Hawke's Bay 3D Aquifer Mapping Project:

Deep borehole interpretation within Heretaunga Plains in the context of SkyTEM data and new Borehole 17137 (3DAMP_Well2)

October 2022
Hawkes Bay Regional Council Publication No. 5591

HAWKES BAY
REGIONAL COUNCIL
TE KAUNIHERA Ā-ROHE O TE MATAU-A-MĀUI

ISSN 2703-2051 (Online)
ISSN 2703-2043 (Print)

(06) 835 9200
0800 108 838
Private Bag 6006 Napier 4142
159 Dalton Street . Napier 4110

Environmental Science

Hawke's Bay 3D Aquifer Mapping Project:
Deep borehole interpretation within Heretaunga Plains in the context of SkyTEM data and new Borehole 17137 (3DAMP_Well2)

October 2022
Hawkes Bay Regional Council Publication No. 5591

Prepared By:
GNS Science

RL Kellett ZJ Rawlinson AG Griffin MJF Lawrence

C Tschritter TR Sahoo M Herpe

For: Hawke's Bay Regional Council

Reviewed by:
S Harper, Hawke's Bay Regional Council
S Cameron, GNS Science
J Lee, GNS Science

.

HBRC Environmental Science Section is ISO 9001:2015 certified

ISSN 2703-2051 (Online)
ISSN 2703-2043 (Print)

Hawke's Bay 3D Aquifer Mapping Project: deep borehole interpretation within Heretaunga Plains in the context of SkyTEM data and new Borehole 17137 (3DAMP_Well2)

RL Kellett
C Tschritter
ZJ Rawlinson
TR Sahoo
AG Griffin
M Herpe
MJF Lawrence

GNS Science Consultancy Report 2022/90
October 2022

DISCLAIMER

Use of Data:

Date that GNS Science can use associated data: March 2023

BIBLIOGRAPHIC REFERENCE

Kellett RL, Rawlinson ZJ, Griffin AG, Lawrence MJF, Tschritter C, Sahoo TR, Herpe M. 2022. Hawke's Bay 3D Aquifer Mapping Project: deep borehole interpretation within Heretaunga Plains in the context of SkyTEM data and new Borehole 17137 (3DAMP_Well2). Lower Hutt (NZ): GNS Science. 44 p. Consultancy Report 2022/90.

CONTENTS

FIGURES

TABLES

APPENDICES

EXECUTIVE SUMMARY

As part of the Hawke's Bay 3D Aquifer Mapping Project (3DAMP), twelve deep (>100 m) boreholes/wells were interpreted / re-interpreted and placed on two regional cross-sections to map the continuity of the stratigraphic units and provide calibration points for the SkyTEM resistivity models. Wells were chosen based on their depth, data reliability, and ability to provide insight into the stratigraphy of the Holocene and Pleistocene sediments within the Heretaunga Plains.

A particular focus for interpretation was placed on Borehole 17137 (3DAMP_Well2), which was drilled in 2021 as part of 3DAMP to provide supporting geophysical, geological, and hydrogeological data for the SkyTEM survey over the Heretaunga Plains. The location of Well 17137 was planned based on a preliminary interpretation of the SkyTEM data. The detailed interpretation of Well 17137 presented herein indicates that the SkyTEM data enabled project 3DAMP to make an accurate prediction of the geological facies as an input to planning a drilling campaign.

The other eleven boreholes selected for interpretation include the following:

- Three boreholes previously drilled for geological and hydrogeological research: Awatoto, Flaxmere, and Tollemache.
- Two boreholes previously drilled for petroleum exploration: Whakatu-1 and Taradale-1.
- Six deep groundwater wells from the HBRC well database: 4402, 2154, 5988, 16300, 16383 and 15795.

Additional information from 3DAMP utilised to understand the geophysical signature of the gravel, sand and clay layers encountered in the boreholes/wells include the following:

- SkyTEM-derived resistivity models that extend from the shallow subsurface (0 m – 5 m) to depths of 300 m to 500 m.
- A data inventory report for the Heretaunga Plains, which identified a wide range of additional geophysical and geological data, including GroundTEM, seismic reflection data, and geophysical borehole logs.

The twelve boreholes used in this study have a combination of sedimentological and geophysical data that were used to analyse the relationship between bulk resistivity, groundwater resistivity, grain-size, lithology and stratigraphy. The result of this work is a description of the main resistivity boundaries based on the SkyTEM resistivity and the other resistivity data available at the research wells. Using the data from Well 17137, Awatoto, Tollemache, and Flaxmere, a set of resistivity thresholds have been developed to characterise the sediments. Discussions are presented on the stratigraphic and hydrogeological implications of the interpretations. Specifically, the lower sections of the Awatoto, Tollemache and Flaxmere boreholes may be younger than previously interpreted, which suggests that deeper units mapped across the basin may have higher permeabilities than previously thought. This interpretation is supported by mean residence times from groundwater samples.

The information presented herein will be used to support future hydrogeological interpretation models within 3DAMP.

This page left intentionally blank.

1.0 INTRODUCTION

The 3DAMP project is a three-year initiative (2019–2022) jointly funded by the Provincial Growth Fund (PGF), Hawke's Bay Regional Council (HBRC) and GNS Science's (GNS) Groundwater Strategic Science Investment Fund (SSIF) research programme. The project applies SkyTEM technology (an airborne transient electromagnetic method) to improve mapping and modelling of groundwater resources within the Heretaunga Plains, Ruataniwha Plains and Poukawa and Otane basins. 3DAMP involves collaboration between HBRC, GNS and the Aarhus University HydroGeophysics Group.

As part of 3DAMP, SkyTEM data were collected in the Hawke's Bay region during January/February 2020 by SkyTEM Australia (SkyTEM Australia Pty Ltd 2020). Using these data, resistivity models were developed for the Heretaunga Plains by Rawlinson et al. (2021); a research borehole (Well 17137) was drilled to provide key geological and hydrogeological information in an area that is poorly mapped at depth (Lawrence et al. 2021); and a data inventory of supporting datasets and current state of information, to support hydrogeological interpretation of these resistivity models, was developed by Tschritter et al. (2022).

The work presented in this report utilises models and data from Lawrence et al. (2021), Rawlinson et al. (2021), and Tschritter et al. (2021). The final SkyTEM-derived resistivity models (both smooth and sharp) that lie close to the twelve selected wells (Well 17137, Awatoto, Tollemache, Flaxmere, Whakatu-1, Taradale-1, and HBRC wells 4402, 16300, 16383, 15795, 5988, 2154) are used to identify the relationship between the geological units and the electrical resistivity structure. These twelve wells are interpreted in detail to fill key data gaps in the deeper geological interpretation, support the structural and stratigraphic interpretation, and provide some key localities where the resistivity of aquifers and aquitards can be verified.

1.1 Well Selection

The location of the twelve wells utilised in this report are shown in Figure 1.1, and the details of each well are provided in Table 1.1. Wells were selected to meet the following criteria:

- The depth of an individual well is greater than 100 m, or in the case of the petroleum wells, a shallow near-by well was chosen to provide detail in the top 80 m. Getting reliable geological information at depth is important because the groundwater well information stored on the HBRC database is typically for shallow wells, with a mean depth of 32 m (Tschritter et al. 2022), and so information at greater depths is limited.
- The wells have a selection of detailed lithological descriptions, including the relative amount of clay, silt, sand, gravel, organic material, and shells.
- Three wells (Tollemache, Awatoto, 17137) have radiocarbon dates that identify the age of the sediment.
- The wells have additional ground geophysical data or borehole geophysical logs that allow more information to be derived about the physical properties that will influence the electrical resistivity and porosity. The GroundTEM data collected at most of the sites by Reeves et al. (2019) provides a good comparison with the SkyTEM data.
- The wells are located over a wide area within the Heretaunga Plains and lie close to SkyTEM profiles with reliable resistivity models.

The wells selected include:

- A research borehole (Well 17137) that was recently drilled as part of 3DAMP (Lawrence et al. 2021). This well has detailed lithology, grain-size analyses, sample resistivity measurements, geophysical log data, radiocarbon dates, and hydrogeological information including water chemistry and pumping tests of the aquifers.
- Three high-quality research wells (Flaxmere, Tollemache and Awatoto) that were drilled in the 1990s to provide information on the stratigraphy and hydrogeology (Dravid and Brown 1997). The current study utilises the data compiled by Tschritter et al. (2022) for these three wells.
- The petroleum well Whakatu-1 that has detailed cuttings logs and geophysical logs through most of the Early Pleistocene and Pliocene sediments. Information in the top 80 m is limited but is provided by a shallow borehole (Well 4402) drilled next to the petroleum well as part of the pre-drill site investigation (Ozolins and Francis 2000).
- The petroleum well Taradale-1 (Darley and Kirby 1969) that lies on the northern edge of the SkyTEM survey where the Holocene/Pleistocene sequence is thin. Well 2154 is located close to Taradale-1.
- Four additional high-quality wells from the HBRC database. Wells 5988, 16383, 16300 and 15795 were previously identified as having detailed geological logs to 100 m depth (mbgl), and GroundTEM data were acquired at each site as a calibration point during planning for the Heretaunga Plains SkyTEM survey (Reeves et al. 2019).

The well reports contain descriptions of the lithology with varying levels of detail (Tschritter et al. 2022). The primary lithology is available at depth intervals of 2 m to 5 m in most wells. A useful presentation of the sediment type, commonly presented on petroleum exploration wells, is the percentages of the main constituents (clay/mud/shale, silt, sand, gravel/pebbles, organics, shells and ash). For the research and hydrogeological boreholes, the percentages have been estimated based on the detailed lithological descriptions. The primary lithology is assumed to be at 75–100% of the sample. Minor amounts are allocated 10–15% based on the order in the description, and trace amounts are allocated 5%. The values are adjusted to sum to 100%. Modifiers on the primary lithology such as clayey, silty, or sandy are treated as a minor component. This approach to characterising the geology is subjective but provides a valuable dataset for rapid comparison across a section of wells. The detailed plots of the well logs are included in Appendix 1.1. The lithology data derived for the full set of wells are included as Excel files in Appendix 1.2.

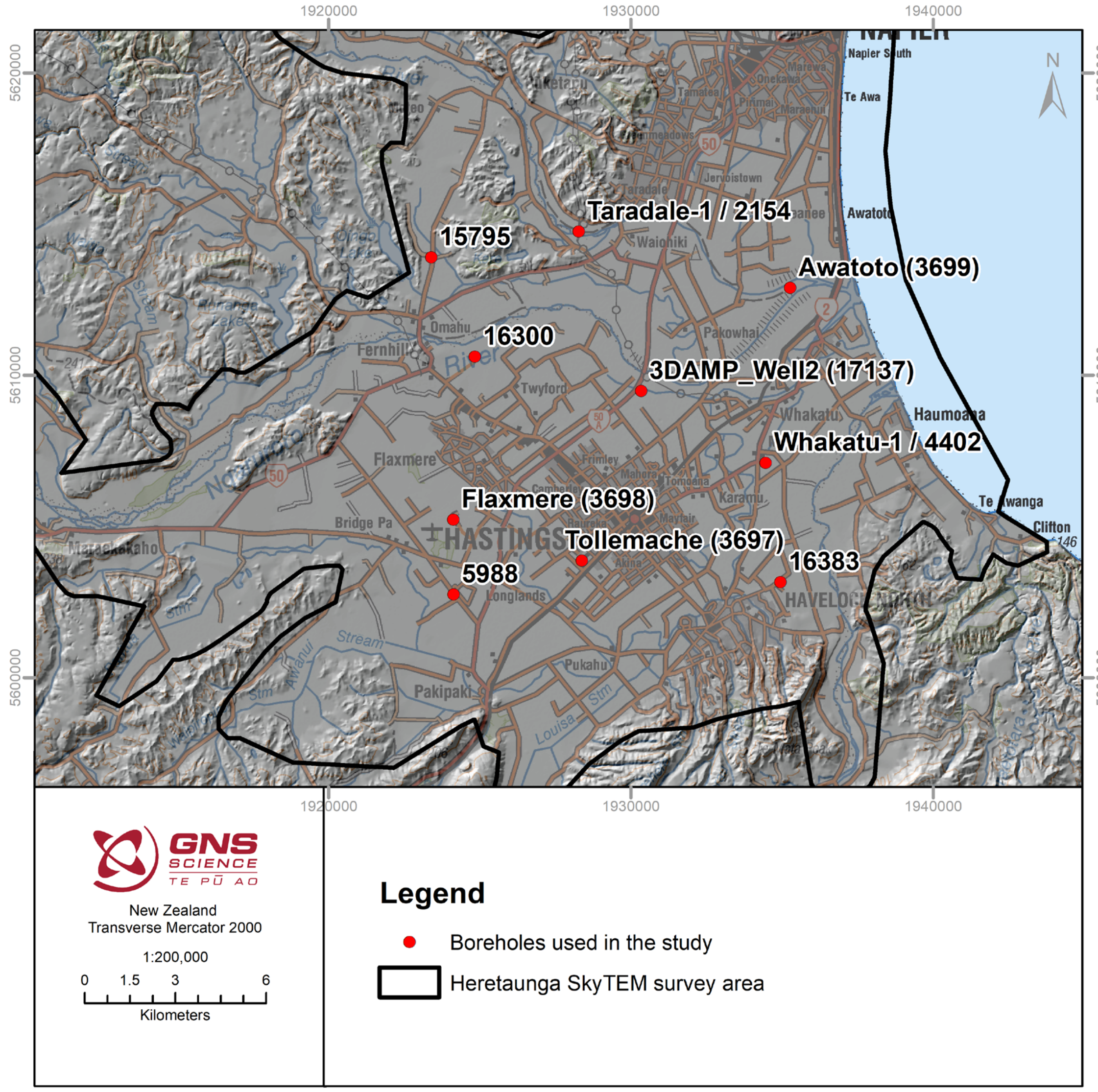

Figure 1.1 Location map of the Heretaunga Plains showing the SkyTEM survey area (Heretaunga SkyTEM survey area), the shaded elevation data and the boreholes included in this study.

Table 1.1 Wells utilised within this report. TD refers to the total depth of the well. Surface elevation, given in m above sea level (masl), have been obtained from a DEM in NZVD2016 (Tschritter et al. 2022). Initial objective refers to the primary use of the borehole. The comments include additional data available at the borehole, alternate names, and the key role of the data.

