 Ma.

The rotation of Port Waikato with respect to Kiritehere is fairly consistent with the overall strike of the Kawhia syncline. The difference in the general strike of the Kawhia syncline at Kiriterere (c. 10°) and Port Waikato (c. 335°) is c. 35° (see Figure 1, based on eastern limb), which corresponds well to our inferred rotation (c. 40°). However, the large rotation of the basement succession in Awakino Gorge with respect to Kiritehere cannot be explained in the same way. Therefore, a substantial part of the rotation at Awakino Gorge must be a local phenomenon. At this point we cannot explain the origin of the rotation at Awakino Gorge, but our data clearly indicate its occurrence.

Additional paleomagnetic studies can usefully be carried out to place tighter constraints on the origin and timing of rotation of the Murihiku Terrane in the Kawhia syncline, and the possible relation to bending of basement terranes. Comparing the amount of rotation predicted from the declination of Cenozoic rocks from the Port Waikato and Awakino Gorge areas with the declinations of this study allows estimation of the timing of rotation. When the age of rotation is more tightly constrained, a hypothesis can be formulated about the origin of rotation in sample host rocks in both the Awakino Gorge and Port Waikato areas, and the possible relation to bending of the basement terranes can be investigated more completely. Importantly, our study shows that remagnetised Murihiku Terrane sedimentary rocks widely exposed in the central–western North Island, are excellent recorders of a Cretaceous paleomagnetic field yet to be completely defined, but which can nevertheless be used to deduce post-Late Cretaceous regional vertical axis rotation and horizontal-axis tilt histories.

A primary, Jurassic magnetisation at Awakino Gorge?

As mentioned previously, eight samples collected from site AG2 (Early Jurassic, Toarcian age, 181–176 Ma) in Awakino Gorge record a magnetic component that is distinct from all other samples. This is a high-temperature component that provides an *in situ* inclination of only 5.8°. If acquired after bedding tilt, as with the regional ChRM interpreted from all other samples, this would require a latitude of magnetisation close to the equator. However, New Zealand has not been close to the equator since the Toarcian. Rather, it was located very close to the South Pole. It is therefore highly unlikely that these samples acquired their magnetisation after tilting.

We therefore tentatively assume that these samples have retained their pre-tilt magnetisation and escaped complete remagnetisation. We thus correct the AG2* directions for bedding tilt to obtain the original inclination. This gives a direction D = 316 ± 27.0° and I = 74.9 ± 7.5° (Figure 4, Table 2). This would imply that Murihiku Basin was located at a paleolatitude of 61.6°N during the Toarcian, which is not possible. Therefore, we assume that these rocks record a reversed magnetic signal and that the Murihiku forearc basin was located at 61.6 ± 12°S during the Toarcian.

Because we previously inferred that Awakino Gorge has been subject to a Late Oligocene to Early Miocene 20° tilt, we have to apply an additional bedding tilt correction. The corrected geomagnetic directions are D = 308.3 ± 27.6° and I = 75.2 ± 7.5°, corresponding to a paleolatitude of 62.1 ± 12°S (Table 2).

This paleolatitude is in agreement with that of Grindley et al. (1980), which is the only other paleomagnetic study that may have found a paleolatitude from a primary magnetic signal of Murihiku Terrane rocks. They obtained a paleolatitude of 66°S for the Glenham Porphyry of Early Jurassic (c. 190 Ma) age in the Southland syncline part of the Murihiku Terrane. Both studies therefore imply that the Murihiku Terrane was located in the vicinity of the New Zealand sector of the eastern Gondwana margin during sediment accumulation.

When compared with the apparent polar wander path of northern Zealandia, our calculated paleolatitude is located within c. 20° expected for Zealandia in the Toarcian (Figure 10). This would thus provide a first-order estimate that the intra-oceanic arc to which the Murihiku forearc basin was paired, was probably located within 1000–2000 km, but possibly up to 3500 km, north of the contemporary Gondwana margin (Figure 11).

The similarity in paleolatitude from our small data-set and the one of Grindley et al. (1980) is promising, but the results of both studies are subject to uncertainties. The findings of Grindley et al. (1980) have been called doubtful due to uncertainty in tilt-corrections for volcanic rocks (Kodama et al. 2007), while our data set is very small and lacks independent field tests. Therefore, we emphasise the tentative nature of our interpretation, and a larger data set is needed to

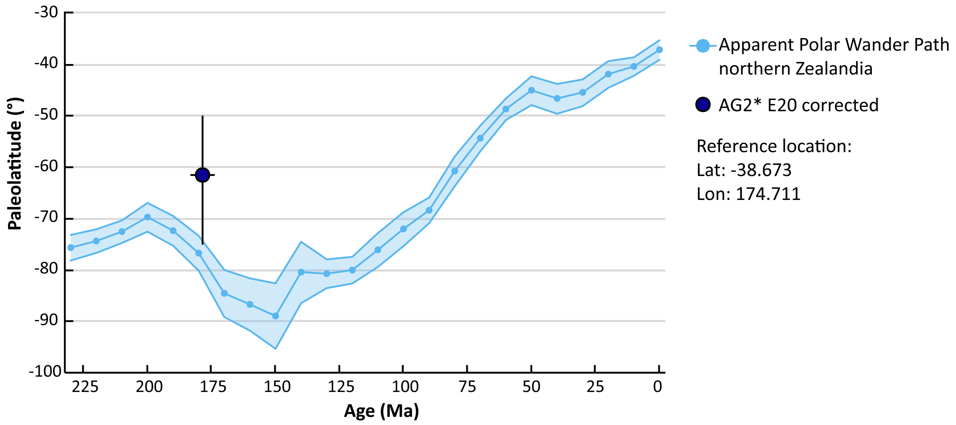

Figure 10. Apparent Polar Wander Path (APWP) of northern Zealandia and the paleolatitude of site AG2*, first corrected for the eastward dip of 20° (plunge correction), and subsequently tilt corrected with the plunge corrected bedding plane.

put better constraints on the original paleolatitude of the Murihiku forearc basin.

