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**THE CLAY MINERALOGY AND EROSION
OF THE
WAIPAOA RIVER CATCHMENT,
GISBORNE, NEW ZEALAND.**

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A thesis presented in partial fulfilment of the
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“Look Lorax,” I said. “There’s no cause for alarm.
I chopped just one tree. I am doing no harm.”

The Lorax, Dr Seuss



ABSTRACT

The Waipaoa River Catchment lies N-NW of Gisborne, covering 2181 km² it drains south into Poverty Bay ~10 km SW of Gisborne. It carries approximately 15 million tonnes of suspended sediment annually, ranking it as one of the most sediment - laden rivers in the world. Deforestation in the early 1900's has led to severe landslide and gully erosion. To assist in catchment analysis and sediment budgeting, Landcare Research divided the Waipaoa River Catchment into 16 land systems, based on the Land Resource Inventory; principally rock type and erosion type and severity. Four of these land systems were chosen to test the hypothesis that clay mineralogy will influence whether landslide or gully erosion is dominant. And, if mineralogical signatures could be established for the different land systems, they could be traced downstream onto the floodplain and into the marine environment.

There is no consistent mineralogical difference between the two chosen landslide dominated land systems and the two gully dominated systems. The Mangatu Land System is dominated by gully erosion. Samples taken from the Tarndale Gully complex within the Mangatu Land System for example, are dominated by quartz in the clay fraction, whereas gullies in the Waingaromia Land System are dominated by mica and smectite. The landslide dominated Te Arai Land System, like the Waingaromia Land System, is also primarily mica and smectite, while the clay minerals of the Mako Mako Land System consist of mica and the clay – sized mineral feldspar. It appears that tectonic influence of uplift and faulting, and its influence on headward erosion by streams, is most important in predisposition to gully erosion.

The Mangatu Land System dominates the clay mineralogy of both the bedload and suspended sediment of the Waipaoa River at normal flow. However, dilution of this signature does occur at Te Karaka with the influence of the Waingaromia, Waikohu, and Waihora Rivers. In major flood events during high intensity storms, landsliding is more prevalent. Floodplain sediments are thus predominantly soil mantle materials derived from shallow landsliding and bare little resemblance to the dominant Mangatu Land System sediments. Whereas, the Poverty Bay marine core MD2122 sediment, representative of the annual Waipaoa River sediment yield, is produced by the continuous gully erosion. The effect of differential settling gives the core mineralogy a similar signal to that of the floodplain cores; however, sediment is considered to be predominantly Cretaceous material.

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CHAPTER 1: INTRODUCTION

This chapter introduces the area being studied for this thesis. It will focus initially on the area and its background, past through to present day events and implications. Secondly, the tectonic and geological setting, and regional geology of the study area will be described. This chapter is written so the reader can follow sedimentation through the catchment from the hill-country to the plains and to marine deposition in Poverty Bay. The third aspect of this chapter strengthens the theme of erosion, defining and discussing the forms readily occurring within the catchment; and finally how erosion has been used as part of the criteria in defining land systems within the Waipaoa River catchment.

STUDY AREA

The Waipaoa Catchment lies N-NW of Gisborne (Figure 1.1) and has a total area of 2181 km², of which low coastal hill country and alluvial plains cover 570 km² and steep hill country 1580 km². The Waipaoa River rises on the eastern side of the Raukumara Ranges at 1440 m elevation, at the junction of two headwater streams – the Wairangiora and the Waimatau, and has a mainstem length of 104 km. The river flows south into Poverty Bay approximately 10 km SW of Gisborne and carries approximately 15 million tonnes of suspended sediment annually (Hicks *et al.*, 2000).

The catchment is drained by seven tributaries, three of which are major sediment contributors: Upper Waipaoa, Mangatu and Waingaromia Rivers, and four minor rivers that do not contribute to the bulk of sediment (Eden & Trustrum, 1994). The Waipaoa River changes from a braided channel to a meandering one at the gorge (Figure 1.3.1) at the Mangatu Forest boundary, and continues meandering until it reaches the coastline. Henderson and Ongley (1920) first noted the general trend of rising streambeds throughout the district; in recent times this has been confirmed through continuing council projects. At Kaiteratahi (south of Te Karaka) in 1910 the Waipaoa Riverbed had risen two metres in 15 years due to aggradation (Allsop, 1973), and between 1948 and 1968 in the upper basin the riverbed rose five metres (Eden & Trustrum, 1994). Since deforestation begun in the 1880s the Waipaoa Riverbed is believed to have risen a total of 33.5 m. One of the most spectacular examples of this aggradation is the

Te Weraroa Streambed (Plate 1.1), in which the sediment from the Tarndale Gully complex is first deposited. The width of debouchment of Te Weraroa Stream and Waipaoa River increased from 60 metres in 1896 to 360 metres in 1940 (Allsop, 1973).

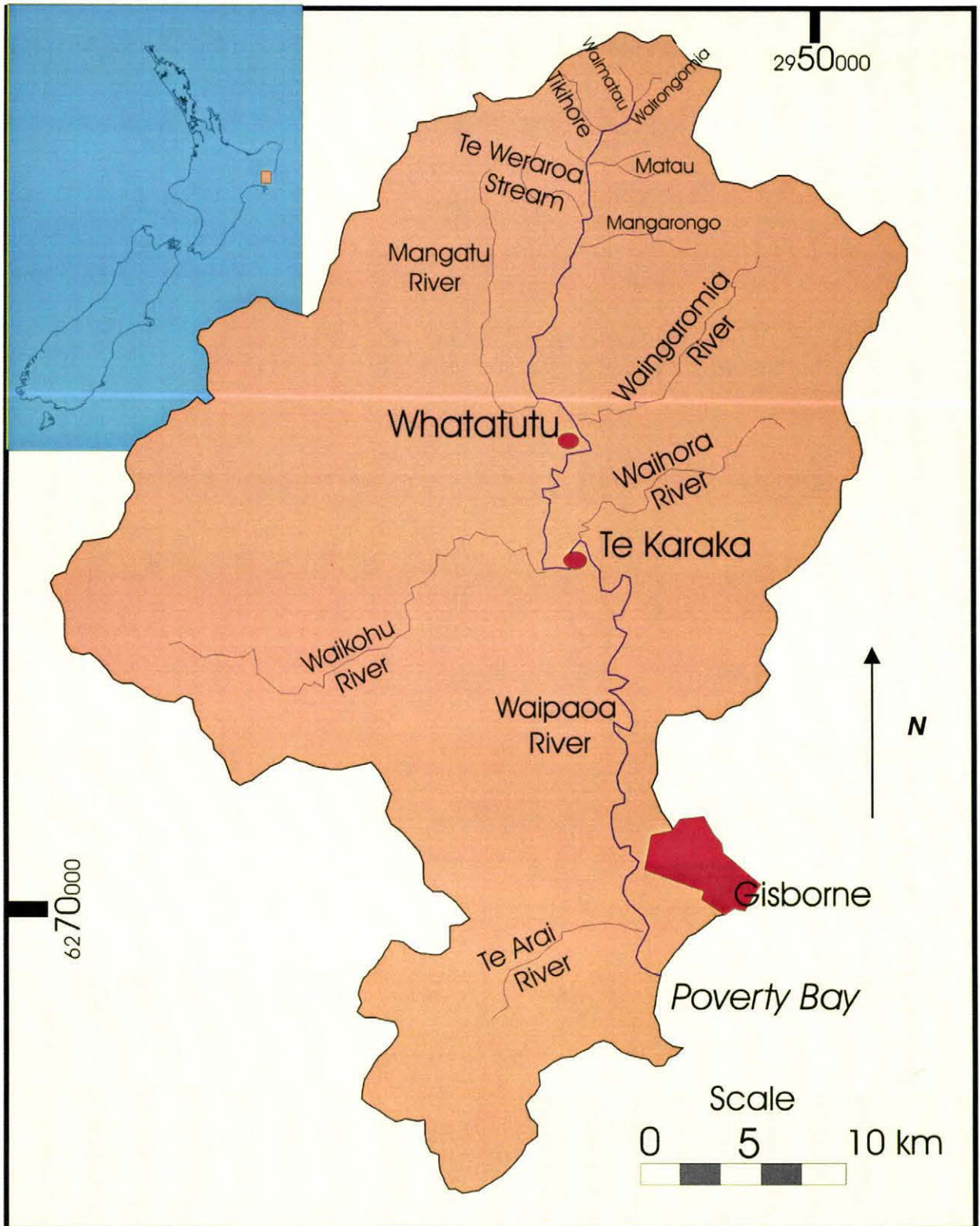


Figure 1.1 Location of the Waipaoa River catchment, East Coast, North Island, New Zealand.



Plate 1.1 The base of the Te Weraroa Stream on the Waipaoa River floodplain (photo: M. A. D'Ath, 1999).

1.1 BACKGROUND

Before 700 B. P. the basins and lowlands were vegetated with dense podocarp - broadleaved and hardwood forests; species such as rimu (*Dacrydium cupressium*) and matai (*Prumnopitys taxifolia*) were dominant above the mixed hardwood canopy (McGlone *et al.*, 1984). Disturbance of this forest cover, due to volcanic eruptions or lightning strikes, came in the form of fire, a method employed after 700 B. P. by the Maori who settled the Gisborne region. The Maori settling around Ormond, Waituhi, Repongaere and Waerenga a Hika, developed horticultural sites on the surrounding hillslopes after clearing forests through slash and burn practices (Eden & Trustrum, 1994).

Permanent forest clearance of the Waipaoa Catchment began in the 1820s when European settlers felled the low lands for settlement and grazing. Wheat, maize and potatoes were being grown by the 1840s. A rapid advancement of settlement took place on the Gisborne plains between 1871 – 1875 as Gisborne town was becoming established, and to cater for this influx of Europeans, hillslopes were brought into production. Large portions of kahikatea and kahikatea – matai – puriri forests were destroyed in 1865 and 1878, by accidentally lit fires (Pullar, 1962). By the 1880s the lower river reaches were deforested, and clearance of most of the upper

headwaters was completed forty years later. While this conversion to pasture was taking place, the first signs of soil erosion became apparent. Slipping, gullying, slumping, and the amount of bare ground increased with every rainfall (*see* section 1.10). Evidence of the severity of this erosion could be seen by the rising streambeds, and increased flooding and sediment inundation of the Gisborne plains (*see* section 1.4). Large amphitheatre-like gully complexes, Tarndale and Mangatu (*see* section 1.10.2), opened in the winter of 1915 (Allsop, 1973) in the extensively sheared argillite steeplands that prominently scarred the landscape (Plate 1.1.1). Government geologists noted and warned of the hazards that accompanied the continuing erosion in the early 1900s, but public recognition of its severity did not really take hold until the war and post - war years (Allsop, 1973).

Stop banks were constructed in 1953 as the first attempt to protect the intensively farmed alluvial plain from further inundation. Reforestation began in 1960 (Plate 1.1.1) with the planting of the Mangatu Forest and the introduction of the exotic species pine (*Pinus radiata*).



Plate 1.1.1 Tarndale Gully 1961 (photo: *J. Johns*, 1961).

The Mangatu Forest reforestation scheme was targeted primarily to combat accelerated soil erosion within the catchment, the economic production of timber served as a dual – purpose,

and secondary to the erosion role (Allsop, 1973). Within ten years, pine covered 70 km² of the Waipaoa Catchment; by 1999 16 % (1366 km²) of the Gisborne District Council area was planted in exotic forestry, including Douglas fir (Plate 1.1.2).



Plate 1.1.2 Tarndale Gully 2000 (photo: *N. Trustrum*, 2000).

Commercial timber harvesting (Plate 1.1.3) commenced in 1990 and is ongoing. Exotic forestry now covers 20 % of the Waipaoa Catchment while pasture covers 71 %, scrub covers 4 % and native forest and crops cover 2.5 % each.



Plate 1.1.3 Timber harvesting in the Mangatu Forest 2000 (photo: *A. Palmer*, 2000).

The ongoing effects of the erosion caused by the afore mentioned combination of activities is being studied in the modern environment. Sediment budgets, storm damage assessments, spatial and temporal erosion trends, magnitude and frequency, and sediment and nutrient transfer through stream networks to deposition sites are part of an interdisciplinary research project presently ongoing (Trustrum *et al.*, 1999). The effect this erosion has downstream is an important rationale behind this research. Page *et al.* (1999) state that the downstream affects of landslides (during infrequent, high magnitude storms) can amount to the following environmental implications: water quality and aquatic ecosystem degradation, plain flooding and siltation, and harbour and coastal siltation. All of which ultimately pollute fishery habitats.

The sediment moving down the Waipaoa River into Poverty Bay is being used in stratigraphic studies and the interpretation of erosion history. Landcare Research divided the Waipaoa Catchment into 16 'Land Systems' derived from the New Zealand Land Resource Inventory (NZLRI) (*refer* section 1.11); work is being done to find out why some of these land systems are prone to gully erosion, while others are prone to landslide erosion. Land systems dominated by severe gully erosion may have a different mineralogy to those dominated by landslides, and if land systems have different mineralogies, it may be possible to trace a mineralogical signature downstream. Landcare Research and NIWA have obtained cores from the Gisborne floodplains and Poverty Bay that have important time constraints through stratigraphic control of identifiable tephras. The mineralogy of sediment fluxes within this stratigraphy may provide important information of the provenance of the material; it may be possible to see alternating gully and landslide contribution of sediments to the river system at different times, or a signal to distinguish between glacial and Holocene sediments.

1.2 TECTONIC AND GEOLOGICAL SETTING

The Hikurangi Subduction Margin occurs where the Pacific Plate is being subducted beneath the Australian Plate at *c.* 44 mm/yr (Berryman *et al.*, 2000) approximately 100 km off the East Coast of the North Island (Figure 1.2.1). The interface of these colliding plates lies 30 km beneath the headwaters of Waipaoa River and 15 km below Gisborne (Ansell and Bannister, 1996).

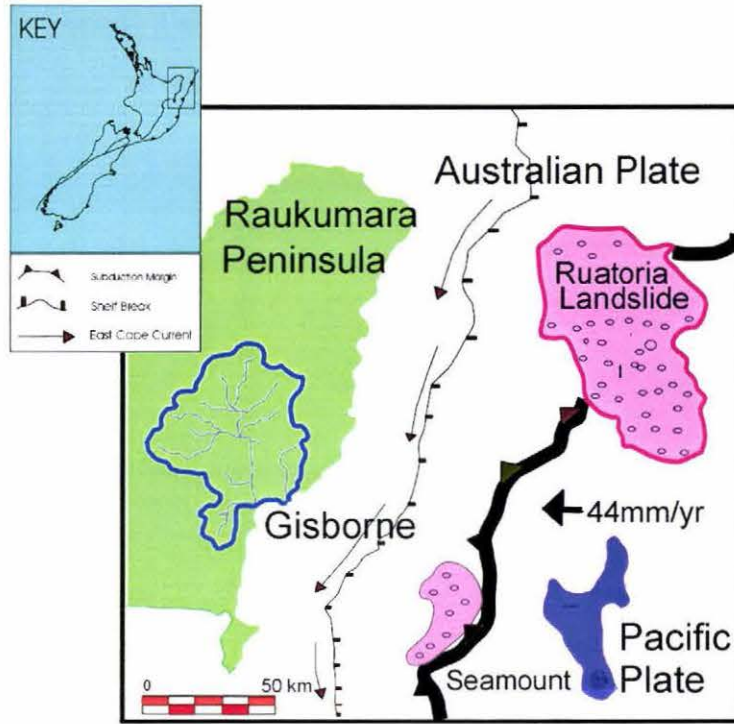


Figure 1.2.1 The Hikurangi Subduction Margin occurs as continental crust overrides the denser oceanic crust at a rate of 44 mm/yr. The Waipaoa Catchment is outlined in blue north of Gisborne; off the east coast of the North Island the east coast current flows south along the continental shelf. The inset (top left) illustrates the subduction margin on a greater scale (adapted from Berryman *et al.*, 2000).

Reyners *et al.* (1999) have suggested that the uplift of the Raukumara Range is occurring as subducted seamounts accrete or ‘pond’ at the interface of the hard ‘backstop’ mantle of the Australian Plate (Figure 1.2.2). Above the accretionary prism created at this interface lies the study area, astride the Neogene prism and the forearc locale (Lewis, 1980).

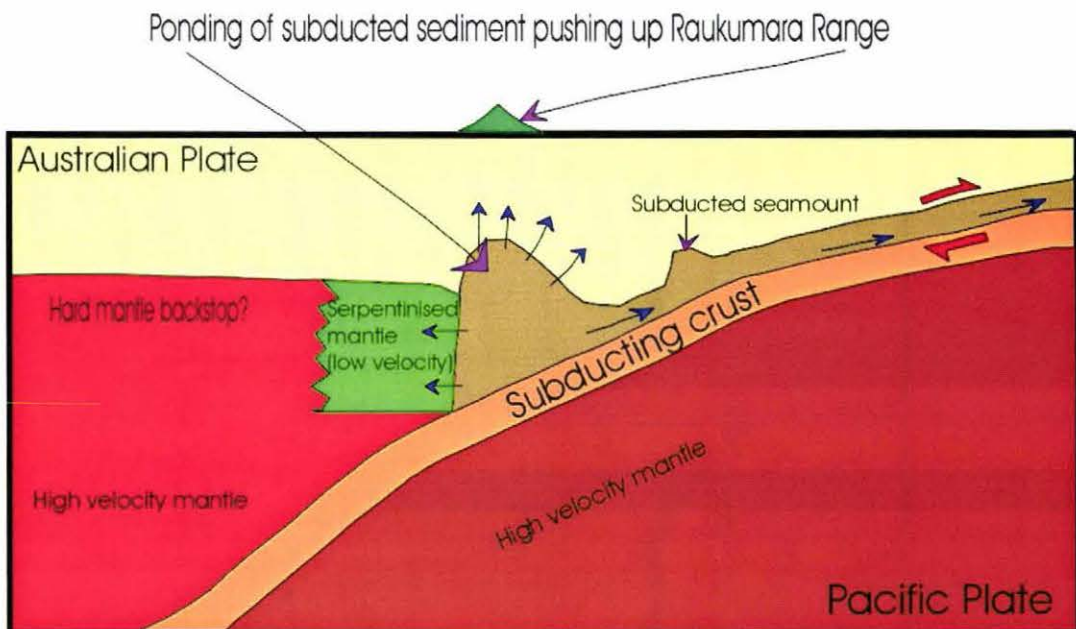


Figure 1.2.2 Uplift of the Raukumara Range. Oceanic crust of the Pacific Plate is being subducted beneath the buoyant continental Australian Plate, creating an accretionary wedge of subducting sediment at the plate interface. Ponding of this sediment creates an area of uplift, the Raukumara Range (adapted from Reyners *et al.*, 1999).

Structural style along the length of the Hikurangi Margin (north to south) exhibits marked variation. Berryman (1988) and Lewis and Pettinga (1993) discuss these tectonics in two different sectors. North of Gisborne widespread normal faulting occurs, while reverse faulting and strike-slip faulting is evident south of Gisborne (Beanland (1995) attributes this to the translational component of oblique subduction).

1.3 REGIONAL GEOLOGY

This section will be discussed in four blocks as defined by Mazengarb *et al.* (1991): Motu Block, East Coast Allochthon, Neogene rocks, and late Quaternary sediments. Black (1980) divided the upper Waipaoa Catchment into four geological formations: the oldest unit – Tikhore Formation, then the conformable Mangatu Formation which in turn is unconformably overlain by the Te Arai and Tokomaru Formations (Miocene sediments) (Figure 1.3.1). Mazengarb *et al.* (1991) introduced a new stratigraphic nomenclature for Black's (1980) Te Arai Formation; it will be referred to in this section as the Tolaga Group. Mazengarb *et al.* (1991) also describe two other groups, the Matawai and Tinui (Figure 1.3.1).

1.3.1 Motu Block

The Motu Block is situated NNW of the Waipaoa Catchment and consists of an autochthonous group of Cretaceous sediments including the Matawai and Tinui Groups.

The Early Pliocene marine *Karekare Formation (Matawai Group)* (Figure 1.3.1) sediments are dominated by mudstone, with packets of alternating sandstone, mudstone and conglomerate. Barite and calcareous concretions, and pyrite nodules are also evident (Mazengarb *et al.*, 1991).

The Late Cretaceous – early Tertiary *Whangai Formation (Tinui Group)* (Figure 1.3.1) has been divided into two facies. The western facies and the eastern facies are distributed in the Motu Block and the East Coast Allochthon, respectively. The western facies consists of siliceous to moderately calcareous mudstone, which contains calcareous concretions, chert nodules, pyrite and rare microfossils.

1.3.2 East Coast Allochthon

The East Coast Allochthon is made up of slices of sediment displaced from their original depositional site in the east (*see* section 1.3.4).

The Late Cretaceous *Tikihore Formation (Ruatoria Group)* (Figure 1.3.1) is distributed north of the Tikihore Fault Block, throughout the Te Weraroa, Tikihore and Waimatau catchments. Consisting of alternating sandstone and minor mudstone, conglomerate and rare basaltic rocks (Mazengarb & Speden, 2000) Mazengarb *et al.* (1991) suggest that the *Tikihore Formation* was deposited in a high energy, shallow marine, shelf environment.

The eastern facies of the *Whangai Formation* (*see* section 1.3.1) is dominated by jointed, siliceous argillite (indurated mudstone), and although bioturbation is evident, macrofossils are very rare.

The Eocene *Mangatu Group* marine sediments (Mazengarb & Speden, 2000) (Figure 1.3.1) crop out in the Wairangiora catchment, along the Waipaoa River valley, and the upper Mangatu, Te Weraroa and Matakonekone catchments. Although predominantly composed of fine-grained calcareous mudstones, minor amounts of marl and limestone, sandstone and glauconitic sandstone, and conglomerate and coarse sedimentary breccia are also present (Eden & Trustrum, 1994).

1.3.3 Neogene Rocks

The Neogene is characterised by a thick sequence of sediment deposited in the developing fore-arc basin (*see* section 1.2.1).

Composed of calcareous mudstone, alternating with minor coarse to fine sandstone, the *Tolaga Group* (Figure 1.3.1) often contains poorly sorted conglomerate of mafic igneous boulders and some coarse coquina limestone (Mazengarb *et al.*, 1991); the *Tolaga Group* is thought to represent offshore deposition in an outer shelf to upper slope (?) situation during the Miocene (Mazengarb *et al.*, 1991). Outcrops of this formation can be found along the eastern margin of the Waipaoa and Wairangiora catchments, in the Mangaorongo Stream catchment, and through the Waipaoa gorge (Figure 1.3.2)(Rosser, 1997).

The Late Miocene massive blue-grey *Tokomaru Sandstone* was deposited during the rapid deepening of the basin (Mazengarb *et al.*, 1991) and represents the top of the Tertiary sequence in the headwaters of the Waipaoa River.

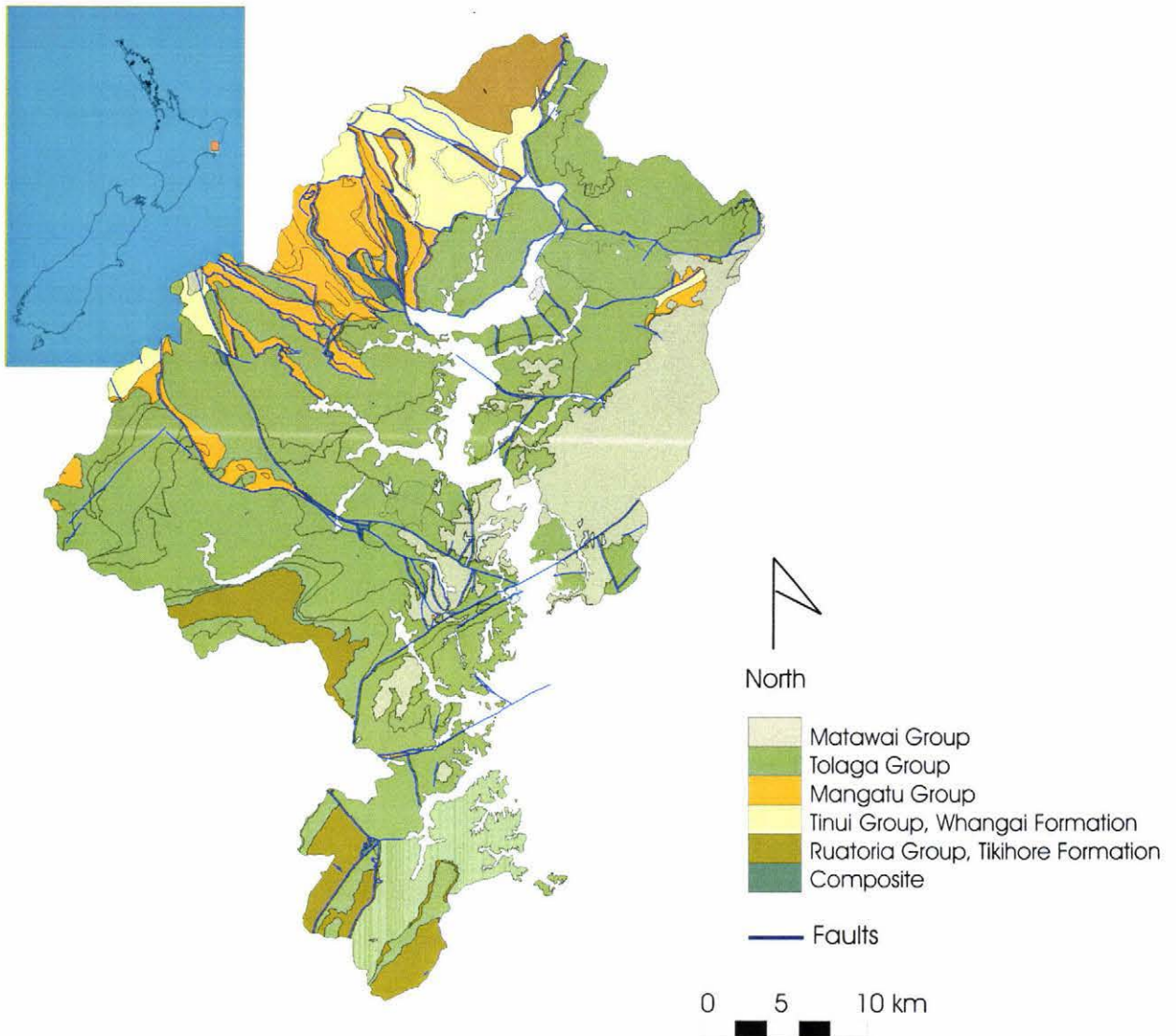


Figure 1.3.1 Basic geology of the Waipaoa Catchment study area. The five main ‘Groups’ that are found in the area have been defined: Ruatoria, Tinui, Mangatu, Tolaga, and Matawai. The major fault zones are shown in blue (adapted from Mazengarb & Speden, 2000).

1.3.4 East Coast Allochthon Structure

The structurally complex region surrounding the Waipaoa Catchment contains extensive sedimentary rock units that have been displaced from their original East Cape depositional basin environment (Pearce *et al.*, 1981). Stonely (1968) mapped 16 thrust slices of sediment (but theorised of a 20-slice sequence) that he considered were transported southwest of their original environment of deposition. Mazengarb *et al.*, (1991) found that fold and fault alignment within

the thrust slices exhibited a strong preferential, northwest - southeast trend, thus supporting Stonely's (1968) hypothesis. The four unmapped thrust slices ("Uppermost Thrust Masses", Stonely, 1968) have since been subdivided by Black (1980) into three definite blocks: Mangatu Fault Block, Matakonekone Fault Block, and Tikhore Fault Block (Figure 1.3.2). These fault blocks are bound by the four major faults Black (1980) also defined within the head water region: Te Weraroa, Te Waka, Waipaoa, and Wheturau (Figure 1.3.2).

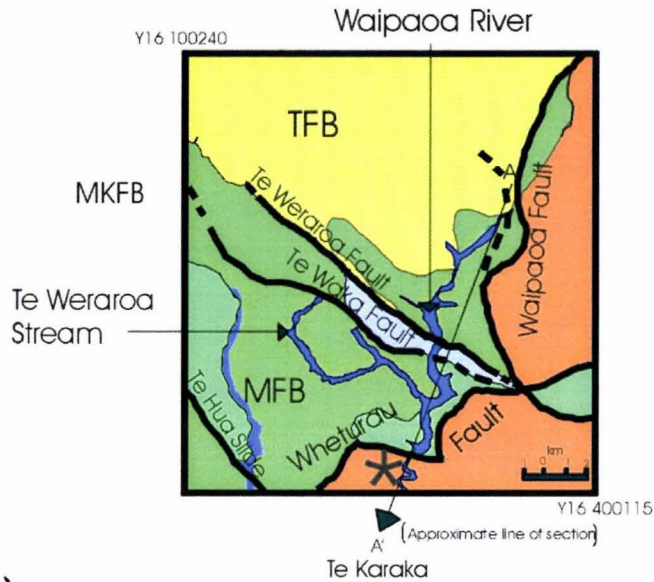
The East Coast Allochthon consists of the Ruatoria Group, Tinui Group (eastern facies) and the Mangatu Group (Figure 1.3.1), and is faulted over the Motu Block (NNW of the Waipaoa Catchment) (*see* section 1.3.1) by a southeast dipping low decollement fault surface (Mazengarb, *et al.*, 1991). These allochthonous sediments come in contact with Miocene-Pliocene sediments at the Wheturau Fault (Figure 1.3.2).

The *Mangatu Fault Block* (MFB, Figure 1.3.2) is bounded by three of the major faults, Wheturau, Waipaoa and Te Waka to the south, east and north, respectively, and by the Te Hua Slide in the west (Figure 1.3.2). Thrust Slices XIV, XV, XVI (Stonely, 1968), Mangatu Group sediments, two wedges of Tikhore Formation sandstone, and one of Whangai Formation sandstone are contained within this block.

The Te Weraroa Fault bounds the *Matakonekone Fault Block* (MKFB, Figure 1.3.2) to the north, while the Te Waka Fault bounds it in the south (Figure 1.3.2). It consists of a fault bounded wedge of a sequence of cropping out Tikhore and Mangatu rocks that extends southeast across the Waipaoa River from the upper Mangatu catchment, until pinching out in the Whakauaponga Stream.

The *Tikhore Fault Block* (TFB, Figure 1.3.2) is bounded to the east by the Waipaoa Fault and to the south by the Te Weraroa Fault, while the northern boundary in the Mangatu catchment is unknown. Black (1980) suggested that the western Raukumara autochthonous siltstone-dominated rocks are in 'fault contact' with this block.

a)



b)

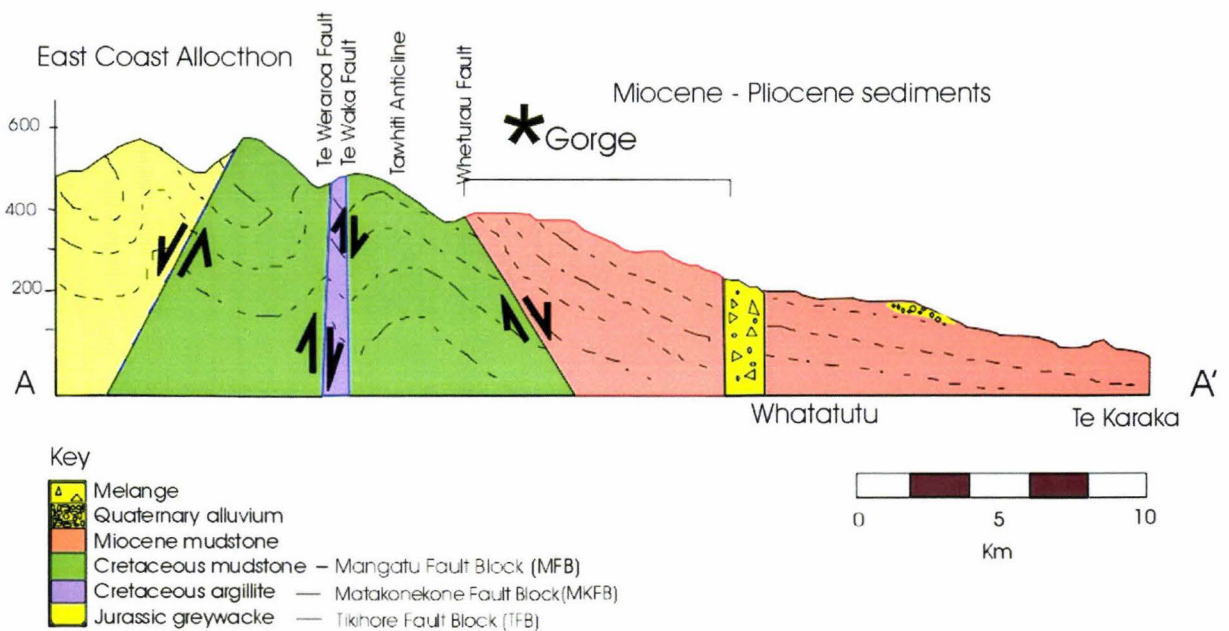


Figure 1.3.2 a) Head water faults. Black (1980) defined three major fault blocks in the headwater region, Mangatu (MFB), Tikiore (TFB), and Matakonekone (MKFB), bounded by four major faults, Te Weraroa, Wheturau, Waipaoa, and Te Waka. b) Cross section A-A' from figure a, running parallel with Waipaoa River flow, shows the sequence of strata, faults, and fault blocks (adapted from Black, 1980 & Mazengarb *et al.*, 1991).

Folding within the thrust slices demonstrates a strong, preferential, northwest – southeast alignment (Mazengarb *et al.*, 1991). While the Tikiore Formation exhibits parallel, recumbent folds and the Mangatu Group demonstrates angular folds, the Tolaga Group and the Tokomaru Sandstone have formed an anticline and an open syncline, respectively. Unlike the folds, not all the faults trend along the same northwest axis, the Te Weraroa Fault and Te Waka Fault for example are high angle, southeast-trending faults. The sequence is complicated still as the folds

and faults along this northwest-southeast axis are folded into the broad truncated Tawhiti Anticline.

1.3.5 Quaternary Sediments

Fluvial sediments are the predominant Quaternary deposits in the Waipaoa Catchment. Berryman *et al.* (2000) have mapped four aggradational terraces (Plate 1.3.1) along the lower 45 km of the Waipaoa River. These terraces have been correlated to the Quaternary climate change fluctuations (*see* section 1.6). Three of the four terraces have been correlated with those seen in the lower North Island, which represent periods of glaciation, Ohakean, Ratan, and Porewan age.



Plate 1.3.1 River terraces cut in the Late Quaternary in the upper Waipaoa River catchment. The highest terrace broadly correlates to the Ohakean stadial ~15 000 years B.P. (photo: J. Johns, 1964).

Waipaoa 1 terrace emerges from the Holocene surface *c.* two kilometres north of Te Karaka (Figure 1.1), and continues upstream into the headwaters, where a small remnant of terrace remains preserved on the older suite of Cretaceous rocks *c.* 120 metres above the modern river level. The oldest part of the covered sequence for the Waipaoa 1 terrace contains the

Rerewhakaaitu Tephra (17 700 cal. Yr B.P, Lowe *et al.*, 1999), which probably indicates that cessation of aggradation occurred around 16 ka BP, which broadly correlates with the Ohakean age terraces seen in the lower North Island. Waipaoa 2 terrace is slightly older than the Mangaone Tephra (28 ka) identified as the lowest ash in the terrace tread coverbeds, and it correlates with the Ratan terrace; this terrace is only one to two metres thick, which may indicate an oscillating climate, and not full glacial conditions like the other terraces (Berryman, 1992). The Waipaoa 3 terrace (Porewan equivalent) is overlain by the Rotoehu Tephra (55 – 57 ka BP) indicating aggradation cessation at ~ 65 ka BP; and the Waipaoa 4 terrace is broadly dated to oxygen isotope 5 or 6, making it between 90 – 140 ka (Berryman *et al.*, 2000).

Berryman *et al.* (2000) and Eden *et al.* (2001) postulated that as the average rates of downcutting and infilling exceeded those of tectonic uplift by four times; they therefore represented a major change in river hydrology probably due to glacial climate changes.

1.4 THE INFILLING OF THE GISBORNE PLAINS

Pullar and Penhale (1970) postulated that the infilling of the Gisborne plains occurred in five key phases: 1480 B. C. -A.D. 131, A. D. 131-1650, 1650-1820, 1820-1932, and 1932-1950 (radiocarbon years).

The Kaiti Formation formed during Period 1 – c. 1480 B. C. to c. A. D. 131 beginning with the eruption (near Lake Taupo) of the Waimihia Lapilli and ending with that of the Taupo Pumice. Buried soils above the Waimihia Lapilli contain larger quantities of smectitic (bentonitic) clays than do other soils in later formations, possibly indicating sedimentary mudstone and argillaceous source rocks (Pullar & Penhale, 1970). Pullar and Penhale (1970) attributed tree stumps found within the Kaiti Formation to represent a period of rapid erosion and subsequent sedimentation, resulting from tectonic movements. Eden and Page (1998) however, correlate a period of sedimentation, Marapa 2 at Lake Tutira with Period 1, and report no evidence of sudden earthquake initiation within the sediment pulses in their cores. They do, however, suggest regular seismicity over this period may have disrupted the soil enough to contribute to the magnitude of these ‘storm sediment pulses’, instead of the frequency.

Period 2 – c. A. D. 131 to c. A. D. 1650 is called the Waihirere Formation. The basal marker bed consists of the Taupo Pumice (A. D. 131) which is widespread at shallow depth and overlain by the Kaharoa Ash (A. D. 650). A period of negligible infilling occurred before the development of the Kaiti and Waihirere soils. The Taupo Pumice is present in two of this

projects cores; the Matawhero floodplain core (*see* section 3.4.3) contains the Taupo Pumice at 2.1 m, while the Poverty Bay marine core MD2122 has it at 2.97 m (*see* section 3.4.4).

The third Period (Early Matawhero Formation) occurred from *c.* A. D. 1650 to *c.* A. D. 1820 and began with what has been described as catastrophic storm damage (Pullar & Penhale, 1970). Rapid erosion of the Gisborne hill country led to rapid infilling of the Gisborne Plains. The Makauri and Matawhero soils formed on these plains from the alluvial sediments deposited during the interval of negligible infilling.

The Late Matawhero Formation (Period 4) began with a large flood in 1820 and ended with another large flood in 1932. Ten floods between 1820 and 1918 deposited thin layers of sediment from which the Late Matawhero Formation is defined (Pullar & Penhale, 1970). Gomez *et al.* (1988) identified this series of floods in the McPhail's Bend core (*see* sections 1.9, 2.1.2, 3.4.1), although the 1820 flood is not readily identified. Between this time and 1918 they identified 11 other floods, mostly thin graded sediment deposits, which are banded together. The period between 1918 and 1932 experienced no flooding and soil formation was initiated, until it's inundation in the 1932 flood. While bank erosion along the Waipaoa River provided sediment for the flood deposits of 1820, 1853, 1876 and 1879 (Pullar and Penhale, 1970), sediment from the 1894, 1906, 1910, 1914, 1916, and 1918 floods, is assumed to have been derived from the erosion of deforested Gisborne hill country (Pullar and Penhale, 1970), as these years extend over the time of intensive forest clearance. The first extensive slipping occurred between 1893 and 1894 following tree removal (Hill, 1895).

Period 5 (Post-Matawhero Formation) (1932-1950+), as with Period 4, began with a large flood; this period is considered to be continuing still. Stop banks were built following the 1950 flood so all deposition or any subsequent infilling was taking place within the confines of the stop banks, particularly in meander troughs (Pullar & Penhale, 1970). Cyclone Bola flooding topped these stop banks at Te Karaka in 1988 (*see* section 1.9.1), causing extensive damage to housing. The Waipaoa soils formed from thick flood deposits of 1932, 1938, 1944, 1948, and 1950, from which the formation is defined. Accelerated erosion of the hill country due largely to the deforestation of the Waipaoa catchment was the primary source of sediment deposited on the plains (*see* section 1.1). According to Pullar and Penhale (1970) the gradual erosion of the hill country became more severe after 1936 (Table 1.4.1). This increase of erosion rate led to the initial Mangatu forestry plantings (*see* section 1.1). However, Allsop (1973) suggests that this is when public recognition of the erosion occurred, there is no evidence that erosion was less severe before 1936, as evidenced by the rising streambeds in 1910 (*see* section 1.1).

Eden and Page (1998) attributed much of the sedimentation and infilling in Lake Tutira, 100 km south of the Gisborne plains, over the last c. 2250 years to periods of increased storm activity occurring during ENSO La Niña phases. They recognized 365 storm sediment pulses in an analysed core within six periods of increased sedimentation; five of these periods represent increased storm frequency (Table 1.4.1) decades in duration (Eden and Page, 1998).

