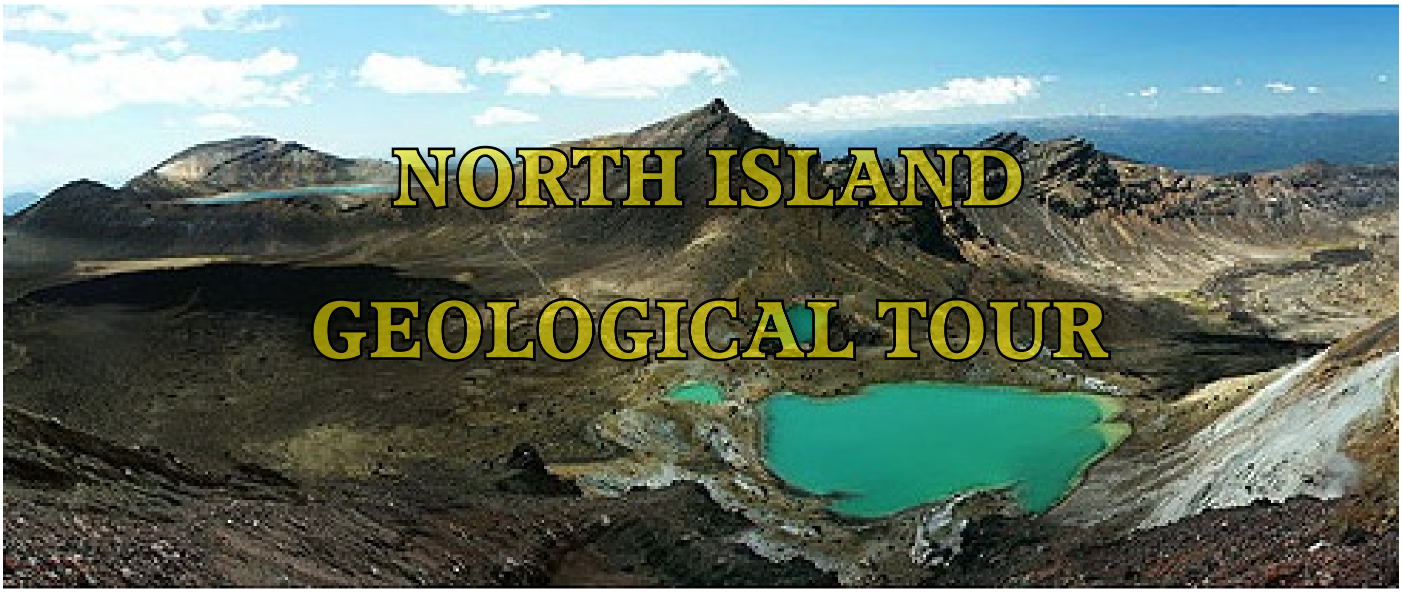


NORTH ISLAND GEOLOGICAL TOUR

New Zealand lies astride the *Pacific Ring of Fire*, a belt of volcanic and earthquake activity that surrounds the Pacific Ocean. The Ring of Fire is a geological phenomenon resulting from the convergence of *crustal plates*, segments of the outer surface of the Earth which move relative to one another in response to forces deep within the Earth's mantle. The plates may rub past one another (as they do on South Island), one may be forced down below another (as occurs off the east coast of North Island), or they may buckle at the edges as they meet head on. Wherever there is a plate boundary there is geological activity of a volcanic and/or tectonic nature. New Zealand straddles the boundary between the Pacific and Indo-Australian plates. To the north of New Zealand and beneath the eastern North Island, the thin, dense, Pacific plate moves down beneath the thicker, lighter Indo-Australian plate in a process known as subduction. This subduction zone sits within the Hikurangi Trough (Figures 1 & 2). Within the South Island the plate margin is marked by the Alpine Fault and here the plates rub past each other horizontally. To the south of North Island the Hikurangi Trough subduction zone is truncated by a fault that extends into South Island and into the Alpine Fault. South of New Zealand the Indo-Australian plate is forced below the Pacific plate. Plate movement results in volcanic activity in the North Island and in earthquakes that are felt throughout the country.

New Zealand's North Island is an interesting geological contrast to South Island. North Island lies to the west of the Indo-Australian—Pacific Plate boundary, so lacks the landforms and geological features associated with the Alpine Fault. Both islands share the crustal instability expected from land located immediately adjacent to converging plates, with seismicity and earthquakes a common event. And both have been subjected to volcanic eruptions associated with intra-plate, hotspot volcanoes (see our east and central Otago tour guide).

North Island differs markedly from its southern counterpart by the presence of numerous active and dormant volcanoes related to subduction (Figure 2). These lie within the *Taupo Volcanic Zone* (described later) and include the vents of White Island, Rotorua, Okataina, Maroa, Taupo and Tongariro (including Ngauruhoe and Ruapehu). These often highly explosive vents have produced lavas and extensive *ignimbrite* flows (a widespread deposit of hot ash which flowed outward from an explosively erupting volcano). Indeed, North Island contains the world's greatest concentration of youthful rhyolitic volcanoes. Their lavas are dominantly *andesite* and *rhyolite*, with some *basalt* (see glossary). The Taupo Volcanic Zone (TVZ) is also associated with geothermal activity, including hot springs, geysers, boiling mud pools and steam vents. A number of geothermal power stations are sited throughout the TVZ.

The TVZ is a region of high crustal heat flow and abundant circulating groundwaters. The combination of these two factors has produced a number of gold-rich mineral deposits about the TVZ. Anomalous gold (and other metals) are present within the geothermal waters and hot spring pools of areas such as Rotorua.

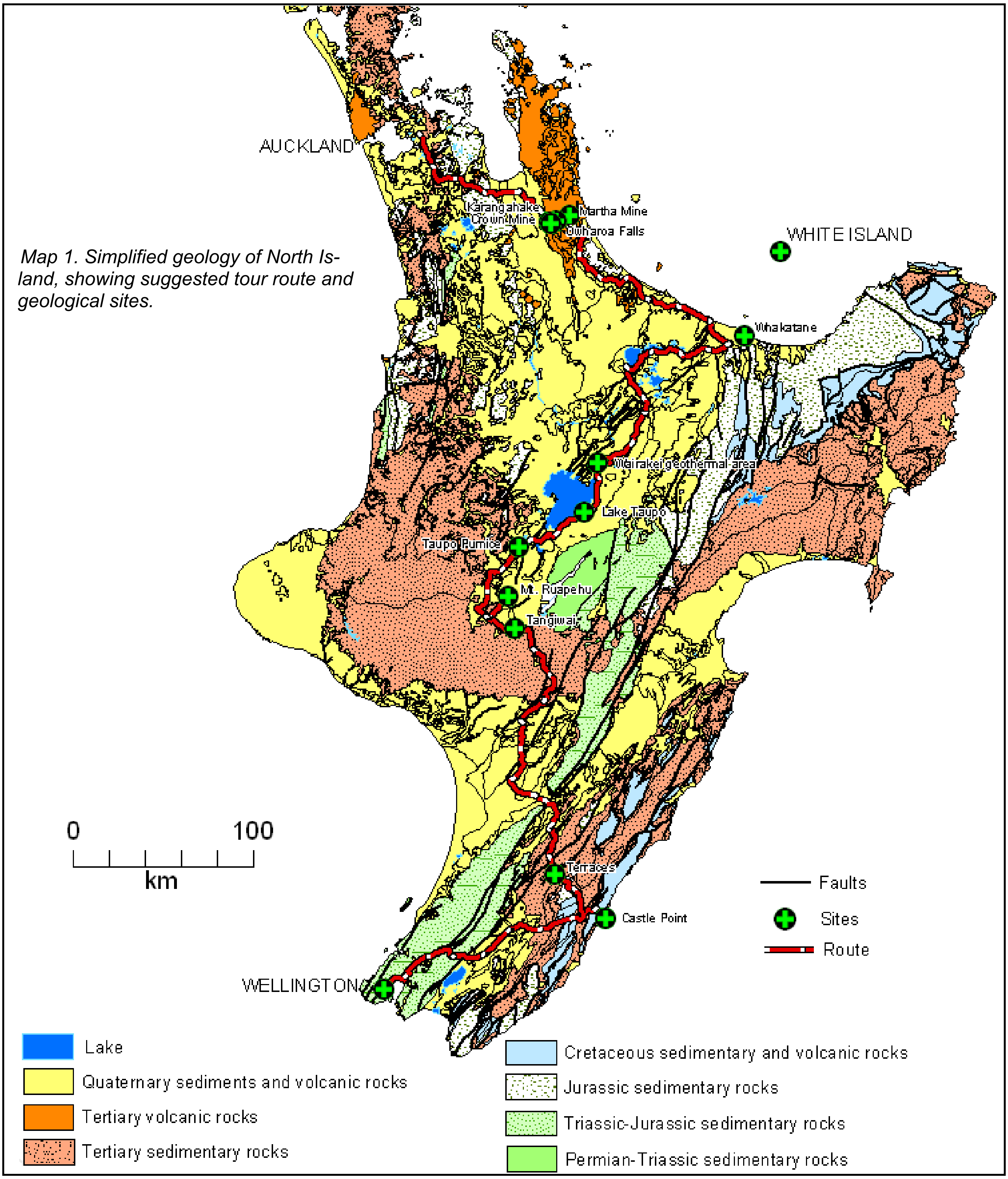
Acknowledgement: This tour is based largely on a geology field excursion developed by Dr Nick Cook

Figure 1. The tectonic setting of New Zealand. Red arrows show the angle and rate of plate convergence.

PERIOD	YEARS AGO	LIFE FORMS	GEOLOGICAL EVENTS
Holocene	0 - 10,000	Human Beings	Earthquakes, landslides, northeast trending ridges continue to rise. Continued rising of land, down-cutting by rivers and sea, glaciation, continued formation of alluvial terraces. Continued eruption of Taupo Volcanic Zone. Major devastating eruptions of Taupo volcano.
Pleistocene	10,000 - 1,800,000		
Pliocene	1,800,000 - 5,300,000	Grazing and carnivorous Mammals	Widespread glaciation started about 2 million years ago. Gravels and sands deposited on land, whilst sands, gravels and limey sediments form in shallow ocean. Uplift of marine sediments along coast form sandstone, conglomerate and limestone. First volcanic activity in Taupo Volcanic Zone about 2 million years ago, cessation of activity in Coromandel Arc.
Miocene	5,300,000 - 23,000,000		Commencement of subduction, formation of Northland Arc (23 million years). Coromandel Arc commenced at 18 million years. Geothermal activity in Coromandel forms major gold-silver epithermal deposits.
Oligocene	23,000,000 - 33,900,000		New Zealand mostly under sea to 25 million years ago, resulting in widespread sandstone, limestone, siltstone, greensand and coal. Initial movement on Alpine Fault results in regional uplift and retreat of ocean.
Eocene	33,900,000 - 55,800,000	Modern mammals	Australia separated from Antarctica 55 million years ago. Boundary between Australian and Pacific Plates formed through New Zealand 45 million years ago. Deposition of marine sediments.
Paleocene	55,800,000 - 66,500,000	Placental animals	Tasman Sea fully opened by 60 million years. Continued erosion of New Zealand land mass. Deposition of marine sediments.
Cretaceous	66,500,000 - 145,500,000	Last dinosaurs. First flowering plants	Collision of Gondwana margin 130 million years ago uplifted New Zealand area. New Zealand separated from Gondwana 130-85 million years ago, resulting in formation of Tasman Sea.
Jurassic	145,500,000-200,000,000	First birds. Reptiles and ammonites abundant.	Continued deposition of marine sediments. Crustal compression 160 million years ago resulted in metamorphism with formation of schists in Caples Terrane. Rocks of Murihiku Terrane deposited in a deep ocean adjacent to a plate boundary offshore of Gondwana.
Triassic	200,000,000-250,000,000	First dinosaurs, ammonites and primitive mammals	
Permian	250,000,000-299,000,000	Mammal-like reptiles. Last trilobites.	New Zealand area part of Gondwana. Erosion of continent formed marine muds, sands and, gravels and minor limestone. Some volcanic activity. Rocks of Caples, Maitai and Brook Street Terranes formed in deeper ocean waters adjacent to a plate margin which was associated with volcanic islands.
Carboniferous	299,000,000-359,000,000	First reptiles, fern forests	Earliest intrusion of Median Batholith magmas along margin of south Gondwana.
Devonian	359,000,000-416,000,000	First amphibians and insects	Final deposition of Takaka Terrane rocks.
Silurian	416,000,000 443,000,000	Vascular land plants	
Ordovician	444,000,000-488,000,000	First corals, fish with vertebrae	Rocks of Buller and Takaka Terranes deposited in a deep ocean adjacent to a continental margin.
Cambrian	488,000,000-542,000,000	Shellfish, trilobites	Rocks of Takaka Terrane deposited in ocean adjacent to plate margin.

Table 1. Simplified geological history of part of North Island New Zealand.

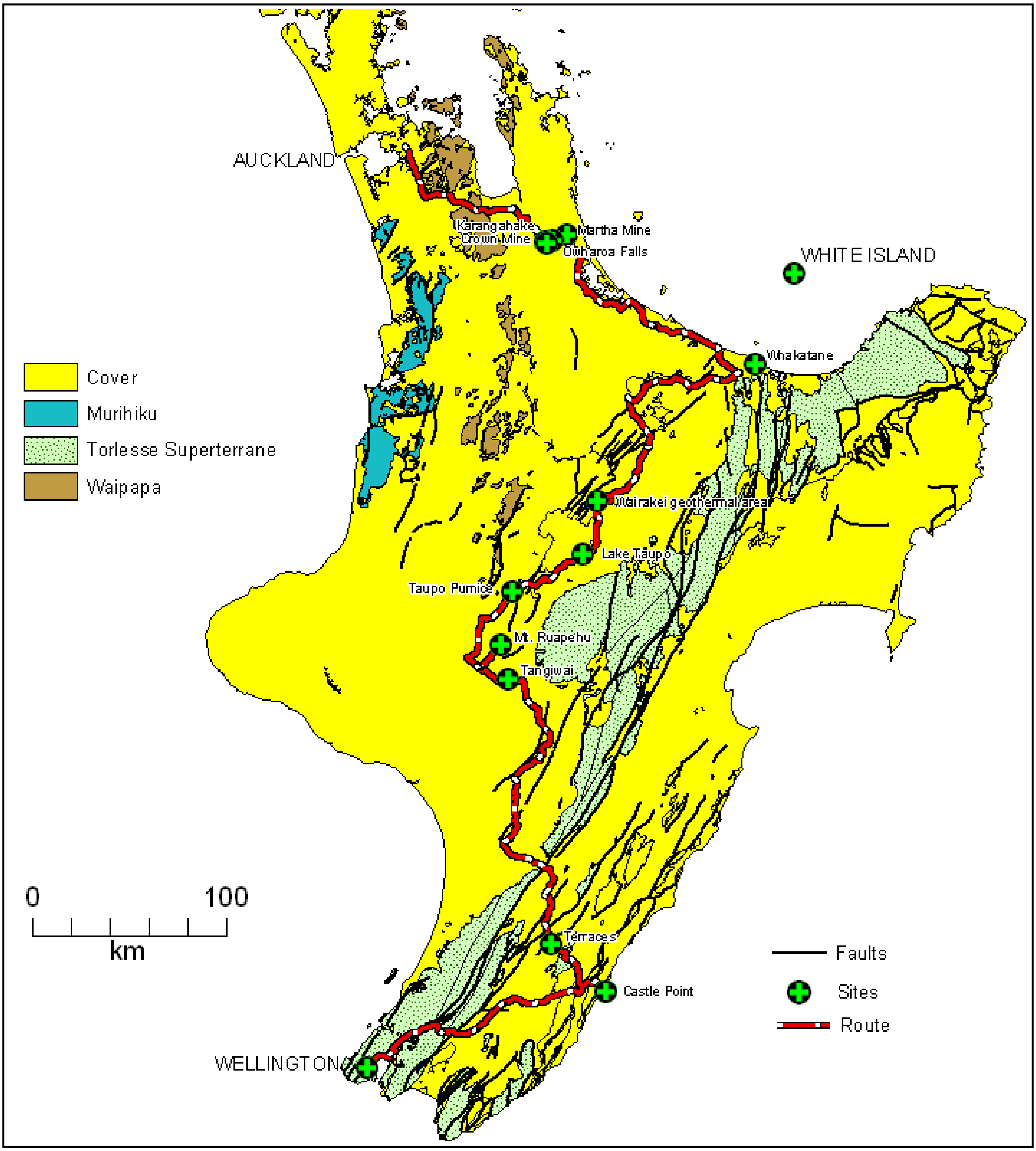
and Assoc. Prof. Paul Ashley from the University of New England. The tour has been conducted by Dr Paul Ashley over the past two decades and has evolved into the present format with recent input from the authors.



Map 1. Simplified geology of North Island, showing suggested tour route and geological sites.

This tour guide examines some of the major aspects of North Island geology. The route passes from Wellington to Auckland (Maps 1 & 2) and visits sites which examine and describe:

- The Wellington Fault
- Folded 1.7 million year old fossiliferous limestone and calcareous sandstone at Castlepoint
- The site of the Tangiwai rail disaster - a *lahar* flow down the Whangaehu River from Mt Ruapehu
- Volcanic rocks on Mt Ruapehu, and the significance of the Taupo Volcanic Zone
- Volcanic rocks and landforms on the western half of the Tongariro Crossing
- The Taupo Pumice and its significance
- Lake Taupo and its significance
- Wairakei and Wai-o-tapu geothermal areas - geothermal power, hot springs, mud pools, fumaroles
- White Island active volcanic crater
- Coromandel Peninsula ignimbrite
- Gold mines and epithermal mineralisation - the Martha Mine, Crown Mine and Karangahake Gorge



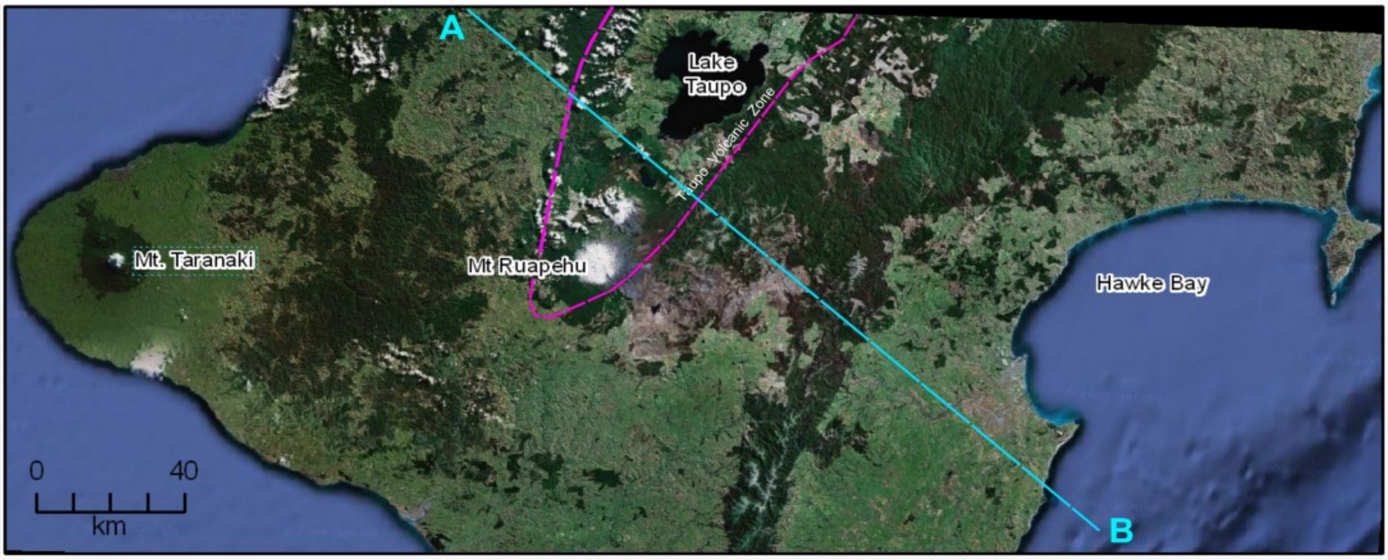
Map 2. Simplified terrane map of North Island, showing suggested tour route and geological sites.

