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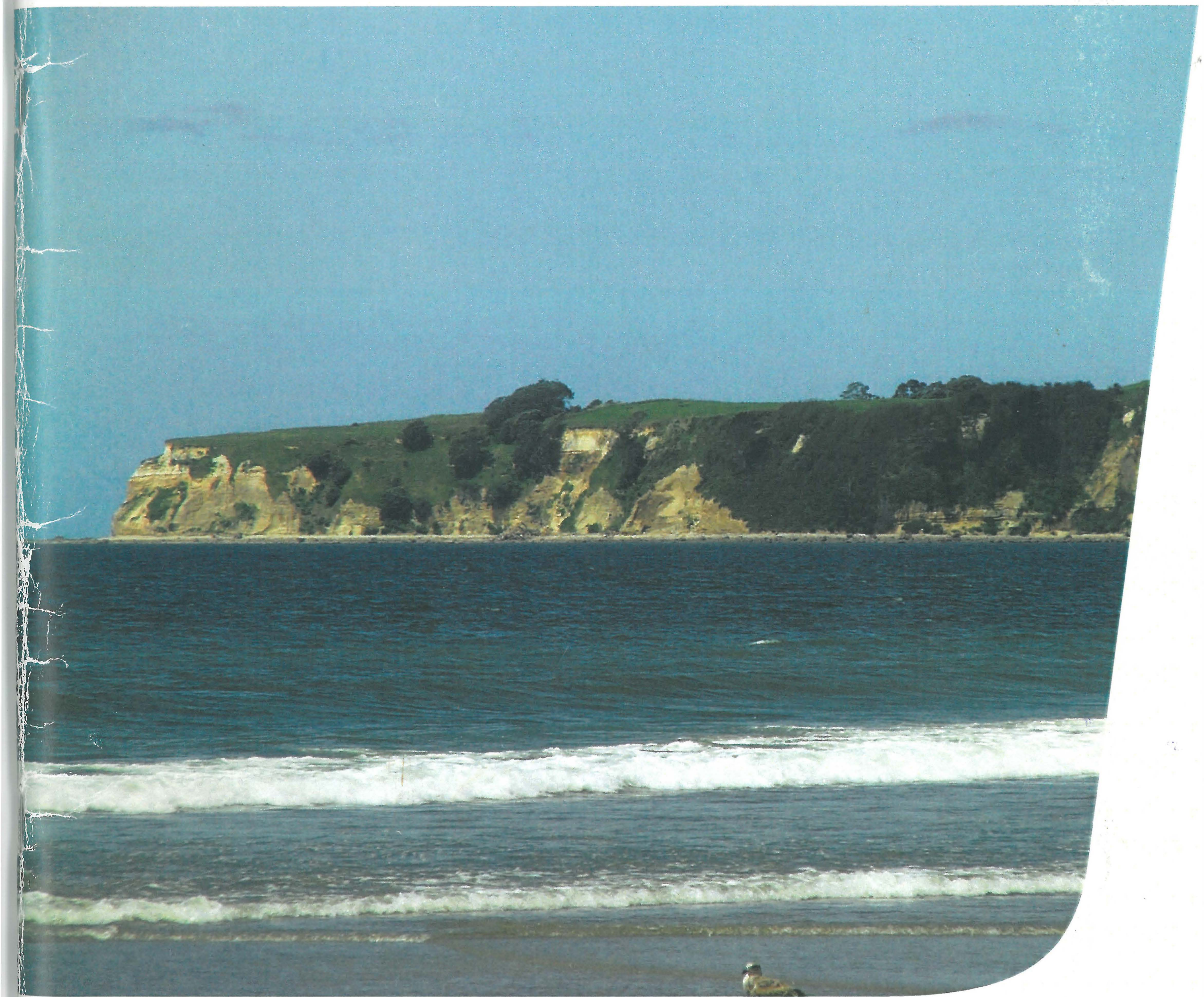
Geology of the Maketu Area

Bay of Plenty, North Island, New Zealand



SHEET V14 1:50 000

Occasional Report No. 26
Department of Earth and Ocean Sciences, University of Waikato, Hamilton, New Zealand

Geology of the Maketu Area, Bay of Plenty, North Island, New Zealand

SHEET V14 1:50 000

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Cover photo: *Maketu peninsula and Okurei Point (Town Point)*

Back cover photo: *Entrance to Maketu Estuary*

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GEOLOGY OF THE MAKETU AREA

GEOLOGICAL LEGEND

		Age	
Sand and mud of modern streams	fa	HOLOCENE	QUATERNARY
Fixed foredunes	fo	HOLOCENE	QUATERNARY
Moving dune sand	fm	HOLOCENE	QUATERNARY
Peat (on estuarine deposits), thin tephras	fs	HOLOCENE (11.5 ka)	QUATERNARY
Fluvial terrace deposits post-dating Mangaone Subgroup Tephras	tt	PLEISTOCENE	QUATERNARY
Matua Subgroup fluviatile sands, silts, gravels, lahar deposits, aeolian sands, loess, tephras (including Mangaone Subgroup Tephras)	tm	PLEISTOCENE (1.8 Ma)	QUATERNARY (2.5 Ma)
Orongatea Formation, andesite and basaltic andesite lavas, volcanic breccias, tuffs, dikes	or	PLIOCENE	
Motiti Formation, andesite and basaltic andesite lavas and volcanic breccias	mo	PLIOCENE	

Contact

Located accurately

Located approximately

Fault

Definite (U = up, D = down)

Inferred

Concealed

Topographic

Rivers, Streams

Canals

State Highways

Roads

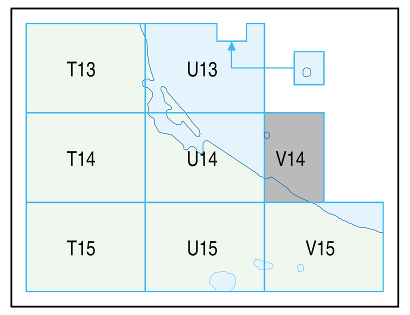
Features

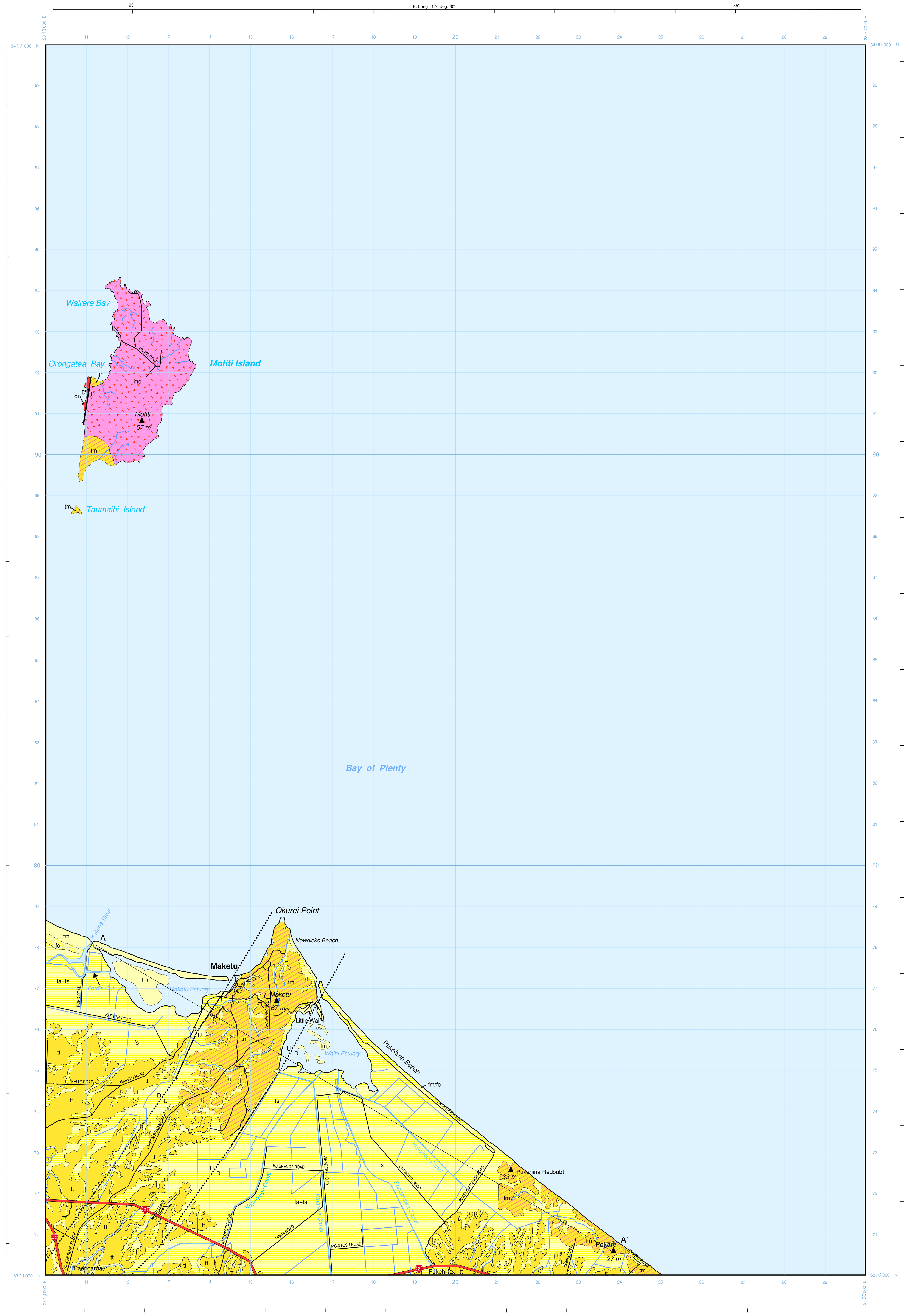
Trig Station - beaconed

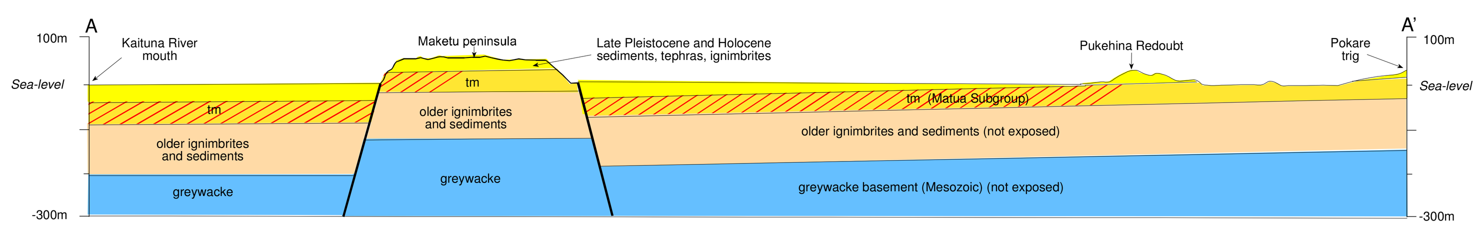
MAGNETIC NORTH on this map is 22 1/2 deg. EAST of GRID NORTH during 2000 increasing at the rate of approx. 1/2 deg. over 33 years.

GRID NORTH — G - M Angle — MAG. NORTH

NZMS 260 SERIES SHEET LAYOUT







SCALE 1:50,000

1 0.5 0 1 2 3 4 5 km

This map is drawn on the New Zealand Map Grid Projection, a minimum-error conformal projection. The grid is the New Zealand Map Grid, showing coordinates in metres in terms of the Geodetic Datum 1949, based on the International (Hayford) Spheroid.

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DISCLAIMER

This map shows an interpretation of the geology of the Maketu area. The small scale of the map has necessitated the omission of some small features and exaggeration of others in the interests of clarity. The map should not be used for building-site assessment, land-use planning, engineering projects, quarry operations, or any other work for which site-specific investigations should be made.

REPRODUCTION NOTICE

Contents

Summary

The area covered in this report on the geology of Sheet V14 Maketu 1:50 000 includes Motiti Island and a small triangular section of the Bay of Plenty coastal lowlands from the Kaituna River mouth to Pukehina Beach within the Maketu Basin, eastern North Island.

Motiti Island is situated 12 km offshore from the Bay of Plenty coast and is an eroded remnant of a Pliocene (4.3–3.4 Ma) andesitic composite cone. It is a flat-lying island surrounded by cliffs up to 30 m high, and the highest point is 57 m above sea level. The island is constructed on a base of andesitic rocks that have been divided into two new formations, the *Motiti Formation* consisting of thick massive or platy jointed lava flows and volcanic breccias, and the *Orongatea Formation* comprising thin lava flows, volcanic breccias, lapilli tuffs, tuffs, and dikes that are considered to be proximal strombolian and phreatomagmatic deposits. The andesitic formations are unconformably overlain by a 20-m thick sequence of middle to late Quaternary volcanogenic sediments (fluviatile sands, silts, and gravels), which in turn are covered by a 6-m thick blanket of late Quaternary tephras including Rotoiti Tephra Formation at the base. Originally the island would have been manifested as an andesitic composite cone and tuff ring complex, but it is now characterised by the strong angular unconformity that truncates the older andesitic rocks, which have been planed flat, presumably by marine erosion. The andesites and basaltic andesites of Motiti Island have ages and geochemical compositions similar to those of the Waihi district and southern Coromandel Volcanic Zone.

The **Maketu peninsula (Town Point)** forms a 67-m high headland on the Bay of Plenty coast, and is considered to be a horst, bounded by NE (035°)-striking normal faults and downfaulted blocks on both sides. The oldest rocks in the Maketu area are exposed in cliffs around the peninsula and consist of fluvial sands, silts, and gravels, aeolian sediments, and a 25-m thick lahar or lake-breakout flood deposit (*Newdicks Formation*, new) with a stratigraphic age of *c.* 0.25 Ma. The source of the lahar/flood deposit is unknown, but it contains clasts up to 7 m across of a densely welded ignimbrite that form a litter of boulders around the Maketu peninsula. The fluvial sediments are similar in rock type and stratigraphic position to those on Motiti Island, and both sequences have been included here in the Matua Subgroup. Intercalated with the sediments of the Matua Subgroup are thin Mid-Pleistocene pumiceous tephra fallout beds of the Huntress Creek and Kukumoa subgroups, and a c. 5-m thick non-welded ignimbrite identified as Mamaku Ignimbrite (*c.* 0.22 Ma). The uppermost part of the Matua Subgroup is marked by a well-developed, dark paleosol formed in clayey loess, and is Last Interglacial in age (*c.* 125 ka).

The Maketu peninsula is capped by a 15-m thick sequence of late Quaternary pumiceous and unweathered to weakly weathered tephra beds that include Rotoiti Tephra Formation, four tephras of the Mangaone Subgroup, and numerous younger tephras derived from the volcanic centres of Okataina (ten tephras), Taupo (six tephras), and Tuhua (Mayor Island) (one or more tephras), and minor loess deposits. The youngest of these tephras include the white, pumiceous rhyolitic Kaharoa Tephra erupted from Mt Tarawera in *c.* 1314 AD, Rotomahana Mud from the 1886 AD eruption of Mt Tarawera, and thin dustings of andesitic ash from the 1995-1996 AD eruptions of Mt Ruapehu.

In the **Kaituna and Pongakawa lowlands** and around the Maketu and Waihi estuaries there is a late Pleistocene to Holocene sequence of fluvial terraces, alluvial plains, dune sands, minor loess, estuarine sands and muds, peats, and intercalated tephra layers.

Preface

This report is a collaborative venture between the Department of Earth and Ocean Sciences, University of Waikato, and Environment B.O.P. (Bay of Plenty Regional Council). The report is largely based on MSc theses by Mark Henry (1991), Heidi Wehrmann (2000), and a section from David Manning's (1995) PhD thesis, and partly from other information (both published and unpublished) including from theses by Ken Murray (1978), Glenn Wigley (1990), Nenad Domijan (2000), Jess Rae (2002), Haydon Easton (2002), and others. The report incorporates a geological map of Sheet V14 (Maketu) on a scale of 1:50 000, and includes geological descriptions on the nature and characteristics of the rocks, sediments and tephras (volcanic ashes) in the Maketu and Motiti Island areas.

The report describes the general physiography and landscape features of the region, and the stratigraphy of the different rock groups in order from oldest to youngest. For each rock unit, there is a definition, a description of the rock type, its distribution within the map area, stratigraphic relations, age, and a brief note on the rock character. The scheme used for description, terminology, and quantification of rock character follows that of Brown (1981) (see Appendix). At the end of the report there is also a glossary of many of the geological, volcanological, stratigraphic and other terms used.

The map and report show an interpretation of the geology of the area, and should not be used for building site assessment, land-use planning or management, engineering projects, quarry operations, or any other work for which site-specific investigations should be made.

Physiography

The Maketu area lies within the Maketu Basin (Healy et al. 1964) and consists of six main physiographic units (Fig. 1): Motiti Island; Maketu peninsula; low terraces; alluvial plains; coastal estuaries; and dunes.