	Location (NZTM)	Surface Elevation (masl)	Depth (m)	Initial Objective	Comment
Well 17137	1,930,336 E 5,609,483 N	4.97	114.5	Research	3DAMP_Well2, GroundTEM
Flaxmere	1,924,123 E 5,605,229 N	17.16	137.5	Research	Well 3698, GroundTEM
Tollemache	1,928,379 E 5,603,871 N	10.24	256.5	Research	Well 3697
Awatoto	1,935,268 E 5,612,897 N	16.4	254.0	Research	Well 3699, GroundTEM
Whakatu-1	1,934,456 E 5,607,110 N	4.5	1455.0	Petroleum exploration	Good data below 75 m, GroundTEM
Well 4402	1,934,409 E 5,607,111 N	4.4	81.0	Petroleum pilot well	Provides uppermost 80 m of Whakatu-1, GroundTEM
Well 5988	1,924,136 E 5,602,753 N	15.44	109.0	Hydrogeology	GroundTEM
Well 16383	1,934,945 E 5,603,164 N	9.79	150.0	Hydrogeology	GroundTEM
Well 16300	1,924,835 E 5,610,620 N	18.65	126.5	Hydrogeology	GroundTEM
Well 15795	1,923,398 E 5,613,908 N	15.82	96.0	Hydrogeology	GroundTEM
Taradale-1	1,928,273 E 5,614,758 N	15.9	1660.0	Petroleum exploration	Thin Holocene/Pleistocene section
Well 2154	1,928,625 E 5,614,739 N	14.8	122.0	Hydrogeology	Provides uppermost 60 m of Taradale-1

1.2 Stratigraphy

The stratigraphic description of the Heretaunga Plains has evolved over time as various studies have interpreted the outcropping and subsurface geology in increasing detail. A summary of the different geological models for the Heretaunga Plains is provided in Tschritter et al. (2022). In the current report we include a description of the main developments in stratigraphy as they pertain to the borehole data.

Dravid and Brown (1997) derived a geological framework for the Heretaunga plains by constructing a series of cross-sections using well data from the regional council. They included the Flaxmere, Tollemache and Awatoto boreholes, which provided more detail to depths of 250 m (mbgl). Their approach was focussed on identifying depositional environments based on the descriptions of the sediments, and then assigning them to seven units associated to post glacial, glacial, and interglacial intervals. The Holocene comprised the post-glacial gravel channels, beach and shallow marine deposits, and a fluvial facies. The Pleistocene comprised two interglacial to glacial cycles determined by the presence of gravel dominated units (glacial) and sand/silt dominated units (interglacial). Dravid and Brown (1997) propose that the gravels at the base of the Awatoto and Tollemache wells could represent an older glacial event at 250 ka (MIS 8).

The stratigraphic architecture established by Dravid and Brown (1997) has been adopted by most hydrogeological studies to date. The model works well when focused on the research wells such as Awatoto, Tollemache, and Flaxmere. The challenge with the model is that it is difficult to extrapolate the facies across the large number of water wells in the Heretaunga Plains because the variability in the top 50 m is large. The second challenge is the deeper section and reconciling it with the outcrop pattern of the Kidnappers Group along the coast and along the edges of the basin.

Paquet et al. (2009) approached the stratigraphy by looking at the offshore high-resolution seismic and the Kidnappers Group exposed along the coastal section. They correlated unconformities and other boundaries in the offshore high-resolution seismic data with the mapped boundaries in outcrop, in boreholes, and the development of raised river and marine terraces onshore to establish a detailed early to middle Pleistocene stratigraphy based on high-order glacio-eustatic cycles. The stratigraphy was extended into the late Pleistocene and Holocene with a reinterpretation of the Awatoto and Tollemache wells. Paquet et al. (2009) interpret the gravels encountered at the base of the Tollemache and Awatoto wells to be the top of the penultimate glacial interval, so less than 150 ka (MIS 6), and interpret many of the gravel units in the wells to be higher order sequences within the interglacial periods. The disadvantage of this interpretation is that the level of detail in the model is not able to be extrapolated across the basin due to the lack of well data or high-resolution seismic data onshore.

A major refinement of the stratigraphy occurred in 2014 with the development of a 3D geological model designed to improve groundwater modelling (Lee et al. 2014). This model extended to 2500 m depth (mbgl), although there is less constraint below the base of the Holocene. The units mapped were lithological and based on surface geology and borehole data. Lithological units defined were Q1 river gravels and beach gravels, Holocene undifferentiated, Q2–4 glacial, Q5 interglacial, Q6 glacial, Q7 interglacial, early to middle Quaternary undifferentiated strata, and undifferentiated hydrogeological basement (Lee et al. 2014, Tschritter et al. 2022).

The 1:75,000 surface geological map (Lee et al. 2020) refined the detailed stratigraphy of the outcropping units based on the QMAP geology (Lee et al. 2011) and developed new formation and member names. The 2014 geological model was adjusted accordingly (Begg et al. forth coming). The Holocene was refined to include the new Heretaunga Formation with a fluvial member (Tollemache Member) and a shallow marine member (Awatoto Member), and the upper part of the new Maraekakaho Formation (post-glacial fluvial unit). The lower part of the new Maraekakaho Formation correlated with the Last Glacial Maximum (MIS 2–4). To better represent the large uncertainties at depth, the Q5-Q7 (the older glacial and interglacial units of Dravid and Brown (1997)) and early to middle Quaternary units were simplified into a combined Early to middle Pleistocene unit.

Figure 1.2 summarises the stratigraphy used in the recent mapping for the Heretaunga Plains (Lee et al. 2020). The global Marine (Oxygen) Isotope Stages (MIS) are adopted locally using absolute ages from radiocarbon dates and tephra chronology (Shane et al. 1996, Shane et al. 2002, Schulmeister et al. 2001) as well as relative dating of sea level changes based on marine and river terrace formation (Litchfield and Berryman 2005). Quaternary units Q1 to Q8, commonly used to describe lithological intervals and key horizons, are age equivalent to Marine Isotope Stages (MIS) 1 to 8. Figure 1.2 also includes the New Zealand Stage names and ages that are used primarily for the Early Pleistocene and Pliocene. The older petroleum wells refer to the New Zealand Stage names, so it is important to understand their relationships to the more detailed stratigraphy. Some of these units are not identified in the sub-surface but are present on the edges of the basin. It is likely that they extend into the basin and may be of value in supporting the geological interpretation of the SkyTEM geophysical models.

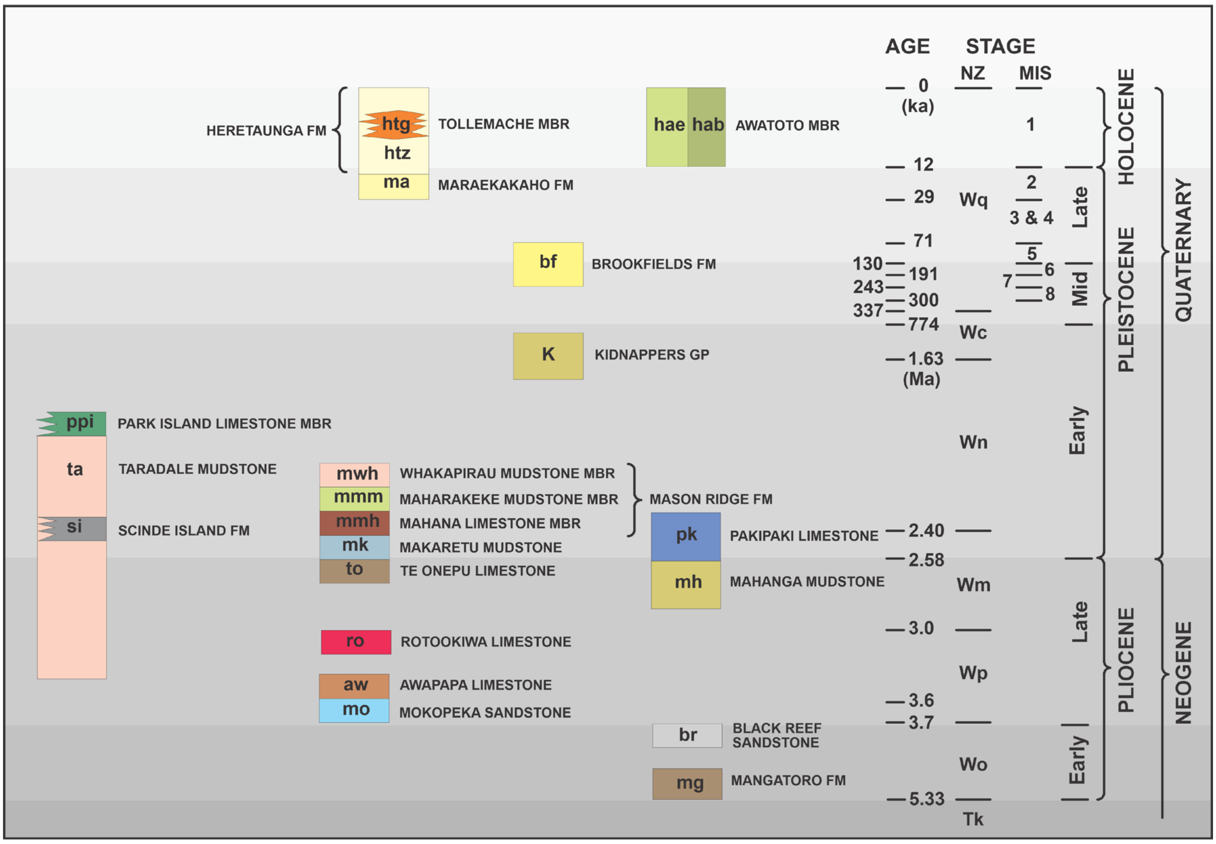

Figure 1.2 Stratigraphic column for the region (modified from Lee et al. 2020). The Heretaunga Formation includes “htg” river gravel, “htz” gravel, sand, silt, “hae” estuarine facies, and “hab” modern coastal plain deposits. New Zealand Stages are: Wq Haweran, Wc Castlecliffian, Wn Nukumaruan, Wm Mangapanian, Wp Waipipian, Wo Opoitian, and Tk Kapitean.

The geology map for the Heretaunga Plains is shown in Figure 1.3. The Heretaunga Plains are dominated by a basin that is formed in the structural depression (Napier syncline). The older Pleistocene – Pliocene units crop out on the southern and northern edges of the basin. There are several faults (Awanui and Tukituki faults) and local structural features (Taradale and Elsthorpe anticlines) that divide the basin into smaller depocentres.

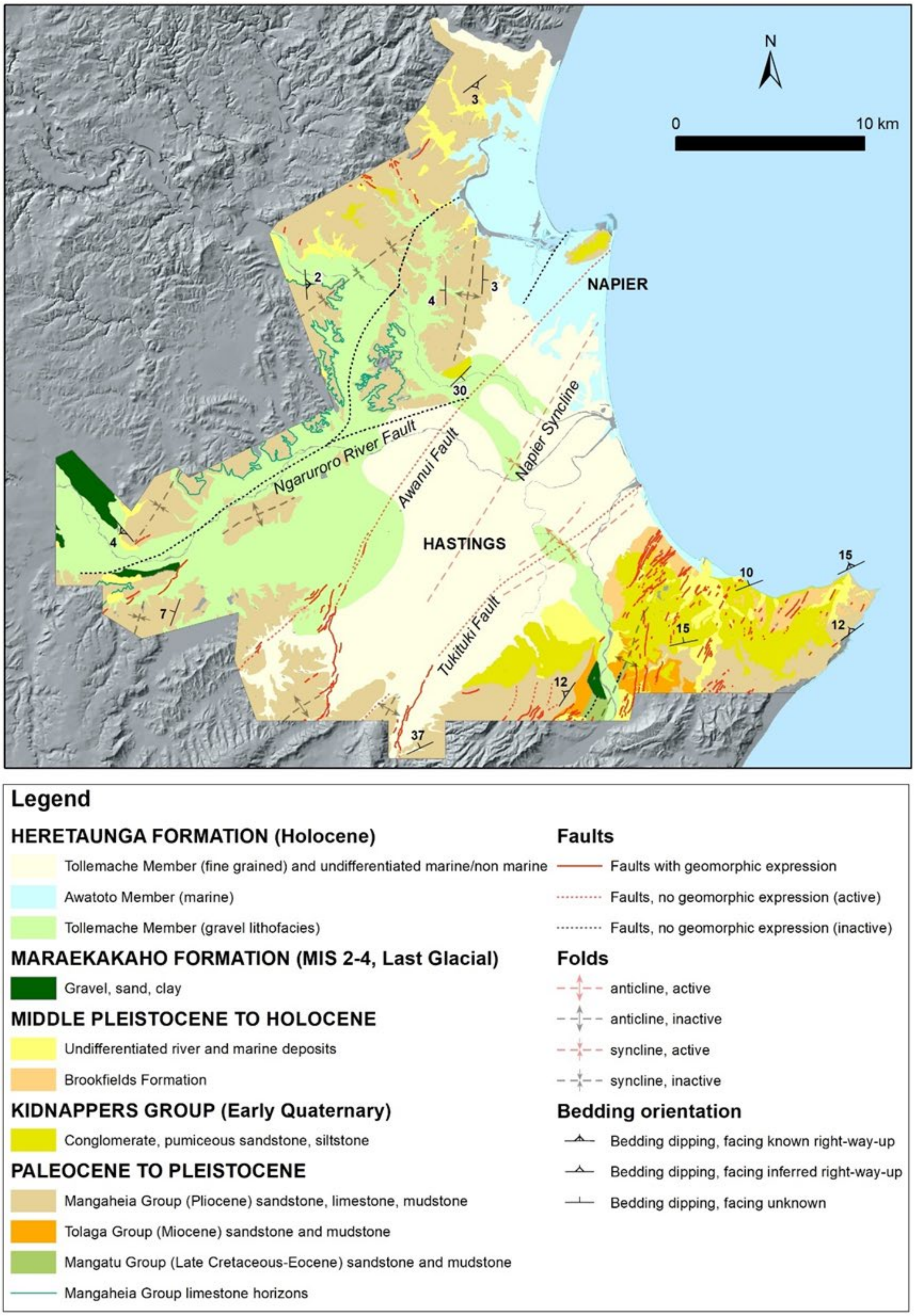

Figure 1.3 A simplified version of the 1:75,000-scale geological map of the Napier-Hastings urban areas (Lee et al. 2020). Figure from Begg et al. (forthcoming 2022).

All of the models for the subsurface geology of the Heretaunga Plains rely on an understanding of the complex relationship between glacial/interglacial periods, relative sea level change, tectonic uplift or subsidence, climate related vegetation changes, and the changes in sediment sources, transport, and deposition (Lee et al. 2014). The Heretaunga and Maraekakaho formations described in the extensive shallow borehole dataset display facies variations that reflect these influences. The older early to middle undifferentiated Pleistocene (including Kidnappers Group) will have similar patterns based on studies of the outcropping sections (Kamp 1982, Hull 1985, Paquet et al. 2009). The global relative sea level curve for the last 250,000 years can be used to identify the main drivers in sediment deposition (Figure 1.4). The New Zealand glacial intervals (Otira and Waimea) as well as the interglacial periods (Kaihinu and Karoro) defined by major South Island glacial features, are shown for reference (Barrell 2011). The major sea level lowstands are present in Q2 and Q6 and are referred to as the Last Glacial Maximum (LGM) and penultimate glacial maximum respectively.

During glacial intervals (MIS 2, 3, 4, 6, 8) sea level is low, the coastline is farther east on the continental shelf, there are higher levels of erosion on land due primarily to decreased vegetation coverage and cooler climates. The sedimentation process is dominated by gravel and sand deposited in rivers.

During interglacial intervals (MIS 1, 5, 7) sea level is close to modern day levels, the coastline may be farther inland from the current coast, and the warmer climate results in widespread forests. Erosion levels are lower, and deposition is dominated by finer grained sediments such as silts and clays. Shallow marine and estuarine deposits will also be more widespread in the vicinity or inland of the modern coast.