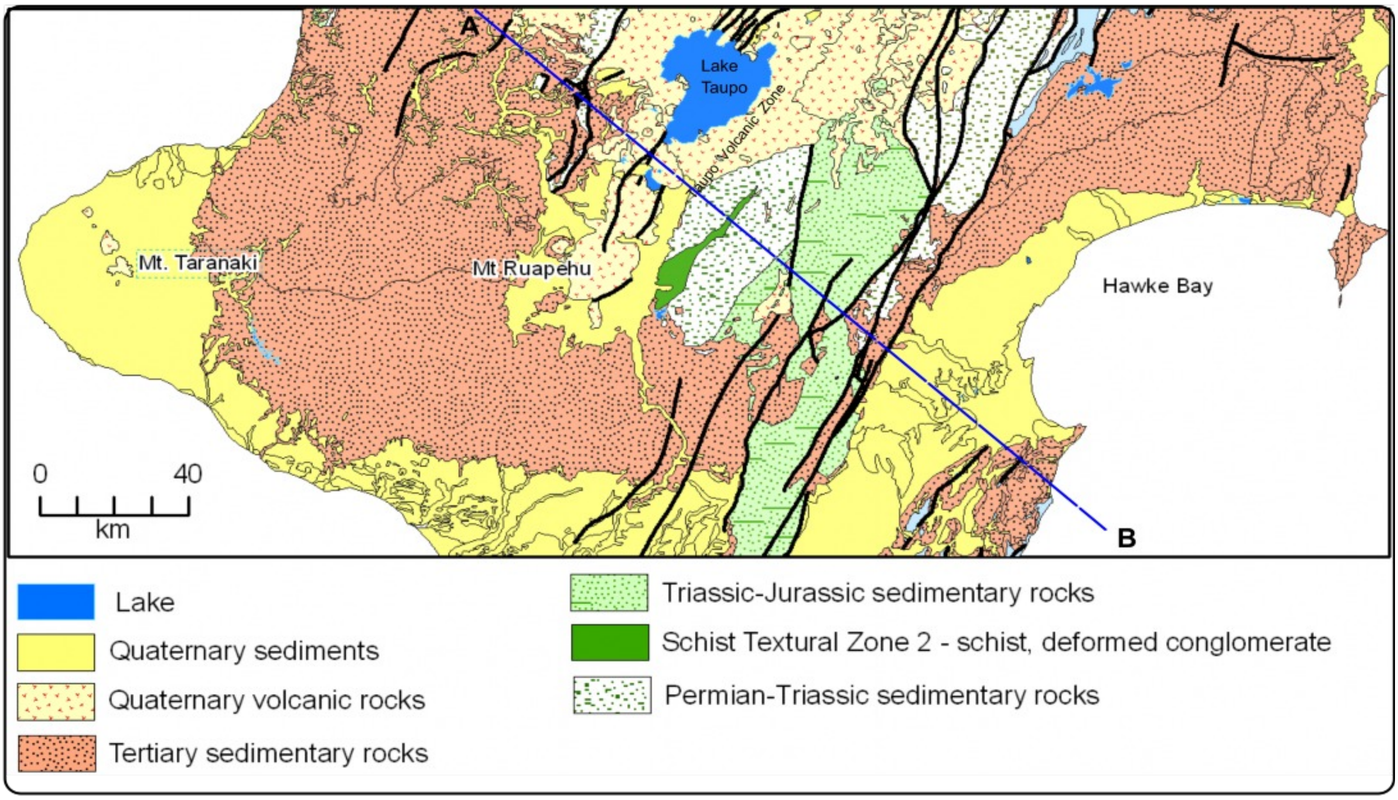
THE WELLINGTON FAULT

The regional presence and previous effects of the Wellington Fault are best studied from the Mount Victoria Lookout (Map 3). This site provides some excellent visual display boards explaining many of the aspects of the Wellington Fault.

Toward the northern end of the South Island the Alpine Fault splays into a number of faults which together, take up the movement along the Alpine Fault. These splays pass through the North Island within a 50 km-wide zone of north-northeast–trending faults (Maps 1 & 2). These are known as the *North Island fault system*, which persists into the Bay of Plenty over a distance of about 450 km. The faults mainly move horizontally, with the west flank of each fault moving northward relative to the eastern flank. These faults absorb a significant amount of strain associated with collisional movement between the Indo-Australian and Pacific Plates. This has resulted in both lateral dislocation and uplift of the ranges in eastern North Island.

The Wellington Fault is one of the most active structures within the fault system. It displays a prominent fault scarp which is evidence of its prolonged and regular movement. The most recent major movements on the fault were between 1510 and 1660, with major activity recurring every 500-1000 years. The fault moves sideways about 4 - 6 m





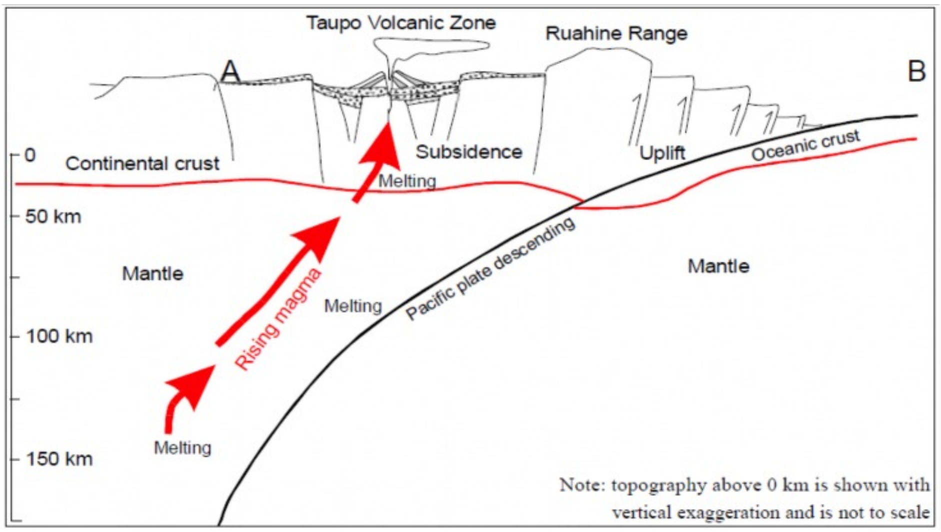
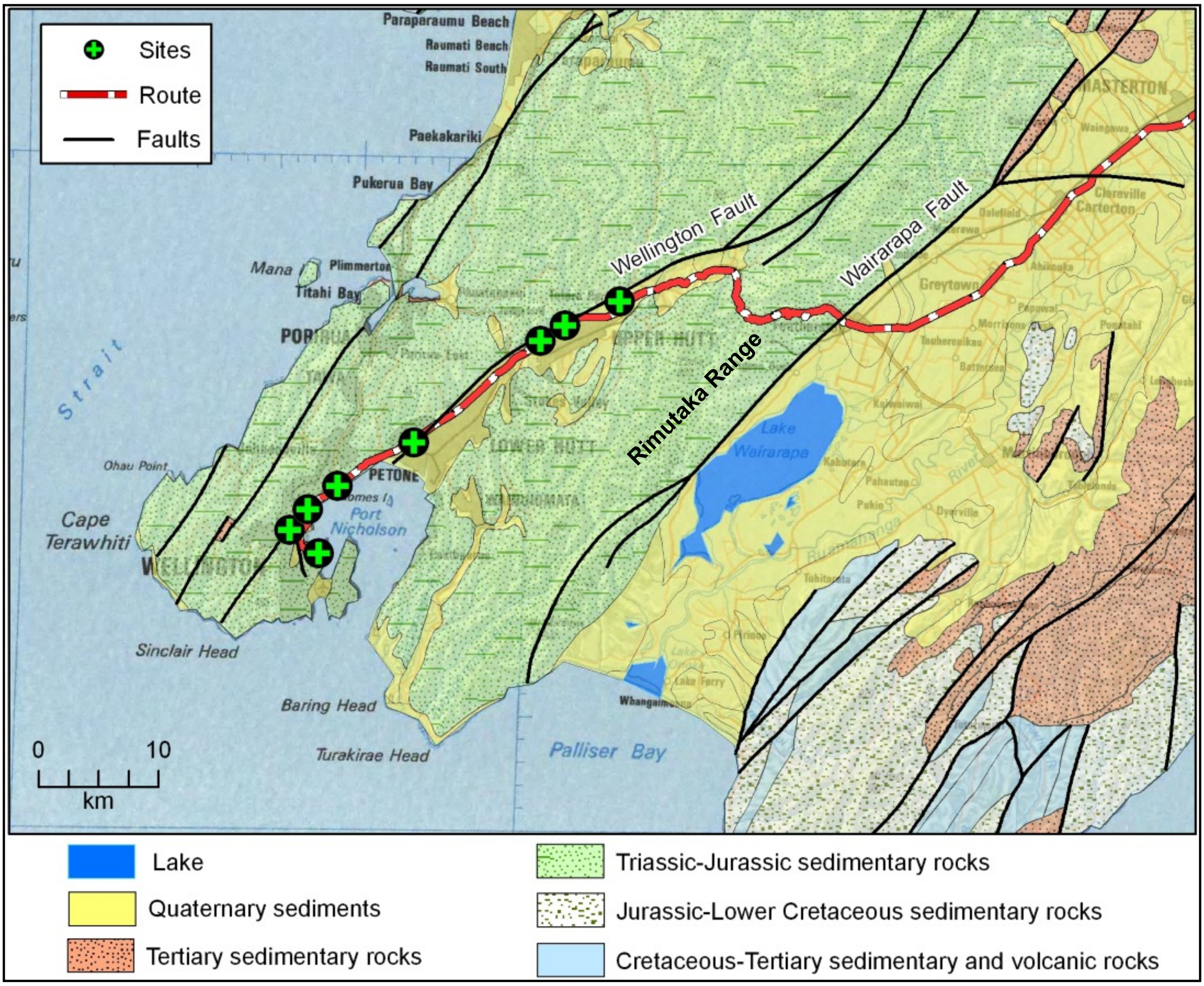


Figure 2. Cross section across the Taupo Volcanic Zone showing its relationship to the Hikurangi subduction zone. Cross section line superimposed on satellite image (top) and simplified geological map (centre). Cross section constructed from figures in Thornton (1985) and Graham (2008).



Map 3. Simplified geology of the Wellington region, showing the Wellington and Wairarapa Faults.

each time, with the western side of the fault moving northward relative to the eastern side. The fault also moves vertically, with the land to the west moving upward, and that to the east subsiding. This movement, and subsequent erosion by rivers and the sea has resulted in a prominent, linear escarpment through Wellington City, along the harbour, and through the western side of the Hutt Valley to the north. The fault is presently not moving, resulting in the build-up of stress which will eventually be released as a major earthquake.

Some of the present landforms of Wellington resulted from major earthquakes associated with the Wairarapa Fault (Map 3). In 1855 this fault moved 15 m laterally, the greatest sideways movement of a fault ever observed, resulting in an estimated 8.1 magnitude earthquake. Its movement has uplifted and tilted the land to the west, with significant effects at Wellington.

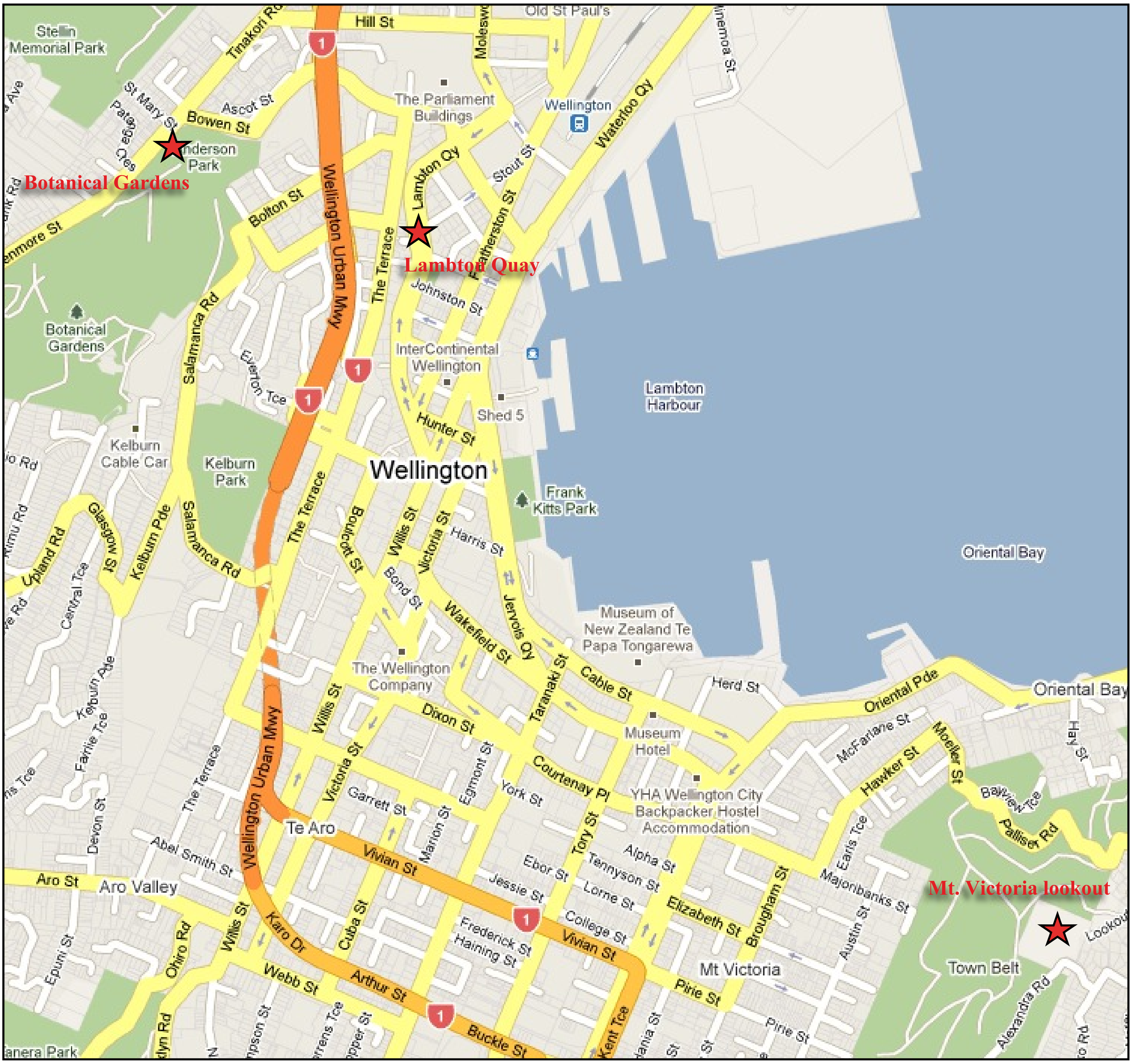
A number of locations within Wellington City and northwards through Lower Hut to Upper Hut (Map 3) show some of the characteristic features of the fault. These sites are described on-line by GNS Science (see Bibliography) and are included in this guide as recommended sites.

MT. VICTORIA LOOKOUT

The Mt. Victoria lookout (Map 4) is an excellent vantage point to view the fault-influenced landscape of the Wellington region. A series of informative boards illustrate the changes which the region has undergone as a result of movements associated with the Wellington and Wairarapa Faults. From here, the scarp associated with the Wellington Fault is visible, trending from amongst the ridges to the south of the city, through the urban area, past the ferry terminal, beneath the western side of the harbour, and through the sediment-filled Hutt Valley to the north.

From the lookout it is also possible to imagine the uplift in the Wellington CBD as a result of the 1855 earthquake. Prior to that event shipping in the harbour docked at the Lambton Quay (Map 4). Following the quake, and with more recent reclamation, the former shoreline is now more than 200 m inland.

The interplay of the Wellington and Wairarapa Faults is strikingly evident from this site. The major uplift associated with the 1660 movement of the Wellington Fault is clearly illustrated by the presence of the low, flat ground linking the hilly terrain about the former island upon which Miramar is situated and the mainland (Photo 1). The airport is built upon this lowland, which was raised from the sea floor during that earthquake. This was then raised a further 1.5 m during the 1855 Wairarapa Fault earthquake, immediately followed by a tsunami which washed across the



Map 4. Street map of Wellington City showing the location of the Mt. Victoria lookout and the Botanical Gardens sites.

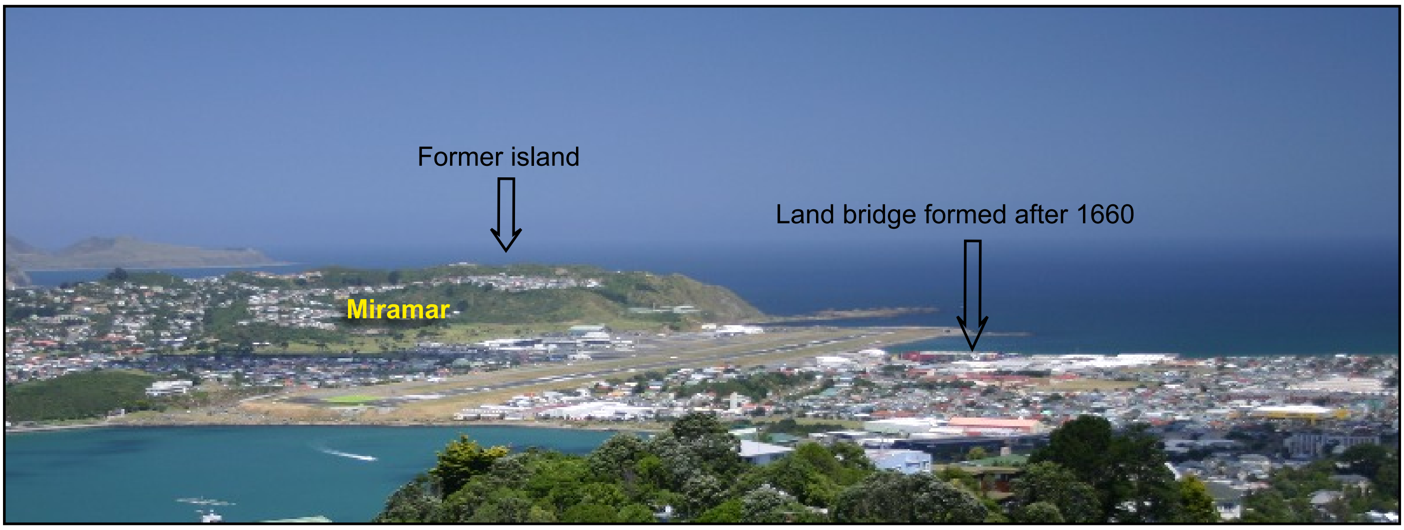


Photo 1. View from Mt. Victoria lookout of the Wellington Airport with Miramar in the close background. Miramar was an island prior to the 1660 Wellington Fault movement which uplifted the local area, forming a land bridge. The 1855 earthquake raised this a further 1.5 m.

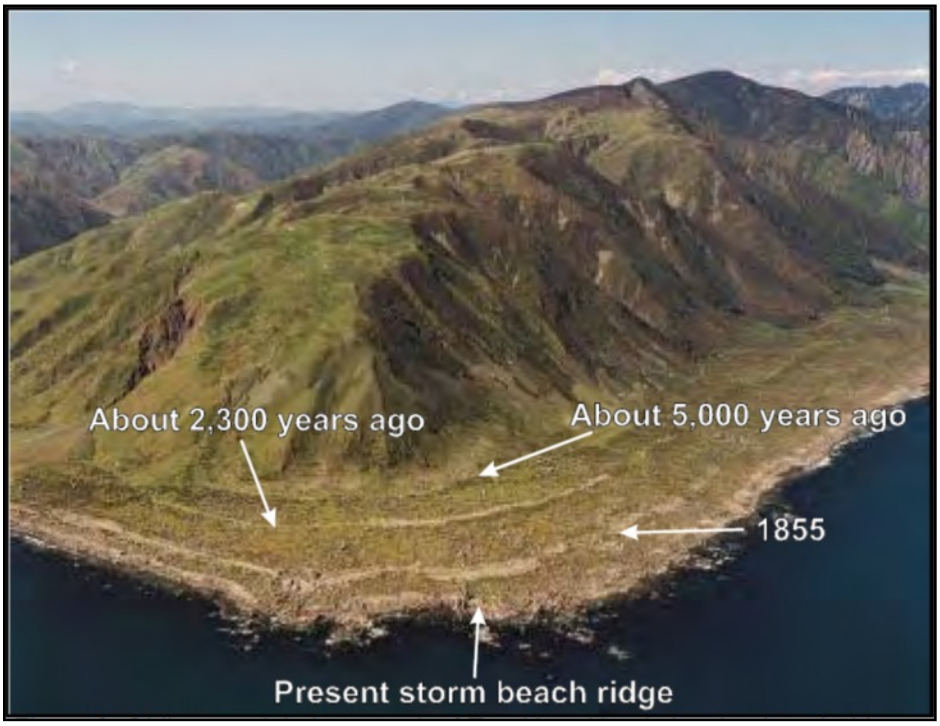


Figure 3. Oblique aerial photograph of Turakirae Head showing beach ridges related to movement along the Wairarapa Fault.

lowland. This latter earthquake tilted and drained a number of shallow lakes on the former island.

The Rimutaka Range on the skyline to the east is flanked by the Wairarapa Fault (Map 3). Uplift during the 1855 earthquake reached a maximum of 6.4 to 7.8 m on the southern end of the range near Turakirae Head (Map 3). A series of four marine terraces at Turakirae Head demonstrate the history of major movement associated with the Wairarapa Fault (Figures 3 & 4). Each movement was associated with seismicity similarly devastating as that of the 1855 earthquake. Uplift prior to the 1855 event took place about 200-382 BC with a maximum uplift of 9.1 m. The oldest preserved ridge was elevated by 3 m about 5100-5400 BC. Each terrace is tilted westward, with the angle of tilt increasing with age.

