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RESEARCH ARTICLE

Quaternary sedimentology and tephrostratigraphy of the lower Pohangina Valley, New Zealand

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ABSTRACT
Shallow-marine to fluvio-estuarine deposits in Pohangina Valley represent an underexplored portion of the Whanganui Basin, a globally significant archive of Quaternary climate change. To address this, we document environments of deposition through facies analysis, tephrostratigraphy and biostratigraphy. The marine shelf environment is characterised by fossiliferous mudstone containing marine Mollusca. Estuarine facies consist of pumiceous sandstone, tephra, lignite and carbonaceous mudstone. Volcaniclastic and tephra-fall deposits record seven eruptions from the Taupo Volcanic Zone between c. 1.6 and 0.9 Ma. We identify and define Awahou Tephra (new) (c. 1.03 Ma), through mapping and geochemical analysis of constituent glass shards. Progressive retreat of the sea (c. 1.6 Ma) is indicated by a change from shallow-marine to fluvio-estuarine sedimentation. An east–west drainage system developed (c. 1 Ma), including ponding near Woodville from which an early ancestor of the Manawatu River exited, establishing an antecedent path to the Tasman Sea across the uplifting paleo-axial range.

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Introduction

Whanganui Basin (WB) in the lower North Island of New Zealand (Figure 1) provides one of the most complete sedimentary records of Quaternary climate change, exposed onland, anywhere in the world (Carter and Naish 1998; Pillans 2017). Dominantly shallow marine to innermost shelf sediments deposited throughout orbitally forced eustatic sea level cycles occur as sedimentary packages bound by unconformities, representing sub-aerial exposure and erosion during sea level low stands (Naish et al. 1998; Carter et al. 2014). Less common preservation of incised valley fill and coastal plain facies has occurred intermittently throughout WB history, particularly within the eastern basin toward the actively uplifting main axial range. Marginal marine to coastal plain facies of the WB present relatively unexplored archives of volcanic and environmental signals (Mildenhall 1975; Bussell 1984, 1986, 1992; Bussell and Mildenhall 1990; Naish et al. 2005; Pillans et al. 2005).

Research interest, driven by the early recognition of cyclothems along the coastal type section near Whanganui city (Fleming 1953) has led to a concentration of studies within the central (Seward 1976; Thompson 1982; Ker 1991; Journeaux 1995; Naish and Kamp 1995; Van Der Neut 1996; Turner et al. 2005; Grant et al. 2018) and western basin (Beu and Edwards 1984; Carter et al. 1991, 2014; Abbott 1994, 1997, 2000; Abbott and Carter 1994, 1999; Abbott et al. 2005; Naish et al. 2005). As a result, relatively few studies have focused on the eastern basin succession (Rich 1959; Milne 1968; Carter 1972; Browne 1978; Rees et al. 2018b). This has led to a knowledge gap concerning the nature of the sedimentary deposits adjacent to the main axial range within eastern WB, deposits that record a story of the tectonic, volcanic and paleogeographic evolution of the lower North Island. We address this knowledge gap through description and interpretation of a Quaternary shallow marine to fluvio-estuarine succession preserved in the lower Pohangina Valley, Manawatu (Figure 1) exposed by present-day tributaries of the Pohangina River.

Our approach focuses on facies analysis and geological mapping of the local succession, providing evidence of estuarine sedimentation including lignite and carbonaceous mudstone with shellbeds consisting entirely of small, stunted *Austrovenus stutchburyi* (estuarine cockle). Castlecliffian strata of the lower Pohangina Valley represent only the upper transgression and peak highstand of the sea level curve, due to deposition on the basins far eastern margin where subaerial exposure occurred for a majority of each cycle. We apply tephrostratigraphy, correlating the succession using a series of seven tephra-fall and/or volcaniclastic deposits to the well-documented WB chronostratigraphic framework developed over the

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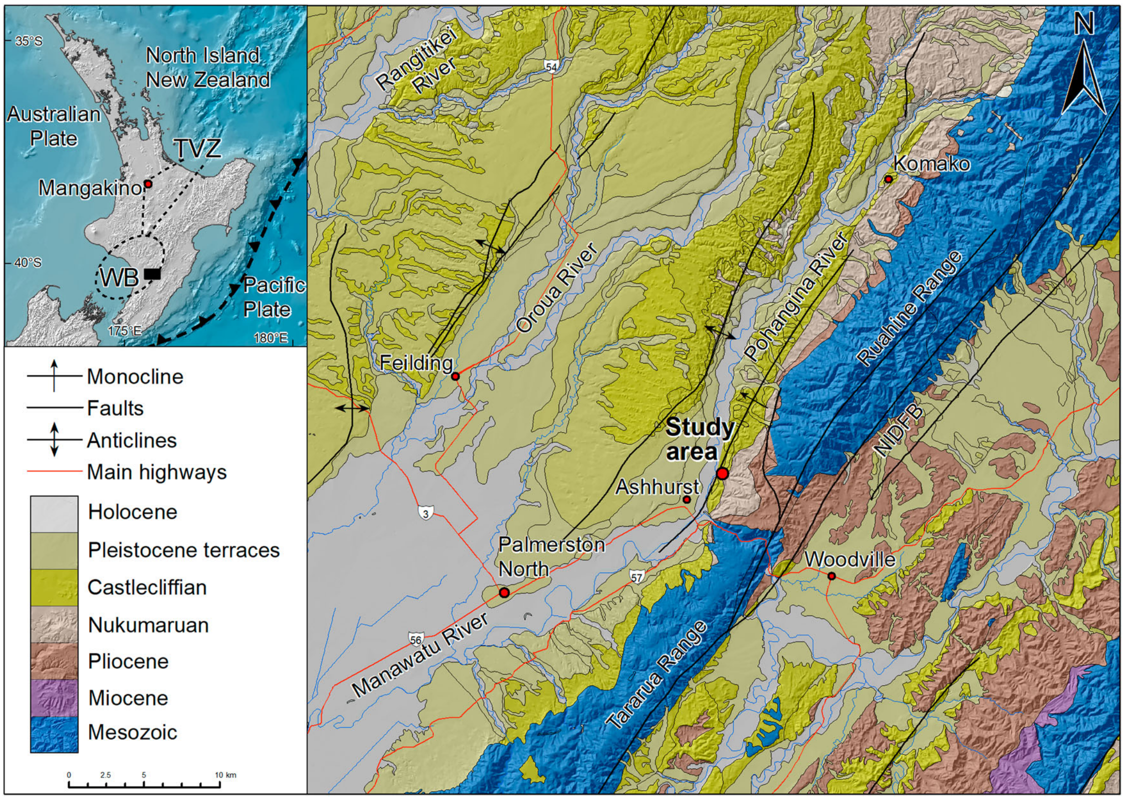

Figure 1. Map displaying the location of the study area near Ashhurst, 20 km northeast of Palmerston North. Simplified geological units and structures are adapted from the QMAP 1:250 000 database licensed under the Creative Commons Attribution 3.0. Inset displays location of the Whanganui Basin (WB) in relation to the Taupo Volcanic Zone (TVZ), a major provenance for the Pleistocene to Holocene WB fill. NIDFB = North Island Dextral Fault Belt.

past 100+ years (Feldmeyer et al. 1943; Te Punga 1952; Fleming 1953; Seward 1974b; Beu and Edwards 1984; Abbott 1994; Naish and Kamp 1995; Saul et al. 1999; Naish et al. 2005; Pillans et al. 2005). A new tephra, the Awahou Tephra (c. 1.03 Ma) is defined through stratigraphy, geological mapping and major element analyses of constituent glass shards, including designation of a type section in the lower Pohangina Valley.

The study area (Figure 1) located 25 km northeast of Palmerston North City, contains an important Quaternary sedimentary record, resting unconformably above Pliocene mudstone and Mesozoic basement rock of the Torlesse Composite Terrane. During the Early Quaternary, marine basins existed on both sides of the modern day main axial range, connected by marine seaways (Beu et al. 1981; Browne 1986, 2004; Rees et al. 2018a). A majority of the uplift in the main axial ranges has occurred over the last 1 Ma (Beu et al. 1981; Shane 1991), resulting in piercement of the overlying marine basin fill, and formation of the present day topography. Progressive retreat of the sea at c. 1.6 Ma is indicated in the present study area by a change from shallow marine sedimentation to intermittent influxes of volcaniclastics within fluvio-estuarine environments. East–west drainage developed c. 1 Ma, including ponding near Woodville from which an early ancestor of the Manawatu River exited, establishing an antecedent path to the Tasman Sea across the uplifting paleo-axial range.

Nomenclature

In this paper, we use the word tephra for all unconsolidated pyroclastic deposits irrespective of their origin or nature of emplacement, as defined by Thorarinsson (1974), Howorth (1975), Schmid (1981), Froggatt and Lowe (1990), Lowe (2011) and Lowe et al. (2017). Following the definition of tephra as primary volcanic material by Thorarinsson (1954), we do not use the term 'tephra' for epiclastic sediments dominated by volcanic detritus. Such volcaniclastic units are common in the Pleistocene succession of the WB and we follow recommendations by Schmid (1981) and Froggatt and Lowe (1990) in our terminology, describing such units as 'tephric'. The original stratigraphic names 'Potaka Pumice' and 'Pakihikura Pumice' set out by Te Punga (1952) are retained here in preference to other terms used to encompass a variety of reworked tephric silts, sands and pumice. Due to the frequent incidence of a particular formation containing both a tephra-fall and volcaniclastic deposit characterised by identical glass chemistry, we suggest they are ascribed member status. For instance, we propose that the Rewa Formation contains a Rewa Tephra Member and Rewa Volcaniclastic Member. Given the well-established correlation between Potaka Pumice and the c. 1 Ma Kidnappers ignimbrite from the Mangakino Volcanic Centre (Wilson, Houghton, Kamp, et al. 1995, 2009; Carter et al. 2004; Cooper et al. 2012, 2016, 2017; Shane 2017), the terms 'Kidnappers' and 'Potaka Pumice' are now used interchangeably in the literature. This paper uses the spelling 'Whanganui' rather than 'Wanganui' as recommended by the New Zealand Geographic Board (Ngā Pou Taunaha o Aotearoa).

Geological setting

Whanganui Basin

The WB (Figure 1) contains c. 4500 m of marginal to shallow marine sedimentary deposits, providing a rich archive of environmental change throughout the Quaternary Period (Anderton 1981; Pillans 1994). The basin, located 200 km west of the Hikurangi Trough, formed through a combination of lithospheric loading and compressional downwarping driven by coupling of the Pacific and Australian plates (Davey 1977; Stern et al. 1993; Pillans 2017) (Figure 1). Southward migration of the depocentre through the Plio-Pleistocene at the same time as uplift along the northern and eastern basin margins has resulted in excellent on-land exposure of the gently dipping marine succession (Anderton 1981; Pillans 2017). The basin records eustatic sea-level fluctuations, volcanic events, and phases of regional subsidence and uplift related to the paleogeographic development of the lower North Island (Pillans 1994; Proust et al. 2005).

The Pleistocene succession of the WB is characterised by siliciclastic to bioclastic sediments deposited within coastal plain, shoreface and shelf environments during climatically controlled sea-level cycles (Abbott 1998; Carter and Naish 1998; Abbott and Carter 1999). The cyclothemic strata exposed along the Whanganui coastal section documented by Fleming (1953) and Abbott (1994) among others (Saul et al. 1999; Naish et al. 2005) were deposited within the late rise, high stand and early fall of sea level, with low stand periods characterised by erosional surfaces formed during subaerial exposure of the continental shelf (Naish et al. 1998). Some WB sequences, particularly within the eastern basin sector, contain regressive and low stand subaerial surfaces including soils, lignite layers and coastal plain facies (Abbott 1998).

Fluvio-estuarine facies within WB coastal plain settings are conducive to the preservation of organic matter and volcanic products, evidenced by abundant lignite, leaf, wood, fossil and frequent tephra layers (Te Punga 1952; Milne 1968; Brackley 1999; Rees et al. 2018b). Spatio-temporal changes in both depositional style and extent of preservation become evident within the WB succession between the coastal type section near Whanganui and the present day axial range (Fleming 1953). A particularly long-lived 500 ka unconformity at the base of the Butlers Shell Conglomerate, along the Whanganui coast, is not present to the same extent within the eastern WB succession, replaced by a more complete volcaniclastic record (Abbott 1994; Pillans et al. 2005). The eastern WB succession has only been lightly explored and presents difficulties in correlation to the central and western basin succession due to deposition at a basin margin characterised by frequent subaerial exposure and erosion (Naish et al. 2005).

