Annual Conference of the Geoscience Society of New Zealand

7th Symposium of IGCP 632: Continental Crises of the Jurassic

Field Trip 6

Friday 30th November–Thursday 6th December 2018

Jurassic sequences of the North Island

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Cover image: Conglomerate and sandstone within Opango Formation, Newcastle Group, Murihiku Supergroup (Murihiku Terrane). Near Ururoa Point, south of Te Maika, west coast North Island. Age: Ururoan Stage, Toarcian. To be visited on Day 5. Photo: Hamish Campbell.

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OVERVIEW

This field excursion will traverse continental crust of the central North Island of New Zealand. The North Island is located on the eastern edge of a segment of Australian Plate. This excursion will proceed from east to west, commencing in Napier and ending in Auckland. It will involve stopping for the night in Taihape, Taupō, Waitomo, Kawhia (2 nights) and Tuakau. The principal objective is to explore Jurassic sequences exposed within the North Island. Localities within three basement terranes will be visited: Kaweka, Murihiku and Waipapa. The journey will traverse the Taupō Volcanic Zone, an active subduction-related arc superimposed on an active back-arc continental rift.

Basement geology of New Zealand (Figs 1, 2) (modified from Adams et al. 2007, 2009)

The basement geology of New Zealand has been subdivided into three meta-sedimentary “provinces” Western and Eastern, which are separated by the Median Batholith, a long-lived magmatic complex.

The Western Province has two terranes: (1) The more extensive western Buller Terrane, of Early Ordovician age is intruded by Carboniferous to Late Devonian (Karamea Batholith) and Cretaceous (Paparoa, Hohonu batholiths) granitoids and extends over much of the Campbell Plateau south of New Zealand, and (2) The smaller eastern Takaka Terrane of Cambrian to Devonian age comprises more varied quartzites, black shales, greywackes and limestones.

The Median Batholith, only exposed in the South Island, comprises Late Jurassic–Early Cretaceous (mainly) and Late Triassic and Late Permian granite–granodiorite–diorite plutons that intrude the Brook Street and Takaka terranes. It extends offshore in the Cook Strait region and probably along the northeast margin of the Lord Howe Rise, to West Norfolk Ridge.

The Eastern Province comprises several tectonostratigraphic terranes of principally Permian to Cretaceous, low-grade meta-sedimentary rocks. In general, the major sedimentation cycles are of Late Permian, Late Triassic to earliest Cretaceous and Late Jurassic–Early Cretaceous age.

The Torlesse Composite Terrane is the easternmost and most extensive, comprising relatively quartzose, turbidite-dominated greywacke successions (Torlesse Supergroup) in a Permian–Triassic Rakaia Terrane, Jurassic Kaweka Terrane and a Jurassic–Early Cretaceous Pahau Terrane. These form the major part of an accretionary wedge. Within the Rakaia Terrane there are two Carboniferous–Permian micro-terranes (Kakahu and Akatarawa) having probable Tethyan faunal provenances. Fossil occurrences, although sparse, establish a biostratigraphy at the Stage level. The Rakaia terrane rocks pass into extensive areas of medium-grade metamorphic rocks (Haast Schist) in the South Island and extend along the Chatham Rise eastwards to the Chatham Islands.

The Kaweka Terrane in the North Island (Adams et al. 2009) occurs on the western side of the Ruahine and Kaweka ranges and throughout the Kaimanawa Range. It comprises extensive sandstone-dominated turbiditic rocks in which fossils are very rare or absent. Near the boundary with Waipapa Terrane, the rocks pass from prehnite–pumpellyite facies into higher grade pumpellyite–actinolite facies Kaimanawa Schist which yield Early Cretaceous, ~135 Ma, Rb–Sr metamorphic ages. Kaweka Terrane meta-sediments are intermediate between those of the Waipapa and Rakaia terranes. The youngest U–Pb detrital zircon ages probably reflect contemporary volcanism and constrain maximum depositional ages to the Early and Middle Jurassic.