BOTANICAL GARDENS

Evidence of the surface trace of the Wellington Fault can be examined

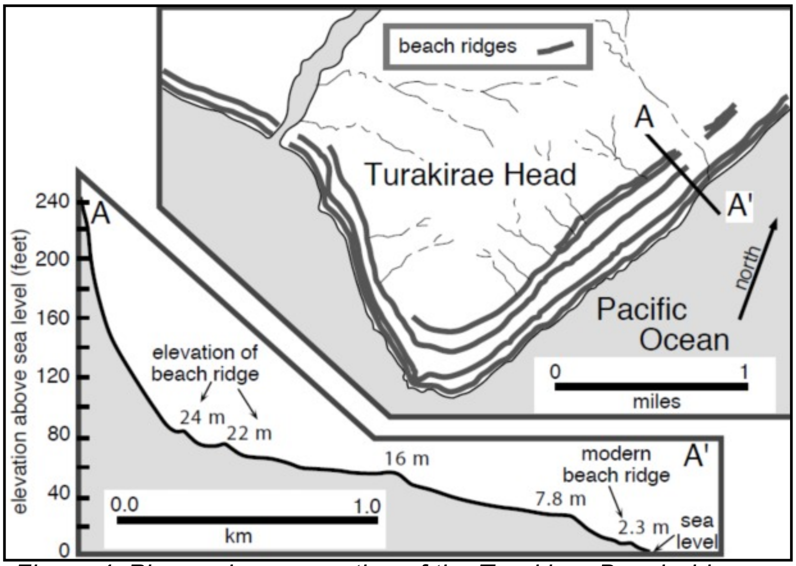


Figure 4. Plan and cross section of the Turakirae Beach ridges showing their elevation above present sea level. From Burbank and Anderson 2001.

Map 5. Satellite image of the area of crushed rock outcrop in the Botanical Gardens.

along the entrance driveway into the Lady Norsewood Rose Garden at the Botanical Gardens (Maps 4 & 5).

As the Wellington Fault moves, the opposite walls of the fault grind together, crushing the rocks into angular fragments of various sizes. This crushed rock can be examined at this site, and possibly compared with similar material to be visited at Mains Rock near Upper Hutt.

THORNDON OVERBRIDGE AREA

Many significant items of city infrastructure cross the Wellington Fault at this site (Map 6). The motorway, railway, ferry terminal and water supply pipelines cross the fault line here. A number of engineering initiatives, some of which are visible here, have been undertaken to attempt to minimise the catastrophic effects caused by a rupture of the Wellington fault.

Wide steel bands around the support columns of the overbridge are to prevent the bridge collapsing in a catastrophic earthquake. Aerial catch frames have been designed and

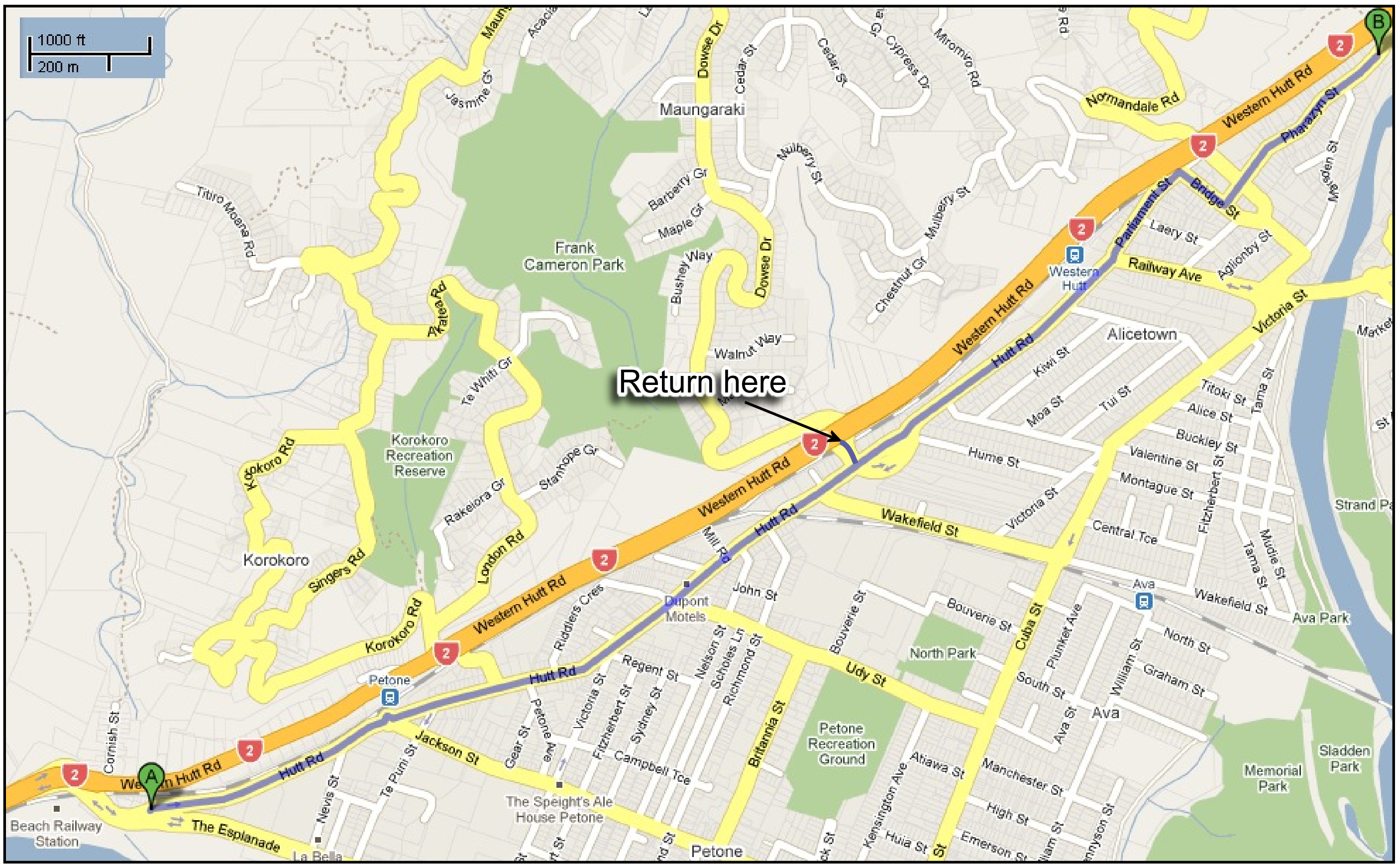
Map 6. Location of the Thorndon Overbridge area.

placed under the motorway to prevent the motorway falling onto the rail tracks in the event of fault movement. As the fault passes directly under the motorway overbridge, it is likely to displace it by several meters.

Continue along Hutt Road toward the Hutt valley and Lower Hutt. This section of the route passes along a narrow, flat rock platform bordered by the harbour on the east and steep ridges on the west. The platform was raised from the floor of the harbour during the 1855 Wairarapa Fault earthquake, which uplifted and tilted the entire Wellington area.

WELLINGTON FAULT SCARP IN LOWER HUTT URBAN AREA

Continuing along the highway, upon entering the start of the Hutt Valley floodplain, turn onto Hutt Road (Map 7). From Jackson Street to Pharazyn Street the Hutt Road follows the fault line. Those houses on the eastern side of the road are 2-3 m lower than the road, due to the fault line passing between the road and the houses. If the fault were prone to slow, continuous creep, then it would be possible for the front yards of these houses to gradually displace laterally into their neighbour's, resulting in shifting fences, paths, gardens, pipelines and other infrastructure!. Unfortunately, the fault is not subject to gradual creep, so that stresses continue to build up toward a major rupture.



Map 7. Suggested route A-B along Hutt Road to Pharazyn Street to observe the Wellington Fault scarp in an urban setting.

The edge of the ridge on the opposite side of the motorway to the west is set back about 150 m from the fault line. This represents the uplifted side of the fault which has been eroded away from the fault line by the Hutt River over hundreds of thousands of years.

Return to the motorway at Dowse Drive and continue northwards for 14 km. A prominent, low rise on the river side of the road is Mains Rock. Park safely off the roadway to examine the outcrop.

MAINS ROCK

This outcrop consists of crushed rock from within the plane of the Wellington Fault. The crushed rock has formed from grinding together of rocks forming the opposite sides of the fault. At times, the fault plane itself is exposed on the western bank of the river. This site is used as a reference survey point by researchers checking for movement on the fault.

Continue along the motorway for 3.2 km, situated to the east of Riverstone Terraces.

RIVERSTONE TERRACES

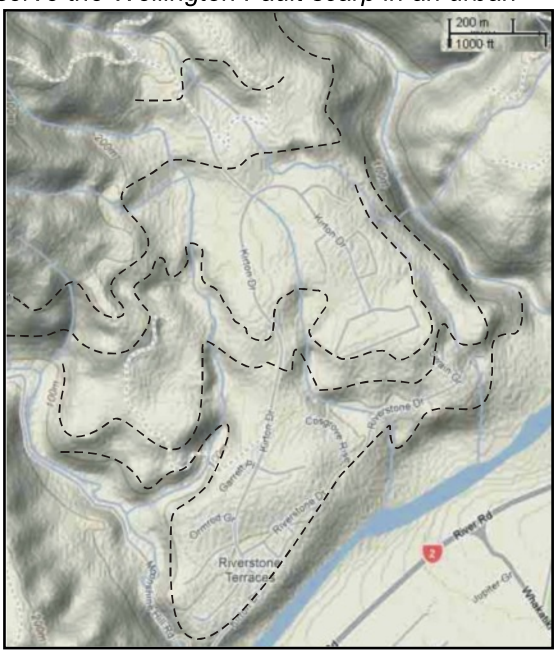


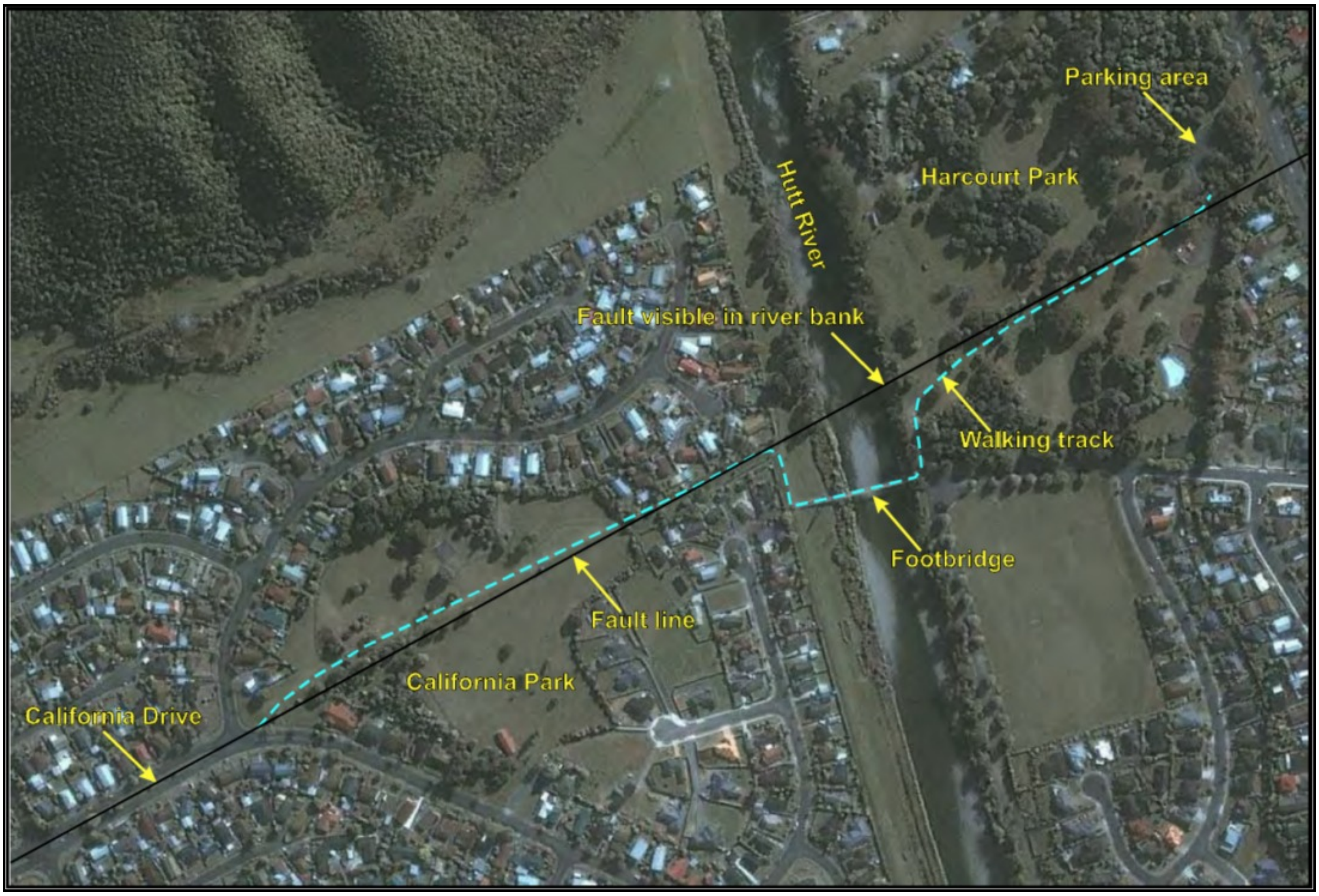
Figure 5. Terrain map of the Riverstone Terraces. Broken lines show interpreted terrace edges.

These are a series of river terraces (Figure 5) that have been uplifted by the Wellington Fault. Gravel deposits from the Hutt River and a tributary have been progressively elevated over the last few hundred thousand years, resulting in prominent terraces. The highest terraces are about 200 m above river level.

Continue along the motorway for about 5.5 km until Akatarawa Rd is encountered on the left. Turn into this road and follow it for about 400 m, stopping in the Harcourt Park parking area on the left.

SURFACE EXPRESSIONS OF THE WELLINGTON FAULT

A number of features in Harcourt Park and California Park to the west of the Hutt River display some of the most recent horizontal and vertical expressions of the Wellington Fault (Map 8).



Map 8. Satellite image of the Harcourt and California Parks area, showing walking track and Wellington Fault line.

Harcourt Park contains a number of stepped river terraces which have been offset by the Wellington Fault. Four terraces are present, with their steep frontal sides (*risers*) showing displacement by the fault which is approximately parallel to the walking track (Figure 6). The higher, older terraces are displaced more than the younger ones, as the older terraces have been subjected to more earthquakes and associated displacements than the younger terraces.

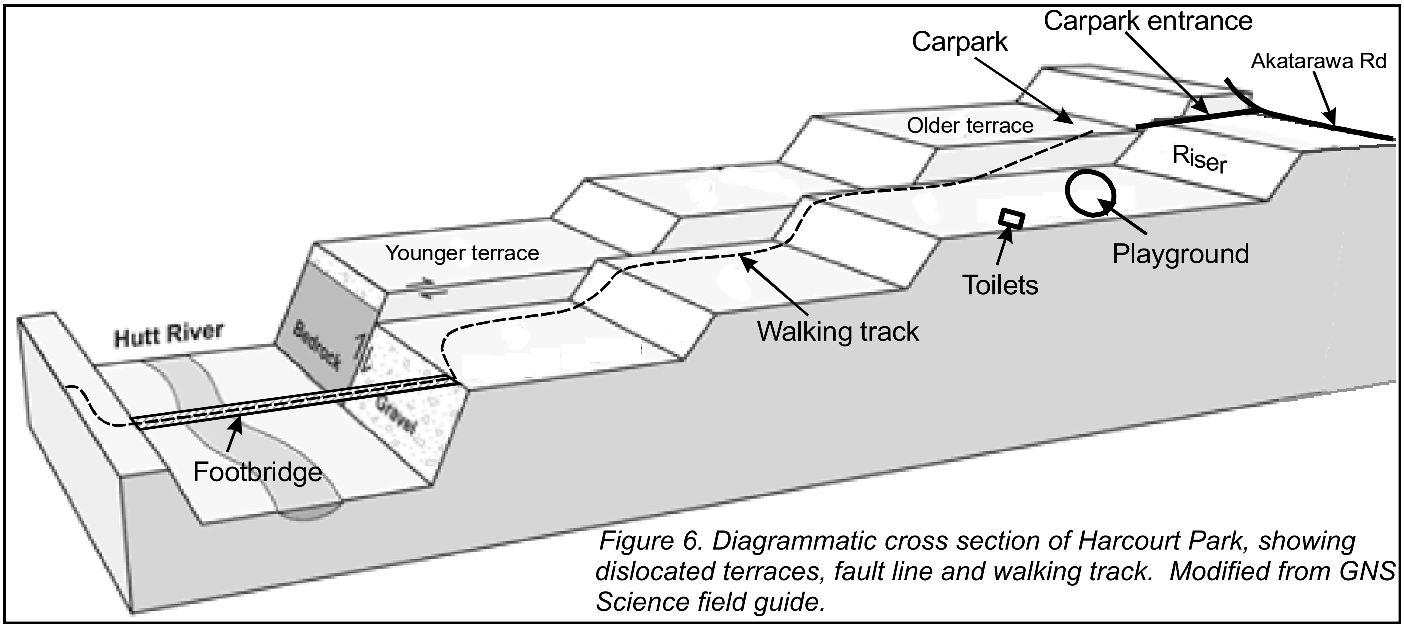


Figure 6. Diagrammatic cross section of Harcourt Park, showing dislocated terraces, fault line and walking track. Modified from GNS Science field guide.

Close to the river the fault scarp becomes very prominent. Cross the river by the footbridge and walk upstream for about 50 m until the fault plane is visible in the river bank on the opposite side (Photo 2). On the uplifted, western side of the fault plane grey bedrock is visible in the lower part of the bank and is overlain by gravels. On the east of the fault only down-faulted river gravels are visible.

Follow the walking track into California Park. The track now follows along the west side of the fault scarp, which is a prominent, linear slope across the park. A number of green, concrete survey pillars have been installed to measure movement of the fault. Accurate surveys show that there has been no movement of the fault in recent times. This confirms that the fault is locked in position, accumulating strain that will eventually be released to produce significant motion along the fault and an accompanying earthquake.

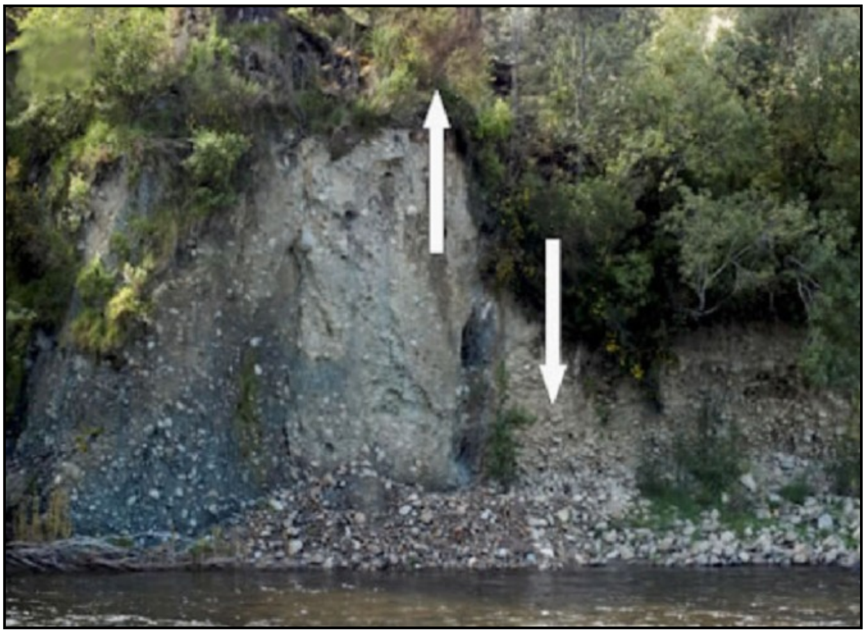


Photo 2. View of Wellington Fault plane in bank of Hutt River, Harcourt Park. Arrows show direction of vertical fault movement.