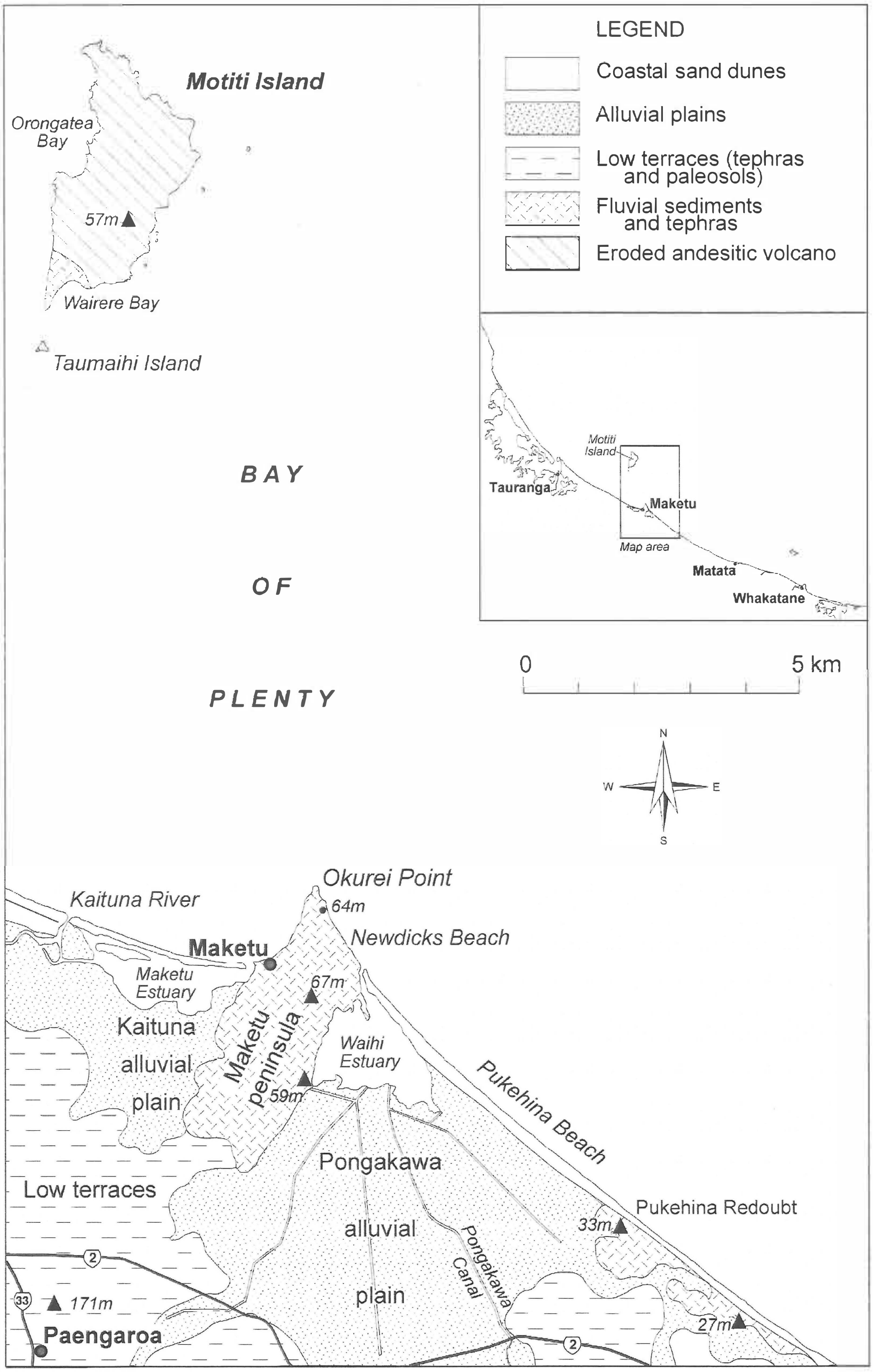


Fig. 1 Map showing the main geographic and geologic-physiographic features of the Maketu area.

Motiti Island

Motiti is a low-lying, flat island approximately 8 km^2 in area situated about 12 km offshore from the Bay of Plenty coastline (Fig. 2). It is bounded by cliffs up to 30 m high, with a highest point of 57 m above sea level. Motiti Island was originally a Pliocene andesitic cone but it has been deeply eroded and planed into a flat-lying feature, covered with Quaternary sediments and a cap of tephra deposits.

Motiti Island has a pronounced elongation oriented NNE-SSW, which is controlled by a set of NNE-striking (020°) faults seen in coastal exposures. Variations in lithology and degree of hydrothermal alteration of the older andesitic rocks have allowed differential erosion of the coastline into a series of embayments and headlands, with some isolated rock promontories and numerous offshore shallow reefs.

Maketu peninsula

Maketu peninsula (Town Point) is a prominent headland on the central Bay of Plenty coastline (Fig. 3). At the coast the peninsula forms a dissected flat lying plateau reaching 67 m elevation (Fig. 4), similar in height to Motiti, but it slopes very gently inland and merges with the low terraces. The plateau is bounded on both sides by NNE-oriented faults, and downfaulted blocks now covered by the low terraces, alluvial plains, and estuaries. The Maketu peninsula is underlain by a thick sequence of middle to late Pleistocene fluvial and aeolian volcaniclastic sediments, and interbedded pyroclastic deposits including Mamaku Ignimbrite. These are blanketed by Mid-Late Pleistocene and Holocene tephra deposits and minor loess. The peninsula is flat because the sediments, ignimbrites and tephras were deposited on a more-or-less flat surface, in contrast to Motiti Island which is flat because of marine erosion which has planed off the underlying andesitic rocks, and hence the similarity in heights of Maketu and Motiti is considered coincidental.

Low terraces

Farther inland from the coast, and along the margins of alluvial plains, is a series of low-lying, flat terraces (Fig. 5). They are constructed mainly of a sequence of late Pleistocene and Holocene tephras which have paleosols developed on them (Pullar 1970; Wigley 1990; Cotching 1998).

To the south of the map area, higher terrace levels are constructed mainly on Mangaone Subgroup tephras at intermediate terrace heights (25–35 m), and Rotoiti Ignimbrite (to the south) and Mamaku Ignimbrite (to the southwest) at higher levels (>40 m). The underlying ignimbrites and tephra-fall deposits are mainly unconsolidated and non-welded to weakly welded, and hence readily eroded to form a deeply dissected landscape with flat interfluves sloping gently to the north, bounded by steep-sided ravines.

Alluvial plains

This physiographic unit includes the alluvial flood plain of the Kaituna River to the west of Maketu (Fig. 6) and margins of the Kaituna peat swamp, and alluvial plain of the Pongakawa River to the east and the Waihi peat swamp. The alluvial flood plains are formed from alluvial sands, silts, peats, tree stumps and logs, and intercalated tephra layers. They are underlain by estuarine deposits in many places. The Kaituna swamp, around the margins of the Maketu Estuary, contains peat up to 1.3 m thick (Murray 1978; Davoren 1978). The Waihi swamp comprises peat up to 2.6 m thick near State Highway (SH) 2, thinning towards the Waihi Estuary (Davoren 1978; Cotching 1998). The alluvial plains and swamps have been largely drained by canals, and the peats have shrunk considerably through oxidation, compaction, and dewatering (Pullar 1970; Newnham et al. 1995).

Coastal estuaries

The Maketu (Fig. 7) and Waihi (Fig. 8) estuaries are low mesotidal estuarine lagoons dissected by numerous narrow tidal channels and enclosed by barrier sand spits (Burton 1987; Domijan 2000; Easton 2002). The estuaries are characterised by strong tidal currents and intermittent river inflow within the estuarine channels.

The Kaituna River used to flow into the Maketu Estuary but has been diverted both naturally and artificially at various times, most recently in 1958 (see below) (Murray 1978; Domijan 2000). Following the Postglacial rise of sea-level to about its present position, c. 6000–7000 calendar (cal.) years BP[2] (Table 1), the Maketu Estuary was much more extensive than now (Murray 1978; Wigley 1990). Peat began forming on top of estuarine deposits in the Te Puke area after c. 5300 cal. years BP (Newnham et al. 1995) and had extended over estuarine deposits in the Maketu area by c. 2000 cal. years ago or possibly earlier (Pullar and Patel 1972; Murray 1978; Wigley 1990).

The low-lying Kaituna swampland surrounding the Maketu estuary was flood-prone and in 1907 the flooded Kaituna River formed a new outlet on the coast west of Maketu. In 1922, in an attempt to reduce flooding in the area, a canal (Ford's Cut) was excavated parallel to the coast and the river mouth blocked to force the Kaituna River to flow back into the Maketu Estuary (Domijan 2000). However, the river resumed flowing to the sea through the mouth after a flood in 1928. After 1939, the Kaituna River flowed into the estuary, but continued flooding led to the decision (in 1954) to block Ford's Cut with a stopbank. The river was subsequently diverted along a canal to the coast in February

[2] *Throughout this report, calendar years are used for dates determined using the radiocarbon technique (i.e. spanning the last c. 50, 000 years), and are derived from calibrations based on Hughen et al. (2004a, 2004b), Reimer et al. (2004) and Bard et al. (2004). Errors on the calibrated ages are not reported and probably exceed 100–200 years in some cases.*

Fig. 2 *Oblique aerial photograph of Motiti Island, viewed from the southwest. Taumaihi Island (bottom right) is joined to Motiti at low tide. (Photo: Stephen Park, Environment BOP.)*

Fig. 3 *Oblique aerial photograph of Maketu peninsula, looking southeast along the Bay of Plenty coastline. Maketu Estuary at lower right. (Photo: Stephen Park, Environment BOP.)*

Fig. 4 *View towards the east from near the Kaituna River mouth, showing the flat-lying Maketu peninsula and Okurei Point (Town Point) at far left.*

Fig. 5 *Low terrace (right foreground) and alluvial plain (left middle distance), southwest of Maketu peninsula (higher terrace in background).*

1958 (Domijan 2000), thus bypassing Maketu Estuary apart from some leakage through the stopbank and overflows during large floods and spring tides (Murray 1978). The diversion of the river has resulted in some sedimentation within the estuary, including enlargement of the flood tide delta in the lower estuary (Burton 1987; Healy and de Lange 1988; Domijan 2000).

The Waihi Estuary has also been diminishing in size since the eruptions of the Taupo Tephra and Kaharoa Tephra, and probably extended as far inland as SH 2 before c. 2000 cal. years ago (Cotching 1998). Currently it seems to be infilling as a sediment sink (Easton 2002).

Dunes

Along the coast west of the Maketu Estuary, dune sand forms a strip about 500 m wide, but this narrows on the sand-spit seaward of the Maketu Estuary (see map). There is a dominant southeast-flowing littoral current along the Bay of Plenty coast (Healy et al. 1977), and the entrance to the Maketu Estuary is at the eastern end of the sand-spit, adjacent to the upstanding Maketu headland. The presence or absence of key mid-Holocene tephras (Whakatane and Unit K tephras) on the dune sands (Fig. 9), and radiocarbon dates from interdune peats, indicate that the Papamoa dune system to the west of Maketu began to prograde seaward from c. 5500 cal. years ago (Wigley 1990; Newnham et al. 1995; Cotching 1998). However, a radiocarbon date obtained from cockle shells (Wk1440, Table 1) in estuarine sands landward of the dune barrier suggests that the oldest dune must have been in place by c. 6500 cal. years BP (Dahm et al. 1994). Two radiocarbon dates of c. 6000 cal. years BP (Wk132, Wk1462, Table 1) obtained on cockle shells in estuarine sands from drill cores between ~0.5 and ~1 km southwest of Maketu Estuary (Table 1) similarly indicate the existence of a dune barrier enclosing an estuary at or before this time. These indications are consistent with the formation of dune barriers at other sites along the Bay of Plenty and Coromandel coasts in the Holocene, the oldest dunes being dated at c. 7000 ± 500 cal. years BP (Dahm and Munro 2002; Murdoch 2005).

The strip of sand dunes along Pukehina Beach southeast of Maketu peninsula is only about 160 m wide (Cotching 1998). Most of these dunes may have been formed after the Kaharoa Tephra was erupted because it has not been found on them. However, inland of the main dune ridge, the Kaharoa Tephra has been recognised, and possibly also Taupo Tephra, so part of the dune system had been established by Kaharoa time (c. 1314 AD) and possibly prior to the deposition of Taupo Tephra (c. 232 AD) (Cotching 1998). A similar model was proposed for the narrow coastal sand-spit enclosing Maketu Estuary (Murray 1978).

The frontal dunes are an integral part of the equilibrium beach system and are liable to prograde or erode depending on the wave energy inputs and other factors, for example sea-level rise or fall, storm surges, or sediment transport into adjacent estuaries (Phizacklea 1993; Domijan 2000; Easton 2002). Consequently, they are inherently unstable, and should not be considered a permanent feature of the landscape.

Table 1. Radiocarbon ages obtained on estuarine shells (**Chione stutchburyi*****) from the Kaituna alluvial plains near Maketu.***

CORE NO.	REFERENCE	DEPTH IN CORE WITH RESPECT TO MEAN SEA LEVEL	LOCATION (grid reference)*	WAIKATO RADIOCARBON LAB. NO.	RADIOCARBON AGE (^{14}C yr BP)	RESERVOIR-CORRECTED CALIBRATED AGE (cal. yr BP)¶
M14	Murray (1978)	+0.20 m	V14/114764	Wk132	5000 ± 200	5580–5070 (68.2%) 5800–4800 (95.4%)
Kt2	Wigley (1990)	-1.50 m	U14/021775	Wk1440	6220 ± 160	6870–6480 (68.2%) 7100–6300 (95.4%)
D4	Wigley (1990)	-1.10 m	V14/105761	Wk1462	5710 ± 250	6400–5850 (68.2 %) 6750–5550 (95.4%)

** New Zealand Map Series 260 (1: 50,000); see Fig. 1 and Map*

¶ *1σ- and 2σ-age range probabilities given in parentheses. Calibrations based on Marine04 calibration curve of Hughen et al. (2004a) with delta-R corrections of 11 ± 12 years and using OxCal v3.10 (updated from Bronk Ramsey 2001).*

Fig. 6 *Alluvial plain and canal alongside Kaituna Road, east of Kaituna River mouth.*

Fig. 7 *Maketu Estuary (middle distance) and Papamoa Range (far sky-line). Maketu township in foreground.*

Fig. 8 *View overlooking Little Waihi campground, Waihi Estuary, and Pukehina Beach spit (left).*

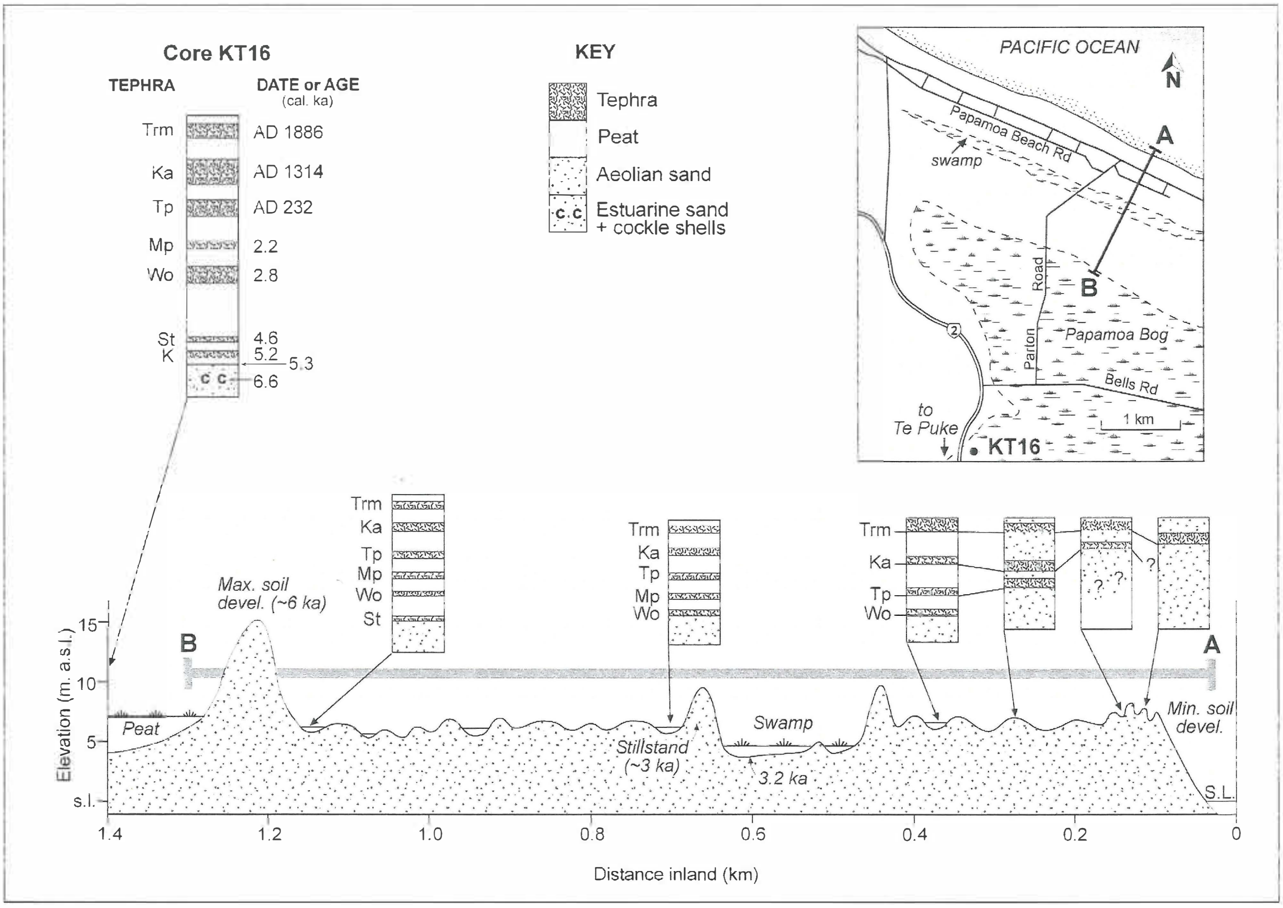


Fig. 9 *Transect across dunes and peaty swales at Papamoa (part of U14), and associated tephrostratigraphy. Tephra abbreviations are: Trm, Rotomahana Mud; Ka, Kaharoa Tephra; Tp, Taupo Tephra; Mp, Mapara Tephra; Wo, Whakaipo Tephra; St, Stent tephra; K, unit K. After Lowe et al. (1992), Alloway et al. (1994), and Newnham et al. (1995). Core KT16 is located at U14/008793 (see inset map), and is c. 5 m deep. All other cores are approximately 1 m deep (tephra thicknesses are exaggerated).*