The local variations in bedrock geology, topography, and vertical land motion will produce subtle changes to these patterns of erosion and deposition.

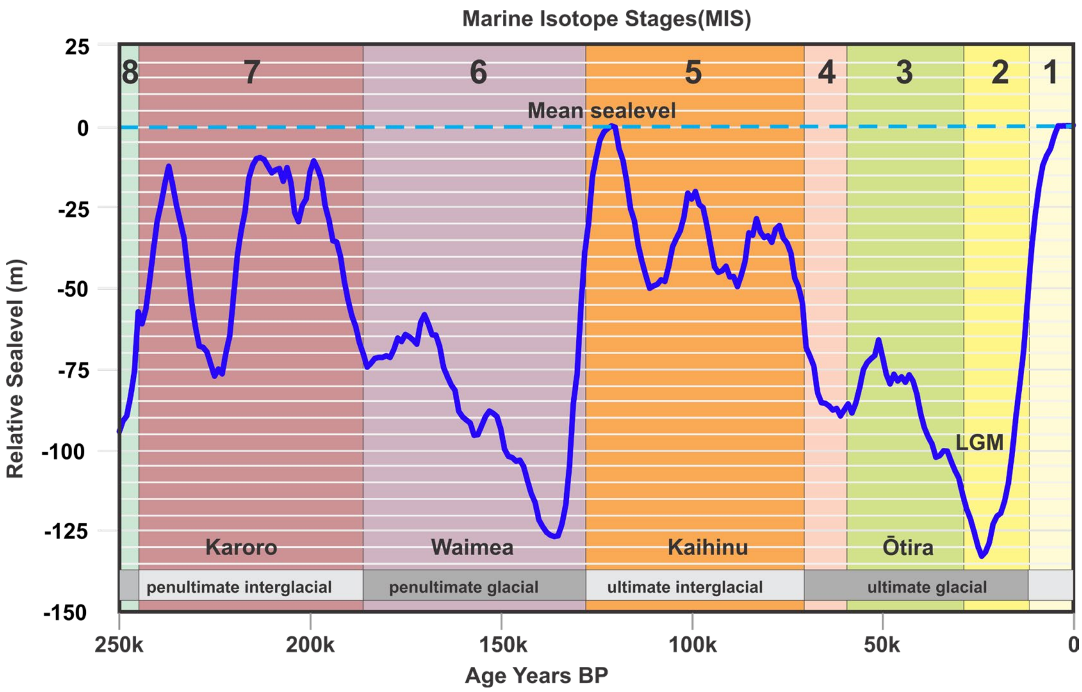

Figure 1.4 Relative sea level curve from 250 ka to present showing the Marine Isotope Stages (MIS) 1 to 8. The Last Glacial Maximum (LGM) is shown at 19–28 ka and the penultimate glaciation terminates at 128 ka (Adapted from https://www.sealevels.org/).

1.3 Description of Geological Formations

1.3.1 Heretaunga Formation

The Heretaunga Formation is composed of up to 50 m of Holocene-age river and marine deposits that crop out at the surface and are found in boreholes. The formation represents river and marine sediment deposited onto the plains after the LGM when sea level was rising. The Heretaunga Formation consists of the Tollemache and Awatoto Members. The Tollemache Member represents predominantly fluvial deposits of sand, gravel, silt and clay that were deposited mainly by the Tūtaekurī, Ngaruroro and Tukituki rivers. The Awatoto Member consists of shelly, fine-grained sand, silt, beach gravel and clay that represents marine deposition in the Holocene as sea level rose. The Awatoto Member is found predominantly in the northeastern part of the study area and represents the most recent incursion of the sea across low lying areas during MIS 1 (Figure 1.3).

1.3.2 Maraekakaho Formation

The Maraekakaho Formation is mapped as river gravel deposits that crop out at the surface in river terraces in the side valleys of the Heretaunga Plains. The formation is predominantly gravel but also contains sand, silt and clay. The formation is interpreted to occur in the subsurface throughout the Heretaunga Plains and is recognised as a widespread layer of gravel that underlies the finer-grained Heretaunga Formation. Maraekakaho Formation gravels are considered to have been deposited during the Last Glacial Maximum (MIS 2–4), when sea level was lower and large volumes of gravel were deposited in proximal settings by large river systems (Begg et al. forthcoming).

1.3.3 Early to Middle Pleistocene

There is a significant thickness of undifferentiated Pleistocene sediments in the Heretaunga Plains. Many of the units are only identified in isolated areas so cannot be extended across the entire basin. The Brookfields Formation is a beach-face sand mapped in the area southeast of Hastings. The Kidnappers Group is exposed along the coast of southern Hawke Bay[1] and in the hills south of Havelock North and west of Napier (Lee et al. 2011, 2014, 2020). It has been studied in detail by Kamp (1978), Hull (1985), Proust and Chanier (2004), and Paquet et al. (2009). The unit contains over 500 m of conglomerate, sandstone, siltstone, minor shales and tephra layers deposited in terrestrial and shallow marine settings in cycles with 100 kyr (80 m) and 20 kyr (10 m) periodicity in the early to mid-Pleistocene (Proust and Chanier 2004).

1.3.4 Paleocene to Early Pleistocene

The Kidnappers Group is deposited unconformably on the Paleocene to Pliocene units (Lee et al. 2011). Across central Hawke's Bay[1], the Kidnappers Group lies unconformably on late Pliocene sediments in the west and early Pliocene sediments in the east (Figure 1.2 and Figure 1.4). In the study area, the Late Pliocene to Early Pleistocene Pakipaki Limestone is present west of Hastings. In the centre of the basin, the Mahanga Mudstone is likely to be the hydrogeological basement, while along the southern coast of Hawke Bay, the early Pliocene Black Reef Sandstone is present (Proust and Chanier 2004, Paquet et al. 2011).

[1] Hawke Bay is the official name of the bay, whereas Hawke's Bay is the name of the region.

The Plio-Pleistocene limestone formations have been described in detail by Harmsen (1985), Kamp et al. (1988), Bland (2006), Caron and Nelson (2009), and Lee et al. (2011). The limestones are skeletal rudites, grainstones and packstones with interbedded siliciclastic sediments deposited in shoals associated with growing anticlines (Caron and Nelson 2009). The units dominated by mudstone, siltstone, and sandstone were deposited in deeper marine to shallow marine sections of the basins between the structural highs (Bland et al. 2008).

1.4 Most Recent Geological Model Stratigraphic Interpretation

The wells chosen for this study to support the interpretation of Well 17137 have also been included in the compilation used by Begg et al. (forthcoming) to build a 3D model of the Quaternary and Upper Pliocene – Lower Pleistocene strata in the Heretaunga plains. This model has been described in Tschritter et al. (2022). Figure 1.5 shows the complete set of ten wells (Well 17137 was not available at the time of this work and Whakatu-1 and 4402 are combined into a single log) with the primary lithology and the following tops:

- Base Heretaunga Formation
- Base Maraekakaho Formation
- Top Undifferentiated Pliocene-Pleistocene
- Top Taradale Mst

These tops have been picked based on any radiocarbon dates from samples (Awatoto, Tollemache), the lithological descriptions, and careful analysis of the adjacent wells (Lee et al. 2014). The primary lithology has been classified from the descriptions in the HBRC well data base. As discussed in Section 1.1, more detailed lithological descriptions are available for Awatoto, Flaxmere, and Tollemache (Brown 1993, Brown and Gibbs 1996, Brown et al. 1997, and Dravid and Brown 1997). The radiocarbon ages from organic material in Tollemache and Awatoto enables a more accurate determination of the base of MIS 1 (Base Heretaunga Formation). The base of the Maraekakaho Formation is less well determined due to an absence of absolute ages, and the predominance of gravel layers with few marker horizons.

At Taradale-1, the petroleum well report identified the top of the Pliocene mudstone based on cuttings (Darley and Kirby 1969). The adjacent water well 2154 encountered sandstone at a similar depth interval, which may be a sampling bias or the result of cave-ins from shallow units. The petroleum report (Ozolins and Francis 2000) picked the top of the Pliocene Mahanga Mst at 390 m depth (mbgl).

Well 16383 lies on the southern edge of the basin and the only tops picked in the well are the base of the Heretaunga Formation and the top of the Undifferentiated Pliocene-Pleistocene. The deeper strata was interpreted as Kidnappers Group that crops out immediately to the south (Figure 1.3).

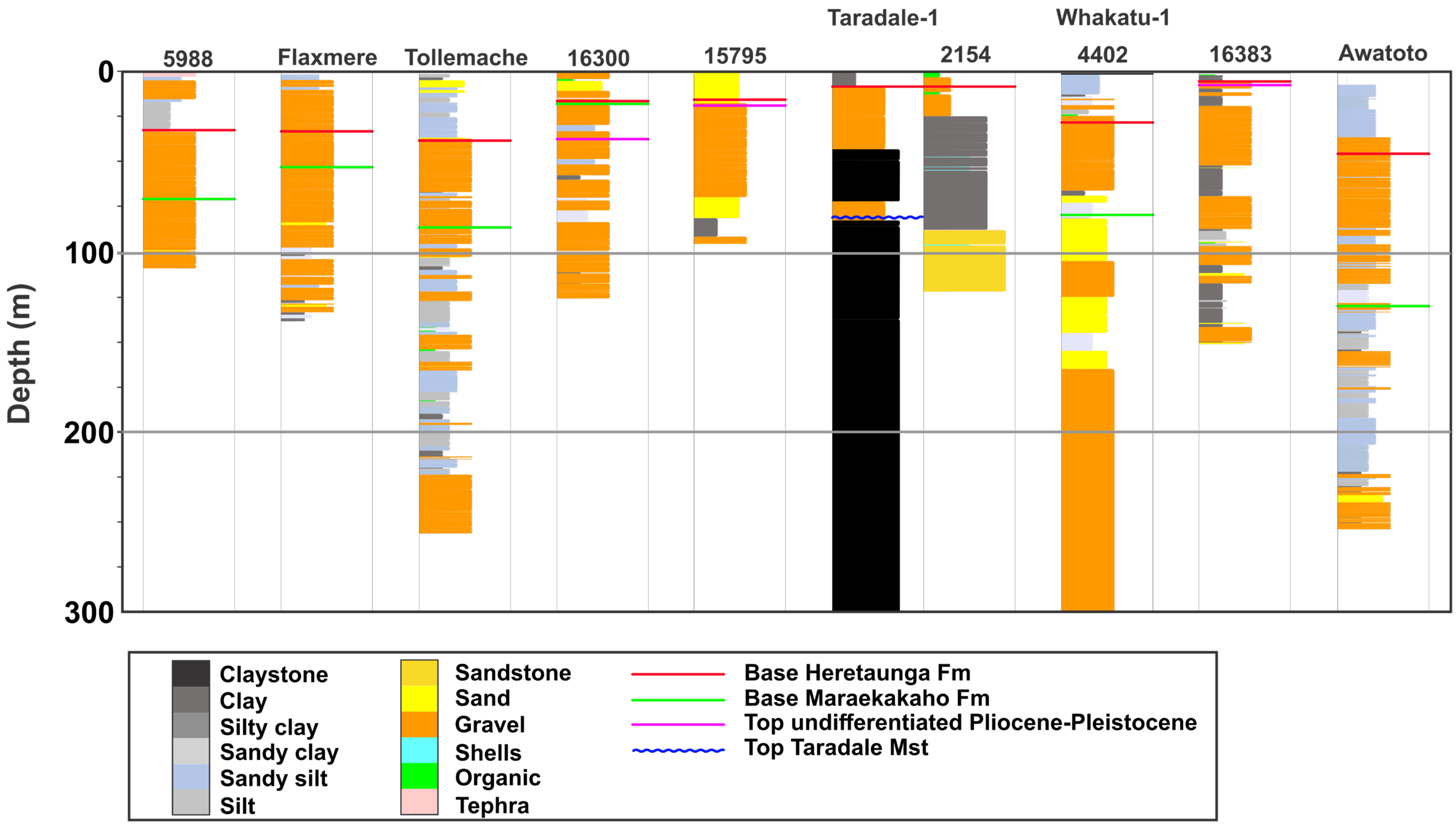

Figure 1.5 Lithology logs for wells 5988, Flaxmere, Tollemache, 16300, 15795, Taradale-1, 2154, Whakatu-1 / 4402, 16383 and Awatoto showing the geological interpretation of Begg et al. (forthcoming).

2.0 WELL 17137 DRILLING LOG INTERPRETATION

Well 17137 was drilled to the northeast of Hastings, just south of the Ngaruroro River (Figure 1.1). The location was designed to provide a point of geological control between the Awatoto well that is located near the coast, and the Flaxmere well located west of Hastings. The details of the drilling and associated geophysical and geological data collection are provided in a well completion report (Lawrence et al. 2021). The location of Well 17137 was planned based on a preliminary review of the SkyTEM data. The well was expected to show similar stratigraphy to the Awatoto well to the east, and the Flaxmere well to the west, as well as confirm the distribution of gravel aquifers and clay-rich aquitards close to Hastings.

The lithology was described continuously as material was brought to the surface during the augering and drilling with the cable tool and rotary drill bit (Lawrence et al. 2021). Samples were collected at specific intervals for grain-size analysis and electrical resistivity measurements. Wood and shell material were sampled at 5.9 m, 11.25 m, 14.8 m, 31 m and 54.7 m depth, and radiocarbon dates were obtained for these horizons. A composite log is shown in Figure 2.1 that characterises the samples as the dominant lithology:

- clay, silty clay, or sandy clay
- silt or sandy silt
- sand
- gravel
- wood and organic material
- shell material
- ash or tephra
- fill

The fraction of main lithologies in each sample is shown as a separate track.

The composite log for Well 17137 can be divided into two parts based on the lithological log (Figure 2.1). The upper 40 m are dominated by silt, sand, and clay layers. There are several discrete gravel layers and an organic rich layer at 15 m depth (mbgl). The layers are typically 2 m to 3 m thick. From 40 m to 114 m depth (mbgl), the geology is almost entirely gravel with one layer of organic material and clay (2 m thick), and two thin sand layers (<0.5 m). The recovery of samples from 76 m depth (mbgl) to the end of the well was restricted to one per 5 m or at locations of key changes, due to the uniformity of the material that was being encountered.

2.1 Detailed Lithological Interpretation

2.1.1 Unit 1 (0–20 m depth mbgl)

The top 10 m are dominated by medium brown to greenish brown silty clay. The first sand layer is encountered at 8.5 m depth (mbgl), and a thicker sand layer is present between 9.5 m and 11.5 m depth (mbgl). A layer of pumice is found at 11.5 m depth. From 12 m to 20 m depth (mbgl), the geology is a mixture of thick organic layers and gravel with only thin sand beds.

Wood sampled from a depth of 6 m yielded an age of 2795 +/- 21 yr BP. A sample of wood from the clay layer at 11.5 m depth (mbgl) has an age of 3321+/- 21 yr BP. The ash layer at 11.5 m depth is too old to be the Taupo Volcanic Eruption (1800 yr BP) but may be related to the older Waimihia Tephra dated at 3300 yr BP and identified in the Poukawa drillholes to the south (Shane et al. 2002). The organic rich layer present between 14.5 m and 16.5 m depth (mbgl) yielded an age of 4973 +/- 32 yr BP.