Taupo Volcanic Zone

Rhyolitic volcanism is thought to have begun in the Taupo Volcanic Zone (TVZ) at around 1.6 Ma (Houghton et al. 1995; Pillans et al. 2005; Wilson et al. 2009). Since c. 1.6 Ma at least 34 ignimbrite sheets have been erupted during explosive volcanic events, resulting in large influxes of volcaniclastic sediments into peripheral sedimentary basins (Wilson et al. 1984; Alloway et al. 2005). Initial volcanic activity originated from the Mangakino caldera (Figure 1), during two periods of caldera forming activity from 1.68–1.53 to 1.21–0.95 Ma (Briggs et al. 1993; Houghton et al. 1995; Krippner et al. 1998). Voluminous widespread welded and non-welded ignimbrites and tephra-fall deposits originating from the Mangakino Volcanic Centre provided an important source of sediment to the WB during Castlecliffian time (Shane 1993; Shane, Alloway, et al. 1996; Rees et al. 2018b).

Each influx of geochemically discrete tephra-fall and/or volcaniclastic sediment into the succession has been used to aid in development of the WB chronostratigraphic framework, providing extremely useful horizons for field mapping (Feldmeyer et al. 1943; Te Punga 1952; Seward 1974b; Pillans et al. 2005). Tephrostratigraphy augments biostratigraphic and magnetostratigraphic records to provide accurate correlation and dating of the basin succession (Pillans 1994; Turner et al. 2005; Beu 2012).

Pohangina geology

The geology of the Pohangina Valley is characterised by a Pliocene to Holocene sedimentary succession unconformably overlying Torlesse Composite Terrane basement of Mesozoic age. The main axial range, a geologically young piercement structure that has undergone a majority of its uplift over the last 1 Ma, is bound by major regional structures trending approximately NE-SW that act to deform the unconformably overlying Plio-Holocene succession into a sharp monocline (Beu et al. 1981; Shane 1991; Trewick and Bland 2012; Rees et al. 2018b). The geology of the area has been documented in stratigraphic studies by Ower (1943), Rich (1959), Piyasin (1966), Carter (1972), Finlayson (1980), Marden (1984), Beanland (1995), Brackley (1999), Milner (2017) and Rees et al. (2018b). The Plio-Holocene sediments of the Pohangina Valley have been subdivided into the Komako, Konewa and Takapari formations, in order of decreasing age (Carter 1972). A key feature of the younger Takapari Formation is the episodic occurrence of volcaniclastic deposits that have been fluvially transported into coastal plain to shallow marine environments following voluminous volcanic eruptions originating from the TVZ. At this time the direction of fluvial transport to the area was to the south to southeast, as evidenced by the paleo-current work of Brackley (1999).

Methods

We compiled a 1:30 000 geological map of the Lower Pohangina Valley correlating work by Carter (1972) in the Komako District to other stratigraphic studies in the wider WB (Te Punga 1952; Fleming 1953; Rich 1959; Milne 1968; Pillans et al. 2005). Mapping benefited from the work of Feldmeyer et al. (1943), Seward (1976), Pillans (1991, 1994) and local stratigraphic studies by Piyasin (1966), Mildenhall (1975), Finlayson (1980), Beanland (1995) and Brackley (1999). Key marker horizons, many described in existing literature, were recognised in the field and traced laterally across the landscape and used as formation and group boundaries within the proposed stratigraphic framework for the lower Pohangina Valley (Rees et al. 2018b).

Important sections within the tributaries and interfluves of the Pohangina River were identified, logged and sampled in order to cover the study area in a similar level of detail, compiling existing and new data. We traced important marker units laterally over interfluves into adjacent tributaries, in order to gain an understanding of facies changes across the area through time.

Volcaniclastic and primary tephra-fall horizons were sampled in sections during stratigraphic logging, with particular attention paid to documenting the environment of deposition and facies changes between outcrops. Beds composed entirely of glass were targeted during sampling. Pumice clasts were sampled, when necessary, within volcaniclastic beds, before being gently crushed during sample preparation. The glass was washed through a 63 µm sieve, discarding silt and clay sized particles. Following drying, samples were then dry sieved collecting the 125–250 µm fraction for mounting. The glass was set in epoxy plugs, ground and finally polished to 1 µm using diamond paste.

Glass-shard major elements were determined using a JEOL JXA-8230 Electron Probe Microanalyser (EPMA) at Victoria University of Wellington. Analyses were determined using an 8 nAmp beam current, 10 µm beam diameter. Standard calibration blocks were used for calibration and glass standards ATHO-G from the MPI-DING collection (Jochum et al. 2006) and VG568 (Jarosewich et al. 1980) were analysed at regular intervals to monitor instrumental drift and assess the accuracy and precision of analyses. All analyses are presented as weight percent, recalculated to 100% on a water-free basis (Table 2, Supplementary Data File A). Total Fe (FeO_t) was calculated as FeO while H_2O was calculated by the difference from 100%. Individual shard analyses allow the homogeneity of the glass to be assessed as well as chemically fingerprinted. Ternary and bivariate plots were constructed using FeO: 1/3, K_2O: CaO wt%, and FeO vs CaO wt %, to aid tephra correlation via the existing published datasets of Pillans et al. (2005).

Stratigraphy

The stratigraphic record of the lower Pohangina Valley (Figure 2) represents an eastern margin succession of the Whanganui Basin. Influxes of both primary tephra-fall and reworked volcaniclastic deposits allow direct correlation to the well-established WB chronostratigraphic framework (Beu and Maxwell 1990; Abbott 1994; Naish and Kamp 1995; Saul et al. 1999; Pillans et al. 2005; Turner et al. 2005; Pillans 2017). Castlecliffian strata preserved within the lower Pohangina Valley have been correlated to Takapari Formation of Carter (1972) in recent mapping of the area (Rees et al. 2018b). Identification of the widespread c. 0.99 Ma Potaka Pumice (Te Punga 1952; Pillans 2017) within the Pohangina Valley succession has allowed an upper contact to be set for the Takapari Formation of Carter (1972), providing a direct link to the lower boundary of the Kaimatira Pumice Sand Formation of Fleming (1953). Kaimatira Pumice Sand Formation, defined as the first influx of Potaka Pumice into the WB, is a particularly widespread chronostratigraphic marker bed facilitating inter-and intra-basin correlation (Te Punga 1952; Fleming 1953; Seward 1974a, 1974b; Shane 1991, 1994; Pillans et al. 2005).

The Takapari Formation, cropping out in Pohangina Valley (Figures 2 and 6), consists of sandy mudstones, sandstones and shellbeds interbedded with vitric volcaniclastic sandstone and carbonaceous mudstone. The lower Waitokanui Member (Rees et al. 2018b) is composed of laminated sandy mudstone with lenses of siltstone and fossiliferous horizons. This unit is unconformably overlain by the Awahou Member, comprising a succession of coarse to fine grained sandstones interbedded with massive siltstone and laminated mudstone. Pumice first appears in bed 9 and 10 of the presented section (Figure 2), defining the base of Awahou Member. The volcaniclastic units occur in close association with high energy bed forms, such as cross bedding with erosional lower contacts, overlain by carbonaceous mudstone and

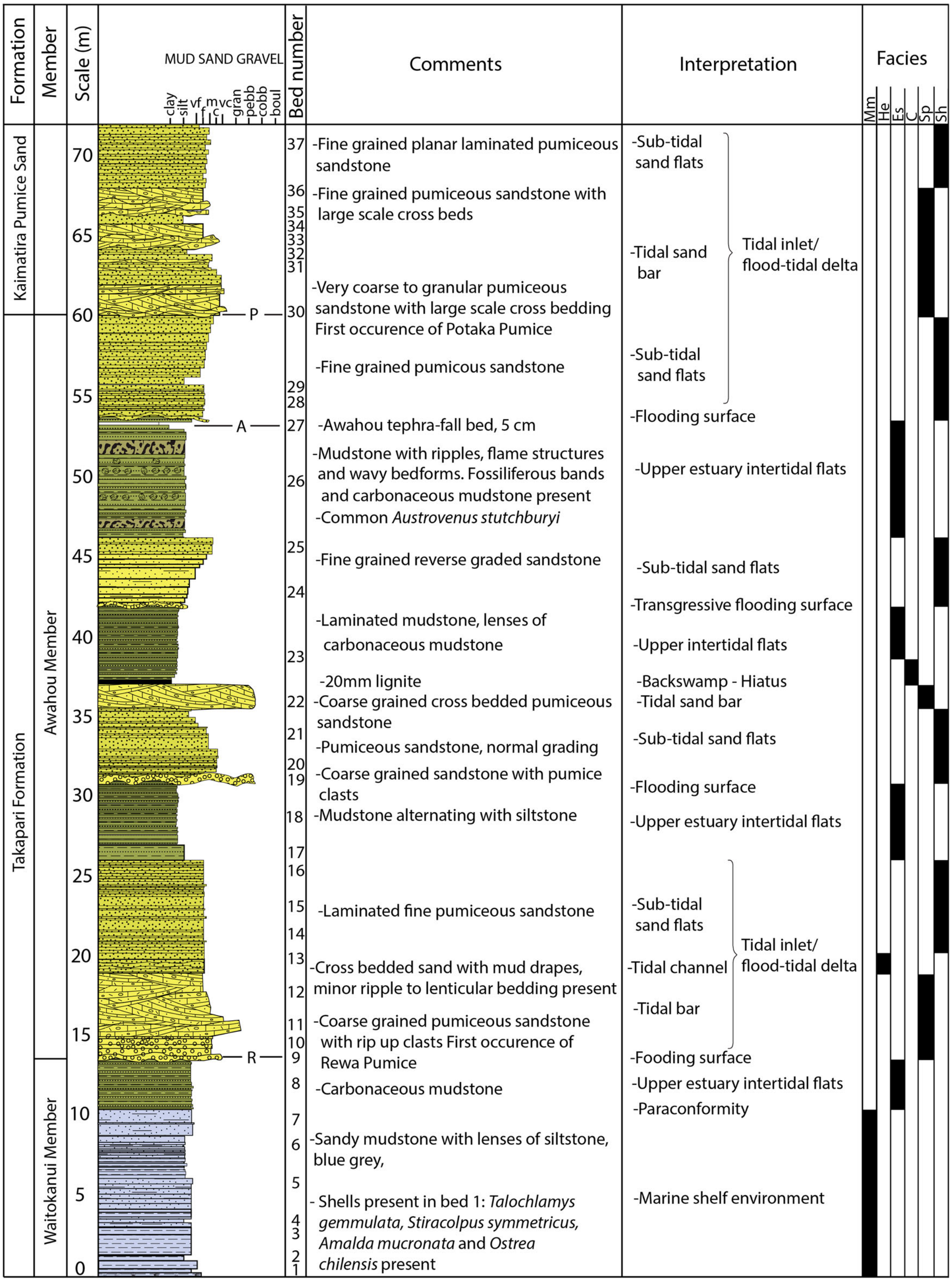

Figure 2. Stratigraphic column of Awahou Member, Takapari Formation exposed on Awahou South Road, Broadlands Station, lower Pohangina Valley (NZGD2000 -40.280017 S, 175.773869 E).

common thin beds of lignite. Well-preserved, closely spaced, small (15–30 mm) *Austrovenus stutchburyi* occur within bed 26, below Awahou Tephra.

Facies analysis

We recognise six facies in the Takapari and Kaimatira Pumice Sand Formation (Table 1 and Figures 2 and 3), providing descriptions below.

Facies Mm is characterised by massive, blue grey sandy mudstone. Beds range from 1 to 4 m in thickness. Intermittent mafic rich lenses 0.2–0.3 m thick within the sandy mudstone are highlighted by secondary iron oxides in outcrop. *Amalda mucronata, Talochlamys gemmulata, Stiracolpus symmetricus* and *Ostrea chilensis* occur in a 0.1 m thick lens of partially crushed shell material (bed 1). Lower bounding surfaces are commonly gradational in nature.