The remaining, narrower, terranes to the west have increasing degrees of volcanic and volcaniclastic input. The overwhelmingly dominant redeposited volcanic detritus of Waipapa and Caples terrane rocks have acid–intermediate igneous sources, again forming a more volcanogenic part of the accretionary wedge, whereas Dun Mountain–Maitai, Murihiku and Brook Street terrane volcanic rocks are mainly intermediate to basic and contemporaneous with the adjacent accretionary wedge.

Waipapa Terrane rocks are monotonous, medium grained greywacke–siltstone successions (Waipapa Group). Rare fossil occurrences indicate extensive Late Jurassic and lesser Triassic clastic sequences. These are intercalated with rarer but ubiquitous Late Permian, Triassic and Early Jurassic, hemipelagic oceanic associations containing faunas of both Tethyan and Nothal affinities. Waipapa Terrane rocks extend through the North Island and pass into the Haast Schist in Marlborough, South Island.

Caples Terrane rocks are mainly confined to the South Island, where monotonous greywacke-dominated, intermediate-volcaniclastic successions (Caples and Pelorus groups). Rb–Sr (and K–Ar) metamorphic ages indicate a pre-Jurassic stratigraphic age. Although diagnostic fossil localities are exceedingly rare, a Permian to Triassic age is probable, and several lithostratigraphic formations are recognized.

The Dun Mountain–Maitai Terrane is more variable: An Early Permian ophiolite (Dun Mountain Ophiolite Belt) is overlain by a moderately fossiliferous Late Permian to Middle Triassic to Late Permian succession (Maitai Group) of volcaniclastic sedimentary rocks and bioclastic calc-turbidite limestones.

The Murihiku Terrane consists almost entirely of volcaniclastic sedimentary successions, with some richly fossiliferous horizons (Murihiku Supergroup), mostly acid to intermediate igneous rock source compositions, and with a few extrusive/intrusive bodies. The terrane forms a long synclorium through both North and South islands, without certain extensions to the north or southeast and again is in a probable intra- or fore-arc position.

Significant volcanic edifices are only present in the Brook Street Terrane. These are mainly Middle to Late Permian basalt, andesite and minor dacite–rhyolite, with voluminous gabbro, diorite and rarer granodiorite intrusives, and thick redeposited volcaniclastic sedimentary aprons (Takitimu Group). A more varied succession of Middle–Late Permian siltstones and limestones (Productus Creek Group), and very local Jurassic conglomerates and sandstones (Barretts Formation), overlie this.

For the Torlesse Composite Terrane, petrographic, geochemical and detrital mineral age evidence suggests a continental arc-derived sediment supply, principally of Permian and Triassic granitoid materials, into an accretionary prism environment. A similar situation is recognized for the Waipapa and Caples terranes, but with more mafic–intermediate volcanic influences. In contrast, more probable back- and fore-arc environments are suggested for Murihiku and Dun Mountain–Maitai terranes, respectively, with some continent-derived sediment input in the latter. Finally, the Brook Street Terrane represents an isolated and dissected, predominantly Permian, volcanic island arc environment but with some platform sediments.

The relative positions of the Eastern Province terranes, with respect to the Gondwana margin, suggest that the Torlesse, Waipapa, and possibly Caples, terranes are “suspect”, and must have distant sediment sources. Two possible origins have been suggested: (1) partly in the Lachlan Fold Belt (with continuations in New Zealand and Antarctica), and partly in the Median Batholith (and its continuations in Antarctica) and (2) partly or completely in the New England Fold Belt of northeast Australia. Comprehensive detrital zircon age studies of sediment provenance of all the Eastern Province terranes strongly favour the latter model (2).

The Triassic–Jurassic rocks of the Murihiku Terrane (Fig 3, 4) (modified from Edbrooke 2005)

Late Triassic to Late Jurassic fossiliferous conglomerate, lithic sandstone, siltstone, carbonaceous beds and tuff of the Murihiku Supergroup (Murihiku Terrane) outcrop on the west side of the North Island, from Port Waikato south to Awakino, and are particularly well-exposed in the area south of Kawhia Harbour. Their western limit is the concealed offshore Taranaki Fault and the eastern limit is the Waipa Fault. The rocks are broadly and regularly folded into the Kawhia Regional Syncline, a north- to northwest-trending series of asymmetric open folds.