The grain-size distribution is centred on the silt to clay fraction from 0 m to 7.5 m depth (mbgl) but becomes more sand dominated at 10 m depth (mbgl). The gravel unit between 16.5 m and 20.0 m depth (mbgl) was not sampled for grain-size analysis but the resistivity is high and it has a low clay content.

Based on the lithological descriptions and the ages derived from organic layers, the upper 20 m of the borehole are interpreted to be the Tollemache Member of the Heretaunga Formation. The lithologies are consistent with the sediments having been deposited in or adjacent to a large river such as the current Ngaruroro.

2.1.2 Unit 2 (20–32 m depth mbgl)

From 20 to 32 m depth (mbgl) the upper section is dominated by sand and gravel layers, but the lower 10 m are fine-grained silt and clay. Shell fragments are present in the sand, silt, and clay layers. No samples were collected for dating.

The grain-size distributions change rapidly with depth. Some units are dominated by medium gravel, some by coarse silt, and others show an equal distribution of clay, silt, and very fine sand.

The presence of shell fragments indicates that this unit is the Awatoto Member of the Heretaunga Formation. The Awatoto Member is associated with shallow marine conditions which implies that the marine transgression extended as far inland as the eastern edge of Hastings. This is consistent with the mapped transgression shorelines in Dravid & Brown (1997; Figure 2.20). The sediments recovered from this interval are consistent with a depositional environment dominated by estuaries and coastal swamps with sea level changing frequently and facies varying laterally over short distances.

2.1.3 Unit 3 (32–40 m depth mbgl)

From 32 m to 40 m depth (mbgl), the lithologies are also interbedded clay, silt, sand, and gravel, but there is an absence of shell fragments. An age of 7964 +/- 30 yr BP was derived from a sample at 31 m depth (mbgl). The grain-size distribution for a gravel unit at 35 m depth (mbgl) is dominated by coarse gravel.

The strata are assigned to the Tollemache Member of the Heretaunga Formation. This unit is interpreted to be the immediate post-glacial interval where sediment is being deposited by low gradient rivers and fans as the marine transgression progresses across the shelf.

2.1.4 Unit 4 (40–57 m depth mbgl)

The interval between 40 m and 54 m depth (mbgl) is dominated by gravel with a thin sand layer at 48 m depth (mbgl). There is a sharp boundary at 54 m depth (mbgl). The underlying layer is a thin band of organic material sitting on a thicker layer of clay.

A 2 m thick clay layer at 54.5 m depth (mbgl) contained a wood fragment with an age of 13,685 +/- 55 yr BP.

The gravel has a medium to fine grainsize. The finer grainsized units below are dominated by medium to fine sand with very coarse silt.

The upper part of the unit could be included in the Tollemache Member and be a fluvial interval within MIS 1. Alternatively, it could indicate the transition to a glacial interval and be the upper part of the Maraekakaho Formation. A date of 13.7 ka for the organic layer places the lower part of the unit within MIS 2 (Figures 1.2 and 1.4).

2.1.5 Unit 5 (57–114 m depth mbgl)

There is another sharp contact at 57 m depth (mbgl) indicating the top of a massive gravel layer. This layer extends to the bottom of the hole. Sand layers were encountered at 67.5 and 93 m depth (mbgl). No samples were available for dating in this interval.

The gravel beds have grain-size distributions dominated by coarse clasts with some being very coarse. The two sand layers showed some variation in grain-size with the upper layer being dominated by very coarse sand and the deeper layer very fine to fine sand.

The presence of thick gravel units within MIS 2 are a good indication that the unit may correspond to the LGM.

2.1.6 Discussion

The well can be divided into two intervals based on the lithological descriptions. Units 1, 2 and 3 are within the upper part (0–40 m depth mbgl) and units 4 and 5 are in the lower interval. Unit 4 could be a transitional interval between the upper and lower section.

Well 17137 lies between Awatoto and Flaxmere (see Figure 1.1). Using the 3D geological model (Begg et al. Forthcoming) the presence of the Awatoto Member at this location was expected. The base of the Heretaunga Formation was estimated to be at 40 m depth (mbgl). The offsetting well 3393, located 70 m to the northeast, has the top of a gravel unit at 43.7 m depth (mbgl) This depth agrees well with the interpretation that the base of the Heretaunga Formation is within Unit 3 between 40 and 57 m depth (mbgl). The base of the Maraekakaho Formation was estimated to be at 104 m depth (mbgl) based on the 3D model (Begg et al. forthcoming). Unfortunately, the well was only drilled to 114 m depth and there is little variation in the geology from below 95 m. It is not possible to identify a contact within the lower part of Unit 5. The base of the Maraekakaho Formation could be deeper than 114 m depth (mbgl).

The SkyTEM geophysical data were also used to predict the geological strata at Well 17137 prior to drilling (Lawrence et al. 2021). The prognosis based on a combination of preliminary SkyTEM inversion models and seismic interpretation placed the base of the gravel deposit at 120 m depth (mbgl). It is clear from the interpretation of Well 17137 that the base of the gravel is not shallower than 114 m depth (mbgl). Information from the final SkyTEM inversion models and GroundTEM data related to this depth are presented in Section 4.0.

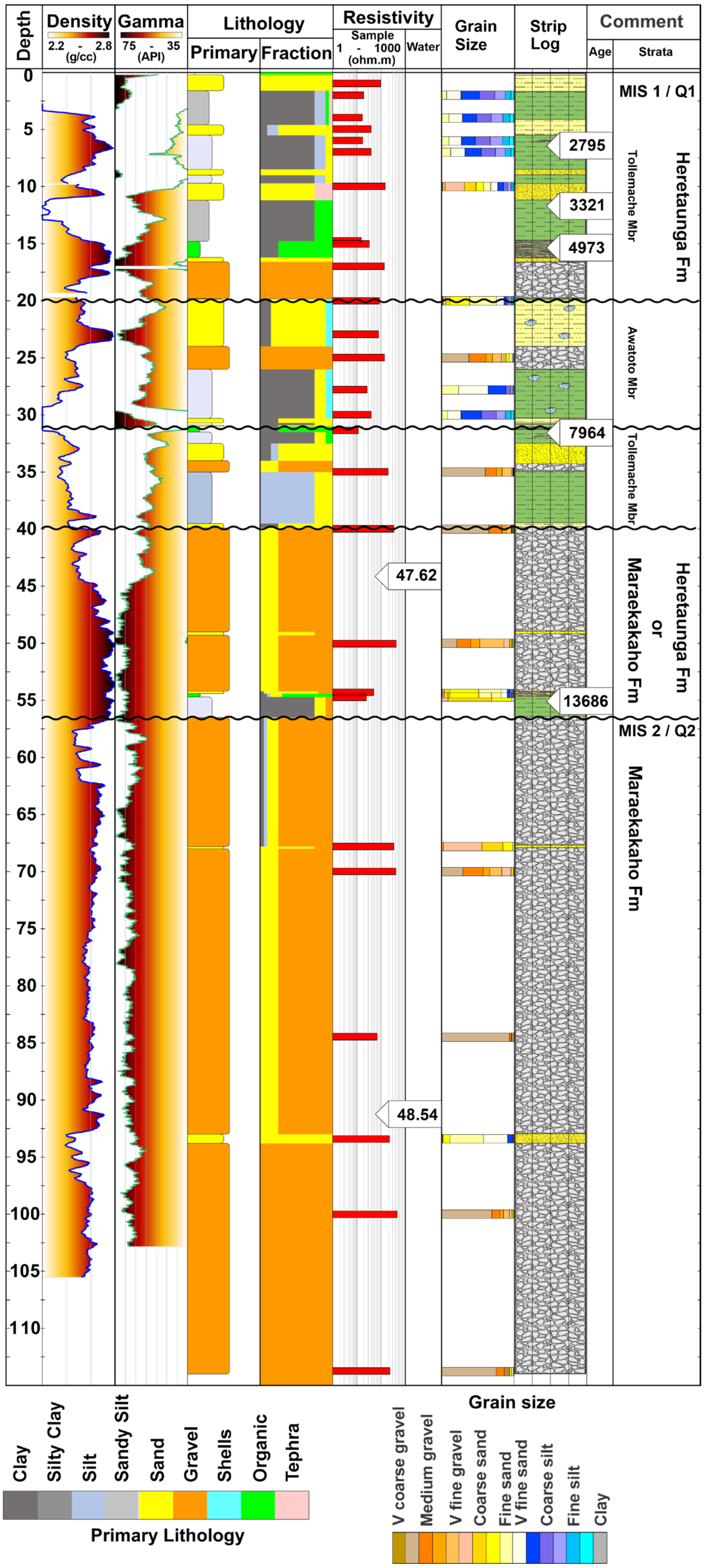

Figure 2.1 Composite log for Well 17137. The tracks from left to right are density, gamma ray (plotted in reverse), lithology (primary and fraction of each component), sample resistivity and groundwater resistivity (ohm.m), grain-size distribution, strip log from wellsite geology, radiocarbon dates in years from wood samples, and a comment on the stratigraphy (separated into 5 units). The gamma log is wrapped when it goes off scale to the right.

2.2 Geophysical Logs and Sample Measurements

Geophysical logs were collected at the completion of the drilling, so only tools capable of measuring rock properties through steel casing were run, i.e. gamma ray and density (Figure 2.1). During drilling, resistivity measurements were also made on a selection of the lithological samples (Lawrence et al. 2021). The resistivity data are displayed in Figure 2.1 as an interval log.

2.2.1 Geophysical Log Responses

The gamma ray tool provides estimates of the relative abundance of K, U, and Th in the sediments (Rider 1996). In typical sequences of sandstone, siltstone, and shale, the gamma ray log is used to separate units with high shale content from the sandstones with low shale content. In general, high gamma ray signatures indicate the presence of silty and clay-rich sediments, while low gamma ray signals are usually produced by sand, gravel, and more coarse-grained sediments. In some cases, gravel and sand can produce a significant gamma ray response if the grains and clasts contain anomalous amounts of K, U, or Th, such as those derived from volcanic or metamorphic rocks.

The density tool is also capable of determining some relative geological information from cased holes. The long-spaced and short-spaced density readings are designed to provide an estimate of the influence of the borehole on the measurement. The data can be combined to yield a compensated density measurement that provides an estimate of the bulk density of the geological units behind the steel casing (Rider 1996).

In the current well, the presence of the steel casing and potential washouts of the borehole wall behind the casing complicate the response of both the gamma ray tool and the density tool. For example, the geophysical logs in Figure 2.1 show the presence of a washout zone between 29.5 m and 31.5 m depth (mbgl). A washout zone occurs when the drill hole is enlarged due to erosion (associated with sediment consolidation and stresses during drilling).

The resistivity measurements on samples are described in Lawrence et al. (2021). There is an overall pattern of samples with higher proportions of fine-grain material (finer than sand or 63 μm) having lower electrical resistivity. The resistivity of the thick gravel units and the sand within these units is typically greater than 100 ohm.m. The silt and clay dominated samples have resistivities of less than 50 ohm.m.

The geological summary in Section 2.1 indicated that the well was divided into two main parts, with the upper 40 m more silt and clay rich and lower part (40 m – 114 m) more gravel-rich. The geophysical logs show a more complex pattern with potentially four intervals (Figure 2.1).

The upper 32 m of the well has a systematic pattern of variations in gamma ray and density signals over 3 m to 5 m depth intervals. Increases in density are matched with increases in gamma ray counts. In some intervals the pattern of log response is consistent with a fining-upwards sequence from gravels to silt and clay (Rider 1996). However, in most cases there is no apparent correlation with the boundaries picked from the samples. The resistivity samples do show that sand and gravel layers have higher resistivity than the clay layers. The organic-rich clay layers have a resistivity of as low as 15 ohm.m while the sand and gravel layers are up to 150 ohm.m. Figure 2.2 illustrates the repeated pattern of fining-upwards signatures in the gamma and density logs. The organic layer at 15 to 17 m depth (mbgl) has high density and high gamma ray response.

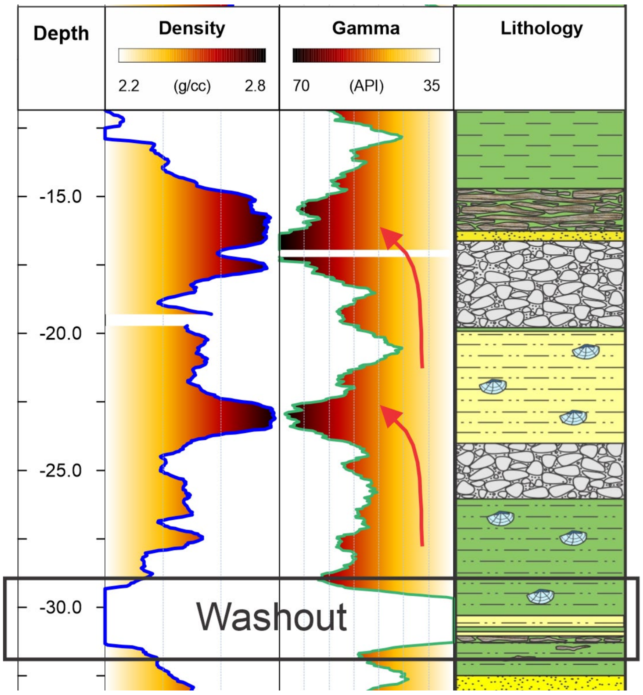

Figure 2.2 Example of gamma and density log response illustrating two fining upwards cycles (red arrows). The washout behind the casing results in sudden drop in signal for all of the logs.

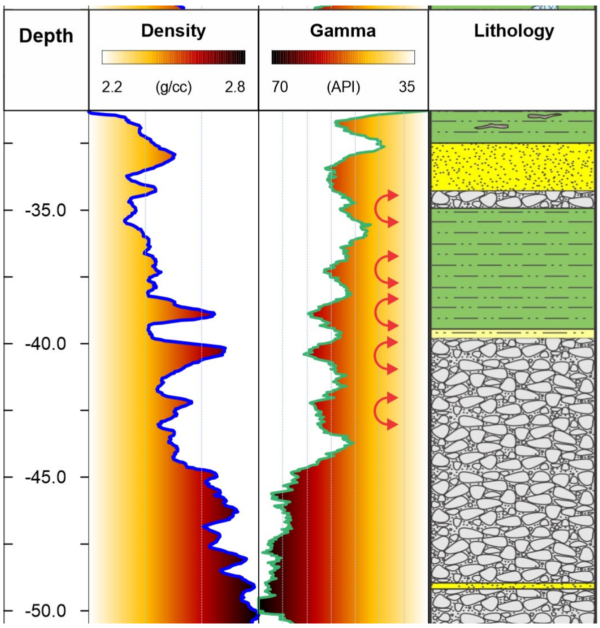

Figure 2.3 Example of gamma and density log response for fine scale (1–2 m) variations. The red arrows indicate the scale of the lithological variations seen in the gamma log.

The interval between 32 m and 45 m depth (mbgl) shows a gradual increase in density (2.2 to 2.4 g/cc), gamma ray signal (45–60 API), and the resistivity (10–350 ohm.m). A second-order variation can be seen at the 1 to 2 m scale in the density and gamma, indicating subtle variations in layering (Figure 2.3).