Table 1. Lithofacies of Takapari Formation and Kaimatira Pumice Sand Formation; facies codes are modified from Smith (1987); Horton and Schmitt (1996); Miall (1977); and Waresback and Turbeville (1990).

Facies code	Description	Interpretation
Mm	Massive to laminated sandy mudstone with interbedded siltstone lenses	Marine shelf, suspension fall out and traction deposition
He	Cross bedded sandstone with discontinuous mud drapes	Tidal channel
Es	Alternating laminated mudstone and siltstone	Upper estuary intertidal flats
C	Lignite and carbonaceous mudstone	Vegetated estuarine back swamp environment, anaerobic conditions
Sp	Cross bedded pumiceous sandstone	Sub-tidal linguoid bars and sand waves within tidal inlet/flood-tidal delta
Sh	Fine grained laminated sandstone	Planar bed flow, subtidal sand flats within lower estuary/flood-tidal delta

We interpret Facies Mm as an inner to mid shelf deposit. Sedimentation processes have been dominated by fine material falling out of suspension, resulting in mineral segregation by density, as evidenced by mafic rich bands within the sandy mudstone. *Amalda mucronata* is characteristic of an inner to mid shelf environment and is common together with *S. symmetricus* in siltstone beds along the Whanganui coastal section, indicative of a soft ground shallow marine environment (Beu 1995; Hayward et al. 2002; Taylor and Morrison 2008). The presence of *T. gemmulata* and *O. chilensis* suggests a hard substrate such as a shell ground environment was present nearby. This sub-environment likely developed on areas of the sea floor characterised by siliciclastic bypass and concentration of bioclastic material, providing suitable habitat for byssally-attached organisms, similar to the modern day Whanganui shelf (Gillespie and Nelson 1996; Beu 2006). The species identified likely inhabited different laterally adjacent sub-environments on the paleo-shelf and were later concentrated together into a single detrital shellbed by strong, coast-parallel, geostrophic currents that we infer to have occurred during westerly to south-westerly storms similar to today (Lewis 1979; Gillespie 1992; Gillespie and Nelson 1996).

Facies He is a sand dominated heterolithic facies composed of coarse to fine sandstone with mud draped bidirectional trough crossbed sets. Minor ripple to lenticular bedding is also present. Crossbed sets are 0.3–0.4 m thick and are commonly bounded by reactivation surfaces. Towards the base of the small-scale cross-bedded sets, mud drapes converge resulting in lenticular bedding. The overall bed thickness ranges from 0.3–1 m. The basal contact of this facies is a sharp surface.

We interpret Facies He as a tidal channel deposit within the outer estuary zone, adjacent to the flood-tidal delta (Figure 3). Mud drapes are commonly associated with tide-influenced environments that have alternating strong and slack currents (Abbott 1998; Ichaso and Dalrymple 2009; Nichols 2009). Bidirectional crossbedding also implies a strong tidal influence while the sharp erosive base suggests intermittent scouring and erosion. Reactivation surfaces are likely produced by erosion of the subordinate current, resulting in truncation of underlying foresets (De Mowbray and Visser 1984; Fenies and Tastet 1998).

Facies Es is characterised by thick beds (up to 7 m) of mudstone and siltstone. Shellbeds 0.1–0.2 m thick contain common, small (<30 mm), well preserved *Austrovenus stutchburyi* fossils and layers enriched in organic material. Dominant sedimentary structures include planar laminae (25–100 mm thick), asymmetrical ripples, flame and water escape structures. The fine-grained tephra in bed 27 (50 mm thick) belongs to this facies. Lower contact surfaces are sharp to gradational.

Facies Es is interpreted as an estuarine intertidal mud flat deposit, most likely positioned on the landward side of the estuarine environment away from the main fluvial channel zone (Figure 3). Evidence for estuarine deposition is supported by the presence of 0.1–0.2 m thick shellbeds dominated entirely by the intertidal mollusc *Austrovenus stutchburyi* and common carbonaceous mudstone. The fine rhythmic bedding characteristic of this facies is indicative of alternating periods of current activity and relative quiescence (Reineck and Wunderlich 1968; Shanmugam et al. 2000), typical of estuarine intertidal mud flats (deVries Klein 1977; Dalrymple et al. 2012). Asymmetrical ripples imply unidirectional current flow within a tide-influenced environment, whereas flame and water escape structures are probably related to liquefaction of the sediment within a water saturated, unconsolidated state. A potential seismic trigger for soft sediment deformation in WB sediments is discussed in a separate paper by Rees et al. (2018c).

Austrovenus stutchburyi is encountered on many sand and mud flats in the outer parts of estuaries, although larger shells are typically found in the outer parts of bays with higher salinity and greater faunal diversity (Beu and Maxwell 1990; Morely and Hayward 2009). *A. stutchburyi* is unknown from fully marine situations (Beu and Raine 2009). The specimens encountered in this study are of generally small size (<30 mm), indicative of brackish water within the inner estuarine zone (Figure 3). In the past, WB sediments with shellbeds consisting entirely of *A. stutchburyi,* a distinct lack of any marine dwelling

Table 2. Electron Probe Microanalyser data for glass shards from the lower Pohangina Valley, eastern Whanganui Basin.

Sample	Grid Ref.	SiO_2	Al_2O_3	TiO_2	FeO_t	MgO	CaO	Na_2O	K_2O	Cl	H_2O	*n*
Kawakawa Tephra												
CJR-T3	BM35/36884158	79.38 (0.34)	11.81 (0.11)	0.13 (0.02)	1.01 (0.05)	0.1 (0.02)	1.02 (0.06)	3.68 (0.30)	2.63 (0.06)	0.24 (0.01)	6.66 (1.36)	20
Kaukatea Tephra												
CJR-T2	BM35/37724079	77.07 (0.28)	12.74 (0.11)	0.13 (0.02)	1.51 (0.13)	0.06 (0.02)	1.01 (0.06)	3.85 (0.10)	3.39 (0.11)	0.25 (0.02)	5.00 (0.81)	19
Potaka Pumice												
CJR-T1	BM35/36573991	78.2 (0.18)	12.32 (0.09)	0.12 (0.02)	1.01 (0.07)	0.07 (0.02)	0.86 (0.08)	3.44 (0.11)	3.69 (0.26)	0.29 (0.01)	3.76 (1.24)	16
CJR-T10	BM35/34433523	73.84 (0.96)	11.33 (0.15)	0.1 (0.03)	0.88 (0.17)	0.07 (0.03)	0.78 (0.10)	3.41 (0.15)	3.29 (0.23)	0.28 (0.03)	6.02 (1.19)	22
CJR-T16	BM35/36724101	78.58 (0.27)	12.13 (0.12)	0.11 (0.02)	0.97 (0.12)	0.07 (0.02)	0.85 (0.12)	3.34 (0.12)	3.66 (0.18)	0.29 (0.01)	4.89 (1.41)	24
Awahou Tephra												
CJR-T7	BM35/35373579	76.49 (0.42)	13.78 (0.18)	0.14 (0.02)	1.42 (0.11)	0.29 (0.02)	1.46 (0.04)	3.59 (0.56)	2.62 (0.08)	0.21 (0.03)	6.76 (2.59)	13
CJR-T8	BM35/35823750	76.53 (0.22)	13.70 (0.09)	0.14 (0.01)	1.4 (0.08)	0.28 (0.02)	1.44 (0.03)	3.74 (0.13)	2.59 (0.07)	0.18 (0.03)	6.88 (1.06)	15
Rewa Pumice												
CJR-T12	BM35/35883747	76.13 (0.48)	13.20 (0.14)	0.17 (0.02)	1.88 (0.10)	0.08 (0.02)	1.12 (0.05)	3.54 (0.46)	3.64 (0.13)	0.23 (0.02)	6.56 (1.05)	17
CJR-T13	BM35/35863747	76.54 (0.30)	12.95 (0.16)	0.16 (0.02)	1.83 (0.09)	0.06 (0.02)	0.98 (0.06)	3.82 (0.15)	3.38 (0.12)	0.26 (0.01)	7.00 (0.57)	21
CJR-T14	BM35/35843748	75.8 (0.33)	13.28 (0.14)	0.19 (0.02)	1.99 (0.16)	0.09 (0.02)	1.17 (0.06)	3.94 (0.12)	3.31 (0.13)	0.24 (0.02)	6.03 (0.76)	19
Mangapipi Tephra												
CJR-T5	BM35/35963768	75.52 (0.21)	13.27 (0.10)	0.20 (0.01)	1.98 (0.11)	0.10 (0.02)	1.14 (0.03)	4.36 (0.11)	3.17 (0.11)	0.26 (0.01)	6.36 (0.81)	20
CJR-T6	BM35/37053942	75.70 (0.20)	13.16 (0.11)	0.21 (0.02)	1.92 (0.07)	0.11 (0.02)	1.13 (0.02)	4.35 (0.15)	3.16 (0.07)	0.25 (0.01)	6.79 (1.08)	20
Ridge Tephra												
CJR-T9	BM35/38684127	76.75 (0.33)	12.57 (0.20)	0.17 (0.02)	1.86 (0.08)	0.07 (0.02)	0.99 (0.03)	4.04 (0.21)	3.28 (0.13)	0.28 (0.02)	6.66 (1.04)	18
CJR-T11	BM35/38494144	75.94 (0.25)	13.22 (0.20)	0.19 (0.01)	1.96 (0.08)	0.09 (0.01)	1.05 (0.04)	4.62 (0.39)	2.68 (0.40)	0.25 (0.02)	7.21 (0.56)	21
Pakihikura Pumice												
CJR-T4	BM35/39314344	78.57 (0.31)	12.29 (0.14)	0.09 (0.02)	1.16 (0.10)	0.07 (0.02)	1.16 (0.06)	3.44 (0.32)	3.02 (0.16)	0.2 (0.02)	5.82 (1.04)	14
ATHO-G												
ATHO-G	n/a	77.25 (0.30)	11.87 (0.17)	0.27 (0.01)	2.76 (0.15)	0.07 (0.02)	1.68 (0.04)	3.63 (0.17)	2.42 (0.08)	0.05 (0.01)	1.93 (0.66)	24
VG568												
VG568	n/a	78.44 (0.24)	11.92 (0.12)	0.07 (0.01)	0.93 (0.07)	0.03 (0.02)	0.42 (0.02)	3.67 (0.08)	4.39 (0.12)	0.13 (0.01)	1.28 (1.07)	20

Notes: Oxide values recalculated to 100% on a water-free basis. Total Fe (FeO_t) calculated as FeO. H2O calculated by the difference from 100%. ± 1 standard deviation presented in parentheses. Grid references refer to NZ Topo50 map sheets.