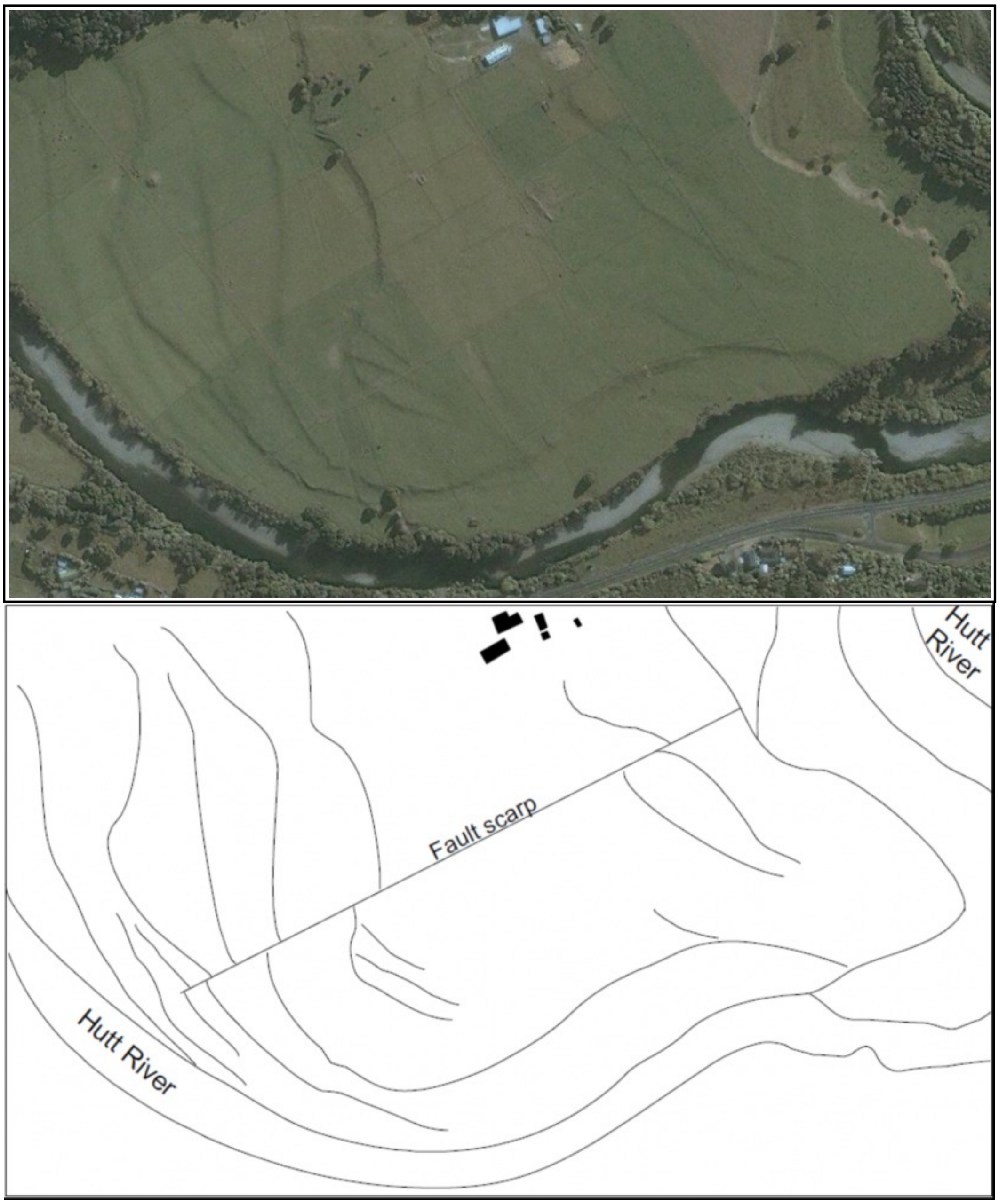


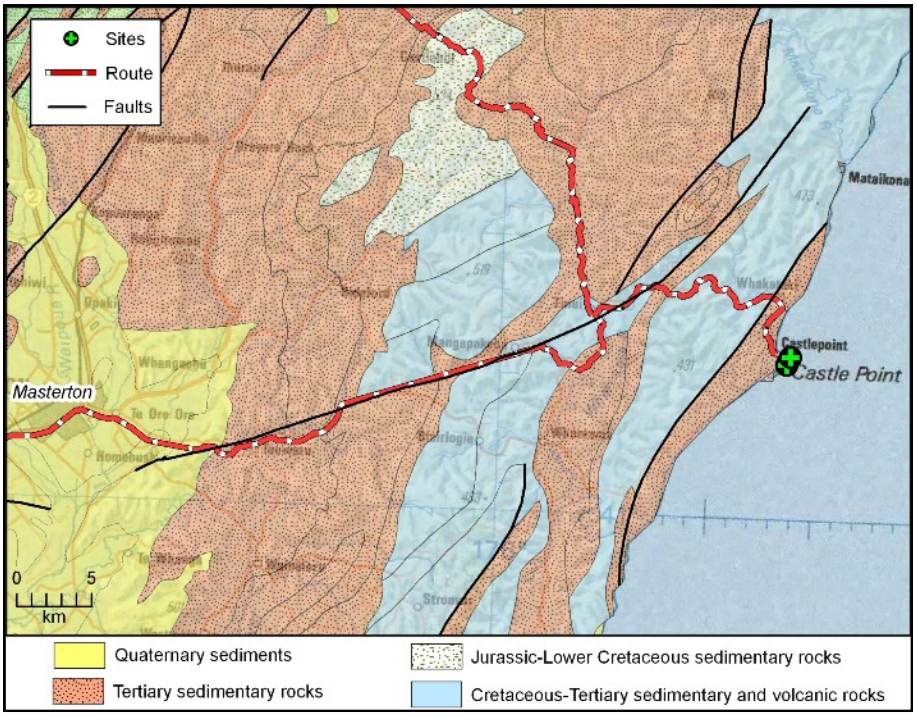
Figure 7. Satellite image (top) and interpretative map (bottom) of offset terraces adjacent to the Hutt River, northeast of Harcourt Park.

From the southwestern end of California Park the fault passes down the centre of California Drive. This broad road has been developed to allow for a substantial distance between the houses bordering the road and the fault plane. Note how the houses on the northwest side of the road are elevated relative to those on the southeast, with the fault scarp running down the centre of the divided road.

Return to the highway and turn left, continuing along the Main North Road for 1.8 km where the Hutt River returns to the northern side of the road. Although it is not possible to view from the road, a series of terraces have been offset on the adjacent floodplain by the Wellington Fault (Figure 7). The satellite image in Figure 7 shows the fault scarp and offset terraces. Note how the younger terraces toward the river bank are offset less than those away from the river. The youngest, small terraces immediately adjacent to the river have not been offset at all, and no fault scarp is apparent, indicating that they post date the last movement of the Wellington Fault.

The route now continues toward Castlepoint on the east coast. Triassic to Jurassic, sandstone-rich sedimentary rocks of the Torlesse Superterrane form the high and steep Rimutaka Range, which has been uplifted by the Wairarapa Fault on its eastern flank (Maps 1, 2 & 3). On the east side of the range a broad, sediment-filled valley occupied by the towns of Featherston, Greytown, Carteton and Masterton represents the subsided eastern flank of the Wairarapa Fault. From Masterton, turn into the Te Ore Ore Road on the northern side of the river. Follow the road to Castlepoint, a distance of 66 km.

About 10 km from Masterton the road enters rounded hills of Tertiary calcareous sandstone, limestone, siltstone and conglomerate (Map 3). These sedimentary rocks were deposited in a shallow ocean which covered most of New Zealand during the Tertiary period. Areas of similar Cretaceous marine sedimentary rocks occur in places. Numerous north-northeast - trending faults of the North Island Fault System have interleaved and deformed the Tertiary and Cretaceous strata.



Map 9. Simplified geology between Masterton and Castle Point.

CASTLEPOINT SYNCLINE AND FOSSILIFEROUS SANDSTONE

After entering Castlepoint village, drive to the end of the road and park safely (Figure 8).

This locality shows some folded, very fossiliferous Late Pliocene (1.7 million year old) calcareous sandstones. The rocks have been locally folded into a syncline (a canoe-shaped fold) which has been faulted by a number of north-northeast trending structures. The outcrops along the headland are on the eastern side of the syncline, and so are tilted toward the west (Photo 3).

The rocks cropping out along the headland were deposited close to a shoreline, in shallow, cold waters. We know this because of the abundant shelly fossils which were prevalent in regions closer to the Antarctic than New Zealand is today. The characteristics of the sandstones and the abundance of shelly remains indicates very shallow waters, with strong wave and current action. These shelly rocks are best examined at the locality shown on Figure 8 (Photo 4). Care should be taken here, as large waves can break across the headland. The highest rocks at this locality are limestones and sandy limestones, which overlie the shelly sandstones.

Photo 3. West-dipping shelly sandstone overlain by shelly and pebbly sandstone (foreground).

Figure 8. Satellite image of the Castlepoint area, showing suggested walking route and sites of interest.

A northeast-trending fault lies immediately to the west of the headland, separating the shelly rocks from slightly older sandstone and mudstone which forms the hills to the west. This fault, and the event which tilted the sandstones has obviously occurred within the past 1.7 million years, following deposition of the rocks.

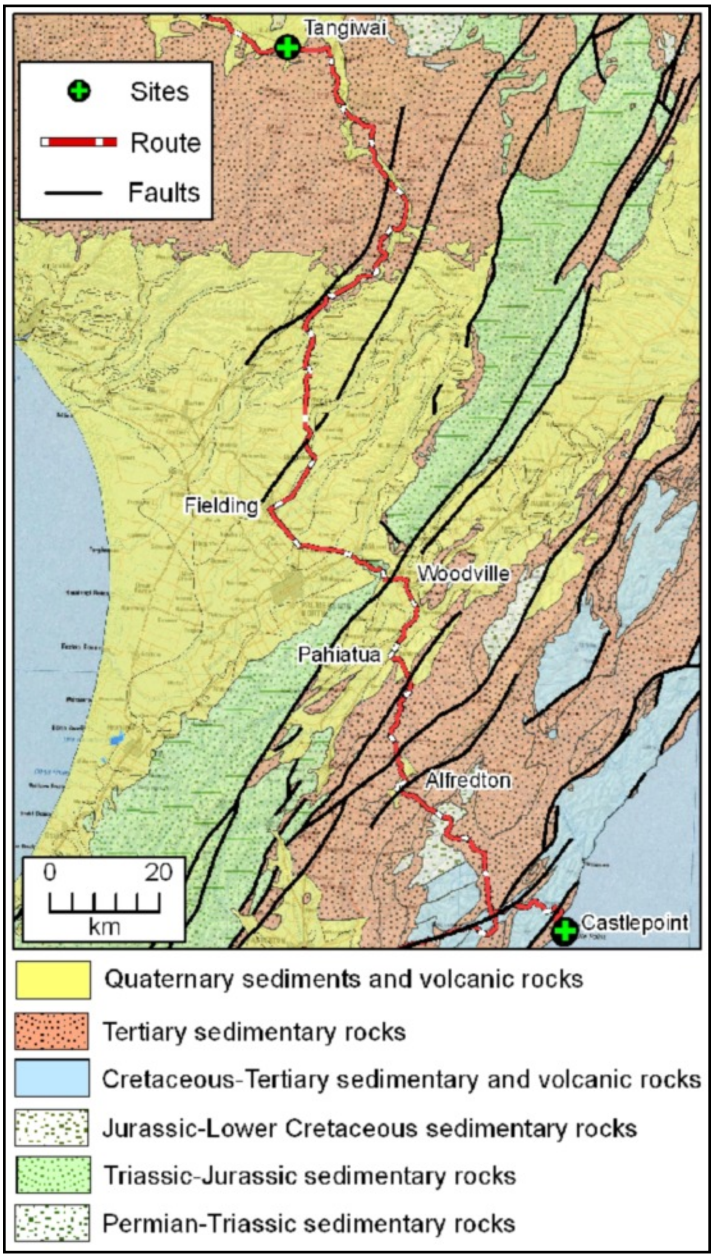
The most common shelly fossils include *Glycymeris, Chlanys, Phialopecten, Mesopeplum, Venericardia, Dosina,* and *Neothyris.*

The northern end of the headland, near the lighthouse, shows the extent and geometry of the dipping rocks as they extend southward to The Castle. Individual fossil shells can be found where they have weathered out of the soft sandstone.

Photo 4. Coarse shelly fossils at Castlepoint.

The next stage of the route is directed towards the Taupo Volcanic Zone, with the first site at Tangiwai (Map 10). The suggested, most direct route involves:

1. a 22 km return to Tinui, from where the route turns northward into Manawa Road en route to Alfredton, a distance of 40 km.
2. Turn north onto Route 52 and follow this for 2.4 km, then turn left onto the Pa Valley Road. Follow this for 10 km to the intersection with the Mangaone Valley Rd. Turn right and follow the Mangaone Valley Rd for 12.6 km to the edge of Kaitawa village. Turn left into Kaitawa Rd and follow this for 6.5 km to State Highway 2.
3. Turn right and travel directly through Pahiatua to Woodville, a distance of 16 km
4. Turn left into Napier Road for 13 km before turning right into Ashhurst Road and following this to Fielding, a distance of 20 km.
5. Follow State Highway 54 (Kimbolton Rd) for 54.5 km to its intersection with State Highway 1. Turn right and follow the highway for 70.7 km to the edge of Waiouru.
6. Turn left into State Highway 49 and follow this toward Tangiwai for 9 km. After crossing the bridge across the Whangaehu River, turn right into the parking area at the Tangiwai Memorial.



Map 10. Geology and route between Castlepoint and Tangiwai.

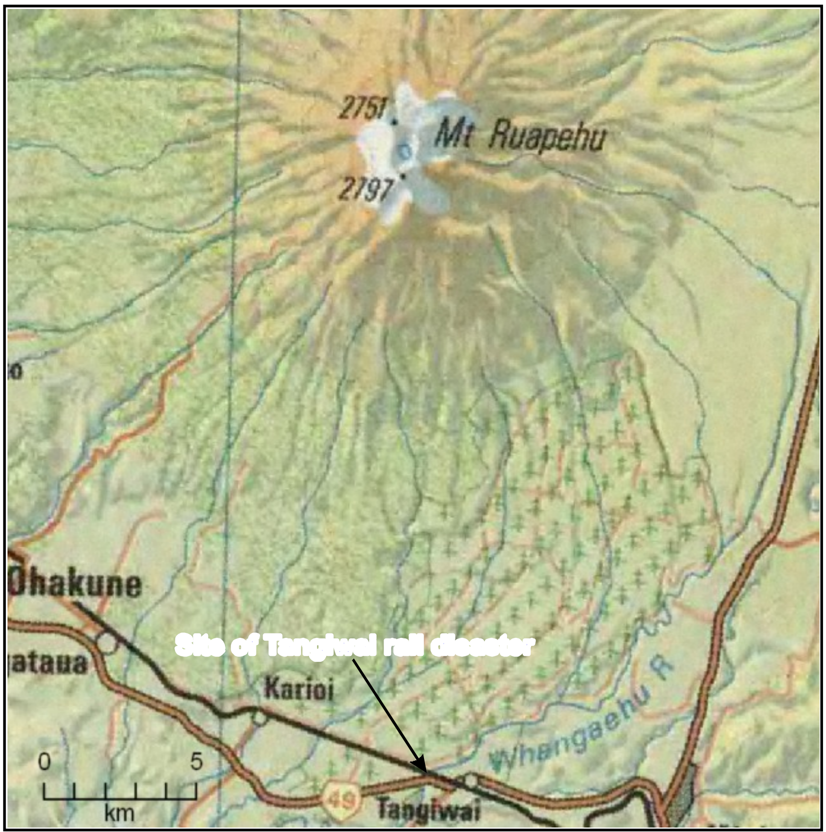
The route crosses a broad region of Tertiary marine limestones, sandstones and shales, before entering a region of alluvial cover after Pahiatua (Map 10). Multiple levels of alluvial terraces are visible in many places. The route re-enters rolling hills of Tertiary sedimentary rocks through to the next site at Tangiwai.

TANGIWAI RAIL DISASTER SITE

This site, on the banks of the Whangaehu River, marks the scene of one of New Zealand's greatest natural disasters. The information boards at this locality explain the disaster, where at 10.21 p.m. on Christmas Eve 1953 the Wellington–Auckland night express plunged into the flooded river. Of the 285 passengers on board, 151 died.

The rail disaster was caused by the sudden release of approximately 1,650,000 cubic metres of water from the crater lake of nearby Mt Ruapehu (Map 11). The resulting 6-metre-high wave of acidic water, ice, mud and rocks surged tsunami-like, down the Whangaehu River, striking the concrete pylons of the Tangiwai railway bridge and destroying the bridge superstructure. This occurred on a fine evening, with insignificant rainfall.

The rapidly flowing mixture of water, mud, boulders and ice flowing from Mt Ruapehu is known as a *lahar*. Lahars resemble wet concrete as they flow. They are readily influenced by relief, being guided along stream channels and into deep gorges or even along shallowly incised stream channels at low gradients. Lahars are a recurring natural event associated with Mt Ruapehu. They form when an eruption or crater instability ejects or spills large volumes of water in a rapid event from the normally water-filled crater onto surrounding glaciers, and/or into the Whangaehu River and other catchments (Map 12). Some form by rapid melting of snow and ice by volcanic activity, and others by heavy rainfall on steep,



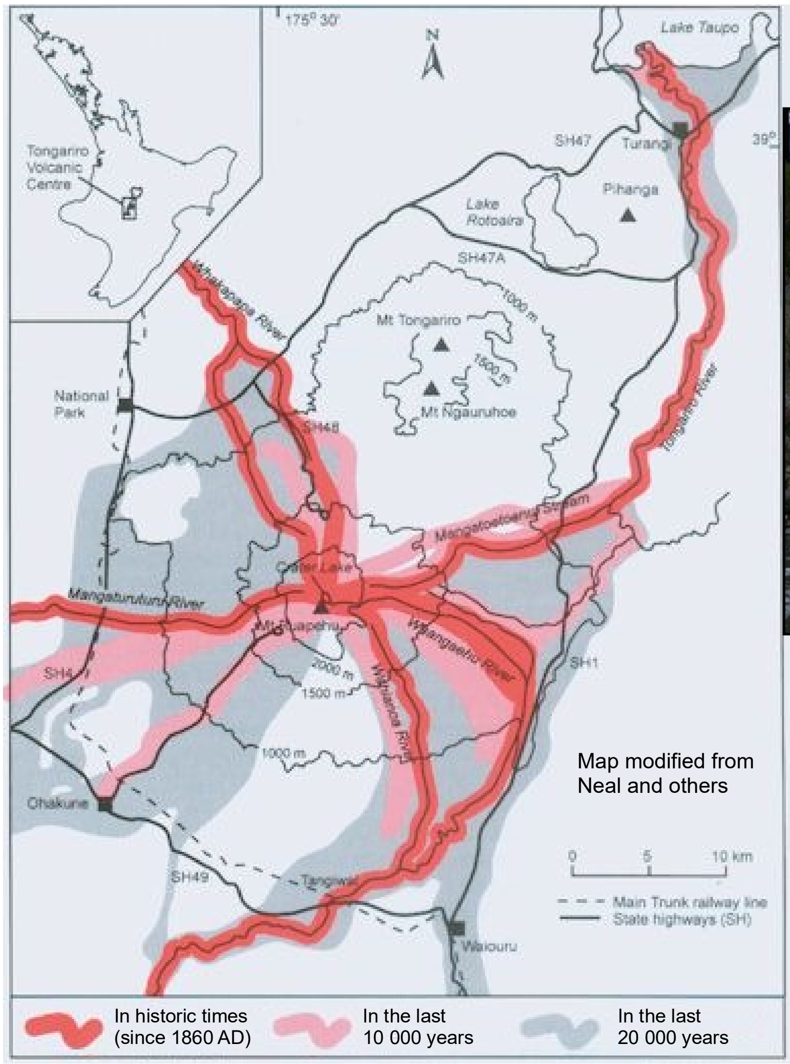
Map 11. Topographic map of the Mt Ruapehu-Tangiwai area, showing the course of the Whangaehu River and the site of the 1953 rail disaster.

unconsolidated volcanic debris. On the eastern flank of Ruapehu, the abrupt surge of huge volumes of water rips up ice and snow, loose ash and volcanic boulders and plummets at speeds up to 180 kph (more commonly 20-40 kph) down the flanks of the volcano into the Whangaehu River. The lahar picks up further debris as it flows, and historical accounts indicate that the leading edge of the lahar comprises a mass of muddy water and logs.

Lahars have been reported in this river since 1861, but have been active for about 1800 years. Many lahars followed the 1861 event, with one in 1925 weakening the Tanwiwai bridge structure. A significant eruption in 1945 formed a deep crater which subsequently filled with water, eventually breaking through an ice and debris barrier to form the 1953 lahar. Significant lahas have formed in 1968, 1969, 1975, 1995 and 2007.

The Whangaehu River carries an acidic mixture of toxic chemicals from the Ruapehu crater. Most normal aquatic life is unable to exist in the river waters until they have been diluted with water from other rivers, many kilometres downstream of Tangiwai.

The present banks and bed of the river are composed of floodplain material sourced from previous lahars and normal floods (Photo 5). Note the coarseness of the boulders transported by the powerful flow of lahars. The bouldery material includes a range of volcanic rocks derived from Ruapehu.