The gravel unit at 45 m to 56 m depth (mbgl) has a consistently high density (>2.6 g/cc) and a high gamma value (>65 API). The resistivity measurement on the sample from 50 m depth (mbgl) is the highest in the well (>400 ohm.m). The base of the unit is an organic-rich clay layer that is not distinguishable in the log response from the gravel layer above. The high gamma and high density indicate that the layer is dominated by a combination of lithologies with low porosity, and either high clay content or gravel clasts with high K, Th or U concentrations.

The geophysical logs show that the unit between 56 m and 114 m depth (mbgl) is dominated by gravel with uniform density (2.6–2.7 g/cc) and uniform gamma ray response (60–70 API). There are two well-defined beds at 57 m – 63 m and 92 m – 97 m depth (mbgl) where the density and gamma signals drop. The lower of these beds was sampled (92.5 m) and the grain-size analysis classified it as a very fine to fine sand (Figure 2.4).

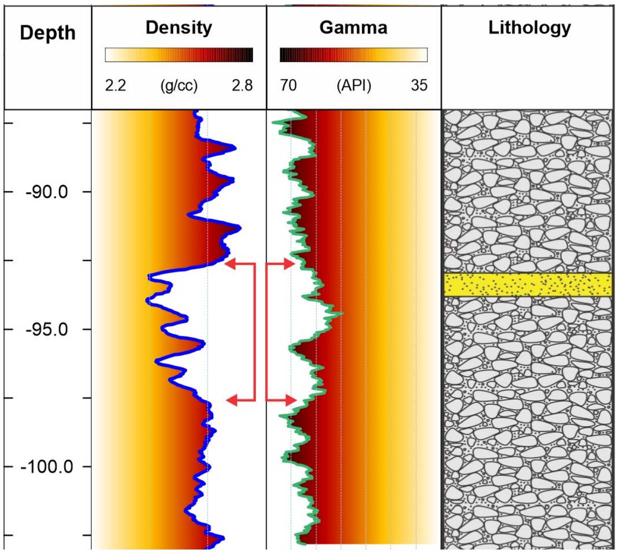

Figure 2.4 Example of gamma and density log response for a blocky channel.

2.2.2 Interpretation

There may be some uncertainty in the log responses due to casing effects and washouts as identified in Section 2.2.1. However, over a large section of the well the high density and high gamma ray signature of the Units 4 and 5 is unexpected because gravel beds with low clay content are usually identified by low gamma signatures (Rider 1996). The samples of gravel recovered from the well are described as a mixture of sandstone and mudstone clasts (Lawrence et al. 2021). The provenance of these clasts is expected to be the greywacke basement exposed in the Kaweka and Ruahine ranges west of the Heretaunga Plains. The greywackes are part of the Torlesse Composite Terrane (Mortimer 1994) and are composed of both sandstones and mudstones. The sandstones have a typical quartz, feldspar and lithic content for Mesozoic greywacke. Sandstone clasts with higher feldspar and lithic content could potentially produce anomalously high gamma ray signatures. A higher concentration of mudstone clasts could also produce elevated gamma ray levels. Alternatively, there may be a more pervasive clay matrix or thin clay layers that are not recovered in the samples collected on the rig. This geophysical response requires more investigation as it may be a tool for distinguishing gravel units from different sources. From the perspective of the hydraulic properties the high density indicates that the macro-porosity is low. Macro-porosity is controlled by a combination of the grainsize distribution, grain angularity, and clay content.

The fining upwards signatures in Unit 1 and Unit 2 (Figure 2.2) is potentially an indication of the presence of meandering fluvial channels. The finer scaled cycles shown in Units 3 and 4 are consistent with the transgression of the marine sequences over the area following the glacial interval.

In Unit 5, the blocky channel signature at 57 m – 63 m and 92 m – 97 m depth (mbgl) is consistent with a depositional environment with less silt and clay in the system. This unit is interpreted to be the Maraekakaho Formation that was deposited within the LGM and the immediate post glacial period.

3.0 CROSS-SECTIONS

3.1 Data

The detailed interpretation of Well 17137, presented in Section 2.0, has been combined with the lithological and stratigraphic data from the 11 wells described in Section 1.0 to build two regional cross-sections (Figure 3.1). The data from each location include:

- Primary lithology
- Percentage clay, silt, sand, gravel, shells, organic material, and tephra
- Radiocarbon dates (Awatoto, Tollemache, Well 17137)
- GroundTEM geophysical models (not available at Tollemache)
- SkyTEM geophysical models

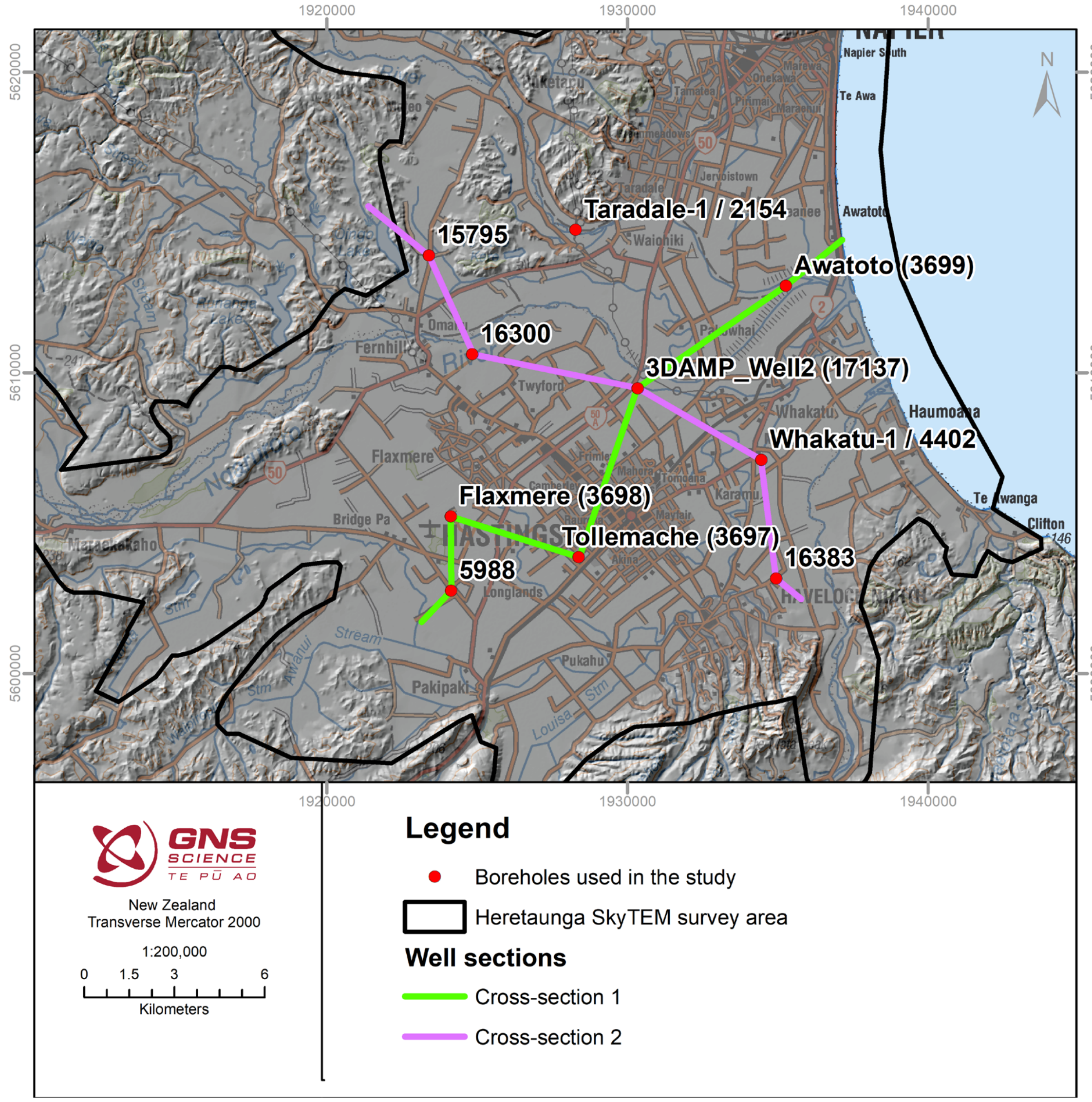

Figure 3.1 Cross-sections used to interpret the high-quality boreholes in the Heretaunga Plains. Cross-section 1 is oriented along the axis of the Napier syncline and cross-section 2 is perpendicular to the axis. The cross-sections intersect at Well 17137.

The geological interpretation framework of Lee et al. (2020) was used to interpret the lithological units (Figure 1.3). Reeves et al. (2019) made an initial interpretation of the resistivity structure at each of the wells based on the GroundTEM-derived resistivity models. These interpretations were used as the starting point for the interpretation of the SkyTEM data. Cross-sections 1 and 2 are shown in Figure 3.2 and Figure 3.3, respectively.

3.2 Resistivity Models

The GroundTEM and SkyTEM models can be described in terms of four prominent resistivity units.

- Resistivity Unit 1 is a shallow layer from 0 to 50 m depth (mbgl). The resistivity unit shows some lateral changes. The unit has a moderate resistivity at Tollemache and a high resistivity at Flaxmere and Well 16383. At all other sites, the unit is divided into two layers with a shallow high resistivity layer overlaying a low resistivity layer.
- Resistivity Unit 2 is a thick high resistivity layer at all sites. It extends to a depth of 100 to 150 m (mbgl).
- Resistivity Unit 3 is a layer from 150 m to 400 m depth (mbgl) that can be either a single layer of moderate resistivity (Flaxmere, Tollemache, Awatoto, Whakatu-1), or divided into an upper low resistivity unit and a lower moderate to high resistivity (Well 17137, Well 15795, Well 16300, Well 5988, Well 16383).
- Resistivity Unit 4 is the base of most GroundTEM and SkyTEM models and extends from 300 to 500 m depth (mbgl). At most sites the layer is poorly resolved due to its depth. The unit can be divided into three characteristic responses. At wells 5988, Flaxmere, 17137, and 16383 the resistivity is low. At wells Whakatu-1, Tollemache and Awatoto the resistivity is moderate to high. At wells 16300 and 17595 the unit is divided into an upper low resistivity layer and a lower high resistivity layer.

A more detailed analysis of the resistivity values derived from the SkyTEM and GroundTEM models is presented in Section 4.0.

3.3 Stratigraphic and Lithological Correlation

The cross-sections are presented as a well-to-well section with a summary of the lithological, stratigraphic, and geophysical data displayed at each well. For each well we have interpreted the following stratigraphic tops as primary boundaries (black wiggly line) and secondary boundaries (black dashed line) where they are present:

- Base of the recent alluvium (Recent)
- Top of the immediate post glacial interval (Post Glacial)
- Top of the Maraekakaho Formation or MIS 2 (LGM)
- Top of the last interglacial or MIS 5 (Interglacial)
- Top of the earlier glacial events in Awatoto and Tollemache (Glacial?)
- Top of Pleistocene / Pliocene bedrock in the petroleum wells (Pliocene mudstone)

The stratigraphic control is strongest at wells Awatoto, Tollemache, and Well 17137 where radiocarbon dates are available to constrain the Holocene sea level maxima (6.5–7.5 ka) and the top of MIS 2 (11–12 ka). Ages derived from biostratigraphical analysis in Awatoto, Tollemache, Flaxmere, Whakatu-1, and Taradale-1 are the next most reliable source of stratigraphic control. Lower confidence must be placed on interpretations based on changes in lithology. However, geophysical log data can support the lithological interpretation in wells where lithological changes may be missed in the sampling. Similarly, the presence of shell material can be a reliable indicator of shallow marine conditions, provided the samples can be confirmed to be representative of the interval.

The process of making correlations between the wells included identifying similar patterns of lithologies, complying with any stratigraphic boundaries constrained by dating, and using the GroundTEM, and SkyTEM data to guide the lateral changes in physical properties. The cross-sections have the following interpreted horizons:

- Ground surface (grey)
- Marine transgression or Awatoto Member (cyan)
- Top of the gravel either MIS 1 or MIS 2 (yellow)
- Base of the gravel either Maraekakaho Formation or older (green)
- Gravel or coarse-grained unit within the Early to Middle Pleistocene (pink)
- Top mudstone or Taradale/Mahanga/Makaretu Formation (blue)
- Top limestone or Scinde Island Formation (purple)

The ground surface (GL) is derived from the surface location of each well, which varies from 4.5 m to 18.7 m above mean sea level. The ground level is recorded in the header for each well.

The marine transgression is picked as the top of the fine-grained units (clay and silt) that contain shell fragments. This horizon is the top of the Awatoto Member of the Heretaunga Formation and is present over the eastern part of the study area. The silts, sands and gravels that lie above this horizon are allocated to the Tollemache Member of the Heretaunga Formation.

The top of the shallowest main gravel unit is marked as the top gravel and is correlated with a gravel in the Tollemache Member or the Maraekakaho Formation. In places, this top lies below the Awatoto Member, but in other places it is overlaid by silts, sands and gravel with no marine component.

The top of the Maraekakaho Formation is difficult to pick in the lithological logs as it is often only marked by a thin finer grained layer within a thick gravel sequence. Radiocarbon dates are needed to definitively identify the boundary between MIS 1 and MIS 2.

The top of the undifferentiated Pleistocene is a pick in the Awatoto and Tollemache wells. The exact age of this horizon is not defined but it is interpreted to be younger than the top of the Kidnappers Group (Lee et al. 2020).

The gravels in the middle sections of Awatoto and Tollemache are interpreted by Dravid and Brown (1997) to represent the penultimate glaciation (MIS 6) and the gravel at the base of the wells to be as old as the preceding glaciation (MIS 8). However, Paquet et al. (2009) interpret the basal sections of Awatoto and Tollemache to be younger and describe them as MIS 6 fluvial to shoreface deposits. If the gravel units at the base of Awatoto and Tollemache are significantly younger than originally proposed by Dravid and Brown (1997) then these units and deeper gravels may have better aquifer properties that originally considered. The young mean residence time (MRT) for samples at the base of Flaxmere supports better hydraulic properties at depth (Morgenstern 2021).

The top of the Late Pliocene to Early Pleistocene mudstones is present in the petroleum wells Whataku-1 and Taradale-1. A second bedrock horizon is picked based on the Whakatu-1 well as the top of the Late Pliocene / Early Pleistocene Limestone that is equivalent to the Scinde Island Formation (Figure 1.3) that crops out on Napier bluff (Lee et al. 2011 and 2020).

The two cross-sections are described in more detail in the following sections.

3.4 Cross-section 1

This cross-section extends from Well 5988 (north of Pakipaki) to Awatoto (at the coast) and includes Wells 17137, Tollemache, and Flaxmere (Figure 3.1). Whakatu-1 lies on a structural high that trends parallel to the profile, so it has not been included in this section. Figure 3.2 is the well-to-well section with equal spacing between the five wells. The actual distance is indicated in the labels at the top of the figure. The resistivity units and geological units are described from deeper to shallower intervals.