Table 1.4.1 demonstrates the rate at which each period contributed sediment to the infilling of the Gisborne plains. The rate of erosion and deposition increased with each period and was considerably more significant in the 20th Century.

Period of Infilling	Formation (alluvial)	Buried Soils	Datings of Events	Probable Causes of Events	Volume of Infilling ($m^3 \times 10^6$)/yr	Rate of Infilling Vol. Thickness ($m^3 \times 10^6$)/yr (mm yr)		Eden & Page Erosion Periods
5	POST MATAWHERO	(Waipaoa soils)	1932-1950+	Large-scale deforestation	492	0.30	1.5	European
4	LATE MATAWHERO	Makaraka and Matawhero soils (dark greyish brown (2.5 Y 4/2) and granular)	c. 1820	European settlement; Waipaoa River bank corrosion	230	0.15	0.8	European 1878-1985
3	EARLY MATAWHERO	Matawhero (friable topsoil phase) and Makauri soils (very dark greyish brown (2.5 Y 3/2) and granular)	c. 1650	Catastrophic erosion after storm damage	44	0.25	2.3	Burrell period 1575-1594
2	WAIHIRERE	Waihirere and Kaiti soils (black (5 Y 2/1) and granular) (Buried soil with humus-darkened horizon) Kaharoa Ash (Buried soil with humus-darkened horizon) Taupo Pumice	c. 1450 c. A.D. 1020 c. A. D. 131	Little sedimentation Volcanic eruption Volcanic eruption	21	0.19	3.7	Tufa Trig period (?) 2. 1416-1419 1. 864-1014 Taupo (?) 496-515
1	KAITI	(Stumps) Kaiti silt loam (Buried soils without humus-darkened horizons) Waimihia Lapilli)	c. 250 B. C. c. 1480 B.C.	Earthquakes, tectonic movement Volcanic eruption	30	1.64	16.0	Possibly Mapara 2 Period, numerous thick sediment pulses - considered to be initiated by storms 34 B.C-94 A.D

Table 1.4.1 Two studies are combined to establish defined periods of infilling of the Gisborne plains. Five periods are defined by soil horizons and tephric deposits (adapted from Pullar and Penhale, 1970 & Eden and Page, 1998).

1.5 FLOODPLAINS

Bordered on the southeast by a raised beach and on the south by tidal flats, the floodplains are the predominant physiographic landscape unit of the Gisborne region. The area is naturally drained by the Waipaoa River and three other main tributaries, the Pourua, Whakaahu, Te Arai. South-west of the above tributaries small independent streams flow onto the tidal flats at Muriwai, and a fourth (Wairekaia) discharges into the Maraetahi River near its mouth.

The five classes of soil Pullar (1962) recognised on the floodplains were – Recent Soils from alluvium, Gley Soils from alluvium, Sandy Recent and Brown Soils from young and older dune sands respectively and Pumice Soils from alluvial pumice. The Recent Soils form from accumulating river sediments from Cretaceous and Tertiary calcareous sedimentary rocks (*see* section 1.3) and the Gley Soils form on the tidal flats. Sands and shell fragments make up the Sandy Recent or Brown Soils, while the Pumice Soils are derived from rhyolitic pumice.

The fertility of the soils on the floodplains followed the shifting pattern of erosion; as erosion shifted from bank erosion to landslides to gullies in the early part of the twentieth century, the sediment deposited on the floodplains became less fertile (Mike Page, *pers. com.*, 2001). The initial bank erosion and landslides contributed soil mantle materials to the river system increasing fertility, but by 1918 fertility was lowering as gullies begun to contribute sediment. By 1932 the extensive gullies were unloading bedrock directly into the streams; this bedrock through flooding, was deposited on the plains creating infertile farmland. Recognition of this problem eventually led to the initial flood protection and forestry programmes (*see* section 1.1) and since 1960 gullies have been contributing less sediment to the plains, which in turn are becoming more fertile (Mike Page, *pers. com.*, 2001).

1.6 TEPHRA COVERBEDS

Tephra layers play a crucial part in the identification or correlation of ages of landforms. In Gisborne there is an excellent record of volcanic eruptions (from the Okataina, Taupo and Tongiriro volcanic centres). Using tephro - stratigraphy these tephtras can now be used as a correlative dating technique.

Vucetich and Pullar (1964) described an outcrop in Matawai believed to contain an almost complete stratigraphic sequence of tephric cover beds (Figure 1.6.1).

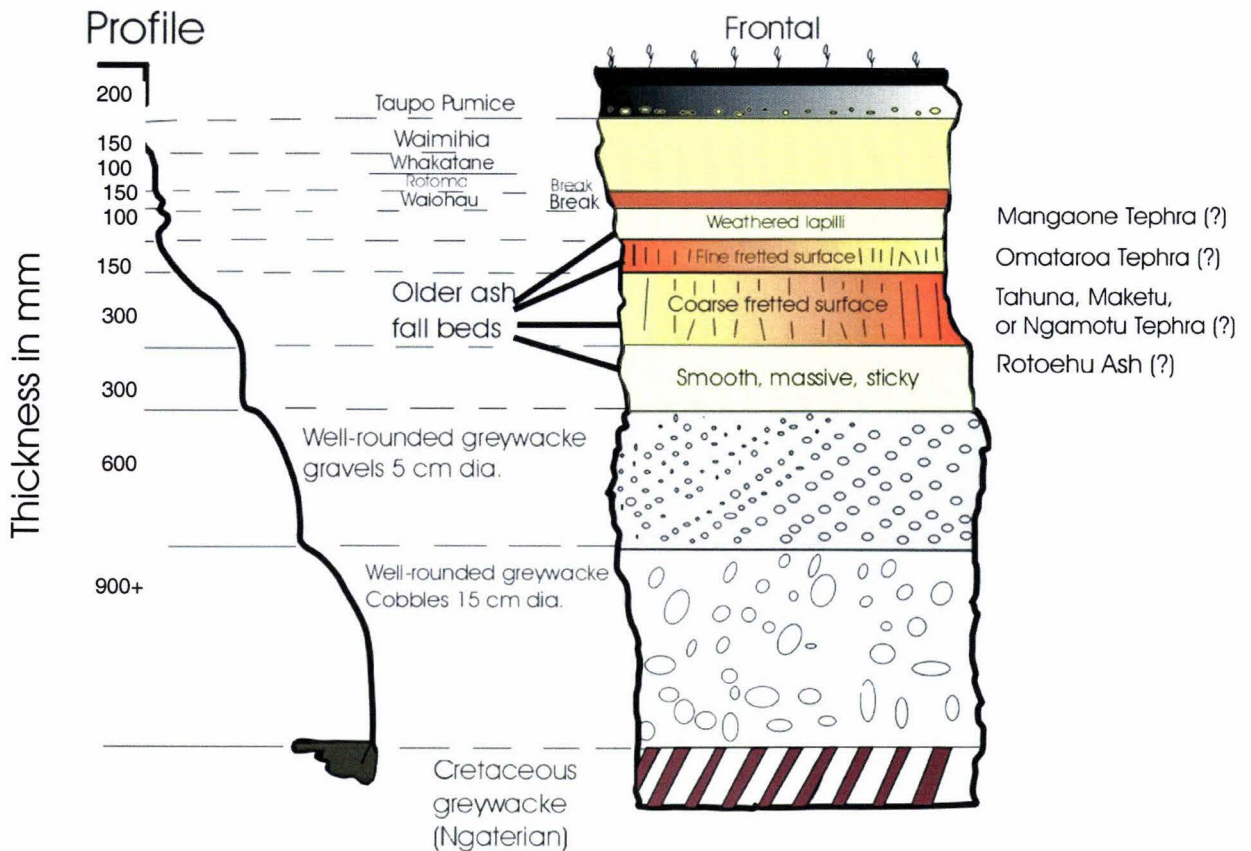


Figure 1.6.1 Coveredbed Sequence at Matawai, Gisborne (adapted from Vucetich & Pullar, 1964 and 1973; Vucetich & Howorth, 1976).

Extensive terraces have formed along the reaches of the Waipaoa River. These terraces are believed to represent a major shift in the river hydrology in response to climatic changes towards the ends of the Quaternary glaciations (Berryman *et al.*, 2000) (*see* section 1.3.5). The coverbeds mantling these terraces contain various airfall deposits from the afore mentioned volcanic centres. Eden *et al.* (2001) believe that the Waipaoa Valley terraces and tephra may provide New Zealand's best terrestrial glaciation - Holocene transition chronology because of the presence of the datable tephra.

Berryman *et al.* (2000) carried out research on four extensive terraces (longer than 25 km) in the Waipaoa Valley (*see* section 1.3.3). The terrace treads have had minimum ages implied by the overlying dated tephric coverbeds providing stratigraphic markers or time control. Time control provided by tephra identification was primarily used to determine the downcutting, uplift, and sedimentation rates of the Waipaoa Valley. The sequence of coverbeds and aggradation gravels have been interpreted to represent a downcutting period in response to climate change occurring towards the end of the last glacial period.

The tephra layers occurring within the main terrace mantle were identified using their mineralogy, glass major element composition, and stratigraphic position (Eden *et al.*, 2001). The Rerewhakaaitu Tephra (17 700 cal. Yr B.P, Lowe *et al.*, 1999) was found to be the lower most tephra in the sequence, so aggradation of the terrace must have ceased around 18 000-19 000 cal. Yr B.P. 100 km offshore Hawke Bay aeolian quartz deposition on the seabed reduced markedly around this same time (Stewart & Neall, 1984).

1.7 MARINE SEDIMENTATION

The highly erodible nature of the soft mudstone terrain (Trotter, 1988) and active tectonism (Lewis, 1980) results in a mud dominated sediment discharge into Poverty Bay (Foster & Carter, 1997) (Figure 1.7.1). These two factors accompanied by deforestation (*see* section 1.1) over the last century and meteorological extremes (Sinclair, 1993) have led to the mud supply for the last century being five times higher than that previously in the late Holocene (Foster & Carter, 1997). Foster and Carter (1997) postulate that sediment discharged from the Waipaoa River is trapped in a midshelf depocentre, which is enclosed to the northeast and southwest by the Monowai Rocks and Mahia Peninsula, respectively, with the Ariel and Lachlan Anticlines providing partial closure to the east. This source to sink scenario is the one of the founding reasons for this research (*see* sections 1.1 & 2.1.1).

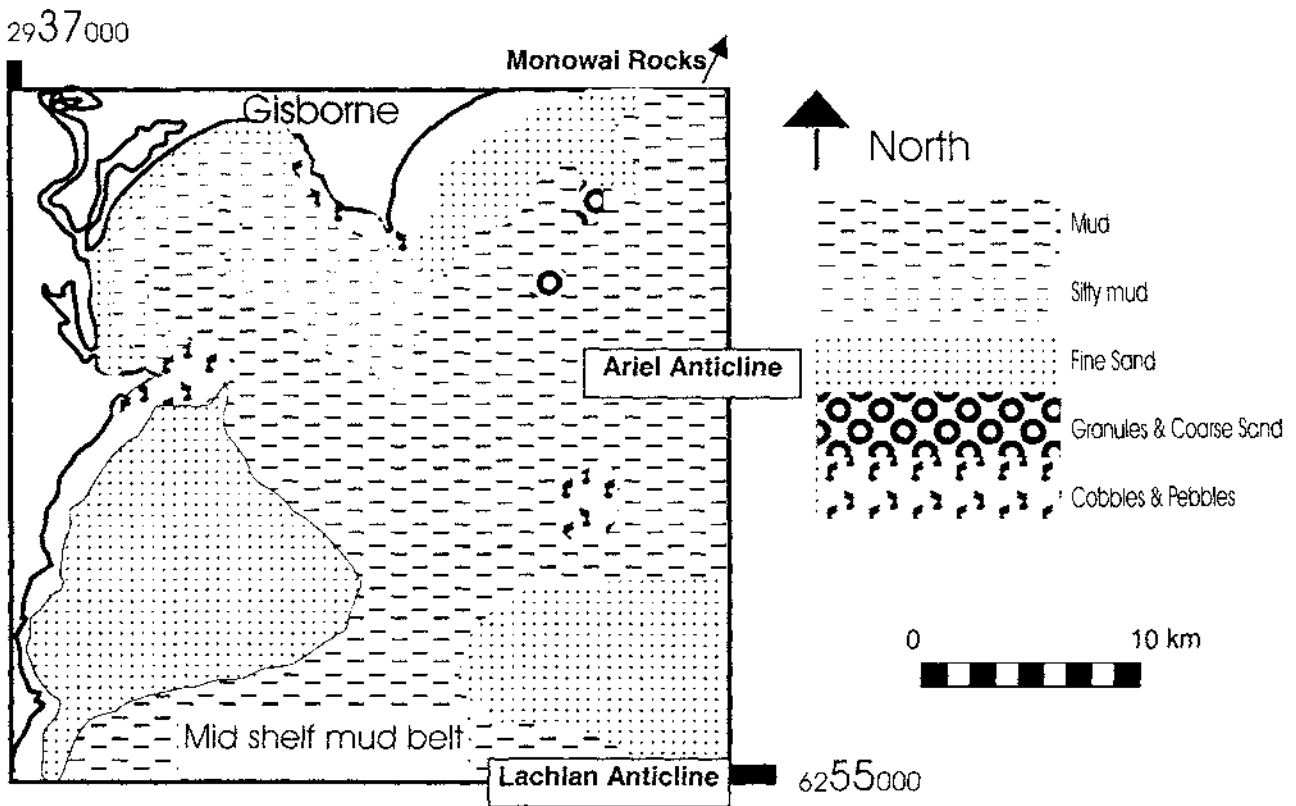


Figure 1.7.1 Distribution of sediments mantling Poverty Bay and adjacent continental shelf (modified from Foster and Carter, 1997).

The mean grain size of the sediment mantling the Poverty Bay seafloor progressively fines offshore (Figure 1.7.1). Coarse sand along the beaches and in the river mouths becomes fine and silty in the central bay and eventually mud farther out (Miller, 1981). Outside Poverty Bay the sands that occupy the inner shelf are replaced gradually at 30-40 metres water depth by mud, which extends to the shelf margin (Carter, 1975).

During normal flow sediment contained in a 'hypopycnal (buoyant) plume' disperses as the surface currents circulate along the shelf, responding to the prevalent winds; but gravity and shelf currents disperse sediment during periods of increased fluvial suspended sediment discharge i.e. flooding, as the middle shelf is inundated with mud (Foster & Carter, 1997). This sediment discharge is termed 'hyperpycnal' or 'negatively buoyant'. During storms, cohesive mud particles form a highly concentrated suspension or 'fluid mud' which can be mobile, moving across the seabed (McCave, 1984; Dyer, 1994). This mud layer may increase in volume/mass, until gravity will halt mobility allowing deposition to occur (Foster & Carter, 1997).

1.8 CLIMATE

Rainfall patterns are primarily topographically controlled. The mean annual rainfall ranges from 1000 mm at the Gisborne coast to 3000 mm in the elevated Raukumara Ranges (Smith, 1977). Despite a winter maximum and summer minimum, rainfall is generally well distributed throughout the seasons (Hessel, 1980). Wind averages <11 km/h and gale forces (>63 km/yr) are recorded only 48 days of the year on average (Hessel, 1980). The area is subject to high rainfall events or tropical storms i.e. Cyclone Bola.

	Mangatu Forest				Waerenga O Kuri				Gisborne Airport			
	Min RF (mm)	Max RF (mm)	Ave RF (mm)	Ave Temp (°C)	Min RF (mm)	Max RF (mm)	Ave RF (mm)	Ave Temp (°C)	Min RF (mm)	Max RF (mm)	Ave RF (mm)	Ave Temp (°C)
Jan	26	155	49	18.5	17	267	95	16.8	4	233	72	18.7
Feb	16	220	93	18.2	8	281	89	17.1	3	242	69	18.8
Mar	6	267	115	16.8	18	297	117	15.5	12	376	91	17.1
Apr	44	241	104	14.1	11	290	115	13.3	8	283	98	14.7
May	24	237	108	11.0	29	289	125	10.7	18	343	103	12.0
Jun	31	240	129	8.7	29	440	152	8.5	26	328	116	9.7
Jul	72	246	130	8.2	27	313	136	7.8	19	321	115	9.1
Aug	50	379	151	9.2	41	470	166	8.5	38	294	116	9.9
Sep	57	306	129	11.0	9	414	113	10.1	8	207	83	11.6
Oct	33	175	91	12.7	22	350	101	12.1	20	238	70	13.5
Nov	21	108	70	14.9	23	406	96	13.7	3	224	57	15.5
Dec	25	473	131	16.9	16	316	109	15.4	8	204	68	17.4

Table 1.8.1 Minimum, maximum and mean rainfall, and mean temperature data for three weather stations Mangatu Forest (1967 – 1980), Waerenga O Kuri (1948 – 1980), Gisborne Airport (1937 – 1980), within the Waipaoa Catchment. Data between was collaborated from the NZMS misc publication 177.

1.8.1 Southern Oscillation Index (SOI)

El Niño – Southern Oscillations (ENSO) have been suggested as responsible for pre - European climate fluctuations (Eden & Page, 1998). Southern Oscillations are discernible on the New Zealand East Coast, by variations in precipitation (Gordon, 1986); during SOI negative (El Niño) years, rainfall is lower than average, as compared to La Niña (SOI positive) years when rainfall is higher than average. When the SOI is positive, temperatures will be higher, and tropical storms are more likely to occur towards New Zealand. Eden and Page (1998) linked increased storms and rainfall at Lake Tutira (*see* section 1.4) in pre – European times to positive SOIs; and Allan (1993) suggested that over the 20th century El Niño – Southern Oscillations were active, being weaker in Australia between 1921 – 41 and stronger between 1963 – 83.

1.8.2 Cyclone Bola

Cyclone Bola is recorded as the largest storm to have hit the region since 1894 (Mike Page, *pers. com.* 2001). Up to 900 mm rain fell in 72 hours, the Kakanania gauging station measured river discharge at 5287 m³/s and the river level rose 11 metres (*see* Juene & Masters, 1985 – additional note). The Waipaoa River overtopped its banks in several places (*refer* section 1.4) (Plate 1.8.1), and extensive damage was done to transportation infrastructure, communication networks, and services. Cyclone Bola is considered to have been a channel-forming event, which redistributed sediment held in storage, down through the catchment (Eden & Trustrum, 1994). Over the past 13 years the affect Cyclone Bola had on the riverbed, annual sediment production (Table 1.8.2), gully complexes, area of landsliding, pastoral grazing, exotic crops e.g. *Pinus radiata*, have all been investigated, and is ongoing.

Month	Min	Max	Ave	Med	Month	Min	Max	Ave	Med
Jan	10	536,420	49,333	12,980	July	46,980	6,537,040	1,122,803	416,735
Feb	0	1,729,230	104,512	7,810	Aug	27,280	4,137,150	1,141,309	492,440
Mar	0	43,012,880	2,439,589	101,030	Sep	11,180	8,601,480	1,668,222	619,200
Apr	170	5,900,340	534,792	77,450	Oct	730	3,087,060	382,347	160,780
May	2,960	1,426,740	326,807	133,700	Nov	90	1,099,290	165,134	28,810
June	40,730	5,385,720	1,076,972	470,540	Dec	30	6,685,360	413,038	53,420

Table 1.8.2 Monthly statistics of suspended sediment yields (tonnes) for the Waipaoa River at Kakanania, from 1972 – 1991 (Jeune & Masters, 1985, *plus additional information from* S. Jeune, GDC). Note the maximum value is that of March, which was obtained during Cyclone Bola in 1988.

Suspended sediment of the Waipaoa River was estimated at 32×10^6 t, which is twice the estimated annual yield (*see* section 1.1; Hicks *et al.*, 2000), landsliding alone contributed 64 % (20.5×10^6 t) of the suspended sediment load (Page *et al.*, 1999). Generally, the tail of landslides is deposited downslope (~ 50 % of sediment) (Page *et al.*, 1999) and not accessible to the stream channel system (*see* section 1.10), however, during Cyclone Bola the rainfall was possibly high enough to mobilise this debris and incorporate the sediment into the stream system. This was probably true for many of the temporary sediment storage areas throughout the catchment, the high volume of rain meant that these areas were literally flushed, emptying into the river system. Phillips *et al.* (1989) estimated that landslide densities increased by 47% during Cyclone Bola; and Trotter *et al.* (1989) calculated that on individual farms bare ground following Bola ranged from 1 – 21 %.



Plate 1.8.1 Waipaoa River floodplain - sedimentation following Cyclone Bola 1988 (photo: N. Trustrum, 1988).

Hicks (1992) postulated that the planting of pines in the Waihora subcatchment had reduced mass movements during Cyclone Bola by 22 %; this could have been increased to 74 % if all unstable hill slopes in the catchment had been planted and adequately maintained. Increased planting after Cyclone Bola has seen a downcutting of the Waipaoa River, and gully erosion is reducing as scrub is regenerating (Page *et al.*, 2000).

1.9 HYDROLOGY

The gauging site at Kanakanaia (Figure 3.3.1) has shown that the majority of water passing during low flow comes from the Mangatu and upper Waipaoa tributaries, which also carry the highest quantity of suspended sediment, therefore, the lowest quality of water. The majority of flooding occurring within the Gisborne district since 1853 is due to the Waipaoa River. There were 28 extreme flood events ($>1500 \text{ m}^3/\text{s}$) at Kanakanaia last century (Eden & Trustrum, 1994). Of these 28 extreme flood events, Gomez *et al.* (1988) identified 11 sediment units preserved within the McPhail's Bend core, which they attributed to major floods and correlated them with the Gisborne Region's recorded flood history (Table 1.9.1) (*see* sections 1.4, 2.1.2, 3.4.1).

Droughts (average monthly rainfall equal or less than 25 mm) of two consecutive months can be expected to occur once in 2.2 years on the Poverty Bay flats, and 4.1 years in the central basin, but they can last up to six months (Smith, 1977).

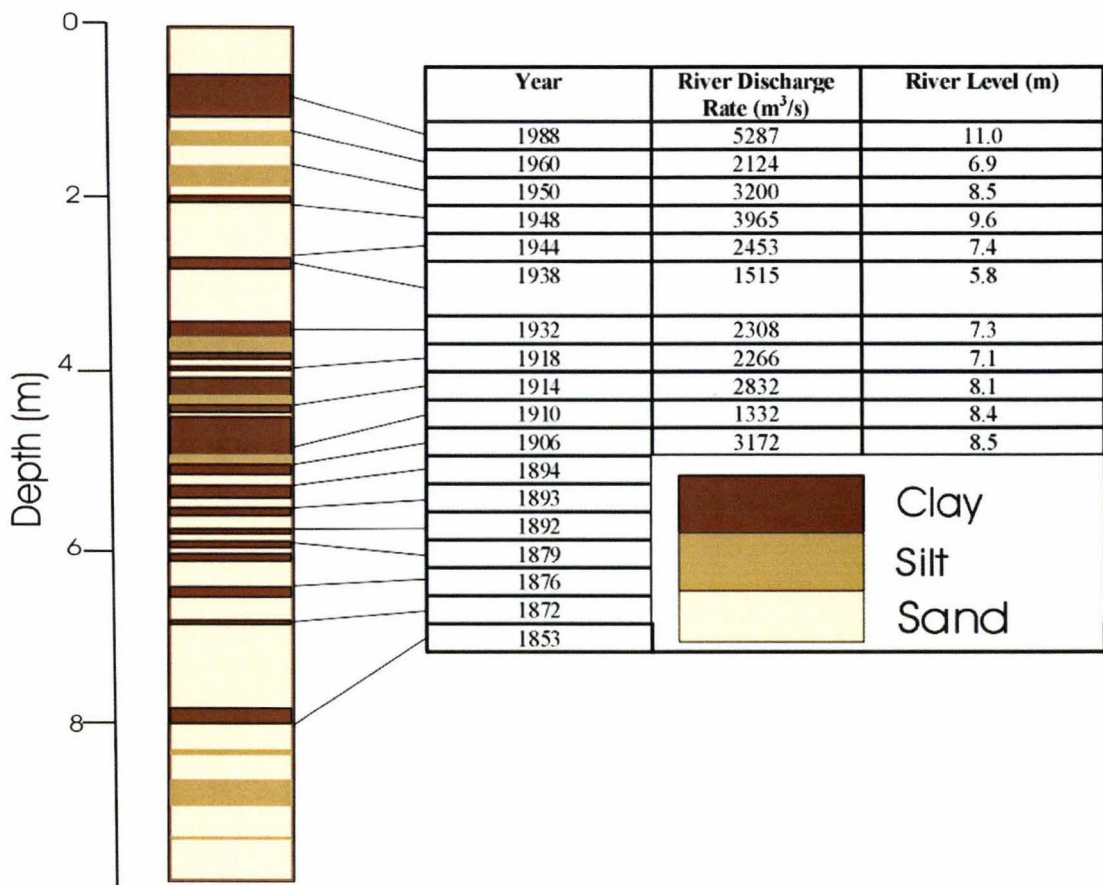


Table 1.9.1 Stratigraphy of flood units within McPhail's Bend core. NB. The stratigraphy of McPhail's Bend core has been correlated with river discharge information collected at the Kanakanaia gauging station (Data sources: *see* Juene & Masters additional note; Gomez *et al.*, 1988).

1.10 EROSION PROCESSES

In the Waipaoa Catchment many forms of erosion occur: landslides, gullies, slumps, sheet erosion, earth flows, debris flows, and stream bank erosion. The relative contribution long term by each of these processes varies; gully erosion contributes more than 50 % of the annual sediment yield of the Waipaoa River, landslides *c.* 15 %, sheet erosion *c.* 10 %, stream bank erosion *c.* 10 %, and the rest is a combination of tunnel gullying, erosion of forestry roads, and earthflow, etc (Page *et al.*, 2000; Mike Page *pers. com.*, 2001).

1.10.1 Landslide Erosion

Landslides are downward displacements of soil, regolith and rock (Figure 1.10.1). Movement occurs along the plane surface from which slope failure occurs depending on the type of material, water content and speed of movement. Shallow landslides (planar failures) move only the uppermost surface of weathered rock and the overlying soil profile; Eyles (1985) defines shallow as less than one metre deep. Landslides in a broader sense encompass a group of erosion processes under a 'landslide umbrella'. This involves, rock and debris falls and slides, soil slides, and rotational slumping. This thesis though, will refer to landslides as defined earlier.

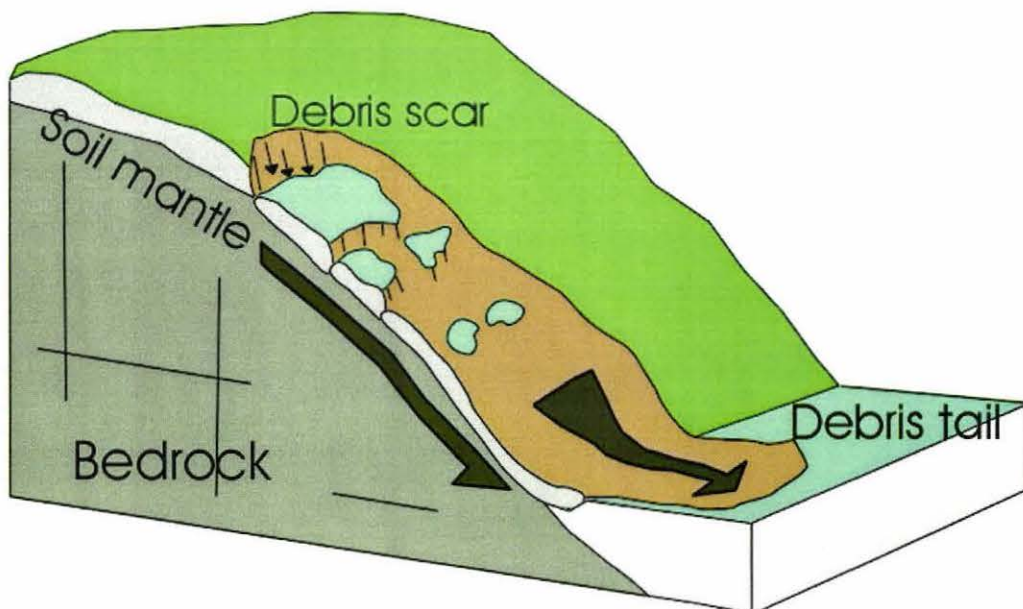


Figure 1.10.1 Landslide morphology is shown as the soil mantle slides over the bedrock creating a scar in its place and a debris tail towards its base. A deeper slide will remove the weathered regolith as well as the soil mantle down slope.

Landslides are generally a product of a combination of geologic, topographic, and climatic factors, yet seldom can a landslide be attributed to any one definite factor (Varnes, 1978). Zolotarev (1974) showed the process behind the development of a landslide begins foremost with the lithologic formation. The physical properties of the bedrock acting with subsequent events e.g. crustal movement, erosion and weathering, require an action or an outside factor that triggers the movement of material downhill. Conversely, if these conditions or factors are not met e.g. rainfall threshold not reached, slope angle too shallow, then even on the most landslide susceptible terrain, erosion may not occur (Rib & Liang, 1978).

Alternating layers of permeable and impermeable rocks on a slope are conducive to sliding, as are thick isotropic mudstones. Permeable layers will slide over the impermeable layers of rock on a film of water unable to penetrate further; while massive mudstones may have a loose crumbly overlay which will wet up in the moist winter months and fail, creating the slide. Any sedimentary rock may fail by sliding in areas that have been tectonically steeply tilted. This movement may take any number of forms e.g. rock slides, topples, block slides etc., depending on the dip angle, joint system, and climate (Rib & Liang, 1978).

1.10.2 Gully Erosion

Gully erosion involves channels scoured into steep slopes by runoff from the surrounding landscape. These channels continue to enlarge through small frequent rainfalls (Page *et al.*, 1999) by a process called 'headward erosion' (Coch, 1995) creating the gully formation. Oostwoud Wijdenes and Bryan (2001) suggested that gully head retreat occurs by several processes: the rim and vertical walls of the gully head experience hydraulic shear by overland flow; the splash impact from any plunge pool at the front of a headcut and the vortex erosion in the pool; and tension and desiccation cracks, seepage erosion and tunnelling leads to mass wasting of the walls. Gully head rate of retreat can behave as sensitive environmental change indicators (Oostwoud Wijdenes & Bryan, 2001), as these formations are greatly increased as during major storms the gully erosion process intensifies, creating an increased area of bareground.

Although they account for a combination of water erosion (runoff) and mass wasting for gully head retreat, Oostwoud Wijdenes and Bryan (2001) go on to say that the actual sediment

production occurs from the headwall, collapsing side walls and from storage deposits, and is dependant moreso on runoff and than retreat.



Plate 1.10.1 The ridge saddle at the head of the Tarndale Gully complex. This road separates the Mangatu (left) and Tarndale (right) gullies, continuous collapsing has meant that the road is now closed to most traffic (photo: *M. A. D'Ath*, 2000).

There is an intimate relationship between the extent and the type of erosion that occurs on the underlying lithology/bedrock. With decreasing strength of the bedrock, there is an increasing occurrence of particularly deep-seated gully complex failures.

Gully erosion is widespread in New Zealand's North Island; Eyles (1985) calculated these erosive processes affect 10% of the land area, which can be associated (generally) with crushed Cretaceous argillite rocks underling the landscape.

1.10.3 Other Processes

Covering from a few square metres to several hectares, earthflows move water saturated soil, regolith and/or weak shale down slope. This can occur under both pasture and forest (Strahler & Strahler, 1989). Sheet erosion occurs when overland flow removes thin layers of soil from areas recently deforested. Sheet is one of the predominant erosion forms to occur on farmland

and is responsible for the removal of topsoil or the soil mantle. Slumps, unlike both earthflow and sheet erosion, come under the landslide umbrella (*see* section 1.10.1) involving a rotational movement where material moves down shear planes that are concave upwards (Selby, 1985); slumping is evident in areas which are both vegetated and deforested. Bedrock, regolith or soil that is progressively removed from the sides or floor of a channel is referred to as stream bank erosion. Pullar and Penhale (1970) postulated that during the floods of the 19th century, most of the sediment being transported down the Waipaoa River was due to stream bank erosion, but that this changed following intensive deforestation (*see* section 1.1).

Rib and Liang (1978) defined three major factors: geological, environmental, and human, to be considered when evaluating a particular terrain and the erosive processes occurring therein (Table 1.10.1). The New Zealand Land Resource Inventory (NZLRI) and Land Use Capabilities (LUC) (*see* section 1.11.1) classification systems also combine some of these factors to differentiate between landforms.

Factor	Element	Examples
Geologic	Landform	Geomorphic history; stage of development
	Composition	Lithology; stratigraphy; weathering products
	Tectonics	Uplift; tilting; folding; faulting
	Structure	Spacing and attitude of faults, joints, foliation, and bedding surfaces
Environmental	Climate and Hydrology	Rainfall; stream, current, and wave actions; groundwater flow; slope exposure; wetting and drying; frost action; stream power and discharge, suspended sediment yield
	Catastrophes	Earthquakes; volcanic eruptions; hurricanes; flooding; subsidence
Human	Human Activity	Construction; quarrying; deforestation; vibrations; stripping of surface cover

Table 1.10.1 Factors to be considered when evaluating a terrain (adapted from Rib and Liang, 1978).

Geomorphic processes modify the physical and chemical composition and structure of the bedrock; most important are processes involving water, mass wasting, and erosion (Rib and Liang, 1978). Environmental factors are important; variation in microclimate e.g. altitude, exposure to moisture bearing winds, and exposure to sunlight, can cause significant differences in geomorphic processes, and these processes together can accelerate the rate at which erosion occurs, as can human activity.

1.10.4 Extent of erosion in the Waipaoa Catchment

Of the 16 land systems devised by Landcare Research (*see* section 1.11.1) six are rated as susceptible to severe shallow landslide erosion (Figure 1.10.1). These six land systems cover approximately 148 480 ha (67 %) of the Waipaoa Catchment, of which 83 % (123 365 ha of landslide prone catchment) was in pasture in 1988 when Cyclone Bola hit (*see* section 1.8). Page *et al.* (1999) estimated landslide density by combining geographic information system (GIS) data of landslide terrain, vegetation, and storm rainfall, with information calculated from the relationship between storm rainfall and landslide frequency, as defined for different landslide prone areas. Total sediment generation and delivery to streams was calculated by combining field measurements of landslide dimensions with air – photo – based estimations of sediment delivery; a comparison was then made between the calculated sediment input for upstream locations with the estimation of total sediment load. From this, Page *et al.* (1999) determined that 48 % of the suspended sediment measured at the Kanakanaia gauging station (Figure 3.3.1) (*refer* section 3.3.5) was contributed through landslides during Bola, while at the Waipaoa River mouth 64 % of the suspended sediment came from landslides. This increase in sediment load at the Waipaoa River mouth, infers major contribution of landslide - derived material downstream; the Te Arai Land System (*see* section 1.11.1, 2.1.1) could be considered to be this predominant landslide influence.

The Tertiary silts and muds (*see* section 1.3) are prone to shallow landsliding, often initiated by positive pore pressures. Sediment that is removed from the hillslopes makes its way to the stream channels and is virtually all transported in suspension (DeRose *et al.*, 1998). But only a proportion of sediment generated during these storms and landslides is contributed to the stream systems immediately. Much of the mobilised sediment is redeposited as a debris tail downslope of the scar (Figure 1.10.1). The sediment delivery ratio (that which is contributed to the stream system) is dependent on a series of factors: location of slip relative to stream network, scar area and size, and the nature of topography over which the debris must travel (Page *et al.*, 1999).

Reid and Page (2000) identified periodic sediment influxes into the Te Arai Catchment, believed to represent high magnitude rainstorms or those exceeding 200 mm (Page *et al.*, 1999). Although these storms are infrequent they have a substantial effect on the catchment. Not only are the storm derived sediments evident within cores as measurable fluxes, but the landslide

scars/tails appear to continue sediment generation over the following one to two years before stabilising and revegetating (Hicks *et al.*, 2000).

Despite the high contribution of sediment during storms from these shallow landslides, the same process produces little sediment in the long-term suspended sediment yield. Page *et al.* (1999) postulated that during normal flow, landslides contribute between 10-16 % of the suspended sediment (*see* section 1.10 introduction) of the Waipaoa River (*see* section 1.8.2), so is of lower relative importance as compared to gully erosion, over the long-term period. It is the on-site effects of this erosion on pasture production that is of high concern. As mentioned earlier only 50 % of sediment generated from landslides is contributed into the stream system, the main problem then is the area of bare - ground left from the slide, the scar, and the debris tail. Production on the remaining scar will take 20-40 years to recover to 60-80 % of original productivity (Blaschke *et al.*, 2000). Thus, landslides are a major concern for the farming community and regional councils.

On the Raukumara Range the headwaters of the Waipaoa River catchment exhibit some of the extreme examples of gully erosion in the North Island (Plate 1.10.1). The Mangatu and Tarndale Gully complexes (each *c.* 0.2 km² of the Waipaoa Catchment) are two of at least eight extreme gully complexes formed within the Late Cretaceous/Early Tertiary rocks of the Waipaoa Catchment (*see* section 1.3). The Tarndale Gully complex began to form in the winter of 1915 (Allsop, 1973) due to increased runoff as the headwaters were being converted to pasture, and now covers an area of 0.2 km² (DeRose *et al.*, 1998); since afforestation began in 1960 (*see* section 1.1), stabilisation appears to be occurring.

Although gullies cover a relatively small area of the Waipaoa Catchment (in comparison with landslides), their contribution of suspended sediment to the system is considerable. Unlike landslides these gullies generate sediment during small frequent rainfalls (section 1.10.1), so a continuous supply of fine sediment is being released in small quantities into the stream systems at all times (Page *et al.*, 1999). Over the long-term period this makes gully erosion a major contributor of sediment into the catchment and therefore of high relative importance.

1.11 FLOODPLAIN LAND USE IMPACTS

Landcare Research chose the Waipaoa River catchment as an environment that best presented some of the problems land use had on steep lands and the associated floodplains. The Waipaoa River catchment has been subjected to intense deforestation, grazing, erosion, flooding, and sedimentation. More recently, in light of these problems, the impact land use has had on the region has come under considerable review; this project was set up to investigate floodplain management, and river control problems associated with the erosion and sedimentation. One of the main aims of the land management research was to link erosion processes and erosion rates to the influences of land use change, to develop a sediment budget (Eden & Trustrum, 1994).

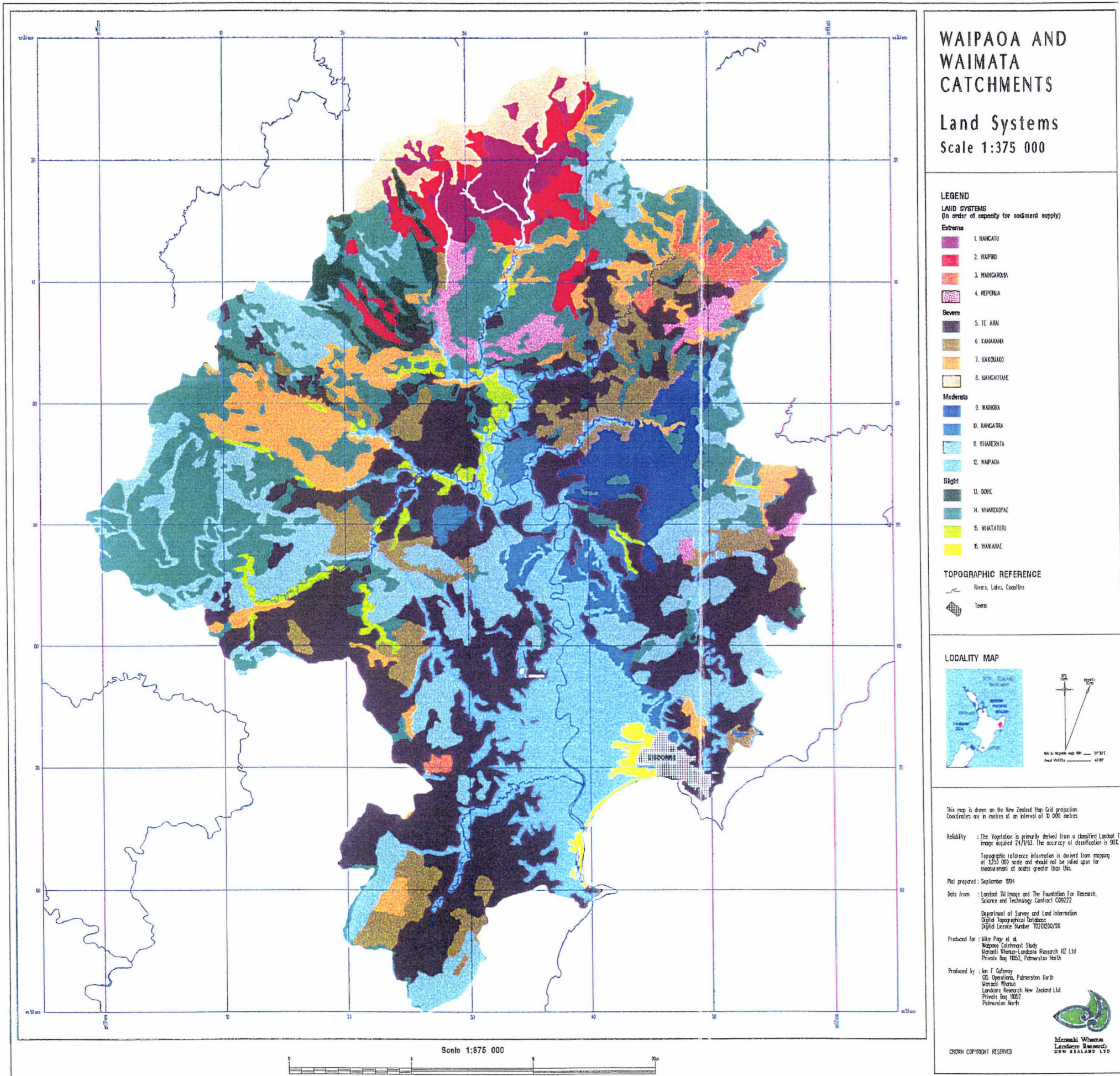
A focal point of this study was floodplain accretion and streambed aggradation. Aggradation of a streambed decreases the capacity of flood control schemes and undermines the engineering of structures e.g. bridges. Compromised stopbanks in turn lead to floodplain accretion, sedimentation, and put settlements and stock at risk. Ultimately water quality is reduced and biological activity in both the river and marine environments diminishes. Cyclone Bola (*see* section 1.8.2) provided much data, which have for most parts been the starting point for this research.