The Murihiku basement rocks of the Kawhia Regional Syncline are exposed by virtue of E–W oriented faults, which may relate to Late Cretaceous–Cenozoic rifting of the New Caledonia Basin that lies west of and parallel to the Norfolk Ridge. The very distal NW–SE-oriented southern margins of the New Caledonia Basin trend towards the North Island coast more or less between Awakino (to the south) and Port Waikato (to the north).

Murihiku Terrane rocks have a total thickness of over 7000 m and are subdivided, on the basis of lithology and fossil content, into five groups within Murihiku Supergroup. Well-exposed sections on the south side of Kawhia Harbour include the type localities for all six New Zealand Jurassic Stages. Murihiku Terrane rocks are interpreted as an accretionary wedge of mainly volcanogenic forearc sediments that have undergone burial diagenesis and extensive zeolitisation.

Late Triassic (Oretian–Otapirian; Norian–Rhaetian) rocks of the Newcastle Group (Tn) outcrop along approximately north–south oriented bands on the western and eastern sides of the Kawhia Regional Syncline. In the west they are present from east of Albatross Point to Awakino and form the western side of Herangi Range. In the east they form the Taupiri and Hakarimata ranges and extend south to Aria. The Triassic rocks are up to 4000 m thick and are dominated by thin-bedded to massive siltstone with fine- to coarse-grained sandstone, mainly in the upper part, and rare shellbeds. Zeolite veins are common throughout and there are some tuff beds. A thick (>1000 m) conglomerate (Moeatoa Conglomerate) that outcrops south of Kiritehere is the oldest exposed unit in the Kawhia Regional Syncline. It contains a high proportion of plutonic clasts as well as andesite, greywacke and rare gneissic clasts. Late Triassic Newcastle Group strata are inferred to have been deposited in a marine shelf setting with nearby contemporaneous volcanism.

Early Jurassic (Aratauran–Ururoan; Hettangian–Toarcian) rocks of the Newcastle Group (Jn) also outcrop on both sides of the Kawhia Regional Syncline, parallel to and inboard of the older Newcastle Group rocks. They consist of up to 2000 m of thin-bedded to massive siltstone and fine- to coarse-grained sandstone with thin conglomerate beds, mainly near the top, and some tuff beds. Shellbeds, dominated by the bivalve *Pseudaucella marshalli*, are present in the upper part of the group. Early Jurassic Newcastle Group probably accumulated in a moderately deep to shallow marine environment, with waning or more distal contemporary volcanism.

Early to Middle Jurassic (Ururoan–Temaikan; Toarcian–Callovian) Rengarenga Group rocks (mJr) are up to 1500 m thick and outcrop on both sides of the Kawhia Regional Syncline. The contact with underlying Newcastle Group may be locally unconformable. In the west, Rengarenga Group rocks outcrop from Te Maika Peninsula to the Herangi Range, and at Albatross Point. In these areas,
Rengarenga Group is mainly terrestrial in the north, consisting of carbonaceous sandstone with interbedded conglomerate, shale and minor siltstone. Small plant fragments are abundant in many sandstones and some have larger pieces of debris including tree trunks and roots. Near the middle of the group, generally thin fossiliferous marine sandstones are intercalated with the terrestrial beds. Further south, towards Mahoenui, the rocks are predominantly marine, fossiliferous siltstones and sandstones. In the east, Rengarenga Group outcrops from near Glen Afton south towards Piopio are

predominantly marine with only minor terrestrial beds. Well-bedded, fossiliferous sandstone and siltstone are the major lithologies, with thin conglomerate beds near the base.

The Middle to Late Jurassic (Heterian–Ohauan; Callovian–Early Tithonian) Kirikiri Group (Jk) appears to conformably overlie Rengarenga Group and outcrops in central parts of the Kawhia Regional Syncline, from Pepepe south to Mahoenui. It is commonly exposed in the eroded crests and cores of local folds within the regional syncline. The group is up to 1800 m thick and dominated by massive, variably fossiliferous siltstone with minor sandstone, conglomerate, and tuff and carbonaceous beds. Well-bedded alternating sandstone and siltstone are common near the top and base. Complex intraformational folding is a feature of these rocks in some areas, particularly north of Kawhia Harbour. Kirikiri Group accumulated in a marine, near-shore to outer shelf environment with nearby contemporaneous volcanism.