3.4.1 Resistivity Unit 4

At the western end of the cross-section (Well 5988) the GroundTEM resistivity decreases rapidly at 305 m depth (mbgl) to less than 10 ohm.m. At Flaxmere the same contact is seen at 465 m (mbgl). At Well 17137 the resistivity drops to 10 ohm.m at a depth of 405 m (mbgl). At the eastern end Awatoto the layer has moderate resistivity and is not significantly different from the layer above.

3.4.2 Resistivity Unit 3

At Well 5988 the unit is 150 m thick and is divided into an upper layer of 20 ohm.m and a lower layer of 50–60 ohm.m based on the GroundTEM model. At well 17137 the same two layers are detected but the thickness of the unit has doubled to 300 m. At the remaining wells the unit is characterised as a transition from high resistivity (>100 ohm.m) in the unit above to moderate resistivity values (70–80 ohm.m).

3.4.3 Resistivity Unit 2

This unit is the most laterally uniform of the four units. It is characterised by high resistivities (200 to 500 ohm.m) at all wells. The thickness of the unit varies from 75 m at Wells 5988 to greater than 120 m at Flaxmere.

3.4.4 Resistivity Unit 1

At the western end of the cross-section (Well 5988) the unit is 40 m thick and has a 15 m thick upper layer of high resistivity (>500 ohm.m) and a lower layer of <20 ohm.m. The low resistivity layer pinches out at Flaxmere where the entire unit is greater than 100 ohm.m. From Tollemache to the coast the unit is dominated by low resistivities (20–40 ohm.m) with only a thin high-resistivity surface layer present at Well 17137 and Awatoto.

3.4.5 Interpretation

Establishing a relationship between the geophysically derived resistivity units and the lithological and stratigraphic boundaries requires interpretation and consideration of the uncertainties associated with each unit.

3.4.6 Top Mudstone (Mahanga / Makaretu Fm)

The shallowest Pliocene to Early Pleistocene consolidated sediments are identified as the Mahanga Mudstone in Whakatu-1 and Hukarere-1 (Ozolins and Francis 2000, Westech Energy 2001). The Makaretu Mudstone is mapped in outcrops in the southwest of the study area (Lee et al. 2020). The resistivity of the mudstones is generally less than 10 ohm.m in geophysical logs due to the high clay content. None of the wells on this cross-section are deep enough to confirm this boundary but we interpret the top of Resistivity Unit 4 (blue) to be the top of the Mahanga or Makaretu formations.

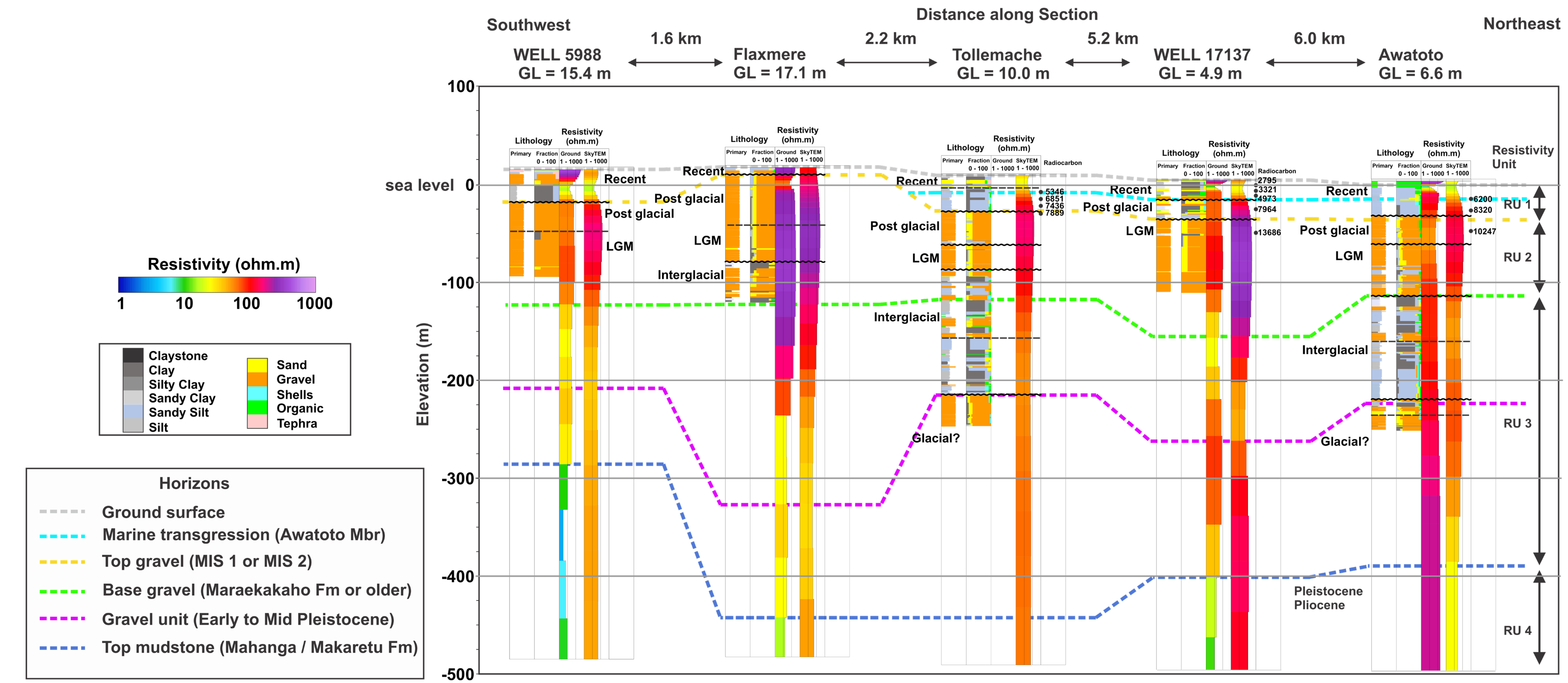

Figure 3.2 Section 1. Each well is presented as a SkyTEM model (smooth), a GroundTEM model, and the lithology (primary and fraction). GL refers to ground level elevation calculated from a DEM (Tschritter et al. 2022). Radiocarbon ages in years are shown. Southwest is inland and Northeast is near the coast. See Figure 3.1 for location of cross section. The SkyTEM inversion models are sampled from the following distances away from each well: Well 5988 152 m, Flaxmere 108 m, Tollemache 647 m, Well 17137 153 m, Awatoto 48 m. The resistivity units (RU) are shown on the right side of the section.

This page left intentionally blank.

3.4.7 Early to Middle Pleistocene

The early to middle Pleistocene is represented by the interbedded clay, silt, and thin gravel units that are present in the lower half of Awatoto and Tollemache. They are interpreted to be interglacial and glacial sediments of MIS 5–6 age. A thicker interval of gravel is intersected at the base of the two wells. The Kidnappers Group comprises similar alternating sequences of mudstones, siltstones, sandstones and conglomerates but it is not clear if these strata have been intersected by the Awatoto and Tollemache wells. Resistivity Unit 3 has an upper layer of low resistivity that correlates with the middle Pleistocene clay and silt sections. The lower layer has higher resistivity and may indicate a thicker interval of gravel and sand. The top of the undifferentiated Pleistocene (purple) is picked at the top of this resistivity increase. The purple boundary is a marker within Resistivity Unit 3.

3.4.8 Maraekakaho Formation

Between the Base Maraekakaho Formation horizon (green) and the Top gravel horizon (yellow), the GroundTEM and SkyTEM resistivities are high (up to 500 ohm.m) corresponding to Resistivity Unit 2. This interval comprises thick gravel layers and some thin clay beds. Based on the resistivity models it is not possible to separate the older LGM gravel from the younger post-glacial gravel (MIS 1). In Tollemache, Awatoto, and Well 17137 there is a silt and clay layer between the two gravel packages that may indicate a boundary between MIS 2 and MIS 1. However, this layer is too thin to be mapped with the GroundTEM and SkyTEM data.

3.4.9 Heretaunga Formation

Resistivity Unit 1 correlates well with the Heretaunga Formation. The combination of high and low resistivity layers can be interpreted in terms of the different members of the Heretaunga Formation. The geological unit above the Top gravel (yellow) is a combination of immediate post-glacial silt and sand of the Tollemache Member, and the shallow marine deposits of the Awatoto Member.

Above the top of the Awatoto Member (cyan) the surficial layer is a combination of silt, organic material, tephra and modern river gravel that is up to 20 m thick. The resistivity is greater than 500 ohm.m for gravel deposits at Flaxmere and Well 5988. At Well 17137 and Awatoto, the resistivity is less than 200 ohm.m with some fine-grain sediments up to 10 m thick. At Tollemache, the surficial layer is dominated by sand and clay and the resistivity is 50 ohm.m.

The Awatoto Member represents a rapid marine transgression and is detected as low resistivity clays and shell-rich horizons in the Awatoto and Tollemache wells, and Well 17137. The unit pinches out to the east of Flaxmere.

3.5 Cross-section 2

The second cross-section is roughly perpendicular to cross-section 1. Well 16383 is located northeast of Havelock North on the southern edge of the basin, and Well 15795 lies north of Fernhill on the northern edge (Figure 3.1). The petroleum well Whakatu-1, Well 17137, and Well 16360 are included on the section. Whakatu-1 is merged with the shallow borehole Well 4402 to provide more detailed geological information in the top 75 m.

At Taradale-1, the SkyTEM data show shallow low resistivity hydrogeological basement in the region so this well is a good calibration point for the Lower Pleistocene/Pliocene strata. The well contains geophysical logs, drilling parameters such as rate of penetration, and good cuttings descriptions. Well 2154 lies 300 m away from Taradale-1 but it confirms the presence of 20–30 m of gravel overlying siltstone and sandstone at 50–80 m depth (mbgl). Unfortunately, the SkyTEM survey data close to the wells are noisy due to the presence of a large powerline. These two wells have not been included in the section because they overlap with the data from Well 15795.

The well-to-well section shown in Figure 3.3 has the same tops and horizons used in cross-section 1 (Figure 3.2). It has the additional horizon at the base of the section that corresponds to the top of a Pliocene limestone unit. The shallow horizon corresponding to the top of the Awatoto Member is present at Well 17137 but is not present at any other well on the section so is not shown. The resistivity units and geological units are described from deeper to shallower intervals.

3.5.1 Resistivity Unit 4

At the southern (Well 16383) and northern (Well 15795) ends of the cross-section, the top of Resistivity Unit 4 is defined at the depth where the resistivity drops below 10 ohm.m. The same contact is seen at Well 16300 and Well 17137. Resistivity Unit 4 also includes a deeper high resistivity layer that is detected at wells 16383, 16300, and 15785. The resistivity increases above 20 ohm.m at a depth of 300–320 m (mbgl) at the northern end of the cross-section.

3.5.2 Resistivity Unit 3

Resistivity Unit 3 is defined as the unit below the high resistivity zone but above the 10 ohm.m boundary. At Well 16383, in the south, it is approximately 150 m thick. It increases to approximately 250 m thickness at Well 17137. For the wells in the centre of the cross-section the unit includes a high resistivity layer at its base and a low resistivity layer at the top. At the northern end of the cross-section the unit may be absent or be a gradational unit between Resistivity Unit 4 and Resistivity Unit 2.

3.5.3 Resistivity Unit 2

Resistivity Unit 2 is the layer that is greater than 100 ohm.m. It extends across the entire cross-section but is thinner in the south (<50 m), thickest at Well 17137 (150 m) and thins again at the north (75 m). At Well 16300 the resistivity exceeds 500 ohm.m.

3.5.4 Resistivity Unit 1

As with cross-section 1, the top resistivity unit is either a single layer of moderate resistivity (Wells 16383 and 16300) or it has a shallow high resistivity cap on the lower resistivity layer (Whakatu-1 and Well 17137). At Well 15795 the surficial high resistivity layer is either very thin or absent.

3.5.5 Interpretation

The interpretation of cross-section 2 uses the same relationships between the geophysically derived resistivity units and the lithological and stratigraphic boundaries discussed in cross-section 1 to determine the lateral extents of the layers.

3.5.6 Pliocene – Early Pleistocene

The Pliocene – Early Pleistocene section in Taradale-1 is dominated by claystones of the Taradale Mudstone formation (Figure 1.5). At Whakatu-1 the same interval is a mudstone (Mahanga Mudstone). The resistivity of a mudstone is less than 10 ohm.m but increases in resistivity are seen when sandy or shell rich layers are encountered. At the northern edge of the Heretaunga Basin the shallowest limestone unit is the Scinde Island Formation that crops out on Napier bluff (Lee et al. 2011, 2020, Bland 2006). The increase in resistivity at the base of Resistivity Unit 4 is interpreted to indicate the presence of a shell-rich layer equivalent to the Scinde Island Formation. The contact between the high resistivity limestone unit and the lower resistivity mudstone unit is indicated on the cross-section by the purple horizon. The blue horizon is the top of the Pliocene – Pleistocene mudstones. At Whakatu-1 this contact is gradational over a depth interval of 50–75 m (Ozolins and Francis, 2000).

3.5.7 Early to Middle Pleistocene

The undifferentiated Pleistocene and the Kidnappers Group coincide with Resistivity Unit 3. At Whakatu-1 the interval from 80 m to 300 m depth (mbgl) is mixture of sand and gravel that is interpreted to be interglacial and glacial deposits of Early to Middle Pleistocene age (older than MIS 5). These intervals likely extend to the south to Well 16383. The same units are predicted to be below Well 17137 at depths of 150–400 m (mbgl). However, at the northern end of the cross-section the early to middle Pleistocene section is less than 50 m thick and may pinch out completely.

3.5.8 Maraekakaho Formation

The highly resistive gravels that were deposited during the onset of the last glaciation, the LGM, and immediate post-glacial time are seen across the entire section forming Resistivity Unit 2. They are thickest at Well 17137. The resistivity is highest at Well 16300. The sensitivity of the TEM system is reduced at high resistivities, but there does seem to be some significant patterns in resistivities between values less than 500 ohm.m and greater than 500 ohm.m. A resistivity of greater than 500 ohm.m is interpreted to mean that the amount of fine-grained material in the interval is significantly lower, the porosity of the gravel is lower, the water saturation is lower, or a combination of all three factors.

3.5.9 Heretaunga Formation

Resistivity Unit 1 is a mixture of high resistivity gravel and sand layers, and lower resistivity silt layers that are part of the Tollemache Member of the Heretaunga Formation. The Awatoto member is interpreted to be present at Well 17137 but may not be present at any other wells on the cross-section. The top gravel marker (yellow) defines the base of Resistivity Unit 1 but in some wells it is the top of a Q1 gravel and in other wells it may be the top of a Q2 gravel.

This page left intentionally blank.