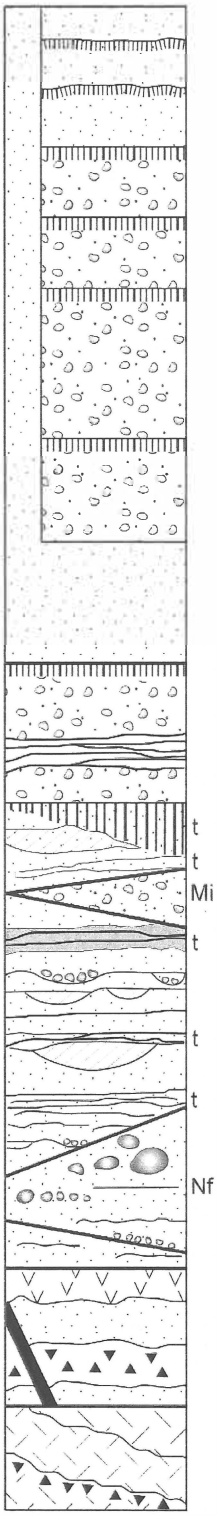
Geological history

The Maketu area and Motiti Island are composed of Pliocene to Holocene volcanic deposits (both lavas and pyroclastic material) and volcanogenic sediments, together with Holocene dunes, peats, and estuarine deposits in coastal environments. A generalised summary of the stratigraphy is given in Fig. 10. Each of the main stratigraphic units identified is described in the following section from oldest to youngest, and for each unit there are notes on the definition, composition, distribution, stratigraphic relations and age, and some simplified geotechnical properties. Most of the strata or rock units are highly variable in character, and it must be emphasised that these notes are generalised and not site specific. Note that some of the stratigraphic units are time transgressive, spanning considerable periods of time, and that several overlap chronologically (Fig. 10).

The oldest rocks covered by this map of sheet V14 are found on Motiti Island which is a remnant of a former subaerial andesite composite cone volcano that was constructed in Pliocene times (3.4–4.3 Ma). It has since been eroded to form a flat-lying island (presumably by marine erosion although there are no marine deposits preserved), and then overlain unconformably by a 20-metre-thick sequence of fluvial sediments capped by up to 6 m of tephra beds. The uppermost of these tephras form the composite parent material from which the modern soils have developed (e.g. Lowe and Palmer 2005). The tephras have been deposited from several explosive volcanic eruptions from the Okataina Volcanic Centre east of Rotorua, and possibly other volcanic centres, and blanket large areas of the Rotorua and Bay of Plenty regions (e.g. Pullar and Birrell 1973).

The oldest deposits in the Maketu area are fluvial silts, sands, and gravels, very similar to those seen on Motiti Island (and probably the same age), except at Maketu there is also a thick lahar deposit that is intercalated with these sedimentary rocks. This lahar (here named Newdicks Formation) is well exposed in the cliff sections around the Maketu peninsula, and represents a catastrophic deposit produced by a deluge or debris flow of gravel and sand down a former river valley, possibly from sudden collapse of a lake in a crater or caldera (a breakout flood event). The lahar/breakout flood deposit is overlain by further fluvial sands, silts, and gravels, and a number of relatively thin intercalated pumiceous tephra beds from eruptions in the Taupo Volcanic Zone. Near the top of the sequence is an ignimbrite (identified as the Mamaku Ignimbrite by Manning 1995; 1996), overlain by aeolian sediments (dune sands and loess) on which a distinctive, well-developed dark paleosol has formed. The environment thus changed from a fluvial sedimentary one to a subaerial one with the deposition of Mamaku Ignimbrite and subsequent dune sands and loess, and then a series of tephra-fall deposits and ignimbrites derived largely from the Okataina Volcanic Centre. The Rotoiti Tephra Formation and four tephra formations of the Mangaone Subgroup make up the bulk of this pyroclastic sequence. The youngest tephras include the rhyolitic Kaharoa Tephra, from the eruption of Mt Tarawera in 1314 AD ± 12, and Rotomahana Mud from the 1886 AD eruption of Tarawera, both of which have been preserved in peats in the Papamoa basin (Newnham et al. 1995) and in foredunes (Lowe et al. 1992). About 2–3 cm of Rotomahana Mud was originally recorded at Maketu by Thomas (1888).

In the Kaituna and Pukehina lowlands (collectively part of Te Puke lowlands) surrounding the Maketu peninsula there is a late Pleistocene to Holocene sequence of fluvial terraces, alluvial plains, dune sands, minor loess, estuarine sands and muds, peats, and intercalated tephras. Several studies have shown that this part of the Bay of Plenty coastline has been prograding (i.e. progressively building out seawards by the accumulation of sediments) at an average rate of 0.188 m per year (Fig. 9; Wigley 1990; Lowe et al. 1992; de Lange 2001). The last ~700 to 1000 years of dune progradation at Papamoa-Te Puke has been at very low rates, suggesting that sediment supply is a major limiting factor and that the existing beach and dune reserves at Maketu should be regarded as essentially a finite 'inheritance' from the past (Dahm et al. 1994; de Lange 2001; Shepherd and Hesp 2003). These slow rates, hence low sediment supply, are consistent with detailed investigations of Holocene barrier evolution along the Coromandel Peninsula coast further north, where the rate of seaward progradation of the barriers has similarly slowed markedly over the last 1000–2000 years (Dahm and Munro, 2002).



Unit	Age
POST-MANGAONE SUBGROUP TEPHRAS Kawakawa Tephra, Rotorua Subgroup and Taupo Subgroup tephras, Tuhua Tephra, distal andesitic tephras, paleosols	< *c.* 32,000 cal. yr BP
Omataroa Tephra Mangaone Tephra Hauparu Tephra Maketu Tephra } MANGAONE SUBGROUP TEPHRAS Pumice-rich fall deposits, paleosols	*c.* 32,000 – *c.* 36,000 cal. yr BP
LATE PLEISTOCENE AND HOLOCENE SEDIMENTS Alluvium, peats, estuarine deposits, dune sands, loess, paleosols	< *c.* 50,000 cal. yr BP
ROTOITI TEPHRA FORMATION Crystal and pumice-rich ignimbrite (Rotoiti Ignimbrite) interbedded with finely bedded ash (Rotoehu Ash), paleosol	*c.* 50,000 cal. yr BP
Dark, strongly developed Last Interglacial paleosol on weathered loess or dune sands or ash	*c.* 125,000 yr BP
MID-PLEISTOCENE TEPHRAS Huntress Creek Subgroup and Kukumoa Subgroup tephras (t), non-welded ignimbrite (Mamaku Ignimbrite, Mi, *c.* 220,000 yr BP)	*c.* 50,000 cal. yr BP – *c.* 285,000 yr BP
MATUA SUBGROUP Fluviatile sands, silts, gravels, dune sands, loess, and lahar deposits (Newdicks Formation, Nf, *c.* 250,000 yr BP)	*c.* 50,000 cal. yr BP – 2.09 Ma
ORONGATEA FORMATION Andesite and basaltic andesite lavas, volcanic breccias, tuffs, dikes	3.42 Ma
MOTITI FORMATION Andesite and basaltic andesite lavas and volcanic breccias	4.32 Ma

Fig. 10 *Generalised stratigraphy of the Maketu area.*

Stratigraphy

Coromandel Group (Skinner 1976)

Kaimai Subgroup (Houghton and Cuthbertson 1989)

Motiti Formation *mo*

(new formation)

Definition and description

Motiti Island is a deeply eroded remnant of a Pliocene andesite composite cone volcano, made up of two formations, the Motiti Formation and Orongatea Formation (previously informally defined by Henry 1991) (Fig.11). The Motiti Formation is comprised of two-pyroxene andesites, forming massive to strongly platy jointed lavas, with minor volcaniclastic breccias. The andesite lavas are light grey with visible phenocrysts of plagioclase and pyroxene. They contain light green andesitic xenoliths (up to 10 mm in size) similar to those observed in many Coromandel andesites. The volcanic breccias consist of monolithologic clasts of subangular scoriaceous andesite set in a tuffaceous matrix, and are most likely autoclastic breccias produced by break-up of a slowly moving aa or blocky lava flow.

There are localised areas of hydrothermal alteration within the Motiti Formation, with zones of silicification, and propylitic and argillic alteration commonly adjacent to quartz veins. Some quartz veins are up to 75 cm wide and are oriented parallel to the dominant NNE (020°) trending strike of the fault pattern on Motiti Island.

Chemically, the lavas from the Motiti Formation are basaltic andesites and andesites (56.1–60.7 wt.% SiO_2) and have medium-K (0.59–1.63 wt.% K_2O) and trace element compositions (low Nb, high Ba, Rb, Th, Zr) very similar to andesites of the Coromandel arc (Henry 1991).

Distribution

Motiti Formation is considered to form the bulk of Motiti Island, although most of it is covered by fluvial sediments and tephra deposits. It is well exposed around the northern, eastern, and most of the southern cliffs of the island.

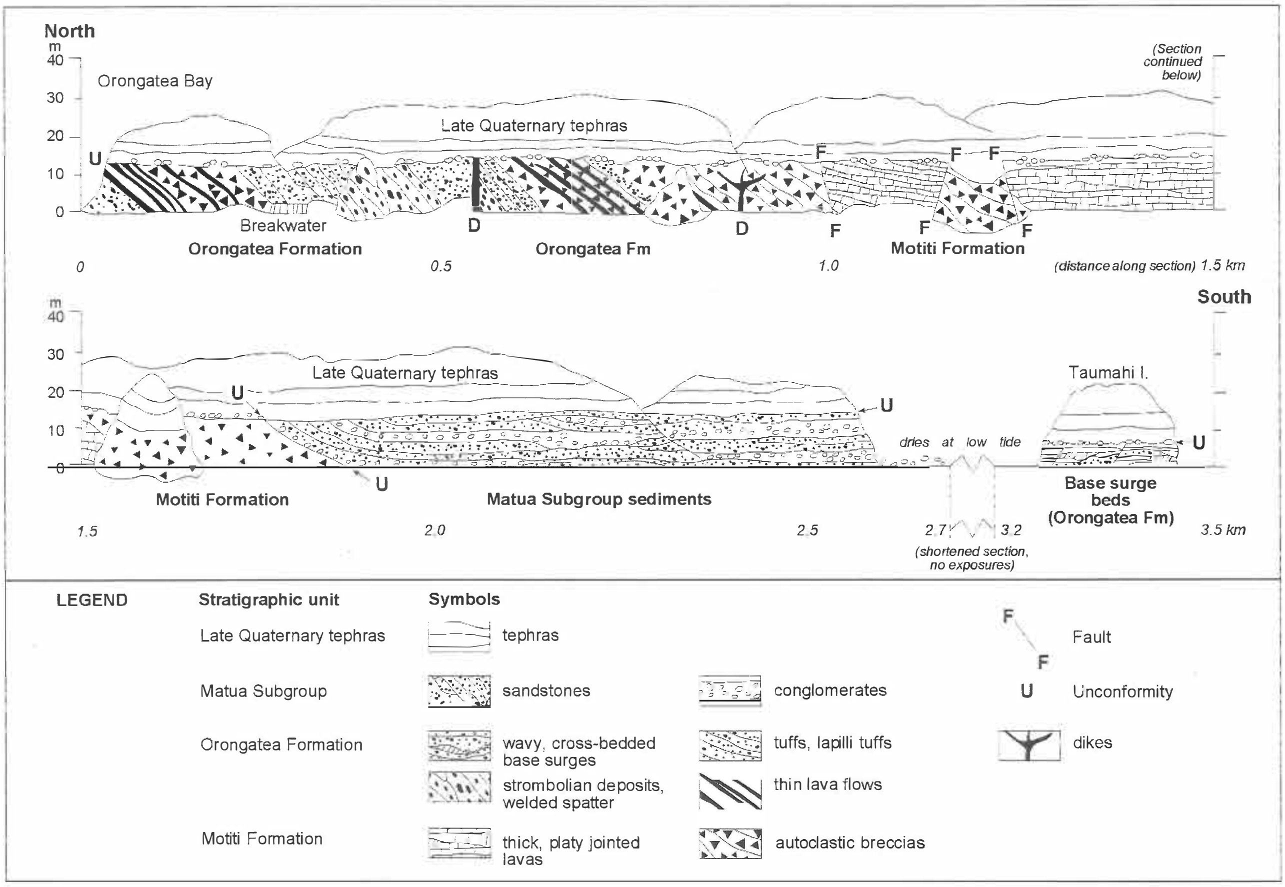


Fig. 11 *Coastal section of the southwestern coastline of Motiti Island from Orongatea Bay (north) to Taumaihi Island (south) (from Henry1991). Length of section = 3.5 km. Vertical scale in metres. Mid-Late Quaternary tephras include Mid-Pleistocene tephras, Rotoiti Tephra Formation, Mangaone Subgroup tephras, and post-Mangaone Subgroup tephras.*

Stratigraphic relations and age

The Motiti Formation is the oldest exposed stratigraphic unit in the map area; no contacts have been observed with underlying rocks. Motiti Formation is in fault contact with the Orongatea Formation, and is overlain by the sedimentary sequence of the Matua Subgroup and tephras derived from eruptions in the Taupo Volcanic Zone.

Motiti Formation has been dated by whole-rock K/Ar methods by T. Itaya (in Henry 1991) at 4.32 ± 0.68 Ma. This age has a large error but is similar to the age of the andesites, dacites, and rhyolites dated by Brathwaite and Christie (1996) in the Waihi region. It is distinctly older than the Otawa Volcanics (2.54–2.95 Ma, Stipp 1968) in the Papamoa Range within the Tauranga Volcanic Centre (Briggs et al. 2005).

Rock character

Unweathered rock is very strong to extremely strong (R5-R6). Joints are common and vary in spacing from very close (5 cm) to very wide (5 m). Weathered rock may be very weak (R1), but may be soft or firm clay (S2-S3) in breccias or hydrothermally altered zones.

Orongatea Formation *or*

(new formation)

Definition and description

The Orongatea Formation is the younger of the two andesitic formations that form the basement of Motiti Island, as previously informally defined by Henry (1991). The Formation consists mainly of moderately dipping (28°–40°) alternating layers of agglutinated or welded spatter, fall deposits, volcaniclastic breccias, and thin lava flows, intruded by vertical or steeply dipping dikes (Fig. 11). It was interpreted by Henry (1991) as a proximal volcaniclastic facies of a composite cone, built up by alternating and cyclical effusive (strombolian) and explosive (phreatomagmatic) eruptions. The consistent dip of these beds to the south, along with large ballistic bombs up to 1 m across in strombolian beds, implies proximity to source with a possible vent to the north in the Orongatea Bay area.

Base surge deposits, intercalated with finely stratified and laminated fall beds, are preserved in stratigraphically lower sections of the cliffs on Taumaihi Island at the southern tip of Motiti Island. They represent part of a tuff ring formed from explosive interaction of basaltic andesite magma with water, and the orientation of bedforms such as cross bedding and channel structures indicate a source vent located to the northwest of Taumaihi Island. These deposits have also been included in the Orongatea Formation.

Lavas of Orongatea Formation are porphyritic basaltic andesites and andesites with phenocrysts of plagioclase, and lesser amounts of orthopyroxene, augite, and rare titanomagnetite and ilmenite set in a fine grained groundmass of plagioclase, pyroxene, Fe-Ti oxides, and minor glass. They show little variation in geochemical composition, ranging from 55.4 to 58.8 wt.% SiO_2, and 0.99–1.51 wt.% K_2O (Henry 1991).

Distribution

The Orongatea Formation is restricted to a narrow strip on the western side of the island, where it is in fault contact with Motiti Formation. The fault strikes NNE (020°), dips 80° to the west, and extends from Orongatea Bay to the SSW sector of the island. Tuff ring deposits of the Orongatea Formation are restricted to Taumaihi Island.

Stratigraphic relations and age

The base of the Orongatea Formation has not been observed. The upper part has been planed off by erosion and is overlain unconformably by Matua Subgroup gravels, sands, and silts on Taumaihi Island. In the western coastal sections the Matua sediments have been entirely eroded, and the Orongatea Formation is unconformably overlain by Late Quaternary tephras. The Orongatea Formation has been dated by whole-rock K/Ar methods by T. Itaya (in Henry 1991) at 3.42 ± 0.19 Ma.