The Late Jurassic (Ohauan–Puaroan; early–late Tithonian) Apotu Group (lJa) overlies Kirikiri Group rocks, with apparent conformity, and outcrops in central parts of the Kawhia Regional Syncline north of the Marokopa Fault. It is up to 2700 m thick and comprises predominantly fossiliferous bedded siltstone, carbonaceous towards the top, and several conglomerate sequences up to 500 m thick in total. The distinctively red-brown weathering conglomerates are composed of rounded volcanic and angular sandstone and siltstone clasts in a sandstone matrix, with interbedded sandstone, grit and minor siltstone. The group contains the youngest fully marine sediments of the Murihiku Supergroup and represents deposition in progressively shallower environments from bathyal fan through inner shelf to shallow marine.

Up to 800 m of terrestrial and shallow marine sediments of the latest Jurassic (Puaroan; late Tithonian) Huriwai Group (lJh) conformably overlie the Apotu Group. The Huriwai Group contains the youngest exposed rocks of the Murihiku Supergroup and they outcrop in the core of the Kaimango Syncline near Kauroa, south of Raglan Harbour, further north near Matira, and on the west coast between Sunset Beach and Huriwai Beach (Port Waikato). The group is dominated by carbonaceous sandstone, siltstone and conglomerate with some thin mudstones. The sandstones and conglomerates are volcanic-derived, probably from contemporaneous eruptions in a nearby andesitic–dacitic arc. Plant fragments are abundant throughout and there are rare thin coal seams. Plant beds and tree stumps in positions of growth are found locally. The Huriwai Group is interpreted as fluvial, lacustrine and marginal marine deposits of a coastal braid-plain delta that experienced periodic influxes of coarse-grained sediment from volcanic eruptions.

Some thoughts on the history of Jurassic research on sedimentary sequences in New Zealand

The earliest scientific recognition and geological exploration of Jurassic fossils and rocks in New Zealand began with Hochstetter and the “Novara” Expedition (1857–1859) commissioned by the Austro-Hungarian Empire and its leaders the Emperor Franz Josef and his brother Archduke Maximillian. With formation of the New Zealand Geological Survey (NZGS) in 1865, under the directorship of James Hector, organised geological mapping commenced. The first palaeontologist employed by NZGS was James Allan, appointed in 1911. He was the architect of the New Zealand local stage scheme, but it was John Marwick who established and named the Jurassic Stages of New Zealand in the early 1950s. Trechmann (1923) was the first in the 20th Century to attempt “modern” taxonomic description of the New Zealand Jurassic shelly fossils, but others were before him in the 19th Century including Zittel and Hector.

Concerted mapping campaigns at various scales (1:63,360, 1:250,000, 1:50,000) by NZGS, now GNS Science, has greatly contributed to our current understanding of New Zealand’s Jurassic stratigraphic record. In the interests of standardization across current digital databases, including mapping at

1:250,000 scale, there is a well-established high-level stratigraphic nomenclature that embraces all New Zealand rock formations (Mortimer et al. 2014).

University BSc (Hons), MSc and PhD studies on Jurassic topics began in the 1950s with area-based mapping projects. Since the 1960s, more detailed paleontological and biostratigraphic studies have been undertaken on belemnites, ammonites, bivalves (retroceramids, buchiids, trigoniids, monotids, pholadomyids, astartids), brachiopods (rhynchonelides, terebratulides, spiriferinids), plants, spores and pollen, forams, radiolarians, crinoids, vertebrates (dinosaur, shark).

Major monographic studies include the following fossil groups: plants (Arber 1917), shelly fossils (Marwick 1953), belemnites (Stevens 1965), trigoniid bivalves (Fleming 1987), Early Jurassic miospores (de Jersey & Raine 1990), rhynchonellide brachiopods (MacFarlan 1992), Late Jurassic ammonites (Stevens 1997) and Early Jurassic ammonites (Stevens 2004).