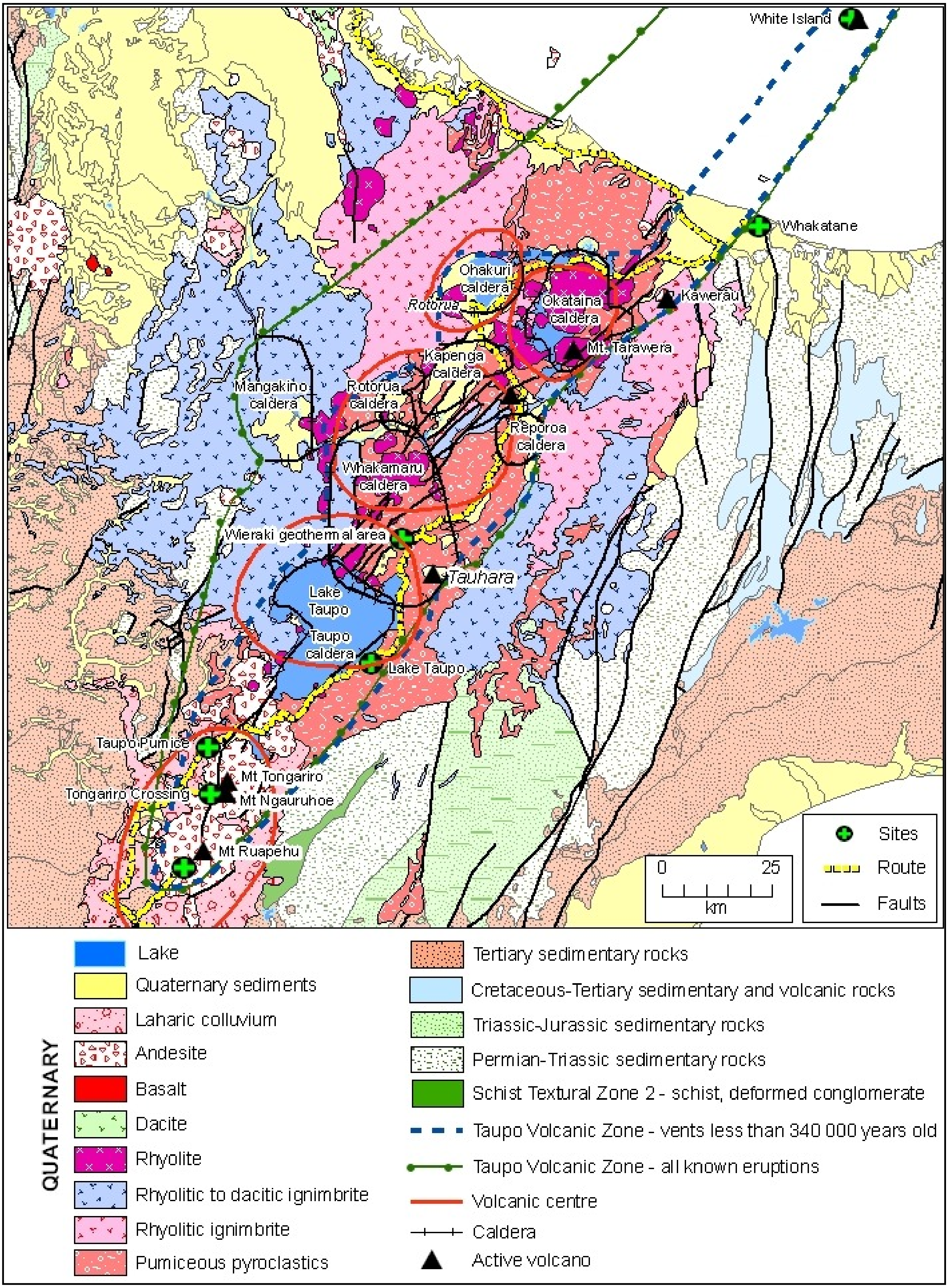
Map 12. Areas inundated by lahars (or volcanic debris avalanches) and associated floods from Ruapehu.

Photo 5. Very large boulders intermixed with pebbles and sand in the banks of the Whangaehu River are the product of previous lahas.

Many of the following sites are within the Taupo Volcanic Zone (TVZ). Before proceeding, it is appropriate to describe the origin, landforms and geological features of the TVZ.

AN INTRODUCTION TO THE TAUPO VOLCANIC ZONE

The Taupo Volcanic Zone is a highly active volcanic area 350 km long by 50 km wide in North Island (Maps 1, 13). Mount Ruapehu marks its



Map 13. Simplified geology of the Taupo Volcanic Zone, showing active vents, volcanic centres, and recommended geological sites. Compiled from GNS data, and Graham (2008).

southwestern end, while the submarine Whakatane volcano (85 kilometres beyond White Island) is considered its northeastern limit. The TVZ is defined by vent positions and caldera structural boundaries. This is an example of a *volcanic arc* (a belt of volcanic activity related to eruption of magma above a subduction zone) which has been partially split open by clockwise rotation of the eastern North Island, resulting in a region of *rifting* (Figure 2). Rifting takes place in areas of crustal tension, where the crust sinks along faults into the upper mantle. This results in thinning of the crust and partial melting of some crust (giving rise to rhyolitic volcanic rocks), and the eruption of volcanic materials of mantle origin (producing basalts). Eruption of magma derived from melting associated with the subduction zone most commonly produces andesite and dacite (intermediate in composition between basalt and rhyolite).

Rotation of the eastern North Island to produce the TVZ is related to oblique motion between the Pacific and Australian Plates (Figure 1). The southwesterly motion of the Pacific Plate uplifts and compresses the leading edge of the Australian Plate, and pulls the northeastern corner of the North Island to the southeast, thereby producing a V-shaped zone of rifting, the TVZ. The TVZ ends near Ruapehu because the crust from this point southward is about 10 km thicker, thereby blocking the upward passage of magma.

The relatively thin crust of the TVZ (about 15 km) and the numerous faults passing through these rocks makes an ideal situation for magma to breach the crust and erupt. A thin film of magma 50 km wide and 160 km long has intruded to within 10 km of the surface of the TVZ, elevating crustal temperatures and heating waters within the crust, forming the geothermal areas about Taupo and Rotorua. Most of this water has been transported deep into the crust along the subduction zone and subsequently driven into the upper crust with some mantle-derived water by convection.

Volcanic activity commenced in the TVZ about 2 million years ago as arc-related andesitic eruptions. Voluminous rhyolitic (plus minor basaltic and dacitic) activity commenced about. 1.6 million years ago as a result of rifting of the arc. The most recent eruptions were at Ruapehu in 1995-96.

The total volume of TVZ volcanic deposits is uncertain. Present estimates suggest bulk volumes of 15-20,000 cubic kilometres. Rhyolite is the dominant magma erupted with about 15,000 cubic km, andesite is an order of magnitude less abundant, and basalt and dacite are minor in volume (< 100 cubic km each).

The andesitic to dacitic magmas presently erupt on opposite ends of the TVZ. White Island in the north is a largely submerged *stratovolcano* (a tall, steep, cone-shaped volcano), whilst Tongariro, Ngauruhoe and Ruapehu in the south are land-based, composite stratovolcanoes. Arc volcanism has existed in the past through the central part of the TVZ. An extinct 700,000 year old stratovolcano is present to the northeast of Taupo, and andesitic lavas are recorded from drill holes in the central areas. The Tauhara volcano (Map 13) is dacitic, resulting from the near-surface mingling of andesitic and rhyolitic magma. Arc volcanism in the central area has largely been replaced by, and submerged under, rift-related rhyolitic products.

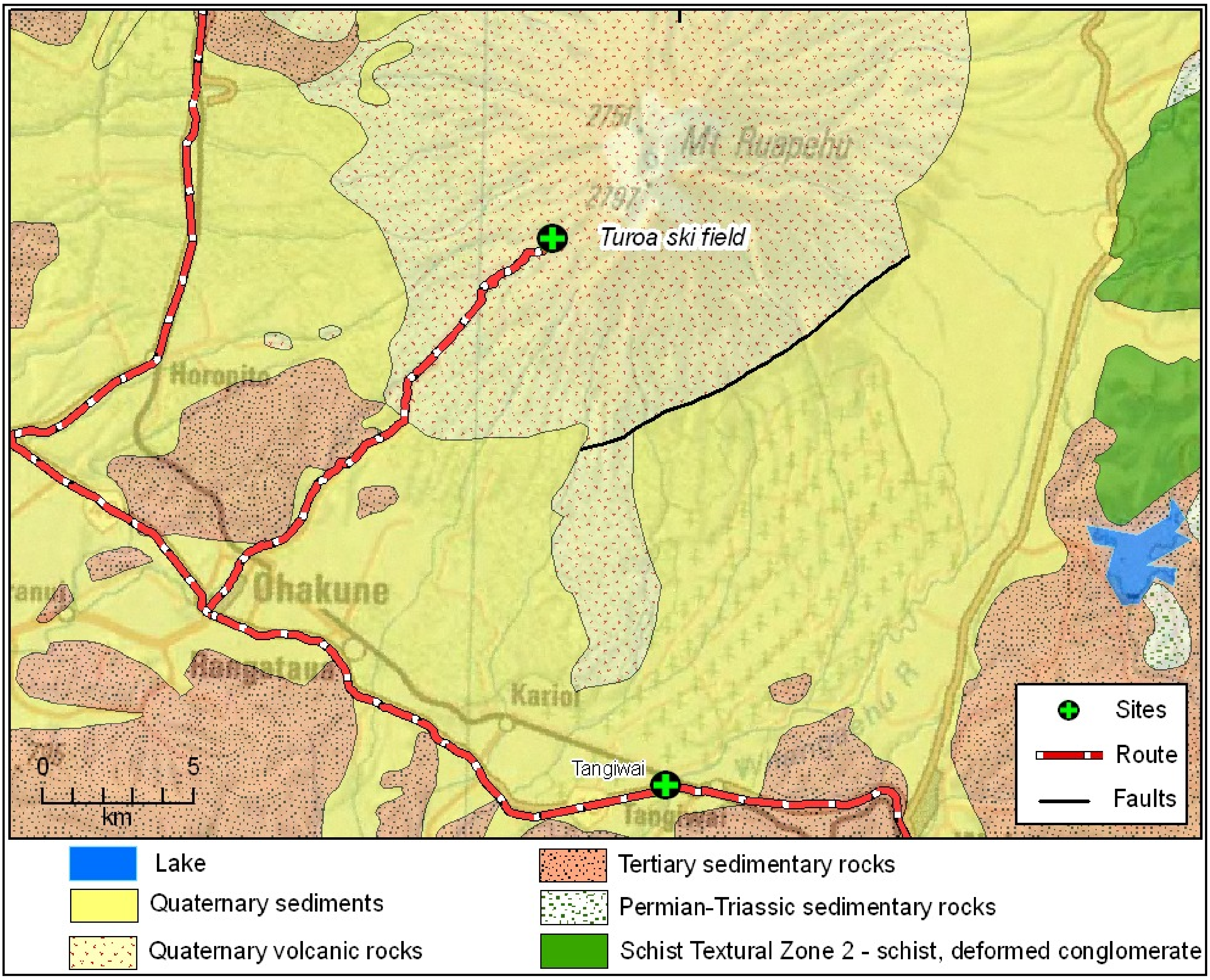
The rhyolitic magmas form at relatively low temperatures of 700-850°C, are highly viscous and contain significant amounts of dissolved water and gases. As the magma nears the surface and ambient pressures decrease, the dissolved water and gases begin to separate and expand. If they are able to escape the magma reaches the surface as a thick, liquid lava which will only flow for short distances. If they can't escape readily, the magma froths. Upon reaching the surface the frothing magma begins to solidify, and the expanding gases shatter it into fragments of pumice and fine rock particles. These are carried high into the atmosphere as a dense cloud of intermixed hot gases and ash. If this mixture is less dense than the surrounding atmosphere it will be blown laterally and begin raining ash and pumice, draping airfall ash deposits across the landscape. If the mixture is heavier than the atmosphere it collapses upon itself, surging outward in a rush as a hot flow of ash and pumice which can travel at very high speeds and for up to 200 km. These are known as *ash flows.* They produce *ignimbrite*, a rock type which outcrops extensively throughout the central parts of the TVZ. They erupted from broad, dome-like vents, some of which may have had lakes within their centre. These are present in the central area of the TVZ about Taupo and Okataina. These vents subsequently collapsed to form *calderas,* a cauldron-like volcanic feature usually formed by the collapse of land following a volcanic eruption. Eight rhyolitic caldera centres have so far been identified in the central segment, of which two (Mangakino and Kapenga) are adjoining (Map 13). These caldera are regarded as the remnants of *supervolcanoes*, whose eruptions were so huge, and expelled so much magma, that they emptied their magma chambers, causing the ground surface to fall back into the empty void.

TUROA SKI FIELD - MT RUAPEHU VOLCANIC ROCKS

The next geological site is the Turoa ski field north of Ohakune (Map 14). This site is best visited in the warmer months when no substantial snow covers the ground. The site is reached by driving 18 km from the Tangiwai site to Ohakune, then turning north into Goldfinch Street in the centre of town and following this directly through to the Ohakune Mountain Road to the Turoa ski field. The distance from Ohakune to the parking area at the ski field is 18 km. A well formed access road behind the buildings (Figure 9) leads part way up Mt Ruapehu and gives walking access to the lower slopes.

Mt Ruapehu is the southern-most volcano in the Taupo Volcanic Zone (Maps 13, 14). It is one of the world's most active volcanoes, the largest active volcano in New Zealand and the highest point in the North Island.

Mt. Ruapehu is largely composed of lava interlayered with fragmental rubble of andesitic composition. It began erupting at least 250,000 years ago and in recorded history undergoes a major eruption approximately every 50 years, including 1895, 1945 and 1995–1996. Minor eruptions are frequent, with at least 60 since 1945. Between major eruptions the crater fills with water from melting snow. Expulsion of water from the lake results in significant lahars, as was examined at the previous site at Tangiwai. During 2009 the crater lake experienced elevated warming and gas activity which prompted hazard warnings.



Map 14. Simplified geological map of the route between Tangiwai , Ohakune and Mt. Ruapehu.

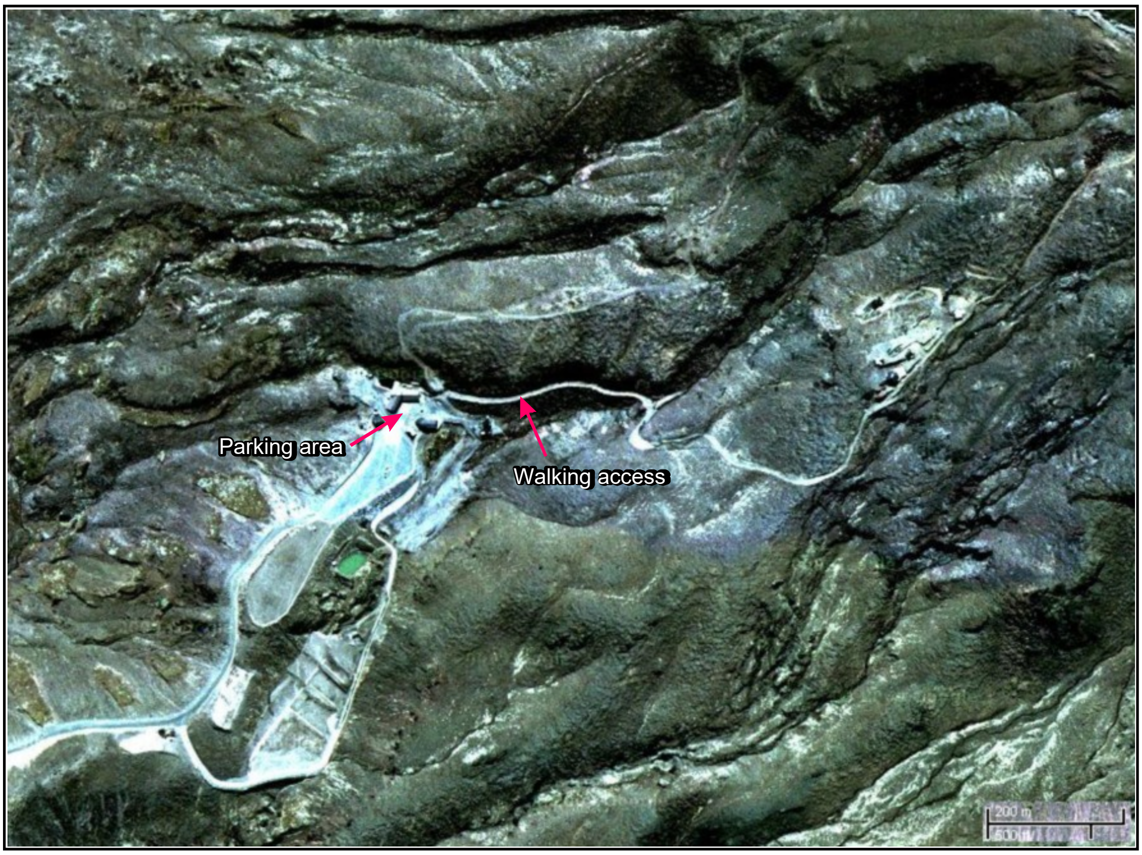


Figure 9. Satellite image of the Turoa ski field area, showing parking area and walking track. Note the black lobes of lava flows which dominate the flanks of Ruapehu.

Photo 6. Mt. Ruapehu viewed from the south.

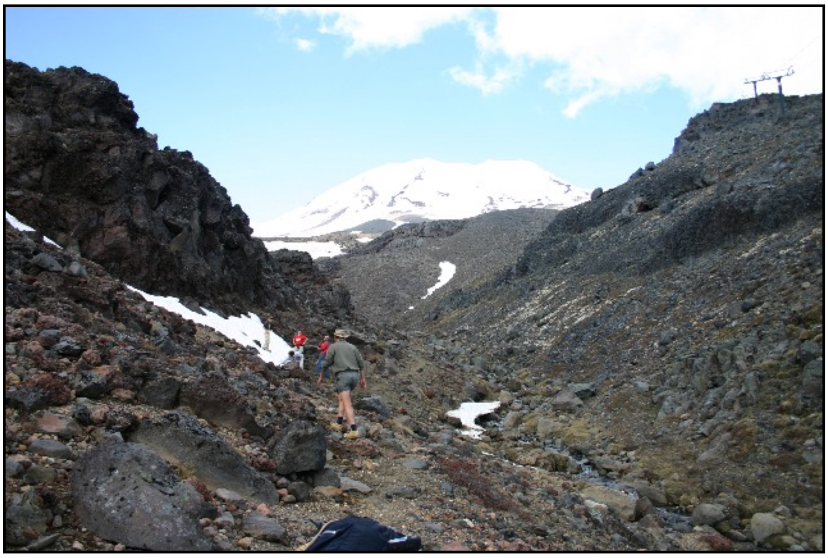


Photo 7. Blocky, dark grey andesitic lavas on the flanks of Mt. Ruapehu.

The walking route across the flanks of Ruapehu passes through a number of hard, blocky, grey andesitic lava flows. These are interspersed with blocky, unconsolidated rubble layers which are the products of explosive activity from the volcano, and blocks of solidified lava which broke loose from flows during their emplacement.

Andesitic lavas will be examined in more detail on the flanks of Ngauruhoe volcano at the next site (Map 13).

Return to Ohakune and travel for 9 km along the Tohunga Road to the intersection with State Highway 4. Turn right and travel for 26 km to the intersection with State Highway 47 near National Park village. Continue along SH47 for 13.2 km until the intersection with Mangatepopo Road on the right (east). Travel down this road to the parking area at the end, about 6 km. This marks the western end of the Tongariro Crossing walking track. The track is 19.4 km long and requires transport from either end. An alternative which allows examination of the volcanic rocks and landforms involves a return walk of about 16 km to Blue Lake (Map 15), passing Mt Ngauruhoe, and South Crater, Red Crater, Emerald Lakes, and Central Crater of Mt. Tongariro. **Appropriate clothing is required and food and water. Weather conditions can change dramatically and become severe rapidly! Be prepared.**

TONGARIRO CROSSING

This full day walk passes through excellent examples of young, arc volcano landforms and rock types. Fresh and altered andesitic lavas, active and dormant craters and crater lakes can be examined in spectacular scenery.

The Tongariro and Ngauruhoe volcanoes are part of the Tongariro volcanic centre, which comprises the volcanoes Tongariro and Ruapehu, plus at least six other volcanoes (Figure 10). Most are composite volcanoes, with multiple vents. Tongariro is composed of at least 12 vents, which includes Ngauruhoe, the youngest and still active vent (Figures 11 & 12). The physically largest volcanoes of the Tongariro volcanic centre are those of Tongariro, Ruapehu, Kakaramea and Pihanga. Maungkatote and Hauhungatahi are two smaller eroded eruptive centers. Pukeonake is made of a satellite cone and associated flows. Ohakune consists of four craters. The volcanic centre is surrounded by an extensive ring plain made of stream, debris flow, lahar, lava, and ashflow deposits.