1.11.1 *Land Systems*

To assist in catchment analysis and sediment budgeting, Landcare Research divided the Waipaoa Catchment into 16 land systems (Figure 1.11.1), their spatial distributions being derived from the NZLRI (Page *et al.*, 1999). Land use capability units based on rock type were grouped together to devise separate land systems, each named from typical local areas, each exhibiting a particular fusion of environmental factors e.g. drainage density, rock type, landforms, channel morphology, erosion processes and sediment supplying capacity (Harmsworth *et al.*, 1994; Eden & Trustrum, 1994).

These 16 land systems are ranked on the basis of sediment supplying capacity into four divisions:

- 1-4 Extreme erosion
- 5-8 Severe erosion
- 9-12 Moderate erosion
- 13-16 Slight erosion



Within each land system it is recognised that one erosion process may dominate over others. This thesis compares four land systems undergoing different erosion processes (*see* section 2.1). The Mangatu and the Waingaromia land systems demonstrate severe gully erosion, while the Te Arai and Mako Mako land systems (Figure 1.11.1) are undergoing severe land sliding. Descriptions of these four land systems are available in section 2.1.4.

1.11.2 Work Prior to this Thesis

Page *et al.* (1999) studied sediment production during Cyclone Bola and assessed what contribution landslides made to the suspended sediment load of the Waipaoa River (*see* section 1.10.4). Hicks *et al.* (1996) found that the main factors that contributed to spatial variation in the annual average suspended sediment yields were rainfall and basin geology: lithology, tectonics, and Quaternary history. Sediment delivery ratios, and temporary sediment storage and input were calculated by Marutani *et al.* (1999), and Hicks *et al.* (2000) worked on sediment yield and discharge event – yield magnitude – frequency, and their relative importance during large flows. Gomez *et al.* (1988) studied rapid vertical accretion at McPhail’s Bend, and the construction of the floodplain, noting that increased suspended sediment promoted inchannel deposition. DeRose *et al.* (1998) estimated the amount of sediment produced by gullies during two periods (1939 – 1958, 1958 – 1992) using digital elevation models (DEMs). Betts and DeRose (1999) took this method one step further and discussed gully degradation and future applications of DEMs toward land use. Kasai *et al.* (2001) calculated that between 1988 – 1996 sediment yield from gullies had decreased 77 %, sediment scouring in channels had increased by 124 %, and sediment delivered from catchments had decreased by 78 %, possibly due to increased forestry. The focus of the afore mentioned project has moved sideways into the area of tracing soil carbon from source (hillslope) to sink (floodplain).

1.12 CLAY MINERALS

Clay minerals occur abundantly only in the outer layers of the earth in soils, sediments, sedimentary rocks, hydrothermal alteration zones, etc. As soils weather in a given environment, parent material minerals will weather to clays, which in turn will weather to other clays, and so on.

Clay minerals are defined as the fraction of sediment $<2\mu\text{m}$ and occur in many different forms, shapes and sizes; as domains, aggregates, pore linings or infillings, coatings around stable grains, bridges between grains, and they have various patterns of preferred orientation. Clay minerals are either 1° (primary), occurring through the physical breakdown of rock (e.g. mica, chlorite), or 2° (secondary), formed *in situ* through precipitation from solution (authigenic) or by the alteration of pre-existing minerals (e.g. mica \rightarrow vermiculite \rightarrow beidellite) (Eslinger & Pevear, 1988). Primary clay minerals in the modern environment reflect the sediment source or provenance and distribution system, and as such are termed detrital (Eslinger & Pevear, 1988).

Clay minerals are constituents of mudstones, claystones and shales and are primarily detrital in origin; clays settle in a quiescent environment and over time form a massive fine - grained impermeable rock. Clays in sandstones, however, are mostly secondary or authigenic, and have formed due to subaerial weathering and hydrolysis.

The common clay groups identified in sedimentary deposits are: micas, vermiculites, kaolins, smectites, and chlorites. Mica clays are primary minerals that form in environments which have high potassium concentrations such as Recent Soils; they also occur as detrital assemblages in sedimentary rocks. Micas weather readily forming vermiculites and smectites, and are generally found in immature sediments. Vermiculite forms through the degradation of mica in strong leaching environments, or from chlorite when magnesium is high and $\text{pH} < 7$. Smectites in comparison are 2° minerals, forming in environments with a high magnesium content and often poor drainage. They often develop from tephra within the makeup of mudrocks and on floodplains, as the main end product of terrestrial weathering (Pearson, 1990). Pearson (1990) identified laterally persistent bentonite beds in sedimentary sequences; it was suggested that this was due to *in situ* alteration in seawater of volcanic ash horizons. Kaolinite is a secondary mineral; its presence indicates that the primary minerals have already weathered. Kaolinite is one of the larger clay minerals, readily distributed in silts as well as clays, and will often settle out first in suspended sediment environments due to its size. Chlorite clay can be present in primary or secondary form, occurring as detrital minerals with mica in Recent Soils and sedimentary rocks that have undergone little weathering, or as secondary minerals in interstratified minerals with vermiculite and smectite. Interstratified minerals are products of partial transformation of 1° and 2° minerals.

1.12.1 *Clay Minerals and Erosion*

Mazengarb and Speden (2000) list clay minerals as one of the major rock properties which influence erosion susceptibility, along with grain size, cementation, induration, fracturing, crushing, orientation of bedding surfaces, and weathering. One of the ways that this happens, Matsukura and Mizuno (1986) postulated, is that clay alteration by weathering reduces the residual angle of shearing resistance, Φ , which determines the slope angle. Slope angle is a main controlling factor in landslide erosion. Pearce *et al.*, (1981) also refer to the weathering of clay minerals as a factor in the determination of not only slope form, but the actual erosion process.

Clay minerals generally associated with erosion are the smectites or montmorillonites. Minerals in the smectite family swell when subjected to water and shrink when dried out. This process weakens the structure of the soil, regolith, or bedrock making it susceptible to erosion. Storm conditions with heavy rainfall will create positive pore pressures that will dislodge soil and weathered regolith initiating slides, flows, and slumps. In bedrock expanded (wet) smectite will become greasy, thus allowing permeable layers of bedrock to literally slide over impermeable rock below, hence creating a landslide (*see* section 1.10.1).

In the river system water velocity governs particle size, after the initial erosion process of physical, chemical, and biological weathering (Irion, 1991). Coarser material generally transported in the bedload can be moved in suspension during high flow, and be incorporated into the finer material, which consists predominantly of clay and silt.

Irion (1991) relates river erosion rates to four factors, when not considering human influence:

1. Age and morphology of the surface material
2. Composition or mineral makeup of the bedrock
3. Tectonics e.g. uplift
4. Regional climate and natural vegetation cover.

A combination of these four factors are operational in the Waipaoa Catchment. Tectonics and uplift have created steeply inclined surfaces and areas of intense shearing (section 1.3), which are prone to erosion. The bedrock is primarily marine in origin, mudrocks and sandstones, some with large quantities of swelling clays (*see* section 3.1). The area is prone to high rainfall and there is little natural vegetation, instead it is now primarily exotic forestry. The human

influences (*see* section 1.1) of deforestation, forestry, engineering forestry roads etc, have created conditions for a prime erosive system.

1.12.2 Clay Minerals and Alluvial Sedimentation

Erosion and transport will mask mineralogical signals, mixing sediments from various sources prior to deposition. Initially sediments deposited on floodplains will be detrital in origin, but over time chemical weathering may alter the clay mineral assemblage. This may be recognisable by tracing mica and vermiculite quantities down the length of a core; mica will transform into vermiculite over time.

Particle size determines what transport mechanism minerals are moved by (e.g. fluvial), and the way in which they are deposited. While bedload is generally restricted by size, being deposited closer to source, suspended sediment (fine fraction) can be carried right through a river system and into the marine environment; deposition may take place in a bay or further offshore in the shelf environment.

Not all rivers carry large suspended sediment loads, the clay types found in the drainage areas will control some of the erosion and therefore the sediment load. Irion (1991) noted how rivers draining kaolinite – rich weathering horizons have low suspended sediment loads as compared to those with smectite – rich regoliths, which erode more readily. Two very contrasting examples of this are the River Nile and the Niger. Before the Aswan Dam was built, the Nile carried 3700 mg/l of suspended sediment of which >80 % was smectite (Irion, 1991), in comparison the Niger has an average sediment load of 78 mg/l and is rich in kaolinite (Martins, 1982).

1.12.3 Clay Minerals and Marine Sedimentation

Figure 1.7.1 demonstrates the way in which sediment is distributed in Poverty Bay, off Gisborne. Recent marine sediments, according to Cole and Shaw (1983), are largely detrital clay mineral assemblages derived from the adjacent continents, in turn reflecting the nature of soil-clay minerals formed by weathering.

Mica dominates the fine sediment clay fraction in modern oceans, averaging about 50 % in Atlantic sediments and slightly less in the Pacific. Smectite is in great abundance in the Pacific as compared to the Atlantic (Eslinger and Pevear, 1988), although it is not fully understood why.

Differential settling is considered to be the major cause of smectite enrichment with distance from the coast e.g. Niger Delta (Porrenga, 1966), although much evidence is coming to light of authigenesis of smectite in deep marine environments (Cole & Shaw, 1983; Singer, 1984). Thiry (2000) postulated that despite this near shore pattern of settling, in the deeper areas of both the Pacific and Atlantic Oceans the abundance of smectite is generally thought to be due to authigenesis within the basin occurring during early diagenesis (under low sedimentation rates) at the water/sediment interface. The sediments circulating in modern oceans generally reflect much older terrestrial landforms or Pleistocene sediments. Variations in the clay mineral assemblages are often due to change within the sedimentary environment or tectonic activity, despite the known effects of burial diagenesis (Pearson, 1990).

Marine clays in ancient deposits have been used to reconstruct paleoclimates in recent studies based on the observation that the distribution of clay minerals in modern oceans appears to be climatically controlled in the contemporary environment (Thiry, 2000). The Waipaoa River – Poverty Bay is considered to be a closed system (sediment moves down river and is deposited in the bay only), therefore cores taken from the marine environment should contain clay minerals within sediment fluxes from the terrestrial environment, and these clays/sediments could be used in paleoclimate interpretation and provenance studies.

CHAPTER 2: METHODOLOGY

This chapter is divided into two main sections. The first section 2.1 outlines the hypotheses and objectives, and the sampling strategy employed for the fieldwork. Four land systems are defined and described as the areas sampled, and four suites of samples are described. Section 2.2 works step by step, through the x-ray diffraction (XRD) analysis procedure: sample preparation, particle size separation, saturation with cations, slide preparation, and calculations (Figure 2.2.1). Other techniques are described, as are errors and uncertainties.

2.1 FIELD METHODS

The two hypotheses, as mentioned in section 1.1, involved sampling material from land systems experiencing different erosive processes i.e. gully or landslides, to attempt to establish a mineralogical signature for the different landforms which could be traced downstream. To test these hypotheses four objectives were outlined regarding field methods for sediment sampling (e.g. bedrock, suspended sediment, regolith, and pebbles) and the rationale behind the sampling techniques (e.g. suspended sediment to demonstrate the mixing of sediment down stream). In this section the main focus of the fieldwork will be described and related to the land systems concept.

2.1.1 Focus

The main focus area for this research was on steep land and hill country, where land systems (*see* section 1.11) were deemed as severe to extreme gully and landslide erosion prone. Tributaries flowing into the Waipaoa River were targeted for suspended sediment sampling, as being the outflow of sediment from chosen land systems. For this research land systems were used instead of geological units, because they incorporate information on erosion type and severity, drainage density, sediment supplying capacity, together with geology to create units ranked on severity of erosion; this allowed areas of extreme and severe landslide and gully erosion to be targeted. At the time of sampling design and strategy the Raukumara geological map (Mazengarb & Speden, 2000) was unavailable.

Four of the 16 land systems (*see* section 1.11) were chosen for sampling on the basis of erosion susceptibility: two land systems prone to gully erosion e.g. Mangatu and Waingaromia, and two land systems prone to landsliding e.g. Te Arai and Mako Mako (Figure 2.1.1). A summary of each of the four land systems follows (Page, 1998):

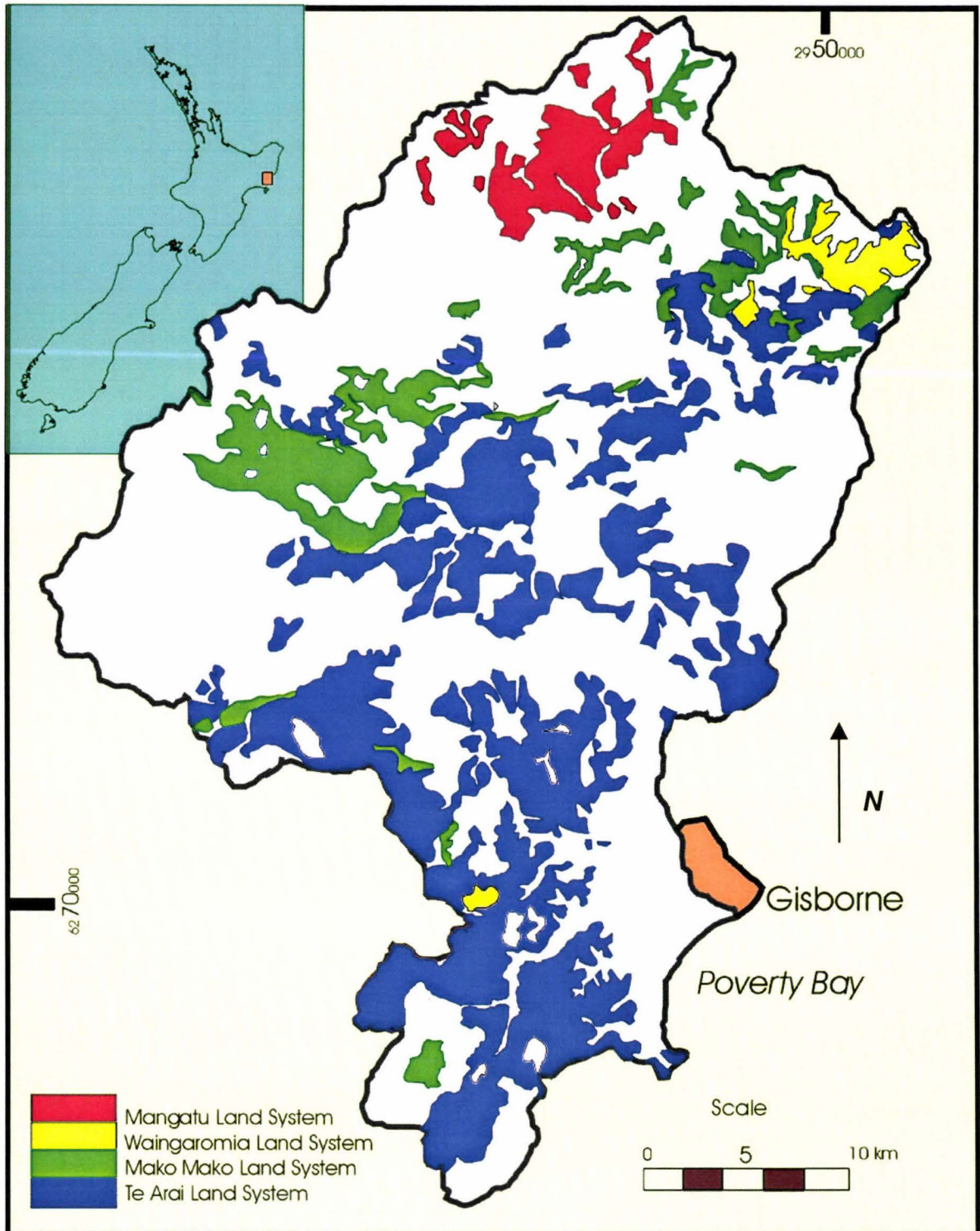


Figure 2.1.1. The four land systems, chosen on the basis of landslide and gully erosion severity for sampling, are illustrated in: red – Mangatu, and yellow – Waingaromia (gully erosion), green – Mako Mako, and blue – Te Arai (landslide erosion) (adapted from Manaaki Whenua - Landcare Research Land Systems Map).

Mangatu Land System – (Plate 2.1.1)

- Cretaceous-Paleogene argillite – Whangai and Mokoivi Formations
- 6303 ha (3% of Waipaoa Catchment) of moderately steep to steep slopes, with large deep-seated gullies
- Once vegetated with podocarp and mixed broadleaved forests, since reforestation it is now dominantly exotic forest, pasture and some native shrubbery
- Annual rainfall of 1400-3000 mm
- Dominant soil: Typic Orthic Recent, Weathered Orthic Recent
- Erosion status: Extreme



Plate 2.1.1 Tarndale Gully complex formed in crushed Cretaceous Whangai Formation – Tinui Group (photo: A. Palmer, 2000).

Te Arai Land System

- Miocene-Pliocene weak mudstones – Tolaga Group, Tunanui Formation
- 51 320 ha (23% of Waipaoa Catchment) of moderately steep to steep slopes, prone to landslides
- Once vegetated with podocarp and mixed broadleaved forests, since reforestation it is now dominantly pasture, some native shrubbery, and increasing plantings of exotic forest
- Annual rainfall is 1000 mm at the coast and 2000 mm inland
- Dominant soils: Weathered Orthic Recent, Pallic Orthic Brown soils, tephric phase, Typic Orthic Recent. Soils vary in depth from 100 cm on ridges to 0-30 cm on slopes
- Erosion status: Severe

Mako Mako Land System

- Miocene-Pliocene alternating massive mudstone and thin sandstone – Tolaga Group, Tunanui Formation
- Moderately to very steep slopes, prone to landslides
- Once vegetated with podocarp and mixed broadleaved forests, since reforestation it is now dominantly pasture, some native shrubbery, and exotic forest
- Annual rainfall: 1200-2000 mm
- Dominant soils: Weathered Orthic Recent, Typic Orthic Recent. >80 cm soil depth in places, the 0-20 cm found on eroded slopes
- Erosion status: Severe

Waingaromia Land System

- Miocene-Pliocene mudstone
- 2890 ha (1.5% of the Waipaoa Catchment) moderately steep and long dip slopes which are broken by gullies, deep seated mass movements and slides
- Once vegetated with podocarp and mixed broadleaved forests, since reforestation it is now dominantly pasture, some native shrubbery, and exotic forest
- Annual rainfall: 1000-2000 mm
- Dominant soils: pedal Immature Pallic, Weathered Orthic Recent
- Erosion status: Extreme

2.1.2 Sampled Suites

The primary focus of sampling was fresh and weathered bedrock from within these land systems, although some samples were gathered from land systems with different geological groups (Figure 3.1.1). Samples were collected from actual gullies and landslides, as well as outcrops not affected by erosion processes. Bedrock was disaggregated by hand where possible or gently crushed taking care to cause as little damage to grain size as possible. Statistical analysis was carried out on the clay fraction of these bedrock samples (*see* section 3.1).

The second suite of samples comprised of pebbles collected from the Waipaoa River and tributaries (Figure 3.2.1), as representative of the bedload contributing to the river system. Pebble samples were collected from tributaries throughout the land systems selected. Care was taken to sample representative lithologies contributing to the bedload *e.g* Waipaoa River above Te Karaka (site M7) – 75 % mudstone, 20 % sandstone, 5 % other; Waingake Stream (Te Arai,

site TA10) – 85 % mudstone, 10 % sandstone, 5 % other. These pebbles were crushed and analysed in the same manner as the bedrock samples (*see* section 4.2)

Suspended sediment made up the third suite of samples and was collected at points in the rivers where flow permitted sampling. In some places the flow was low and carrying little sediment so sampling was not possible. Other samples were collected from gauging stations at Omapere, and Kanakanaia (Figure 3.3.1).

The final set of samples was obtained from four cores taken by Landcare Research at McPhail’s Bend, Ormond (NZMS 260 Y17/384809), and Matawhero floodplain, and in Poverty Bay (Figure 3.4.1). Samples from the first two cores came from influxes of sediment considered to represent overbank flood deposits from the last century. The Matawhero and Poverty Bay cores were sampled in three centimetre intervals until the Taupo Pumice was reached at 210 cm depth in the Matawhero and three metres in the Poverty Bay Core. McPhail’s Bend (NZMS 260 Y17/373847) was chosen as a core site as it is subject to overbank deposition, and since forest clearance, has always been in grass, never being disturbed by cropping. The Matawhero floodplain core site (NZMS 260 Y18/395766) is currently not a flood deposition site. It provided a longer record (~ 15 m) than McPhail’s Bend and demonstrated long-term changes in sediment deposition within the catchment area (Mike Page, *pers. com.* 2001). The Poverty Bay marine core (MD2122) was sited in the middle of the midshelf basin depocentre (NZMS 260 Y18/587548), enclosed by the actively growing Ariel and Lachlan anticlines. This shelf morphology essentially “closes” the basin in contemporary conditions, trapping up to 80 % of the sediment discharge from the Waipaoa River into Poverty Bay (Noel Trustrum *pers. com.* 2001).

2.2 X-RAY DIFFRACTION (XRD) ANALYSIS

Crystalline species present in clay fractions of soils and rocks can be identified by x-ray diffraction (XRD). Each crystalline substance diffracts x-rays in a unique pattern due to their own characteristic arrangement of atoms; the principles of XRD are based on this concept. Bragg’s law explains how x-ray diffraction occurs:

$$n\psi = 2d \sin \theta$$

where d is the lattice spacing,

ψ is the wavelength of the x-rays,

θ is the glancing angle of diffraction

n is the order of the diffraction, which can be any whole number.

ψ is dictated by the chemistry, structure and excitation potentials of the element in the x-ray tube (e.g. Co, Cu, etc) (*pers com.* R. C. Wallace, 2002) and is therefore known and constant. Each mineral present will give characteristic peak patterns at certain spacings and intensities when scanned by a range of angles of reflection with a detector.

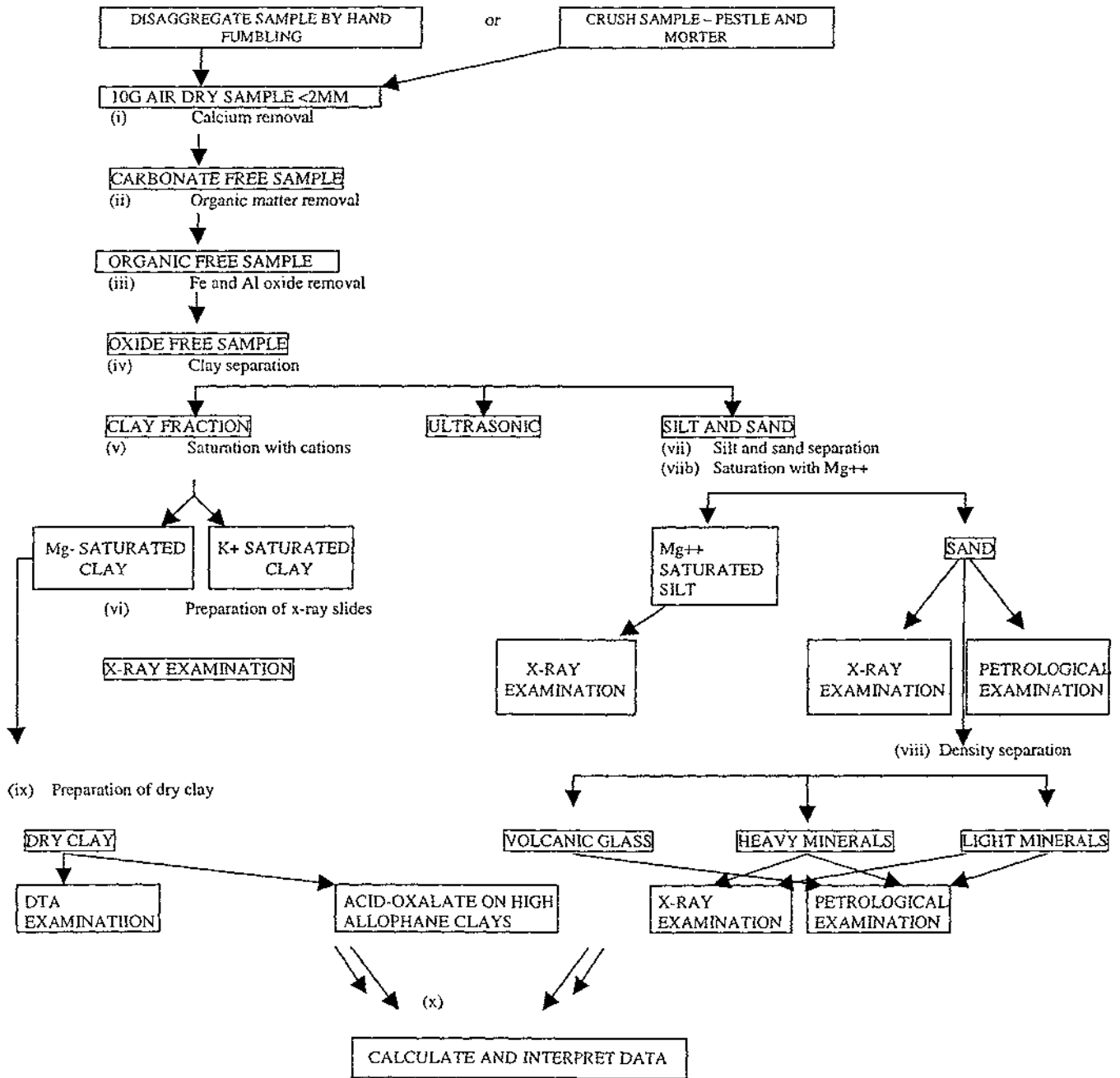


Figure 2.2.1 This flow diagram illustrates the procedure for mineralogical analysis of samples collected for the four chosen land systems (adapted from Whitton & Churchman, 1987).

2.2.1 Sample Preparation

Reagents

- a) Bromophenol blue indicator; 1% in ethyl alcohol.

- b) Citrate reagent; 75g $C_3H_4(OH)(COONa)_3 \cdot 2H_2O$ dissolved in 1L distilled water and pH adjusted to 7.3 by addition of a few drops of citric acid solution.
- c) 1:1 Hydrochloric acid (AR grade); concentrated HCL diluted with an equal volume of distilled water.
- d) Hydrogen peroxide "100 volume" used as supplied.
- e) Sodium chloride solution; 350g NaCl dissolved in 1L water.
- f) Sodium dithionite; $Na_2S_2O_4 \cdot H_2O$ used as solid powder supplied.

1.1 Calcium Removal

1. 10 g of each air-dried soil was placed into a 100 ml test tube named with the identifier of each sample. 50 ml of distilled water were added, and stirred well with a teflon stirring rod.
2. 1-2 ml of 1:1 HCL were added to each test tube and stirred well. Once all reactions had ceased the tubes were placed in the centrifuge for five mins at 1500 rpm. The clear supernatant liquid was then discarded.

1.2 Organic Matter Removal

1. 10 ml of distilled water was added to each test tube using a squeeze bottle, then a further 10 ml of hydrogen peroxide was added, and the mixture stirred. These were left to stand overnight.
2. The next day the tubes were placed in the water bath and heated until boiling or until such time that the frothing ceased. Care was taken not to allow the samples to become dry or boil over.
3. When all reactions had ceased the tubes were filled with water, stirred well and centrifuged for five mins at 1500 rpm. The clear supernatant liquid was then discarded.

1.3 Iron Removal

1. 30 ml citrate reagent and 5 ml of sodium bicarbonate was added to each tube, stirred, and placed in the water bath for 5-10 mins.

2. Each tube was then stirred well and 1g of sodium dithionite was added to each tube. Gentle stirring and the occasional squirt of water allowed mixing without excessive frothing and sample loss. The tubes were then left in the water bath for another 20 mins.
3. The tubes were removed from the water bath, stirred and centrifuged for five mins at 1500 rpm; clear supernatant liquid was discarded.
4. This process (steps 1-3) was repeated once.

2.2.2 Particle Size Separation

Reagents

- a) 1:1 hydrochloric acid concentrated (AR grade); HCl diluted with an equal volume of distilled water
- b) Potassium chloride; 100 g of KCl dissolved in 1 L distilled water
- c) Magnesium chloride solution; 100 g of $MgCl_2$ dissolved in 1 L distilled water

2.1 Clay Separation

1. 1 L beakers were labelled each with a name of one of the samples being analysed.
2. The tubes from the process above were filled with distilled water and stirred with the motorised stirrer, and then centrifuged at 1000 rpm for five mins. The supernatant suspended clay from each sample was poured into its respective beaker.
3. Step 2 (above) was then repeated with the centrifuge at 900 rpm for four mins.
4. The process in steps 2 and 3 were then repeated a third time with the centrifuge set at 800 rpm for three mins.
5. Step 4 was repeated two or three more times or until such time that the supernatant liquid was clear.
6. The tubes were then filled with water, stirred using the motorised stirrer and placed in the ultrasonic bath for 35-40 mins, while being stirred at five minute intervals with a teflon stirring rod.
7. The tubes were then centrifuged again at 800 rpm for three mins and the supernatant liquid poured into each sample beaker. This process was repeated until such time that the supernatant liquid was clear or very nearly so.

2.2 Silt Separation

1. 600 ml beakers were labelled each with a name of one of the samples being analysed.
2. The tubes from the process above (step 7 – clay separation) were filled with distilled water and stirred with the motorised stirrer, then left to stand for six mins.
3. The supernatant suspension formed contained silt only, and this was poured into the corresponding sample beaker.
4. The tubes were then filled with water again, stirred by hand with the teflon stirrer and left to stand for five mins. The supernatant liquid was then poured into the sample beaker.
5. Step 4 was then repeated with the sample being left to stand for four mins. This step was repeated until such time that no silt remained in suspension i.e. supernatant was clear.
6. 5-6 ml of $MgCl_2$ solution and 1-2 ml HCL was added to each beaker, stirred well and left to stand overnight.
7. The supernatant liquid was sucked off the next day and each beaker was filled with distilled water, stirred and allowed to stand 5-6 hours or overnight until the supernatant liquid was clear.

2.3 Sand Size Fraction

The residue left in the tubes after silt separation was treated as the sand size fraction. These tubes were placed in an oven set at 105°C to dry.

2.4 Density Separations: Heavy Mineral and Volcanic Glass

The sand fraction may be separated into a heavy mineral component and a volcanic glass component for further analysis and quantification.

1. 0.5 g of sand was weighed out and placed into a narrow stemmed 10 ml centrifuge tube marked with its own identifier.
2. For heavy mineral separation 6-7 ml of 2.85 Sodium polytungstate (SPT) was added to each sample, while for volcanic glass separation 6-7 ml of 2.45 SPT was added to each sample. Each tube was then stirred and centrifuged for five mins at 1000 rpm.

3. A glass rod with a button on the end was slowly pushed down through the floating material (ensuring no sediment was carried down the tube) until the button sealed the narrow stem. For volcanic glass separation the sediment at the top of the tube was washed onto filter paper, while the residue in the tube was discarded. For heavy mineral separation the sediment in the top was discarded and the sediment in the narrow stem was carefully washed on to filter paper and left to drain then dry.
4. Once dry the contents of the filter papers were weighed and stored in vials until x-ray and optical analysis could be done.

2.2.3 Saturation with Cations (clay fraction)

Saturation with cations is carried out to ensure the clay particles present either collapse or expand to their characteristic spacing. Saturation with potassium leads to a collapse, while saturation with magnesium ensures that the clays will expand when sprayed with glycerol.

1. Potassium saturation - After the 1 L beakers of clay suspension were stirred well with a teflon stirring rod, 10 ml of clay suspension was extracted from each beaker and poured into the appropriate 15 ml test tube for each sample. 3 drops of 1:1 HCL and 3-5 ml of KCL solution were then added to each test tube, and left to stand overnight.
NB. HCL is added to aid flocculation of clay particles.
2. The clear supernatant liquid was then sucked off each of the tubes and a further 10 ml of KCL was added. The tubes were shaken gently and allowed to stand overnight.
3. Step 3 was repeated the next day but the tubes were filled with water instead of KCL. This step was repeated until such time that the clay remained dispersed, i.e. cloudy.
4. 1-3 drops of 1:1 HCL was then added to each cloudy tube and they were then left to stand until clear.
5. Magnesium saturation – 10 ml of $MgCl_2$ solution was added to the remaining bulk of the clay suspension in the 1 L beakers together with 2-3 ml of 1:1 HCL, stirred with a teflon stirring rod and left to stand overnight.
6. The next day the supernatant liquid was drawn off; the beakers were refilled with distilled water, stirred and left to stand overnight.

2.2.4 Slide Preparation

4.1 Clay Slides

1. Microscope slides were marked for each sample and then turned over; five sets were made.
2. Mg⁺⁺ slides – 2 ml of clay suspension was extracted from each 1 L beaker using a dropper tube and placed on the appropriate slide.
3. After being left to dry overnight the slides were run through the XRD (Plate 2.2.4.1) and then placed on a perspex tray, which had been covered in absorbent paper. The slides were then gently sprayed with a glycerol and water solution, left to dry over night and again run through the XRD.
4. K⁺ slides – 2 ml of clay suspension was extracted from the 15 ml tubes using a dropper tube and placed on to the appropriate slide.
5. Once dried, the slides were run through the XRD and then put in the muffle furnace (heated at 550°C) for 2-3 hours. When they had cooled the slides were run through the XRD again.

4.2 Silt Slides

1 ml of silt suspension was extracted from each of the 600 ml beakers using a dropper tube, and placed on the appropriate slide. Once dried the slides were run through the XRD.

4.3 Sand Slides

1. Approximately 1 g of sand was ground in an agate pestle and mortar until very fine.
2. About half of this material was placed onto a glass slide bearing its name and 1-3 ml of acetone was squeezed onto the slide.
3. The sand powder and acetone was stirred and spread evenly over the slide.
4. Slides were left to dry and then run through the XRD.

4.4 Heavy Mineral Slides

The same process that was used to make the sand slides was followed to make the heavy mineral slides.



Plate 2.2.4.1 X-ray diffraction machine (XRD) (centre), the orange light on the left hand side indicates that the process is active. Diffraction patterns are being printed on the thermograph paper exiting the unit on the right hand side of the photo. In front of the XRD is the centrifuge (lower left hand corner) that is used in particle size separation (photo: *M. A. D'Ath*).

2.2.5 Calculations

5.1 Semi-quantitative Analysis – (Whitton & Churchman, 1987)

Based on the assumption that peak heights are proportional to the quantity of the constituents in each sample, we are able to semi-quantitatively calculate the percentage (or amount) of each mineral present in a particular sample, using a succession of concurrent equations (Johnson *et al.*, 1963; Whitton & Churchman, 1987).

The kandite (kaolinite + halloysite) fraction is determined by differential thermal analysis (DTA), while the other 11 minerals possibly present are determined by XRD data inserted in the following equations.

The peak heights 10 Å (x), 12 Å (y), 14 Å (z) if present are measured from the heated 550°C diffractogram, where x is the 10 Å peak height etc.

14 Å	- chlorite
12 Å	- sum of mica-chlorite + chlorite-vermiculite + chlorite-smectite if present
10 Å	- sum of several constituents (Table 5.1)

Whereby the first two equations are:

<u>SUM</u>	<u>FORMULA</u>	<u>EQUATION No.</u>
% chlorite (b) =	$\frac{z}{x+y+z}$	1
% (h+i+k) =	$\frac{y}{x+y+z}$	2

where the characters h, i, and k represent components from Table 2.2.5.1 – mica-chlorite etc.

Measurements from the Mg⁺⁺ - glycerated diffractogram include: 10 Å (u), 12 Å (v), 14 Å (w), 18 Å (x), 28 Å (y) and 32 Å (z). Obtaining another six equations:

% mica (a) =	$\frac{u}{u+v+w+x+y+z}$	3
% (f+g+h) =	$\frac{v}{u+v+w+x+y+z}$	4
% (b+c+d+i+j) =	$\frac{w}{u+v+w+x+y+z}$	5

$$\% \text{ smectite (e)} = \frac{x}{u+v+w+x+y+z} \quad 6$$

$$\% (i+j) = \frac{y}{u+v+w+x+y+z} \quad 7$$

$$\% \text{ chlorite - } = \frac{z}{u+v+w+x+y+z} \quad 8$$

smectite

Measurements from the K^+ - saturated diffractogram include: 10 Å (x), 12 Å (y), 14 Å (z).
Obtaining another two equations:

$$\% (g+h+i+k) = \frac{y}{x+y+z} \quad 9$$

$$\% (b+d) = \frac{z}{x+y+z} \quad 10$$

Measurements from the Mg^{++} - saturated, in air, diffractogram include: 10 Å (v), 12 Å (w), 14 Å (x), 18 Å (y), 28 Å (z). Hence one equation is obtained:

$$\% (i+k) = \frac{z}{u+v+w+x+y+z} \quad 11$$

By solving the equations (as below) the character components were calculated:

<u>Component</u>	<u>Equation/s</u>
mica (a)	3
chlorite (b)	1
vermiculite (c)	5, 7, 10
hydroxy interlayered vermiculite (HIV) (d)	1, 10
smectites (e)	6
mica-vermiculite (f)	4, 9, 11
mica-HIV (g)	2, 9
mica-chlorite (h)	2, 11
chlorite-vermiculite (i)	8, 11

mica-smectite (j)	7, 8, 11
chlorite-smectite (k)	8

In practice, combinations of a few of the above components are present in each sample, therefore considerably reducing the number of simultaneous equations.

The amounts of quartz and feldspar are obtained from the Mg^{++} - saturated, air-dried, diffractogram, by calculating the peak height intensities (counts/sec) of 4.26 Å (quartz) and 3.19 Å (feldspar). These are compared with graphs of peak height intensity against concentration which are derived from reference quartz and feldspar samples.

I Discrete Minerals

MINERAL	Treatments				
	Mg^{++} -air	Mg^{++} -glycerol	K^+	Heated 550°C	Formamide
(a) Mica*	10	10	10	10	-
(b) Chlorite	14	14	14	14	-
(c) Vermiculite	14-10	14	10	10	-
(d) HIV**	14	14	14	10	-
(e) Smectites	15-10	18	10	10	-
Kaolinite	7.2	7.2	7.2	No peak	7.2
Halloysite	7.2	10-11 (not all)	7.2	No peak	10.4

* Mica is considered synonymous with illite as the two are generally indistinguishable.

** HIV = Hydroxy interlayered vermiculite

II Regularly interstratified minerals

MINERAL	Treatments			
	Mg^{++} -air	Mg^{++} -glycerol	K^+	Heated 550°C
(f) Mica-vermiculite	12 + 14	12 + 14	12	10
(g) Mica-HIV	12 + 14	12 + 14	12	10
(h) Mica-chlorite	12 + 14	12 + 14	12	12
(i) Chlorite-vermiculite	14 + 28	14 + 28	12	12
(j) Mica-smectite	12 + 14	14 + 28	10	10
(k) Chlorite-smectite	14 + 28	32	12	12

III Irregularly interstratified minerals

Mineral	Treatments			
	Mg ⁺⁺ -air	Mg ⁺⁺ -glycerol	K ⁺	Heated 550°C
Interlayered hydrous mica	10-14	10-14	10-14	10-12

Table 2.2.5.1 Basal (001) spacings (Å) of clay minerals: I discrete minerals, II regularly stratified minerals, and III irregularly interstratified minerals, as determined following treatment with: Mg⁺⁺ - in air, Mg⁺⁺ - in glycerol, K⁺, and K⁺ - heated at 550°C.