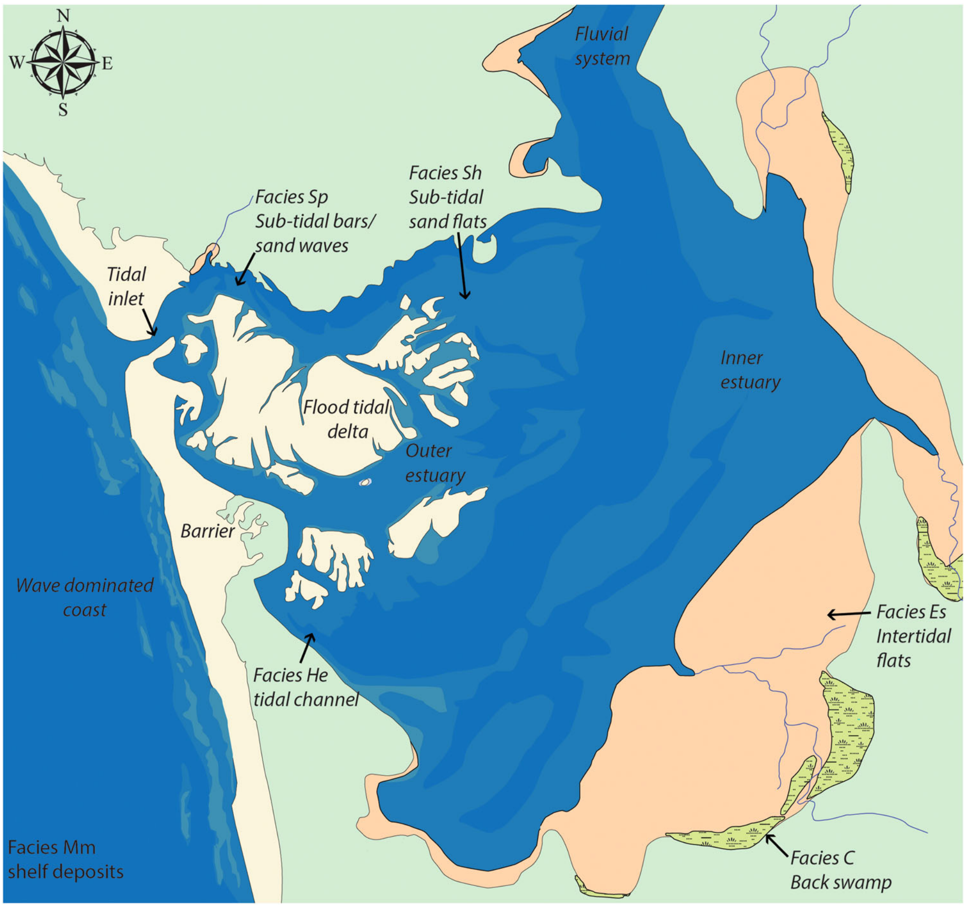

Figure 3. Schematic diagram showing the location of facies within a wave dominated estuarine system. Note this interpreted estuarine system is suggested as a transient feature in the coastal plain setting of the eastern WB, only able to occur during upper transgressive and peak highstand sea levels before a return to alluvial plain sedimentation during intervening regression and sea level low stands, represented by erosional unconformities and incised valley fill in the sedimentary record.

Mollusca and strong association with organic rich sediment have been interpreted as marginal marine to estuarine (Te Punga 1952; Bussell 1986). However, this interpretation must be treated with some caution as it is also very common to find *A. stutchburyi* within fully marine shell beds of the WB, resulting from transport of shells from their living environment and incorporation within diverse marine assemblages (Hayward and Stilwell 1995). These instances are typically characterised by larger specimens showing obvious signs of abrasion and reworking, characteristics not observed in Facies Es.

Facies C is composed of a 20 mm thick lignite bed at its base grading upwards into laminated carbonaceous mudstone. The mudstone then shows reverse grading into siltstone and fine sandstone. Overall, this facies is 1.5 m thick, characterised by very carbonaceous sedimentary deposits near its base with siliciclastic content gradually increasing up section. The lower contact of Facies C is wavy.

Facies C is interpreted as an estuarine back-swamp deposit (Figure 3). The basal 20 mm lignite represents a partially vegetated area of the estuary, likely an estuarine back-swamp able to facilitate organic matter accumulation and preservation in anaerobic conditions. We suggest high ground water levels within the depositional environment led to year round saturation thereby limiting decomposition and decay. Subsequent accumulation of carbonaceous mudstone over the lignite is interpreted to represent the persistence of anaerobic conditions in the depositional environment, despite evidence the area was receiving influxes of siliciclastic sediment. The incoming sediment likely included colluvium and alluvium transported into the swamp from the surrounding estuarine system and valley sides. The presence of reverse grading is interpreted to represent alluvial sediments gradually infilling the back-swamp environment, likely related to base level change during a marine transgression.

Facies Sp is composed of granule to fine grained, trough cross-bedded, pumiceous sandstone. Minor ripple and laminae bedding is present. The bi-directional cross-bed sets are up to 2 m thick, generally becoming thicker up section. The lower bounding surfaces of this facies are sharp and wavy with frequent incorporation of sub-rounded, pumice and/or mudstone rip up clasts up to 50 mm in diameter.

Facies Sp represents a migrating sub-tidal sand bar within the outer estuary zone (Figure 3). Bi-directional crossbedding is indicative of a strong tidal influence.

The increasing thickness of the cross bed sets up section is interpreted to represent a change from the bar slope to the bar crest. The granule to fine-sand grain size within the stacked crossbed sets is interpreted as a function of low suspended-sediment concentration within the seaward end of the estuary (Dalrymple and Rhodes 1995; Plink-Bjorklund 2005), with a majority of the silt and clay sized particles deposited within the inner estuary or bypassing the outer estuary into coastal waters. The very erosive lower contact in bed 9 (Figure 2) is interpreted as a transgressive flooding surface formed during migration of channel and bar networks within the outer estuary zone, during sea level rise.

Facies Sh consists of fine-grained, laminated sandstone. Minor ripple bedding and intercalated siltstone lenses occur sporadically. Iron oxide is present, often accentuating the planar laminae within the beds. Beds are between 0.4 and 1 m thick. The lower contact of Facies Sh is sharp and wavy in nature.

Facies Sh is interpreted as a sub-tidal sand flat deposit within the lower estuary/flood-tidal delta zone (Figure 3). Laminated sandstone is deposited during high flow periods in the upper flow regime. Minor intercalated siltstone deposits represent periods of slack water, where finer sediments are able to fall out of suspension. Lamination dominates the bedding, suggestive of planar bed flow within a high-energy depositional environment.

Volcaniclastic interpretation

The volcaniclastic facies of the Takapari Formation (Facies He, Sh and Sp) are composed of nearly pure vitric pumiceous sandstone ranging in thickness from 4 to 17 m. Grain sizes range from granular to fine sand. Some units contain sub-rounded pumice clasts up to 150 mm in size (Figure 4). Primary sedimentary structures indicative of subaqueous deposition in a tidal environment include bidirectional cross bedding, mud drapes and ripple to lenticular bedding. Cross stratification ranges from millimetre scale ripples to 2 m scale trough crossbedding. In some cases (bed 9–16, Figure 2), the entire range of cross stratification occurs in a single volcaniclastic unit, suggesting a rapid change in paleo-current strength. Generally sedimentary structures indicate very variable flow strength up section, with many changes from low flow (ripples) to higher flow (cross beds, laminae) indicators.

The grain size, clast shape and sedimentary structures of the pumiceous facies suggest they are reworked volcanic deposits rather than distal, primary tephra-fall products. This interpretation is consistent with the position of the most likely source area, the Mangakino Volcanic Centre, located over 200 km north of the lower Pohangina Valley (Figure 1). Tephra-fall products in the WB typically range from silt to fine sand grain-size and occur as relatively thin ash beds < 40 cm thick (Milne 1973; Pillans et al. 1993, 2005).

The presence of rip up clasts and erosive basal contacts represent strong, viscous paleo-currents and high rates of fluvial discharge. We interpret these lower contacts as flooding surfaces related to a relative rise in sea level, inundating landward portions of the depositional environment. Alternating fine and coarse-grained sedimentary units described here are suggested to contrast with the typical Castlecliff Motif, where fine-grained units represent periods of sea level highstand. Instead, fine-grained deposits in the Takapari Formation are considered to have formed during sea level transgression and progressive flooding and sedimentary infilling of the paleo-valley. Eventual maximum flooding during peak sea level is suggested to be characterised by coarse-grained facies typical of more seaward sub-environments.

The sediments preserved in Takapari Formation only represent the upper transgression and peak highstand of the sea level curve, due to deposition on the basins far eastern margin where subaerial exposure occurred for a majority of each cycle. Intermittent preservation of low stand fluvial and alluvial plain sediments also occurs (Brackley 1999), although these deposits lack the reliable repetition of the shallow marine to innermost shelf sediments preserved at the Castlecliff type section because of more extensive subaerial exposure and erosion resulting in relatively chaotic changes in sedimentary preservation. We consider the sequence bounding unconformities in Takapari Formation to occur at horizons typical of significant sedimentary hiatuses (lignite development) or erosional surfaces separating units of greatly differing lithology (Figure 5).

We suggest influxes of pumiceous material into the sedimentary environment are derived from a paleo-fluvial system with headwaters located in the central North Island. Periodic emplacement of ignimbrite sheets following TVZ eruptions was followed by substantial erosion, particularly of the distal unwelded portions, leading to dramatically increased sedimentation rates within paleo-river systems draining the central North Island (Shane 1994; Manville and Wilson 2004; Manville et al. 2009). Fluvial channels likely became constrained by rapid aggradation and levee formation leading to recurrent flooding and deposition across the paleo-floodplain (Segschneider et al. 2002). An aggrading riverbed allows rivers to sit high in the landscape, enabling rapid channel migration and frequent deposition in overbank settings (Manville et al. 2005, 2009).

Periods of volcaniclastic deposition appear to have been followed by times of relative quiescence. This can be observed in bed 22 (Figure 2) where a thin lignite overlies coarse cross-bedded pumiceous sandstone,

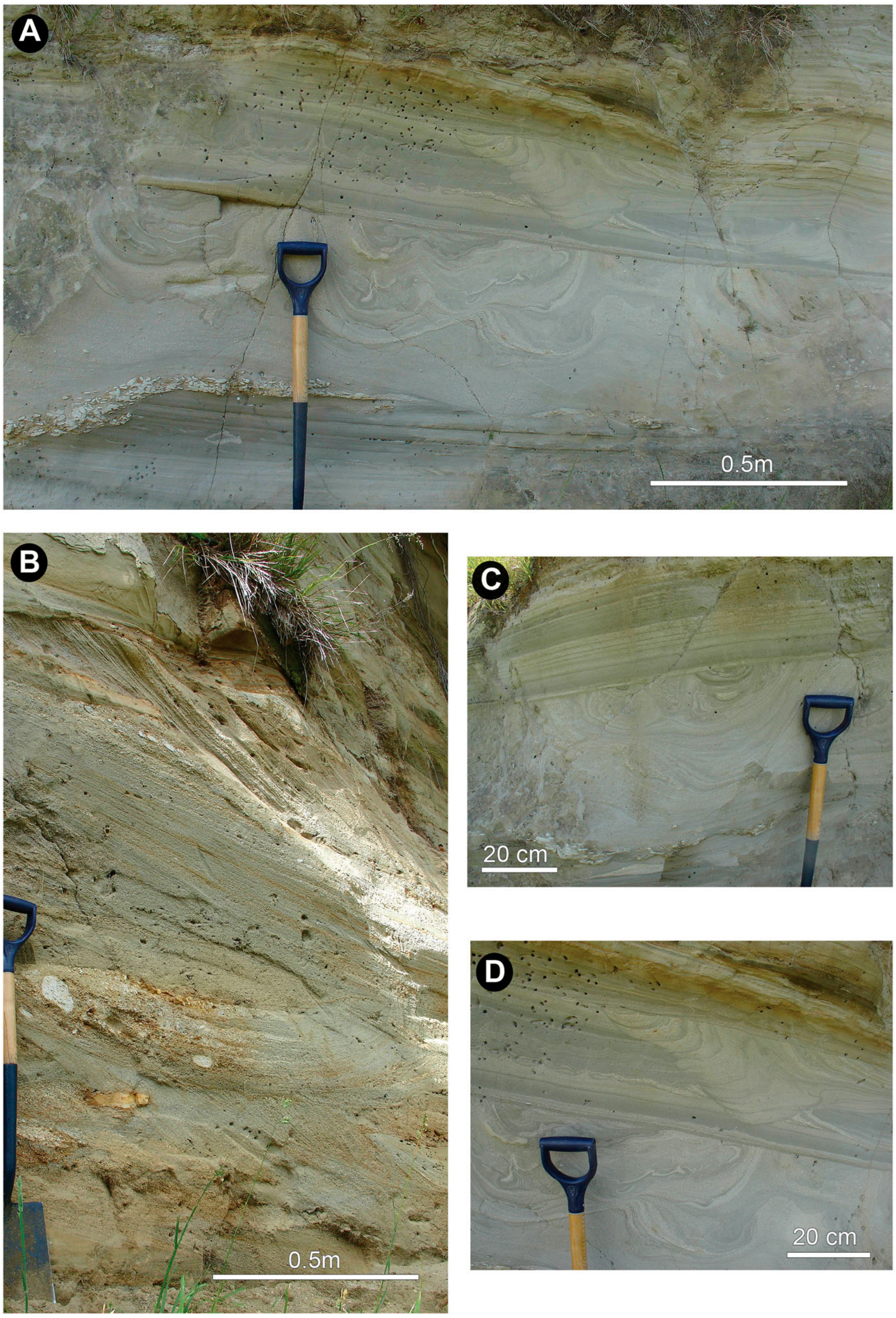

Figure 4. Potaka Pumice, Kaimatira Pumice Sand, Kai Iwi Group exposed at Broadlands Station, lower Pohangina Valley. **A**) Erosive wavy lower contact with rip up clasts of siltstone, overlying tephric rich fine sandstone and siltstone displaying planar laminae, convolute and water escape structures, Potaka Pumice exposed within an unnamed tributary of the Pohangina Valley (NZGD2000 -40.25792 S, 175.78157 E). **B**) Potaka Pumice displaying cross bedding, channel cut and fill and large pumice clasts up to 150 mm in diameter in an unnamed tributary of the Pohangina River, Broadlands Station, lower Pohangina Valley (NZGD2000 -40.256112 S, 175.783567. **C**) Close up of photograph A showing the centre bed of water escape structures within tephric rich fine sandstone and siltstone. **D**) Close up of photograph A showing upper bed of water escape structures.

suggesting that emplacement of the volcaniclastic sediment was followed by a significant hiatus in the sedimentary record. This hiatus was marked by the establishment of vegetation and a marked reduction in siliciclastic sedimentation, suggesting a major change in sediment supply, drainage conditions and depositional processes. We consider the sedimentary hiatus to be related to a retreat in sea level characterised by a reduction in siliciclastic deposition and landscape stabilisation allowing for soil formation and re-vegetation.