Rock character

The unweathered rock is highly variable, ranging from very strong to extremely strong (R5-R6) in thin lavas (1-3 m thick), to medium strong (R3) in thick breccias and tuffs. Weathered rock changes to firm clay (S3). Outcrops vary from very coarse grained massive agglomerates up to 60 m thick with only very wide spaced joints, to fine grained tuffs and lapilli tuffs with close spaced joints or discontinuities.

Matua Subgroup *(of Tauranga Group)*

Definition and description

The Matua Subgroup is part of the Tauranga Group as defined by Kear and Schofield (1978). Matua Subgroup includes all the terrestrial and estuarine sedimentary deposits formed after the deposition of Waiteariki Ignimbrite (2.09 ± 0.03 Ma, Briggs et al. 2005), excluding those of the late Pleistocene and Holocene fluvial regimes (Houghton and Cuthbertson 1989; Briggs et al. 1996). The upper age limit of the Subgroup was previously defined as up to the Mamaku Ignimbrite (Briggs et al. 1996), but here it is extended further to Rotoiti Tephra (Fig.10; discussed further below). It contains a wide variety of lithologies which change rapidly laterally and vertically, and includes fluviatile sands, silts, and gravels, estuarine sands and silts, and minor dune sands and loess. In the Tauranga area it also includes lignites and lacustrine silts. The Matua Subgroup represents a period of time when there was voluminous volcanism in the southern Coromandel and Taupo volcanic zones, with widespread reworking by fluvial and occasionally aeolian processes, and also laharic deposition of rhyolitic material into adjacent low-lying sedimentary basins. These processes have all been terrestrial or estuarine.

On Motiti Island, the Matua Subgroup deposits (referred to simply as "Quaternary sediments" by Henry 1991) are up to 20 m thick and consist of laminated or lensoidal beds of well sorted tuffaceous silts, sands and gravels, trough cross-bedded pumiceous sands, and poorly sorted conglomerates (similar to deposits shown in Fig. 12). The conglomerates form thick lensoidal channel structures that dip c.12° to the west, and the clasts are well rounded.

At Maketu peninsula, the Matua Subgroup was formerly referred to as the Little Waihi Formation by Chappell (1975) (now obsolete). It includes a thick laharic or breakout flood deposit named the Newdicks Member by Wehrmann (2000), after Newdicks Beach (e.g. V14/158786) on the northeast side of the peninsula (Fig. 12). We have re-named this unit **Newdicks Formation** (new formation) because its previous status as a member of the defunct Little Waihi Formation no longer holds. The basal beds of the Matua Subgroup at Maketu consist of moderately sorted planar, wavy, and cross-bedded pumiceous sands and gravels up to 10 m thick, overlain by 3.5 m of white siltstones. These beds are overlain by the Newdicks Formation which is up to 25 m thick, and contains boulders up to 7 m in diameter set in a matrix of coarse sands and gravels (Figs. 13, 14). The boulders are well rounded and show no grading, and there is a clast-supported basal conglomerate which overlies the white siltstone. The Newdicks Formation is heterolithologic, and most of the boulders (about 70%) are composed of densely welded ignimbrite or lenticulite containing dark grey fiamme (Fig. 15). This ignimbrite was informally named the Okurei ignimbrite by Wehrmann (2000), after Okurei Point on the peninsula. The remaining clasts are comprised of Quartz-Biotite Ignimbrite, Matahina Ignimbrite, other densely welded ignimbrites, rhyolite, obsidian, propylitically altered andesite, augite basalt, greywacke, siltstone, and hydrothermally altered clasts of uncertain composition. Parts of the underlying siltstone have been entrained in the deposit, which has been interpreted by Wehrmann (2000) as representing a lahar deposit. However, because most of the clasts are unrecognised, the source of the lahar or breakout flood event is unknown.

The Newdicks Formation is overlain by up to 12 m of fluvial trough cross-bedded pumiceous sands and gravels, planar bedded silts and sands (Fig. 16), c. 4–6 m of laminated aeolian sands, and c. 1.5 m of weathered tephric loess. Interbedded within these sediments are five or more unnamed pumiceous ash and lapilli fall beds and a c. 5-m thick pyroclastic flow deposit, probably Mamaku Ignimbrite (Manning 1995) (Fig. 17), which we refer to collectively here as Mid-Pleistocene tephras (Fig. 10).

Distribution

The Matua Subgroup is up to 20 m thick at the southern end of Motiti Island and on Taumaihi Island, but thins out to the north where it has been either completely eroded and planed off, or not deposited.

Matua Subgroup is well exposed at Maketu peninsula (Fig. 12) where it has a combined thickness of 52 m (Wehrmann 2000). It extends from Little Waihi, and around steep coastal cliffs from Newdicks Beach, Okurei Point, to Maketu township. Hence it is considered to underlie the whole of Maketu peninsula. Correlation of the Matua Subgroup between Maketu and Motiti is based on their similar stratigraphic position and lithology, except the Newdicks Formation lahar was not deposited at Motiti, or has been completely eroded.

Stratigraphic relations and age

Matua Subgroup sediments unconformably overlie the Orongatea and Motiti formationson Motiti Island. There is a strong angular unconformity at the base, indicating that a significant period of time elapsed between erosion of the underlying volcanic formations and deposition of the basal Matua sediments. The upper surface of the Matua sediments has also been eroded, and there is a well developed paleosol on weathered material immediately beneath the Rotoiti Tephra Formation.

No basal contact of the Matua Subgroup has been observed at Maketu. The Newdicks Formation lahar/breakout flood deposit contains clasts of Matahina Ignimbrite (Wehrmann 2000), which has been Ar/ Ar dated at 0.28 ± 0.01 Ma (Houghton et al. 1995), and thus the formation is >= 0.28 ± 0.01 Ma in age. A minimum age for the Newdicks Formation is provided by the overlying Mamaku Ignimbrite, which is dated at c. 0.22 Ma. Hence we assign a tentative age of c. 0.25 Ma to the Newdicks Formation.

The dune sands and loess deposits that overlie Mamaku Ignimbrite at Maketu most likely were deposited during marine isotope stage (MIS) 7 (c. 0.24–0.19 Ma), MIS 6 (c. 0.18–0.13 Ma), and MIS 5 (c. 0.13–0.075 Ma) (Martinson et al. 1987) with Mamaku Ignimbrite being deposited during MIS 7 (Shane et al. 1994). The distinctive, dark reddish brown paleosol developed in loess or weathered tephra, previously referred to as 'undifferentiated brown ash' or 'Hamilton Ash' (e.g. Vucetich and Pullar, 1969; Chappell 1975), probably formed during the Last Interglacial (see below).

Houghton and Cuthbertson (1989) and Briggs et al. (1996) suggested that the whole Matua Subgroup should be extended up to the Mamaku Ignimbrite. Hence in the Tauranga region the Matua Subgroup post-dates the Waiteariki Ignimbrite (dated by Briggs et al. (2005) at 2.09 ± 0.03 Ma) and extends to Mamaku Ignimbrite at c. 0.22 Ma. Although Mamaku Ignimbrite has now been identified in the Maketu area, we propose that the Matua Subgroup be extended to encompass

Fig. 12 *View to the southeast of coastal cliff section, about 100 m southeast of Okurei Point (Town Point), exposing Matua Subgroup sediments and lahar deposits of Newdicks Formation in lower part of cliff, overlain by aeolian dune sands, loess, Last Interglacial paleosol, Rotoiti Tephra Formation, and Maketu and Hauparu tephras in uppermost sections. Note boulders mainly of lenticulite ignimbrite eroded out of the Newdicks Formation covering the shore platform.*

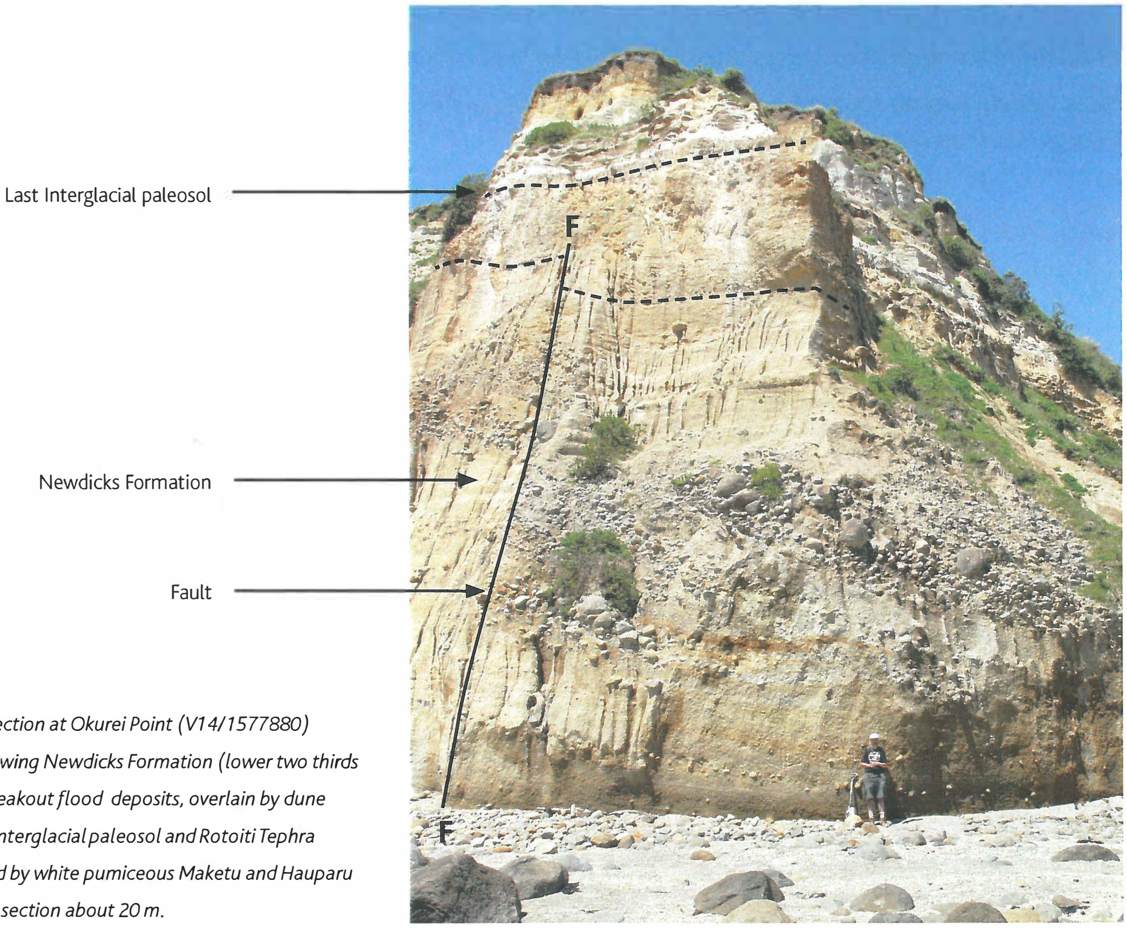


Fig. 13 *Coastal section at Okurei Point (V14/1577880) looking south, showing Newdicks Formation (lower two thirds of cliff) laharic/breakout flood deposits, overlain by dune sands, loess, Last Interglacial paleosol and Rotoiti Tephra Formation, capped by white pumiceous Maketu and Hauparu tephras. Height of section about 20 m.*

Fig. 14 *Newdicks Formation laharic/breakout flood deposits of channelised coarse sands and gravels. Note large ignimbrite boulder about to land on person for scale (David Lowe, 1.88 m).*

Fig. 15 *Beach boulder of lenticulite ignimbrite eroded out of Newdicks Formation. Length of scale = 8 cm.*

sediments deposited up to the time of eruption of the Rotoiti Tephra Formation c. 50,000 cal. years BP. Rotoiti Tephra, especially the shower bedded fallout component Rotoehu Ash, is a very widely distributed and distinctive marker bed in the Bay of Plenty and elsewhere in the North Island (Pullar and Birrell 1973; Walker 1979; Newnham et al. 2004).

The Matua Subgroup is overlain by a thick sequence of tephra-fall deposits and ignimbrites of the Rotoiti Tephra Formation and the Mangaone Subgroup.

Rock character

The Matua Subgroup comprises unconsolidated sands, silts, and coarse gravels that vary from extremely weak rock (R0) to firm clay (S3) including minor clayey units of weathered loess. It is massive to finely laminated, joints are mainly absent, but there are several faults in the sequence. Matua Subgroup is very prone to marine cliff and platform erosion and landslides, especially under wet conditions. The absence of weathered material (apart from loess) and the litter of boulders along the coastline that have fallen out of the cliffs, indicates that most exposures are actively eroding because of their extremely weak character.

Mid-Pleistocene tephras

This composite 'grab-bag' unit comprises around five or more Mid-Pleistocene-aged rhyolitic, pumiceous tephra-fall deposits, and a c. 5-m thick non-welded ignimbrite (Mamaku Ignimbrite) that are intercalated within the fluvial and aeolian sedimentary deposits of the Matua Subgroup at Maketu peninsula (Fig. 10). The tephra interbeds, assumed to be primary fall deposits or reworked very soon after deposition, occur above the Newdicks Formation and typically comprise massive or bedded white ash or lapilli layers, or alternations of both (Manning 1995). They have been named informally and described in brief by Manning (1995; 1996), in ascending stratigraphic order, as 'Maketu-D' (2 m thick, c. 0.275 Ma, probably reworked) (Fig. 18), 'Maketu-H' (0.20 m thick, c. 0.260 Ma), 'banded pumice beds' (possibly four tephra-fall units, c. 4 m thick in total), 'Maketu-L' (c. 0.22 Ma, equivalent to Mamaku Ignimbrite, Fig. 17), and 'Maketu-M' (0.15 m, c. 0.08 Ma). The tephras may be assigned to the Huntress Creek (c. 0.285–0.24 Ma) and Kukumoa (c. 0.24 Ma to c. 50,000 cal. years BP) tephra subgroups informally defined by Manning (1996).

Relationship of 'Hamilton Ash Formation' to Mid-Pleistocene tephras

Previously, tephras of this age range in the Bay of Plenty and elsewhere were collectively termed Hamilton Ash Formation (Birrell et al. 1977; Briggs et al. 1996). Originally defined by Ward (1967) and Pain (1975) for the Waikato region, but also recognised in South Auckland and on Coromandel Peninsula (Bakker et al. 1996), this formation comprises a weathered sequence up to 6-m thick of reddish brown to dark brown, clayey tephra beds, denoted H1/H2 (base) to H7 (top), and associated paleosols, aged from c. 0.35 to c. 0.10 Ma (Pillans et al. 1996; Lowe et al. 2001). Such a composite sequence, up to 2.5 m thick, is well represented in the Tauranga area and so use of the portmanteau term 'Hamilton Ash' was appropriate there (Briggs et al. 1996; 2005). However, in the Maketu area, more downwind and closer to the locus of Mid-Pleistocene volcanic activity in the Taupo Volcanic Zone, a combination of circumstances has resulted in some tephras being preserved as individual layers by rapid burial within sediments of the Matua Subgroup rather than being 'telescoped' and 'welded' together by weathering and soil formation into essentially massive 'Hamilton Ash' as occurred elsewhere. Consequently, we contend that 'Hamilton Ash Formation' is inappropriate as a stratigraphic unit for the Maketu area.

Mamaku Ignimbrite

Definition and description

The Mamaku Ignimbrite was named by Martin (1961) who designated the gorge of the Mangorewa River at the bridge of the Pyes Pa-Tauranga Direct Rd (grid reference U15/887554) as the type site where it is 130 m thick (Briggs et al. 1996). It was deposited during the formation of Rotorua Caldera (Milner et al. 2003).

At Maketu peninsula, Mamaku Ignimbrite comprises a slightly pinkish, greyish brown, non-welded, weakly weathered and weakly cemented, firm and massive ash-grade deposit c. 5 m thick (Fig. 17) containing minor pumice clasts (Manning 1995). Informally designated 'Newdicks ignimbrite' or 'Maketu-L', it was tentatively identified as Mamaku Ignimbrite by Manning (1995) on the basis of its stratigraphic position and the similarity of the major-element composition of its volcanic glass (obtained by electron microprobe) with that of Mamaku Ignimbrite (Black et al. 1996). Our analyses of glass from two samples from Newdicks Beach and Little Waihi Road, and from reference material from boreholes in Rotorua Basin, confirm the correlation by Manning (1995) (Table 2).

Distribution

The Mamaku Ignimbrite is one of the most widespread ignimbrites from Taupo Volcanic Zone, but is not found on Motiti. It forms a fan capping the Mamaku Plateau and part Kaimai Range between Te Puke/Maketu in the north and Atiamuri in the southwest, and has a minimum erupted volume estimated at 339 km^3 (Milner et al. 2003). In the Maketu area, it is seen near the top of the cliffs around much of the peninsula (Manning 1995). It also occurs in outcrop and drill holes around 15 km southwest of Maketu (Healy et al. 1964; Briggs et al. 1996).

Stratigraphic relations and age

The Mamaku Ignimbrite is intercalated with the volcanogenic fluvial and aeolian deposits of the Matua Subgroup. It has an age of c. 0.22 Ma based on both Ar/Ar and isothermal-plateau fission-track ages of 0.23 ± 0.12 Ma, 0.22 ± 0.10 Ma, and 0.23 ± 0.10 Ma derived by Shane et al. (1994), Houghton et al. (1995) and Black et al. (1996), respectively. It was erupted during a geomagnetic excursion which has been correlated with the Pringle Falls event dated at 0.218 ± 0.10 Ma (Black et al. 1996; Tanaka et al. 1996; Lowe et al. 2001).