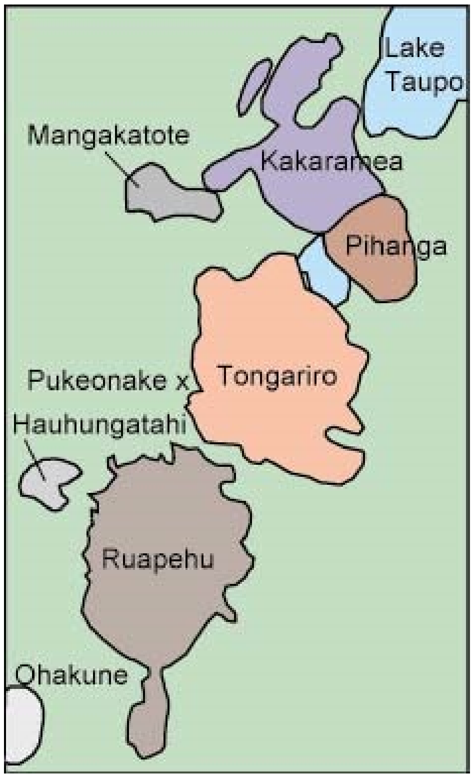
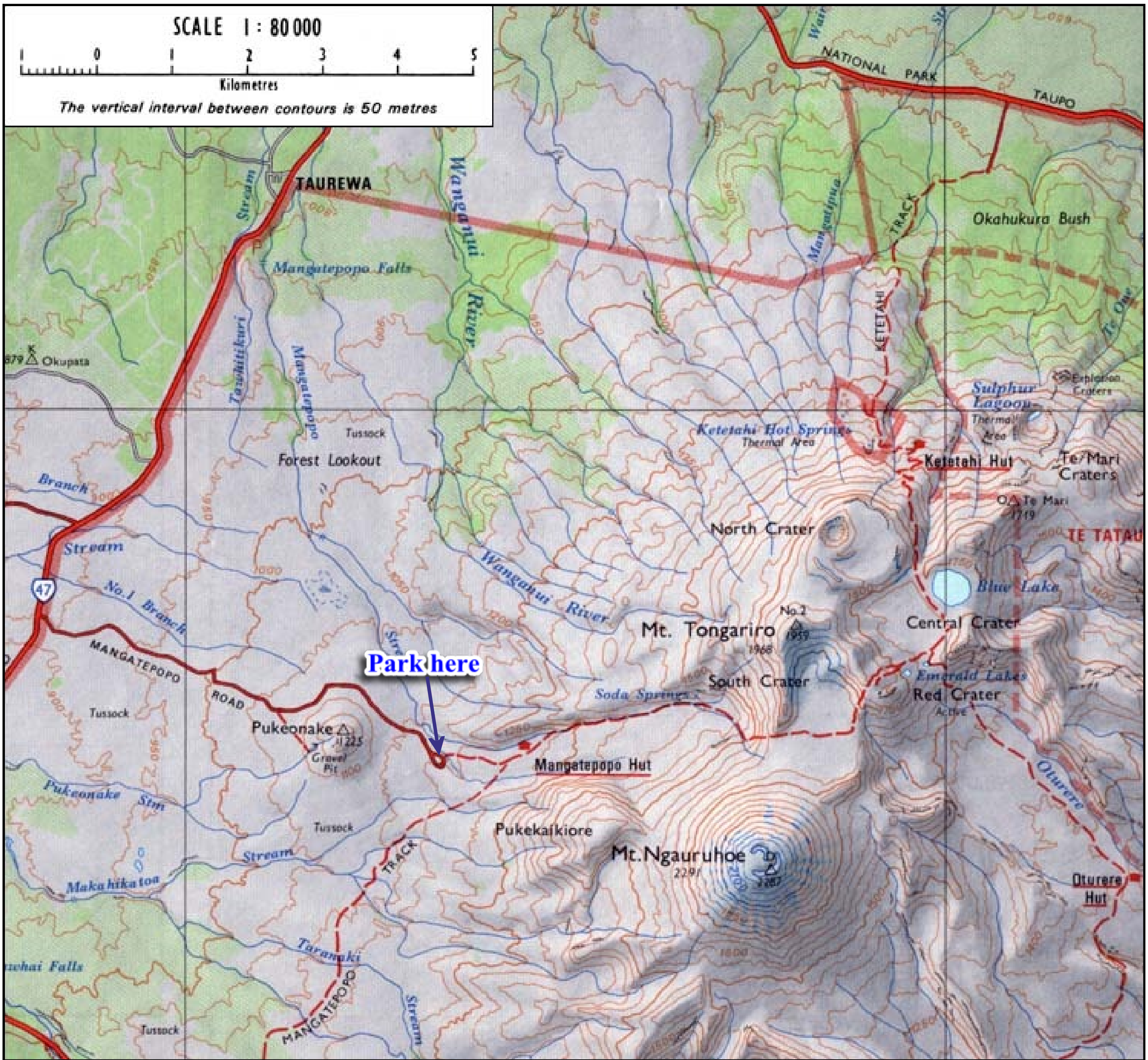


Figure 10. Volcanoes of the Tongariro volcanic centre.

The exposed portion of the Tongariro volcanic complex has grown steadily over the past 275,000 years. By 65,000 years ago the cones and vents of North Crater, Tongariro summit, Pukekaikiore, Blue Lake and Tama Lakes had developed. Over the past 15,000 years 11 cones and vents have formed, including Red Crater, which was last active in 1850.

Ngauruhoe commenced erupting about 2500 years ago as a parasitic cone on the side of Tongariro. It has had frequent eruptions, the most recent in 1870, 1949, 1954-55, and 1973-75. Its last major eruption was on 19 February 1975, when strong explosive activity sent eruption columns to 10 km and ash flows moved down the flanks. Its lavas show significant variation in composition between events, suggesting that its magmas form in small batches within complex and rapidly changing magma chambers beneath the volcano. The erupted lava commonly contains fragments of partly melted sedimentary and metamorphic rocks acquired from the continental crust during ascent.

The drive along Mangatepopo Road passes the extinct *scoria cone* (a vent which produced rough, bubble-filled lava or ash) of Pukeonake (Figure 13). The walk follows the valley of Mangatepopo Stream before commencing



Map 15. Topographic map of the Tongariro Crossing.

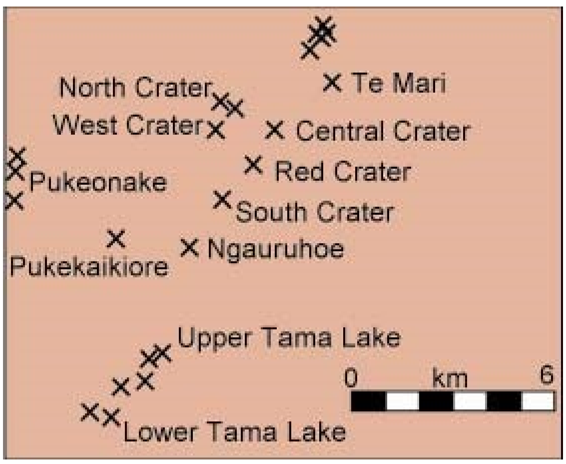


Figure 11. Location of the main vents of the composite Tongariro volcano.

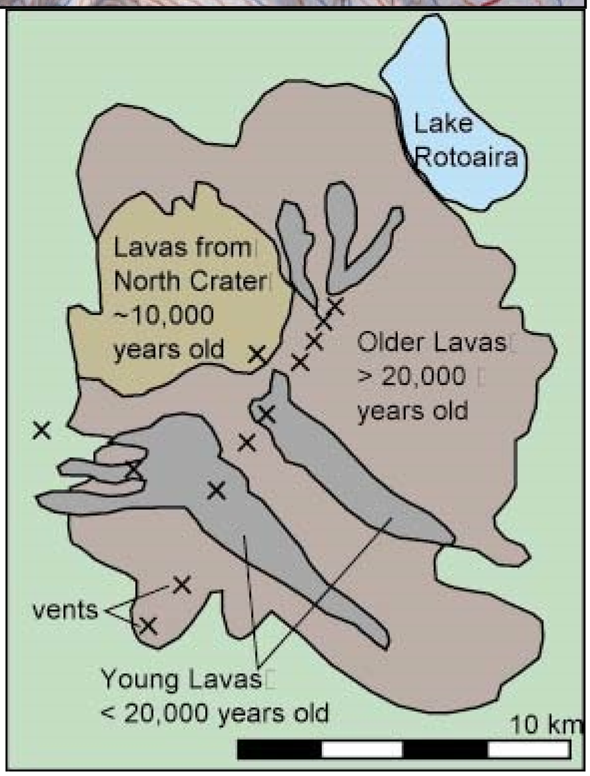


Figure 12. Simplified geological map of the Tongariro volcano. Crosses show the location of active vents in the last 50,000 years.

the steep climb toward the plateau linking Tongariro and Ngauruhoe (Figure 14). The extinct and eroded remnant cone of Pukekaikiore is evident south of the track. Thick, columnar jointed lava flows are visible on the flanks of Pukekaikiore. As the high cone of Ngauruhoe is approached the abundant, relatively young. blocky pyroclastic flows spreading down its flanks are clearly visible. These were erupted in 1949, 1954 and 1975 and are shown as dark, radiating lobes on Figure 14, and relatively darker features in Photo 8. As the track approaches, and then ascends the flank of Ngauruhoe, the characteristics of the pyroclastic flows can be examined. These comprise blocks of andesitic lava, which grade inward from glassy margins, to crystalline cores. Gas bubbles are commonly preserved in the outer parts of the blocks as irregular voids known as *vesicles*. The pyroclastic flows moved sinuously to the foot of the cone where they formed small lobes in the floor of the valley. The end of these lobes can be seen along the track and in Figure 14. Pyroclastic flows were formed rather than lava flows as the gas-rich magma frothed and exploded in

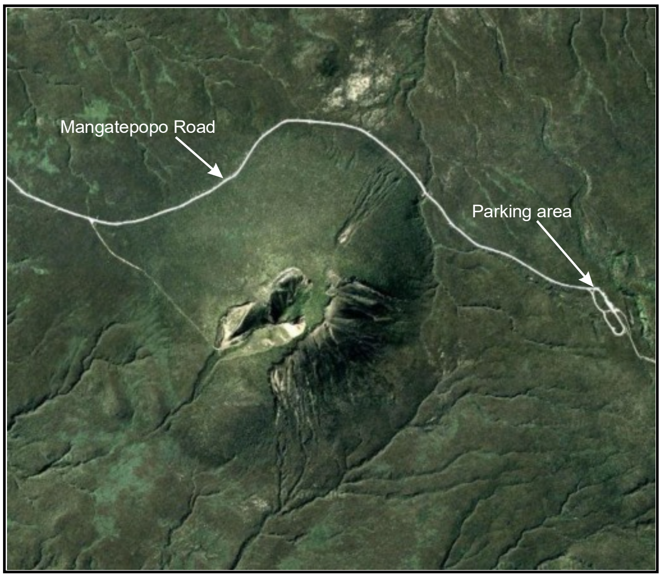


Figure 13. Satellite image of Pukeonake scoria cone (centre of image).

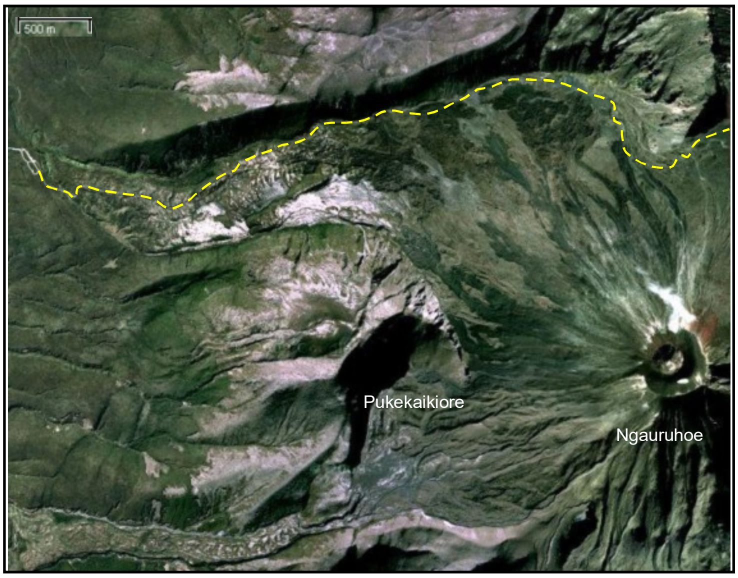


Figure 14. Satellite image of the Tongariro Crossing route from the parking area to the foot of Ngauruhoe.

Photo 8. Ngauruhoe with Ruapehu in background. Note the recent, dark pyroclastic flows which have streamed down Ngauruhoe.

Photo 9. Ngauruhoe showing the remnant rim and infilled floor of South Crater.

Ngauruhoe's crater, forming blocks of congealed magma which were forced over the crater rim. The lower sections of the ascent pass alongside a cliff showing several thick andesitic lava flows erupted from Tongariro. These flows show massive interiors and brecciated tops. The reddish, blocky brecciated tops resulted from cooling and crystallising of the magma top as it flowed, the congealed top then fragmenting into blocks as the lava continued to flow beneath it.

From the top of the ascent above the Mangatepopo valley, the track passes across the fine ash-strewn floor of South Crater (Photo 9). This not a true crater but a drainage basin between the surrounding volcanic landforms. The track then commences a climb up the crater rim toward Red Crater. The rim is characterised by abundant altered layers of ash and lava which spill over from Red Crater. The altered rocks are pale yellows and whites, with many of the original minerals of the volcanic rocks altered by hot, acidic fluids and gases to form clays. Rust-coloured voids in the rock indicate the original presence of sulphide minerals, probably *pyrite* (iron sulphide), now altered to hematite.

Red Crater is an aptly named crater with a rim of iron-rich, oxidised lava and ash. This crater was formed about 3,000 years ago and has erupted extensive lava flows into the floor of South Crater and the adjacent valley. Eruptions ceased from this vent about 160 years ago. The crater includes a spectacular lava tube (Photo 10) which is interpreted to have erupted lava from the vent through its walls, and was subsequently exposed by erosion. The coating of solidified magma on the walls of the tube have preserved it from erosion whilst the softer, altered rocks around it have been steadily removed.

The track continues across variably altered ash and lava toward the Emerald Lakes (Photo 11). To the north the large, flat-topped landform of North Crater is apparent. North Crater once contained a lava lake which cooled to

Photo 10. Red Crater, showing the tube-like dyke on right.

Photo 11. The descent to the Emerald Lakes.

infill the crater. A scoria covered ridge leads down to the Emerald Lakes. These three lakes fill old vents which erupted ash. Their brilliant colouring is caused by minerals washed down from the altered rocks about Red Crater.

From the Emerald lakes the track crosses Central Crater which like South Crater is actually another drainage basin. A short climb leads up to the ridge beside Blue Lake. Blue Lake has formed where cold fresh water fills an old vent. The track then circles around North Crater.

From here the route descends into native forest. Unless transport has been organised at the end of the track it is recommended that the route be retraced to the parking area.

After returning to the parking area, navigate to the main road and turn right towards Taupo. This next section of the route examines features relevant to the eruption of the Taupo Volcano.

From the intersection, travel along State Highway 47 for 10.1 km. The road passes through a steep road cutting. Stop and park safely on the northern side of the cutting. Walk back to the northern end of the cutting to examine the rocks exposed here.

THE TAUPO ERUPTIONS

The Taupo Volcano, whose main vents sits beneath Lake Taupo, is a dormant supervolcano. This areally large volcano has been in existence for more than 65 000 years. In that time it has shown a random pattern of exceptionally large events interspersed by smaller eruptions. The volcano has produced some of the world's largest recorded eruptions.

Prior to 65,000 years ago the earliest preserved eruptions were from small lava domes. About 330,000 years ago an exceptionally large and widespread ignimbrite eruption took place, and then about 150,000 years ago a pumice-rich ignimbrite was erupted. At least 5 eruptions followed between 65,000 and 27,000 years ago, producing coarse pumice layers from vents now under Lake Taupo.

The largest eruption from Taupo, the *Oruanui eruption*, occurred 26,500 years ago producing 300 cubic km of ignimbrite, 500 cubic km of pumice and ash fall. The rapid venting of such a large volume of material caused several hundred square kilometres of surrounding land to collapse and form the caldera. The caldera later filled with water, eventually overflowing to cause a huge outwash flood. The water-filled caldera is now Lake Taupo.

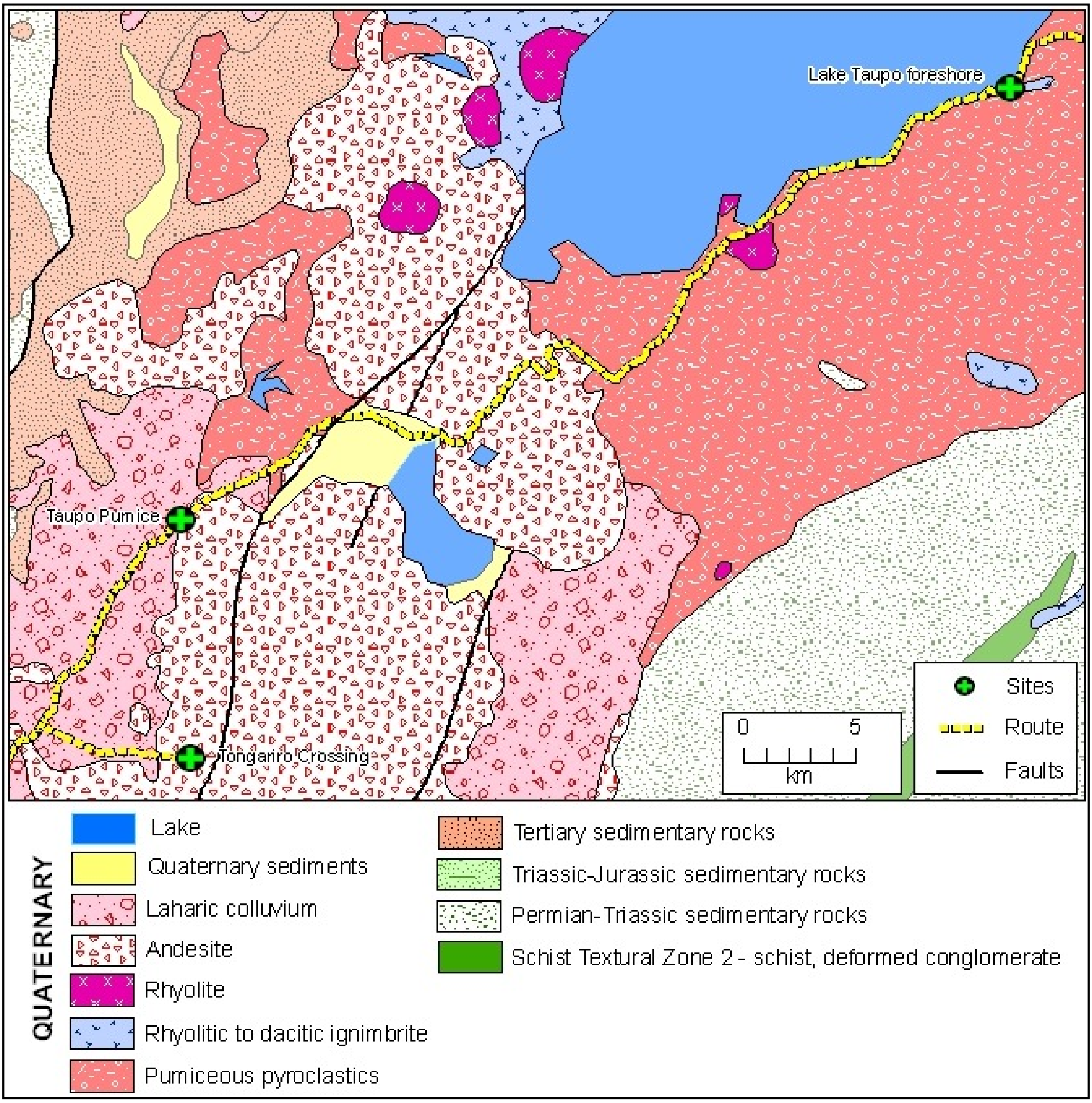
Since the Oruanui eruption there have been at least 28 more eruptive events. These were from vents further south of the original vents, but still beneath Lake Taupo. These younger eruptions were of dacitic composition.

The most recent eruption of Taupo, the *Taupo (or Hatepe) eruption*, was in 233 AD. The Taupo eruption was a complex series of events which ultimately ejected 100 cubic km of material, of which 30 cubic km was ejected in the space of a few minutes when part of the main vent area collapsed inward. The first phases of the eruption produced a series of five pumice and ash fall deposits over a wide area of the central North Island. The second phase erupted a large and very energetic ash flow that devastated an area of about 20,000 square km at a speed of 600-900 kmh, filling all the major river valleys of the central North Island with pumice and ash within a span of 10 minutes. This eruption further expanded the lake.

The Taupo eruption took place from a line of vents near the eastern side of the modern lake. At the beginning of the eruption, the vent was clear of the lake as there is minimal evidence for water involvement with the erupting magma. However the lake eventually breached the vent and several stages of the eruption were dominated by mixing of the magma and lake water, with fine ash being formed.