Awahou Tephra (new)

Awahou Tephra occurs c. 40 m above Rewa Pumice and c. 7 m below Potaka Pumice within Takapari Formation (Figure 2). The tephra comprises a 5 cm layer of fine ash within carbonaceous mudstone. The type section is located on Awahou South Road, Broadlands Station, accessible from the Saddle Road near Ashhurst (Figure 6) (NZGD2000 40°16′48.07″S 175° 46′26.04″E). We chose this location for its ease of

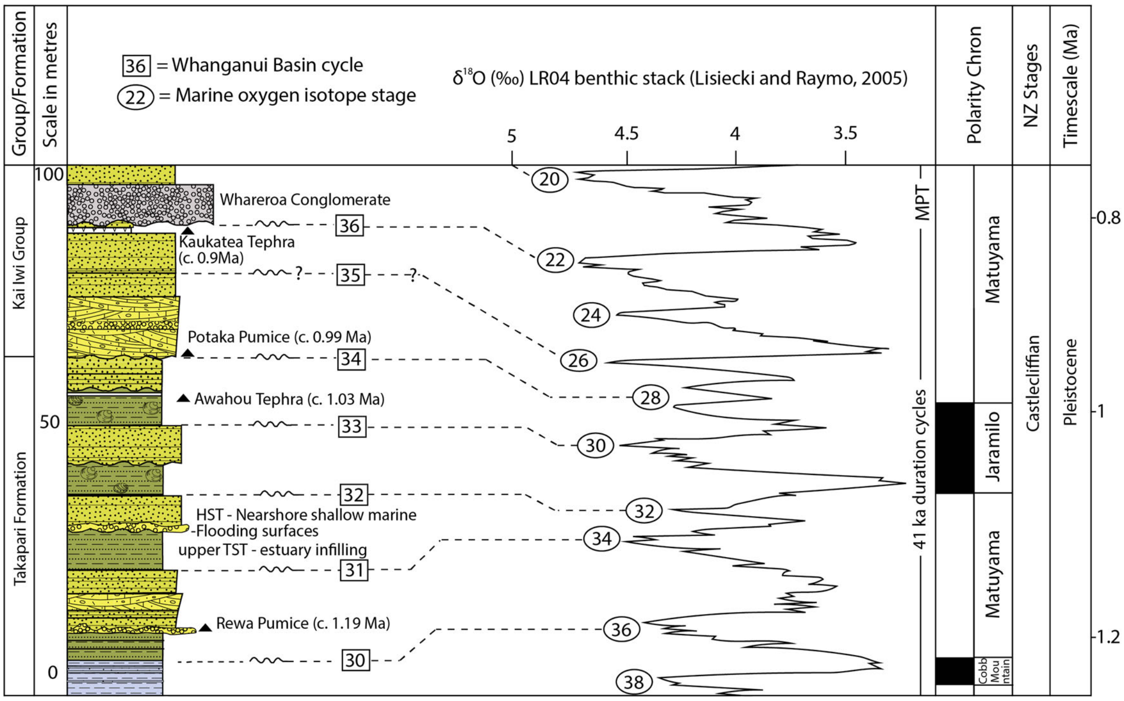

Figure 5. Simplified stratigraphic column of Takapari Formation and basal Kai Iwi Group displaying interpreted correlations to WB cyclothems and the marine oxygen isotope scale. MPT = Mid Pleistocene Transition characterised by a change from 41 ka to 100 ka cycles at c. 950 ka (Medina-Elizalde and Lea 2005). Note uncertainty arises to the exact position of Cycle 35 due to the nature of the Kaimatira Pumice Sand Formation (base of Kai Iwi Group) in WB. As a result there is an uncertainty of ± one cycle in the work presented here (Saul et al. 1999; Pillans et al. 2005). Whareroa Conglomerate is the lateral equivalent of the Waitapu Shell Conglomerate (Te Punga 1952) in the Rangitikei section and Makuhou Shell Conglomerate (Van Der Neut 1996) in the Turakina section. HST = High stand systems tract, TST = Transgressive systems tract.

access and good exposure of over 70 m of section, enclosing Rewa and Potaka pumice.

The tephra can be traced for 1.75 km SSW to an outcrop on the true left side of the informally named Turanga Stream (Figure 6). We sampled both outcrops for glass-shard based geochemical analysis (Figures 6, 7 and 8). The tephra pinches and swells substantially between the sections before becoming offset and lost against the Raukawa Fault (Rees et al. 2018b). A potential correlative exists to the south of the Manawatu Gorge within the Tua Paka Formation of Rich (1959) (A. Palmer unpubl. data).

Awahou Tephra has glass shards characterised by relatively high calcium (1.44–1.46 wt%) and low potassium (2.59–2.62 wt%) compared with analysis of glass within the Potaka and Rewa pumice (Table 2, Figure 7**A** and **B**). Its glass also has relatively high total iron at 1.4–1.42 wt% compared with that of Potaka Pumice which averages between 0.88 and 1.01 wt%, while glass of Rewa Pumice contains higher total iron (1.83–1.99 wt%) (Figure 7**A** and Figure 8). Magnesium (0.29–0.28 wt%) content in Awahou Tephra is higher than in both Potaka (0.07 wt%) and Rewa (0.06–0.09 wt%) pumice (Figure 7**B**).

We correlate Awahou Tephra to Cycle 33 within the WB cyclostratigraphy, correlated to marine isotope stage (MIS) 29. Potaka Pumice (c. 0.99 Ma) occurs 7 m above Awahou Tephra within the Cycle 34, a 6th order cycle corresponding to the 41 ka Milankovitch obliquity frequency (Naish et al. 1998). We provide an estimated astronomical age of c. 1.03 Ma for Awahou Tephra, based on its stratigraphic position below Potaka Pumice within Cycle 33. The first influx of Rewa Pumice within Cycle 30 (MIS 35), c. 40 m below Awahou Tephra provides further constraint on interpretation of the succession and correlation to the WB cyclostratigraphy.

Tephrostratigraphy

Pohangina Valley contains a volcanic record dating from the 1.58 ± 0.08 Ma Pakihikura Pumice (Pillans et al. 2005) through to the 25 ± 0.16 ka Kawakawa Tephra (Vandergoes et al. 2013). We identify seven distinct mid Pleistocene volcaniclastic and primary tephra-fall beds in the lower Pohangina Valley based on stratigraphic position, glass-derived EPMA data and correlation to the well-documented WB tephrostratigraphic record (Figure 7**A** and **B**) (Pillans et al. 2005). Two volcaniclastic beds that are of particular importance in mapping the WB Plio-Pleistocene succession are discussed below.

Pakihikura Pumice

Geologists of the Superior Oil Company (Feldmeyer et al. 1943) originally mapped the Pakihikura Pumice

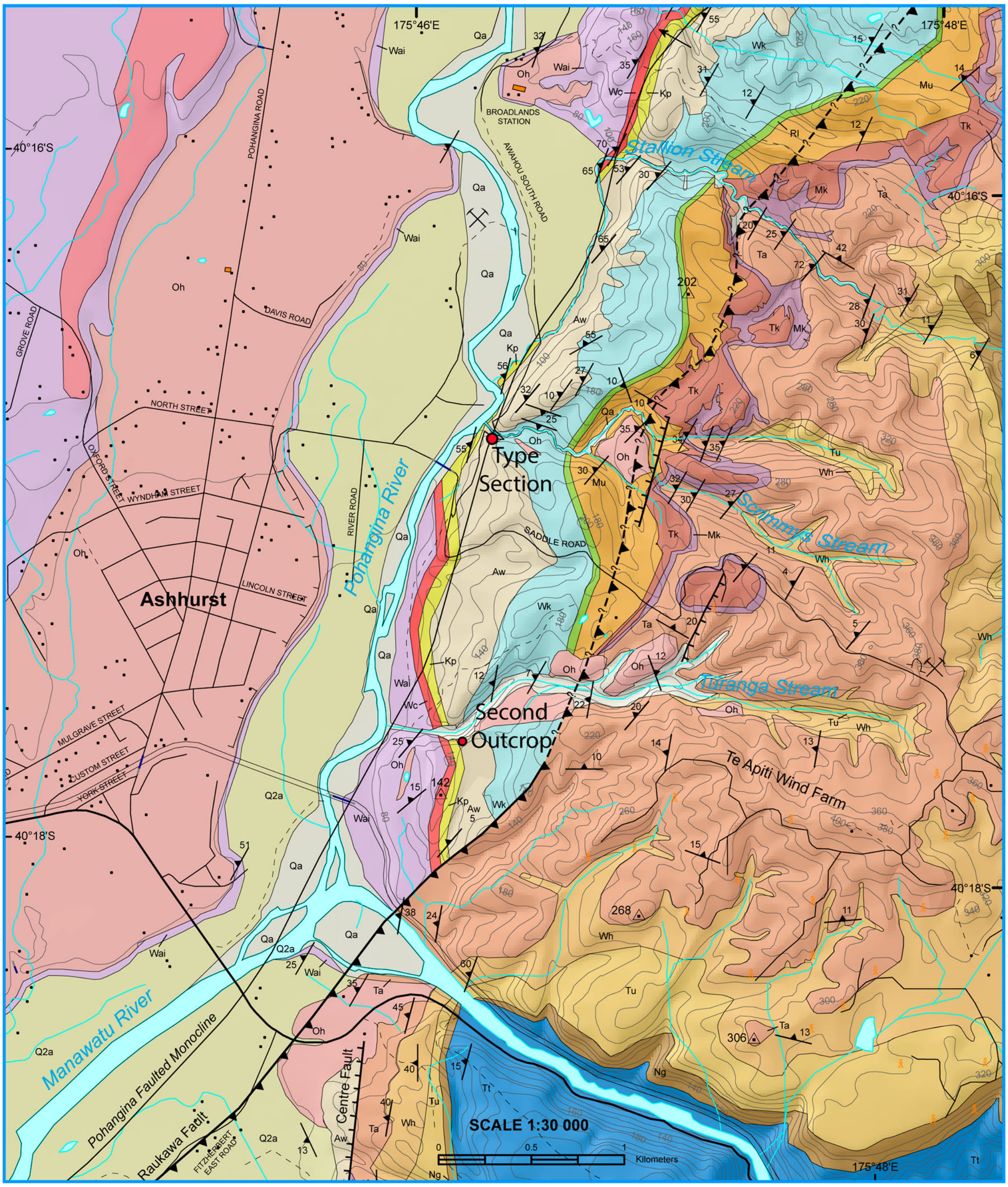

Figure 6. Geological map of the lower Pohangina Valley including location of the type section for the Awahou Tephra located on a road cutting on Awahou South Road, Broadlands Station (NZGD2000 -40.279886 S, 175.774126 E). A second key outcrop is also shown, located on a farm track beside a unnamed tributary of the Pohangina River, referred to informally as Turanga Stream (NZGD2000 -40.295403 S, 175.769491 E) (Rees et al. 2018b).

as the 'Basal Castlecliffian Ash' from the lower Pohangina Valley, across the basin to Makirikiri Valley 9.5 km NE of Whanganui City, a feat and level of detail unmatched by any study since. Te Punga (1952) originally introduced the name Pakihikura Pumice during his comprehensive mapping of the Rangitikei Valley, a study that early on was conducted for the Superior Oil Company before later submission as a PhD thesis at Victoria University of Wellington and publication in the New Zealand Geological Survey Memoir 8, 1952 (Beu, A.G. Pers. coms. 2018). Fleming (1953) mapped an equivalent pumiceous horizon, the Makirikiri Tuff Formation, from Makirikiri Valley to Turakina Valley, correlating it with the Basal Castlecliffian Ash of Feldmeyer et al. (1943). Seward (1976) summarised past nomenclature, recognising at least three distinct, separate tephra-fall and/or volcaniclastic deposits within the Makirikiri Tuff Formation, based on ferromagnesian mineral assemblages. The three deposits where named as Pakihikura Pumice, Ridge Tephra and Mangapipi Tephra (Figure 9). This work formalised the Pakihikura Pumice as a member within the Makirikiri Tuff Formation of Fleming (1953).