It is interesting to note that the earliest of these major studies was on plant fossils (Arber 1917). Subsequent paleobotanical studies include research by Tom Harris, Ian Raine, Mike Pole (1998) and Vanessa Thorn (2001). Most paleontological effort has concentrated on shelly marine biota of which perhaps the most well-known study is that of Stevens (1985) on the world's largest Jurassic ammonite: the Giant Ammonite *Lytoceras taharoaensis*.

There has been university interest in the Jurassic from all six of New Zealand's mainstream universities. However, two in particular, Auckland and Otago (in Dunedin), have inspired many students (e.g., Meesook & Grant-Mackie 1995), largely under the leadership of Jack Grant-Mackie and JD (Doug) Campbell (1927–2001).

Much of our knowledge of the Jurassic in New Zealand is based on the collective published research of three retired New Zealand palaeontologists: Graeme Stevens, Jack Grant-Mackie and Brian Challinor. Unfortunately, none of them are able to participate in this symposium or excursion due to their great age. However, the next generation, which is also largely retired (!) is able to participate and this includes us authors: J Ian Raine, Donald MacFarlan, Neville Hudson and Hamish Campbell.

A useful "census" of New Zealand fossils was compiled in 2000 and published as part of the "New Zealand Inventory of Biodiversity" (Gordon 2009), and it includes lists of New Zealand's Jurassic fossils. Since 2009, some new studies include the following: Akikuni et al. (2010), Hori et al. (2011), Stevens (2014), Okada et al. (2015), MacFarlan (2016), Challinor and Hudson (2017), and Cappetta and Grant-Mackie (2018). These publications should serve as a spring-board into the older established scientific literature on the Jurassic record in New Zealand, and indeed wider Zealandia including New Caledonia.

Currently, as far as we authors are aware (and we would love to be proved wrong), there are no New Zealand university research students involved in projects on Jurassic rocks and fossils in New Zealand. There may be some overseas research projects under the auspices of the long-standing New Zealand–Japan Collaboration of which Professor Rie Hori has been a significant leader.

Earlier this year, as part of efforts to "modernise", GNS Science has indicated an intention to reduce investment in research on the sedimentary basement rocks of Zealandia, as of June 2019. In recent decades, there has been significant effort on refinement of the New Zealand Geological Timescale (Cooper 2004), and herein we follow Raine et al. (2015; Fig 19).

In recent decades there has been some research, led by Chris Adams, on the provenance of Jurassic sedimentary rocks in New Zealand using U–Pb dating of detrital zircons (e.g., Adams et al. 2011, 2018), and Andy Tulloch has been dating and describing granite plutons of Jurassic age within the Median Batholith (e.g., see Appendix 1 in Turnbull and Allibone 2003).

From the perspective of IGCP 632, the Jurassic record of New Zealand offers a unique opportunity to explore life and environmental conditions at the very southern-most edge of Gondwana, and more or less at the South Pole. Seton et al. (2012) have produced very compelling paleogeographic reconstructions for southern Gondwana and hence Zealandia (Mortimer et al. 2017) based on the age of oceanic crust.

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ITINERARY

Day 1: Friday 30th November: Napier to Taihape: a romp in the Neogene (Figs 5, 6)
160 km; 4 hours

Main geological objective
To observe basement "'greywacke" rocks within Kaweka Terrane. These rocks are Jurassic in age, on the basis of provenance research: U–Pb dating of detrital zircons. As yet, no fossils have been found within Kaweka Terrane.

Route
We shall traverse Pleistocene alluvial deposits from Napier to Fernhill and then quickly pass into very gently dipping late Pliocene (3.6–2.58 Ma) marine mudstone (Mangaheia Group) with conspicuous bioclastic limestone (Petane Formation) and minor conglomerate and sandstone, within a broad, gentle fold structure (Matapiro Syncline), which is truncated to the W by the active Mohaka Fault. We shall cross strands of this fault between Waiwhare and Willowford, but they are not obvious from the road.

These young marine sediments accumulated within the East Coast Basin prior to significant tectonic uplift of the axial ranges (Ruahine, Kaweka, Kaimanawa ranges), at a time when there was a prominent seaway, the NE–SW oriented Ruataniwha Strait. This seaway was connected with the Whanganui Basin on the west side of the North Island, by the E–W Kuripapango Strait. There are remnants of this late Pliocene marine sequence visible throughout our trip to Taihape.