Taupo's last known eruption occurred around 260 AD, with lava dome extrusion.

There is currently no evidence for unrest at Taupo Volcano. Swarms of small earthquakes that have regularly shaken Taupo in historical times appear to be associated with fault lines and the ongoing subsidence and widening of the region rather than the movement of magma. Underwater thermal activity persists near one vent.



Map 16. The simplified geology of the route between the Tongariro Crossing and Lake Taupo.

This road cutting displays an excellent section through the base of the Taupo Pumice (Photo 12). This thick layer of unconsolidated pumice was deposited as a single, catastrophic outpouring of extremely hot pumice fragments during the Taupo eruption. The pumice is deposited upon unconsolidated, thinly layered ash fall deposits which are draped over unsorted laharic deposits of sand, gravel and boulders (Photo 13). The older, non-layered laharic material has shed from the andesitic vents between Tongariro and Lake Taupo (Figure 10). The overlying, thinly layered, brown to pale yellow material is ash probably erupted from the Taupo volcano as an airborne plume in a previous eruption. The overlying Taupo Pumice is non-layered, and composed of a multitude of grainsizes of angular to well-rounded pumice fragments (Photo 14).

Photo 12. The Taupo Pumice overlying ash fall and laharic colluvium.

Photo 13. Bouldery laharic colluvium draped with thinly layered airfall ash.

Photo 14. Detailed view of the Taupo Pumice.

Photo 15. The base of the Taupo Pumice, showing the charcoal remains of vegetation burned by the ashflow.

Photo 16. Road cutting in pumice-rich volcanic ash.

Pieces of carbonised plant remains can be found near the base of the pumice unit (Photo 15), representing trees and shrubs which were incinerated and enveloped by the hot ash flow. Many of the pumice blocks are very well rounded, similar to pebbles. This rounding took place as the ash flow moved across the landscape, interior friction grinding the angular edges from the blocks.

The route continues to Lake Taupo, where a stop is made adjacent to the shoreline and a road cutting (Photo 16) to examine the volcanic rocks proximal to the eruption site. This is a drive of 42.2 km. The route passes through Turangi village, then along the foreshores of Lake Taupo, with the site just on the eastern side of Waitetoko village.

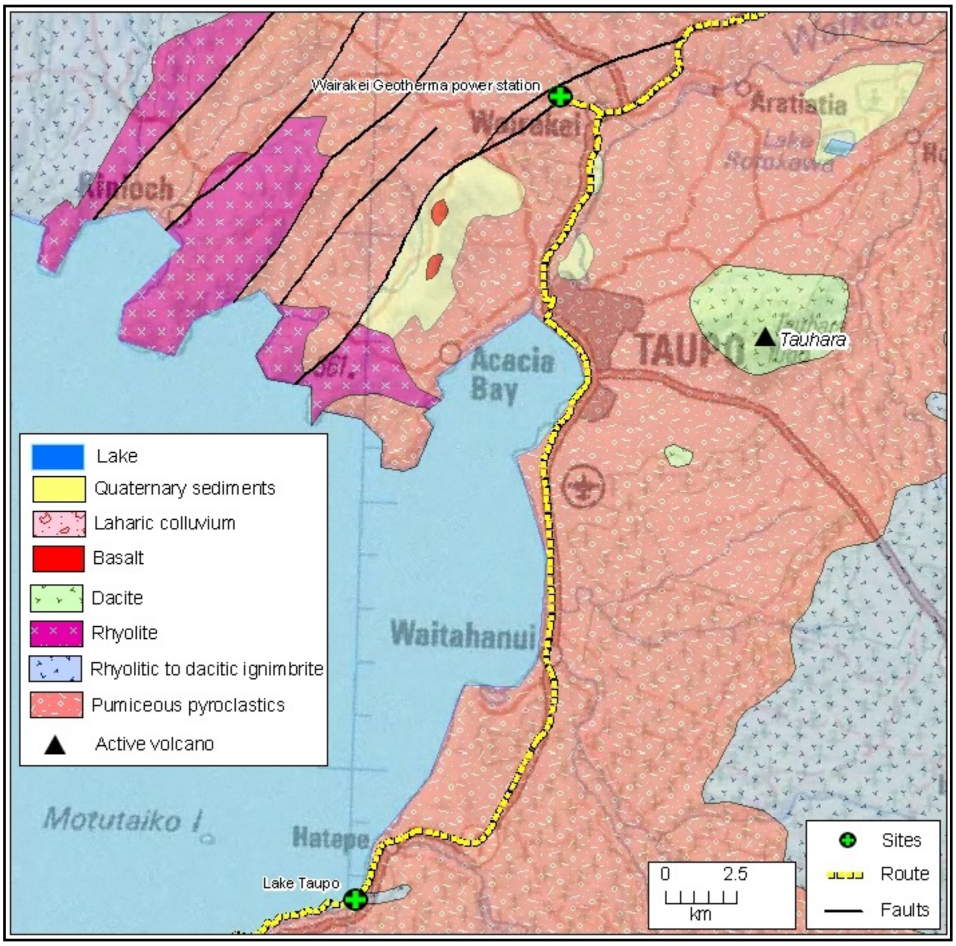
The road cutting at this site is composed almost entirely of white fragments of pumice. This rock is poorly layered, and the fragments of pumice are rounded and angular. It has resulted from the last eruption of Taupo, which typically produced large volumes of rhyolitic pumice as airfalls and ash flows. Numerous large, well rounded pebble-like blocks of pumice can be found along the lake shoreline, eroded from the many deposits of pumice-rich ash in the region.

Lake Taupo fills the caldera of the Taupo supervolcano. A number of vents lie dormant beneath its waters, associated with elevated heat flows and *hydrothermal* (i.e. heated groundwater) activity. The water in the lake is largely derived from watercourses entering the lake.

The route continues for 33.3 km through the town of Taupo and northwards toward the Wairakei geothermal power station. A signposted turnoff to the left (just before the steam pipeline to the power station is reached) runs parallel to the line of steam pipes, before passing under the pipes and leading up a hill to a lookout over the geothermal field. Park here, and proceed to the lookout, where an information board provides an insight to the operations of the power station and the geothermal field.

Photo 17. Part of the Wairakei geothermal well-field area, showing steam pipelines and steam vented from flash plants.

The TVZ contains a number of high temperature geothermal fields. Geothermal fields are associated with young and active rhyolitic volcanism. Magma intruded into the stretched and fractured crust of the TVZ has resulted in temperatures of at least 350ºC at depths of less than 5 km. This has provided a huge heat source from which



Map 17. Simplified geology of the route between Lake Taupo and the Wairakei geothermal area.

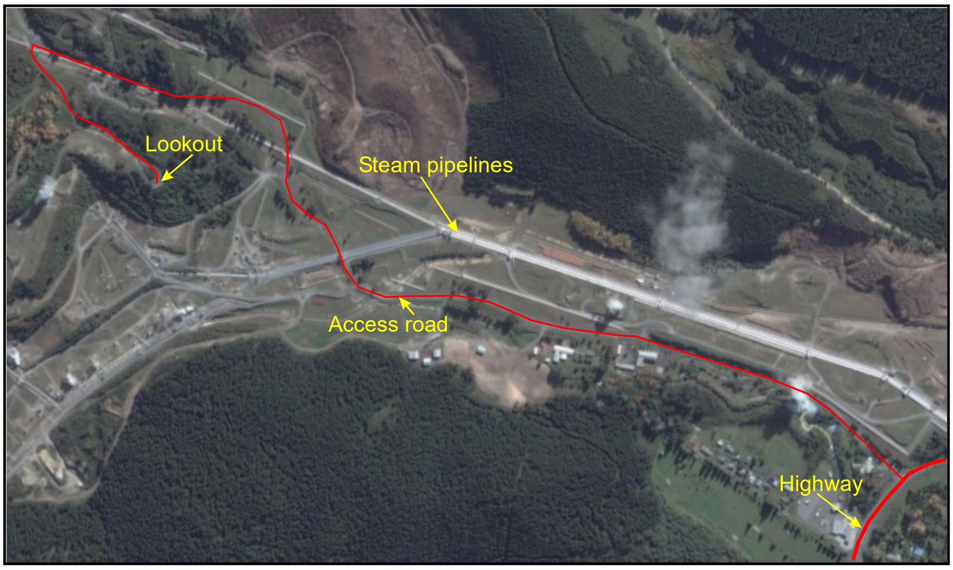


Figure 15. Satellite image of the Wairakei geothermal area, showing access route to lookout (red line).

geothermal systems have developed and been sustained for periods of up to hundreds of thousands of years. A total of 29 geothermal areas have been identified, although only about half of these have potential for resource utilisation. Individual fields are typically about 12 sq km in area and spaced 15 km apart. Much of the water which is converted to steam in the crust was rain water which percolated downward. The geothermal fluids contain gases such as carbon dioxide, hydrogen sulphide and ammonia which are expelled into the atmosphere when the steam is vented. Dissolved elements and minerals include silica, boron, arsenic, gold, and sodium and potassium chloride. These dissolved materials can be present in toxic amounts.

The Wairakei geothermal power station is a 181 MW plant which draws steam from 60 wells in the local field (Photo 17). More than 200 wells have been drilled into the hot (230-260°C), volcanically-heated rocks to depths of 2 km. About 1400 tonnes per hour of steam are extracted from the subsurface for electricity generation, after which the condensed hot water is pumped back into the ground. .

Built in 1958, this was the first geothermal power station developed in the world. After decades of steam extraction from the geothermal field visible geothermal activity has increased throughout the region. This is due to changes in the water table / water pressure which allows more steam to be created underground. Increased fumarolic activity is common, but hot springs have ceased flowing in the Taupo area. In places there has also been some land subsidence and reduction in steam volumes from the field. The Wairakei geothermal field is generally experiencing subsidence. The total subsidence as a result of 50 years of geothermal fluid extraction is about 15 m. Subsidence rates in the centre of the subsidence bowl have decreased from over 450 mm/year during the 1970s to 80-90 mm/year during 2000-2007.

There are many easily accessible sites within the TVZ to experience the surface manifestations of the geothermal activity of the region. The Craters of the Moon thermal area near Taupo, Rotorua and Wai-o-tapu are a few of the many localities which cater for visitors intent on examining the hot springs, fumaroles, mud pools, geysers, thermal pools and altered and cavernous rocks which characterise the geothermal fields.

Wai-o-tapu displays all the surface features of a geothermal area. The site comprises rhyolitic ash deposits which have been leached, altered and dissolved (to form caverns) by prolonged exposure to hot, acidic groundwater (Photos 18 & 19). Dissolved silica and sulphur precipitate about fumaroles and along the margins of hot pools (Photos 20, 21 & 22). The “Champagne Pool” is a 62 m deep, steep-sided explosion crater about 700 years old which fills with geothermal water through a conduit in its base. The water in this pool enters at about 230°C and cools to about 74°C near-surface. The pH of the water is 5.4, meaning that it is somewhat acidic. Bubbles of carbon dioxide, formed by volcanic processes, constantly rise through the water. The orange colour of the pool margin is formed by arsenic- and

Photo 18. Bleached, intensely altered rhyolitic rocks with staining resulting from the precipitation of iron oxide and sulphur.

Photo 19. A collapsed cavern in altered, now very porous rhyolitic volcanic rocks. Yellow sulphur has precipitated from fumarolic activity. About 6 m deep.

Photo 20. A cavern corroded into altered rhyolitic rocks, showing yellow sulphur crystals precipitated from a fumarole. Nearly 2 m high.

Photo 21. A terrace of silica precipitated from cooling, pooled geothermal water.

Photo 22. The "Champagne Pool" showing mineral precipitates and bubbling, hot geothermal water.

Photo 23. A collapsed cavern partly filled with a bubbling mud pool

antimony-rich sulphides, with significant gold and silver. The pool rim is formed from silica which has precipitated from the hot water.

A dramatic appreciation of active volcanism can be obtained by visiting White Island (Map 13). Tours leave from Whakatane, by sea and helicopter. A short, low resolution video of some of the highlights of White Island can be downloaded from http://ozgeotours.110mb.com/html/north_island.html.

WHITE ISLAND

White Island is an active andesitic stratovolcano located 48 km off the coast in the Bay of Plenty. The island is roughly circular, about 2 km in diameter at sea level, and rises to a height of 321 m above sea level. However the bulk of the

Photo 24. White Island, showing crater lake and mineral-stained water discharge into the ocean.

peak is submerged, with the total height being about 300-400 m. The volcano has been continually active for about 100,000 years, and is monitored by scientists remotely via a range of instruments and cameras. At most times the volcanic activity is limited to steaming fumaroles and boiling mud. In March 2000, three small vents appeared in the main crater and began erupting ash which covered the island in fine grey powder. An eruption in 2000 blanketed the island with mud and scoria and produced a new crater. Major eruptions in 1981–83 altered much of the island's landscape and destroyed forests. The large crater created at that time now contains a lake, whose level varies substantially. The water in this crater is strongly acidic.

Attempts were made in the late 1800s and 1913-1914 to mine sulphur from White Island. The last of these came to a halt when part of the western crater rim collapsed, creating a lahar which killed all 11 workers. Mining was again attempted from 1923-1930 but was abandoned because of the low quality of the fertiliser produced from the sulphur. The remains of the buildings can still be seen, much corroded by the sulphuric gases.

White Island is composed of lava and ash. All recent White Island ash has been of andesitic composition, although some earlier lavas have been of dacite and basalt. The volcanic activity at White Island is caused by the presence of a large body of hot magma deep beneath the island. Gases dissolved in this magma body continually escape and rise towards the ground surface, heating groundwater at shallow depths beneath the crater floor. Steam from this heated groundwater mixes with the volcanic gases from the magma to produce the white steam/gas cloud which is usually present above White Island. The size of this cloud is controlled by the total amount of gas and heat flowing out of the volcano, but is also affected by other factors such as the amount of recent rainfall, and wind strength and atmospheric humidity at the time, so that variations in cloud size and height are not always directly related to volcanic activity.

Explosions at White Island can occur during otherwise quiet periods, as well as during periods of increased activity. These intervals of increased activity occur when small volumes of magma rise to shallow depths (less than 1 km beneath the crater floor) from the main body of magma sited at depths of 5 km or greater. Gases given off by the shallow magma, and steam derived from heated groundwater, ream out a conduit to the crater floor. The top of the magma body is exposed to the atmosphere, and incandescent lava bombs, block and magmatic ash are erupted.

Photo 25. White Island fumaroles. Note the yellow sulphur crusts and black ash deposits in foreground.

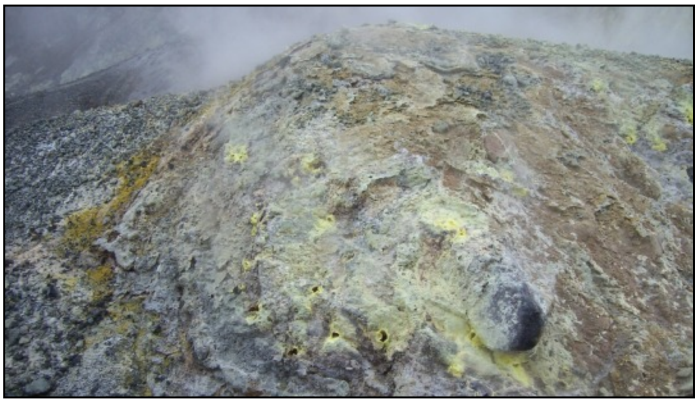


Photo 26. Sulphur-encrusted fumaroles on a silica mound.

Photo 27. Boiling mud pool.

Photo 28. The present acid-filled White Island crater.

Gases are continually emitted from the craters and fumaroles on White Island, at rates of several hundred to several thousand tonnes per day. These gases are mostly steam, carbon dioxide and sulphur dioxide, with small quantities of halogen gases (chlorine and fluorine). The acid gases combine with water in the steam/gas clouds to form liquid acid droplets which sting the eyes and skin, and affect breathing.

A tour of White Island is a unique experience. The sounds and smells of volcanic activity and the sights of innumerable fumaroles (Photos 25 & 26), mud pools (Photo 27), the crater lake (Photo 28) and imposing, surrounding crater walls are memorable.

THE COROMANDEL ARC - VOLCANIC ROCKS AND MINERAL DEPOSITS

The final segment of the North Island tour examines rocks and mineral deposits that are related to arc-style volcanic activity in the Coromandel Peninsula area. The rocks in this area are part of the Coromandel Arc, a series of volcanic rocks which formed prior to those in the Taupo Volcanic Zone. These rocks are referred to here as the Coromandel Volcanic Zone (*CVZ*).

The start of the Miocene period, about 23 million years ago saw the commencement of plate convergence in the region now known as Northland. This developed into a subduction zone, and a volcanic arc formed in response along the Northland Peninsula. The formation of the Northland Arc, off the present west coast of North Island, resulted in 8 million years of volcanic activity which ended after the formation of the CVZ about 18 million years ago (Figure 16). The CVZ was finally depleted when volcanism switched seamlessly to the Taupo Volcanic Zone about 2 million years ago. The migration from the Coromandel to Taupo Volcanic Zones was related to the oblique motion along the subduction zone, which is rotating the east coast clockwise away from the Coromandel Peninsula. This rotation slowly pushed the CVZ away from the subduction zone and steadily initiated arc volcanic activity in the TVZ.

Initial volcanic activity in the CVZ was andesitic. This earliest magmatic activity heated and melted the surrounding crust in the arc, resulting in the formation of rhyolitic magmas about 12 million years ago. The following outpouring of rhyolitic lavas and ash from more than 10 calderas and volcanic centres (Figure 16) dominated the remaining life span of this arc, with much lower volumes of andesite produced. Volcanism was fairly continuous in the CVZ, with a tempo and intensity that increased through the late Miocene–Pliocene and into the Quaternary, when the Taupo volcanic zone formed.

Geothermal systems similar to those at Wai-o-tapu were developed about the andesitic volcanic centres about 6 million years ago. Large amounts of gold and silver were deposited in these geothermal systems, forming *epithermal* mineral deposits (Figure 16). Epithermal deposits are mineral veins and accumulations of ore minerals formed from warm waters at shallow crustal depth (<1 km), at temperatures ranging from 50-200°C, and generally at some distance from the magmatic source. They are commonly formed at the same time as local volcanic activity, and are generally hosted by volcanic rocks. These systems, while active, discharge to the surface as hot springs or fumaroles.

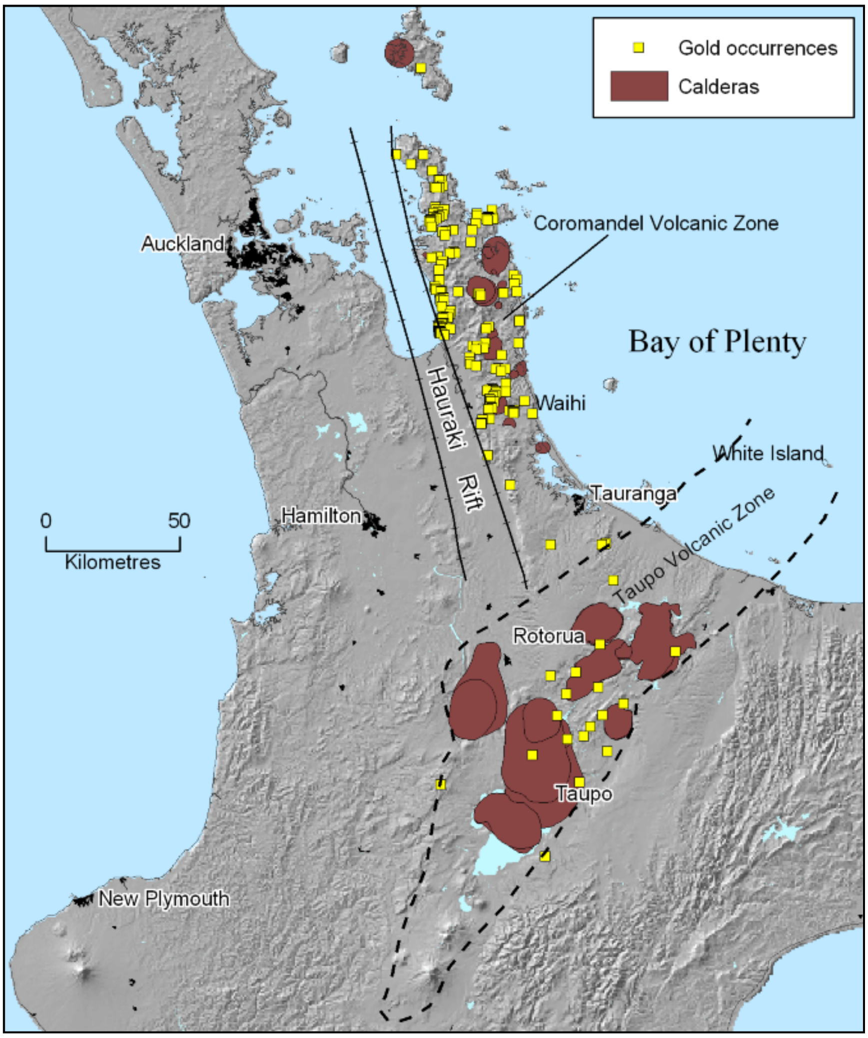


Figure 16. Digital terrain map of the region about the Taupo and Coromandel Volcanic Zones, showing calderas and epithermal gold deposits.