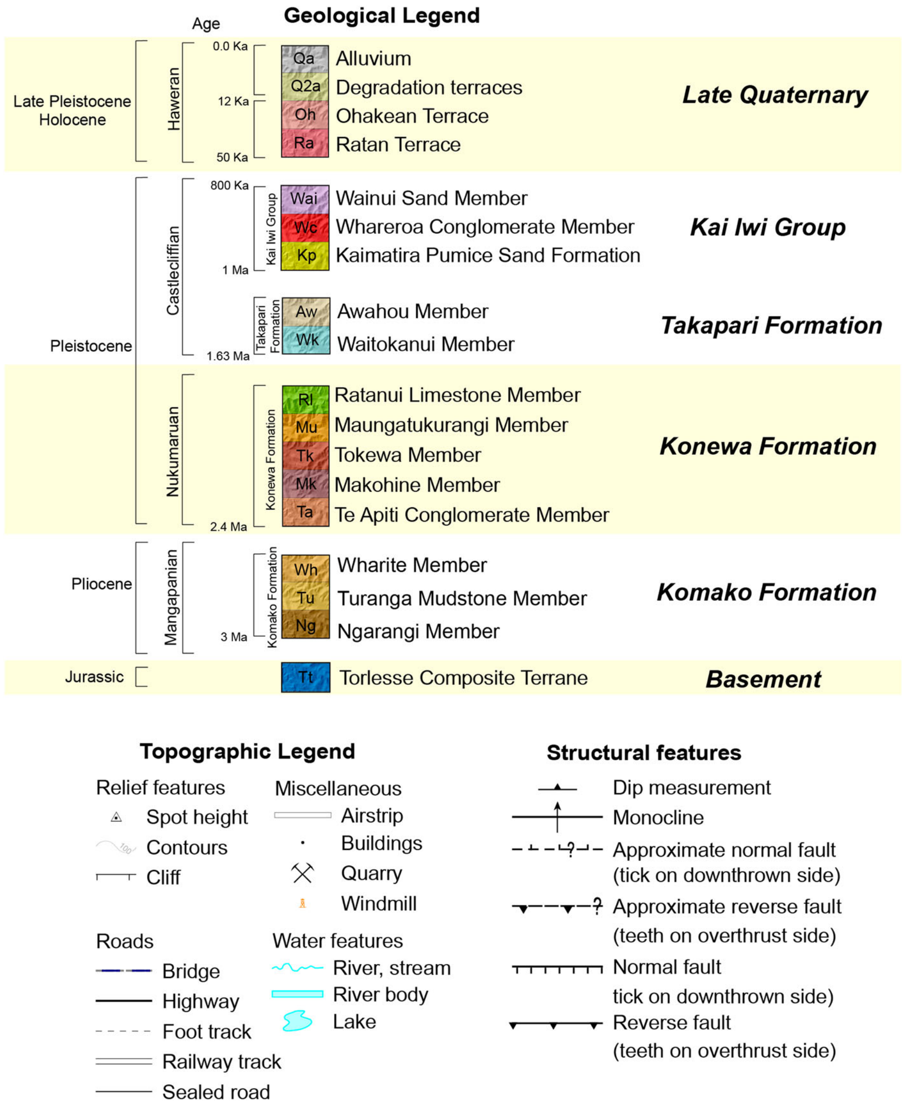

Figure 6. Continued.

Te Punga (1952) described a 25 m section of tephric beds at Pakihikura Bluff on the eastern side of the Rangitikei River, naming it the Pakihikura Pumice. Boellstorff and Te Punga (1977) defined the type locality of the Pakihikura Pumice as a road cutting 200 m south of Pakihikura Stream. Seward (1976) revisited the type section, describing the unit as a white vitric ash 0.5 m thick interbedded within tephric sandstone. In the Turakina and Rangitikei River valleys the Pakihikura Pumice occurs within a 100–150 m thick sequence of marginal marine to non-marine carbonaceous mudstone and tephric sandstone (WB Cycle 22) (Pillans et al. 2005). In the lower Pohangina Valley, the Pakihikura Pumice occurs as a 0.5 m thick white tephric bed in a succession of alternating tephric sandstone and carbonaceous mudstone including common lignite, within Waitokanui Member, Takapari Formation (Carter 1972; Rees et al. 2018b).

The source of the Pakihikura Pumice is uncertain, however, two ignimbrites named Ngaroma Ignimbrite and ignimbrite Unit-B erupted from the Mangakino caldera have $^{40}Ar/^{39}Ar$ ages consistent with the zircon and glass fission track ages of the Pakihikura Pumice (Wilson et al. 1986, 2009; Briggs et al. 1993; Houghton et al. 1995). Ages of 1.55 ± 0.05 Ma for Ngaroma Ignimbrite and 1.53 ± 0.04 Ma for ignimbrite Unit-B are presented by Wilson et al. (2009). Difficulties arise from limited exposure, partial welding and vapour phase alteration of the ignimbrite sheets, resulting in an inconclusive match with their suspected volcaniclastic equivalent. Alloway et al. (1993) presented an isothermal plateau fission track (ITPFT) age of 1.63 ± 0.15 Ma for the Pakihikura Pumice during revision of the WB chronostratigraphic framework. Pillans et al. (2005) presented an ITPFT age of 1.58 ± 0.08 Ma for the Pakihikura Pumice, correlating it to the upper regressive part of Cycle 22, late MIS 55 and early MIS 54.

Pakihikura Pumice is a particularly important bed for mapping in the WB, largely due to its striking character in outcrop. It signals a prominent change in the WB sedimentary succession, after which point deposits become highly tephric and carbonaceous with shellbeds dominated by *Austrovenus*

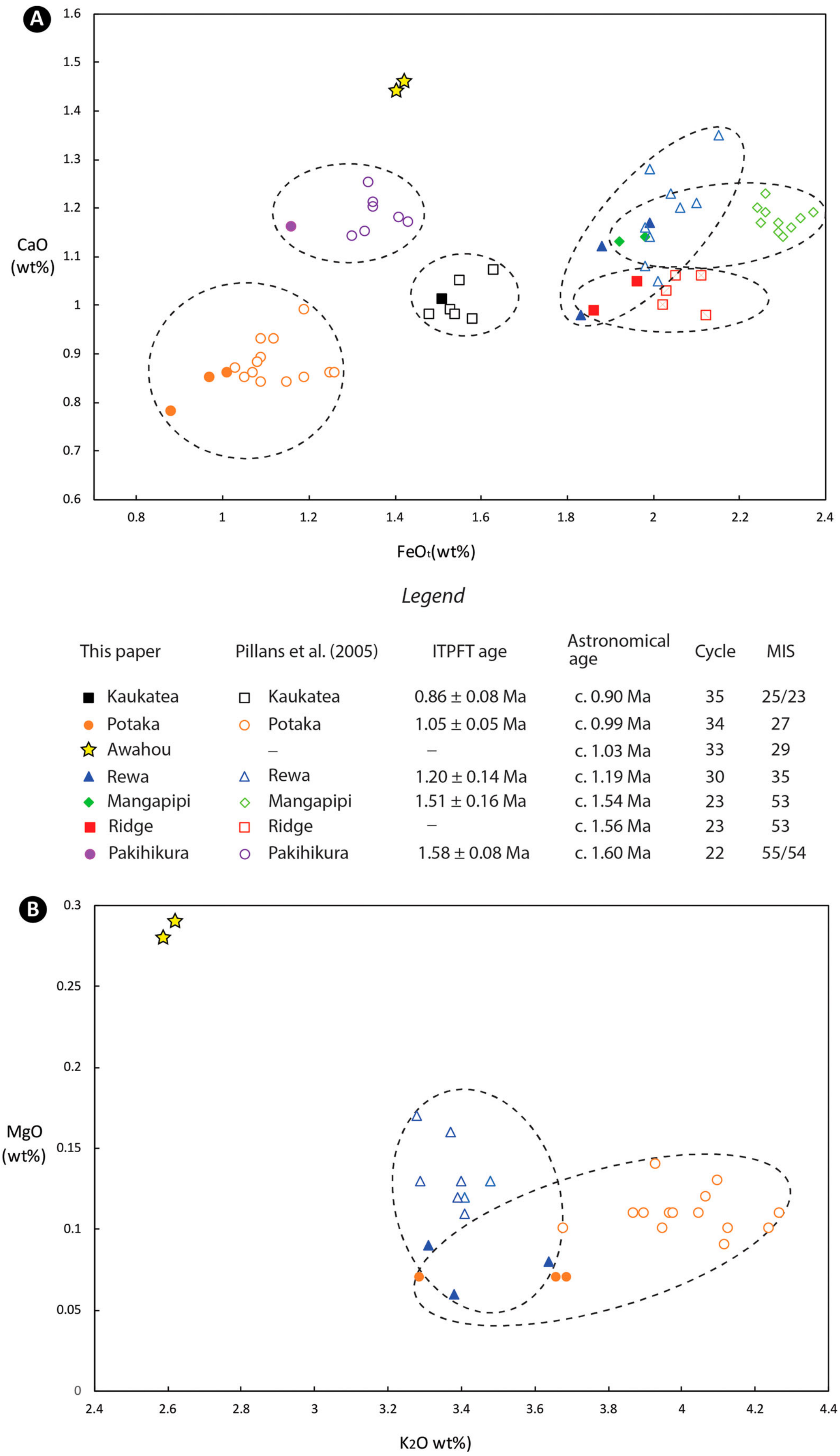

Figure 7. A) Mean CaO versus FeO_t (wt%) composition of glass shards analysed from seven tephra-fall and/or volcaniclastic deposits in the lower Pohangina Valley and correlation to the published datasets of Pillans et al. (2005). Note some overlap in major element, glass shard geochemistry occurs between the different deposits; however, they have been separated through the law of superposition in combination with EPMA analysis and geological mapping. **B**) Mean MgO versus K_2O (wt%) composition of Awahou Tephra, Potaka Pumice and Rewa Pumice from the lower Pohangina Valley and published datasets of Pillans et al. (2005). Ages and correlation to the WB cycles is from Naish et al. (1998) and Pillans et al. (2005).