2.2.6 Other Techniques Used

6.1 Differential Thermal Analysis (DTA) –(Plate 2.2.6.1)

Exothermic and endothermic effects (water loss, recrystallisation, etc) are measured as a sample is heated or cooled. A sample is heated until its temperature differs from that of a reference temperature, upon which time it will produce an opposing peak on the curve of temperature differential (ΔT) against temperature (T). The minerals present will have particular peak position, which allows for identification, and the peak area provides a measure of quantity (Figure 2.2.6.1a).

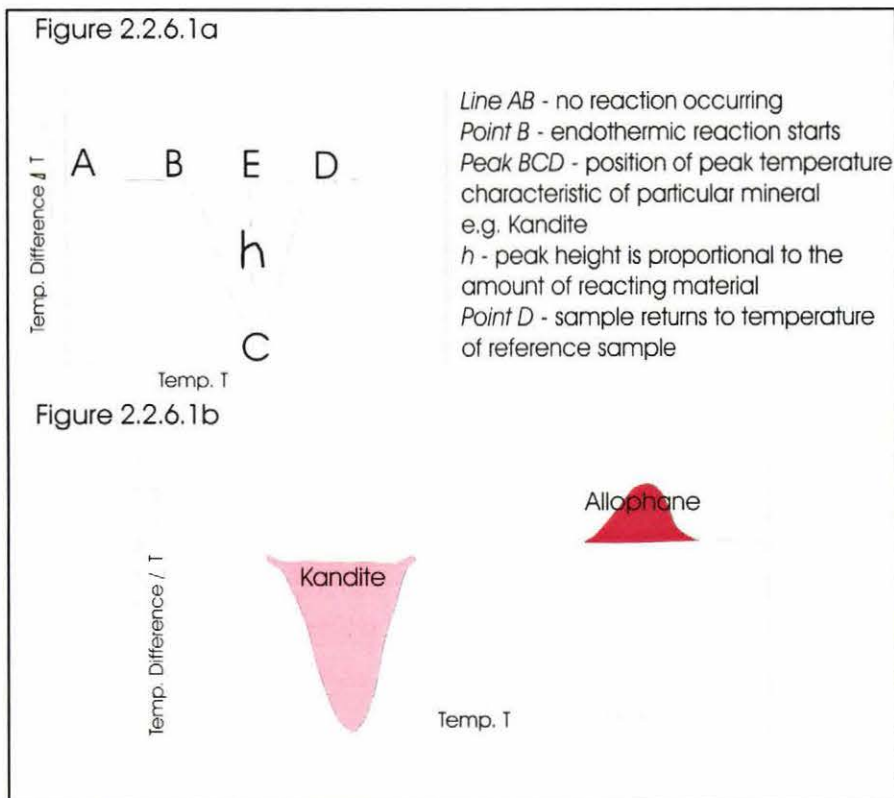


Figure 2.2.6.1 DTA pattern interpretation. a) peak area and position determine the quantity and the mineral present. b) kandite is identified at 520 - 560°C and can be quantitatively measured by peak area. Unlike allophane, whose presence is noted but requires a different procedure to establish quantity (Parfitt & Childs, 1987).

Kandite (520-560°C) was measured in this way for this project (Figure 2.2.6.1b). Although allophane was not measured quantitatively by the DTA, its presence was noted by the opposing peak on the DTA pattern (Figure 2.2.6.1b).



Plate 2.2.6.1 DTA machine. The main unit is shown on the left, with one furnace in place as active and a spare furnace is upside down cooling. On the right hand side the attached printer is producing a DTA pattern (photo: *M. A. D'Ath*).

6.2 Optical Microscopy

Temporary grain mounts were made for examination of the sand and heavy mineral fractions. A small quantity of sample was placed on a microscope slide and a drop or two of clove oil was added. These were examined using a polarising microscope for presence of volcanic glass and identification of other minerals which may not specifically be identified using XRD.

6.3 Chemical Dissolution for Minerals of Short Range Order

Short-range minerals do not give crystalline peaks during the XRD process; therefore other methods of extraction and quantification have been developed. For the quantification of allophane the acid-oxalate-extractable Al and Si (Al_o and Si_o) values and pyrophosphate-extractable Al (Al_p) values method (Parfitt & Wilson, 1985) was used.

2.2.7 Errors and Uncertainties

X-ray diffraction mineralogical analysis faces two distinct problems: 1 - identification of minerals present, and 2 - quantity estimation of each identified mineral. The first point deals with the difficulty to correctly identify minerals particularly within a common group e.g. feldspars or smectites (Table 2.2.7.1, Churchman *et al.*, 1984). The second point covers a wide range of categories: suitability of pure mineral standards, degree of crystallinity, use of pre-treatment techniques, weighting of different peaks, effect of regularity of interstratification, preferred orientation effects, differential sedimentation (e.g larger kaolinite plates will settle before smaller clay minerals), proportioning techniques, choice of peak areas, background assumption, statistical errors, peak overlap etc. Whitton & Churchman (1987) provide substantial explanation of each of these problems. Although the analysis method chosen for this thesis is that of Whitton & Churchman (1987), there are many different procedures for both the identification and estimation of minerals in samples, e.g. Pierce & Siegel (1969), Avery & Bullock (1977), and Hume & Nelson (1982). Table 2.2.7.1 provides an estimation of uncertainty for each identified mineral under the Whitton & Churchman (1987) procedure.

Mineral name	Method of analysis	%abundance range applicable		Estimated uncertainty % of quoted value		Comments
Mica	XRD!	20-100	(0-20)	± 10	(± 20)	
Chlorite	XRD	20-100	(0-20)	± 10	(± 20)	
Vermiculite	XRD	20-100	(0-20)	± 15	(± 30)	If mica-smectite or chlorite-vermiculite present estimate is less reliable
HIV*	XRD	20-100	(0-20)	± 20	(± 40)	
Smectite	XRD	20-100	(0-20)	± 15	(± 30)	
Kandite	DTA	10-100		± 20		At <20% kaolinite & halloysite are separable by Formamide
Kaolinite	DTA + Formamide	20-100		± 10		
Halloysite	DTA + Formamide	20-100		± 20		
Gibbsite	DTA	10-100	(0-10)	± 5	(± 10)	
Regular Interstratified	XRD	30-100	(0-30)	± 25	(± 50)	
Irregular Interstratified	XRD					
Allophane & Imogolite	Acid Oxalate dissolution	0.5-100		± 20 for whole soils		
Ferrihydrite	Acid Oxalate dissolution	1-100		± 25 for whole soils		
Quartz	XRD	10-100	(0-10)	± 5		
Feldspar	XRD	20-100	(0-20)	± 10		

! by proportion

*HIV = Hydroxy interlayered vermiculite

Table 2.2.7.1 Clay sized minerals – quantitative estimates of uncertainty for each mineral (adapted from Whitton & Churchman, 1987).

CHAPTER 3: RESULTS

In this chapter the results obtained from the analyses described in Chapter 2, will be reviewed. As in Chapter 1, the results section will be examined from the hill country to the coast. To begin, the bedrock mineralogy analyses will be looked at in the clay, silt and sand fractions, followed by a section discussing pebble mineralogy (clay fraction) from the Waipaoa River and several of the tributaries flowing into it. Section 3.3 outlines the results of suspended sediments collected from these rivers, as an introduction to the following section 3.4, which discusses mineralogy for the floodplain and marine cores.

3.1 BEDROCK

Bedrock analyses were completed on fresh and weathered samples for the Mangatu, Te Arai, Waingaromia, and Mako Mako land systems (Figure 3.1.1). The four land systems and two sample types were analysed using x-ray diffraction (XRD) methodologies (*see* Chapter 2). A randomised complete block experimental design was adopted and the results analysed in a factorial structure to determine whether there were differences in mineralogy between and within land systems and sample types. It was postulated that the mineralogy observed in land systems prone to gully erosion would differ from those prone to land slide erosion.

For this project the major clay mineral compositions of the bedrock, pebbles and suspended sediments, are expressed as a percentage. Statistically this is considered to be incorrect as the components of percentage data are not free to vary independently of one another e.g. as the proportion of one parameter increases, in turn the proportion of something else decreases. A negative bias is introduced into correlations, and misleading results are produced (Rollinson, 1993). But as has been found in earlier geochemical studies (*see* Rollinson, 1993) there is no other way to present the sense of closure, or an easier method to present data which can be compared to other analyses. For this thesis statistical analyses were carried out to give the relative magnitudes (%) (not absolute values – ‘*no. of counts*’) of the four main clay – sized minerals found in the sampled bedrocks.

Four minerals: quartz, feldspar, mica, smectite, were analysed as the major constituents of all bedrock samples collected from the Waipaoa catchment. The presence of kandite, chlorite,

vermiculite, mica-chlorite, mica-smectite, and mica-HIV, was noted in some samples although in much lesser quantities than the major constituents. Statistical analysis was not completed on these minor components.

Standard errors (SEM) are provided for each mean, as are the error-based degrees of freedom for each overall analysis. Statistically significant differences ($P < 0.05$) were separated using least significant means, and denoted with different letters and symbols (*see* following graphs – Figure 3.1.2).

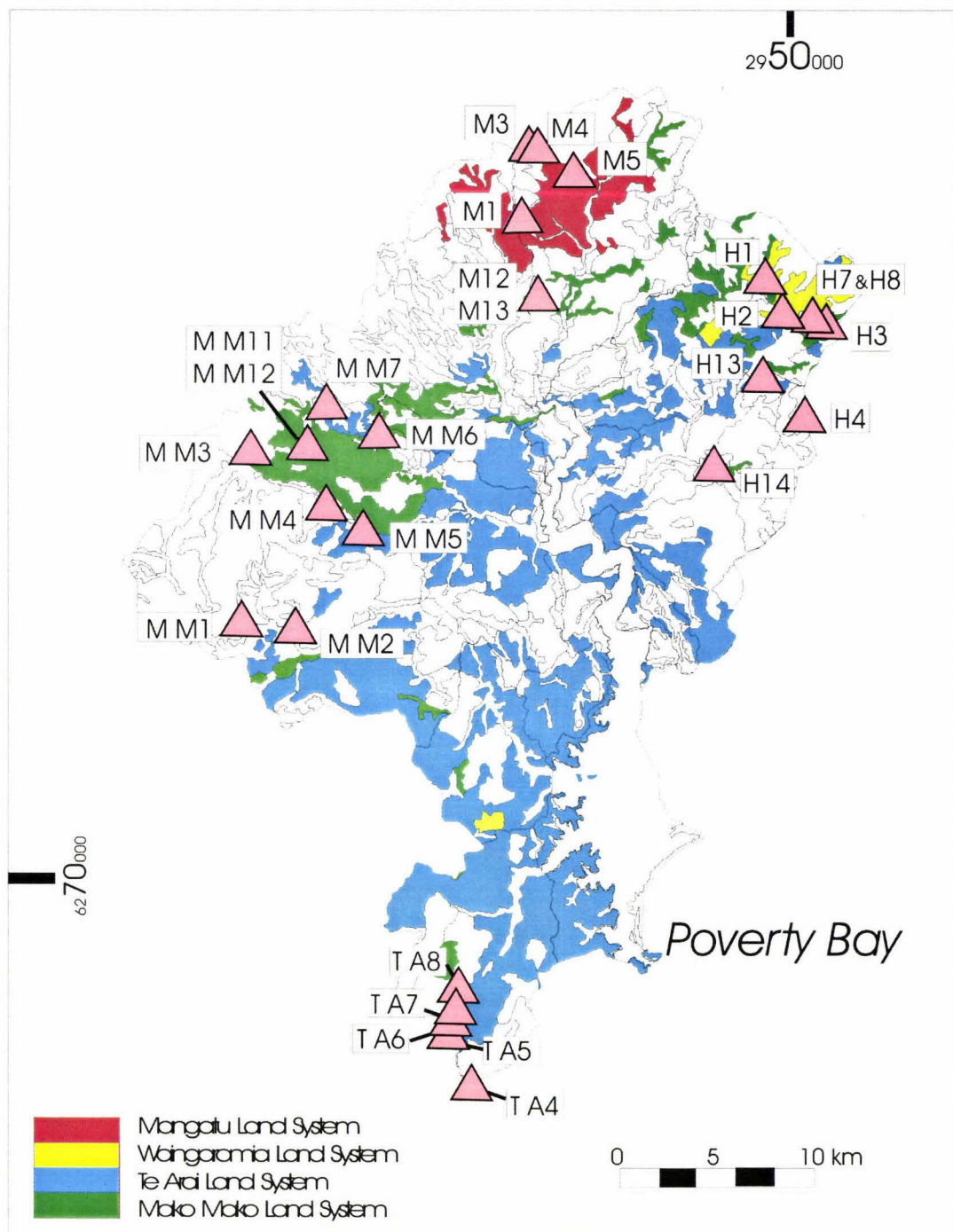


Figure 3.1.1 Sites of bedrock sampling

3.1.1 Clay Fraction

The influence of the four land systems and two sample types on the mean quartz %, feldspar %, mica %, and smectite % contents is shown below (Figure 3.1.2). Of the weathered bedrock in the four land systems, Mangatu (47 %) has a significantly greater mean quartz % than the Te Arai, Waingaromia or Mako Mako Land systems (12 %, 19 %, and 18 % respectively), which were all similar. For fresh bedrock samples once again the Mangatu has a significantly greater quartz (69 %) content than the Te Arai, Waingaromia and Mako Mako Land systems (16 %, 19 % and 19 % respectively) (Table 3.1.1).

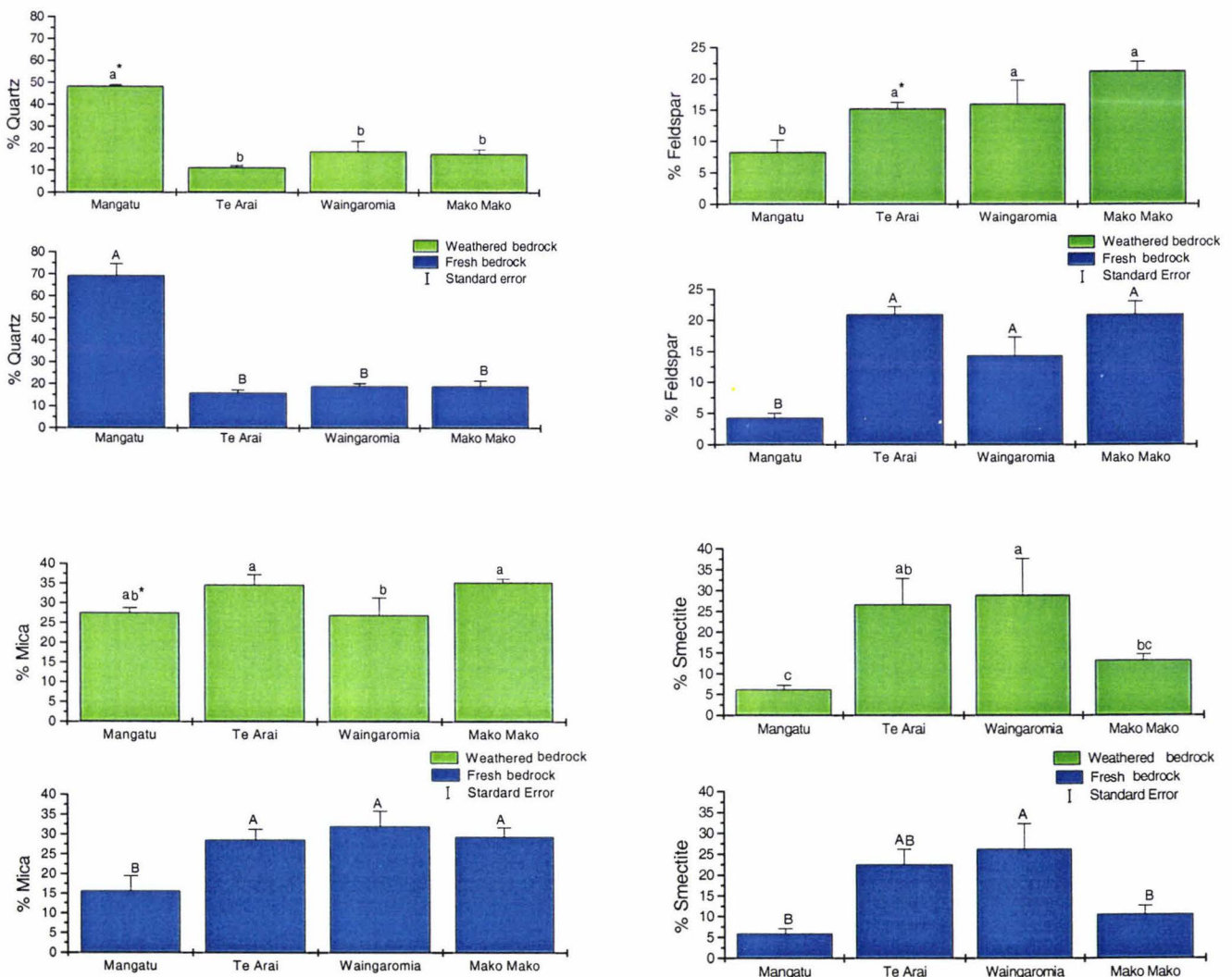


Figure 3.1.2 Mean percent of quartz, feldspar, mica, and smectite in weathered and fresh bedrock samples of Mangatu, Te Arai, Waingaromia and Mako Mako Land systems as separated using least significant means ($\alpha 0.05$) (error $df = 19$) ($n = 32$). Statistically significant differences *between* the land systems are shown with different letters. Lower case lettering is used for the weathered samples and UPPER CASE lettering for the fresh samples. A star (*) symbolises that *within* a land system there is significant difference between fresh and weathered means of quartz, feldspar, mica or smectite.

MINERAL	Mangatu LS		Te Arai LS		Waingaromia LS		Mako Mako LS	
	Weathered	Fresh	Weathered	Fresh	Weathered	Fresh	Weathered	Fresh
Quartz	47	69	12	16	19	19	18	19
Feldspar	8	4	15	21	16	14	21	21
Mica	28	16	35	29	27	32	35	29
Smectite	6	3	27	23	29	26	13	11

Table 3.1.1 Mean quartz %, feldspar %, mica % and smectite % for weathered and fresh bedrock from each of the four chosen land systems (LS).

A comparison was made between the quartz content of fresh and weathered samples within each of the four land systems. The Mangatu Land System has a significantly greater quartz % in the fresh bedrock samples (69 %) compared with the weathered samples (47 %). In other land systems: Te Arai, Waingaromia, and Mako Mako, no significant differences were observed.

Mean feldspar % between land systems followed a similar trend to that observed for quartz. In both the weathered and fresh bedrock samples the Mangatu Land System is significantly different from the Te Arai, Waingaromia, and Mako Mako land systems (weathered 8 %, 15 %, 16 %, 21 % respectively and fresh 4 %, 21 %, 14 %, 21 % respectively) (Table 3.1.1) (*refer section 4.1*). There are no significant differences of mean feldspar % in fresh or weathered samples between the final three land systems mentioned. Differences between feldspar contents of weathered and fresh samples within a given land system are significant only within the Te Arai Land System (15 % and 21 % respectively).

Weathered bedrock samples demonstrate few differences in mean mica % between land systems (Mangatu - 28 %, Te Arai - 35 %, Waingaromia - 27 %, Mako Mako - 35 %). The Waingaromia Land System appears to have significantly less mica than both the Te Arai and Mako Mako land systems. Mean mica % in the fresh bedrock in comparison follows a trend similar to mean feldspar %; Mangatu has significantly less mica % (16 %) than Te Arai, Waingaromia, and Mako Mako land systems (29 %, 32 %, 29 % respectively), which are all statistically similar. The final comparison of mica % between the weathered and fresh samples within particular land systems shows that the Mangatu Land System has a significantly greater mean mica % in the weathered samples compared with the fresh bedrock samples (16 %). There are no significant differences between fresh and weathered samples within the final three land systems.

The mean smectite % of weathered bedrock from the Waingaromia and Te Arai land systems (29 % and 27 % respectively) is significantly greater than for the Mangatu (6 %). The Waingaromia Land System has statistically more smectite than the Mako Mako Land System

(13 %), although the difference between Te Arai and Mako Mako land systems are not significant, albeit the separation large. It is worthwhile to note that there is considerable variation in the smectite content of individual samples in both the Te Arai Land System and the Waingaromia Land System fresh and weathered bedrock samples (Appendix III). There is no significant difference between weathered bedrock smectite content for the Mangatu and Mako Mako land systems. For the fresh bedrock, Waingaromia (26 %) again had significantly greater smectite % than either the Mako Mako or Mangatu land systems (11 % and 6 % respectively), but was similarly high to Te Arai (23 %). As with the weathered bedrock, Te Arai, although higher in smectite than both the Mako Mako and Mangatu land systems, is not statistically different. Fresh bedrock smectite % is not significantly different between Mako Mako and Mangatu land systems. In the comparison of smectite % between weathered and fresh samples within each of the four land systems, there were no statistical differences.

Minerals not included in these analyses were kandite, chlorite, vermiculite, and other interlayered clay minerals found in various samples (*see* Appendix III). Kandite is found in all land systems in small amounts. The quantities vary between the fresh and weathered samples within each land system (Figure 3.1.3); however, in most land systems the quantity of kandite is greater in the weathered bedrock sample. Vermiculite is evident in each land system but varies less than kandite. Highest quantities of vermiculite are found within weathered soil profiles in the Waingaromia Land System. Chlorite, mica-chlorite, mica-HIV and mica-vermiculite occur in most of the land systems, a few samples contained larger quantities than others e.g. Site H7 (Figure 3.1.1) had 5 % of both chlorite-smectite and mica-smectite, MM11 (Figure 3.1.1) had 16 % mica-vermiculite, and Site MM12 (Figure 3.1.1) had 16 % kaolinite-smectite (*see* Appendix III).

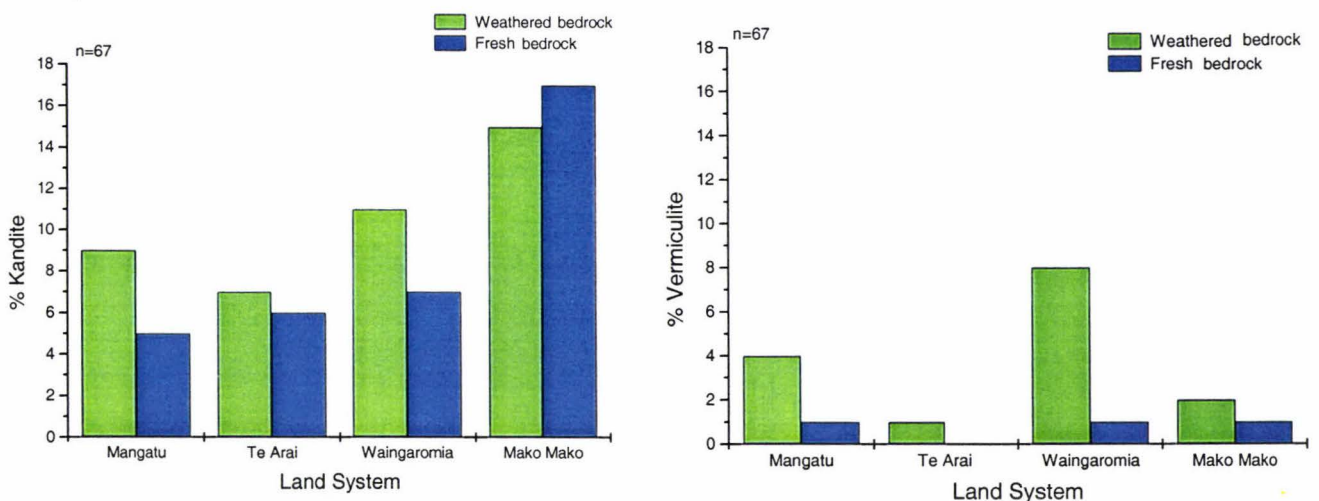


Figure 3.1.3 Comparison of kandite % and vermiculite % between weathered and fresh samples in four chosen land systems: Mangatu, Te Arai, Waingaromia, and Mako Mako ($n = 67$).

3.1.2 Silt Fraction

The silt fraction mineralogy was analysed under the same procedural methodology as the clay fraction (*see* Chapter 2). However, the bedrock silt fraction results differ from the analysed clay fraction results for the same samples (*see* Appendix III). During particle size separation (section 2.3) the large clay minerals (*e.g.* chlorite) can separate out with the silt-sized particles due to their size and structure, therefore they are more dominant in the silt-sized fraction than in the clay fraction (Figure 3.1.4). Quartz, feldspar, and chlorite are present in higher quantities within the silt fraction of the bedrock, while mica and smectite although predominant in the clay fraction are not as common in the silt fraction (*see* section 3.1.1).

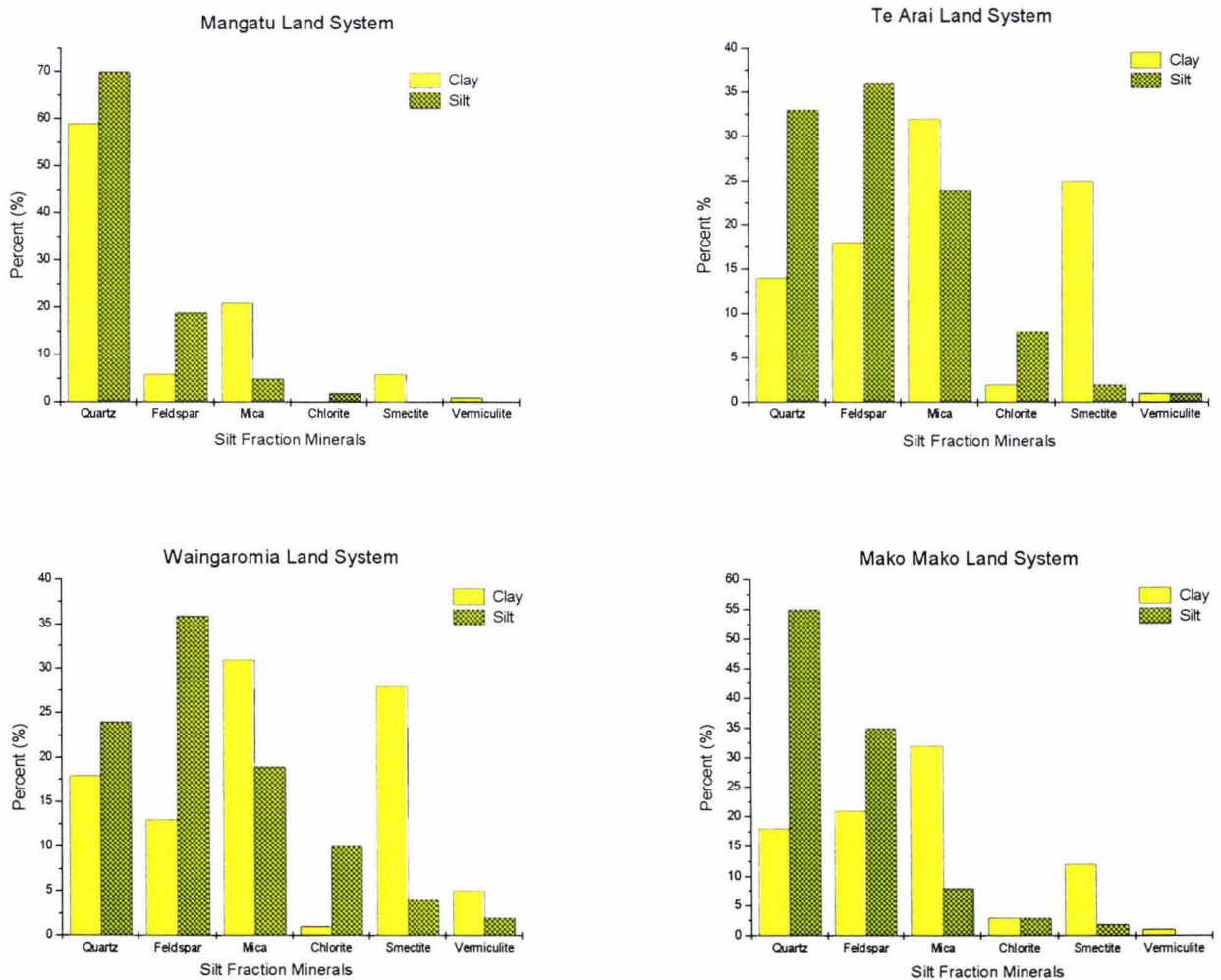


Figure 3.1.4 Comparison between the clay and silt sized fractions within four land systems: a) Mangatu ($n = 35$), b) Te Arai ($n = 19$), c) Waingaromia ($n = 25$) and d) Mako Mako ($n = 22$). Clay is represented by yellow and silt by the hatched bars.

MINERAL	Mangatu Land System (mean %)	Te Arai Land System (mean %)	Waingaromia Land System (mean %)	Mako Mako Land System (mean %)
Quartz	70	33	24	55
Feldspar	19	36	36	32
Mica	5	24	19	8
Chlorite	2	8	10	3
Smectite	0	2	4	2
Vermiculite	0	1	2	0

Table 3.1.2 Mean percentage of silt-sized minerals within four land systems ($n = 32$).

Quartz in the silt-sized fraction for both the Mangatu (70 %) and Mako Mako (55 %) land systems is considerably higher than the Te Arai and Waingaromia land systems (33 % and 24 %) (Table 3.1.2). The Te Arai and Waingaromia land systems, in turn, contain higher mica (24 % and 19 % respectively) than either the Mangatu (5 %) or the Mako Mako (8 %) land systems (Table 3.1.2). Feldspar is *c.* 35 % in all land systems except for the Mangatu Land System, which contains 19 % feldspar.

3.1.3 Sand Fraction

Quartz is the predominant mineral in the sand fraction of most of the samples analysed. Figure 3.1.5 plots quartz, feldspar and others – which constitutes volcanic glass, mica, chlorite, calcite, and zircon. Except for a few samples e.g. TA7a, TA7b, H14a (Bruce Rd site) (Figure 3.1.1), most samples have less than 10 % of other materials (*see above*). The Mangatu Land System has a higher percentage of quartz than do the other land systems; the red symbols tend to be clustered between 70 – 100 % quartz, 0- 30 % feldspar, while the solid brown Te Arai symbols are clustered between 55 – 80 % quartz, 20 – 45 % feldspar. The two exceptions, samples TA7a and TA7b had 82 % and 49 % volcanic glass respectively. The Mako Mako Land System shows little variation between samples with a cluster between 65 – 75 % quartz (the rest being feldspar). In comparison, the few Waingaromia Land System samples are scattered, through the same field as the Mako Mako and Te Arai land systems.

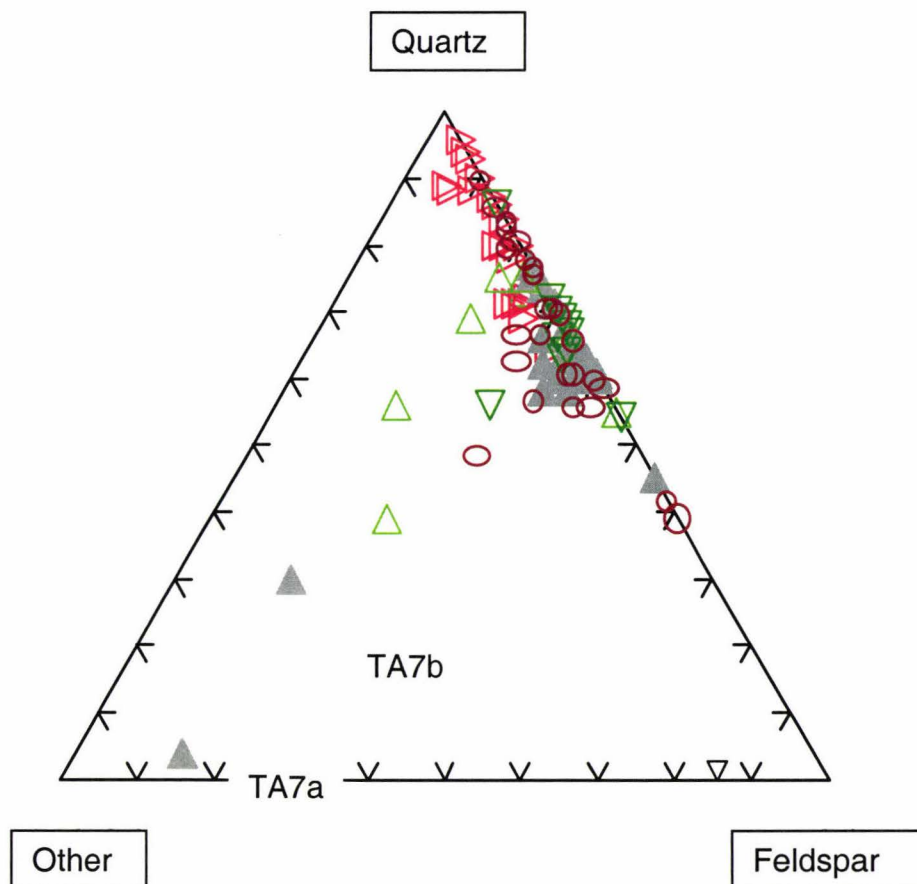


Figure 3.1.5 Ternary diagram representing the proportion of quartz, feldspar, and other constituents in the sand fraction of samples analysed. The triangles represent bedrock samples both fresh and weathered: red \blacktriangle Mangatu; solid grey \triangle Te Arai; green \triangle Waingaromia; black ∇ Mako Mako Land System. The orange \circ circles represent both suspended sediment and pebble samples with no differentiation between land systems.

3.2 PEBBLE MINERALOGY

In this section the results obtained from the analysis of pebbles collected from the four chosen land systems will be reviewed, tabled and graphed. The sites from which the pebbles were collected are shown in Figure 3.2.1.

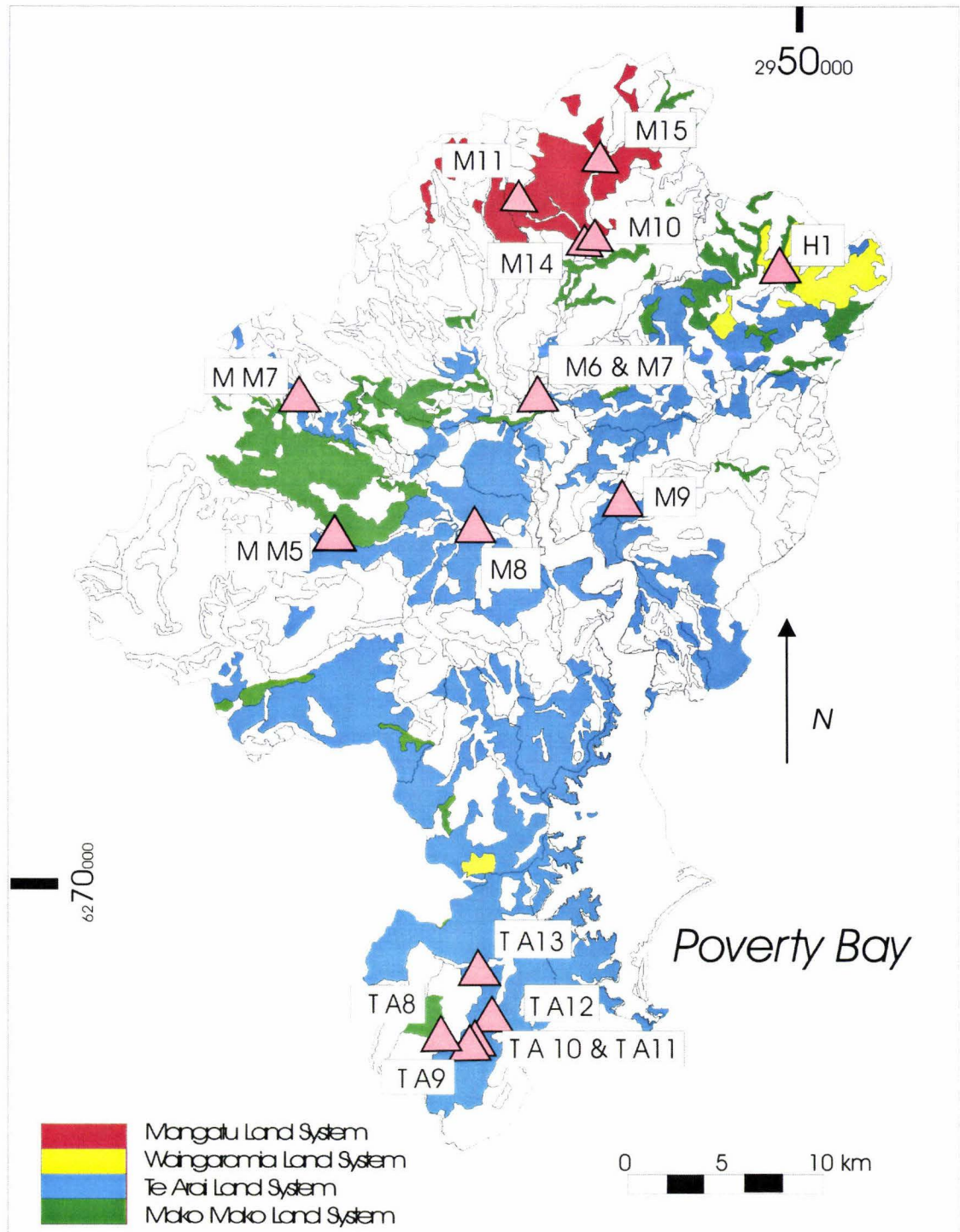


Figure 3.2. 1 Waipaoa Catchment area overlain by the Mangatu, Te Arai, Waingaromia, and Moko Moko land systems and sites of pebble collections.

3.2.1 Tikihore Stream and Upper Waipaoa River

Pebbles from site M15 came from the Tikihore Stream (Mangaotane Land System) and those from site M10 (Mangatu Land System) (Figure 3.2.1) came from further down the Waipaoa River before it meets the Te Weraroa Stream (Figure 1.1). Both these pebble samples have *c.* 27 % quartz, 15 % feldspar, 7 % kandite, and 16 % smectite (Figures 3.2.2a & 3.2.2b). Mica varies between the two samples 33 % at M15 and 23 % at M10 (Table 3.2.1), and while M15 has 5 % chlorite, M10 has 6 % of mica-vermiculite, which is not present in M15.

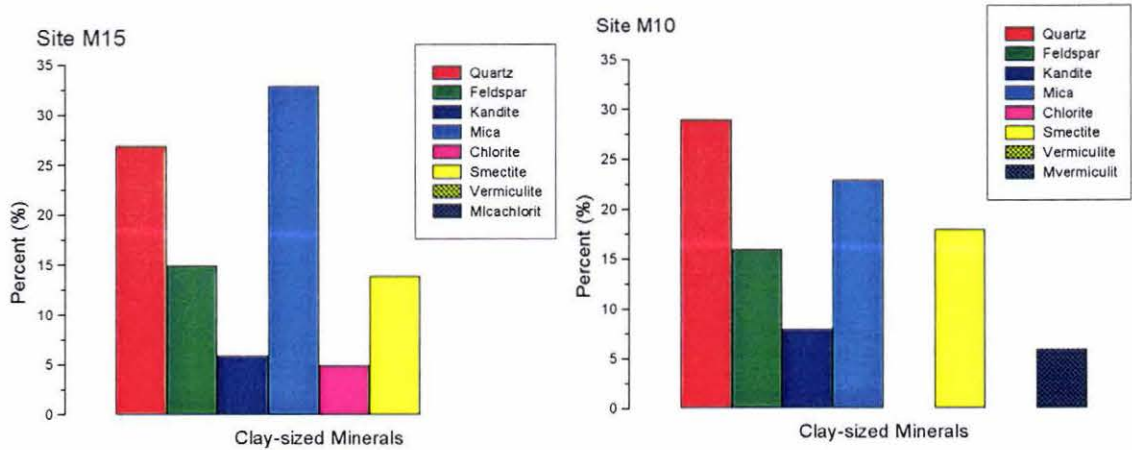
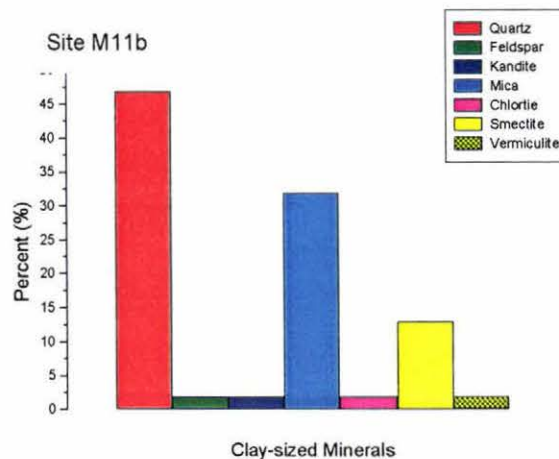


Figure 3.2.2 Mineralogy of clay-sized fraction of pebbles collected from a) site M15, and b) site M10. Bedload comprised of ~50/50 sandstone and mudstone.