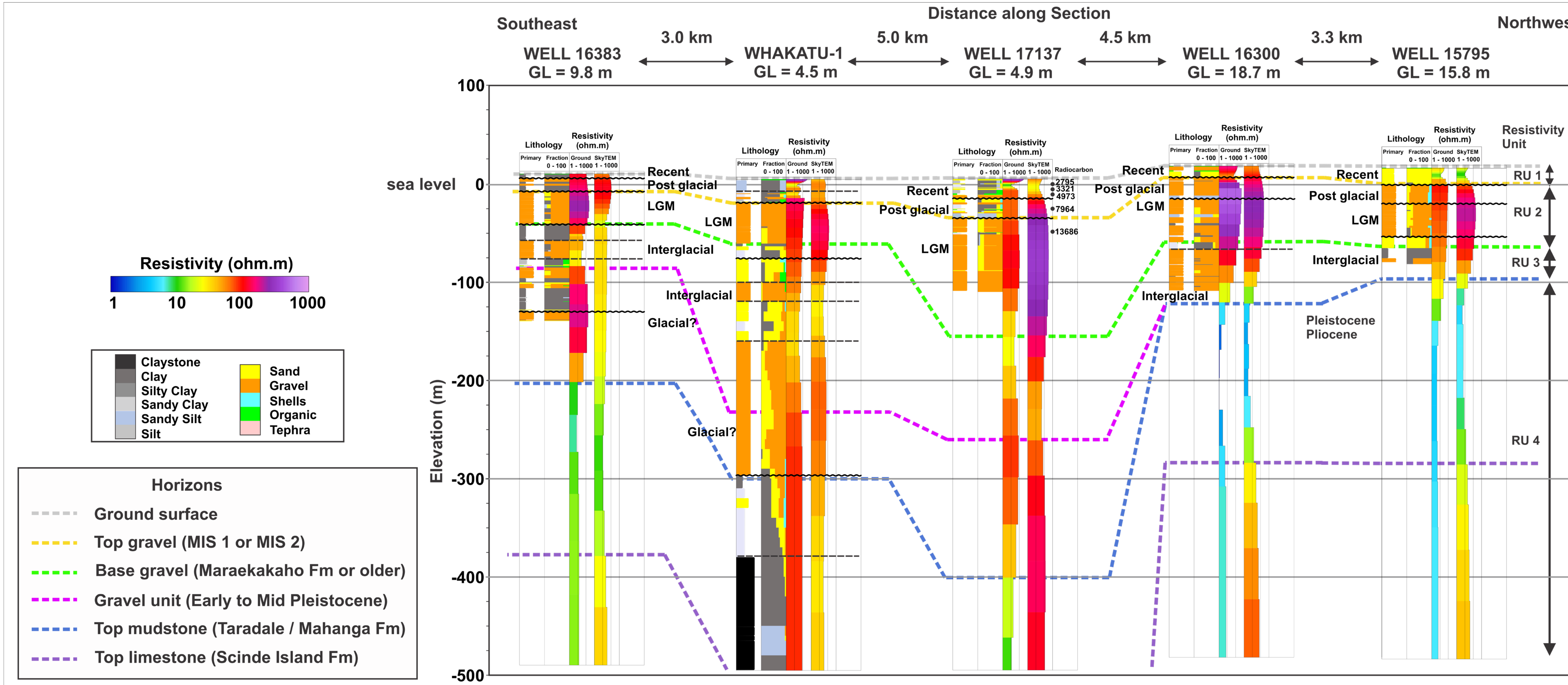

Figure 3.3 Section 2. Each well is presented as a SkyTEM model (smooth), a GroundTEM model, and the lithology (primary and percentage). GL refers to ground level elevation calculated from a DEM (Tschritter et al. 2022). Radiocarbon ages in years are shown. Location of the cross section is shown in Figure 3.1. The SkyTEM inversion models are sampled from the following distances away from each well: Well 16383 177 m, Whakatu-1 99 m, Well 17137 153 m, Well 16300 121 m, and 15795 155 m. The resistivity units (RU) are shown on the right side of the section.

This page left intentionally blank.

4.0 RESISTIVITY DATA

One of the aims of this report is to analyse the relationship between the resistivity of different formations based on the SkyTEM resistivity models, GroundTEM resistivity models, sample resistivity data, and lithology at the research wells. For the SkyTEM data, both the smooth and the sharp resistivity models were used in the analysis (see Appendix 1). The sharp model can have larger changes in resistivity between layers, while the smooth model will be more gradational due to the nature of the model constraints in the inversion process (Auken et al. 2015). The analysis of the resistivity data at the research wells will provide a calibration for the estimates of clay content from the resistivity and lithology data for the entire well database. This work is ongoing research as part of the 3DAMP project. In Well 17137 all four estimates of the resistivity (SkyTEM smooth, SkyTEM sharp, GroundTEM, and sample) are available and these are summarised in Table 4.1. The layers chosen for averaging the physical properties are based on the major changes in lithology shown in the composite log (Figure 2.1) and discussed in Section 2.1. The SkyTEM models from within a radius of 200 m of the well have been averaged to provide a representative value of the resistivity.

4.1 Analysis at Well 17137

The top 1.7 m of Well 17137 is a mixture of fill and sand. The grain-size of this sample has not been determined but the resistivity from the SkyTEM model is from 30 ohm.m to 50 ohm.m. The GroundTEM data produce an anomalously high resistivity (307 ohm.m) likely due the poor model resolution of the shallow NanoTEM data (Lawrence et al. 2021). From 1.7 m to 5 m depth (mbgl) the Heretaunga Formation sediments are silty clays and tephra (Tollemache Member), the coarse fraction (>63 μm) is 27.8%, and the average resistivity ranges from 18 ohm.m to 34 ohm.m. The layer resistivity from the GroundTEM model is over 100 ohm.m and still likely to be affected by the noisy data.

From 5 m to 11.3 m depth (mbgl) the Tollemache Member is composed of clay (30% coarse fraction), grading downwards to sand with tephra (77% coarse fraction). The SkyTEM resistivity is constant at 29 ohm.m within the entire interval. The sample resistivity and the GroundTEM resistivity show the upper part of the interval to be low resistivity (36 ohm.m and 13 ohm.m respectively), and the lower part of the interval to be high resistivity (146 ohm.m and 41 ohm.m respectively).

A layer described as clay and organic matter between 11.3 m and 16.7 m depth (mbgl) has a resistivity that varies between 29 ohm.m and 72 ohm.m. The first main gravel layer in the Tollemache Member occurs at 16.7 m depth (mbgl). The resistivity is between 58 ohm.m and 133 ohm.m. There are no grain-size data available for comparison.

The Awatoto Member is interpreted to be between 19.8 m and 30.2 m depth (mbgl). It is represented by a mixture of shell-rich sands, sandy clays, and a gravel unit. The average coarse fraction is 83.1% and the resistivity falls in a tight range from 72 ohm.m to 93 ohm.m.

The basal section of the Heretaunga Formation (Tollemache Member) from 30.2 m to 40.0 m depth (mbgl) is similar in lithology to the Awatoto Member but does not contain any shell fragments. The resistivity increases to typical values of 144 ohm.m for the SkyTEM models and 68 ohm.m for the GroundTEM model. The sample was recovered from a gravel bed and the coarse fraction is 99% and the sample resistivity is 250 ohm.m (Figure 2.1).

The gravel layer between 40.0 m and 54.2 m depth (mbgl) marks the transition from Q1 to Q2. The beds could be part of the basal part of the Heretaunga Formation or the upper part of the Maraekakaho Formation. The layer has a coarse fraction of 100% and the average resistivity from the SkyTEM and the samples is between 179 ohm.m and 286 ohm.m. The GroundTEM resistivity is still less than 100 ohm.m. Samples from an organic and clay-rich layer between 54 m and 56 m depth (mbgl) still contain an average of 95% coarse material. The average resistivity of the samples is 32 ohm.m. The SkyTEM models do not have the ability to resolve thin sediment layering so the average resistivity is between 225 ohm.m and 239 ohm.m. The GroundTEM model has consistently lower resistivity values than the SkyTEM models.

From 56.4 m to 114 m depth (mbgl) the gravel deposits are older than 13,000 ka and are interpreted to be part of the Maraekakaho Formation that was deposited during the LGM in Q2. The base of the section likely extends into Q3. The grain-size distribution is 97% coarser than silt, and the average resistivity of the samples and the SkyTEM models is between 213 ohm.m and 342 ohm.m. The GroundTEM resistivity is between 96 ohm.m and 102 ohm.m.

Table 4.1 Resistivity and grain-size data for Well 17137. The average and standard deviation (shown in brackets) value is calculated over the depth interval. The smooth and sharp SkyTEM resistivity values are also the average of sites within 200 m of the well. The rows are coloured by the Formation and Member.

Depth (m)		Resistivity (ohm.m)								
Top	Base	SkyTEM Sharp	SkyTEM Smooth	Ground TEM	Samples	Grain-size: Percentage Gravel and Sand (>63 µm)	Lithology	Facies	Formation / Member	Marine Isotope Stage (MIS)
0.0	1.7	33 (7)	41 (12)	307 (31)	50 (37)	No sample	Fill, sand	Fluvial	Recent	1
1.7	5.0	32 (2)	34 (5)	110 (75)	18 (2)	28 (1)	Clay, silt, ash	Fluvial	Tollemache Mbr	1
5.0	8.0	29 (2)	28 (3)	13 (3)	36 (13)	30 (4)	Clay	Fluvial	Tollemache Mbr	1
8.0	11.3	29 (4)	29 (5)	41 (19)	146	77	Sand, ash	Fluvial	Tollemache Mbr	1
11.3	16.7	47 (17)	39 (8)	72 (1)	29 (13)	No sample	Clay, sand, organic	Fluvial	Tollemache Mbr	1
16.7	19.8	67 (2)	58 (7)	72 (1)	133	No sample	Sand, gravel	Fluvial	Tollemache Mbr	1
19.8	30.2	85 (32)	93 (28)	68 (2)	58 (45)	69 (32)	Sand, clay, gravel shells	Shallow marine	Awatoto Mbr	1
30.2	40.0	144 (75)	143 (63)	68 (2)	250 (157)	99 (1)	Silt, sand, clay, gravel, organic	Fluvial	Tollemache Mbr	1
40.0	54.2	212 (91)	179 (107)	78 (2)	286 (116)	100	Gravel, sand	Fluvial	Heretaunga Fm / Maraekakaho Fm	1 / 2
54.2	56.4	239 (107)	225 (94)	78 (2)	32 (15)	95 (7)	Clay, sand, gravel	Fluvial, lacustrine	Maraekakaho Fm	2
56.4	94.0	236 (146)	233 (111)	102 (8)	243 (126)	98 (4)	Gravel, sand	Fluvial	Maraekakaho Fm	2
94.0	114.0	233 (166)	213 (124)	96 (2)	342 (154)	97 (5)	Gravel	Fluvial	Maraekakaho Fm	2 / 3

4.2 Analysis of the Research Wells

In the other research wells (Tollemache, Flaxmere, and Awatoto) only GroundTEM and SkyTEM resistivity values are available for the layers. The analysis of the data from these three wells is summarised in Table 4.2. The layers have been chosen based on the main divisions shown in Figure 3.2.

In Table 4.2 the resistivity values have been colour-coded based on threshold values identified during the interpretation of the SkyTEM data as follows:

- 0–49 ohm.m fine-grain sediments with high clay and silt content (green)
- 50–99 ohm.m coarse-grain sediment with sands and some gravel layers (yellow)
- 100–500 ohm.m thick gravel layers most likely associated with the LGM (red)

The smooth and sharp models produce similar resistivity values for the equivalent depths except in a few cases where the sharp model has increased rapidly across a boundary. An example of this can be seen in Table 4.2 for the Awatoto well over the interval from 44 m to 64 m depth (mbgl). The sharp model changes from 50 ohm.m to 102 ohm.m at 24 m depth (mbgl), while the smooth model does not exceed 100 ohm.m until 36 m depth (mbgl).

Awatoto and Tollemache show similar patterns with low resistivity layers in the top 20 m. The resistivity values range from 13 ohm.m to 51 ohm.m. The surface layer of the GroundTEM model at Awatoto is anomalously high compared to the other models as a result of the noise levels in the shallow NanoTEM data resulting in poorly resolved models (Reeves et al. 2019). Resistivity values of less than 50 ohm.m are similar to those seen at Well 17137 for the shallow part of the Heretaunga Formation (Table 4.1).

The high resistivities (>100 ohm.m) are seen between 24 m and 127 m depth (mbgl) in both Awatoto and Tollemache but the resistivities are lower than those seen in Well 17137 where the resistivity is greater than 200 ohm.m (Table 4.1). This lower resistivity in both Awatoto and Tollemache is interpreted to indicate a lower fraction of coarse-grained sediments in the Q2 age Maraekakaho Formation in these wells compared to Well 17137.

At depths greater than 120 m depth (mbgl), the resistivity in Tollemache and Awatoto drops to less than 100 ohm.m. At Awatoto the interval at the base of the well, interpreted to be Q4 glacial to Q5 interglacial sediments, has a resistivity of less than 50 ohm.m, consistent with a higher proportion of silt and clay and a reduction in the resistivity of the groundwater at depth (Tschritter et al. 2022).

Flaxmere is significantly more resistive at all depths. The resistivity between 30 m and 133 m depth (mbgl) is between 224 ohm.m and 403 ohm.m. These values are similar to the resistivities seen in Well 17137 over the similar depth interval (Table 4.1). The similarity of the SkyTEM response at Flaxmere and Well 17137 is clearly seen in cross-section 1 (Figure 3.2). Well 17137 was predicted to be transitional between Flaxmere and Awatoto given its location. However, the results of the SkyTEM suggest that the Q2 gravel unit is uniform across the interval between Flaxmere and Well 17137, then changes to a more fine-grained deposit eastwards towards Awatoto and southwards towards Tollemache. The Flaxmere well does not extend beyond the Maraekakaho Formation so we are not able to identify any pattern in the deeper gravel units.

Table 4.2 Resistivity ranges for research wells Awatoto, Flaxmere, and Tollemache. The resistivity values are presented as an average and standard deviation (in brackets) in ohm.m. The colours represent the main divisions green <50, yellow 50–100, red >100 ohm.m. The SkyTEM resistivity models have been averaged over a distance of 200 m around the well (800 m for Tollemache).

Awatoto Resistivity (ohm.m)					Flaxmere Resistivity (ohm.m)					Tollemache Resistivity (ohm.m)			
Depth (mbgl)	SkyTEM Sharp	SkyTEM Smooth	GroundTEM	Resistivity Unit	Depth (mbgl)	SkyTEM Sharp	SkyTEM Smooth	GroundTEM	Resistivity Unit	Depth (mbgl)	SkyTEM Sharp	SkyTEM Smooth	Resistivity Unit
0–3	13 (3)	19 (8)	324 (138)	1	0–3	94 (9)	92 (5)	273 (1)	1	0–5	45 (8)	51 (14)	1
3–7	16 (2)	15 (4)	22 (23)	1	3–7	96 (10)	99 (7)	254 (13)	1	5–18	39 (4)	38 (9)	1
7–14	36 (11)	29 (9)	43 (26)	1									
14–24	50 (6)	62 (19)	133 (14)	1	7–30	156 (54)	148 (35)	174 (103)	2	18–37	65 (52)	61 (24)	1
24–36	103 (41)	94 (38)	101 (10)	1									
36–64	115 (57)	113 (43)	64 (14)	2	30–62	277 (13)	257 (44)	403 (263)	2	37–72	161 (53)	126 (18)	2
64–109	145 (19)	100 (23)	61 (11)	2	62–96	277 (12)	290 (18)	301 (17)	2	72–96	155 (59)	124 (14)	2
					96–133	236 (11)	224 (21)	324 (3)	2	96–127	116 (82)	88 (12)	2
109–117	89 (25)	72 (12)	84 (1)	3	133–137	151 (7)	169 (14)	294 (30)	2	127–144	71 (78)	67 (9)	3
117–133	60 (11)	60 (9)	87 (1)	3						144–161	44 (12)	57 (8)	3
133–187	55 (9)	58 (11)	87 (1)	3									
187–254	54 (3)	70 (11)	116 (21)	3						161–256	39 (8)	50 (5)	3

This page left intentionally blank.