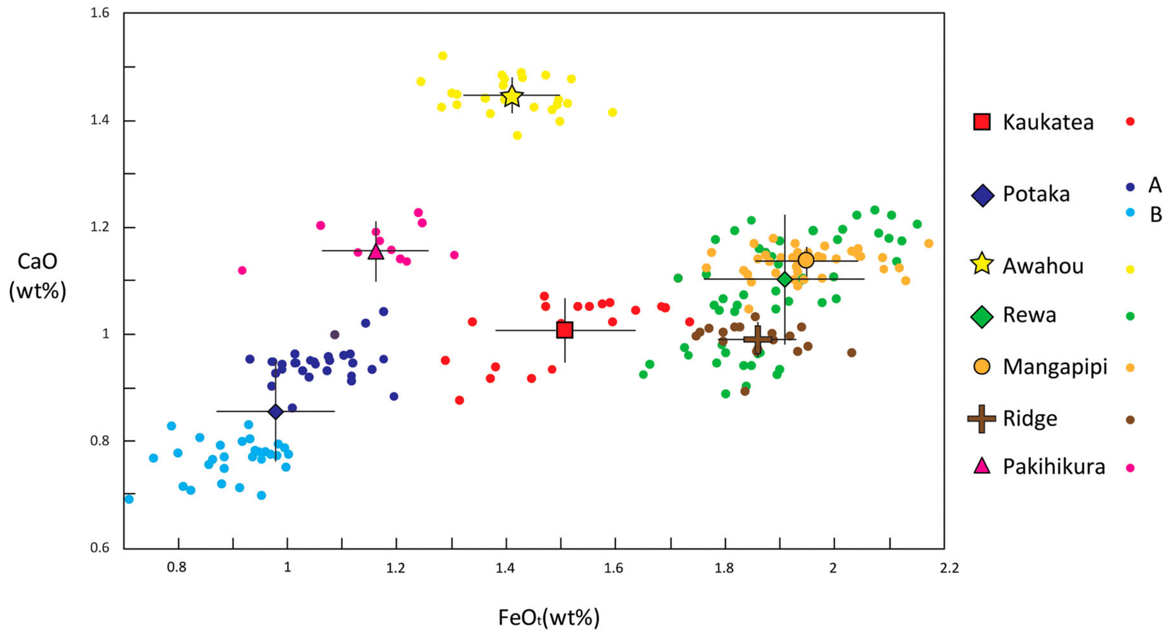

Figure 8. CaO versus FeO_t (wt%) composition of glass shards analysed from seven tephra-fall and/or volcaniclastic deposits in the lower Pohangina Valley. Mean analyses are displayed together with error bars representing one standard deviation (Table 2, Supplementary Data File A). Note the Potaka dataset is separated into two populations A and B. Population A represents the initial eruptive phase that was enriched in FeO_t and CaO.

stutchburyi and *Barytellina crassidens*. This change represents initiation of rhyolitic volcanic activity within the TVZ (Alloway et al. 1993; Krippner et al. 1998; Briggs et al. 2005; Allan et al. 2008) and its influence on the WB. As one surveys the literature concerning geological mapping in the WB, it is plain to see each successive author has become acutely aware of this change in facies associated with Pakihikura Pumice and as such, this horizon forms an important formation and group boundary in the related stratigraphic nomenclature.

Potaka Pumice

Feldmeyer et al. (1943) mapped the Potaka Pumice as the Kimbolton Ash Horizon tracing its extent from Pohangina Valley east to the Rangitikei Valley. Potaka Pumice was originally named by Te Punga (1952) during mapping of the Rangitikei Valley, describing a strongly current-bedded pumiceous unit with abundant rounded pumice pebbles. Seward (1976) summarised existing nomenclature, correlating the Potaka Pumice to the Kaimatira Pumice Sand of Fleming (1953). A critical change has occurred since this time, due to extensive work on the volcaniclastic succession of the WB, summarised in Pillans et al. (2005). Namely, the Kaimatira Pumice Sand is now defined as the first influx of Potaka Pumice into the WB (Pillans et al. 2005), resulting in exclusion of the Rewa Pumice and as a result an emendation of the definition by Seward (1976).

The Potaka Pumice is a widespread marker horizon used to correlate between Pleistocene marine and non-marine facies for a distance of around 600 km (Alloway et al. 1993; Shane 1994). Its occurrence within the Jaramillo Subchron, close to the paloemagnetic transition from normal to reversed polarity, makes it a valuable chronostratigraphic marker bed. Alloway et al. (1993) presents an ITPFT age of 1.05 ± 0.05 Ma for the Potaka Pumice. Naish et al. (1998) correlate Potaka Pumice to the base of Cycle 34 (MIS 27), providing an astronomical age of 0.99 Ma.

The Potaka Pumice has been correlated to two separate ignimbrites; the Kidnappers and Rocky Hill ignimbrites, erupted from the Mangakino Caldera (Wilson, Houghton, McWIlliams, et al. 1995, Alloway et al. 2005; Wilson et al. 2009; Cooper et al. 2012). The Kidnappers eruption generated a fine-grained phreatomagmatic fall deposit followed by an exceptionally widespread, non-welded ignimbrite (Wilson, Houghton, McWIlliams, et al. 1995; Cooper et al. 2017). After a brief interval of erosion, the Rocky Hill eruption occurred, generating a partly-welded ignimbrite (Cooper et al. 2016). The two deposits yield identical $^{40}Ar/^{39}Ar$ ages of c. 1.0 Ma (Wilson, Houghton, Kamp, et al. 1995; Wilson, Houghton, McWIlliams, et al. 1995). Following ignimbrite emplacement, paleo-fluvial systems draining the central North Island eroded and transported Potaka pumice into peripheral sedimentary basins on both sides of the present day main axial range, providing evidence on the timing of uplift and subsequent formation of the ranges (Shane 1991; Pillans et al. 1994; Shane, Black, et al. 1996).

The first influx of Potaka Pumice into the WB sedimentary record defines the base of the Kai Iwi Group at the Kaimatira Pumice Sand Formation. Kaimatira

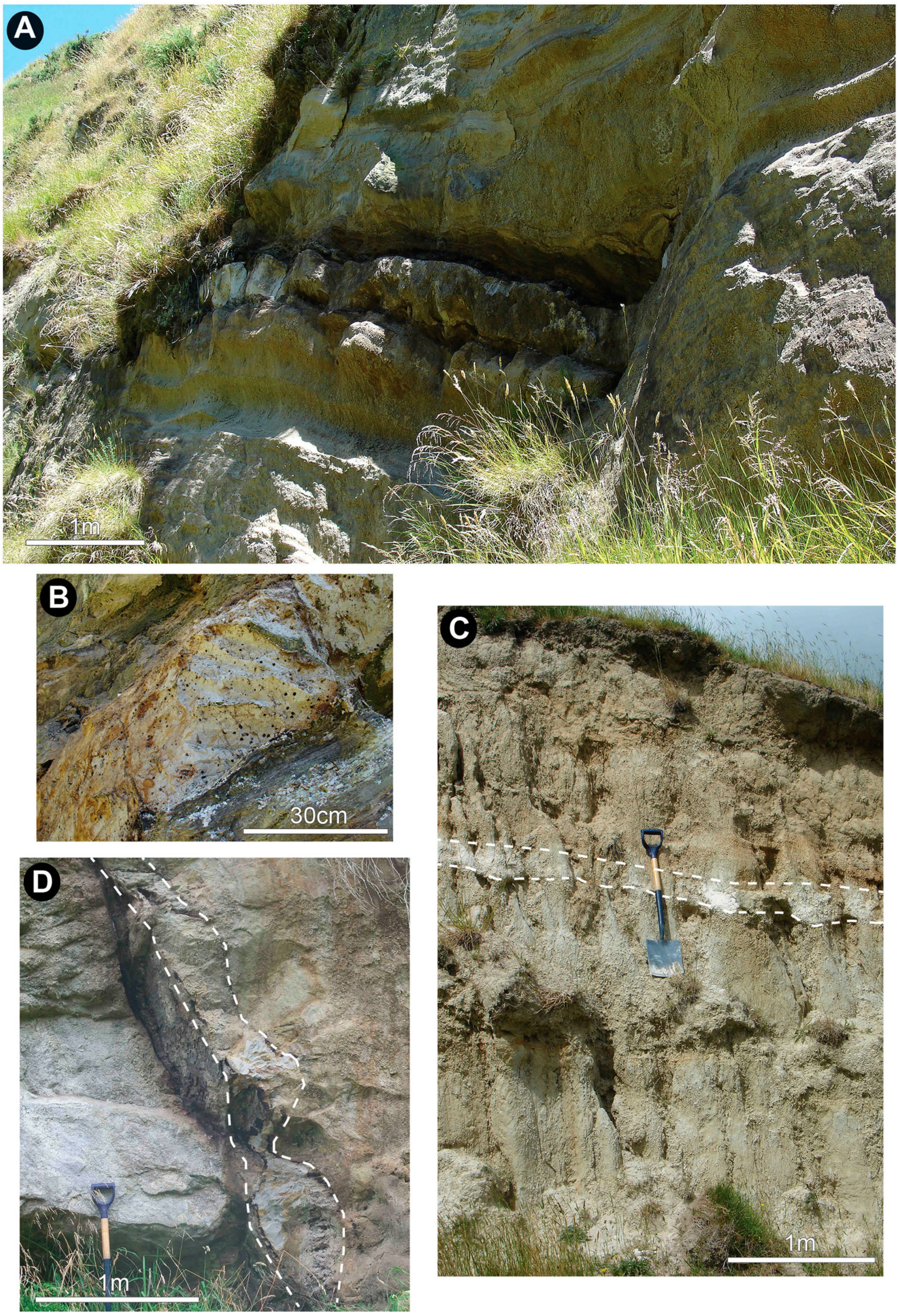

Figure 9. Mangapipi and Kawakawa tephras on Broadlands Station, lower Pohangina Valley. **A**) 30 cm Mangapipi Tephra enclosed by lignites exposed within an unnamed tributary of the Pohangina River (NZGD2000 -40.259584 S, 175.785627 E). **B**) Close up of photograph A displaying Mangapipi Tephra, note lenses of tephric siltstone within the compressed, organic rich, lignite beds. **C**) Kawakawa Tephra (25 ka) enclosed within Ohakea Loess on the Ratan Terrace, Broadlands Station, lower Pohangina Valley (NZGD2000 -40.250282 S, 175.796356 E). **D**) Steeply dipping bed of Mangapipi Tephra (70°@280) enclosed within lignites exposed near the apex of the Faulted Pohangina Monocline in Whareroa Stream (NZGD2000 -40.235738 S, 175.806398 E).

Pumice Sand Formation is able to be traced from the coastal type section to the Rangitikei Valley (Te Punga 1952; Fleming 1953; Seward 1976; Abbott 1994) and Pohangina Valley (Feldmeyer et al. 1943; Milne 1968; Brackley 1999; Pillans et al. 2005; Rees et al. 2018b). The first occurrence of Potaka Pumice has been used to define the upper boundary of the Takapari Formation of Carter (1972) and lower boundary of the Kaimatira Pumice Sand Formation in the lower Pohangina Valley (Rees et al. 2018b). It also defines the boundary between the Mangatarata and Mangahao formations in the Dannevirke and Woodville areas on the eastern side of the Mesozoic ranges (Lillie 1953; Piyasin 1966).