3.2.2 Te Weraroa Stream

Te Weraroa Stream flows from the base of the Tarndale Gully into the Waipaoa River. Sediment within the stream is from the Mangatu Land System. Two stream bedload/pebble samples were collected from the upper Te Weraroa Stream (samples M11b & c) and one sample from the outwash fan before the stream meets the Waipaoa River (site M14). Both samples were made up of predominantly mudstone material. The mineralogy of the clay-sized fraction of the Te Weraroa Stream pebbles is predominantly quartz and mica (Figures 3.2.3a, b, & c). Minor amounts of feldspar, kandite, smectite and vermiculite are also present (Table 3.2.1).



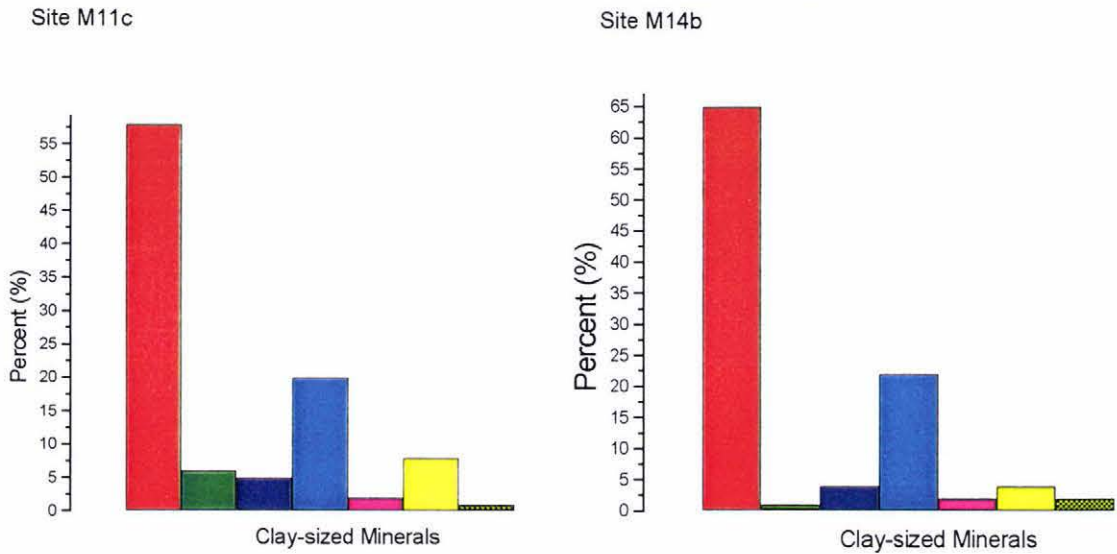


Figure 3.2.3 Mineralogy of clay-sized fraction of pebbles collected from Mangatu Land System a) site M11, b) site M11b, and c) site M14, sample b.

3.2.3 Mangatu River

The Mangatu River headwaters flow down from the Mangatu, Waipiro, and Mangaotane land systems and join the Waipaoa River just north of Whatatutu (Figure 1.1). A pebble sample (65 % mudstone, 30 % sandstone, 5% other) was collected from the Mangatu River just before this meeting of the waters at Te Kowhai Road site M6 (Figure 3.2.1). The mineralogy presented in Figure 3.2.4 (Table 3.2.1) is very similar to that from the Te Weraroa Stream, very high quartz, 19 % mica, and minor feldspar, kandite, chlorite, smectite, vermiculite, and mica-chlorite.

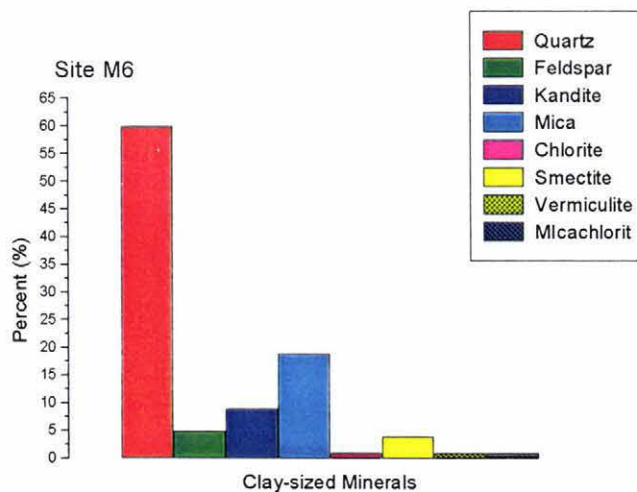


Figure 3.2.4 Mineralogy of clay-sized minerals in Mangatu River pebble sample.

3.2.4 Waipaoa River

The mineralogy of both the Te Weraroa Stream and Mangatu River appears to carry on down stream as pebbles collected from Site M7 Waipaoa River (Figure 3.2.1) have the same mineralogy, high quartz, 17 % mica, and less than 10 % each of feldspar, kandite, and smectite (Figure 3.2.5; Table 3.2.1).

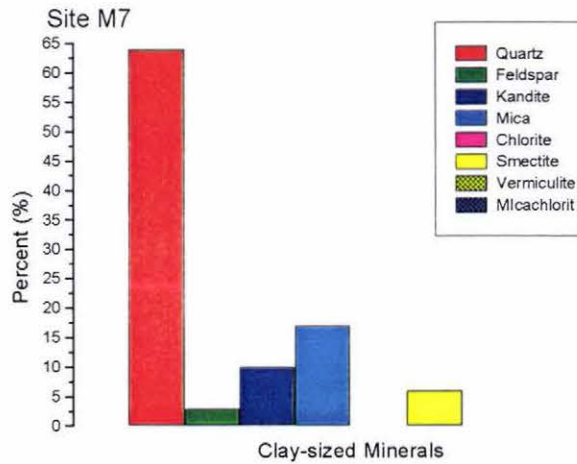


Figure 3.2.5 Mineralogy of clay-sized fraction of Waipaoa River pebbles.

MINERAL	Site M15 (%)	Site M10 (%)	Site M11b (%)	Site M11c (%)	Site M14b (%)	Site M6 (%)	Site M7 (%)
Quartz	27	29	47	58	65	60	64
Feldspar	15	16	2	6	1	5	3
Kandite	6	8	2	5	4	9	10
Mica	33	23	32	20	22	19	17
Chlorite	5	0	2	2	2	1	0
Smectite	14	18	13	8	4	4	6
Vermiculite	0	0	2	1	2	4	0
M-Chlorite	0	0	0	0	0	1	0

Table 3.2.1 Comparison of mineralogy of clay-sized fraction of pebbles collected at named sites.

3.2.5 Waingaromia River

Two pebble samples were collected from the Waingaromia River headwaters within the Waingaromia Land System, one weathered (mudstone/bedrock) and one unweathered (argillite/sandstone pebbles) from the same site H1 (Figure 3.2.1). Quartz varied from 28 % in the unweathered sample to 18 % in the weathered sample of pebbles, feldspar from 19 % - 24

%, kandite from 7 - 10 %, mica from 26 - 30 %, chlorite from 3 - 0 %, and smectite from 14 % - 15 % (Figure 3.2.6a & b; Table 3.2.2).

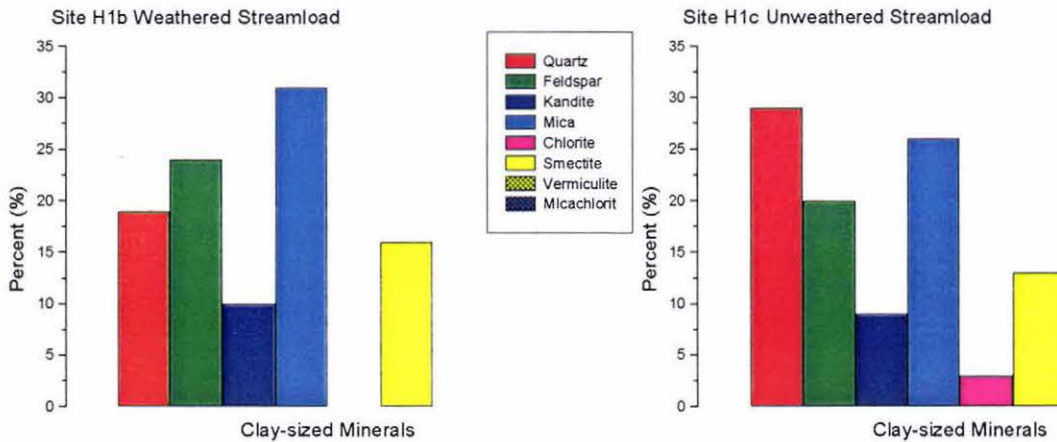


Figure 3.2.6. Comparison of clay mineralogy of two pebble samples collected from the Waingaromia Land System: a) weathered streamload/bedrock, b) unweathered streamload/pebbles.

3.2.6 Waikohu River

The Waikohu River flows from the west into the Waipaoa River near of Te Karaka (Figure 1.1). The land systems contributing most sediment to the river are Mako Mako, Wharekopae, Te Arai and Kanakanaia. Three pebble samples were collected from various stages of the river system. The first sample at site MM5 (Figure 3.2.1) was collected from the Waihuka River, which flows into the Waikohu River west of Te Karaka. The second sample (MM7) came from Rangiriri Stream, a small tributary northwest of Te Karaka. And the third pebble sample (M8) was obtained just before the confluence of the Waikohu River and the Waipaoa River.

The mineralogy of these samples is different from each other and from those of the Waipaoa River headwaters. Quartz, mica and smectite contribute 22 %, 25 % and 26 % respectively to sample MM5 (Figure 3.2.7a), while feldspar and kandite contribute 13 % and 14 %. In comparison, mineralogy at site MM7 has 42 % mica and no smectite (Figure 3.2.7b; Table 3.2.2). Site M8 pebble mineralogy also shows no evidence of smectite, but has a greater content of quartz, chlorite, vermiculite and mica-chlorite than both MM5 and MM7 (Figure 3.2.7c; Table 3.2.2).

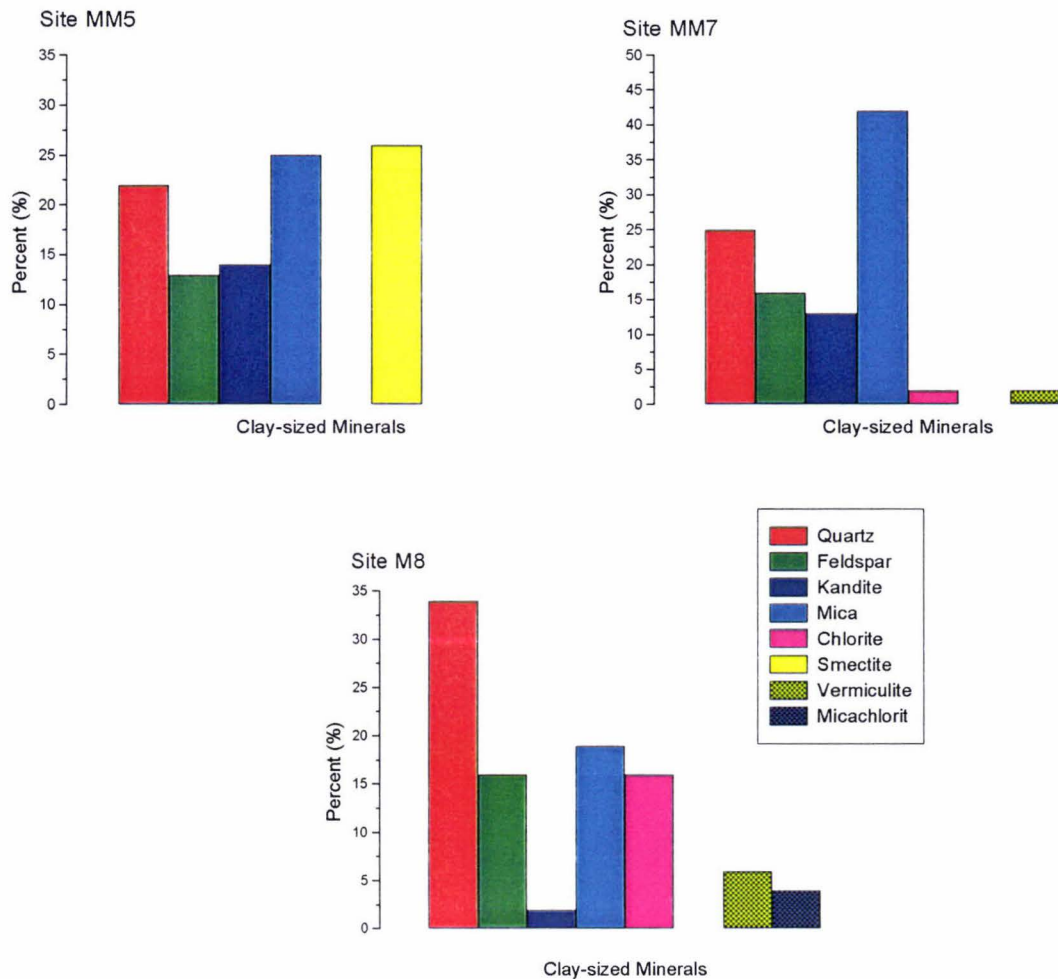


Figure 3.2.7 Clay-sized fraction mineralogy of pebbles collected at sites a) MM5, b) MM7 and c) M8.

3.2.7 Waihora River

The Waihora River drains an area dominated by the Waihora, Kanakanaia, and the Te Arai land systems, and flows from the east into the Waipaoa River at Te Karaka (Figure 1.1). No one mineral appears to be significant in the mineralogy presented in this sample M (Figure 3.2.8), quartz (36 %) and mica (30 %) are the dominant clay-sized minerals, with some feldspar (14 %), kandite (10 %), smectite (3 %), and vermiculite (5 %) (Table 3.2.2).

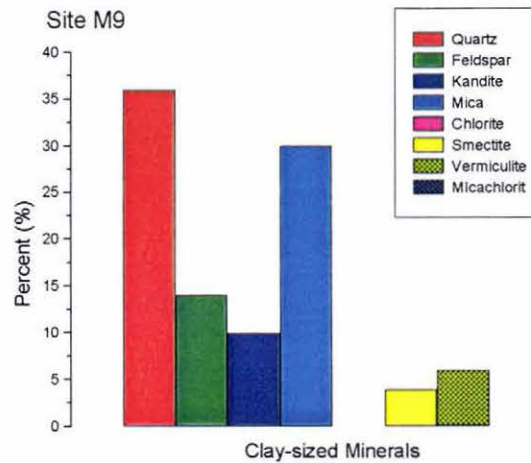


Figure 3.2.8 Mineralogy of clay-sized fraction of pebbles collected at site M9.

MINERAL	Site H1 Weathered (%)	Site H1 Unweathered (%)	Site MM5 (%)	Site MM7 (%)	Site M8 (%)	Site M9 (%)
Quartz	19	29	22	25	34	36
Feldspar	24	20	13	16	16	14
Kandite	10	9	14	13	19	10
Mica	31	26	25	42	16	30
Chlorite	0	3	0	2	0	0
Smectite	16	13	26	0	6	4
Vermiculite	0	0	0	2	4	6
Mica-Chlorite	0	0	0	0	3	0

Table 3.2.2 Comparison of pebble clay-size fraction mineralogy between sites: H1, M8, M9, and MM5, and MM7.

3.2.8 Te Arai River

Five pebble samples were collected from the Te Arai Land System, and one from a small area of Kanakanaia Land System in the same region (site TA8) (Figure 3.2.1), all of which have very similar clay mineralogy (Figure 3.2.9). Four of the samples were taken from tributaries that flow into the Te Arai River: Kauwaewaka Stream (site TA8), Titokanui Stream (site TA9), Waingake Stream (site TA10), Waimata Stream (site TA13), and two samples from the Te Arai River mainstem (sites TA11 & TA12) (Figure 3.2.1). The main lithology of the pebbles being mudstone (~70 – 80 % for most samples) and the remainder were mostly sandstone.

Quartz and feldspar values range from 10 – 25 %, with feldspar % generally being slightly higher than quartz % (Figure 3.2.9). The only exceptions are the pebble samples from sites

TA10 and TA13, where quartz and feldspar contribute practically equal parts (Table 3.2.3). Kandite (measuring between 4 – 10 %) is identified in every sample, as is mica and smectite. Mica contributes 25 – 30 % in all samples except at site TA8, where mica is slightly higher at 34 %. Smectite varies the most between sampling sites ranging from 14 – 28 %, the highest values measured being in the Te Arai River (sites TA11, TA12) and Waimata Stream (site TA13). Small quantities of chlorite, vermiculite and mica-chlorite are evident in some samples (Figure 3.2.9)(see Appendix III).

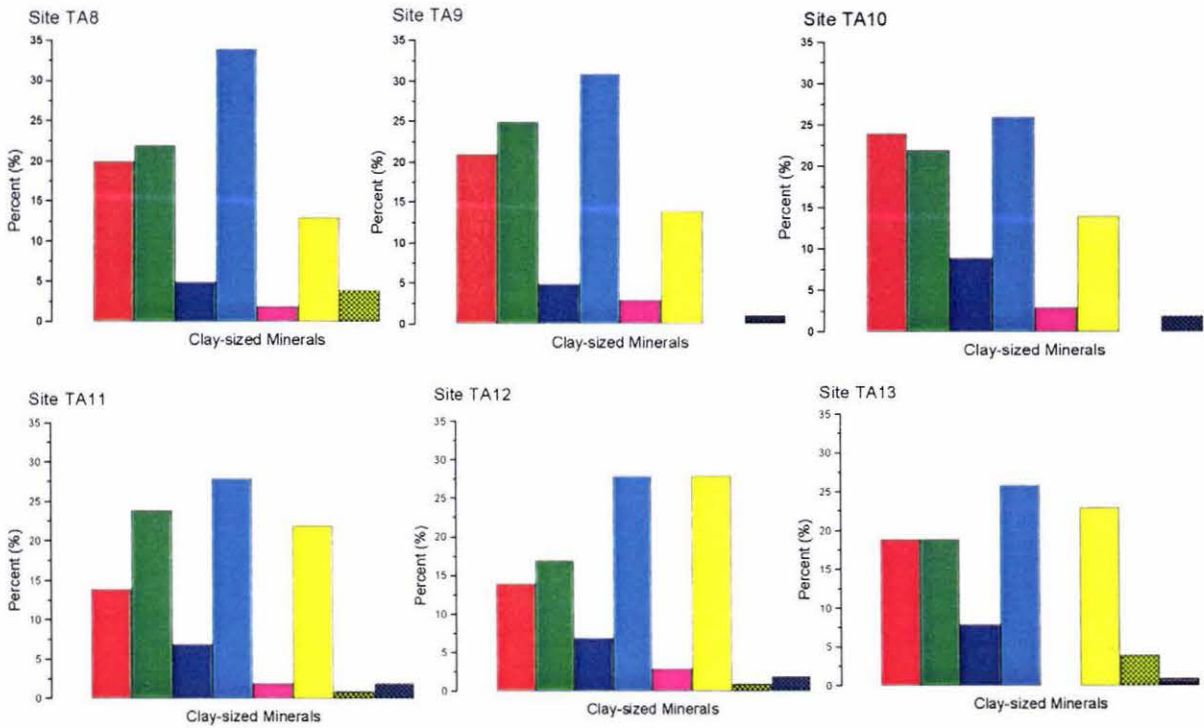


Figure 3.2.9 Comparison of clay mineralogy of pebbles collected from the Te Arai Land System: a) TA8, b) TA9, c) TA10, d) TA11, e) TA12, and f) TA13.

MINERAL	Site TA8 (%)	Site TA9 (%)	Site TA10 (%)	Site TA11 (%)	Site TA12 (%)	Site TA13 (%)
Quartz	20	21	24	14	14	19
Feldspar	22	25	22	24	17	19
Kandite	5	5	9	7	7	8
Mica	34	31	25	28	28	26
Chlorite	2	3	3	2	3	0
Smectite	13	14	14	22	28	23
Vermiculite	4	0	0	1	1	4
Mica-Chlorite	0	1	2	2	2	1

Table 3.2.3 Te Arai pebbles clay - size fraction mineralogy, sites TA8, TA9, TA10, TA11, TA12, and TA13.

3.3 SUSPENDED SEDIMENTS

Suspended sediment samples were collected from the main streams flowing into the Waipaoa River (Figure 3.3.1). Samples were collected both by hand and at several unmanned automatic gauging sites (*see* section 2.1), and were analysed using the procedure set out in Chapter 2. This section outlines the results of those analyses.

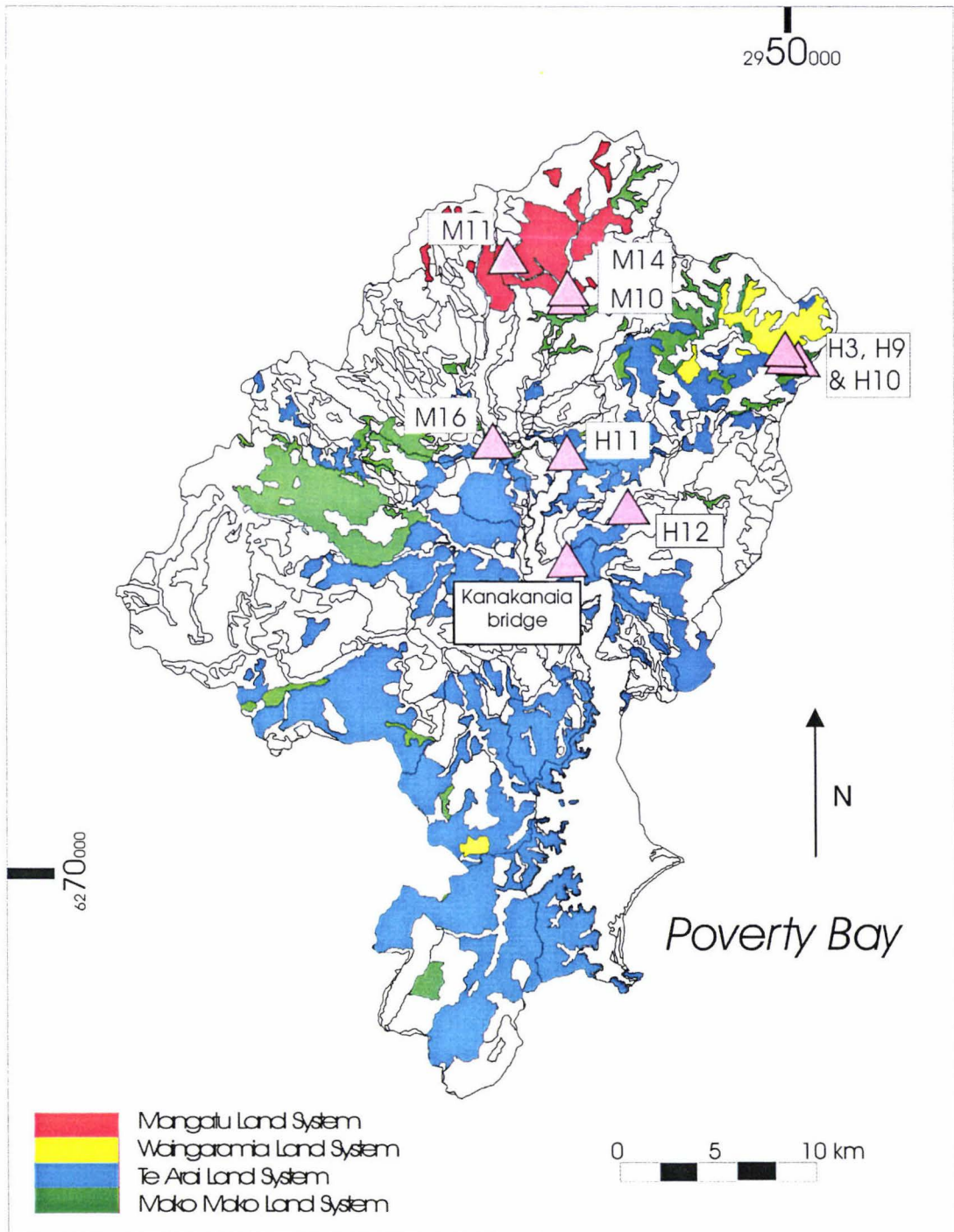


Figure 3.3.1 Waipaoa River catchment overlain by the four chosen land systems and sites where suspended sediment was collected.

3.3.1 *Te Weraroa Stream*

Samples of suspended sediment were taken within the Mangatu Land System, from both the base of the Tarndale Gully (site M11) and on the floodplain just before it joins the Waipaoa River (site M14). The results at both sites are very similar (Figures 3.3.2a & 3.3.2b). Both contained a high percentage of quartz and mica, low feldspar and kandite, and *c.* 15 % smectite. Chlorite, vermiculite and mica-chlorite are present in one or both of the samples (*see* Table 3.3.1).

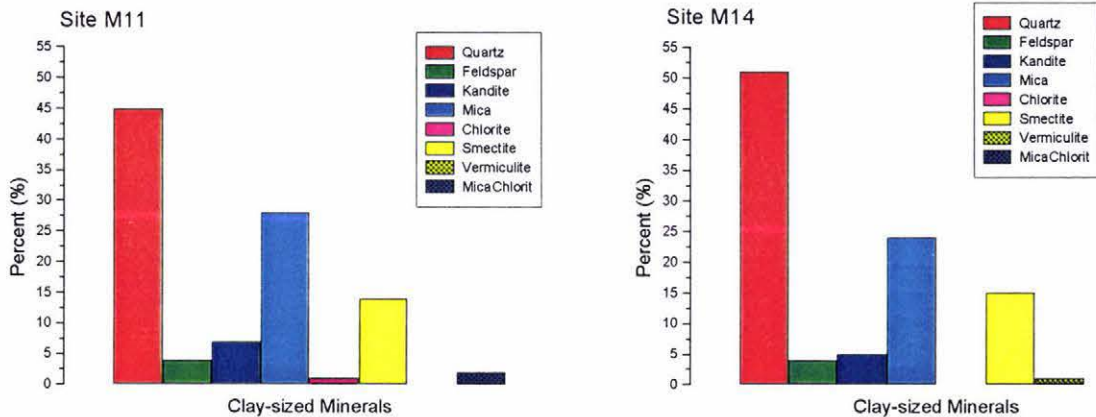
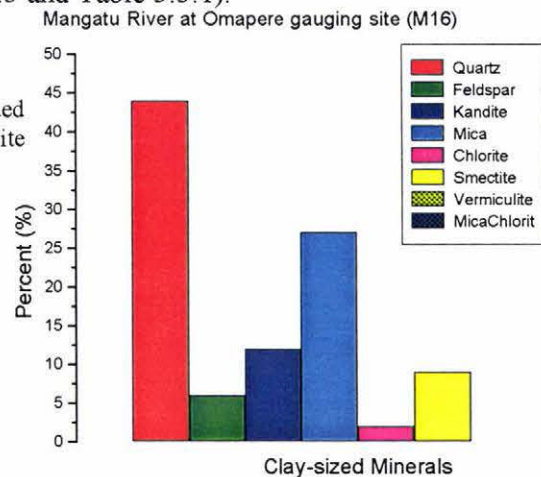


Figure 3.3.2 Clay mineralogy of suspended sediment samples from the Mangatu Land System a) site M11, and b) site M14.

3.3.2 *Mangatu River*

One sample of suspended sediment was obtained from the Mangatu River at Omapere gauging site (M16) (Figure 3.3.1). The clay mineralogy is very similar to that of the Te Weraroa Stream with high quartz and mica, and low feldspar; while kandite is slightly higher at 11 %, and smectite slightly lower at 8 % (*see* Figure 3.3.3 and Table 3.3.1).

Figure 3.3.3 Clay mineralogy of the suspended sediment sample collected at Omapere gauging site (M16).



MINERAL	Te Weraroa Stream (%)	Mangatu River (%)
Quartz	46	44
Feldspar	3	6
Kandite	5	12
Mica	30	27
Chlorite	1	2
Smectite	13	9
Vermiculite	1	0
Mica-Chlorite	1	0

Table 3.3. 1 Comparison between Te Weraroa Stream and Mangatu River clay mineralogy.

3.3.3 Waingaromia River

One suspended sediment sample (site H10 – Figure 3.3.4a) was collected at the head of the Waingaromia River. Two other samples of sediment from the headwaters of the Waingaromia River have been included in this section as concentrated contribution of sediment to the streams, this sediment was not yet directly in the stream flow. The first sample (site H3 – Figure 3.3.4b) was collected in a small tributary where a stream of mud was trickling or oozing out of the base of a small gully directly into the stream and having an immediate effect on the water quality. The sample at site H9 (Figure 3.3.4c) was collected from a tributary farther down stream, from a mud pond, at the base of an active mudflow. The results for these samples are similar, except that H9 has a considerably higher content of vermiculite 21 % (Figure 3.3.4c). All results are tabulated below (Table 3.3.2).

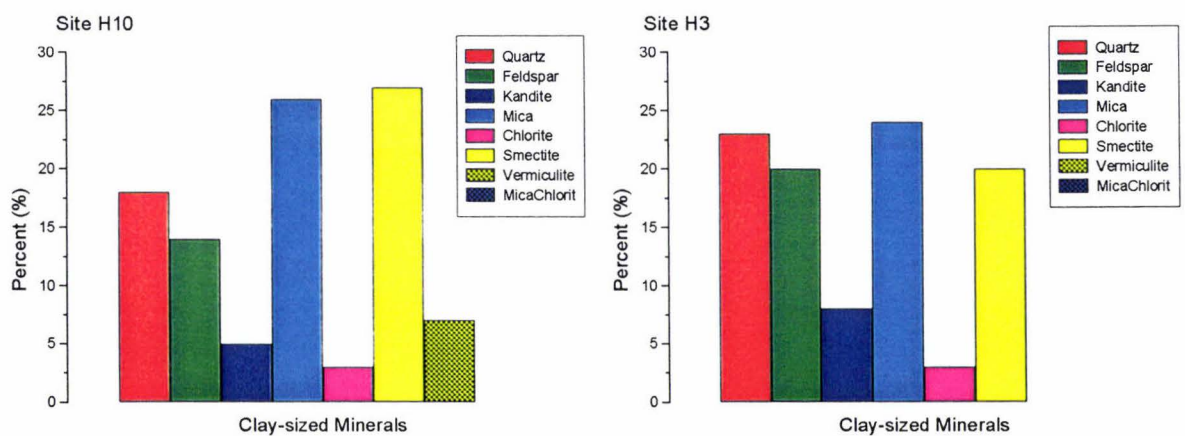


Figure 3.3.4 Clay mineralogy at sites a) H10 and b) H3.

No suspended sediment was obtained from the lower part of this river due to low river flow at the time of fieldwork, but a sample of riverbank material was collected for analysis based on the assumption that it was the remnant of the last high flow deposition. The sample was collected

from Te Hau Rd (site H11 – Figures 3.3.1 & 3.3.4d.) and the results, similar to those at site H9, are included in the following table (Table 3.3.2).

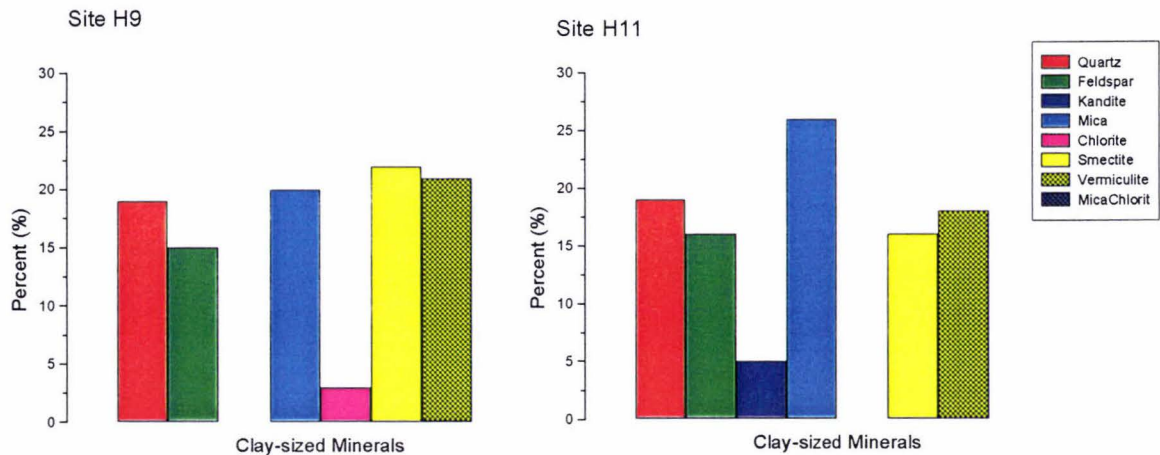


Figure 3.3.4 c) Clay mineralogy of sediment collected at site H9, d) clay mineralogy of sediment collected at site H11.

MINERAL	Site H3 (%)	Site H10 (%)	Site H9 (%)	Site H11 (%)
Quartz	23	18	19	19
Feldspar	20	14	15	16
Kandite	8	5	0	5
Mica	24	26	20	26
Chlorite	3	3	3	0
Smectite	20	27	22	16
Vermiculite	0	7	21	18

Table 3.3.2 Comparison of clay mineralogy between suspended sediment and concentrated sediment samples within the Waingaromia Land System

3.3.4 Waihora River

A sample of suspended sediment was collected from the Waihora River (M9), which flows into the Waipaoa River at Kanakanaia (Figure 3.3.1). The results were comparable to those from the Waingaromia River, and have been graphed (Figure 3.3.5) and tabulated (Table 3.3.3).

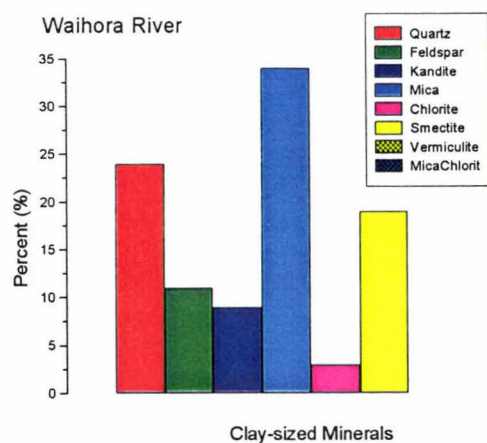


Figure 3.3.5 Clay mineralogy of suspended sediment collected from the Waihora River (M9).

3.3.5 Waipaoa River

A sample of suspended sediment and a sample of riverbank material were collected at the Kanakanaia gauging station (Figure 3.3.1). At this point many of the small tributaries have joined the main stem of the Waipaoa River and the mineralogy is likely to be well mixed. Both samples contained high quartz and mica, smectite, and low feldspar and chlorite (Table 3.3.3). The main difference between the suspended sediment and riverbank samples is in the content of kandite, the suspended sediment contained 5 % and the riverbank material contained 14 % (Figures 3.3.6a & b; Table 3.3.3).

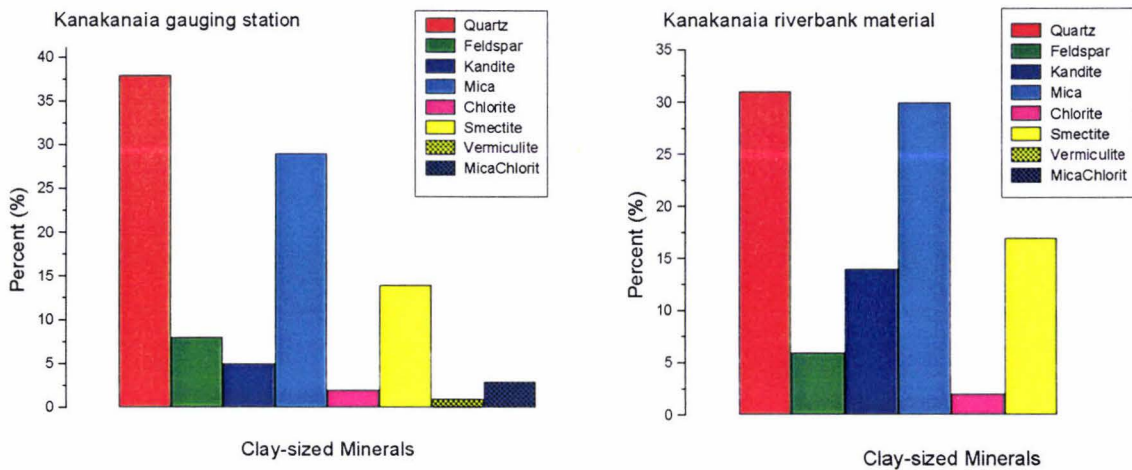


Figure 3.3.6 Clay mineralogy of samples collected at Kanakanaia bridge, a) suspended sediment from Kanakanaia gauging station, b) riverbank material from river.

MINERAL	Waihora River (%)	Kanakanaia Sus. Sed. (%)	Kanakanaia Rvrbk Mat. (%)
Quartz	24	38	31
Feldspar	11	8	6
Kandite	9	5	14
Mica	34	29	30
Chlorite	3	2	2
Smectite	19	14	17
Vermiculite	0	1	0
Mica-Chlorite	0	3	0

Table 3.3.3. Comparison of clay mineralogy of suspended sediment and riverbank material collected from beneath Kanakanaia bridge, Te Karaka.

3.4 CORES

McPhail's Bend, Ormond, and Matawhero cores (Figure 3.4.1) were taken on the low terraces of the Waipaoa River. The marine core, MD2122, is located in 62 metres of water 18 km SE of Gisborne (Noel Trustrum *pers. com.*, 2001), in an area where Waipaoa River sediment is expected to accumulate (*see* section 2.1.4). Samples thought to represent overbank deposits from flood peaks, were taken from the Ormond and McPhail's Bend cores. The Matawhero and marine cores were analysed every three centimetres from the top of the core until the Taupo pumice was reached at 210 cm in the Matawhero, and 300 cm in the marine core. The four sites where the cores were collected are shown in Figure 3.4.1.

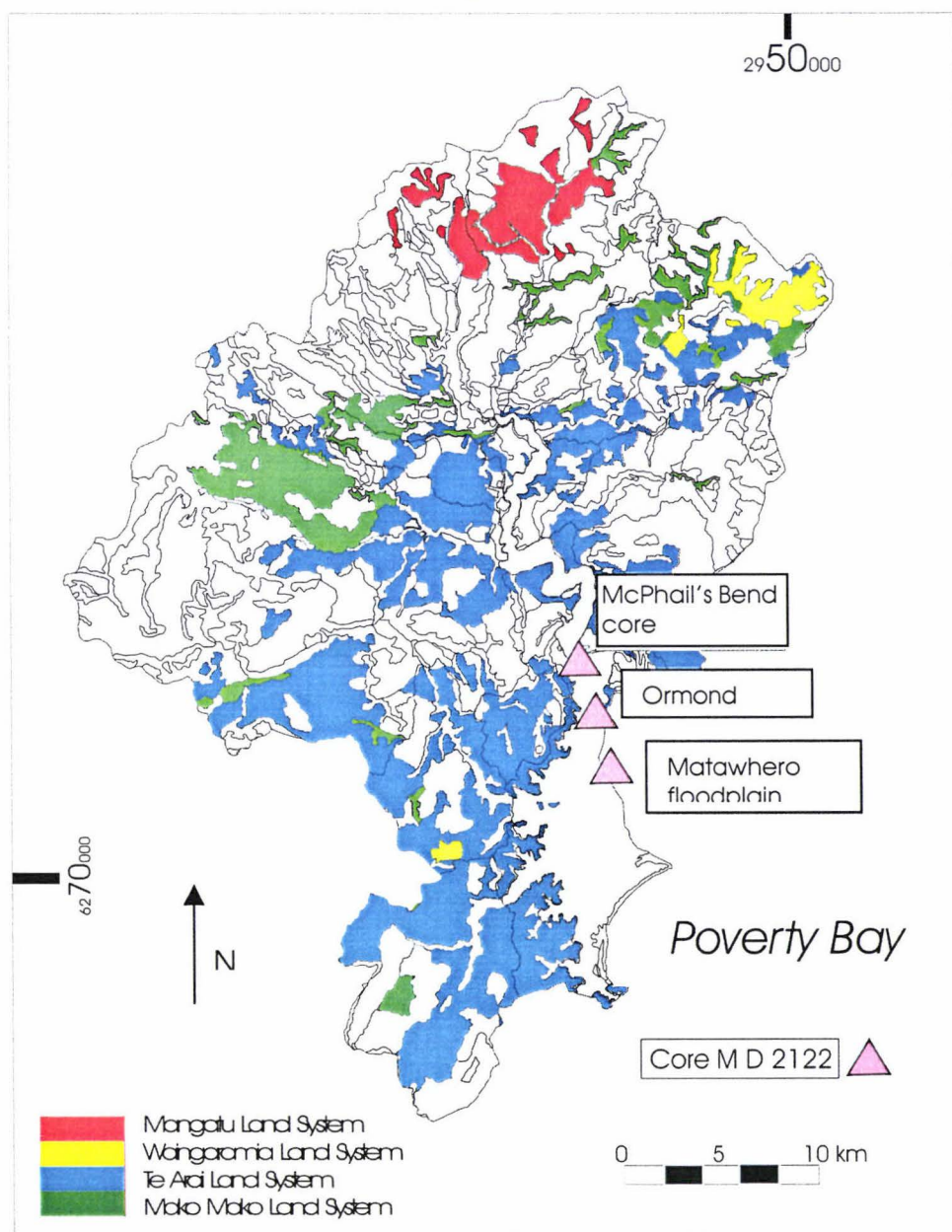


Figure 3.4.1 Waipaoa Catchment core sites.