Finding the original signal has proven to be extremely difficult due to the widespread magnetic overprint. Nevertheless, our data show that such an effort is not futile and provides a lead to identify primary magnetisations in Murihiku rocks. It would be worthwhile to carry out extensive sampling of the rock succession exposed in Awakino Gorge and in Glenham Porphyry to increase the data set and quantitatively constrain the Mesozoic plate kinematic history of the Gondwana margin and adjacent intra-oceanic arcs of New Zealand.

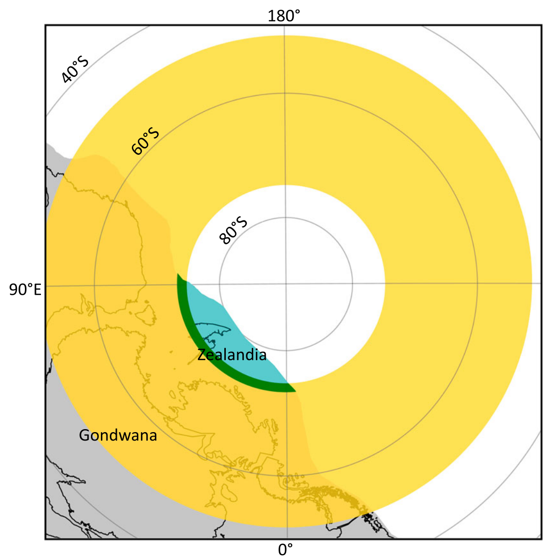

Figure 11. Map showing the possible locations (yellow disc, latitudes 50°S–75°S) of the Murihiku forearc basin based on site AG2* (reference location 38.373°S, 174.711°E). The grey area is the position of Gondwana based on the reconstruction of Müller et al. (2016) in the paleomagnetic reference frame of Torsvik et al. (2012). Present-day coastlines are for reference only. The blue zone indicates the uncertainty of the position of northern Zealandia within Gondwana. The overlap between the paleolatitude belt and the blue zone (green belt) indicates the possible locations of Murihiku forearc basin if it was part of the Gondwana margin.

Conclusions

To aid kinematic restoration of the Mesozoic and Cenozoic plate tectonic and orogenic history of part of New Zealand, we performed a paleomagnetic study on rocks from the Upper Triassic to Lower Jurassic of the Murihiku forearc basin in the central–western North Island, New Zealand. Our results confirm previous interpretations of widespread pervasive remagnetisation throughout the North Island in the form of exclusively normal polarities – despite accumulation of the rocks during times of high reversal frequency – and negative fold tests. We show demagnetisation results for 248 samples from three localities at Awakino Gorge, Port Waikato, and Kiritehere Beach. The latter two record similar *in situ* inclinations of c. −74°, corresponding to a latitude of 61°S during post-tilt remagnetisation. Based on comparison of the expected paleolatitude of these samples with the apparent polar wander path of New Zealand, we estimate remagnetisation to have occurred around 83 ± 5 Ma.

We show that remagnetised directions in Murihiku Terrane sediments provide an excellent datum for post-remagnetisation studies of regional tilt and vertical axis rotation. We show that the lower inclinations in Awakino Gorge paleomagnetic data compared with data for the more northern sample localities are consistent with a regional eastward tilt of c. 20° as a result of reverse displacement on Manganui Fault.

The Murihiku Terrane has, in addition, been subjected to significant rotation since remagnetisation. Port Waikato has been rotated 39.4 ± 9.5° counterclockwise and Awakino Gorge has been rotated 77.3 ± 5.0° clockwise (95.8 ± 12.0° when corrected for eastward tilt), whereas Kiritehere rocks have remained stable with respect to Zealandia. We suggest that these rotations can be used to reconstruct the tectonic bending of basement terranes, which must have occurred, at least in part, after the remagnetisation event estimated at 83 ± 5 Ma.

Only 8 of the 93 demagnetised Awakino Gorge samples, all at the Awakino Gorge 2 site, retain a high-temperature, high-coercivity magnetic component that may represent a primary magnetisation. *In situ* inclinations of only 5° would require equatorial latitudes of magnetisation, which is not possible considering plate reconstruction constraints. A primary magnetisation cannot be confirmed by independent field tests, but pre-bedding tilt directions of these eight samples suggest a paleolatitude for Murihiku Terrane of 62.1 ± 12°S during the Early Jurassic (Toarcian), c. 15° north of the New Zealand sector of the contemporary eastern Gondwana Margin.

Disclosure statement

No potential conflict of interest was reported by the authors.

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