The route from Whakatane to Waihi on the Coromandel Peninsula mainly follows State Highway 2 and is a distance of about 190 km. The journey passes through alluvial deposits and volcanic rocks of the TVZ (initially), and end in andesites, rhyolites and ignimbrites of the CVZ (Maps 18 & 19). In Waihi township, navigate to the Martha Mine on the eastern side of the town. The Waihi Visitor Centre on Seddon St (Figure 17) has an excellent description of the history and geology of the Martha Mine, complete with specimens of mine rocks. A walk about the rim of the open cut can be accessed from the end of Haszard Street (Figure 17).

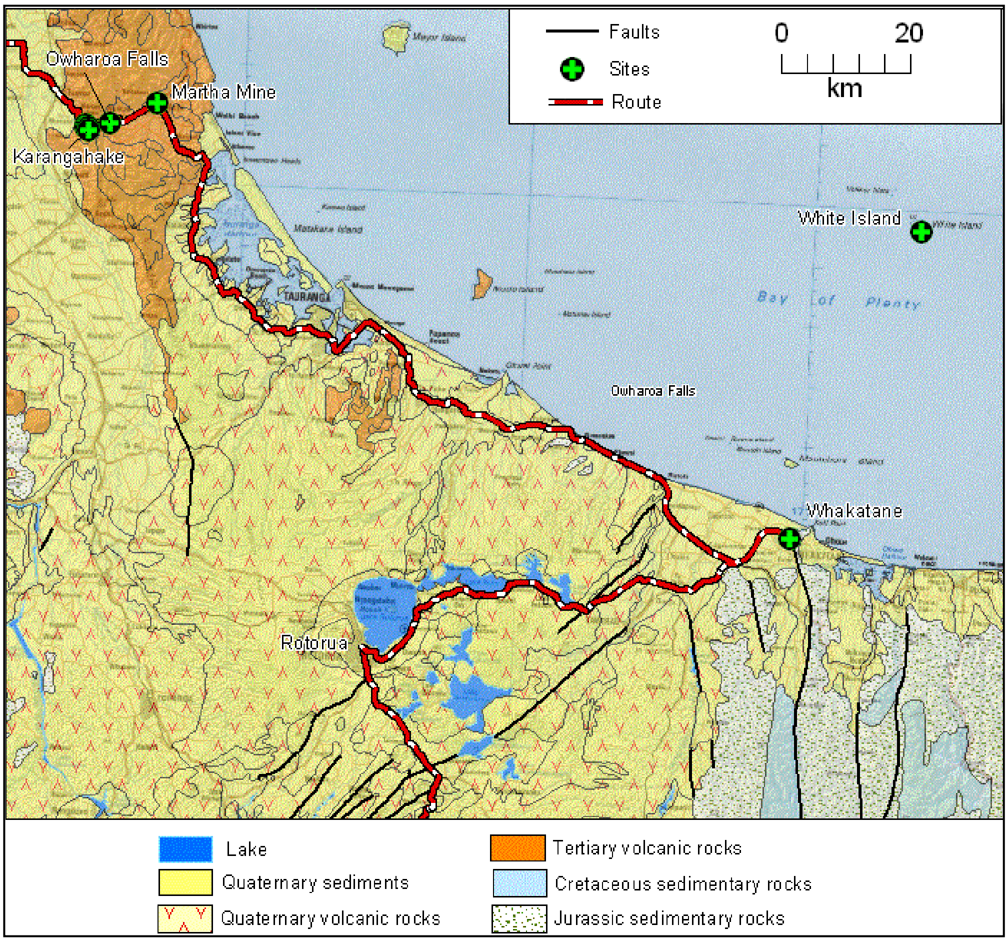
THE MARTHA MINE

The Martha Mine has produced gold and silver since its discovery in 1878. Mining from 1882 to 1952 was by up to 7 shafts and an extensive array of tunnels. The deepest shaft was 600 metres from the surface, and mining took place from 175 kilometres of tunnels on 15 horizontal levels. A workforce averaging 600 men was employed over the seventy year life span of the mine.

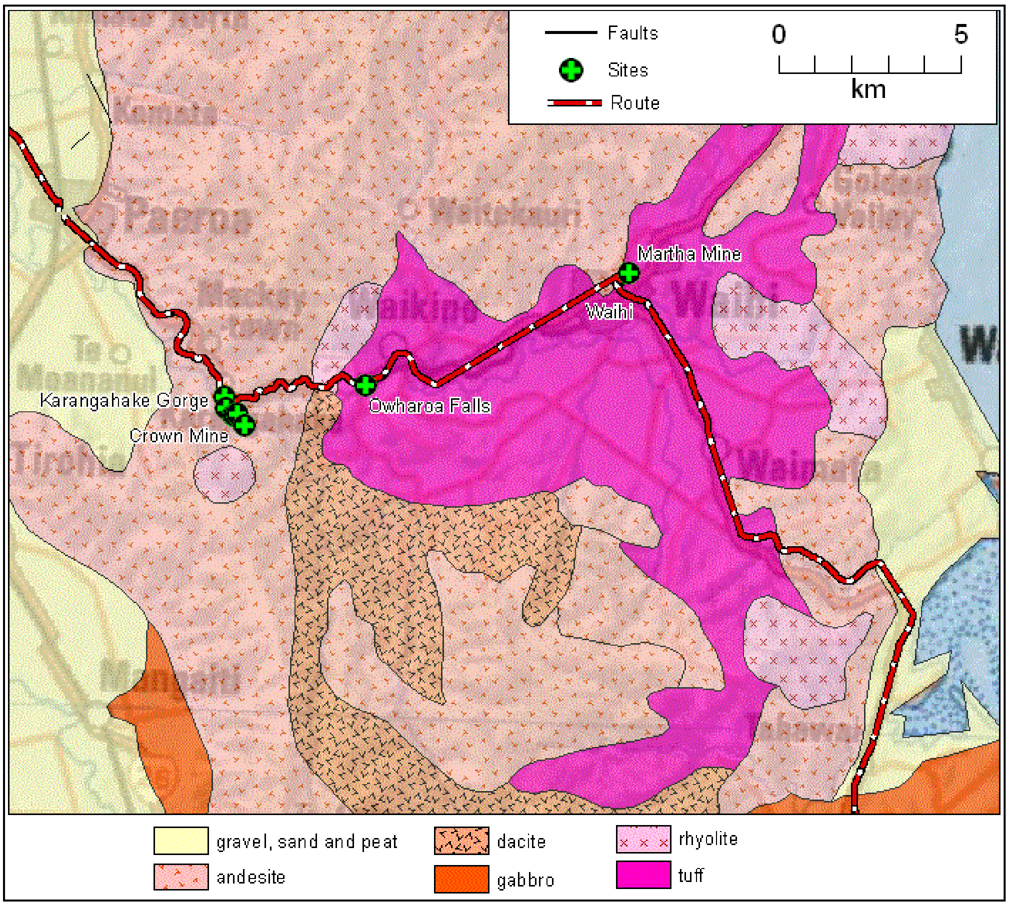
When the underground mine closed, about 5.6 million ounces (174,160 kg) of gold and 38.4 million ounces (1,193,180 kg) of silver had been produced from 11,932,000 tonnes of ore.

Construction of the open pit mine commenced in 1987. In 2000 the one millionth ounce of gold was recovered from the new workings. In 2005 a tunnel was driven from the base of the pit to allow for underground mining. In 2005 the 1.5 millionth ounce of gold was recovered. Mining is now taking place on the southern wall of the pit and underground. A study is nearing completion which proposes to mine the eastern wall of the pit, extending the mine life by three to four years from mid 2010. The average grade of ore in the mine is 3 grams of gold and 30 grams of silver per tonne. Since 1987, an average of around 100,000 ounces of gold has been produced annually.

The processes which resulted in the large Martha Mine orebody commenced about 7 million years ago when the ground surface was about 400 m above its present position. The CVZ produced a thick assemblage of andesitic and dacitic lavas, breccias and ash which were subsequently fractured into numerous near-vertical planes. These fracture planes acted as conduits for large volumes of ascending geothermal water, creating a similar geological and surface environment as is present in the geothermal areas of the TVZ.



Map 18. Simplified geology of the route between Whakatane and Karangahake.



Map 19. Geological map of the Martha Mine-Karangahake region.

As the dissolved mineral-rich water ascended, cooled and dropped in pressure, many minerals came out of solution, crystallising on the sides of the fractures. The predominant minerals were quartz and calcite (calcium carbonate). Gold and silver crystallised as electrum (gold-silver alloy), native gold and acanthite (silver sulphide). The

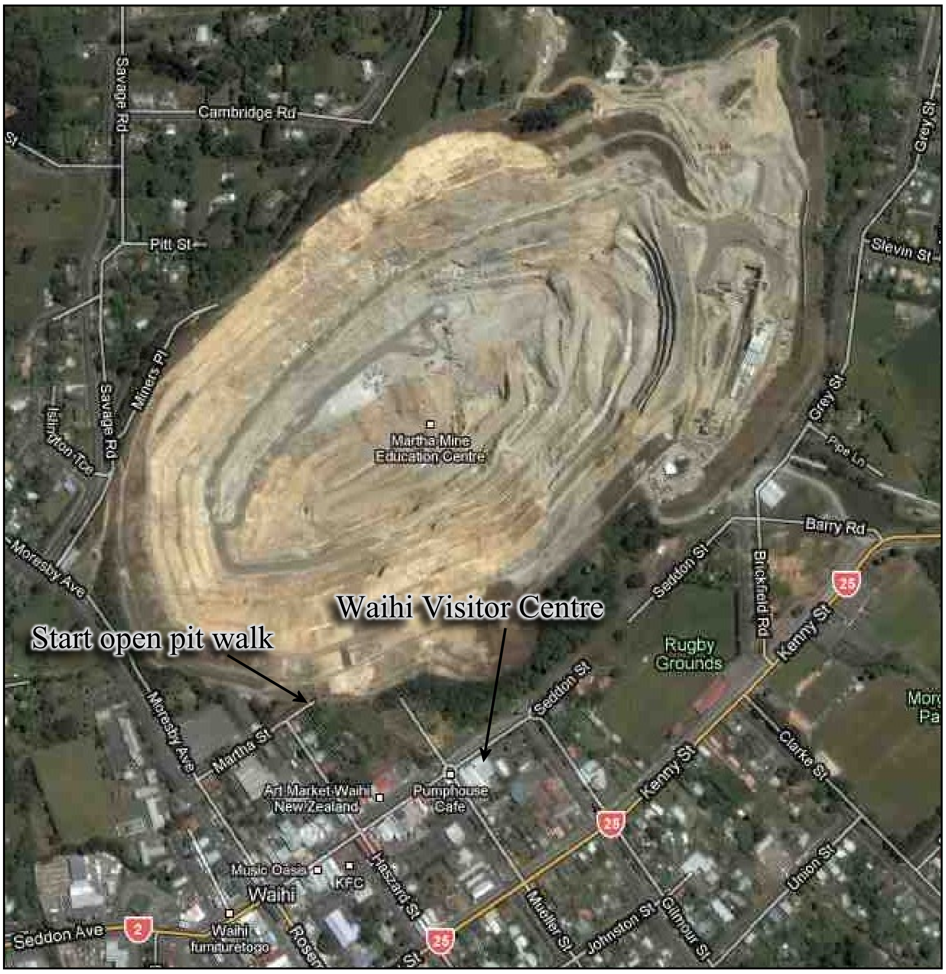


Figure 17. Satellite image of the Martha Mine open pit and immediate town area, showing visitor centre and start of pit edge walk.

geothermal fluids also altered the rocks they passed through, forming new minerals including pyrite (iron sulphide), adularia feldspar, calcite, chlorite and illite clay. Many of these mineral-filled fractures and veins intersected to form a complex lattice framework deep underground. The largest vein (Martha Lode) was at least 1.6 km long, 600 m deep and up to 30 m wide. The ore deposit formed by this geothermal process is known as an *epithermal deposit*.

Following the cessation of geothermal activity in this area, millions of years of erosion removed hundreds of vertical metres off the volcanic rock sequence and progressively exposed the quartz vein lattice. Being relatively resistant to erosion, this lattice caused an ancient topographic high. Cold surface ground waters percolating down caused oxidation reactions in the host andesite, changing it from a blue-grey to an orange-brown colour through the oxidation of pyrite to limonite (iron oxide).

Samples of the veins, breccias and ore from the Matha Mine, which are on display at the Waihi Visitor Centre, show characteristics typifying epithermal deposits. The cyclical action of high pressure water and gases in the geothermal system repeatedly opened and closed fractures, allowing mineralised hot waters to travel through pre-existing veins, creating symmetrical layering along the veins (Photo 29). Rapid and explosively high pressure steam caused the fracturing of rock and pre-existing veins, forming *breccias (Photo 30)*. The breccias are composed of very angular fragments of altered rock which are cemented together with quartz or calcite that may also show internal layering. The gold and silver occurs within these veins and breccias.

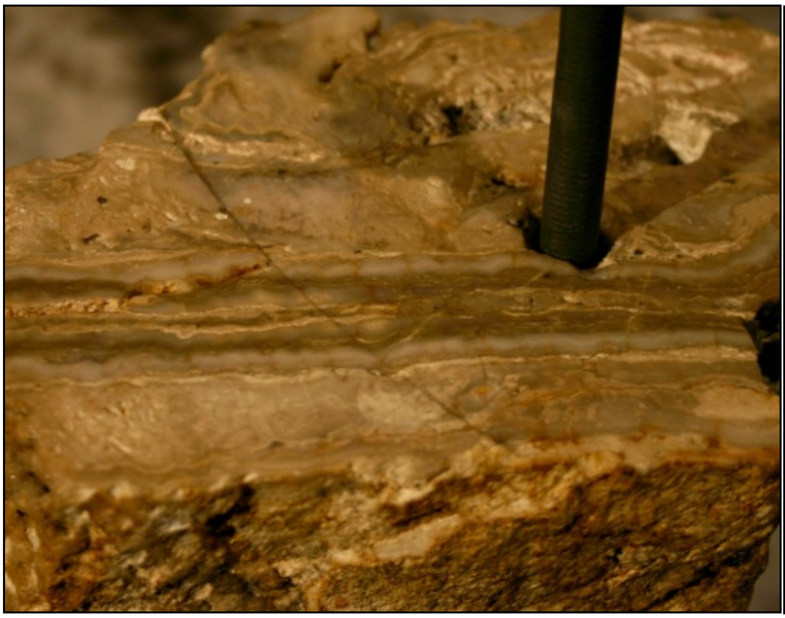


Photo 29. A typical layered epithermal quartz vein from the Martha Mine (Waihi Visitor Centre).

Photo 30. A quartz-filled epithermal breccia from the Martha Mine (Waihi Visitor Centre).

PLIOCENE IGNIMBRITES

From the Martha Mine the route continues through Miocene and Pliocene volcanic rocks (Table 1 and Map 19) which are dominated by rhyolitic ignimbrites. These ignimbrites can be examined at Owharoa Falls, a distance of 9 km from

Waihi along State Highway 2.

Numerous sheets of very hot ash erupted from a number of caldera and flowed across much of the local Coromandel region during the Miocene and Pliocene. These rapidly flowing bodies infilled river valleys and levelled much of the topography. Research (Rutherford 1976) has demonstrated that the ignimbrite magmas formed at temperatures in excess of 1000°C at depths of 20-25 km in the crust. These magmas formed from melting of basement greywacke (sandstones), after which they migrated to shallow magma chambers at depths of 6-15 km. The magmas became water-saturated by reaction with "wet" country rock, creating a mixture of very hot, water-rich magma which erupts explosively upon reaching the surface.

Ignimbrites were first recognised in the world in the Owharoa Falls area. Many road cuttings about here show the characteristics of ignimbrite, and they can be seen at the falls. Easily accessible samples can be obtained from a road cutting on Athol Road (Map 20). The ignimbrite here is rhyolitic and consists of fine-grained volcanic ash which is composed of shards and fragments of volcanic glass, and is intermixed with pumice and crystal fragments. The crystal fragments are commonly angular and shattered by the explosive eruption which produced the ignimbrite. Most crystals grew in the magma, but some may be exotic crystals which were derived from other magmas or rocks which the magma passed through or across. Small rock fragments are also present, representing pieces of older solidified volcanic debris which was taken from conduit walls or from the land surface. However, one of the most significant components of the ignimbrites are flattened pumice fragments, also known as *fiamme*. These are millimetre- to centimetre-size, lens-shaped objects showing internal structures of flattened, original gas bubbles.

Map 20. Location of ignimbrite outcrop near Owharoa Falls.

The route to Karangahake continues along State Highway 2 for 5 km. A large, sealed parking area on the left of the motorway in Karangahake is a convenient place to stop. From here, a foot bridge crosses the river and gives access to the well constructed walking track along Karangahake Gorge.

KARANGAHAKE GORGE AND THE CROWN MINES

The gorge gives a cross section through an epithermal mineral deposit (Figure 18). The historic Crown Mines worked gold from 1883 to 1920 within Karangahake Mountain and part of the adjacent ridge bordering the gorge. Up to 12 levels were mined using kilometres of tunnels and at depths to 270 m below river level. Access was gained by shafts and adits (tunnels into the hillside), and flooding of the lower levels was a constant, major problem. This was the first major mine in the world to use cyanide as a means of recovering gold from crushed ore.

The walking track enters the gorge through rocks on the outer edge of the epithermal system. The rocks here would have been on the outer part of the local geothermal field, and show *argillic* alteration - that is, the rocks have undergone alteration of feldspars and micas to clay. As a result, the rocks are relatively soft and pale yellow coloured (Photo 31). Quartz veining is apparent throughout the rock, but no economic gold concentrations are present.

Several hundred metres along the track the rocks are harder and show features indicative of high fluid pressures, such as *jigsaw* breccias, epithermal veining, and oxidised sulphide minerals. Jigsaw breccias, as the name implies, are rocks which have been shattered with little or no movement or rotation of the broken fragments (Photo 32). The shattering was primarily caused by very high steam and water pressures acting upon the rock, abruptly and explosively pushing it apart and fragmenting it. After fracturing, hot waters penetrated along the fracture surfaces, depositing quartz, gold and sulphide minerals on the fracture walls (Photos 32 and 33). The newly formed veins were commonly re-opened by high ambient fluid pressures and new quartz and other minerals deposited within the veins, or along their outer margins. As a result, the brecciated, altered rhyolite close to, and near the Crown Mines workings, comprise jigsaw breccias with the margins of each fragment outlined by a narrow to thick quartz vein. The presence of sulphide minerals is evident by the brown and yellow-brown staining on the rocks adjacent to the veins. The brown

Photo 31. Rhyolite showing argillic alteration.


Photo 32. Jigsaw brecciated rhyolite with quartz veins and brown to yellow brown limonite and jarosite staining.


Photo 33. Layered epithermal quartz veins with fine, drusy quartz crystals. Note the symmetrical layering within the veins, which have formed about brecciated rhyolite fragments.

stain is *limonite*, an iron oxide. The yellow brown is *jarosite*, an iron-potassium sulphate.

Close to the old mine workings The original rhyolite has been extensively altered by the passage of hot steam and water. The toughness of the rocks here is due to added quartz and the growth of new feldspar (*adularia*).

The very centre of the epithermal system is where the mine workings lie. Here, the veining was most abundant and generally much thicker. Some very large veins were worked as individual deposits, cross cutting the breccias and probably representing major pre-mineralising fault or fracture planes. The greater thickness of the veins, and their abundance made this area economic to mine as the relative proportion of gold in the rocks was much higher than in adjacent rocks.

This concludes the North Island geological tour. New sites may be added to this tour in future years. We hope that you have gained some insight into the geological processes and products of North Island. Any feedback you may wish to make on this guide will be gratefully received.

Bob and Nancy, April 2010

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GLOSSARY

Andesite: a grey to black volcanic rock composed of white plagioclase feldspar and dark green to black pyroxene and/or hornblende. Intermediate in composition between basalt and rhyolite.

Basalt: a black, fine-grained volcanic rock composed of white plagioclase feldspar and dark green pyroxene and possibly olivine.

Dacite: a grey rock intermediate in composition between rhyolite and andesite. It is composed of quartz, plagioclase, biotite, hornblende and possibly pyroxene.

Lahar: a mudflow composed of volcanic ash, pebbles and boulders intermixed with water that that flows down from a volcano, typically along a river valley.

Rhyolite: a pale coloured volcanic rock composed of white plagioclase feldspar, white to pink orthoclase feldspar, colourless to white quartz, and very minor black biotite mica or hornblende.