Rock character

The Mamaku Ignimbrite at Maketu is classed as extremely weak to very weak rock (R0-R1).

Last Interglacial paleosol

At Maketu, the distinctive, dark reddish brown paleosol at the top of the Matua Subgroup (Fig. 19), usually overlain sharply by the pale grey beds of Rotoiti Tephra Formation, was previously described as being formed in Hamilton Ash (Chappell 1975). Our observations, supported by those of Manning (1995), suggest instead that this paleosol, up to c. 1 m in thickness, is formed mainly in massive clay-rich loess overlying layered tephric sand dunes (Fig. 20), not tephra, deposited during MIS 6 or MIS 5. The paleosol thus represents soil formation during the Last Interglacial or MIS 5e at c. 125 ka (Bakker et al. 1996; Lowe et al. 2001), and is probably time transgressive spanning several tens of thousands of years.

Table 2. Electron microprobe analyses[a] of glass from Mamaku Ignimbrite and correlatives at Maketu Peninsula compared with analyses of reference material from Mamaku Plateau and Hamurana borehole in Rotorua Basin.

	MAKETU PENINSULA			MAMAKU PLATEAU	HAMURANA BOREHOLE	
	Newdicks Bch	Newdicks Bch	Little Waihi Rd			
Anal. no.	1	2	3	4	5	6
SiO_2	77.33 (0.17)	78.77 (0.22)	77.15 (0.53)	77.83 (0.22)	77.58 (0.22)	77.17 (0.41)
Al_2O_3	11.90 (0.15)	11.73 (0.15)	12.35 (0.30)	12.34 (0.13)	12.02 (0.13)	12.05 (0.13)
TiO_2	0.17 (0.10)	0.13 (0.03)	0.13 (0.07)	0.08 (0.04)	0.13 (0.08)	0.22 (0.09)
FeO^b	1.26 (0.07)	1.12 (0.09)	1.07 (0.32)	1.04 (0.06)	0.99 (0.18)	1.17 (0.14)
MnO	0.05 (0.07)	nd	0.02 (0.04)	0.05 (0.04)	0.09 (0.08)	0.09 (0.04)
MgO	0.06 (0.10)	0.07 (0.01)	0.09 (0.05)	0.09 (0.03)	0.05 (0.03)	0.06 (0.07)
CaO	0.70 (0.07)	0.67 (0.04)	0.94 (0.15)	0.81 (0.06)	0.76 (0.13)	0.78 (0.11)
Na_2O	4.13 (0.10)	3.50 (0.16)	4.05 (0.18)	3.90 (0.15)	4.16 (0.13)	4.18 (0.06)
K_2O	4.00 (0.06)	3.82 (0.11)	3.87 (0.12)	3.68 (0.09)	3.78 (0.24)	3.98 (0.08)
Cl	0.20 (0.03)	0.22 (0.04)	0.14 (0.04)	nd	0.21 (0.03)	0.19 (0.05)
Water[c]	5.12 (0.36)	1.93 (0.37)	5.36 (0.35)	2.70 (0.96)	5.37 (1.40)	4.26 (0.28)
n	10	14	8	15	9	10

a *Means and standard deviations (in parentheses) of n analyses normalized to 100%-loss-free (wt%). nd, not determined or unavailable.*

b *Total Fe as FeO*

c *Difference between original analytical total and 100*

1 *This study, flow deposit sampled at Newdicks Beach at V14/1588 7796 (analysed using Jeol JXA-840 electron probe fitted with PGT Prism EDS detector at University of Auckland; absorbed current 1.5 nA at 15 kV and beam defocussed to 15 µm (analyst W.R. Esler)*

2 *From Manning (1995, p. 265a, sample 07901), flow deposit sampled at Newdicks Beach at V14/159781 (analysed at Victoria University of Wellington)*

3 *This study, basal pumiceous ash/sand sampled at Little Waihi Rd at V14/1613 7655 (analysed as for 1 above)*

4 *From Black et al. (1996, p. 233, sample 148), sampled at forestry road at U16/777178 (analysed at University of Toronto)*

5 *This study, fresh pumiceous ash and lapilli at 101 m depth from 'lower' Mamaku Ignimbrite (beneath welded unit) in borehole cuttings at Dibley's Farm, Oturoa Rd, Hamurana, at U16/887 465 (analysed as for 1 above)*

6 *This study, fresh pumiceous ash and lapilli at 150 m depth from 'lower' Mamaku Ignimbrite in borehole cuttings at Dibley's Farm, Oturoa Rd, Hamurana, at U16/887 465 (analysed as for 1 above)*

Fig. 16 *Gently tilted Matua Subgroup trough cross-bedded fluvial sands and gravels (just above figure) unconformably overlain by 20-cm-thick Mid-Pleistocene tephra (Maketu-H of Manning 1995), and subhorizontal planar-bedded fluvial sands and silts, Little Waihi Road (V14/163765).*

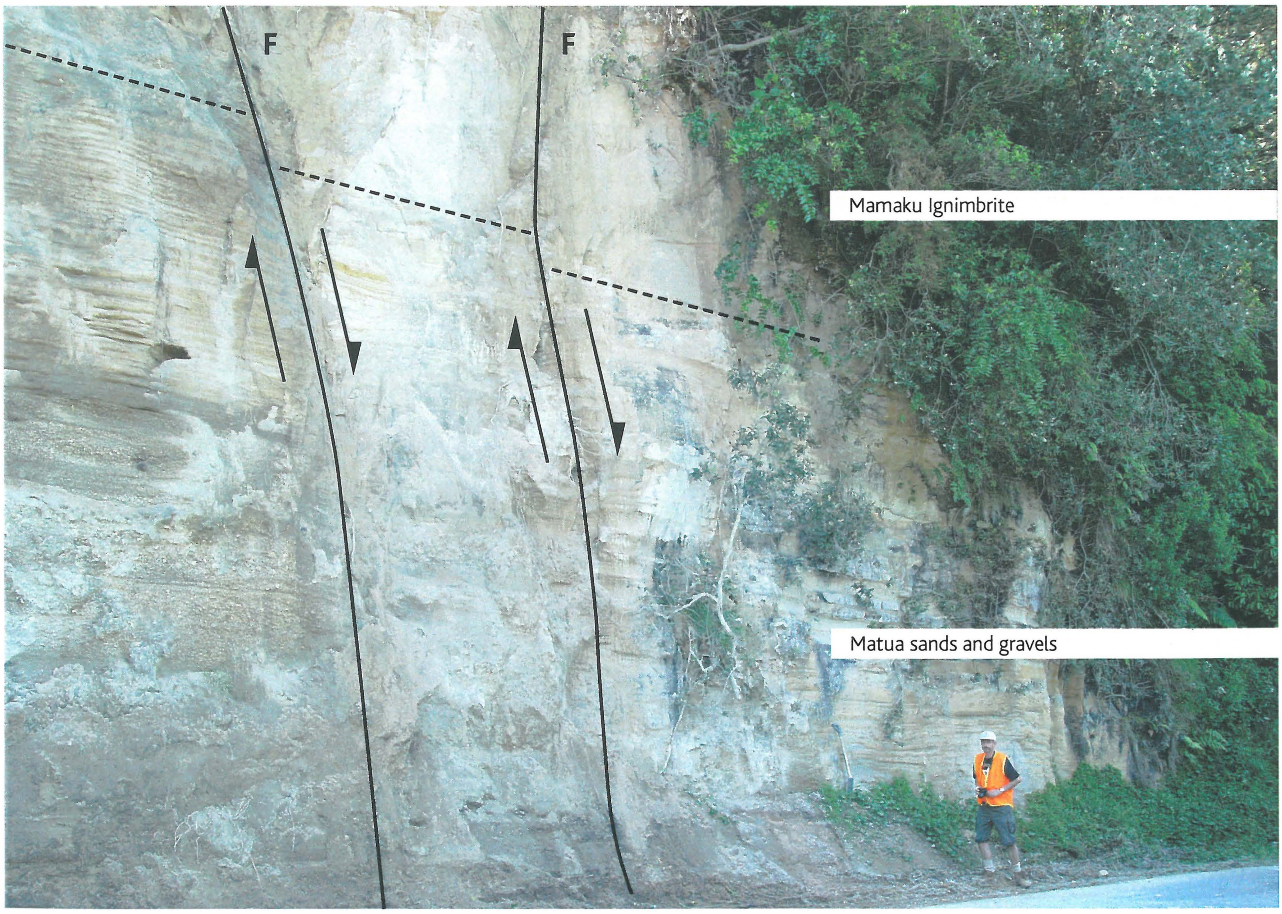


Fig. 17 *Normally faulted planar-bedded Matua Subgroup sands, gravels and silts, overlain by massive pinkish-brown Mamaku Ignimbrite. Roadcut on Little Waihi Road (V14/162765).*

Fig. 18 View to the southwest of coastal cliff section, 150 m southeast of Okurei Point (V14/158787), exposing Matua Subgroup fluvial sands with intercalated Mid-Pleistocene tephras (white beds in upper part of photo), probably 'Maketu-D' (lower) and 'Maketu-H' (upper). Height of cliffs about 20 m.

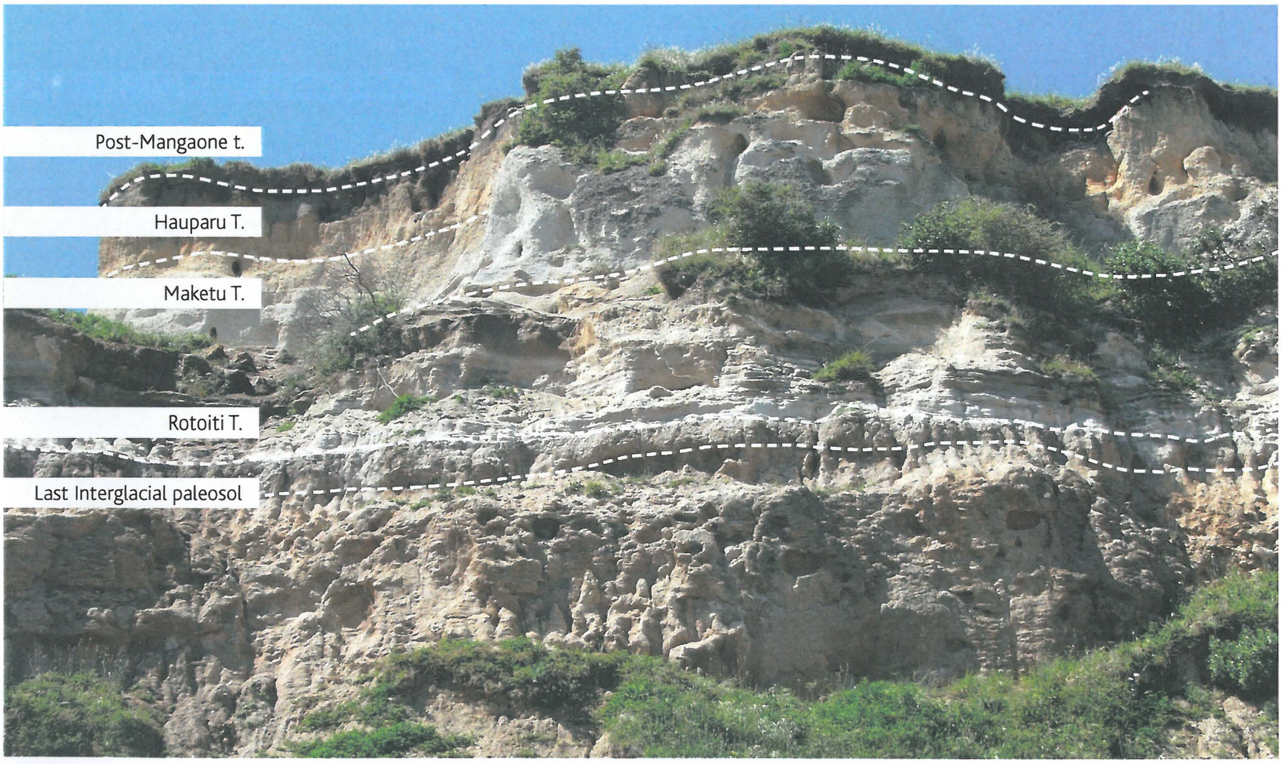


Fig. 19 Top 8 m of section at Okurei Point, comprising weathered dune sands and loess (bottom half), gradational into prominent dark brown Last Interglacial paleosol, overlain in turn by light greyish white bedded Rotoiti Tephra Formation with brown paleosol (middle of upper half of section), Maketu and Hauparu tephras (massive white beds with holes), and a thin cap of yellowish-brown post-Mangaone tephras grading into the modern soil at the top of the cliff.

At Motiti Island, the equivalent paleosol is of similar thickness and very dark brown to dusky purple in colour (Henry 1991). It is uncertain if it is developed in weathered loess or other sediment or in weathered tephra, or some combination of these.

Rotoiti Tephra Formation

The Rotoiti Tephra Formation is defined to comprise the Matahi Scoria (from basaltic fallout), the Rotoiti Ignimbrite (from rhyolitic pyroclastic flows), and the Rotoehu Ash (from rhyolitic fallout) (Froggatt and Lowe 1990). The tephra was previously called the Rotoiti Breccia Formation by Healy et al. (1964) and Nairn (1972). At Maketu and Motiti Island, the Matahi Scoria is absent, and the Rotoiti Tephra Formation is 3.5 m thick at Maketu (>3 m thick at Pukehina Redoubt, Rae 2002) and 2.2 m thick on Motiti.

On Motiti Island the lower 1 m is characterised by white to grey, shower-bedded layers of fine to coarse ash (particle size <2 mm) alternating with yellow to brown pumice lapilli (particle size between 2–64 mm) (Rotoehu Ash), overlain by 1.2 m of massive, fine to coarse ash containing normally graded pumice lapilli (Rotoiti Ignimbrite).

At Maketu, the Last Interglacial paleosol is directly overlain by the Rotoiti Ignimbrite, which in turn is overlain by the Rotoehu Ash (Fig. 19). The Rotoiti Ignimbrite consists of crystal-rich, pale pink-grey coarse ash to lapilli. Pumice clasts reach 15 mm in diameter and the deposit contains rare (<2%) rhyolite lithics up to 3 mm across. The ignimbrite is interbedded with thin pale brown-grey layers of finely bedded, well-sorted ash beds. The Rotoiti Tephra Formation is characterised by containing the index mineral cummingtonite (a pale-green amphibole) throughout the sequence, and at Maketu, Wehrmann (2000) described biotite in all units, suggesting that only the stratigraphically upper units of the formation are represented here, correlating with units 4 and 5 of Davis (1985) (see also Schmitz and Smith 2004).

Determination of the age of the Rotoiti Tephra Formation has been attempted by many workers, and reported ages vary widely between c. 70,000 to 40,000 cal. years BP, as reviewed by Lowe and Hogg (1995), Lian and Shane (2000), Santos et al. (2001), and Shane and Sandiford (2003). We have adopted an age of c. 50,000 cal. years BP for the Rotoiti Tephra Formation, which is supported by stratigraphic data in Berryman et al. (2000) and palaeomagnetic data in Newnham et al. (2004) (see also new ages c. 45,000–50,000 cal. yrs BP in Danišík et al. 2012).

Mangaone Subgroup tephras

Definition and description

The Mangaone Subgroup tephras (Froggatt and Lowe 1990) comprise a sequence of widespread voluminous silicic plinian fall deposits containing coarse pumice with minor ignimbrites or flow units (Jurado-Chichay and Walker 2000). There have been numerous volcanologic and stratigraphic studies of the Mangaone Subgroup, including those of Vucetich and Pullar (1969), Howorth (1975), and Hogg and McCraw (1983), and more recent studies by Jurado-Chichay and Walker (2000; 2001a; 2001b), Nairn (2002), Smith et al. (2002), and Shane et al. (2005a). The Mangaone Subgroup comprises 14 stratigraphic units erupted from sources in the Okataina Volcanic Centre, and isopach maps of the dispersal of these tephras indicate that most of the eruption columns were distributed and blown towards the north and east. Three stratigraphic units were recognised on Motiti Island by Henry (1991) (Maketu Tephra, Hauparu Tephra, Omataroa Tephra), two at Maketu peninsula by Wehrmann (2000) (Maketu Tephra, Hauparu Tephra) (Fig. 21), and three at Pukehina Redoubt by Rae (2002) (Maketu Tephra, Hauparu Tephra, Mangaone Tephra).

Maketu Tephra

The Maketu Tephra (also known as Unit D in Jurado-Chichay and Walker 2000, and Smith et al. 2002) is a widespread, voluminous pumice-rich plinian fall deposit that extends from Tauranga to Mayor Island to Whakatane (Jurado-Chichay and Walker 2000). It is 92 cm thick at Motiti Island, 246 cm thick at Maketu peninsula (Jurado-Chichay 2000), and 330 cm thick at Pukehina Redoubt (Rae 2002). It is characterised by containing normally graded, moderately to highly vesicular, pink-coloured coarse pumice lapilli. Pumice clasts are subangular to subrounded and reach up to 50 mm in size at Pukehina and Maketu peninsula. Lithic fragments (3-5%) are mainly dark grey rhyolite.