5.0 CONCLUSIONS AND RECOMMENDATIONS

As part of the Hawke's Bay 3D Aquifer Mapping Project (3DAMP), twelve deep (>100 m) boreholes/wells were interpreted/re-interpreted and placed on two regional cross-sections to map the continuity of the stratigraphic units and provide calibration points for the SkyTEM resistivity models. The result of this work is a first order description of the main resistivity boundaries based on the SkyTEM resistivity and the other resistivity data available at the research wells.

The work has focussed particularly on Well 17137 (3DAMP Well 2) which is the most recent of a series of research wells drilled in the Heretaunga Plains. The previous wells included Awatoto, Flaxmere, and Tollemache. In addition to these four research wells, there are two petroleum wells (Whakatu-1 and Taradale-1) and six deeper groundwater wells (Wells 5988, 16300, 16383, 15795, 4402, and 2154) that provide valuable insight into the stratigraphy of the Holocene and Pleistocene sediments in the Heretaunga Plains.

Detailed interpretations of the twelve high value wells have been compiled as logs in Appendix A1.1 and as digital datasets in Appendix A1.2 and provided to HBRC. Additional geophysical data including GroundTEM, seismic, and geophysical borehole logs have been used to understand the geophysical signature of the gravel, sand, and clay layers encountered in the wells.

SkyTEM surveys produce a dense volume of resistivity models that extend from the shallow subsurface (0–5 m) to depths of 300 m to 500 m. The boreholes used in this study have some independent resistivity data that was used to analyse the relationship between bulk resistivity, groundwater resistivity, and grain-size. Using the data from Well 17137, Awatoto, Tollemache, and Flaxmere, a set of resistivity thresholds were developed to characterise the sediments and support the interpretation of SkyTEM models.

The new SkyTEM resistivity data combined with the re-interpretation of the research wells provides an opportunity to appraise the validity of the existing models for the Heretaunga Plains based on the work of Dravid and Brown (1997). Specifically, the lower sections of Awatoto, Tollemache and Flaxmere may be younger than interpreted by Dravid and Brown (1997), which has important implications for the permeability of the deeper units mapped across the basin.

Additional work such as characterising the distribution of different clast compositions could help in distinguishing different gravel units in the Holocene and late Pleistocene and support future clay fraction and permeability modelling.

Hydrogeological interpretation of the resistivity results is needed to make full use of the SkyTEM survey results. The detailed interpretation of each well and the two cross-sections will support subsequent three-dimensional interpretations of the Heretaunga Plains SkyTEM data set. This additional work will be described within separate reports.

6.0 ACKNOWLEDGEMENTS

This work has been jointly funded by the New Zealand Government's Provincial Growth Fund, Hawke's Bay Regional Council, and GNS Science's Strategic Science Investment Fund (Ministry of Business, Innovation & Employment). Thank you to Jeff Smith and Simon Harper of Hawke's Bay Regional Council for their contributions to this project. Thank you to Amanda Langley of Project Haus for project management support and Chris Worts for GNS Business Partnerships support. Julie Lee provided a thorough review of the geological interpretation and helped improve the description of the geophysical data. Stewart Cameron provided an internal review of the final report.

7.0 REFERENCES

Auken E, Christiansen AV, Kirkegaard C, Fiandaca G, Schamper C, Behroozmand AA, Binley A, Nielsen E, Effersø F, Christensen NB, et al. 2015. An overview of a highly versatile forward and stable inverse algorithm for airborne, ground-based and borehole electromagnetic and electric data. *Exploration Geophysics*. 46(3):223–235. doi:10.1071/EG13097.

Barrell DJA, 2011. Chapter 75 - Quaternary glaciers of New Zealand. In: Ehlers J, Gibbard PL, Hughes PD, editors. *Developments in Quaternary sciences*. Amsterdam (NL): Elsevier. p. 1047-1064. (Developments in Quaternary science; 15). doi:10.1016/B978-0-444-53447-7.00075-1.

Begg JG, Jones KE, Tschritter C, Lee JM. In press. 3D Geological model of the Napier-Hastings urban area [text to accompany digital data]. Lower Hutt (NZ): GNS Science. XX p + digital data. (GNS Science geological map; 7b). ISBN: 978-1-99-001043-9. DOI: 10.21420/QFEK-9369. ISSN: 117-3014.

Bland KJ. 2006. Analysis of the central Hawke's Bay sector of the late Neogene forearc basin, Hikurangi margin, New Zealand [PhD thesis]. Hamilton (NZ): University of Waikato. 306 p. + appendices.

Bland KJ, Kamp PJJ, Nelson CS. 2008. Late Miocene – Early Pleistocene paleogeography of the onshore central Hawke's Bay sector of the forearc basin, eastern North Island, New Zealand, and some implications for hydrocarbon prospectivity. In: *2008 New Zealand Petroleum Conference proceedings: beyond 08;* 2008 Mar; Auckland, New Zealand. Wellington (NZ): Ministry of Economic Development. p. 22.

Brown LJ. 1993. Heretaunga Plains groundwater resource investigations – Flaxmere and Tollemache orchard exploratory water wells. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. Client Report 732402.11. Prepared for Hawke's Bay Regional Council.

Brown LJ, Gibbs BR. 1996. Heretaunga Plains, groundwater resource investigations: Awatoto exploratory water well – HBRC Well No. 3699. Lower Hutt (NZ): Institute of Geological and Nuclear Sciences. 111 p. Client Report 735102. Prepared for Hawke's Bay Regional Council.

Brown, L.J. Dravid, P.N. Hudson, N.A. 1997. Sustainable groundwater resources, Heretaunga Plains, Hawke's Bay, New Zealand. *Hydrology Journal*. 7:440–453.

Caron V and Nelson CS. 2009. Diversity of neomorphic fabrics in New Zealand Plio-Pleistocene cool-water limestones: insights into aragonite alteration pathways and controls. *Journal of Sedimentary Research*. 79:226–246. doi:10.2110/jsr.2009.029.

Darley JH, Kirby KFS. 1969. Taradale-1 well completion report. 75 p. Located at: Ministry of Business, Innovation and Employment, Wellington, NZ. New Zealand Unpublished Petroleum Report PR331.

Dravid PN, Brown LJ. 1997. Heretaunga Plains groundwater study. Volume 1: findings. Napier (NZ): Hawke's Bay Regional Council. 238 p.

Harmsen FR. 1985. Lithostratigraphy of Pliocene strata, Central and Southern Hawke's Bay, New Zealand. *New Zealand Journal of Geology and Geophysics*. 28(3):413–433. doi:10.1080/00288306.1985.10421196.

Hull AG, 1985. Late Quaternary geology of the Cape Kidnappers area, Hawke's Bay, New Zealand [MSc thesis]. Wellington (NZ): Victoria University of Wellington. 140 p.

Kamp PJJ, 1978. Stratigraphy and sedimentology of conglomerates in the Pleistocene Kidnappers Group, Hawke's Bay [MSc Thesis]. Hamilton (NZ): Waikato University. 276 p.

Kamp PJJ, Harmsen FJ, Nelson CS and Boyle SF. 1988. Barnacle-dominated limestone with giant cross-beds in a non-tropical, tide-swept, Pliocene forearc basin seaway, Hawke's Bay, New Zealand. *Sedimentary Geology.* 60(1):173–195. doi:10.1016/0037-0738(88)90118-2.

Lawrence MJF, Kellett RL, Pradel GJ, Sanders F, Herpe M, Rawlinson Z, Reeves RR, Brakenrig T, Moreau M, Cameron SG, et al. 2021. Hawke's Bay 3D Aquifer Mapping Project: drilling completion report for borehole 17137 (3DAMP_Well2), Morley Road, Heretaunga Plains. Lower Hutt (NZ): GNS Science. 156 p. Consultancy Report 2022/31. Prepared for Hawke's Bay Regional Council.

Lee J. 2021. Personal communication. Geologist, Geological Mapping & Stratigraphy, GNS Science, Lower Hutt. November 2021.

Lee JM, Bland KJ, Townsend DB, Kamp PJJ. 2011. Geology of the Hawke's Bay area [map]. Lower Hutt (NZ): GNS Science. 1 folded map + 93 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 8).

Lee JM, Tschritter C, Begg JG. 2014. A 3D geological model of the greater Heretaunga/Ahuriri Groundwater Management Zone, Hawke's Bay. (GNS Science Consultancy Report 2014/89). Lower Hutt (NZ): GNS Science. 31 p. Consultancy Report 2014/89. Prepared for Hawke's Bay Regional Council. https://www.hbrc.govt.nz/assets/Document-Library/Publications-Database/4814-RM16-28-Simplified-geological-model-for-the-Heretaunga-Plains-Ahuriri-GW-Mngt-June2014.pdf

Lee JM, Begg JG, Bland KJ. 2020. Geological map of the Napier-Hastings urban area. [map]. Lower Hutt (NZ): GNS Science. 1 map, scale 1:75,000. (GNS Science geological map; 7a).

Lee JM, Begg JG, Townsend DB. in. prep. Geomorphological map of the Napier-Hastings urban area. 1 map, scale 1:50,000. Lower Hutt (NZ): GNS Science. (GNS Science geological map; 7c)

Litchfield NJ, Berryman KR. 2005, Correlation of fluvial terraces within the Hikurangi margin, New Zealand: implications for climate and baselevel controls. *Geomorphology*. 68(3–4):291–313. doi:10.1016/j.geomorph.2004.12.001.

Morgenstern U. 2021. Groundwater age at Flaxmere research bore [personal communication]. Principal Scientist, Environmental Chemistry, GNS Science, Lower Hutt.

Mortimer 1994. Origin of the Torlesse Terrane and coeval rocks, North Island, New Zealand. *International Geology Review*. 36(10):891–910. doi:10.1080/00206819409465494.

Ozolins V, Francis D. 2000. Whakatu-1 well completion report. 498 p. + 4 enclosures. Located at: Ministry of Business, Innovation and Employment, Wellington, NZ. New Zealand Unpublished Petroleum Report PR2476.

Paquet F, Proust J-N, Barnes PM, Pettinga JR. 2009. Inner-forearc sequence architecture in response to climatic and tectonic forcing since 150 ka: Hawke's Bay, New Zealand. *Journal of Sedimentary Research*. 79(3):97–124. doi:10.2110/jsr.2009.019.

Paquet F, Proust J-N, Barnes PM, Pettinga JR. 2011. Controls on active forearc basin stratigraphy and sediment fluxes: The Pleistocene of Hawke Bay, New Zealand. *Geological Society of America Bulletin*. 123(5–6):1074–1096. doi:10.1130/B30243.1.

Proust J-N, Chanier F. 2004. The Pleistocene Cape Kidnappers section in New Zealand: orbitally forced controls on active margin sedimentation? *Journal of Quaternary Science*. 19(6):591–603. doi:10.1002/jqs.865.

Rawlinson ZJ, Foged N, Westerhoff RS, Kellett RL 2021. Hawke's Bay 3D Aquifer Mapping Project: Heretaunga Plains SkyTEM data processing and resistivity models. Wairakei (NZ): GNS Science. 90 p. Consultancy Report 2021/93. Prepared for Hawke's Bay Regional Council.

Reeves RR, Rawlinson ZJ, Brakenrig T, Macdonald N. 2019. SkyTEM for groundwater knowledge refinement in the Heretaunga and Ruataniwha Plains: stage 2 – preliminary Transient Electro-magnetic (TEM) soundings. Wairakei (NZ), GNS Science. 44 p. Consultancy report 2019/77. Prepared for Hawke's Bay Regional Council.

Rider MH. 1996. The geological interpretation of well logs. 2nd ed. Caithness (GB): Whittles Publishing. 280 p.

Sahoo TR, Rawlinson ZJ, Kellett RL. 2022. Hawke's Bay 3D Aquifer Mapping Project: delineation of major hydrogeological units within the Heretaunga Plains from SkyTEM-derived resistivity models. Lower Hutt (NZ): GNS Science. 63 p. Consultancy Report 2022/30. Prepared for Hawke's Bay Regional Council.

Shane P, Alloway B, Black T, Westgate J. 1996. Isothermal plateau fission-track ages of tephra in an early-middle Pleistocene marine and terrestrial sequence, Cape Kidnappers, New Zealand. *Quaternary International*. 34–36:49–53. doi:10.1016/1040-6182(95)00068-2.

Shane P, Lian OB, Augustinus P, Chisari R, Heijnis H. 2002. Tephrostratigraphy and geochronology of the ca. 120ka terrestrial record at Lake Poukawa, North Island, New Zealand. *Global and Planetary Change*. 33(3–4):221–242. doi:10.1016/S0921-8181(02)00079-6.

Shulmeister J, Shane P, Lian OB, Okuda M, Carter JA, Harper M, Dickinson W, Augustinus P, Heijnis H. 2001. A long late-Quaternary record from Lake Poukawa, Hawke's Bay, New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology*. 176(1):81–107. doi:10.1016/S0031-0182(01)00327-3.

SkyTEM Australia Pty Ltd. 2020. Acquisition and processing report: SkyTEM helicopter EM survey, Hawkes Bay, NZ. Malaga (AU): SkyTEM Australia Pty Ltd. 33 p. Report AUS 10056. Prepared for Hawke's Bay Regional Council.

Tschritter C, Kellett RL, Rawlinson ZJ, Griffin AG. 2022. Hawke's Bay 3D Aquifer Mapping Project: Heretaunga Plains data and model inventory. Wairakei (NZ): GNS Science. 96 p. Consultancy Report 2021/113. Prepared for Hawke's Bay Regional Council.

Westech Energy New Zealand Ltd. 2001. Hukarere-1 well completion report PEP 38325 385 p. + 4 enclosures. Located at: Ministry of Business, Innovation and Employment, Wellington, NZ. New Zealand Unpublished Petroleum Report PR2656.

APPENDICES

This page left intentionally blank.

APPENDIX 1 LITHOLOGICAL LOGS

A1.1 Well Logs 1:500 Scale (attached in PDF)

- Well 17137
- Flaxmere
- Tollemache
- Awatoto
- Whakatu-1
- Well 4402
- Taradale-1
- Well 2154
- Well 5988
- Well 15795
- Well 16300
- Well 16383

A1.2 Lithological Descriptions (attached in PDF)

- Well 17137
- Flaxmere
- Tollemache
- Awatoto
- Whakatu-1
- Well 4402
- Taradale-1
- Well 2154
- Well 5988
- Well 15795
- Well 16300
- Well 16383

www.gns.cri.nz

Principal Location

1 Fairway Drive, Avalon
Lower Hutt 5010
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin 9054
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Private Bag 2000
Taupo 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4657