3.4.1 McPhail's Bend Core

The McPhail's Bend and Ormond cores were sampled in sediment fluxes believed to represent flood overbank deposits (*see* section 1.4). Gomez *et al.* (1988) identified these layers and estimated ages which fitted with known flood records. The following graphs demonstrate mineralogy on an axis of time not depth, to fit with the established stratigraphy.

Few trends are evident with the samples analysed from the McPhail's Bend core. Little quartz, feldspar, kandite, chlorite and vermiculite are present within the clay of these flood deposits compared with the more prominent minerals mica and smectite (Figure 3.4.1) (Table 3.4.1). Quartz and feldspar are much lower in this core than in the bedrock, pebbles, and suspended sediment analysed from within the catchment area; while vermiculite and mica appear higher than most. Since 1840 the sediment coming down the river has been relatively uniform. Sediment derived from the 1988 Cyclone Bola flood show a peak in the mica content (47 %) (Figure 3.4.1d), and very low quartz (8 %), feldspar (3 %), and kandite (4 %) (Figures 3.4.1a, b, c). Smectite (29 %), chlorite (4 %), and vermiculite (6 %) results fall within the middle of their ranges (Figures 3.4.1 e, f, g) (Appendix IV).

Figure 3.4.1a

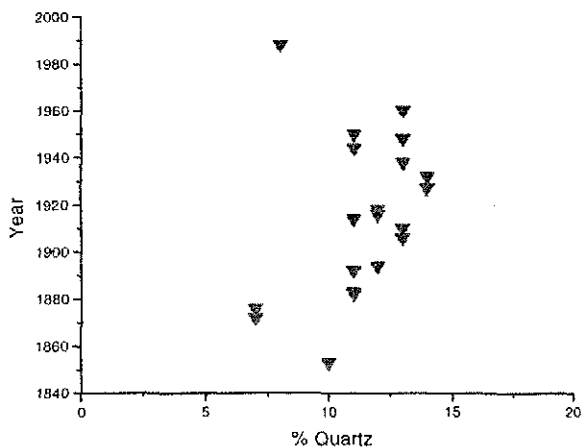


Figure 3.4.1b

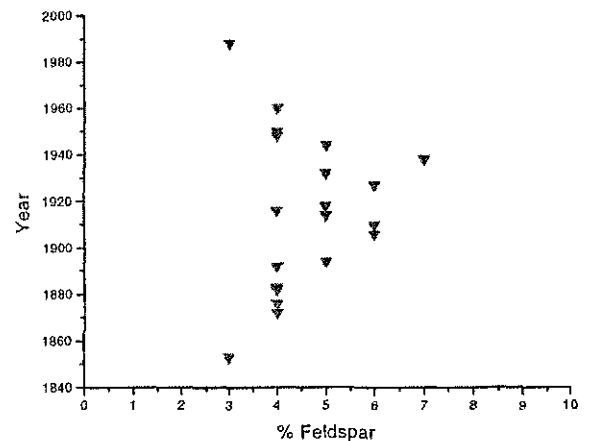


Figure 3.4.1c

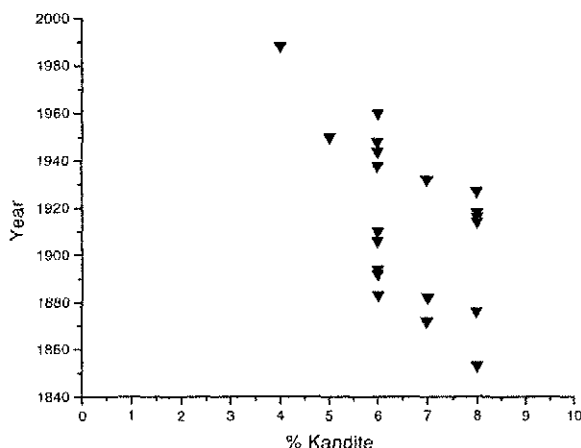


Figure 3.4.1d

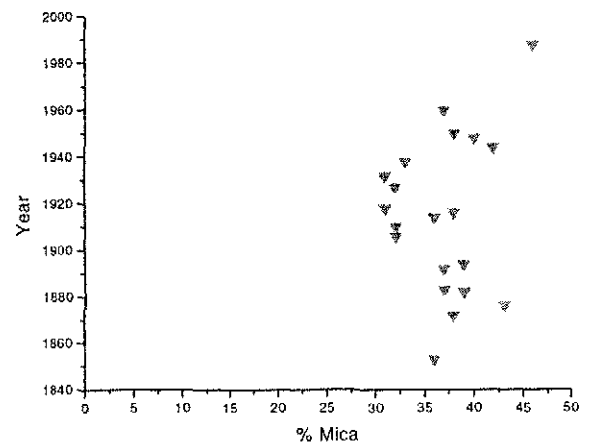


Figure 3.4.1e

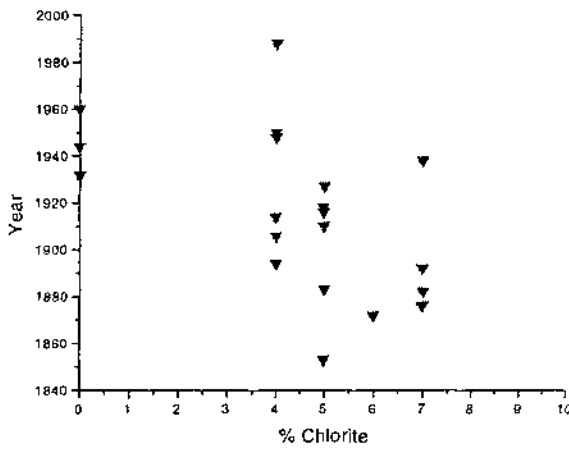


Figure 3.4.1f

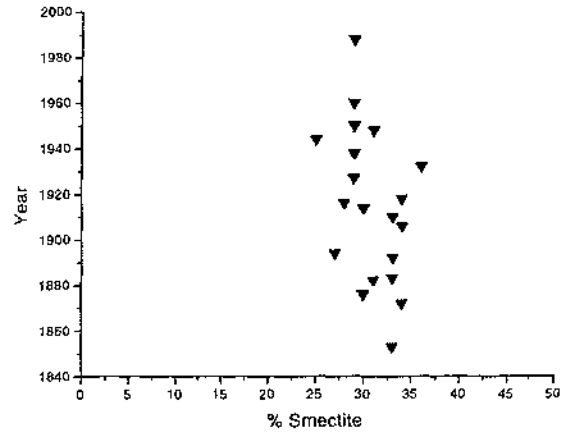


Figure 3.4.1g

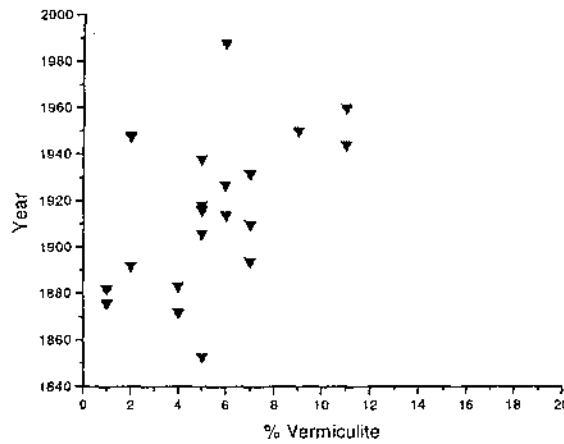


Figure 3.4.1 Clay mineralogy of sediment influxes within the McPhail's Bend core, a) quartz %, b) feldspar %, c) kandite %) d) mica %, e) chlorite %, f) smectite, and g) vermiculite %.

YEAR	Quartz %	Feldspar %	Kandite %	Mica %	Chlorite %	Smectite %	Vermiculite %
1988	8	3	4	46	4	29	6
1960	13	4	6	37	0	29	11
1950	11	4	5	38	4	29	9
1948	13	4	6	40	4	31	2
1944	11	5	6	42	0	25	11
1938	13	7	6	33	7	29	5
1932	14	5	7	31	0	36	7
1927	14	6	8	32	5	29	6
1918	12	5	8	31	5	34	5
1916	12	4	8	38	5	28	5
1914	11	5	8	36	4	30	6
1910	13	6	6	32	5	33	7
1906	13	6	6	32	4	34	5
1894	12	5	6	39	4	27	7
1892	11	4	6	37	7	33	2
1883	11	4	6	37	5	33	4
1882	11	4	7	39	7	31	1
1876	7	4	8	43	7	30	1
1872	7	4	7	38	6	34	4
1853	10	3	8	36	5	33	5

Table 3.4.1 Mineralogy of clay-sized fraction sediment in McPhail's Bend core.

3.4.2 Ormond Core

Three sediment samples were analysed from the Ormond core, those believed to represent the 1948, 1960, and 1988 Cyclone Bola flood. The results of these analyses (Table 3.4.2) are very similar to those of the McPhail's Bend core. High mica and smectite contents dominate the mineralogy and are accompanied by a little quartz, feldspar, kandite, chlorite, vermiculite and mica-vermiculite.

YEAR	Quartz %	Feldspar %	Kandite %	Mica %	Chlorite %	Smectite %	Vermiculite %	Mica-Vermiculite %
1988	14	5	4	38	5	28	6	0
1960	11	4	7	35	5	31	7	0
1948	12	5	6	31	4	28	6	8

Table 3.4.2 Mineralogy of clay-sized fraction sediment in Ormond core.

3.4.3 Matawhero Floodplain Core

The mineralogy of the top 210 cm of the Matawhero core appears to be uniform. There is little variation in the content of quartz (Figure 3.4.3a), feldspar (Figure 3.4.3b), kandite (Figure 3.4.3c) and chlorite (Figure 3.4.3e). Mica (Figure 3.4.3d) ranges between 15 - 65 % and decreases slightly at depth, while smectite (Figure 3.4.3f) ranges between 14 - 55 % with a general increase with depth. Vermiculite also increases slightly (Figure 3.4.3g) towards 210 cm within the range of 0 - 20 % (Appendix IV).

Figure 3.4.3a

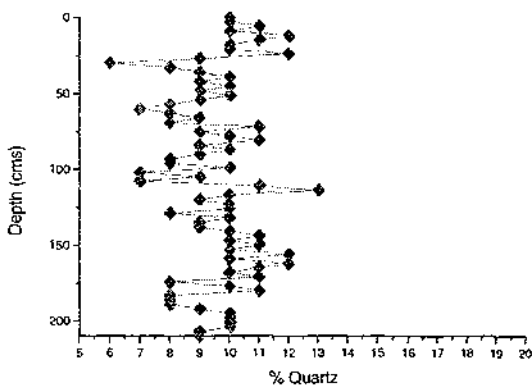


Figure 3.4.3b

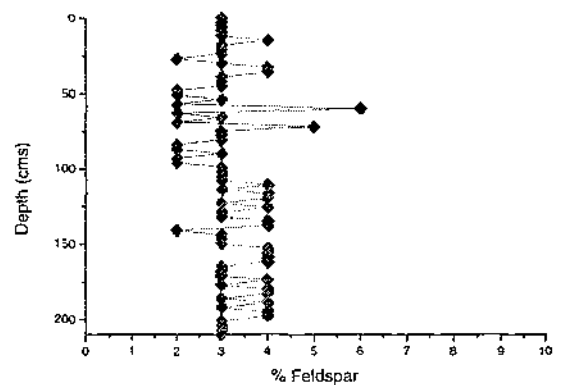


Figure 3.4.3c

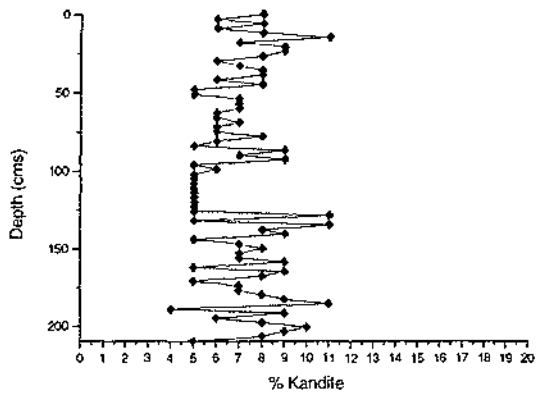


Figure 3.4.3d

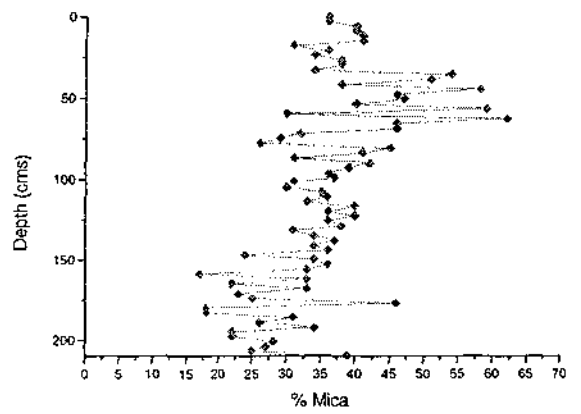


Figure 3.4.3e

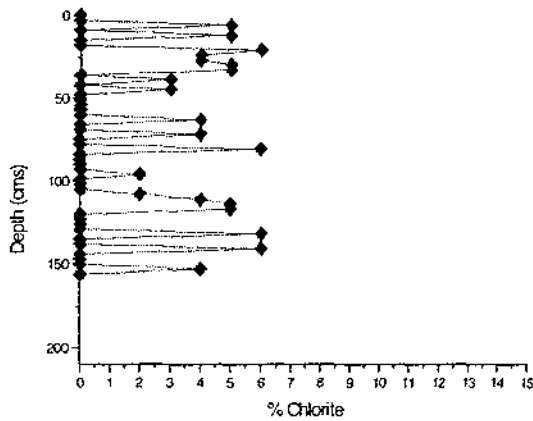


Figure 3.4.3f

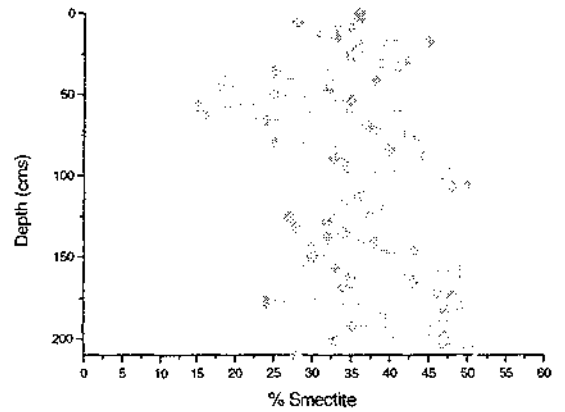


Figure 3.4.3g

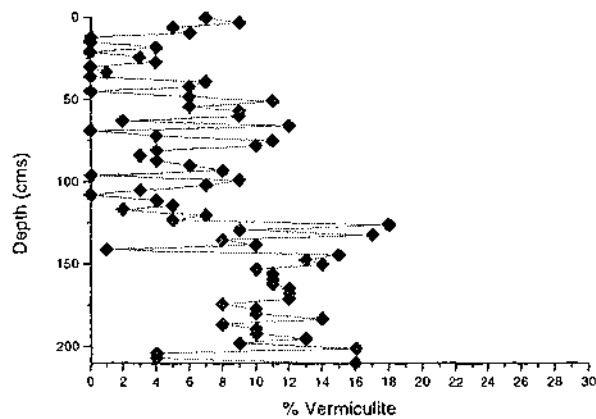


Figure 3.4.3 Clay mineralogy of 210 cm of sediment from the Matawhero floodplain core, a) quartz %, b) feldspar %, c) kandite %, d) mica %, e) chlorite %, f) smectite, and g) vermiculite %.

3.4.4 Poverty Bay Marine Core

The top three metres of the Poverty Bay marine core (sediment preserved above the Taupo pumice), like the Matawhero floodplain core, shows little trend in mineralogy, but some variation is noted. Quartz, kandite, mica, chlorite and vermiculite (Figures 3.4.4a, c, d, e, g) all show a general uniformity with depth. While feldspar (Figure 3.4.4b) also demonstrated little variation from its mean, two points stand out significantly: 91 cm and 273 cm. Smectite (Figure 3.4.4f) too, showed little variability down the three-metre section. All the minerals present showed an evidential drop with the inclusion of the Taupo pumice at 297 cm (Appendix IV).

Figure 3.4.4a

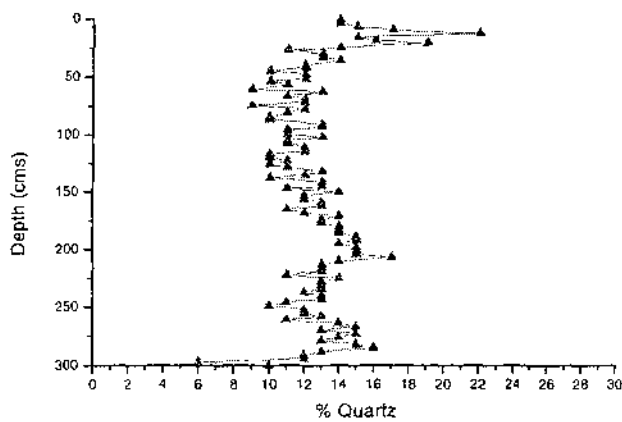


Figure 3.4.4b

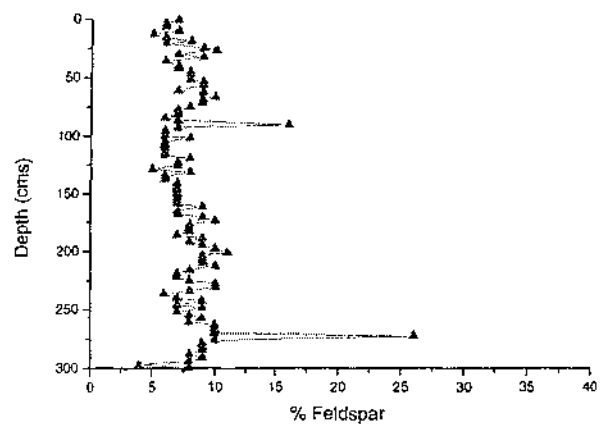


Figure 3.4.4c

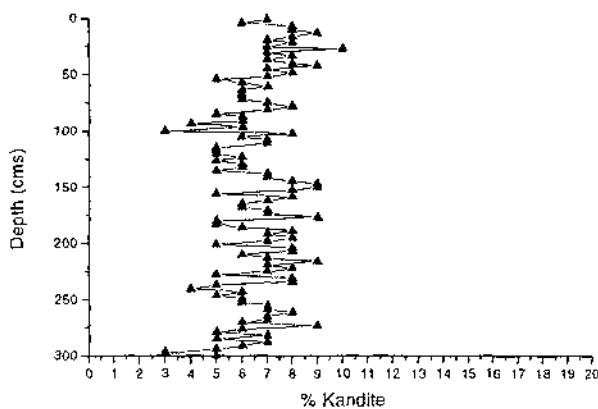


Figure 3.4.4d

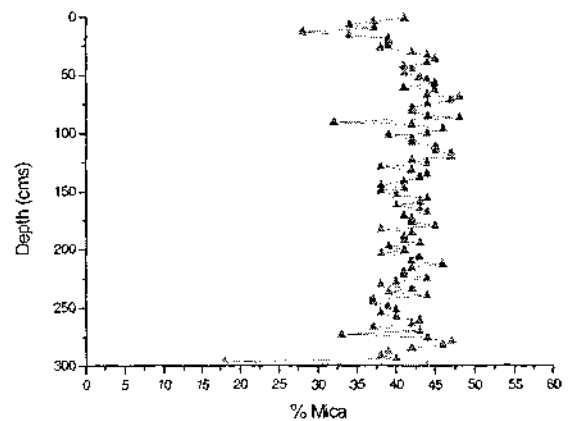


Figure 3.4.4e

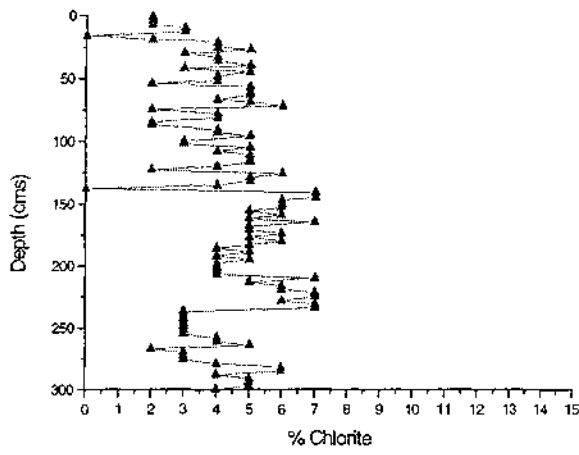


Figure 3.4.4f

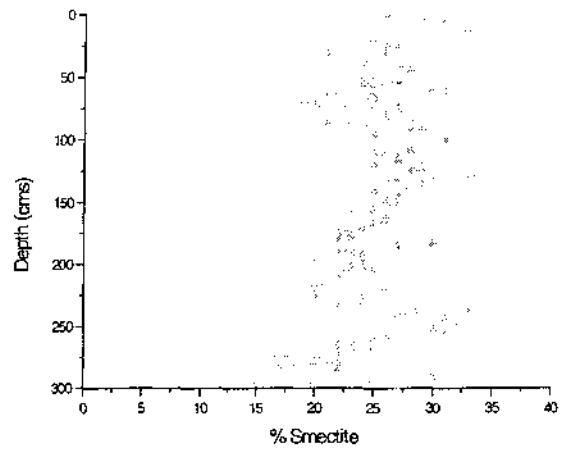


Figure 3.4.4g

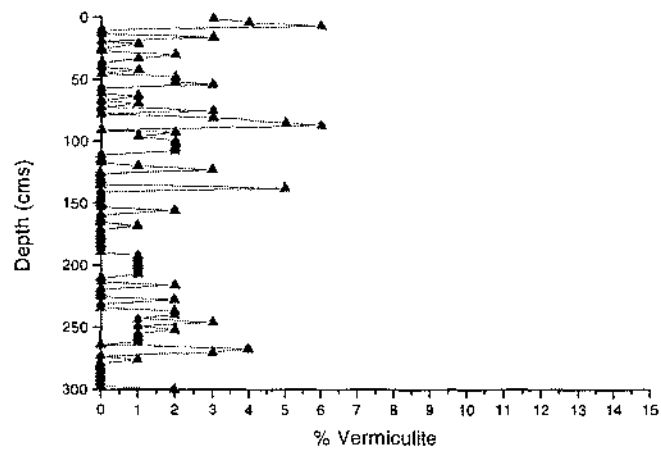


Figure 3.4.4 The mineralogy of the clay-sized fraction of sediment sampled from the Poverty Bay marine core a) quartz, b) feldspar, c) kaolinite, d) mica, e) chlorite, f) smectite, and g) vermiculite.

CHAPTER 4: DISCUSSION

Deforestation in the early twentieth century uncovered a vital weakness in the structure of the Waipaoa River catchment. Landslides and gullies following deforestation of the head waters led to increased sedimentation in the rivers, aggrading stream beds (shallower and wider streams), flooding, and decreased fertility of the plains. Initial erosion consisted of the soil mantle being removed through landslides, but in some catchments, exposure and gullying of soft bedrock followed. Gullies were active prior to human intervention and deforestation. In the East Coast landscape there are features that resemble fossil gullies that were probably active many thousands of years ago. At Mangatu just below the skyline known as the Birches, there are old gullies that were probably active at the time of the formation of the airstrip terrace (14700 yrs BP) and these possibly supplied most of the sediment currently stored as the Rerewhakaaitu terrace (Mike Marden, *pers. com.* 2001). Although sedimentation was reduced due to the forestry programme (*see* section 1.1), erosion is ongoing. The aim of this study is to ascertain if clay mineralogy is a contributing factor to the style of erosion occurring; and if so can the sediment eroding from both landslides and gullies be traced downstream from the eroding bedrock sites, to bedload and suspended sediment, onto the floodplains and into the marine environment. Land Systems as devised by Landcare Research (*see* section 1.11.1) were chosen over geological units as they provided the combination of rock type with erosion type and severity, and at the time of sampling design a detailed geological map of the Raukumara area was unavailable.

As clay mineral assemblages are often particular to lithologies, and considered to be an underlying factor of much erosion (*see* section 1.12), mineralogy was chosen as the form in which sediment would be studied. Bedrock, bedload, suspended sediment, and core material was analysed by x-ray diffraction, and the results will be discussed here.

4.1 BEDROCK

In the stated aims and objectives of this thesis, it was postulated that land systems dominated by landslide erosion may have different clay mineral assemblages to those dominated by gully erosion. The Tarndale Gully complex is an extreme example of a predominant erosion type in the crushed argillite (e.g. Whangai Formation) lithologies of much of the East Coast. Does clay mineralogy play a role?

In this study, from numerous fresh and weathered samples from the Mangatu Land System, I found a high content of quartz (45 – 65 %), in comparison to other clay-sized minerals present in the bedrock (*see* section 3.1). These findings agree with an early attempt by Lillie (1953) who calculated > 50 % quartz, 10 % feldspar and about 25 % clay minerals, as well as results by Nelson and King (1978). Nelson and King (1978) estimated that the clay – sized fraction of bedrock from the Mangatu Formation (*Mangatu Group* - Mazengarb & Speden, 2000) consisted of 40 % quartz, 40 % clay minerals and 5 % plagioclase, with smectite (montmorillonite) and mica (illite) dominating the clay minerals.

In contrast Claridge (1960) and O'Byrne (1967) found smectite varying from 10 – 45 % in the Whangai Formation (Haumurian – Teurian argillites). Nelson and King (1978) attributed the varying results of their study to that of Claridge (1960) to analytical procedure; this is possibly the case for the results obtained from this study. Although smectite is a minor component, Nelson and King (1978) postulated that its distribution was affected by structural deformation, and not directly related to parent material as smectite content decreased with distance from the fault lines within the same lithology.

One of the main differences in technique between this study and previous ones is the manner in which size fractions were separated and analysed. The data set out in previous papers (Claridge, 1960; Nelson and King, 1978) is discussed as separate clay minerals and non – clay mineral populations within the clay fraction, hence the difference in figures. The methodology adopted for this study involved separating each size fraction (*see* section 2.2.2) and analysing each in the same manner. Each size fraction was then discussed. By doing this, the mineralogy and each size fraction from the whole sample is considered, therefore allowing any trends between fractions to be identified.

The Tarndale Gully complex has formed in the Whangai Formation. This Late Cretaceous –

Paleocene hard siliceous mudstone accumulated in an extensive ocean basin at bathyal depths (Figure 1.3.1) (Wilson, Morgans & Moore, 1989), and is now found between two crush zones of local faults. Figure 1.3.2 illustrates the four major faults in the headwaters of the Waipaoa River: Te Waka, Te Weraroa, Wheturau, and Waipaoa Fault. The shearing of the bedrock by this tectonic movement has enabled water to penetrate the jointing, creating a zone of weakness, much like soggy weetbix. The small amount of cohesive layered clay minerals present (*c.f.* quartz) may also prove to reduce strength of the bedrock. From this we can deduce that the reason for the Tarndale Gully complex is not due to high quantities of swelling clays but to its position in the fault zone.

The bedrock mineralogy of the Mangatu Land System is significantly different than that of the Te Arai, Waingaromia, and Mako Mako Land Systems (Figure 4.1.1)(*see* section 3.1.1).

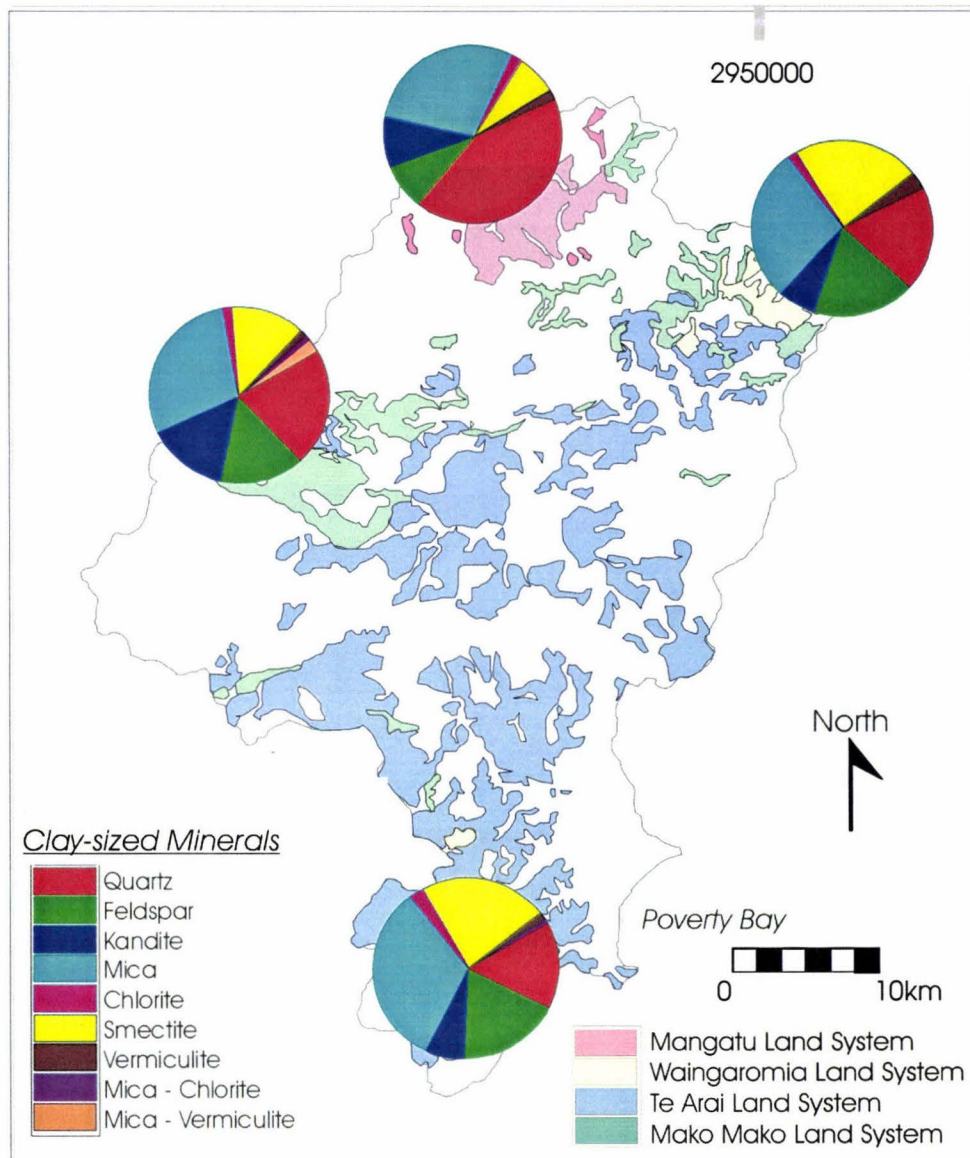


Figure 4.1.1 Clay mineral signatures for Mangatu, Waingaromia, Te Arai, and Mako Mako land systems depicted by the combination of bedrock results from within each land system.

Page *et al.* (1999) considered the Waingaromia Land System (Figure 2.1.1) to be landslide prone, but work since this time has shown much of the landsliding shutting down due to intensive forestry planting (Mike Marden, *pers. com.* 2002). For this thesis the extensive gullies were sampled as the major active erosive process. The Huanui Forest area (Waingaromia Land System) has had all gullies and landslides mapped to assist with forestry plans (Mike Marden, *pers com.* 2000). Despite targeting gullies for planting, active slumping and earthflows within the gully confines are still occurring, muddy water flows from the base of the gullies, and the pine trees have developed hockey stick shaped trunks. The Waingaromia Land System is part of Mazengarb & Speden's (2000) Miocene Tolaga Group (Figure 1.3.1) of marine mudstone, and is primarily exotic forestry. Observations during field sampling noted extensive gully systems that are now planted in pine, and slow moving slumping around the head and sides of the gullies. Samples were taken from areas experiencing intensive gullying; in several places mud was collected as it was oozing out of the base of the forming gullies. The mineralogy of this land system is very different from that of the Mangatu Land System. Mica and smectite are the two most prominent minerals in the clay fraction. While both mica and smectite averaged 30 %, smectite ranged from 0 – 48 %, between stable ridge tops (0 %) and active gullying (48 %).

The main connection between the large deep-seated gullies in both the Mangatu and Waingaromia Land Systems is the extensive faulting and deformation that has occurred (Figure 1.3.1). It may be that the shearing and crushing have created zones of weakness that when subjected to constant wetting and drying, fail, creating these gullies. Pearce *et al.* (1981) suggested that acid – sulphate weathering of pyrite and the subsequent leaching of calcite cement may explain the continuing sediment production from the Tarndale Gully complex; the degree of crushing may be the underlying factor for the penetration of acid solutions. The strength of the rock is reduced as the leaching occurs, which in turn produces a shallow smectite – rich regolith of low strength. However, no pyrite was detected in bedrock samples collected for this thesis, and no smectite – rich regoliths were encountered either. This may be due to varying sampling or analytical procedures. Nelson and King (1978) did however note persistent amounts of calcite (5 – 15 %) in their study.

The gully dominated Waingaromia Land System demonstrates mineralogy very similar to that of the landslide dominated Te Arai Land System (both Tolaga Group) (Figure 4.1.1), and yet they are both prone to, and experiencing, different types of erosion.

The Te Arai Land System (Figure 2.1.1) was chosen to represent areas prone to land sliding.

The landscape itself is moderately to steeply sloping and predominantly in pasture and exotic forestry, except for a small area that remains in native forest. The geology is dominantly mudstone with minor sandstone of Late Miocene age (Tolaga Group, Figure 1.3.1). Unlike the Mangatu Land System, the mineralogy consists of predominantly smectite and mica, with slightly more feldspar than quartz (Figure 4.1.1). The only significant difference between fresh and weathered bedrock in this land system is in feldspar; the fresh bedrock has higher feldspar than does the weathered sample. This is evidence of the feldspar weathering away and being replaced by clay minerals e.g. smectite.

The other land system chosen to represent an area prone to landsliding was the Mako Mako Land System (Figure 2.1.1), steeply sloping pastureland. Although Page *et al.* (1999) rated the Mako Mako Land System as potentially prone to severe landslide erosion, the clay mineralogy (dominated by mica and feldspar), shows little evidence of swelling clays (Figure 4.1.1). There is also little difference between fresh and weathered samples. Because of these observations the Mako Mako Land System is not considered to represent landslide prone hill country. Therefore, conclusions made are mostly a result of data collected from the Te Arai Land System.

The silt fractions from all the land systems bedrock samples followed the same trends; quartz, feldspar, and chlorite were present in larger quantities than other clay minerals in the bedrock silt fractions due to their larger size (Figure 3.1.4). Mica, smectite and vermiculite in comparison contributed little. The sand fraction for every sample was similar, consisting of quartz, feldspar and generally less than 10 % of any clay mineral component (Figure 3.1.5). Sand fractions from the Mangatu Land System bedrock samples generally have higher quartz than samples from the other land systems (Figure 3.1.5), possibly showing that the Whangai Formation has experienced greater weathering than the younger Miocene sediments within the Te Arai, Waingaromia, and Mako Mako land systems. Conversely it may be evidence of a more quartz – rich source material as compared to the younger formations.

Clay mineralogy appears to be a factor in the occurrence of the shallow landsliding within the Tolaga Group sediments (Te Arai and Waingaromia land systems). The high content of smectite evident in both land systems, appears characteristic of the Tolaga Group sediments, and is considered here to be a major element in the ongoing landslide erosion. Without the vegetation to secure the soil and prevent substantial infiltration of water into the bedrock, the smectites readily expand on wetting, weakening the hillslopes.

The Waingaromia Land System (Tolaga Group) however, experiences both gully and landslide erosion, and unlike the Mangatu has a greater amount on smectitic clays in the bedrock. From analyses obtained in this project, it has been deduced that there are no mineralogical differences between areas actively gullying and areas prone to landslides (*see* section 4.5). Mineralogy is no doubt one of the key factors in bedrock stability and erosion (*see* section 1.12.2), but it is only one factor, consideration must be taken of slope (e.g. steepness), drainage (e.g. permeability and overland flow), aspect (e.g. sunshine hours and wind factor), and tectonics (Table 1.10.1). The underlying question remains, would gullying be occurring in the Mangatu Land System if the lithology had not been crushed by tectonics? Both the Mangatu and Waingaromia Land Systems are rated as prone to severe - extreme gully erosion, and are areas of steep hill country bounded by major faults (Figure 1.3.1). The Te Arai Land System (in the south of the catchment) in comparison is moderate to steep land and has not experienced faulting and uplift to quite the same extent (Mike Page *pers. com.* 2001, Mazengarb & Speden, 2000).

It was hypothesised in the introduction that the regolith and fresh bedrock would be mineralogically different due to the weathering process. Minerals such as vermiculite might form from weathered mica and leached smectite, which could then allow periods of soil removal (e.g. landsliding) as opposed to gullying to be recognised in bedload and floodplain cores. However, the results show that mineralogical differences between fresh and weathered samples are generally insignificant. The only evidence of mineralogical differences between fresh and weathered bedrock was in the Te Arai Land System where the fresh rock had higher quantities of feldspar than the weathered bedrock, presumably this is due to the lack of weathering of primary minerals. The Mangatu Land System has less quartz in the weathered bedrock compared with the fresh bedrock samples. There is no explanation for this but Pearce *et al.* (1981) noted a similar result.

Although land systems are grouped on the basis of several key factors, including rock type (Page *et al.*, 1999), they are not restricted to specific geological units. Variation in clay mineralogy can occur within a land system. Samples were collected from three sites outside the four targeted land systems. The Wharekopae Land System consists of massive and bedded mudstone and sandstone units prone to severe landsliding (Page *et al.*, 1999). Site H4 (Figure 3.1.1) is on the eastern side of the catchment on the margin of the Huanui Forest, and samples at sites M12 and 13 (Figure 3.1.1) were also collected from the Wharekopae Land System but in Mangatu Forest (Tarndale Gully area). Site H4 is mapped as mid - Late Cretaceous Matawai Group (Karekare Formation), while the other two are from the Miocene Tolaga group. The

mineralogy is very different between these two stratigraphic units. The main difference is that the smectite content is 0 % in both fresh and weathered samples at site H4 and averages 32 % at sites M12 and M13 (*see* Appendix I). To prevent such wide variation and ensure particular lithological groups were hit, samples were collected from restricted areas of the catchment.

4.1.1 Provenance

There has been some discussion of the provenance of the East Coast sediments. Kingma (1962) and Suggate *et al.* (1978) both support the idea of an eastern source during the deposition of the Cretaceous – Teurian Whangai Formation, the source then shifted to the west for the deposition of later sediments. This theory was based on the observation of mica quantities between the older and younger sediments, sediments deposited after the Teurian had less mica, so a source change was envisaged. Smith (1982) observed both mica and smectite decreasing upwards within the Whangai Formation with the increase of chlorite, although Fergusson (1985) concluded that stratigraphically there were no trends in clay mineralogy within the east coast formations. Moore (1988) says there is no evidence to support the concept of an eastern landmass based on clay mineral distribution patterns.