Hauparu Tephra

The Hauparu Tephra (equivalent to Unit F of Jurado-Chichay and Walker 2000, and Smith et al. 2002) is a thicker and more voluminous, coarse plinian-fall deposit (Figs. 21, 22) that was dispersed mainly to the north, reaching thicknesses of 220 cm on Motiti Island, and 558 cm at Maketu peninsula (Jurado-Chichay and Walker 2000). It contains white and occasionally pink pumice clasts that are highly vesicular, angular to subangular, moderately sorted, and some clasts reach 90 mm across. At Maketu it has a coarser upper pumice block (>64 mm) bed containing loosely packed, highly vesicular, crystal-poor pumices (Fig. 23). Lithic fragments are mainly grey rhyolites and constitute 5%. It becomes progressively more weathered towards the top, shown by a gradual change to an orange brown colour, and indicative of a period of time (soil formation) elapsing before the eruption of the Mangaone Tephra.

Mangaone Tephra

At Pukehina the Mangaone Tephra (equivalent to Unit I of Jurado-Chichay and Walker 2000, and Smith et al. 2002) is < 100 cm thick, and consists of alternating fine ash to coarse lapilli layers containing white, crystal-poor fibrous pumice.

Omataroa Tephra

The uppermost of the three Mangaone Subgroup tephras at Motiti has been tentatively identified as the Omataroa Tephra (equivalent to Unit K of Jurado-Chichay and Walker 2000, and Smith et al. 2002) by Henry (1991), based on the ferromagnesian mineral assemblage and comparison with the mineralogical data of Howorth (1975). It is a light brown to grey, moderately sorted coarse ash, and <1 m thick.

Age

The Mangaone Subgroup tephras range in age from c. 45 000 cal. years BP (lowermost unit) to c. 30 000 cal. years BP (uppermost unit) (Froggatt and Lowe 1990; Lowe and Hogg 1992; Jurado-Chichay and Walker 2000; 2001a). Using the ^{14}C dates and degree of development of the paleosols on them, provisional ages for the four units described here are estimated as follows: Maketu, c. 36,000 cal. years BP; Hauparu, c. 35,500 cal years BP; Mangaone, c. 34,000 cal. years BP; and Omataroa, c. 32,000 cal. years BP. These ages are similar to those reported for the same units identified in offshore cores from the Bay of Plenty (Shane et al. 2005b) and from farther east of New Zealand (Alloway et al. 2005).

Rock character

All the Mangaone Subgroup tephras are non-welded, unconsolidated, highly pumiceous deposits where individual pumice clasts can easily be plucked out of the outcrop by hand. Consequently, they are highly unstable and classify on the lowest grades of extremely weak rock (R0), and are very prone to rapid deep gully erosion.

Post-Mangaone Subgroup tephras

Overlying the Mangaone Subgroup tephras is a group of younger tephras that includes the very widespread marker unit, Kawakawa Tephra (also known as Aokautere or Oruanui eruptives: Froggatt and Lowe 1990; Wilson 2001), overlain by interdigitating tephras of the Rotorua Subgroup and the Taupo Subgroup (Froggatt and Lowe 1990), and the Tuhua Tephra (Hogg and McCraw 1983). These deposits, together with minor loessic material that encapsulates the Kawakawa, Te Rere and Okareka tephras (i.e., loess deposited during the Last Glacial Maximum or MIS 2: Newnham et al. 2003), collectively make up approximately two metres of cover in the Maketu and Pukehina areas. Along with soils

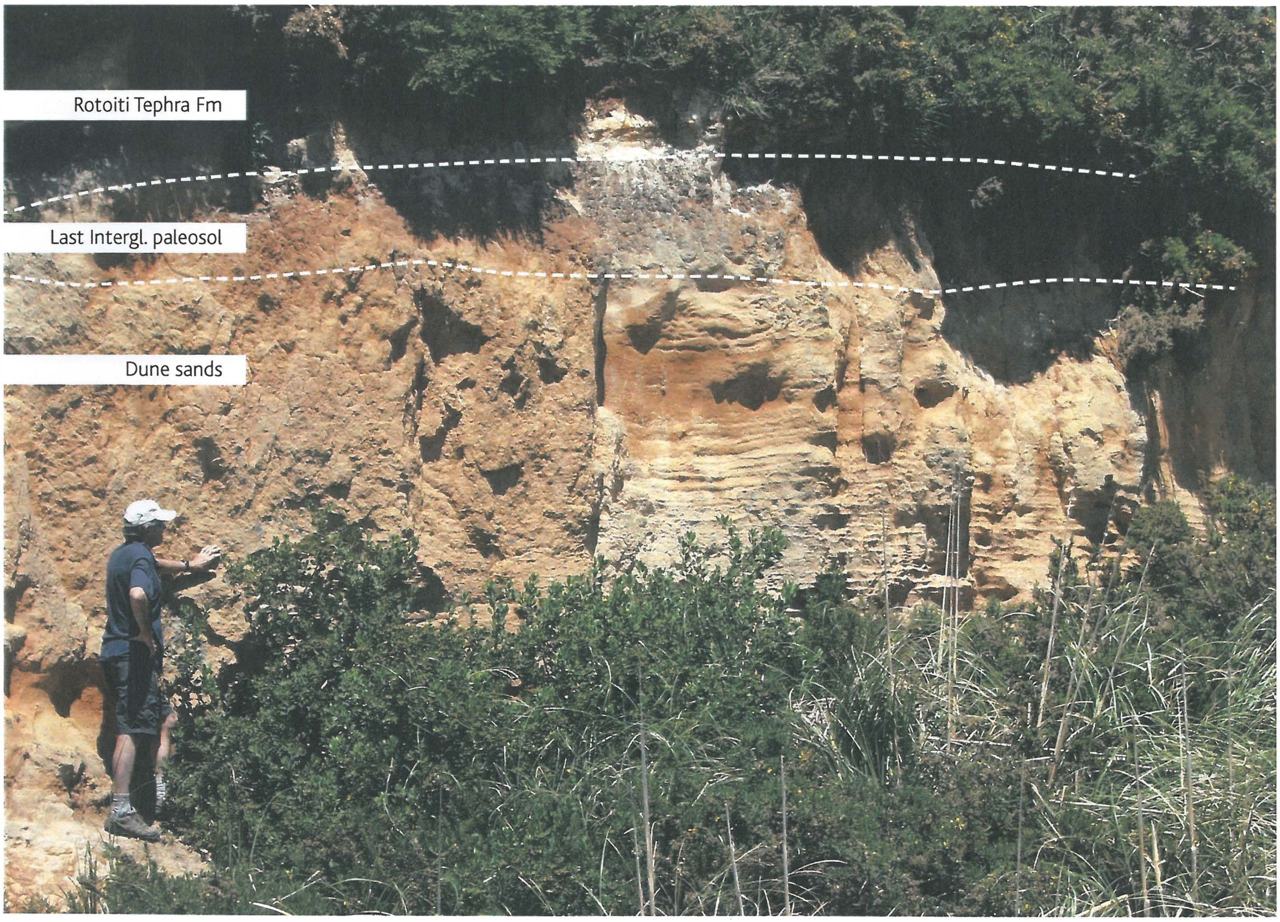


Fig. 20 *Planar-bedded dune sands gradational into purplish-brown paleosol (Last Interglacial), overlain by Rotoiti Tephra Formation. Newdicks Beach upper carpark (V14/160782).*

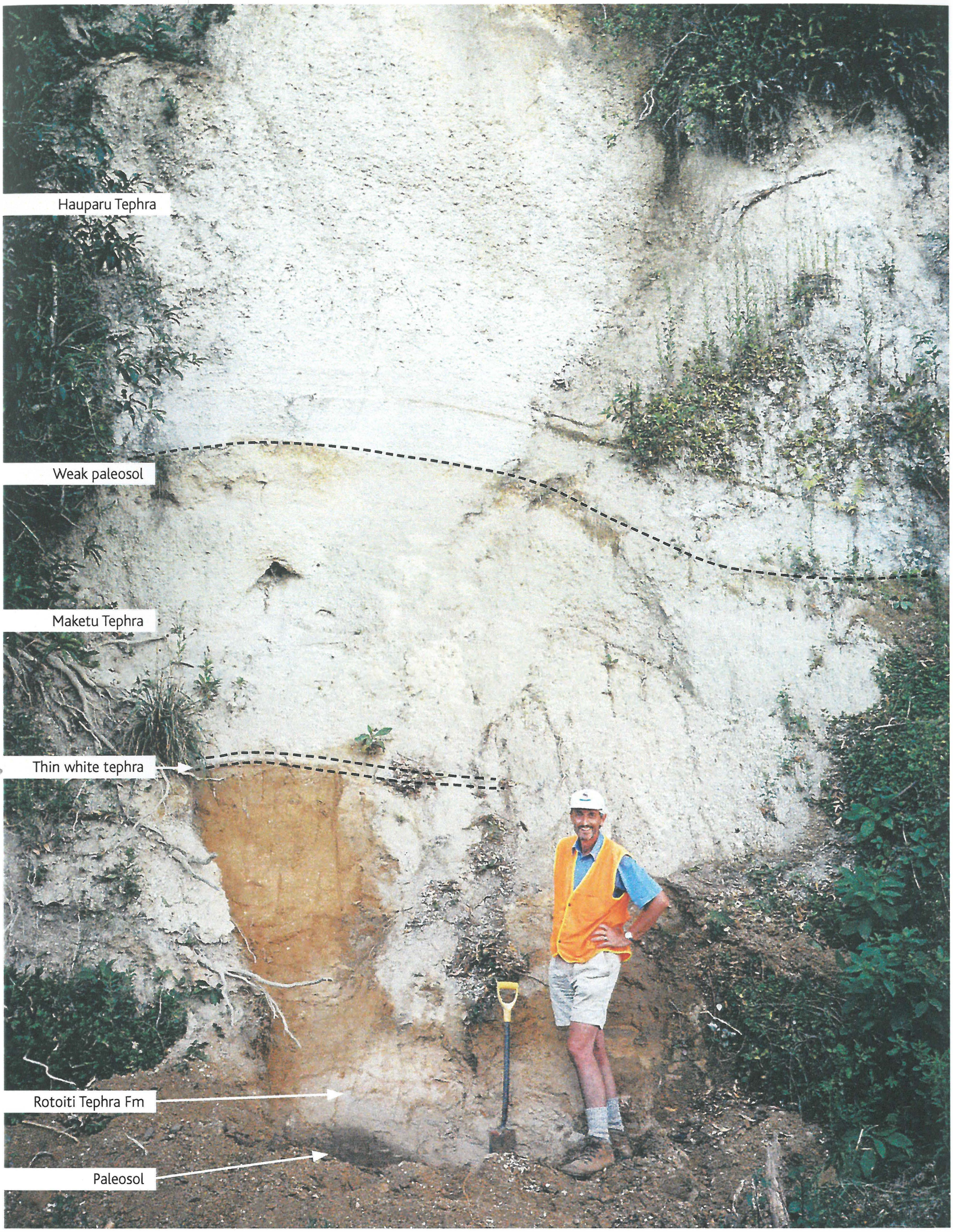


Fig. 21 *Hauparu Tephra (white, pumice-rich bed at top third of section), overlying Maketu Tephra (middle third of section with upper weakly developed light brown paleosol) and a distinct thin (10-cm thick) white uncorrelated tephra at the base. The lower third of the section comprises a prominent brown paleosol (with colluvium and loess?) developed on Rotoiti Tephra Formation (grey bed by spade), and a lowermost dark purplish-brown paleosol. Little Waihi Road at V14/161764.*

Fig. 22 *White pumice-rich Hauparu Tephra in roadcut, Little Waihi Road (V14/151768).*

Fig. 23 *Hauparu Tephra, Little Waihi Road (V14/151768).*

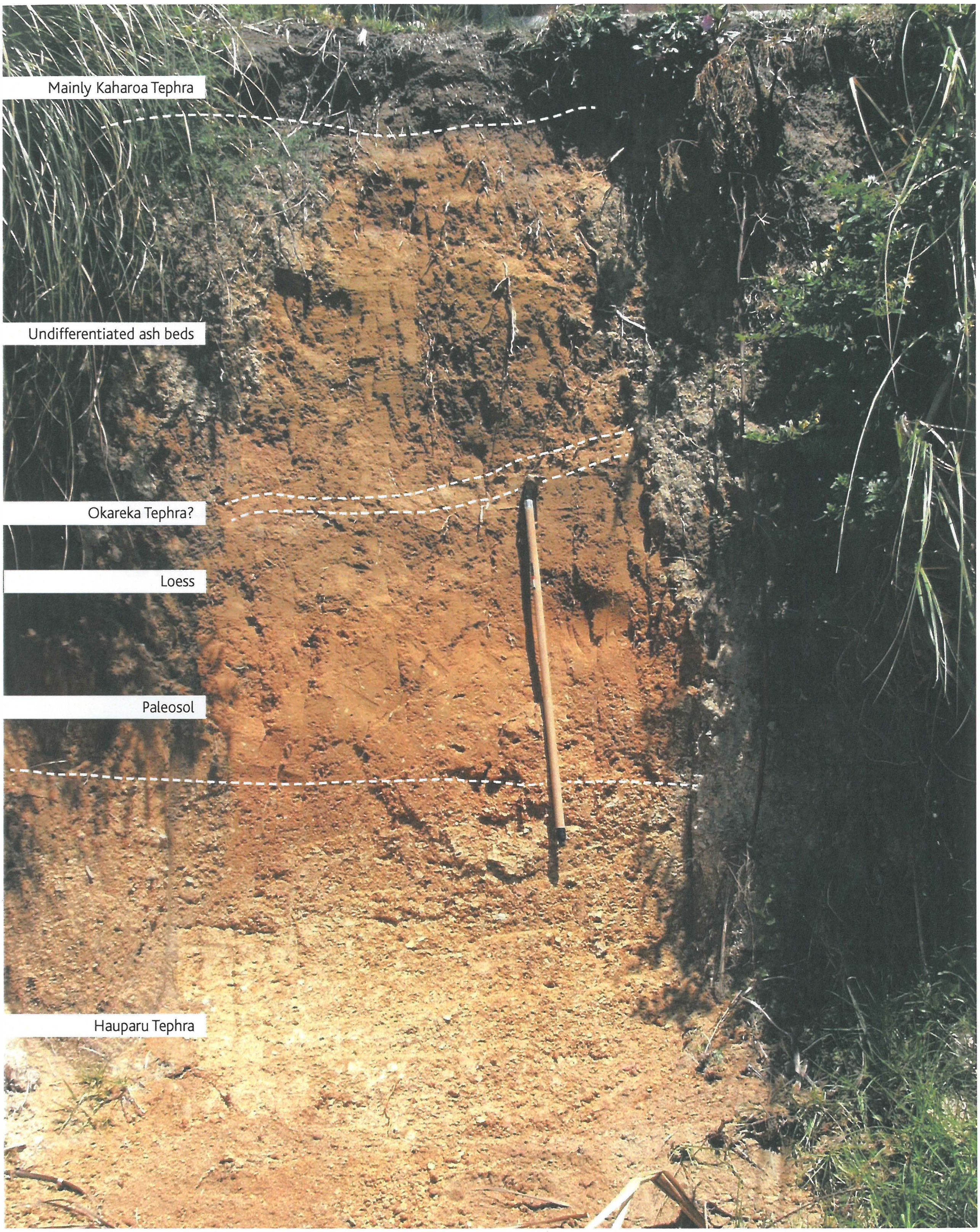


Fig. 24 *Weathered pale pumiceous Hauparu Tephra grading upwards to orange paleosol (lower 2 m of section) overlain by greyish brown loess (~ 30 cm), an indistinct discontinuous white ash bed 2-3 cm thick by blade of tool (possibly Okareka Tephra), and an undifferentiated composite of yellowish-brown post-Okareka Tephra ash beds (upper 1.5 m of section). The modern soil profile is formed in dark grey Kaharoa Tephra at surface and the yellowish-brown composite ash beds to c. 1 m depth. Similar soils cover much of the Maketu peninsula. Cutting tool is 1.15 m long. Roadcut on Little Waihi Road near Whenuariri Place (V14/163766).*

Table 3. Post-Mangaone Subgroup tephras identified in the Te Puke lowlands–Maketu area. Other uncorrelated tephras may additionally be present.*

Note: ages on tephras updated following publication of new age models in 2013 (see references p.39).