A key characteristic of Potaka Pumice is the occurrence of compositional variation within its glass-shard

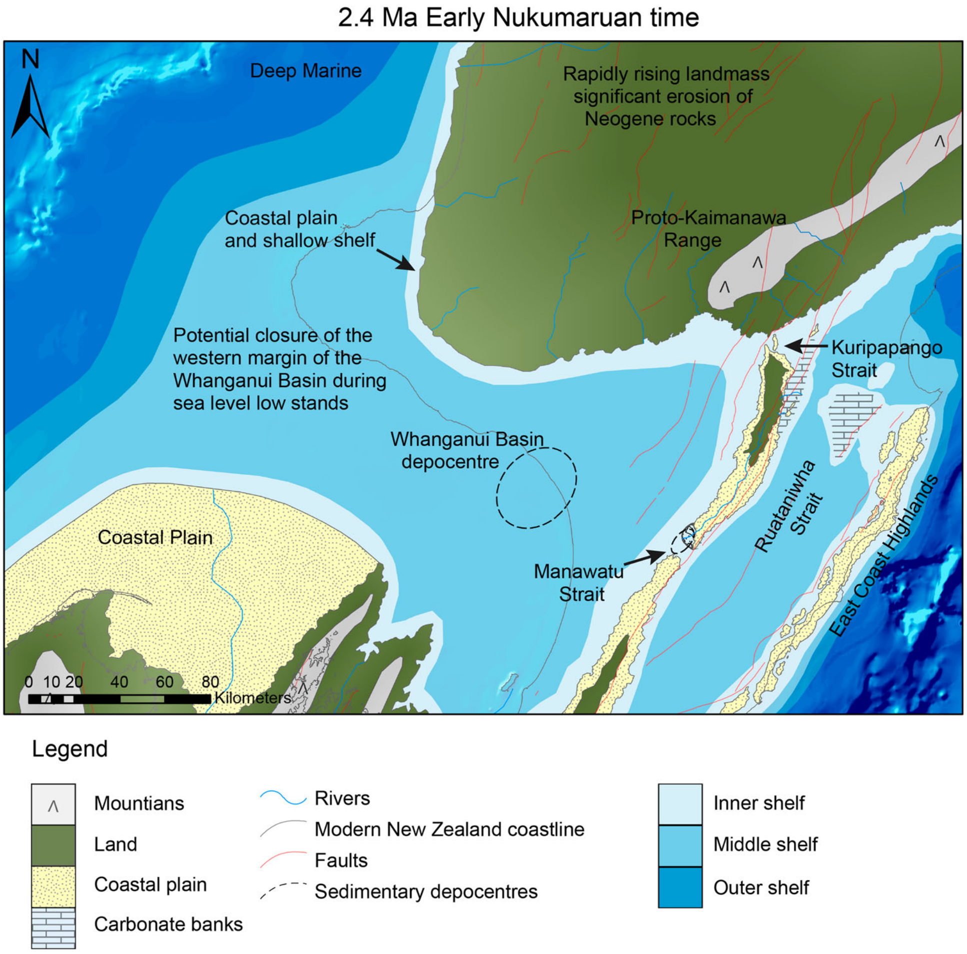

Figure 10. Cartoon schematic of the lower North Island during a sea level high stand in Early Nukumaruan time (2.4 Ma), showing relative location of the Kuripapango, Ruataniwha and Manawatu straits. Sources of information include Beu (1995); King and Thrasher (1996); Field et al. (1997); King (2000); McIntyre (2002); Browne (2004); Kamp et al. (2004); Pulford and Stern (2004); Bland (2006); Kamp and Furlong (2006); Townsend et al. (2008); Bunce et al. (2009); Lee et al. (2011); Nicol (2011); Trewick and Bland (2012).

based major element geochemistry, reflecting variation in the eruptive phase (Shane 1994). A segregation of compositions indicates that glass of the initial eruptive phase was enriched in FeO and CaO (see populations A and B, Figure 8).

Paleogeography

During Early Quaternary time, marine seaways were located across the current day main axial range, connecting the western and eastern lower North Island of New Zealand (Figure 10) (Browne 2004; Trewick and Bland 2012; Rees et al. 2018a). One such marine connection, the Manawatu Strait, was located across the structural low now occupied by the Manawatu Saddle, evidenced by a Plio-Pleistocene marine succession dating from possible Opoitian (5.33–3.7 Ma) to Nukumaruan (2.4–1.6 Ma) (Piyasin 1966; Beanland 1995; Milner 2017; Rees et al. 2018b). By 1.6 Ma the Manawatu Strait was undergoing regression, marked by the occurrence of fluvio-estuarine deposits within the basal succession of the Takapari Formation, containing the c. 1.6 Ma Pakihikura Pumice (Pillans 2017; Rees et al. 2018b). Uplift along the North Island Dextral Fault Belt (NIDFB) and related faults farther west led to gradual regression of the seaway. Movement along the NIDFB was uneven both along the length of the faults and through time, with the least amount of vertical uplift observed within the area of the present day Manawatu Saddle (Beanland 1995). Contemporaneous uplift of the Mt Bruce Block to the southeast resulted in the eventual closure of the southern Ruataniwha Strait by c. 1.6 Ma (Beu 1995).

Tephra-fall and volcaniclastic deposits of the Takapari, Mangatarata and Mangahao formations are preserved within similar fluvial, estuarine and lacustrine environments on both sides of the present day main axial range, suggesting eastern and western basins underwent simultaneous regression triggered by major tectonic and physiographic changes in the lower North Island (Shane 1991; Lee et al. 2011). Following closure of the Manawatu strait in Early Castlecliffian time, marine conditions persisted in eastern WB, evidenced by the intermittent occurrence of shellbeds containing abundant marine Mollusca within the upper Waitokanui Member,

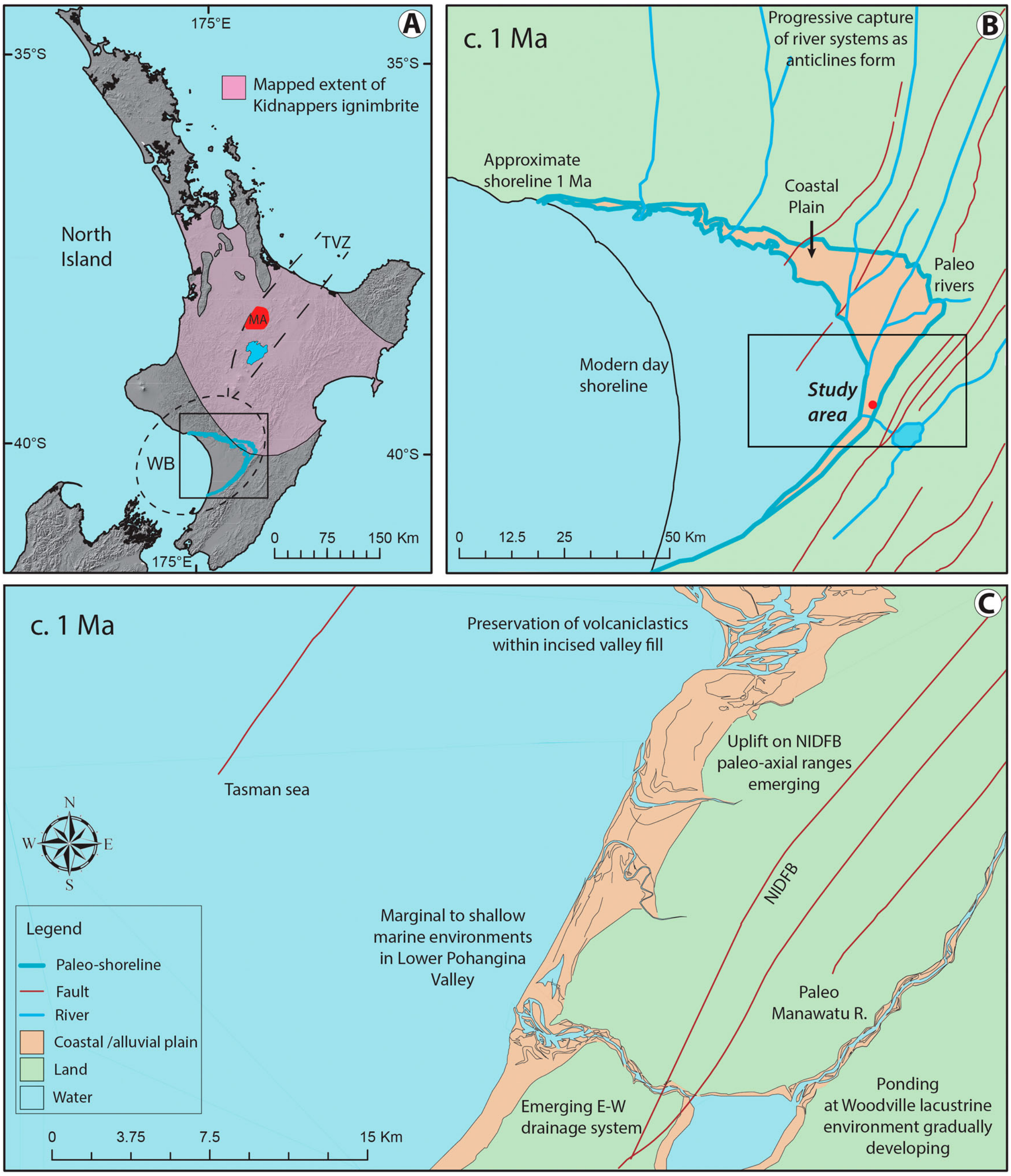

Figure 11. A) Map of the North Island showing mapped extent of the Kidnappers ignimbrite from Cooper et al. (2012) and location of the Whanganui Basin (WB) with respect to the Taupo Volcanic Zone (TVZ) and Mangakino caldera (MA). Blue outlines display the approximate location of the WB shoreline and coastal plain at c. 1 Ma, interpreted from the spatial distribution and facies of the Potaka and Pakihikura pumices. **B**) Schematic interpretation of the paleogeography of the WB at c. 1 Ma. **C**) Close up schematic of the study area showing interpreted paleogeography at c. 1 Ma.

Takapari Formation and equivalent strata preserved farther west.

Increasing tectonic activity along east coast fault systems facilitated evolution of an east–west drainage system across the previous location of the Manawatu Strait, where a structural low existed between the proto-Ruahine and Tararua ranges (c. 1 Ma, Figure 11). A lacustrine basin began to develop near Woodville in response to the changes in and the convergence of drainage networks. An early ancestor of the Manawatu River exited this basin, establishing an antecedent path to the Tasman Sea across the location of the present day main axial range (Piyasin 1966; Morrell 1991; Shane 1991; Lee et al. 2002) (Figure 11).

Conclusion

The lower Pohangina Valley contains an important Quaternary sedimentary record, resting unconformably above Pliocene mudstone and Mesozoic basement rock of the Torlesse Composite Terrane. Fossiliferous, tephra-fall and volcaniclastic deposits facilitate correlation of the local succession to the well-established WB chronostratigraphic framework. Takapari Formation comprises a dominantly fine-grained shallow marine to fluvio-estuarine succession. Marine beds (Facies Mm) are characterised by massive to laminated mudstone deposited in inner- to mid-shelf environments. Estuarine facies (Facies Es, C, Sh, Sp and He) include cross-bedded to laminated pumiceous sandstone, lignite, tephra-fall and mudstone beds deposited within intertidal to subtidal flats, back-swamp, tidal channel and inlet/flood-tidal delta sub-environments of a paleo-estuarine system. Estuarine deposition is consistent with the presence of carbonaceous mudstone, lignite and shellbeds composed entirely of small, closely packed *Austrovenus stutchburyi* (estuarine cockle).

The 5 cm thick Awahou Tephra is identified through stratigraphy, mapping and distinct glass-shard major element geochemistry. We provide an estimated astronomical age of c. 1.03 Ma for Awahou Tephra, based on its stratigraphic position within Cycle 33, 7 m below Potaka Pumice (c. 0.99 Ma). The type section is set at the Awahou South Road section described in Figure 2, lower Pohangina Valley.

Volcaniclastic sediments enter the succession during a marked change from fully marine to fluvio-estuarine deposition, sourced from rapid erosion of the distal unwelded portion of TVZ derived ignimbrites. Rapid entrainment of volcaniclastic sediment chokes paleo-fluvial systems resulting in aggradation and channel migration. Volcaniclastic deposition is followed by periods of relative quiescence characterised by landscape stabilisation, soil formation and preservation of organic matter.

The lower Pohangina Valley succession records the early rhyolite eruptive history of the TVZ between c. 1.6 and 0.9 Ma. Coinciding tectonic and volcanic events have led to preservation of important chrono-horizons on both sides of the present day main axial range, within successions recording the closure of the Manawatu and Ruataniwha straits. Concurrent change in depositional regime suggests eastern and western basins underwent simultaneous regression triggered by major tectonic and physiographic changes in the lower North Island. Following closure of the Manawatu Strait in Early Castlecliffian time (c. 1.6 Ma), marine conditions lingered in eastern WB, evidenced by intermittent deposition of marine sediments in the Pohangina area.

Tectonic activity along east coast fault systems facilitated evolution of an east–west drainage system across the previous location of the Manawatu Strait (c. 1 Ma), exploiting the structural low between the proto-Ruahine and Tararua ranges. Gradual development of a lacustrine basin near Woodville occurred in response to the changes in and the convergence of newly established drainage networks. An early ancestor of the Manawatu River exited this basin, establishing an antecedent path to the Tasman Sea across the location of the present day main axial range.

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