The results in this study show that there is a significant difference in mineralogy between the sediments of the Late Cretaceous and those of Miocene age. Heavy mineral analyses carried out in this study provide strong support for differences observed within the clay minerals. The Whangai Formation (Tinui Group) contains predominantly chlorite, zircon and mica (*see* Appendix III). Although the Tolaga Group heavy minerals also contain chlorite, zircon, and some mica, other minerals such as hypersthene, epidote, ilmenite, rutile, augite, hornblende, and magnetite are present in addition. These heavy minerals commonly occur as detritus within sediments derived from metamorphic or igneous rocks.

The Tolaga Group is most likely derived from the Torlesse terrane material that was uplifted during the Rangitata Orogeny in the Early Cretaceous and eroded during a major phase of tectonism. A mafic igneous conglomerate at the base of the Tolaga Group (some of which are probably sourced from the Matakaoa Basaltic sequence – Mazengarb *et al.*, 1991) has contributed gabbro, diorite and pyroxenite boulders into the formation. These igneous intrusions were emplaced during the early Miocene (Mazengarb *et al.*, 1991) and based on heavy minerals within the Tolaga Group sediments (*see* appendix III) could well be a source for at least some of the material.

4.2 PEBBLES

Pebbles were collected from the bedload from each land system (*see* section 3.2.1). It is hypothesised that bedload downstream will demonstrate mineralogy of upstream bedrock, so the flow of sediment can be traced from source until the point of mixing with other waters. The problems faced when tracing or following mineralogical signals downstream involve the mechanical abrasive action of the river; the reduction of pebble size can be influenced by selective destruction of particular lithologies e.g. argillite breaking down by wetting and drying, and exposing minerals to weathering. Mixing of sediment or bedload occurs as tributaries join the main river system. Streams such as the Te Weraroa Stream contribute large quantities of sediment into the Waipaoa River; this can dominate the suspended sediment or bedload fractions downstream. The higher flow rate may increase the mechanical abrasion of pebbles, and the braided river systems (e.g. upper Waipaoa River) create a broad plain conducive to the wetting and drying (and hence weathering) of pebbles. The predominant mineral would be the most resistant, i.e. quartz.

During the process of preparation for analysis, all the pebbles had to undergo a degree of crushing (not grinding). Care was taken to cause as little damage to grain size as possible, but this must be taken into consideration. The most prominent effect of breaking grains would be reducing the size of larger minerals e.g. quartz, increasing its quantity in the smaller size fractions i.e. clay fraction. Although all pebble samples were treated in the same manner and the differences in mineralogy presented here should be consistent, consideration must be made of the varying hardness of pebbles and the effort required in crushing them.

Pebbles are a difficult medium to sample. The two problems encountered during sampling were pebble size and number. Small pebbles were selected as larger ones would have been physically impossible to prepare for analysis. Also all lithologies had to be represented in the sample on the basis of quantity in the streambed. Samples had to be crushed for analysis, so mixing of lithologies created a homogenous sample. It is assumed that as lithologies were sampled on the basis of quantity, this homogenous mixture will give a representative mineralogy of the bedload.

The pebbles appear to be consistent with trends demonstrated by the fresh and weathered bedrock samples. The Tikiore Formation (Figure 1.3.1) bedrock and stream pebbles have a

similar mineralogy: 55 – 60 % mica and quartz, a mixture of clay minerals, and feldspar. The Tikihore Formation appears to have a strong influence on bedload mineralogy in the Tikihore Stream and Upper Waipaoa River (Figure 1.1), as the mineralogy of pebbles collected from the Tikihore Stream and from the upper Waipaoa River (*see* section 3.2.1) have a similar mineralogy.

Bedload analysed from the Te Weraroa Stream (Mangatu Land System) (Figures 1.1 & 2.1.1) has a very strong mineralogical signal consisting of very high quartz, common mica and less than 10 % of other clay-sized minerals. This trend is followed down stream to the braided riverbed of the Waipaoa River. The Mangatu River flows from the base of the Mangatu Gully which shares an interfluv with the Tarndale Gully. As expected the Mangatu River bedload sample produced the same clay mineralogical signal as that of the Te Weraroa Stream. The Te Weraroa Stream and the Mangatu River appear to have a significant effect on the bedload of the Waipaoa River. The clay – sized fraction mineralogy of pebbles collected at site M7 (Figure 3.2.1) produce a similar signal to that of the upper tributaries (Te Weraroa S. and Mangatu R.), high quartz, 20 % mica and minor feldspar, kandite, and smectite. This suggests that the Mangatu and Tarndale gullies are major sediment sources for Waipaoa alluvium. Kasai *et al.* (2001) support this notion, saying that gullies are the main source of sediment to the streams. Estimates by Page *et al.* (2000) (*see* section 1.10) state that gullies are responsible for more than half of the annual sediment yield, supporting this conclusion. Rosser (1997) noted that the Cretaceous sandstone, siltstone, and argillite dominates the Waipaoa River throughout it's length in all size fractions, so therefore dominates the bedload material. Rosser (1997) goes on to report that from bedload particle size, there is no evidence of gravel transferring from tributaries such as Waingaromia, Waihora, and Waikohu, into the main river system.

Pebble samples from the Waingaromia Land System (Figure 2.1.1) have more feldspar than do pebbles from the headwaters (e.g. Te Weraroa Stream), while the Waihora River (Figure 1.1) shows a dominance of mica and quartz. Pebbles collected from the Waikohu River (Mako Mako Land System) (Figure 1.1) have complex mineralogies. The bedrock mineralogy from this area contains little smectite, so it not surprising that only one pebble sample from the Mako Mako Land System contains smectite (site MM5, Figure 2.1.1).

Pebble mineralogy in the Te Arai Land System (Figure 2.1.1) is different from other land system pebble samples in the Waipaoa Catchment. All tributaries flowing into the Te Arai River have *c.* 10 % smectite in the pebble clay - sized fraction, except for Waimata Stream (20

%) (Figure 1.1). The Te Arai River itself has 20 – 25 % smectite and slightly less quartz than the tributaries. In comparison to bedrock from the Te Arai Land System, all the tributary pebble samples (except for the Waimata Stream) have lower smectite in the clay - sized fraction. Besides this, the bedrock and pebble clay – sized fraction mineralogy is very similar.

Pebble data when viewed collectively demonstrate one particular trend. Pebbles collected from the Mangatu Land System (*Whangai Fm., Tinui Gp.*) are mineralogically different from those collected from the Waingaromia, Mako Mako, and Te Arai land systems (Tolaga Group - stratigraphic unit). Pebbles from the Mangatu formation contribute a high content of quartz to the headwaters, while farther downstream the Tolaga group contributes mica, smectite and feldspar.

4.3 SUSPENDED SEDIMENT

Suspended sediment was collected where possible, but due to low flow during fieldwork many tributaries were not sampled. Some material was obtained during high flows from unmanned gauging stations at Kanakanaia bridge (Figure 4.2.1) and Omapere (site M16, Figure 3.3.1). Suspended sediment is important as it represents a large bulk of the material flowing through the system at all times (Page *et al.*, 2000), and it is this sediment that overtops the stopbanks during flooding (Gomez *et al.*, 1999). Over time as this sediment builds up it can be used in stratigraphic interpretations of historical storm events. Gomez *et al.* (1999) interpreted sediment influxes in the core at McPhail's Bend as storm deposits over the last century (*see* sections 1.4, 1.9, 2.1.2, 3.4.1).

Suspended sediment taken from the Te Weraroa Stream (Figure 1.1) directly reflects the clay mineralogy of the bedrock and pebbles already discussed. There is a slightly higher content of smectite (*c.* 5 % more) in the suspended sediment (Figure 4.3.1), but apart from this, mineralogy is very similar to that of both bedrock and pebbles. Heavy minerals in the suspended sediment collected from this area, are present in amounts less than 3 %. Irion (1991) suggests that this is normal in highly mature sediments.

Suspended sediment at site H10 and mud at site H3 (Figure 3.3.1) emulates the clay mineralogy of bedrock sampled within the Waingaromia Land System (Figure 4.3.1). The pebbles too are comparable, differing only in the greater amount of quartz at the expense of smectite. The

sample taken at site H9 (Figure 3.3.1) was from a mud pond, at the base of an active mudflow and at site H11 (Figure 3.3.1) silty riverbank materials, evidence of deposition from the last high flow, were collected. These samples are different from the others, as vermiculite was present (*see* section 3.3.4), inferring terrestrial weathering (Alan Palmer, *pers. com.* 2001). The sediments deposited in both the mud pond and on the Waingaromia Riverbank are likely to have been sourced from a mature soil mantle. The riverbank material would have been deposited in the previous storm/flood event, therefore is most likely derived from shallow landslide erosion (soil mantle removal) and not gullying, hence the presence of vermiculite. The sediment from the mud pond resulted from slumping and earthflow at the margin of a new - forested gully. It too was from a soil mantle on a steep slope.

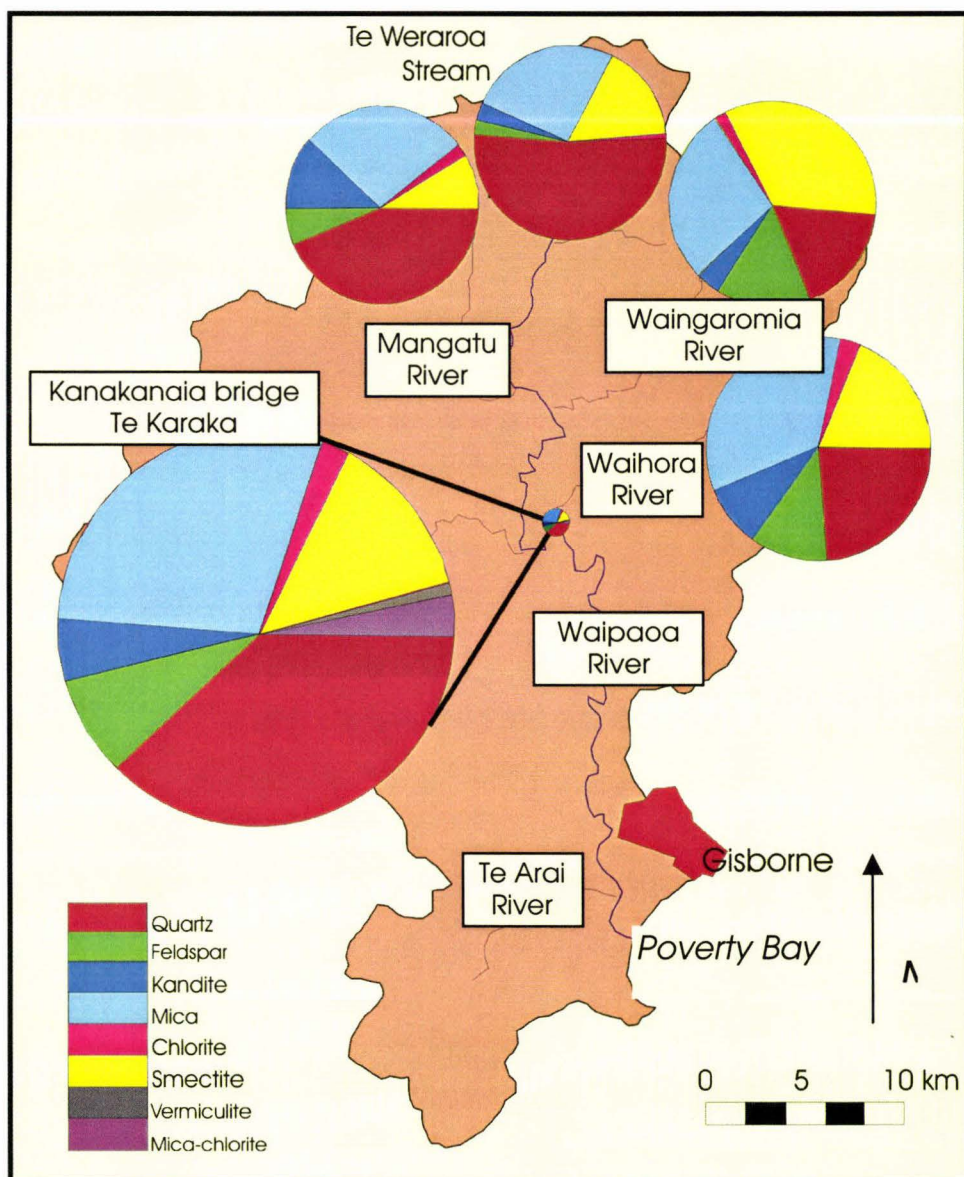


Figure 4.3.1 The clay mineralogy of suspended sediment from the Te Weraroa, Mangatu, and Waingaromia Rivers is demonstrated upstream, and at the point where these three rivers meet in the Waipaoa River – Kanakanaia. The Waihora River meets further downstream in the Waipaoa River.

Two different samples were collected from the Kanakanaia Bridge (Figure 3.3.1) under which the Waipaoa River flows: one suspended sediment at the gauging station and one riverbank clay sample. The clay fractions of the two samples did produce slightly different mineralogy, as the riverbank material had almost 10 % higher kandite than the suspended sediment. A very small quantity of mica-chlorite and more quartz are present in the suspended sediment sample. The sample of suspended sediment bears a strong resemblance to the pattern presented by suspended sediment in the Te Weraroa Stream and Mangatu River: high quartz, followed by mica and smectite. However, the quartz is at least 10 % lower than samples from those sites, showing that some dilution with other minerals from incoming waters has occurred.

Unfortunately no suspended sediment was able to be collected from the Te Arai Land System because of the clear low flow during sampling. During periods of high rainfall, shallow landslides are activated and the soil mantle sediment removed from the hill slopes may enter the river system (*see* section 1.10.4). It may be that suspended sediment from the Te Arai Land System will resemble earthflow sediments from the Waingaromia Land System, as both areas share the same parent material/bedrock (Tolaga Group marine sediments).

At low flow the Waingaromia River is still producing large amounts of suspended sediment with mineralogy characteristic of the Tolaga Group, but at low flow the Te Arai River, which also drains an area of Tolaga Group sediments, runs clear. The reason for this is the active gully erosion in the Waingaromia Land System, but none in the Te Arai Land System, which instead is landslide prone. The Te Arai Land System does not experience the constant stream of sediment provided by gully erosion to the river system (*see* section 1.10.4), instead landslides occur during high intensity rainfall events. Much of the available loose material is carried away at this time, including the pebble fraction of the bedload. Between intense rainfalls, the landslide debris and scar are re-vegetated enough to retard sediment generation.

In Figure 4.3.2 just the bedrock and suspended sediment data is graphed. These figures clearly show the relationships of the clay minerals and the effects of mixing; in contrast to Claridge (1960) who concluded that clay mineral assemblages could not be traced downstream.

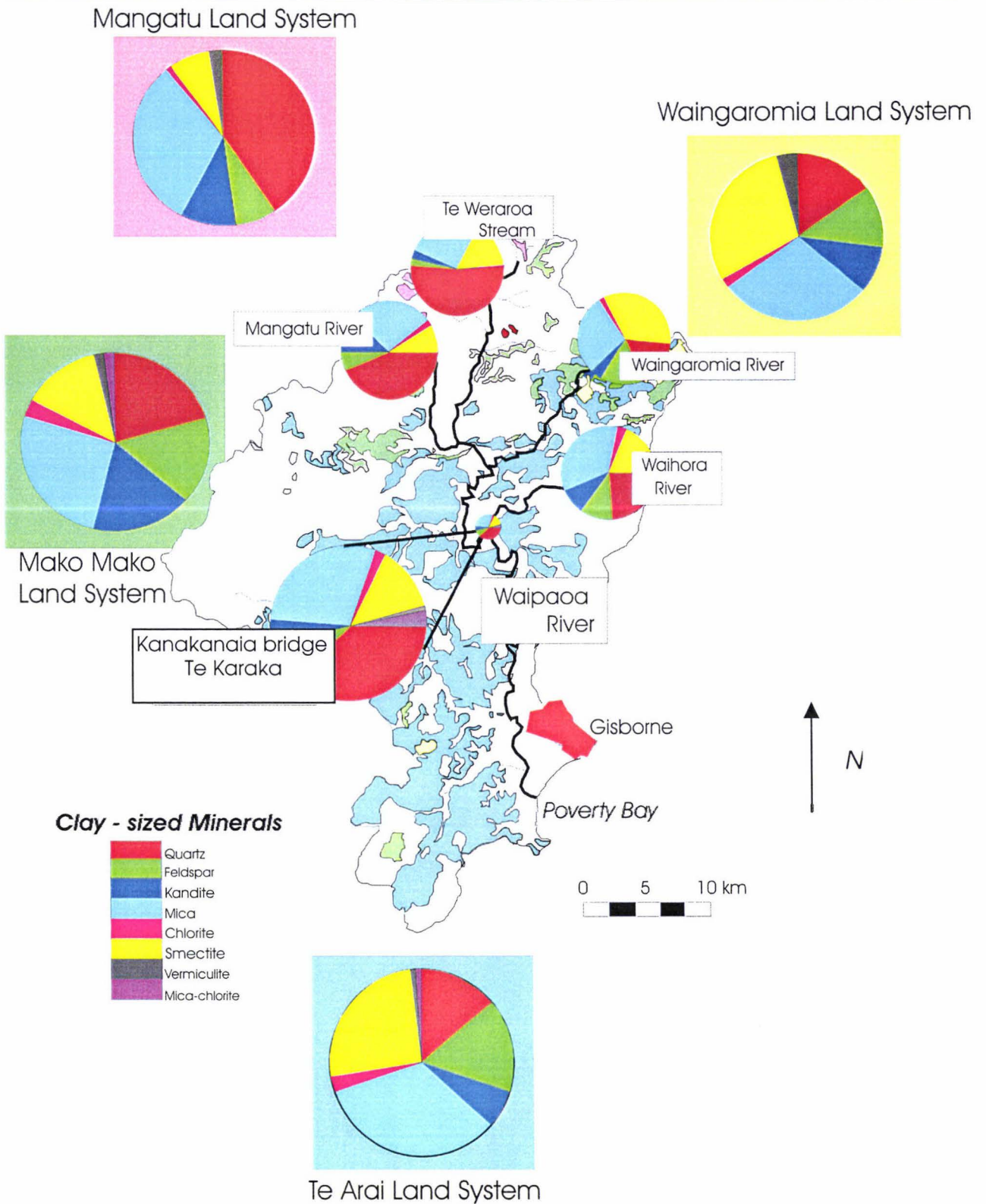


Figure 4.3.2 Suspended sediment and bedrock data pictured here demonstrates the close relationship between eroded bedrock and sediment in the river system. Sediment from the Mangatu Land System clearly dominates the suspended sediment of the Waipaoa River, although mixing occurs at the junction of the Waingaromia River.

Page *et al.* (1999) suggested that once rainfall reaches a certain threshold, landslides are initiated (*see* section 1.10.1); therefore in storms such as Cyclone Bola the majority of the sediment travelling through the river system is derived from landslide erosion. Sediment deposited on riverbanks is likely to have been soil mantle from shallow landslides, and will contain clay minerals such as vermiculite. But these storms are infrequent (Table 1.9.1), so landslides are only a minor contributor of sediment over the long - term yield (*see* section 1.10.1). Suspended sediment collected during periods of normal flow therefore reflects the clay mineralogy of the actual annual sediment yield. From the results presented in this thesis, it is postulated that the sediment from the Mangatu Land System (experiencing gully erosion) dominates the mineralogy of the main drainage system, the Waipaoa River.

4.4 CORES

Sediment in the upper part of floodplain and marine cores is thought to represent the increased erosion of the twentieth century and was analysed with this in mind. Sediment interpreted as major storm deposits (Gomez *et al.*, 1999) in the McPhail's Bend floodplain core was extracted and analysed. The sediment samples from storm deposits analysed from McPhail's Bend and Ormond floodplain cores have similar mineralogy. Each influx of flood sediment contains predominant mica and smectite, with minor quartz, feldspar, kaolinite, chlorite and vermiculite. Suspended sediment collected from the Waipaoa River contains large quantities of quartz in the clay - sized fraction, which has been attributed to the Mangatu Land System or Tarndale Gully complex (*Whangai Fm., Tinui Gp.*); and yet its influence is not evident in any of the cores analysed, as quartz is only present in minor amounts on the floodplains. Why is this? Gullies such as the Tarndale and Mangatu, are providing over half the annual sediment yield as they contribute sediment continuously to the river system during small frequent rainfalls (Page *et al.*, 1999). This sediment is flowing through the catchment and not being deposited on the floodplains. The sediment on the floodplains is only deposited when rainfalls are large enough to allow flood protection to be breached. All suspended sediment collected at unmanned gauging stations (e.g. Omapere, Kanakanaia) may not necessarily represent flood conditions, so may have a different source compared with sediment on the floodplain (gully erosion, not landslide erosion) (Mike Page *pers. com.*, 2001).

The higher content of vermiculite in the cores may reflect ongoing stripping of the soil mantle by landslides, as compared with bedrock contributed by gullies. In the Matawhero floodplain

core mica appears to decrease with depth, with a slight increase in vermiculite, this may be evidence of transformation of mica to vermiculite, or the removal of forest soils to the point where landslides are now involving less weathered material.

Clay mineral assemblages in McPhail's Bend and Ormond cores closely resemble that of the Matawhero floodplain core. It is proposed here that sediment within these cores is derived principally from the Miocene aged marine Tolaga Group based on the observation of landslide contribution during flooding (Page *et al.*, 1999) (*see* section 1.10.4). The land systems north of Kanakanaia that would have contributed to this are the Waingaromia, Te Arai, Wharekopae etc. Quartz content in the McPhail's Bend and Matawhero cores is still much lower than that in the Waingaromia and Te Arai land systems. There are possibly two reasons for this: differential settling or dilution. In the case of the cores, differential settling may have caused the quartz to settle out first, perhaps closer to the banking, whereas the lighter clay minerals may have travelled further onto the floodplain and deposited in the area which was cored. As mentioned earlier dilution will be a factor at the debouchure of streams and rivers with the main river system. Suspended sediment from land systems dominated by mica and smectite will dilute the strong signature supplied by the Mangatu Land System (Figure 2.1.1). Further dilution of sediment in the Waipaoa River would occur at the confluence of the Te Arai River, which flows from an area dominated (like the Waingaromia Land System) by the Tolaga Group marine sediments.

Clays in core marine core MD2122 reflect the continuous flow of sediment from the Waipaoa River, a homogenous mix of clay minerals that represent all sediment carried through the river system. It was unexpected then to see so little quartz in the clay mineralogy, this author believes the reason for this is probably the differential settling of larger clay minerals and non-clay minerals closer to shore (Figure 1.7.1). Griffin (1962) described how sediment from large rivers entering the sea can overwhelm the sediment from other sources e.g. where the Mississippi enters the Gulf of Mexico. The Mississippi River has high kaolinite in the fine fraction, and the nearshore marine has more smectite, this has been interpreted as evidence of differential settling; smectite enriches in a seaward direction as the coarser-grained kaolinite settles out first. Porrenga (1966) gave a similar explanation for the Niger Delta. In the Waipaoa River quartz is present in vast quantities and like kaolinite is coarser-grained than the finer clay minerals. Therefore, it could be assumed that its low quantities in the marine core, which is dominated by mica and smectite, is due to differential settling.

It is likely that much of the sediment in the upper part of the cores is derived from the erosion of

the Miocene - Pliocene marine sediments that occurred during the unroofing of Cretaceous bedrock, which now lies elevated at the surface (Colin Mazengarb, *pers. com.*, 2001). Exactly when this occurred is unknown. The marine core studied in this thesis extends only to the last 1800 years so the influence of the unroofing of the Cretaceous sediment may not have been major.

Marine clays in ancient deposits have been used to reconstruct paleoclimates in recent studies, both successfully and unsuccessfully based on the observation that the distribution of clay minerals in modern oceans appears to be climatically controlled in the contemporary environment (Chamley, 1989; Singer, 1984; Thiry, 2000). The factors to consider when attempting this process are many: differentiation in erosion of material, differentiation in transport and differentiation due to size, shape, sorting, and flocculation. Ultimately, distinction between detrital and authigenic minerals must be made. This study does not cover this scope of research, but if mineralogical analysis was carried out on the greater length of the core then these are important variables to be considered when trying to establish a climatic signal. Only the clay mineralogy of sediment above the Taupo pumice in both the Matawhero floodplain core and MD2122 Marine core was analysed. It would be interesting to analyse the clay mineralogy of cores that contain sediment deposited during the last glacial, the transition to the Holocene, and the Holocene.

Major drainage systems mix both eroded bedrock and soil during transport so the mineralogical signal will be clouded (Thiry, 2000). Thiry (2000) has gone to great lengths to demonstrate the difficulty in reconstructing paleoclimates using clay minerals in marine deposits. Differential settling has been used to explain differences in kaolinite, mica and smectite patterns with distance from the river mouths of large rivers and into the marine environment (Thiry, 2000). Great emphasis has been put on the inheritance of minerals from the soil environment into the marine, creating changes in the vertical distribution of clays in the marine environment, hence revealing global climatic changes. Yet climate is not the only factor responsible for the distribution of terrigenous clay minerals, and detrital clays are not the only form present in the oceans; the abundance of smectite in the ocean basins is considered to be in part authigenic (Thiry, 2000). The clay mineral assemblage of core MD2122 does not vary significantly in the top three metres (Taupo pumice is at 297cm), which may mean that the source of sediment and currents carrying it has not changed since the eruption of Taupo Pumice. Smectite within the cores is likely to have been incorporated into the actual formation of the mudstone, prior to any erosion.

4.5 FUTURE WORK

Future analyses should be focused at suspended sediment samples during both high and low flow stages of the Waipaoa River and its tributaries. The main targets would be within the Waingaromia and Te Arai sub - catchment areas. Selected tributaries joining the Waingaromia and Te Arai Rivers should be sampled and should be traced back to identify the erosional processes occurring in the headwaters (Figure 4.5.1). A similar process should be carried out in the Waipaoa River headwaters beyond the Tarndale Gully complex. These analyses would isolate clay mineral signatures from actual erosion sites, as some of these were missed during this study. Within the Waingaromia Land System this would be of particular interest because both gully and landslide erosion is occurring. Suspended sediment would also be collected downstream in the lower reaches of the Waipaoa River to identify any tributary sediment with significant effect on the mineralogical signature.

Pebbles should also be analysed from terraces identified by Berryman *et al.* (2000) and compared with present bedload to look for mineralogical evidence of climate change. It maybe that contributing lithologies have changed during times of glaciations compared with interglacials, resulting in a different mineralogical signature in bedload e.g. erosion could have occurred elsewhere in the catchment area, perhaps from formations no longer evident in outcrop. Comparisons could also be made between terraces in case mineralogies changed between aggradational periods. Pebbles extracted from the surfaces of these terraces may provide a mineralogical signature for the period when aggradation halted, and a warmer period of downcutting commenced. A mineralogical study of pebbles from the aggradational terraces may also augment a provenance study. It is likely that the proportion of Miocene Tolaga Group being eroded has changed in comparison with the Whangai Formation (Tinui Group) as unroofing of the older rocks has progressed with time.

Both the Matawhero core and core MD2122 should be sampled and analysed to their full lengths. Data collected from these analyses should be used in conjunction with pollen data, grain size data, tephrochronology, magnetic susceptibility, and rate of uplift in an attempt to pinpoint significant events in the regions history. This work would address the following questions:

1. has mineralogy changed over time?
2. can paleoclimatic reconstruction be attempted?
3. are we able to establish a glacial verses Holocene signal through mineralogy?
4. is there any evidence of mineralogical changes as uplift has progressed?

If we are able to answer these questions it may be possible to separate the effects of climate from tectonics in relation to the erosion process and answer the ultimate question:

Is erosion due primarily to rock type, climatic control or uplift, or are they equally important?

CHAPTER 5: CONCLUSIONS

The aim of this research was to ascertain if erosion type e.g. landslide or gully erosion, was influenced by the clay mineralogy of the bedrock. Four land systems (two dominated by gully erosion, and two dominated by landslide erosion) were selected from the Waipaoa River catchment to test this hypothesis and to see whether clay mineralogical signatures could be devised for each land system. If mineralogical signatures could be established for the different land systems, they could be traced downstream onto the floodplain and into the marine environment.

The initial findings concern the mineralogy of the four chosen land systems: Mangatu, Waingaromia, Te Arai, and Mako Mako, the first two being dominated by gully erosion, and the third and fourth land systems dominated by landslide erosion. The clay mineralogy of the Mangatu Land System is significantly different from other land systems studied. High quantities of quartz were found in the clay – sized fraction of the bedrock, which is of Cretaceous age. In comparison the Miocene aged Waingaromia, Te Arai, and Mako Mako land systems produced similar mineralogies. From these findings it is concluded that there is no consistent mineralogical difference between areas that experience landslides and those that experience gullying, therefore it is not possible to conclusively attribute downstream or core sediment to either landslide or gully erosion mechanisms.

In previous studies the Tarndale Gully complex (formed in the Mangatu Land System) has been considered to be influenced by a high smectite content in the bedrock. However, here it is concluded that the Tarndale Gully complex is a result of its position in the crush zone between major headwater faults, rather than a predominance of smectite. The dominance of quartz in the clay fraction may exacerbate the lack of cohesion in the crushed argillite and greywacke bedrock.

The clay mineralogy of land systems can be traced downstream into the main Waipaoa River system. The Mangatu Land System is continuously producing sediment through gullying and contributes most the bedload and suspended sediment to Waipaoa River. This is seen in the clay mineralogy of the clay – sized fraction of the suspended sediment and pebbles in the

Waipaoa River. Although some dilution of this Mangatu signature occurs with the incoming waters of the Waingaromia, Waikohu, and Waihora Rivers, it is not great.

The clay mineralogy of both floodplain and marine cores is dominated by mica and smectite. Sediment on the floodplains is largely deposited during high intensity storms, and is thought to be derived from increased landsliding. The mineralogy of these sediments resembles the mineralogy of the bedrock from the Tolaga Group - Miocene aged, Te Arai, Waingaromia, and Mako Mako land systems. Although the mineralogy of core MD2122 (marine core) is similar to that of the floodplain cores, I suspect it is actually derived from the older Cretaceous material of the Mangatu Land System. Differential settling of the clay – sized minerals may explain why the clay mineral assemblage of Core MD2122, is so different to that of the Waipaoa River, even though the river is the ultimate source of the sediment in the core.

Mineralogical data from a core that spanned a glacial/interglacial cycle would need to be obtained before there would be any prospect of clearly identifying a mineralogical signal due to climate change.

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Noel Trustrum: Landcare Research – Palmerston North, 2001.

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APPENDIX I

HUANUI FOREST

FIELD NOTES

- Site H1** **Y16 485127**
Waingaromia River below the Huanui School Site
- Sample:** **H1a)** Weathered blue grey argillaceous bedrock (toe slope of slide on the left at river level),
 H1b) Weathered streamload/bedrock,
 H1c) Unweathered streamload/pebbles.
- Site H2** **Y17 499102**
Weathered profile with tephra cover (3.4 km past the locked gate)
- A 0-22 cm Dark brown sandy loam; very friable.
AB 22-33 cm Mottled dark brown and yellowish brown fine sandy loam; friable; cream cake inclusions of yellowish Waimahia Tephra?
 32-48cm Yellowish brown fine sandy loam; scattered cream cakes of Whakatane Tephra?
 48-83 cm Pale yellowish brown sandy loam; very friable; tephra.
 83-110 cm Very pale yellowish brown tephric sandy loam; slightly firm; undulating boundary.
 110-210⁺ cm Weathered (mottled brown – grey) mudstone and fine sandstone.
- Sample:** **H2a)** Just beneath the Whakatane Tephra (~48 cm),
 H2b) 130 cm (at top of weathered mudstone).
- Site H3** **Y17 531094**
In tributary below quarry. Stream water is clear upstream but the gully is deeply incised (natural gullying?) – 10-40 m cliff (1st sampled), down stream erosion is polluting stream (2nd sample).
- Sample:** **H3a)** Alternating decimetre bedding of brown grey muddy sandstone and blue grey sandy mudstone; dipping upstream @ 15°,
 H3b) Watery mud flowing into the stream.
- NB** **Bedrock was entirely the bedrock that we sampled earlier, therefore did not sample again.**
- Site H4** **Y17 517022**
In outcrop below trig station – may give a minimum age of stabilisation.
- 0-17 cm Black fine sandy loam; friable; tephric.
 17-24 cm White-light brown coarse ash; very friable; tephric; very undulating boundary (10 cm).
E 24-40 cm Pale brown fine sandy loam; becomes coarser towards base (coarse ash).
Bhs 40-67 cm Mottled yellowish brown to dark red brown greasy sandy loam; very tephric near base; yellowish brown lumps of Whakatane Tephra? Coarsely mottled.
 67-105 cm Yellowish brown – olive brown sandy loam; very tephric.

	105-129 cm	Pale yellowish brown (grading down to pale brownish grey) massive sandy loam (ash); firm; mottled; sharp contact.
	129-229 cm	Pale yellowish grey very fine sandy loam (weathered bedrock); mottled; sharp contact.
	229→	Pale olive grey muddy fine sandstone; massive; very firm.
	Sample:	H4a) 60-65 cm, H4b) 100-105 cm, H4c) 120-125 cm, H4d) 140-145 cm, H4e) 229-234 cm.
Site H5	Y17 526093	Quarry
	100 m down from gate at head of gully sampled in first trip.	
	0 cm	Topsoil
Bw1	15 cm	Horizon varies. Yellow brown fine sandy loam (probably includes some ash); well-developed crumb and nut structure; few fragments of grey sandstone.
Bw2	30 – 60 cm	Weathered sandstone; mostly fragments at top and becoming more solid with depth; moderate crumb structure; numerous fragments of sandstone.
Bw3	110 cm	Gradually becoming more solid sandstone; very fractured with brown sandy loam matrix; weak crumb structure.
	R horizon	Very fractured grey muddy sandstone.
	Sample:	H5a) Weathered bedrock; Forestry cover and grass (Bw2), H5b) Fresh bedrock.
Site H6	Y17 526094	
	20 m down the road from site A	
	Sample:	H6a) Fresh bedrock, H6b) Weathered bedrock, H6c) Slump remnants.
Site H7	Y17 524095	Head of Gully
	Sample:	H7a) Weathered bedrock.
Site H8	Y17 522097	
	Sample:	H8a) Fresh bedrock.
Site H9	Y17 522096	Mud pond
	Sample:	H9a) Suspended muddy sediment.
Site H10	Y17 522101	
	Sample:	H10a) Suspended sediment
Site H11	Y17 347018	Te Hau Road
	Sample:	H11a) Silty riverbank material

Site H12	Y17 396974	Waihora Bridge no. 3
	Sample:	H12a) Suspended sediment
Site H13	Y17 486054	Bentonite Mine
	Sample:	H13a) Bedrock/ Clay
Site H14	Y17 443982	Bruce Road Site
	Sample:	H14a) Bedrock

MANGATU FOREST

Site M1	X16 292176-292183	Tarndale Slip – Tarndale Gully complex
	Sample:	M1a) Shattered weathered in-situ bedrock – orange, red, brown sandstone, M1b) Siltstone, M1c1) Fresh bedrock, M1c2) Fresh bedrock, M1c3) Fresh bedrock, M1d) Black powdery substance – possibly magnetite?.
Site M2	X16 293191	One km beyond slip (moving out of the crush zone).
	Sample:	M2a) Reasonably competent fine sandstone or siltstone, M2b) Incompetent very fine sandstone or siltstone (much softer than sample 1).
Site M3	X16 298230	
	Sample:	M3a) Weathered bedrock 1 m below surface, M3b) Unweathered bedrock sandstone 2 m below surface, M3c) Unweathered bedrock siltstone 2 m below surface.
Site M4	Y16 305229	
	Sample:	M4a) Weathered bedrock 1 m below surface; yellow brown fine sand & mud; scattered pebbles(?) <cm in all directions, M4b) Unweathered bedrock sandstone 2 m below surface; possibly some glauconite inclusions, M4c) Unweathered bedrock siltstone 2 m below surface.
Site M5	Y16 332209	
	Sample:	M5a) Weathered bedrock 1 m below surface; yellow fine sand & mud; scattered pebbles(?) <cm in all directions, M5b) Unweathered bedrock sandstone 2 m below surface; possibly some glauconite inclusions, M5c) Unweathered bedrock siltstone 2 m below surface.

Site M6	Y17 315025	Mangatu River – Te Kowhai Road
	Sample:	M6a) Suspended sediment, M6b) Pebbles.
Site M7	Y17 314032	Waipaoa River – Te Kowhai Road
	Sample:	M7a) Suspended sediment, M7b) Pebbles.
Site M8	X17 271943	Waikohu River
	Sample:	M8a) Pebbles.
Site M9	Y17 375962	Waihora River – Kanakanaia Road
	Sample:	M9a) Pebbles.
Site M10	Y16 348146	Te Weraroa Stream meets Waipaoa River
	Sample:	M10a) Suspended sediment, M10b) Pebbles.
Site M11	Y16 300175	Te Weraroa Stream
	Sample:	M11a) Suspended sediment, M11b) Pebbles, M11c) Pebbles.
Site M12	X16 308112	
	Sample:	M12a) Weathered bedrock, M12b) Fresh bedrock.
Site M13	X16 310118	
	Sample:	M13a) Weathered bedrock, M13b) Fresh bedrock.
Site M14	Y16 347150	Te Weraroa Stream (before it meets the Waipaoa R.)
	Sample:	M14a) Suspended sediment, M14b) Pebbles taken from the Waipaoa River just before it meets up with Te Weraroa Stream.
Site M15	Y16 358204	Tikihore Stream
	Sample:	M15a) Pebbles
Site M16	X17 288027	Mangatu River – Omapere Bridge
	Sample:	M16a) Suspended sediment

- Sample: TA13a) Pebbles.
- Site TA14 X18 250571
- Sample: TA14a) Fresh bedrock,
TA14b) Weathered bedrock.
- Site TA15 X18 243563
- Sample: TA15a) Fresh bedrock,
TA15b) Weathered bedrock.

MAKOMAKO LAND SYSTEM

- Site MM1 RERE WATERFALL ROAD
X17 075862 Mokonui
- Sample: MM1a) Blue grey sandy mudstone.
- Site MM2 X17 087861
- Sample: MM2a) Coarse loose tephra in upper horizon, above thick white tephric layer,
MM2b) 1-1.5 m thick white tephric layer,
MM2c) 4-5 m thick light brown mottled soil above parent material.
- Site MM3 X17 083997 Paptu Scenic Reserve
Slip outcrop
- Sample: MM3a) Fresh bedrock,
MM3b) Weathered muddy fine sandstone.
- Site MM4 X17 140954
- Sample: MM4a) Fresh bedrock,
MM4b) Weathered bedrock.
- Site MM5 X17 169934 Waihuka River
- Sample: MM5a) Fresh bedrock,
MM5b) Weathered bedrock,
MM6b) Pebbles.
- Waihuka Bridge no. 3 mudstone overlain by massive gravels (red/brown in colour).
- Site MM6 WHAKARUA ROAD
X17 185011
- Sample: MM6a) Slip outcrop of yellowish grey sandy mudstone

Site MM7	X17 143032	
	Sample:	MM7a) Fresh bedrock, MM7b) Shattered rock, MM7c) Pebbles.
Site MM8	X17 173020	
	Sample:	MM8a) Bedded sandstone (?) – heavily jointed (shattered), MM8b) Sandy mudstone.
Site MM10	X17 231978	
	Sample:	MM10a) Weathered bedrock, muddy fine sandstone
Site MM11	OLIVER ROAD X17 126999	
	Sample:	MM11a) Weathered bedrock, MM11b) Fresh bedrock.
Site MM12	X17 125995	
	Sample:	MM12a) Weathered bedrock, MM12b) Fresh bedrock.