TEPHRA NAME	SOURCE[1]	CALENDAR DATE OR AGE (cal. yr BP)[2]
Rotomahana Mud[3]	Tarawera, OVC	10 June 1886 AD
Tarawera Scoria[3]	Tarawera, OVC	10 June 1886 AD
Kaharoa Tephra	Tarawera, OVC	1314 ± 12 AD (636)[a]
Taupo Tephra (Y) [4]	Taupo VC	232 ± 10 AD (1718)[b]
Mapara Tephra (X)	Taupo VC	2059 ± 118[c]
Whakaipo Tephra (V)	Taupo VC	2800 ± 60[c]
Stent tephra (Q)	Taupo VC	4322 ± 112[c]
Unit K (K)	Taupo VC	5088 ± 73[c]
Whakatane Tephra	Haroharo, OVC	5542 ± 48[c]
Tuhua Tephra	Tuhua VC (Mayor Is)	7027 ± 170[c]
Mamaku Tephra	Haroharo, OVC	7992 ± 58[c]
Rotoma Tephra	Haroharo, OVC	9472 ± 40[c]
Waiohau Tephra	Tarawera, OVC	14,018 ± 91[c]
Rotorua Tephra	Okareka Basin, OVC	15,738 ± 263[c]
Rerewhakaaitu Tephra	Tarawera, OVC	17,209 ± 249[c]
Okareka Tephra	Tarawera, OVC	21,858 ± 290[c]
Te Rere Tephra	Okareka Basin, OVC	25,171 ± 964[c]
Kawakawa Tephra[5]	Taupo VC	25,358 ± 162[c,d]

* *After Campbell et al. (1973), Pullar and Birrell (1973), Wigley (1990), Newnham et al. (1995), Cotching (1992; 1998), and Rae (2002). Nomenclature after Froggatt and Lowe (1990), Wilson (1993) and Alloway et al. (1994).*

1 *OVC, Okataina Volcanic Centre; VC, Volcanic Centre. Rotorua Subgroup tephras are from Okataina VC; Taupo Subgroup tephras are from Taupo VC.*

2 *Ages in calendar years before present (1950), 2σ-age ranges. Sources: a, Hogg et al. (2003); b, Hogg et al. (2012); c, Lowe et al. (2013); d, Vandergoes et al. (2013).*

3 *Rotomahana Mud and Tarawera Scoria together make up Tarawera Tephra (Froggatt and Lowe 1990).*

4 *Designations in parentheses are volcanological units of Wilson (1993).*

5 *Kawakawa Tephra comprises Oruanui Ignimbrite and Aokautere Ash members (Froggatt and Lowe 1990) (see also Wilson 2001).*

formed on aeolian sands and peat, the tephra cover beds constitute the predominant parent material of soils in the region (Pullar and Birrell 1973; Cotching 1992; 1998; Lowe and Palmer 2005) (Fig. 24).

The tephras identified in soil profiles and peat sections in the Te Puke lowlands (Fig. 25) are listed in Table 3, together with their age and eruptive source. In addition, minor, very thin andesitic ash-fall deposits, derived from eruptions of Tongariro Volcanic Centre and Egmont Volcano, generally during southerly or southwesterly wind conditions, have probably 'dusted' the Maketu area over many millennia. Such events normally leave little or no trace in the geological record, but their occurrence is known from historical evidence – e.g. eruptions of Mt Ngauruhoe in 1974-75 (Nairn and Self 1978), and Mt Ruapehu in 1945 and 1995-96 (Johnson et al. 2000; Cronin et al. 2003) – and from the detailed microscopic examination of peat or lake sediments that have preserved diminutive 'cryptic' (hidden) ash grains (e.g. Shane 2005; Gehrels et al. 2006).

Late Pleistocene and Holocene sediments

Late Pleistocene (c. 50,000 to 11,500 cal. years BP) and Holocene (<c. 11,500 cal. years BP) river and stream-derived alluvium and peat deposits underlie the Kaituna and Pongakawa lowlands. They are composed of silts, sands, clays, gravels, and carbonaceous material, including numerous buried stumps or logs (Pullar 1970; Pullar and Patel 1972; Wigley 1990; Newnham et al. 1995; Cotching 1998). Estuarine sands and muds, dating from c. 6000–7000 cal. years BP (Table 1), are

found around the margins of the present-day estuaries of Maketu and Waihi beneath or within the fluvial and peat deposits (Murray 1978; Wigley 1990).

Peat in the Papamoa arm of the Kaituna swamp began forming c. 5300 cal. years BP (Newnham et al. 1995), probably due in part to a net rise in water table, either by local tectonic subsidence, as suggested by Wigley (1990) for the Te Puke area and by Nairn and Beanland (1989) for the Rangitaiki Plains, or by a small rise of ~1 m in sea level at c. 5300 cal. years BP as suggested by Hull (1985) and Gibb (1986), or both. Dune sands form a strip along the coast, and just inland from this are the estuarine muds and sands of the present-day Maketu and Waihi estuaries (Murray 1978; Domijan 2000; Easton 2002).

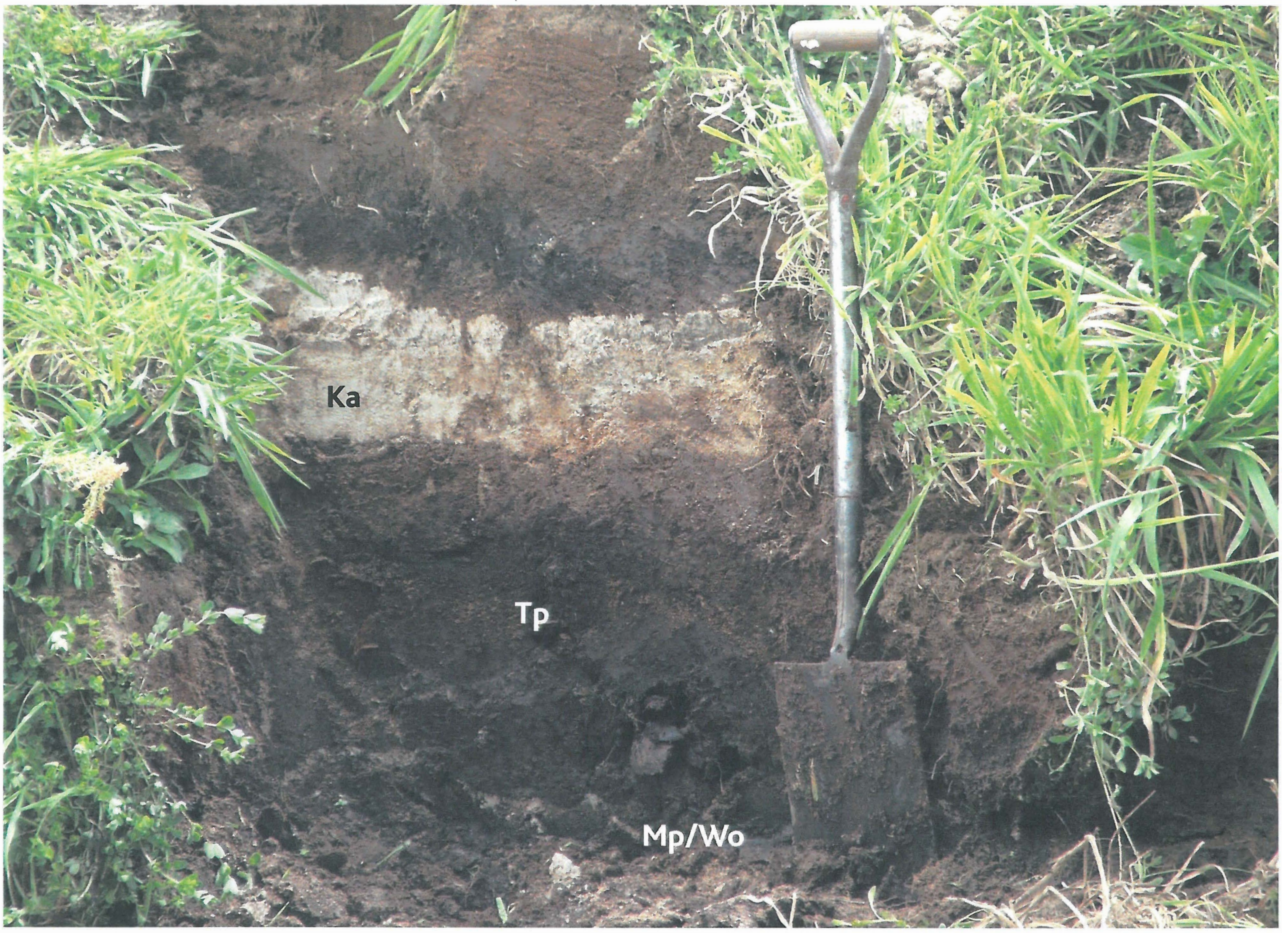


Fig. 25 *Section underlying alluvial plain at V14/126762 (Kaituna Road), exposing peat (black), prominent Kaharoa Tephra (white ash bed 20-cm thick, Ka), indistinct traces of Taupo Tephra (cream-coloured pumice lapilli bed 2-cm thick, Tp), and either Mapara or Whakaipo Tephra (discontinuous white ash bed 2-cm thick, Mp/Wo).*

Structure

The original composite cone at Motiti was composed of intercalated lavas, volcanic breccias, lapilli tuffs, tuffs, and cut by several subvertical dikes. Orongatea lavas and pyroclastic beds dip constantly to the south at 28–40° which probably represent original dips on the flanks of the old andesitic cone, rather than having been tectonically tilted.

Several NNE (020°)-striking faults cut the andesitic rocks of Motiti Island, and these have resulted in a strong NNE orientation to the island. The faults dip steeply at 70–80° to the west, and are generally downthrown to the west, indicating that they are normal faults. The throws are unknown, but are probably 5–30 m. The NNE-striking fault orientation is distinct from the NNW-striking structures in the northwestern part of offshore Bay of Plenty, and also distinct from the present dominant NE trend in the offshore extension of the Taupo Volcanic Zone (e.g., the Tauranga and White Island Fault Zones of eastern Bay of Plenty, Davey et al. 1995). The age of the faults is uncertain, but some faults are associated with hydrothermally altered zones and thick (up to 75 cm wide) quartz veins which are structurally controlled by the faulting, and it is likely that this hydrothermal activity occurred during the waning stages of Motiti Pliocene volcanism. Hence the faults are considered to be late Pliocene in age, but may have been reactivated in the Pleistocene to cause local uplift of the island, or alternatively subsidence of the seafloor around the island.

The Maketu headland is considered to represent an upstanding block or horst, flanked on either side by subsidence of the land. It is bounded on both sides by NE (035°)-striking normal faults (Fig. 26) with minimum throws of about 60 m (see cross-section on map). Neither of the bounding faults has been observed in outcrop but they are inferred to be located along the NW and SE sides of the Maketu peninsula (see map). The inferred NW fault is usually depicted as marking part of the western boundary of on-land Taupo Volcanic Zone (e.g. Wilson et al. 1995; Briggs et al. 2005). The downfaulted block on the southeastern side of the Maketu peninsula (see cross-section) is considered to

Fig. 26 *View to the southwest looking along line of the inferred eastern boundary fault of the upstanding Maketu peninsula (high flat terrace on right). Waihi Estuary and Pongakawa alluvial plain on far left, and settlement of Little Waihi in foreground.*

Fig. 27 *Faulted beds of the Matua Subgroup 200 m southeast of Okurei Point at V14/158786. Note person (David Lowe) for scale standing on (normal) fault zone. Beds to the left of the fault are Newdicks Formation laharic/breakout flood deposits of sands and gravels with lensoidal channels containing large boulders of ignimbrite. Beds to the right of the fault are Matua Subgroup fluvial sands with intercalated white beds of Mid-Pleistocene tephras.*

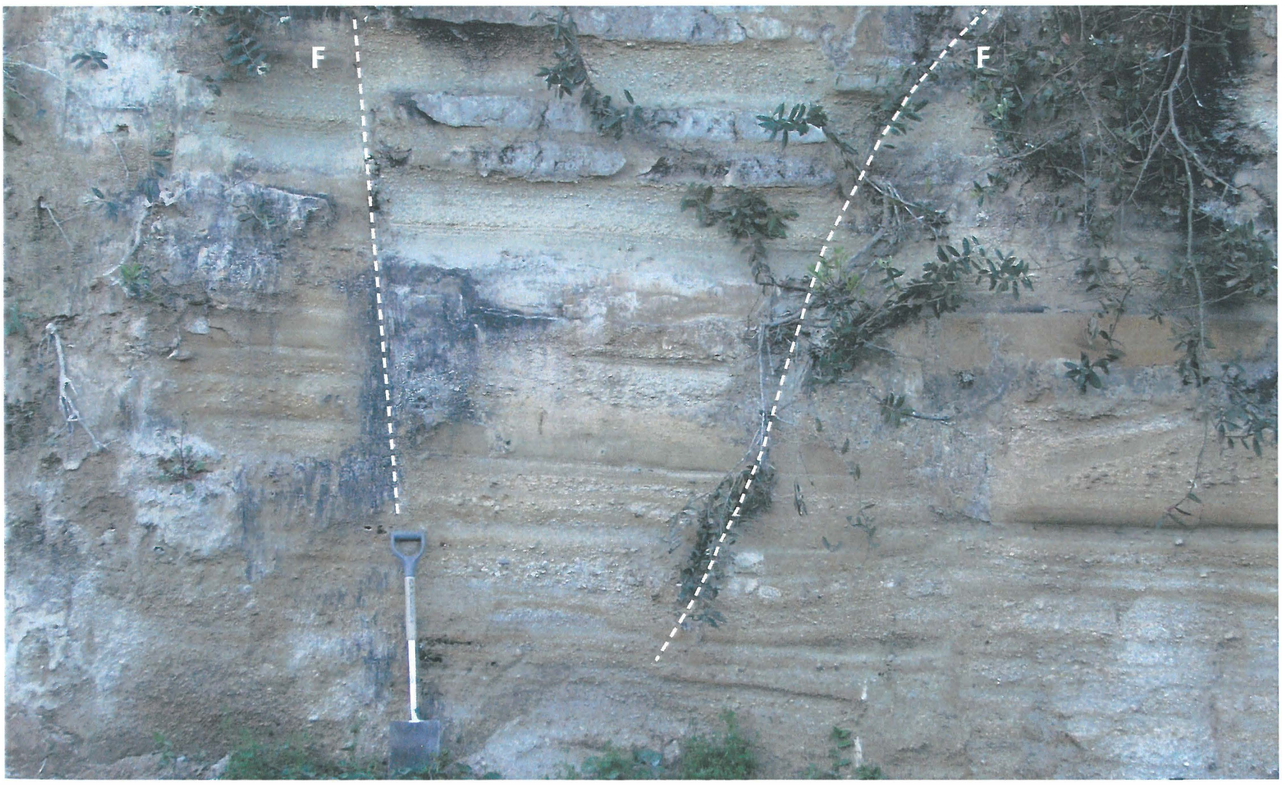


Fig. 28 *Faulted beds of Matua Subgroup fluvial sands and gravels, intercalated with white pumice-rich Mid-Pleistocene tephras (possibly reworked 'Maketu-D'). Little Waihi Road (V14/162765). One fault at spade with about 35 cm offset.*

have a small tilt to the west (<1°) which is responsible for exposing successively older strata further southeast along the Bay of Plenty coast towards Matata (Bailey and Carr 1994; Rae 2002).

Several NE-striking normal faults with offsets ranging from centimetres to a few metres have been observed at Okurei Point that displace bedding structures in the Newdicks Formation (Fig. 27), and these faults parallel the larger scale bounding faults. Some of the faults at Okurei Point appear to die out near the top of the section and there is no evidence for displacement of the overlying tephra beds. There is also no evidence for displacement of the low terraces inland from Maketu and near Paengaroa. Thus the large- scale bounding faults are considered to have ages that pre-date the Last Interglacial paleosol and Rotoiti Tephra Formation, i.e. are older than c. 55 ka, and are therefore not considered active.

Numerous normal faults striking N or NW, of varying throw, are also exposed along Little Waihi Road (Fig. 28). The faults with larger throws (>5–10 m) have caused repetition of the Matua Subgroup sequence but not the overlying younger tephras, and hence have similar ages to the bounding faults described above.

Geological hazards

This section discusses the major geological hazards of the area covered by map sheet V14. The notes are only meant to provide a general regional summary, and should not be used for detailed natural hazard assessment. Detailed hazard information is held by Environment B.O.P.

Slope instability and landsliding

Unfavourable slopes, weak and sensitive rock and soil types, structures, and coastal erosion exist in many areas around Maketu peninsula, especially the steep cliffs from Maketu township to Okurei Point, to Newdicks Beach, to Little Waihi. All the rocks in the cliffs have very weak wall strength (R1) and vary to soft clay (S2), and hence are prone to landsliding, especially during winter months when the rocks may be waterlogged or during high intensity storms (such as occurred in Matata and Tauranga in May 2005). Large boulders up to 7 m across occur in some parts of the cliff, and periodically fall out and litter the foreshore, which testifies to the present instability of the cliffs and effects of active landsliding and coastal erosion. The Maketu peninsula and low hills at the eastern end of Pukehina Beach are covered in thick, highly pumiceous Mangaone Subgroup tephras, and these are extremely prone to instability and rapid gully erosion.

Earthquakes

Maketu peninsula is considered to be bounded by two normal faults, but there is no indication that either of these faults might be active and therefore liable to move during earthquakes. They have a strong physiographic expression, but there is no evidence for displacement of the low terraces. Nevertheless, because the Maketu area is close to the Taupo Fault Belt and the region of active faulting in the Rangitaiki Plains (e.g. Ota et al. 1988; Nairn and Beanland 1989; Beanland and Berryman 1992; Hayward et al. 2004), it is very prone to earthquake hazard. Liquefaction of unconsolidated sands and silts could also amplify earthquake intensities locally.