As we descend down the hill to Kuripapango, we traverse Blowhard Formation (<150 m thick) with outcrops of conspicuous conglomerates and sandstones. These represent a basal sequence of transgressive alluvial fan and braid-plain deposits that are overlain by fully marine sediments. They are of late Miocene age (Tongaporutuan–Kapitean; 10–5.5 Ma) and are the oldest Cenozoic rocks that we will see between Napier and Taihape.

Taihape (500 m asl) is located within the NE corner of the Whanganui Basin, a large Neogene sedimentary basin that occupies the SW region of the North Island. It preserves a well-studied Pliocene–Pleistocene sequence with a remarkable record of Pleistocene global sea-level change. The sequence comprises shallow marine sediments (sandstone, siltstone, mudstone, shellbeds, conglomerate) as well as terrestrial paleosols and tephras. Plate collision tectonism has resulted in deformation (tilting, folding, faulting) and uplift of the eastern side of the Whanganui Basin.

Jurassic
We first encounter basement Kaweka Terrane greywacke rocks in road cuttings beyond Kuripapango.

STOP Rd cutting above Kuripapango on Taihape Rd within Kaweka Terrane.

Route
From Napier we head SW to Fernhill on State Highway (SH) 50.
From Fernhill we cross the Ngaururoro River and head NW to Taihape on Taihape Rd passing through small settlements: Pukehamoamoa, Sherenden, Otamauri, Waiwhare, Willowford (HQ for Kaweka State Forest), Kuripapango, Ngamatea Station, Erewhon Station, Springvale Station, Moawhango, Opaea, Taihape.

From Fernhill to Kuripapango, the Kaweka Range is clearly visible to the NW. We will be traversing ridge tops along the watershed between the Tutaekuri River to the N and the Ngaururoro River to the S.

The road between Kuripapango and Moawhanga is referred to as "The Gentle Annie" and traverses high ground between the Ruahine Range to the south and the Kaimanawa Range to the north. At Kuripapango we cross the Ngaururoro Rover and then ascend Te Whata Hill (775 m) and on over Taruarau Hill.

We shall cross the head-waters of the Rangitikei River between Ngamatea Station and Erewhon Station, and the Moawhango River at Moawhango. Most of our route from Ngamatea Station traverses Matemateonga Formation comprising up to 1,000 metres of limestone, sandstone, siltstone and conglomerate of late Miocene–early Pliocene age, which accumulated in shoreline and shelf settings. As we approach Taihape on Spooners Hill Rd, we pass into the overlying Tangahoe Mudstone.

Day 2: Saturday 1st December: Taihape to Taupō: in the Taupō Volcanic Zone (Fig 7)
245 km: 180 km before lunch; and 65 km after lunch

Main geological objective
To observe geological features of the Taupō Volcanic Zone (TVZ): normal faults associated with crustal (back-arc) rifting, volcanic geomorphology, the "ring plain", andesitic–rhyolitic tephra deposits, lahar deposits, moraine deposits, volcanoes (Mt Ruapehu, Mt Ngauruhoe, Mt Tongariro), andesite lava flows, Taupō Caldera, ignimbrite and pumice deposits associated with the AD232 Taupō Eruption, dacite and rhyolite domes.

Route
Drive N along SH1 to Waiouru passing through Bennetts Siding, Ngawaka, Turangarere, Hihitahi; proceed around the E side of Mt Ruapehu along the 'Desert Rd' to Rangipo; turn left and head W along Lake Rotoaira Rd (SH46) to Papakai, passing Lake Rotoaira to the N and Mt Tongariro to the S; see Te Maari and Ketetahi Hot Springs; turn left onto SH47; then left again to Whakapapa on SH48. Then head NE to Turangi along SH48 and SH47 and the Te Ponanga Saddle on NW side of Mt Pihanga. Stop at Lookout above Tokaanu and Lake Taupō. To Turangi. Lunch next to Tongariro River. Continue along SH1 via settlements of Motuoapa, Oruatua, Te Rangiita, Wiatetoko, Motutere, Hatepe, Waitahanui and Wharewaka to Taupō.