APPENDIX II

GEOLOGICAL CATALOGUE OF SITES

Site	Grid Reference	Landsystem	Rock Type	Map Unit	Stratigraphic Unit	Stratigraphic Age	Description
HUANUI FOREST							
H1	Y16 485127	Waingaromia/Reporua	Mudstone	Marine sediments	Tolaga Group	Mid-Miocene	Mudstone with minor sandstone
H2	Y17 499102	Waingaromia/Reporua	Mudstone	Marine sediments	Tolaga Group	Mid-Miocene	Mudstone with minor sandstone
H3	Y17 531094	Mako Mako	Mudstone Mudstone with minor sandstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
H4	Y17 517022	Wharekopae		Marine (shell)	Matawai Group, Karekare Formation	Early Pliocene	Siltstone, sandstone, tuff
H5	Y17 526093	Waingaromia/Mako Mako	Mudstone	Marine (shell)	Matawai Group, Karekare Formation	Early Pliocene	Siltstone, sandstone
H6	Y17 526094	Waingaromia/Mako Mako	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
H7	Y17 524095	Waingaromia/Mako Mako	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
H8	Y17 522097	Waingaromia/Reporua	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
H9	Y17 522096	Reporua	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
H10	Y17 522101	Reporua	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
H11	Y17 347018	Waipaoa	Mudstone	Marine sediments	Tolaga Group	Mid-Miocene	Mudstone with minor sandstone
H13	Y17 486054	Reporua	Mudstone with minor sandstone	Marine (shell)	Matawai Group, Karekare Formation	Early Pliocene	Siltstone, sandstone, tuff
H14	Y17 443982	Mako Mako	Mudstone with minor sandstone	Marine (shell)	Matawai Group, Karekare Formation	Early Pliocene	Siltstone, sandstone, tuff
MANGATU FOREST							
M1	X16 292176	Mangatu	Mudstone	Marine sediments	Tinui Group, Whangi Formation	Late Cretaceous - Paleocene	Hard siliceous
M2	X16 293191	Waipiro	Mudstone	Marine sediments	Tinui Group, Whangi Formation	Late Cretaceous - Paleocene	Hard siliceous
M3	X16 298230	Mangaolane	Sandstone with minor mudstone	Marine turbidite fan	Ruatoria Group, Tikihore Formation	Late Cretaceous	Alternating sandstone and mudstone
M4	Y16 305229	Mangaolane	Sandstone with minor mudstone	Marine turbidite fan	Ruatoria Group, Tikihore Formation	Late Cretaceous	Alternating sandstone and mudstone
M5	Y16 332209	Mangatu	Sandstone with minor mudstone	Marine turbidite fan	Ruatoria Group, Tikihore Formation	Late Cretaceous	Alternating sandstone and mudstone

M6	Y17 315025	Waipaoa	Gravel	Alluvial		Quaternary	Gravel, sand, siltstone
M7	Y17 314032	Waipaoa	Gravel	Alluvial		Quaternary	Gravel, sand, siltstone
M8	X17 271943	Te Arai	Gravel				
M9	Y17 375962	Te Arai	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
M10	Y16 348146	Waipaoa	Gravel/mudstone	Marine sediments	Tolaga Group	Middle Miocene	Mudstone with minor sandstone
M11	X16 300175	Waipaoa	Gravel	Alluvial		Quaternary	Gravel, sand, siltstone
M12	Y18 308112	Wharekopae	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
M13	Y16 310118	Wharekopae	Mudstone/conglomerate	Marine sediments/marine igneous conglomerate	Tolaga Group	Early Miocene	Mudstone with minor sandstone, igneous conglomerate
M14	Y16 347150	Mangatu/Upper Waipaoa	Mudstone	Marine	Tinui Group	Late Cretaceous	
M15	Y16 358204	Upper Waipaoa/River	Sandstone	Marine Turbidite Fan	Ruatoria/Tikihore	Late Cretaceous	
M16	X17 288027	Waipaoa	Gravel	Alluvial		Quaternary	Gravel, sand, siltstone

TE ARAI LAND SYSTEM

TA4	X18 257501	Wharekopae	Sandstone	Marine turbidite fan	Tolaga Group, Tunanui Formation	Mid-Miocene	Alternating sandstone and mudstone
TA5	X18 247510	Wharekopae	Mudstone	Marine sediments	Tolaga Group	Mid-Miocene	Mudstone with minor sandstone
TA6	X18 235545	Wharekopae	Mudstone	Marine sediments	Tolaga Group	Late Miocene	Mudstone with minor sandstone
TA7	X18 242553	Te Arai	Mudstone	Marine sediments	Tolaga Group	Late Miocene	Mudstone with minor sandstone
TA8	X18 245580	Te Arai	Mudstone	Marine sediments	Tolaga Group	Late Miocene	Mudstone with minor sandstone
TA9	X18 263573	Te Arai	Mudstone	Marine sediments	Tolaga Group	Late Miocene	Mudstone with minor sandstone
TA10	X18 269573	Te Arai	Mudstone	Marine sediments	Tolaga Group	Late Miocene	Mudstone with minor sandstone
TA11	X18 269575	Te Arai	Mudstone	Marine sediments	Tolaga Group	Late Miocene	Mudstone with minor sandstone
TA12	X18 280595	Te Arai	Mudstone	Marine sediments	Tolaga Group	Late Miocene	Mudstone with minor sandstone
TA13	X18 272627	Te Arai/Kanakanaia	Mudstone	Marine sediments	Tolaga Group	Late Miocene	Mudstone with minor sandstone
TA14	X18 250571	Te Arai	Mudstone	Marine sediments	Tolaga Group	Late Miocene	Mudstone with minor sandstone
TA15	X18 243563	Te Arai	Mudstone	Marine sediments	Tolaga Group	Late Miocene	Mudstone with minor sandstone

MAKO MAKO LAND SYSTEM

MM1	X17 075862	Wharekopae/Wharerata	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
MM2	X17 087861	Wharekopae/Wharerata	Sandstone with minor mudstone	Marine turbidite fan	Tolaga Group	Early Miocene	Alternating sandstone and mudstone
MM3	X17 083997	Wharekopae	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
MM4	X17 140954	Whatatutu	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
MM5	X17 169934	Mako Mako/Whatatutu	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone

MM6	X17 185011	Kanakanaia	Greensand	Marine sediments	Mangatu Group, Wanstead Formation	Eocene	Mudstone with minor sandstone
MM7	X17 143032	Kanakanaia	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
MM11	X17 126999	Wharekopae	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone
MM12	X17 125995	Mako Mako	Mudstone	Marine sediments	Tolaga Group	Early Miocene	Mudstone with minor sandstone

APPENDIX III

Disaggregated

CLAY – SIZED FRACTION

		Quartz	Feldspar	Kandite	Mica	Chlorite	Smectite	Vermicu.	Mica-Chl	Mica-Hiv	Mica-Ver.	M-Smec.	Cristoboli.	Allopha.	Baryite	Vol. Gl.	Kao-Sme	Chl-Smec
Huanuí Forest																		
Weathered Bedrock	H2b	24	22	20	26	0	8	10	0	0	0	0	0	0	0	0	0	0
	H4d	18	15	30	19	6	0	12	0	0	0	0	0	0	0	0	0	0
	H5a	15	15	0	26	0	37	7	0	4	0	0	0	0	0	0	0	0
	H6b	19	13	5	38	0	16	9	0	5	0	0	0	0	0	0	0	0
	H7	21	10	5	25	3	26	5	0	0	0	5	0	0	0	0	0	5
Unwthd Bedrock (Fresh)	H4e	17	20	17	33	4	0	9	0	0	0	0	0	0	0	0	0	0
	Bentonite Mine red	35	19	28	6	0	12	0	0	0	0	0	0	0	0	0	0	0
	Bentonite Mine white	35	12	8	11	0	34	0	0	0	0	0	0	0	0	0	0	0
	Bruce Road site H14	9	12	12	40	6	20	1	0	0	0	0	0	0	0	0	0	0
	H5b	13	9	5	32	0	41	0	0	0	0	0	0	0	0	0	0	0
	H6a	11	10	5	34	5	34	1	0	0	0	0	0	0	0	0	0	0
	H8a	14	7	8	23	0	48	0	0	0	0	0	0	0	0	0	0	0
Slip Stuff	H3a	14	15	13	29	4	25	0	0	0	0	0	0	0	0	0	0	0
	H6c	21	6	2	26	3	42	0	0	0	0	0	0	0	0	0	0	0
Mud Slurry (Goop)	H3c	24	21	8	24	3	20	0	0	0	0	0	0	0	0	0	0	0
Tephra	H4a	5	2	1	2	0	0	22	0	0	0	0	10	58	0	0	0	0
	H4b	10	8	0	3	0	0	31	0	0	0	0	0	48	0	0	0	0
	H4c	21	14	7	9	7	0	13	14	0	0	0	0	15	0	0	0	0
Suspended Sediment	Kanakanaia Bridge	38	8	5	29	2	14	1	3	0	0	0	0	0	0	0	0	0
	H10	18	14	5	26	3	27	7	0	0	0	0	0	0	0	0	0	0
Riverbank Material	Kanakanaia Bridge	31	6	14	30	2	17	0	0	0	0	0	0	0	0	0	0	0
	H11	19	16	5	26	0	16	18	0	0	0	0	0	0	0	0	0	0

Mangatu Forest

Weathered Bedrock	M1a	47	7	11	27	0	5	2	1	0	0	0	0	0	0	0	0	0
	M1b	45	4	7	28	1	13	0	2	0	0	0	0	0	0	0	0	0
	M3a	29	12	13	25	2	8	11	0	0	0	0	0	0	0	0	0	0
	M4a	22	9	29	31	0	4	5	0	0	0	0	0	0	0	0	0	0
	M5a	33	11	6	40	0	6	4	0	0	0	0	0	0	0	0	0	0
	M5c	33	9	9	39	0	5	5	0	0	0	0	0	0	0	0	0	0
	M12a	52	6	0	16	0	23	3	0	0	0	0	0	0	0	0	0	0
	M13a	60	2	7	11	1	16	3	0	0	0	0	0	0	0	0	0	0
	M15a	56	9	0	5	0	28	2	0	4	0	0	0	0	0	0	0	0
Unwtd Bedrock (Fresh)	M1c1	61	5	5	22	1	6	0	0	0	0	0	0	0	0	0	0	0
	M1c2	68	3	4	16	0	8	1	0	0	0	0	0	0	0	0	0	0
	M3c	36	11	16	29	1	4	2	1	0	0	0	0	0	0	0	0	0
	M4c	32	8	12	37	0	6	3	2	0	0	0	0	0	0	0	0	0
	M13b	49	3	2	17	0	29	0	0	0	0	0	0	0	0	0	0	0
	M12b	51	1	3	15	0	30	0	0	0	0	0	0	0	0	0	0	0
Fragmented Streambed (mud shards from slip)	M11	47	2	2	32	2	13	2	0	0	0	0	0	0	0	0	0	0
Suspended Sediment	M10a	18	18	10	41	3	10	0	0	0	0	0	0	0	0	0	0	0
	M16 Mangatu@Omapere gauging station	44	6	12	27	2	9	0	0	0	0	0	0	0	0	0	0	0
	Wainora River	24	11	9	34	3	19	0	0	0	0	0	0	0	0	0	0	0
Weathered Bedrock	TA1b	11	10	9	35	2	33	0	0	0	0	0	0	0	0	0	0	0
	TA2a	9	10	7	36	3	35	0	0	0	0	0	0	0	0	0	0	0
	TA2b	19	17	11	30	2	20	1	0	0	0	0	0	0	0	0	0	0
	TA3b	8	11	5	39	4	32	1	0	0	0	0	0	0	0	0	0	0
	TA3	8	14	5	32	4	37	0	0	0	0	0	0	0	0	0	0	0
	TA4c	11	11	19	42	0	12	0	5	0	0	0	0	0	0	0	0	0
	TA6c	14	21	3	19	0	39	4	0	0	0	0	0	0	0	0	0	0
	TA7a	4	3	6	0	0	25	0	0	0	0	0	0	0	0	62	0	0
	TA7b	13	15	5	44	2	19	0	2	0	0	0	0	0	0	0	0	0
	TA8a	14	17	4	41	5	18	0	1	0	0	0	0	0	0	0	0	0
	TA8	14	18	6	30	4	27	0	1	0	0	0	0	0	0	0	0	0

	TA14b	16	22	0	26	0	31	5	0	0	0	0	0	0	0	0	0	0
	TA15b	14	25	8	20	0	31	2	0	1	0	0	0	0	0	0	0	0
Unwthd Bedrock (Fresh)	TA1a	18	16	13	33	2	18	0	0	0	0	0	0	0	0	0	0	0
	TA3a	10	11	4	38	4	33	0	0	0	0	0	0	0	0	0	0	0
	TA5a	18	18	11	34	3	14	0	2	0	0	0	0	0	0	0	0	0
	TA6b	13	21	10	30	2	21	1	0	0	2	0	0	0	0	0	0	0
	TA7	12	23	2	41	6	13	1	2	0	0	0	0	0	0	0	0	0
	TA8c	19	19	7	33	5	16	0	1	0	0	0	0	0	0	0	0	0
	TA14a	14	16	0	32	3	33	0	2	0	0	0	0	0	0	0	0	0
	TA15a	11	14	0	31	3	40	0	1	0	0	0	0	0	0	0	0	0
	Weathered remnants (mud shards from slip)	TA6a	12	23	2	41	6	13	1	2	0	0	0	0	0	0	0	0
Soil Mantle	TA4b	19	14	18	16	4	11	7	11	0	0	0	0	0	0	0	0	0
<u>Mako Mako</u> Weathered Bedrock	MM3b	14	21	8	37	3	16	1	0	0	0	0	0	0	0	0	0	0
	MM4b	19	24	8	34	2	12	1	0	0	0	0	0	0	0	0	0	0
	MM5b	22	11	8	33	4	21	1	0	0	0	0	0	0	0	0	0	0
	MM6b	20	19	11	35	2	12	1	0	0	0	0	0	0	0	0	0	0
	MM11a	29	14	5	21	2	19	4	6	0	0	0	0	0	0	0	0	0
	Unwthd Bedrock (Fresh)	MM1a	18	11	5	31	7	23	2	3	0	0	0	0	0	0	0	0
MM4a		15	22	20	27	4	11	1	0	0	0	0	0	0	0	0	0	0
MM5a		Calculation never completed													XXXX			
MM6a		23	17	21	27	2	7	2	1	0	0	0	0	0	0	0	0	0
MM9 - Rere		10	13	14	29	2	32	0	0	0	0	0	0	0	0	0	0	0
MM11b		11	4	20	23	0	0	0	0	42	0	0	0	0	0	0	0	0
MM12b		35	14	24	6	0	0	3	2	0	16	0	0	0	0	0	16	0
Soil Mantle		MM2a	17	8	19	26	0	0	26	0	0	0	4	0	0	0	0	0
	MM2b	24	14	25	0	0	0	0	0	0	0	0	0	0	0	0	0	
	MM2c	20	14	10	29	0	5	3	0	0	0	0	0	0	0	0	0	

SILT – SIZED FRACTION

<u>Huanui Forest</u>		Quartz	Feldspar	Mica	Chlorite	Smectite	Vermicu.	Mica-Chl	Mica-Ver.	Vol. Gl.	Cristobo.	Mica-HV
Weathered Bedrock		H2b	51	26	13	2	0	5	3	0	0	0
		H4d	44	40	6	7	0	0	0	0	0	3
		H5a	2	46	22	10	0	6	6	10	0	0
		H6b	3	44	21	24	4	7	0	0	0	0
		H7	8	30	18	13	0	0	39	0	0	0
Unweathered Bedrock		H4e	57	34	4	5	0	0	0	0	0	0
		Bentonite Mine red	65	15	12	2	6	0	0	0	0	0
		Bentonite M. white	65	13	11	2	9	0	0	0	0	0
		Bruce Road site	34	22	30	8	6	0	0	0	0	0
		H5b	39	28	20	3	10	0	0	0	0	0
		H6a	39	26	23	6	6	0	0	0	0	0
		H8a	35	21	18	5	21	0	0	0	0	0
Slip Stuff		H3a	58	32	8	2	0	0	0	0	0	0
		H6c	35	19	23	5	18	0	0	0	0	0
Goop		H3c	53	32	7	8	0	0	0	0	0	0
		H9	33	21	17	11	6	12	0	0	0	0
Soil Mantle		H4a	14	7	0	0	0	0	0	57	22	0
		H4b	35	19	1	4	0	0	0	30	11	0
		H4c	48	34	3	6	0	0	0	0	0	9
Suspended Sediment		Kanakanaia Bridge	45	26	21	3	5	0	0	0	0	0
		H10	13	37	16	25	4	15	1	0	2	0
Riverbank Silt		Kanakanaia Bridge	58	28	11	2	1	0	0	0	0	0
		H11	15	42	26	25	2	5	0	0	0	0
<u>Mangatu Forest</u>												
Weathered Bedrock		M1a	70	19	9	0	1	0	0	0	0	0
		M1b	80	12	6	1	1	0	0	0	0	0
		M3a	65	25	5	2	0	1	0	0	0	2
		M4a	52	19	20	5	2	0	0	2	0	0
		M5a	51	23	23	3	0	0	0	0	0	0
		M5c	52	27	16	2	2	1	0	0	0	0
		M12a	5	44	7	29	0	20	0	0	0	0
		M13a	7	73	8	10	0	5	2	2	0	0
		M15a	10	46	5	15	0	23	11	0	0	0
Unweathered Bedrock		M1c1	82	18	0	0	0	0	0	0	0	0
		M1c2	80	20	0	0	0	0	0	0	0	0
		M3c	52	20	24	3	1	0	0	0	0	0
		M4c	44	22	27	3	2	2	0	0	0	0
		M13b	58	4	29	0	9	0	0	0	0	0
		M12b	76	3	10	0	10	1	0	0	0	0
Suspended Sediment		M11	77	13	6	4	0	0	0	0	0	0
		M10a	50	24	19	4	3	0	0	0	0	0
		M16 Mangatu	64	20	14	2	0	0	0	0	0	0

		@Omapere											
Waihora River		50	26	18	6	0	0	0	0	0	0	0	
Te Arai Land System													
Weathered Bedrock	TA1b	52	34	10	2	2	0	0	0	0	0	0	
	TA2a	51	38	7	1	3	0	0	0	0	0	0	
	TA2b	39	27	30	4	0	0	0	0	0	0	0	
	TA3b	51	34	10	3	2	0	0	0	0	0	0	
	TA3	42	21	15	10	12	0	0	0	0	0	0	
	TA4c	36	29	18	10	0	0	7	0	0	0	0	
	TA6c	4	46	21	12	0	4	6	0	11	0	0	
	TA7a	11	6	0	0	8	0	0	0	75	0	0	
	TA7b	42	31	20	5	2	0	0	0	20	0	0	
	TA8a	40	36	19	5	0	0	0	0	0	0	0	
	TA8	47	35	13	3	2	0	0	0	0	0	0	
	TA14b	11	41	36	18	0	2	3	0	0	0	0	
	TA15b	12	48	39	8	3	0	0	2	0	0	0	
	Unweathered Bedrock	TA1a	50	32	13	2	2	0	0	1	0	0	0
TA3a		54	35	7	2	1	0	1	0	0	0	0	
TA5a		45	40	11	3	1	0	0	0	0	0	0	
TA6b		42	29	24	5	0	0	0	0	0	0	0	
TA7		40	42	13	3	1	0	1	0	0	0	0	
TA8c		40	38	15	5	2	0	0	0	0	0	0	
TA14a		47	30	17	3	3	0	0	0	0	0	0	
TA15a		31	25	34	7	3	0	3	0	0	0	0	
Weathered remnants (mud shards from slip)		TA6a	40	37	19	4	0	0	0	0	0	0	0
Soil Mantle		TA4b	55	32	2	11	0	0	0	0	0	0	0
Mako Mako Land System													
Weathered Bedrock	MM3b	40	35	17	6	0	0	0	2	0	0	0	
	MM4b	59	38	3	0	0	0	0	0	0	0	0	
	MM5b	53	21	12	4	8	2	0	0	0	0	0	
	MM6b	62	33	4	1	0	0	0	0	0	0	0	
	MM11a	6	48	17	13	0	9	13	0	0	0	0	
Unweathered Bedrock	MM1a	49	30	12	4	5	0	0	0	0	0	0	
	MM4a	60	34	4	1	1	0	0	0	0	0	0	
	MM6a	52	41	5	1	1	0	0	0	0	0	0	
	MM9 - Rere	53	37	6	1	3	0	0	0	0	0	0	
	MM11b	40	24	Calculation never completed due to possible mis-identification of Mica – HIV in clay sample									
	MM12b	9	42	Calculation incomplete due to possible presence of Kaolinite - Smectite									
Soil Mantle	MM2a	20	12	0	0	0	0	0	0	62	6	0	
	MM2b	54	22	5	1	0	5	0	0	10	3	0	
	MM2c	40	31	16	0	5	5	0	0	3	0	0	

SAND – SIZED FRACTION

		Quartz	Feldspar	Mica	Chlorite	Vol. Gl.	Zeolite	Calcite
Huanui Forest								
Weathered Bedrock								
	H2b	68	32	0	0	0	0	0
	H4d	73	24	1	2	0	0	0
	H5a	65	35	0	0	0	0	0
	H6b	67	33	0	0	0	0	0
	H7	58	37	0	0	0	5	0
Unweathered Bedrock								
	H4e	75	20	2	3	0	0	0
	Bentonite Mine red	75	23	0	0	2	0	0
	Bentonite M. white	69	19	0	0	12	0	0
	Bruce Road site	39	23	0	0	9	0	29
	H5b	55	45	0	0	0	0	0
	H6a	64	34	0	2	0	0	0
	H8a	66	34	0	0	0	0	0
Slip Stuff								
	H3a	62	38	0	0	0	0	0
	H6c	80	20	0	0	0	0	0
Mud Slurry (Goop)								
	H3c	72	21	3	4	0	0	0
	H9	65	35	0	0	0	0	0
Tephra								
	H4a	7	9	0	0	84	0	0
	H4b	36	32	0	0	32	0	0
	H4c	59	19	0	2	20	0	0
Suspended Sediment								
	Kanakaia Bridge	70	30	0	0	0	0	0
Riverbank Material								
	H10	76	24	0	0	0	0	0
	Kanakaia Bridge	77	23	0	0	0	0	0
	H11	82	18	0	0	0	0	0
Mangatu Forest								
Weathered Bedrock								
	M1a	78	20	2	0	0	0	0
	M1b	94	6	0	0	0	0	0
	M3a	71	23	2	4	0	0	0
	M4a	71	24	2	3	0	0	0
	M5a	71	25	4	0	0	0	0
	M5c	69	26	4	1	0	0	0
	M12a	86	14	0	0	0	0	0
	M13a	84	16	0	0	0	0	0
	M15a	87	13	0	0	0	0	0
Unweathered Bedrock								
	M1c1	88	10	0	2	0	0	0
	M1c2	80	20	0	0	0	0	0
	M3c	64	32	2	2	0	0	0
	M4c	72	25	3	0	0	0	0
	M13b	90	10	0	0	0	0	0
	M12b	89	6	2	3	0	0	0
Fragmented Streambed (mud shards from slip)								
	M11	79	21	0	0	0	0	0

		Quartz	Feldspar	Mica	Chlorite	Vol. Gl.	Zeolite	Calcite
Suspended Sediment								
	M10a	62	29	4	5	0	0	0
	Mangatu@Omapere	79	19	0	2	0	0	0
	Waihora River	70	29	0	1	0	0	0
Te Arai Land System								
Weathered Bedrock								
	TA1b	68	32	0	0	0	0	0
	TA2a	45	55	0	0	0	0	0
	TA2b	36	24	0	0	0	0	0
	TA3b	65	35	0	0	0	0	0
	TA3	46	30	0	0	0	0	0
	TA4c	77	23	0	0	0	0	0
	TA6c	71	29	0	0	0	0	0
	TA7a	4	14	0	0	82	0	0
	TA7b	30	15	3	3	49	0	0
	TA8a	66	30	0	3	0	1	0
	TA8	75	24	0	0	0	1	0
	TA14b	60	37	3	0	0	0	0
	TA15b	64	36	0	0	0	0	0
Unweathered Bedrock								
	TA1a	65	35	0	0	0	0	0
	TA3a	76	27	0	0	0	0	0
	TA5a	62	32	2	4	0	0	0
	TA6b	63	34	2	1	0	0	0
	TA7	58	34	4	4	0	0	0
	TA8c	58	37	2	3	0	0	0
	TA14a	64	36	0	0	0	0	0
	TA15a	60	35	2	3	0	0	0
Weathered remnants (mud shards from slip)								
	TA6a	57	35	4	4	0	0	0
Soil Mantle								
	TA4b	65	33	0	2	0	0	0
Mako Mako Land System								
Weathered Bedrock								
	MM3b	62	10	0	0	0	0	0
	MM4b	67	33	0	0	0	0	0
	MM5b	56	28	0	2	14	0	0
	MM11a	68	32	0	0	0	0	0
Unweathered Bedrock								
	MM1a	66	32	0	2	0	0	0
	MM4a	64	34	0	2	0	0	0
	MM5a	69	31	0	0	0	0	0
	MM9 - Rere	70	30	0	0	0	0	0
	MM11b	63	34	0	3	0	0	0
	MM12b	72	28	0	0	0	0	0
Soil Profile								
	MM2a	11	11	0	0	78	0	0
	MM2b	30	24	0	0	46	0	0
	MM2c	73	25	1	1	0	0	0

HEAVY MINERALS

	Mica	Chlorite	Zircon	Rutile	Hyper	Horn- blende	Augite	Epidote	Ilmenite	Magnetite	Hematite	Siderite	Pyrite	Cumming.
<u>Huanui Forest</u>														
Bentonite Mine red	0	13	30	0	0	0	0	0	0	0	0	57	0	0
Bentonite Mine white	0	2	4	0	0	0	0	0	0	0	0	80	14	0
Bruce Road site	0	25	5	3	7	36	3	11	7	2	0	0	0	0
H3a	6	37	18	9	11	0	3	10	6	0	0	0	0	0
Kanekanaia B. S. S.	6	47	19	6	7	4	0	5	3	5	0	0	0	0
Kanak B. silt	6	42	24	4	7	8	0	0	8	0	0	0	0	0
<u>Mangatu Forest</u>														
M1a	23	15	62	0	0	0	0	0	0	0	0	0	0	0
M1b	7	23	51	0	0	0	0	0	13	6	0	0	0	0
M4a	4	84	12	0	0	0	0	0	0	0	0	0	0	0
M5a	5	36	46	0	12	0	0	1	0	0	0	0	0	0
M5c	10	48	25	0	18	0	0	0	0	0	0	0	0	0
M1c1	13	38	30	0	5	5	0	0	9	0	0	0	0	0
M1c2	12	42	35	0	7	4	0	0	0	0	0	0	0	0
M3c	12	27	62	0	0	0	0	0	0	0	0	0	0	0
M4c	10	40	35	0	16	0	0	0	0	0	0	0	0	0
M11	14	76	0	0	1	0	0	0	9	0	0	0	0	0
<u>Te Arai Land System</u>														
TA1b	1	3	23	10	17	0	3	27	17	0	0	0	0	0
TA2a	2	6	0	12	15	5	5	32	20	4	0	0	0	0
TA2b	7	39	0	12	22	8	0	5	8	0	0	0	0	0
TA3b	2	11	19	9	14	0	4	25	13	2	0	0	0	0
TA3	1	12	59	4	5	0	4	0	5	9	0	0	0	0
TA4c	2	41	12	0	11	5	0	18	11	0	0	0	0	0
TA7a	5	26	0	0	0	0	0	0	46	23	0	0	0	0
TA7b	11	59	30	0	0	0	0	0	0	0	0	0	0	0
TA8a	7	48	0	9	8	5	5	9	6	0	4	0	0	0
TA8	5	34	0	12	16	5	8	10	8	0	0	0	0	3
TA1a	2	14	56	8	7	0	0	11	8	1	0	0	0	0
TA3a	3	15	0	12	15	0	5	28	16	7	0	0	0	0
TA6b	10	44	0	11	11	0	4	12	5	3	0	0	0	0
TA8c	6	37	23	9	3	0	4	10	4	0	0	0	0	0
<u>Mako Mako Land System</u>														
MM3b	0	11	0	4	0	0	2	18	5	45	0	0	0	0
MM4b	13	57	0	18	12	0	0	0	0	0	0	0	0	0
MM5b	5	39	23	8	25	0	0	0	0	0	0	0	0	0
MM6b	2	12	78	2	4	0	0	3	0	0	0	0	0	0
MM1a	3	30	16	11	12	0	0	19	9	0	0	0	0	0
MM4a	7	30	34	11	17	0	0	0	0	0	0	0	0	0
MM6a	8	45	47	0	0	0	0	0	0	0	0	0	0	0

CRUSHED SAMPLES - PEBBLES & BEDROCK

CLAY – SIZED FRACTION

		Quartz	Feldspar	Kandite	Mica	Chlorite	Smectite	Vermicu.	Mica-Chl	Mica-HIV	Mica-Ver.	Kao-Sme	Vol. Gl.
<u>Huanui Forest</u>													
Weathered Bedrock	H1a	27	23	5	28	0	12	5	0	0	0	0	0
Unwthd Bedrock	H2a	17	14	30	0	0	0	0	0	0	XXX	0	0
Weathered Streambed	H1b	19	24	10	31	0	16	0	0	0	0	0	0
Unwthd Streambed	H1c	29	20	9	26	3	13	0	0	0	0	0	0
<u>Mangatu Forest</u>													
Weathered Bedrock	M1a	51	11	0	22	0	16	0	0	0	0	0	0
	M1a2	49	6	7	30	0	6	2	0	0	0	0	0
	M2b	49	12	5	26	0	8	0	0	0	0	0	0
Unwthd Bedrock (Fresh)	M1c3	56	2	7	13	2	19	1	0	0	0	0	0
	M2a	79	5	3	9	0	4	0	0	0	0	0	0
	M3b	49	13	10	22	3	3	0	0	0	0	0	0
	M4b	47	10	8	27	4	4	0	0	0	0	0	0
	M5b	50	11	11	21	0	4	3	0	0	0	0	0
Fragmented Streambed (mud shards from slip)	M10b	27	15	6	33	5	14	0	0	0	0	0	0
	M11a	70	6	5	10	1	7	1	0	0	0	0	0
	M11b	39	2	5	17	0	5	2	0	0	0	0	0
	M11c	90	3	5	1	0	1	0	0	0	0	0	0
	M12b	29	16	8	23	0	18	0	0	0	6	0	0
Pebbles	M6	60	5	9	19	1	4	4	1	0	0	0	0
	M7	64	3	10	17	0	6	0	0	0	0	0	0
	M8x	34	16	2	19	16	0	6	4	3	0	0	0
	M9a	36	14	10	30	0	4	6	0	0	0	0	0
	M10	29	16	8	23	0	18	0	0	0	0	0	0
	M11b	47	2	2	32	2	13	2	0	0	0	0	0
	M11c	58	6	5	20	2	8	1	0	0	0	0	0
	M14b	65	1	4	22	2	4	20	0	0	0	0	0
	M15	27	15	6	33	5	14	0	0	0	0	0	0
<u>Te Arai Land System</u>													
Weathered Bedrock	TA6a2	10	20	9	34	2	22	1	2	0	0	0	2
Unwthd Bedrock	TA5b	10	15	3	34	4	34	0	0	0	0	0	0
Unwthd Streambed (Pebbles)	TA8b	20	22	5	34	2	13	4	0	0	0	3	0
	TA9a	21	25	5	31	3	14	0	1	0	0	0	0
	TA10a	24	22	9	26	3	14	0	2	0	0	0	1
	TA11a	14	24	7	28	2	22	1	2	0	0	0	0
	TA12a	14	17	7	28	3	28	1	2	0	0	0	0
	TA13a	19	19	8	26	0	23	4	1	0	0	0	0
<u>Mako Mako Land System</u>													
Weathered	MM5b	22	11	8	33	4	21	1	0	0	0	0	0
	MM10	25	14	3	27	0	28	3	0	0	0	0	0
Unwthd Bedrock	MM3a	19	24	5	34	4	14	0	0	0	0	0	0
	MM8a	45	29	4	17	1	0	2	2	0	0	0	0
	MM8b	36	31	8	19	1	0	3	2	0	0	0	0
Unwthd Streambed (Pebbles)	MM5c	22	13	14	25	0	26	0	0	0	0	0	0
	MM7c	25	16	13	42	2	0	2	0	0	0	0	0

APPENDIX IV

MC PHAIL'S BEND FLOODPLAIN CORE – Clay sized Fraction

<u>Year of Storm</u>	Quartz	Feldspar	Kandite	Mica	Chlorite	Smectite	Vermiculite
1853	10	3	8	36	5	33	5
1872	7	4	7	38	6	34	4
1876	7	4	8	43	7	30	1
1882	11	4	7	39	7	31	1
1883	11	4	6	37	5	33	4
1892	11	4	6	37	7	33	2
1894	12	5	6	39	4	27	7
1906	13	6	6	32	4	34	5
1910	13	6	6	32	5	33	7
1914	11	5	8	36	4	30	6
1916	12	4	8	38	5	28	5
1918	12	5	8	31	5	34	5
1927	14	6	8	32	5	29	6
1932	14	5	7	31	0	36	7
1938	13	7	6	33	7	29	5
1944	11	5	6	42	0	25	11
1948	13	4	6	40	4	31	2
1950	11	4	5	38	4	29	9
1960	13	4	6	37	0	29	11
1988	8	3	4	46	4	29	6

HEAVY MINERALS

<u>Year of Storm</u>	Mica	Chlorite	Hornblende	Hypersthene	Augite	Epidote	Ilmenite
1876	3	8	6	8	4	44	9
1882	5	20	8	12	5	34	7
1892	5	12	7	12	8	40	8
1894	7	13	7	10	6	43	7
1914	6	14	10	11	6	40	7
1938	4	8	3	6	4	48	13
1950	7	13	7	7	6	45	8
1988	6	9	9	10	6	46	8

ORMOND FLOODPLAIN CORE – Clay – sized Fraction

<u>Year</u>	Quartz	Feldspar	Kandite	Mica	Chlorite	Smectite	Vermiculite	M-Vermiculite
0-1948	12	5	6	31	4	28	6	8
0-1960	11	4	7	35	5	31	7	0
0-1988	14	5	4	38	5	28	6	0

MATAWHERO FLOODPLAIN CORE – Clay – sized Fraction

<u>Centremetres</u>	Quartz	Feldspar	Kandite	Mica	Chlorite	Smectite	Vermiculite
0	10	3	8	36	0	36	7
3	10	3	6	36	0	36	9
6	11	3	8	40	5	28	5
9	10	3	6	40	0	35	6
12	12	3	8	41	5	31	0
15	11	4	11	41	0	33	0
18	10	3	7	31	0	45	4
21	10	3	9	36	6	36	0
24	12	3	9	34	4	35	3
27	9	2	8	38	4	35	4
30	6	3	6	38	5	42	0
33	8	4	7	34	5	41	1
36	9	4	8	54	0	25	0
39	10	3	8	51	3	18	7
42	9	3	6	38	0	38	6
45	10	3	8	58	3	18	0
48	9	2	5	46	0	32	6
51	10	2	5	47	0	25	11
54	9	3	7	40	0	35	6
57	8	2	7	59	0	15	9
60	7	6	7	30	0	41	9
63	8	2	6	62	4	16	2
66	9	3	6	46	0	24	12
69	8	2	7	46	0	37	0
72	11	5	6	32	4	38	4
75	9	3	6	29	0	42	11
78	10	3	8	26	0	43	10
81	11	3	6	45	6	25	4
84	9	2	5	41	0	40	3
87	10	2	9	31	0	44	4
90	9	3	7	42	0	33	6
93	8	2	9	39	0	34	8
96	8	2	5	36	2	47	0
99	10	3	6	37	0	35	9
102	7	3	5	31	0	47	7
105	9	3	5	30	0	50	3
108	7	3	5	35	2	48	0
111	11	4	5	36	4	36	4
114	13	3	5	33	5	36	5
117	10	4	5	40	5	34	2
120	9	4	5	36	0	39	7
123	10	3	5	40	0	37	5
126	10	4	5	36	0	27	18
129	8	3	11	38	0	32	9
132	10	3	5	31	6	28	17
135	9	4	11	34	0	34	8
138	9	4	8	37	0	32	10
141	10	2	9	34	6	38	1
144	11	3	5	36	0	30	15

147	10	3	7	24	0	43	13
150	11	3	8	34	0	30	14
153	10	4	7	36	4	29	10
156	12	4	7	33	0	33	11
159	10	4	9	17	0	49	11
162	12	4	5	33	0	35	11
165	11	3	9	22	0	43	12
168	10	3	8	33	0	34	12
171	11	3	5	23	0	46	12
174	8	4	7	25	0	48	8
177	10	3	7	46	0	24	10
180	11	4	8	18	0	49	10
183	8	4	9	18	0	47	14
186	8	3	11	31	0	39	8
189	8	4	4	26	0	48	10
192	9	3	9	34	0	35	10
195	10	4	6	22	0	45	13
198	10	4	8	22	0	47	9
201	10	3	10	28	0	33	16
204	10	3	9	27	0	47	4
207	9	3	8	25	0	51	4
210	9	3	5	39	0	28	16

MARINE CORE MD2122 -- Clay - sized Fraction

<u>Centremetres</u>	Quartz	Feldspar	Kandite	Mica	Chlorite	Smectite	Vermiculite	From sand
								fraction
								Vol.glass
1	14	7	7	41	2	26	3	6
4	14	6	6	37	2	31	4	15
7	15	6	8	34	2	29	6	9
10	17	7	8	37	3	28	0	9
13	22	5	9	28	3	33	0	9
16	15	6	8	34	0	34	3	3
19	18	8	7	39	2	28	0	8
21	19	6	8	39	4	23	1	8
25	14	9	7	39	4	27	0	10
27	11	10	10	38	5	26	0	7
30	13	7	7	42	3	26	2	8
33	13	9	8	44	4	21	1	9
36	14	6	7	45	4	24	0	5
40	12	7	8	44	5	24	0	8
42	12	7	9	41	3	27	1	8
45	10	8	7	42	5	28	0	9
48	12	8	8	41	4	25	2	8
52	12	8	7	43	4	24	2	9
54	10	9	5	44	2	27	3	8
57	11	9	6	45	5	24	0	9
61	9	7	7	41	5	31	0	9
63	13	9	6	45	5	21	1	8
67	11	10	6	44	4	25	0	10
69	12	9	6	48	5	19	1	8
72	12	9	6	47	6	20	0	9
75	9	8	7	44	2	27	3	10
78	12	7	8	42	4	27	0	10
81	11	7	7	42	4	26	3	10
85	10	6	5	44	2	28	5	9
87	10	7	6	48	2	21	6	9
91	13	16	6	32	4	29	0	10
93	13	7	4	42	4	28	2	12
96	11	6	6	46	5	25	1	12
100	11	6	3	44	3	31	2	13
102	13	8	8	39	3	27	2	13
105	11	6	6	42	5	28	2	14
108	11	6	7	42	4	28	2	11
111	12	6	7	45	5	25	0	16
115	12	6	5	45	5	27	0	14
117	10	6	5	47	5	27	0	13
120	10	8	5	47	4	25	1	10
123	11	7	6	42	2	29	3	14
126	10	7	5	44	6	28	0	15
129	11	5	6	38	5	35	0	16
132	13	8	6	42	5	26	0	19
135	12	6	5	44	4	29	0	19
138	10	6	7	43	0	29	5	20
141	13	7	7	41	7	25	0	16
145	13	7	8	38	7	27	0	14
147	11	7	9	41	6	26	0	15
150	14	7	9	38	6	26	0	17
153	12	7	8	40	6	27	0	14
156	12	7	5	44	5	25	2	13
159	13	7	8	43	6	23	0	12
162	13	9	7	40	5	26	0	14
165	11	7	6	43	7	26	0	14

168	12	7	6	44	5	25	1	12
171	14	9	7	41	5	24	0	13
174	13	10	7	42	6	22	0	14
177	13	8	9	42	5	23	0	13
180	14	8	5	45	6	22	0	19
183	14	8	5	38	5	30	0	15
186	14	7	6	42	4	27	0	16
189	15	9	8	41	5	22	0	15
192	15	8	7	41	4	24	1	16
195	14	9	8	43	5	20	1	18
198	15	10	7	39	4	24	1	19
201	15	11	5	41	4	23	1	16
204	15	9	8	38	4	25	1	15
207	17	9	8	43	4	18	1	15
210	14	9	6	42	7	22	0	15
213	13	10	7	46	5	19	0	15
216	13	8	9	42	6	20	2	16
219	13	7	7	41	6	26	0	17
222	11	7	8	41	7	26	0	15
225	14	8	7	44	7	20	0	15
228	13	10	5	40	6	24	2	19
231	13	10	8	38	7	24	0	16
234	13	8	8	42	7	22	0	15
237	12	6	5	39	3	33	2	17
240	13	7	4	44	3	27	2	17
243	13	9	6	37	3	31	1	17
246	11	7	5	37	3	34	3	19
249	10	9	6	39	3	32	1	19
252	12	7	6	40	3	30	2	19
255	12	8	7	38	3	31	1	20
258	13	9	7	40	4	26	1	19
261	11	8	8	43	4	25	1	18
264	14	10	7	42	5	22	0	29
267	15	10	7	37	2	25	4	19
270	13	10	6	43	3	22	3	20
273	15	26	9	33	3	14	0	34
276	14	10	6	44	3	22	1	27
279	13	9	5	47	4	22	0	24
282	15	9	7	46	6	17	0	26
285	16	9	5	42	6	22	0	32
288	13	8	7	39	4	29	0	20
291	12	9	6	38	5	30	0	36
294	12	8	5	40	5	30	0	36
297	6	4	3	18	5	15	0	76
300	10	8	5	44	4	27	2	15