Volcanic activity

The Maketu area and Motiti Island have been repeatedly covered by pyroclastic deposits over an extended period of time. These deposits, described above, were erupted mainly from volcanoes in the Taupo Volcanic Zone, especially Okataina Volcanic Centre (Nairn 2002) (e.g. Mt Tarawera), Taupo Volcanic Centre, and also from the isolated volcano of Mayor Island. A detailed history of volcanism has been established by studies of the sequences of tephras preserved on terraces and dune sands and in peaty deposits in the Te Puke lowlands (e.g. Pullar and Birrell 1973; Newnham et al. 1995; Cotching 1998; Jurado-Chichay and Walker 2000), and in the Rangitaiki Plains to the east (Pullar and Selby 1971; Pullar 1985), and clearly indicate that the Maketu and Motiti areas are situated in a high-fallout zone. Evidence of volcanic ash erupted from White Island has not been found but is recorded historically (e.g. 1976-82, Nairn et al. 1991), and tephras from Mayor Island, including Tuhua Tephra (Hogg and McCraw 1983; Manighetti et al. 2003) and at least one other deposit (W.R. Esler unpublished data), have been identified at Maketu. Andesitic ash has fallen over the Maketu area from time to time, as exemplified by the Mt Ruapehu eruptions in 1995-96 (Johnson et al. 2000).

An additional volcanic-related hazard for this area, but of low probability, is that arising from breakout flood events that may occur many years after an eruption (e.g. White et al. 1997; Hodgson and Nairn 2005).

Coastal erosion

Rapid removal of coastal deposits can occur during extreme storm events, tsunamis, high tides and low pressure surges, and strong onshore winds. Erosion may occur on the beaches and barrier sand spits, and as mentioned above, the cliffs around Maketu peninsula are actively eroding. The barrier spits of Maketu and Waihi estuaries have been overwashed and breached on numerous occasions by storm surges (in excess of 5 m) (Murray 1978; Burton 1987; Domijan 2000).

Floods

The low-lying alluvial plains of Maketu and Pongakawa have had a long history of flooding during high intensity rainfall events. A number of flood protection structures have been built to minimise flooding, including stopbanks along the Kaituna River, and a number of canals built across the Pongakawa alluvial plains and swampland.

Tsunami

Tsunami are impulse-generated sea waves produced mainly by sudden earthquake induced displacement of the seafloor, or large-scale submarine slumping, or volcanic eruption (de Lange 1998). They could be generated locally within the offshore Bay of Plenty region and the active Kermadec Ridge on which there are numerous submarine volcanoes (Wright and Gamble, 1999; Wright et al. 2004), but could also be generated from the other side of the Pacific Ocean. Eruptions and submarine slumping at Mayor Island and White Island could generate tsunamis, and tsunami waves up to 5 m high have been calculated for the Bay of Plenty coast generated from a moderate-sized volcanic eruption involving a pyroclastic flow (de Lange and Healy 1986; de Lange et al. 2001; de Lange 2003). Faults within the offshore parts of the Taupo Volcanic Zone in the Bay of Plenty could also generate tsunamis because of submarine earthquakes (de Lange and Healy 1986; de Lange and Fraser 1999).

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Glossary

Agglomerate

A deposit formed from pyroclastic fragments that are rounded and >64 mm in size.

Andesite

A dark grey coloured, fine-grained, extrusive or volcanic rock containing 57–63 wt.% SiO_2 that is porphyritic and contains phenocrysts of plagioclase, ± pyroxene (e.g. hypersthene, augite), ± hornblende in a fine-grained groundmass.

Ar/Ar age

A method of dating rocks or minerals by measuring the contents of the isotopes of argon (Ar).

Ash (cf. tephra, tuff)

A pyroclastic fragment (or fragments) produced by an explosive volcanic eruption that has a size <2 mm.

Basaltic andesite

A dark grey to black coloured, fine-grained extrusive or volcanic rock containing 53–57 wt.% SiO_2 that is porphyritic and contains phenocrysts of plagioclase, pyroxene, ± olivine, in a fine-grained groundmass.

Base surge

See surge deposits

BP

Abbreviation for 'before present', taken as 1950 AD for reporting radiocarbon ages.

Breakout flood (BOF) deposit

A catastrophically emplaced volcaniclastic alluvial deposit resulting from sudden release of lake water impounded by eruptive debris or alluvium (usually a crater or caldera lake). Examples of BOF deposits include: (1) alluvium deposited by the Tarawera River in Bay of Plenty in 1904 after collapse of an alluvial fan (dam) formed at Lake Tarawera by the 1886 eruption (White et al. 1997; Hodgson and Nairn 2005); (2) alluvial deposition resulting from overtopping of Lake Tarawera impounded by fan deposits near the end of c. 1314 AD Kaharoa eruption event (Hodgson and Nairn 2005); (3) Taupo Pumice Alluvium deposited by the Waikato River c. 20 years after the Taupo eruption of c. 232 AD (Manville et al. 1999); (4) Hinuera Formation deposited over several millennia during the Last Glacial Maximum (LGM) after the Oruanui/Kawakawa eruption c. 26,100 cal. years BP (Manville and Wilson 2004).

Breccia

A coarse-grained clastic sedimentary rock composed of large (greater than sand size, or >2 mm in diameter) angular rock fragments that are cemented together by a finer-grained matrix. Breccia is similar to conglomerate except a conglomerate is composed of large rounded rock fragments. A volcanic breccia is a volcanic rock composed of angular clasts that are >64 mm in diameter.

Cal. (years)

Abbreviation for 'calibrated' or 'calendar', and used to specify an age in true (solar) calendar years that has been obtained from a radiocarbon-determined age calibrated by reference to published calibration curves (e.g. Reimer et al. 2004).

Composite volcano

A large, long-lived constructional volcanic edifice, comprising lava and pyroclastic products erupted from one or more vents. Typically steep-sided and cone shaped.

Cross bedding

The internal arrangement of the layers in a stratified rock, characterized by minor beds or laminae inclined in sloping lines or concave forms at various angles to the original depositional surface. It is characteristic of sedimentary rocks, especially sands and gravels, deposited by fast flowing rivers. Cross bedding is often found in shallow concave structures that represent old river channels. Cross bedding is also characteristic of finely fragmented ash grains in volcanic rocks that have been deposited by extremely fast moving surges associated with explosive volcanic eruptions.

Cryptic

Refers to 'hidden' ash grains (from Gk *kryptein*, hidden), i.e. not visible in the field, typically contained within encompassing peat or lake or aeolian sediments (hence cryptotephra).

Distal

A deposit formed far from source (cf. proximal: a deposit formed near its source; medial: a deposit formed at moderate distance from its source, i.e. intermediate between distal and proximal).

Fiamme

Dark coloured, glassy lenses in densely welded ignimbrite formed from collapse of pumice fragments.

Geomagnetic excursion

From time to time, the Earth's polarity changes from north to south, the last major change (from 'reversed' to 'normal') occurring around 780,000 years ago. Short-lived changes in polarity are referred to as geomagnetic excursions or events, and the Pringle Falls event, for example, was a short-lived period of reversed polarity. Knowing the dates of these events enables them to be used as a tool for correlation and dating.

Glacial

A protracted period of time (stage) when climatic conditions were markedly colder and usually drier than those of today, and when there were major expansions of ice sheets and markedly lower sea levels globally (cf. interglacial). (Note: short-lived periods of modest warmth during glacial stages are called interstadials.)

Holocene

The epoch of geological time during the last 11,500 calendar years (equivalent to the last 10,000 ^{14}C years), including today. Synonymous with Recent and MIS 1.

Hydrothermal alteration

A chemical and mineralogical alteration of rocks by the action of hot springs. It may produce minerals such as quartz, pyrite, chlorite, and clays.

Ignimbrite

The deposit formed from a pumiceous pyroclastic flow, which is also termed a pyroclastic density current. Ignimbrites may range from non-welded to densely welded (cf. welding).

Intercalated

Thin layers or strata of one kind of material that alternate with layers or strata of another kind of material (intercalated beds are sometimes called interbeds).

Interglacial

A period of time (stage) lasting c. 10,000–15,000 years when climatic conditions, sea levels, and vegetation cover were generally similar to those of the Holocene, and ice sheets had largely retreated. Currently we live in the Present Interglacial (also known as the Holocene) (cf. glacial). (Note: short-lived periods of modest cooling during interglacial stages are called stadials.)

Isothermal plateau fission-track date

Fisson-track dating utilises counting of 'tracks' in certain minerals, including zircon and glass, that arise from intense 'recoil' damage from decay (fissioning) of radiometric particles in the minerals. Generally, more tracks indicate older ages, depending on the level of ^{238}U radioactivity in the mineral. The isothermal plateau technique uses a heating method during the measurement of tracks in glass to correct for partial track fading that previously resulted in erroneous ages.

ka

Thousands of years BP.

K/Ar age

A method of dating rocks or minerals by measuring their potassium (K) and argon (Ar) contents.

Lahar

A water-saturated mixture of volcanogenic debris and water that moves rapidly downslope under the influence of gravity.

Lapillus (pl. lapilli)

A pyroclastic fragment produced by an explosive volcanic eruption that has a size between 2–64 mm.

Last Glacial

The cold and generally dry period between c. 115,000 and c. 15,000 years ago (designated MIS 5d-5a to MIS 2 inclusive).

Last Glacial Maximum (LGM)

The coldest point of the Last Glacial at c. 21,000 cal. years BP; sometimes designated the coldest period between c. 23,000 and c. 19,000 cal. years BP, or sometimes equated generally with MIS 2.

Last Interglacial

The last interval of sustained warmth and sea-level maximum comparable to or higher than that of today (Holocene), between c. 130,000 and c. 115,000 years ago (peaking c. 125,000 years ago, designated MIS 5e).

late Pleistocene

A period of time informally defined here between c. 50,000 cal. years BP and c. 11,500 cal. years BP (i.e. younger than Rotoiti Tephra and pre-Holocene) (note lower case late).

Late Pleistocene, Late Quaternary

A formal period of time defined between c. 125,000 years BP (MIS 5e) and c. 11,500 cal years BP (Late Pleistocene) or between c. 125,000 years BP and the present (Late Quaternary) (note upper case Late).

Lenticulite

A densely welded ignimbrite made up of lenticular dark coloured dense obsidian fragments formed from collapsed pumice.

Lithology

The description or characteristics of a rock in hand specimen and in outcrop.

Loess

A fine-textured sediment of aeolian origin (other than sand dunes or tephra) and generated and deposited at relatively fast rates during glacial periods, especially during MIS 2, by glacial grinding or freeze-thaw processes.

Ma

Millions of years BP.

Mesotidal

A tidal range between 1–3.5 m (low mesotidal is 1–2 m).

Middle (Mid-) Pleistocene, Middle Quaternary

A formal period of time defined between c. 0.78 Ma and c. 125,000 years BP (note upper case Middle).

MIS

Abbreviation for marine isotope stage, a formal stratigraphic system derived from oxygen isotopic analyses of foraminifera from ocean cores that relate to sea level and ocean temperature and hence climatic change during the Quaternary. Glacial stages have even numbers, e.g. MIS 2, 4, 6, 8, etc. (getting older); interglacial stages have odd numbers, e.g. MIS 1, 5, 7, 9, etc (getting older). Subdivisions are called substages (e.g. MIS 5e).

Non-welded

Pyroclastic deposits in which there is no sintering together of the originally hot, glassy fragments; the deposits are typically soft and porous, and easily crumbled by hand.

Paleosol

A soil horizon or profile, usually buried, of a landscape or environment of the geological past. Typically yellowish-brown to brown to dark brown (occasionally black) in colour and clay-bearing, the amount of clay relating generally to the length of time exposed at the land surface.

Phenocryst

A large crystal or mineral in a volcanic rock.

Phreatomagmatic

A type of explosive volcanic eruption produced by the interaction of hot molten rock (magma) with steam; the steam may be derived from a large body of groundwater or seawater.

Pleistocene

The epoch of geological time between about 1.8 Ma and 11,500 cal. years ago.

Plinian

A volcanic eruption characterised by a steady, sustained high eruption column that produces a widespread deposit of coarse pumice. Usually associated with silicic, high viscosity magma.

Pliocene

The epoch of geological time between about 5.3 and 1.8 Ma.

Porphyritic

Common texture of a volcanic rock in which large crystals (phenocrysts) are enclosed in a fine-grained groundmass (which may be finely crystalline, glassy, or both).

Postglacial

The period of general climatic amelioration, ice retreat, sea-level rise, and general re-afforestation following the Last Glacial (i.e. since c. 15,000 cal. years ago).

Progradation

The building forward or outward towards the sea of a shoreline by near-shore deposition of river-borne sediments and tephras.

Pumice

A light coloured vesicular volcanic fragment formed from gas-rich frothy magma.

Pyroclastic

Hot fragmental aggregates formed by explosive volcanic activity and deposited by transport processes resulting directly from this activity.

Quaternary

The period of geological time that includes the Holocene (the last 11,500 cal. years) and Pleistocene (1.8 Ma to 11,500 cal. years BP). It has recently been proposed to extend the base of the Quaternary to c. 2.6 Ma (Clague 2005), and we adopt this new age limit here.

Radiocarbon (^{14}C) age

Radiometric age of a deposit or event obtained by measurement of ^{14}C activity of carbonaceous material associated with the deposit or event. Radiocarbon years are not exactly the same as calendar years and must be calibrated to obtain equivalent calendar dates. The current limit of radiocarbon dating is around 50,000 to 60,000 years (depends on certain optimum conditions being met regarding the sample).

Rhyolite

A light coloured siliceous volcanic rock containing greater than 70 wt.% SiO_2; it may be porphyritic, exhibit flow banding, contain spherulites, or may be entirely glassy (obsidian). Porphyritic varieties may contain phenocrysts of quartz, feldspar ± biotite ± hornblende ± hypersthene ± augite.

Silicic rocks

Rocks containing large concentrations of silica, and hence have high abundances of feldspar, quartz, and glass rich in SiO_2. An example is rhyolite.

Stratigraphy

The study of stratified or layered rocks and their relative ages.

Strombolian

A type of volcanic eruption characterised by an intermittent pulsating sequence of bursting gas explosions and a low eruption column. Usually associated with basic, low viscosity magma.

Subgroup

A formally defined stratigraphic unit consisting of one or more formations.

Surge deposit

A strongly bedded pyroclastic deposit emplaced by high-velocity, turbulent, gaseous flows of low particle concentration.

Tephra

A collective term for all the unconsolidated, primary pyroclastic products, of any grain size, of a volcanic eruption (i.e. a loose assemblage of pyroclasts). Plural is either tephra (as a collective noun) or tephras.

Tuff (cf. ash, tephra)

A consolidated deposit of ash-sized particles.

Unconformity

A gap or break in the stratigraphic sequence that marks the absence of part of the rock record.

Vesicular

Containing vesicles, which are round or oval holes in a volcanic rock, e.g. pumice, formed from trapped bubbles of volcanic gas.

Volcaniclastic

A fragmental aggregate originally of volcanic origin but reworked.

Volcanogenic

Any deposit originally having a volcanic origin but reworked.

Welding

The sintering together of hot pumice fragments and glass shards under a compactional load. Welding may occur in four zones: dense welding (rock is hard, pumice clasts break when ignimbrite cracked with hammer), partial welding, weak welding, and non-welding (pumice clasts easily plucked out by hand).

Appendix

Terminology used for Rock Classification (after Brown 1981)

(a) Spacing of joints or Discontinuities

DESCRIPTION	SPACING
Extremely close spacing	<20 mm
Very close spacing	20 – 60 mm
Close spacing	60 – 200 mm
Moderate spacing	200 – 600 mm
Wide spacing	600 – 2000 mm
Very wide spacing	2000 – 6000 mm
Extremely wide spacing	> 6000 mm

(b) Manual index test of wall strength

GRADE	DESCRIPTION	FIELD IDENTIFICATION	APPROX. RANGE OF UNIAXIAL COMPRESSIVE STRENGTH (M Pa)
S1	Very soft clay	Easily penetated several inches by fist	<0.025
S2	Soft clay	Easily penetrated several inches by thumb	0.025 - 0.05
S3	Firm clay	Can be penetrated several inches by thumb with moderate effort	0.05 - 0.10
S4	Stiff clay	Readily indented by thumb but penetrated only with great effort	0.10 - 0.25
S5	Very stiff clay	Readily indented by thumbnail	0.25 - 0.50
S6	Hard clay	Indented with difficulty by thumbnail	>0.50
R0	Extremely weak rock	Indented by thumbnail	0.25 - 1.0
R1	Very weak rock	Crumbles under firm blows with pointof geological hammer, can be peeled by a pocket knife	1.0 - 5.0
R2	Weak rock	Can be peeled with a pocket knife with difficulty, shallow indentations made by firm blow with point of geological hammer	5.0 - 25
R3	Medium strong rock	Cannot be scrapped or peeled with a pocket knife, specimen can be fractured with single firm blow of geological hammer	25 - 50
R4	Strong rock	Specimen requires more than one blow of geological hammer to fracture it	50 - 100
R5	Very strong rock	Specimen requires many blows of geological hammer to fracture it	100 - 250
R6	Extremely strong rock	Specimen can only be chipped with geological hammer	>250

Note: Grade S1 to S6 apply to cohesive soils, for example clays, silty clays, and combinations of silts and clays with sand, generally slow draining. Discontinuity wall strength will generally be characterized by grades R0 - R6 (rock) while S1 - S6 (clay) will generally apply to filled discontinuities (see Filling).
Some rounding of strength values has been made when converting to S.1 units.