STOP Waiouru; 792 metres a.s.l.
STOP Rangipo Fault scarp: an active normal fault developed on E side of the TVZ
STOP Ruapehu and Ngauruhoe: view from near Mangatoetoenui Stream
STOP Tongariro: view from Overflow Carpark for Tongariro Crossing Track
STOP Whakapapa Village, Scoria Flat: Tawhainui Flows; andesite; 6,000–7,000 years old
STOP Turangi Lookout: view over Lake Taupō
STOP Turangi: at the bridge over the Tongariro River; range of basement and volcanic lithologies
STOP Mission Bay between Waitetoko and Motutere: rhyolite and pumice lithologies relating to AD232 Taupō Eruption; proximal to eruption centre
STOP Taupō: lake level is 356 m a.s.l.
OPTIONAL Walk up Mt Tauhara (Tauhara Formation; dacite; 190,000 years old) with "mountain guides", time-permitting

Geology
Drive N out of Taihape: Tangahoe Mudstone (Pliocene, late Opoitian–Waipipian; middle to upper bathyal). Pass into older Matemateonga Formation (late Miocene–early Pliocene; shoreline and shelf)

at about Turangarere and then into pre Waimarino Formation lahar deposits of the Ruapehu “ring plain”, older than 64,000 years.

Desert Rd: Traverse volcanic formations of middle Pleistocene to Holocene age: conspicuous layered coloured tephras relating to eruptions from Ruapehu and Tongariro, and the AD232 Taupō Eruption; paleosols; lahar deposits; some probable glacial moraine deposits.

Lake Rotoaira Rd: Te Maari Formation (pre-Oruanui Eruption; 25,500 years); Murimotu Formation (10,500 years old) as we approach Whakapapa.

From Whakapapa Village to Scoria Flat, drive through moraines and andesite lava flows (Tawhainui Flows, 6,000–7,000 years).

Around Lake Taupō: Traverse lake sediments relating to older versions of Lake Taupō that relate to the Oruanui Eruption (26,500 years) and the Taupō Eruption (AD232). For some period (tens to hundreds of years) immediately after these huge eruptions, the lake level was , respectively, 141 metres and 38 metres higher than today. The current lake level is 356 metres a.s.l.

Day 3: Sunday 2nd December: Taupō to Waitomo: tourism; into the Oligocene (Figs 8, 9)
230 km: 85 before lunch; 145 km after lunch

Main geological objective
To observe and explore geological features of the Taupō Volcanic Zone (TVZ): the spectacular Huka Falls on the Waikato River; the geothermal hot-springs at Wai-O-Tapu; Lake Rotorua within the Rotorua Caldera; visit underground caves within Oligocene limestone (Te Kuiti Group) at Waitomo Caves.

Geology
From Taupō, the road traverses Taupō Group deposits relating to the AD232 Taupō Eruption. The Wai-O-Tapu Geothermal Field lies to the N of the Reparoa Caldera which formed 230,000 years ago. From Wai-O-Tapu to Rotorua, the road traverses the buried Kapenga Caldera and descends into the Rotorua Caldera.

Between Rotorua and Tirau, the road will cross the Mamaku Range through Mamaku Plateau Formation comprising ignimbrite and ash deposits that erupted ~240,000 years ago from the Rotorua Caldera. As it approaches Tirau, the road passes through some older ignimbrites, Whakamaru Group, that erupted ~347,000 years ago from the Whakamaru Caldera. From Tirau, the road heads NW through older volcanics (mainly welded ignimbrites) of the Pakaumanu Group that are thought to have erupted from the Mangakino Caldera between 1.6 and 0.95 Ma. The road will cross the western margin of the TVZ more or less where it joins the Waikato River valley, N of a prominent hill, Maungatautiri, which is Maungatautiri Formation (andesite and dacite lavas) dated at 1.8–1.6 Ma.

Beyond Lake Karapiro, the road passes through Cambridge and Otorohanga, crossing the Hamilton lowlands comprising mainly reworked Pleistocene pumice derived from eruptions of the TVZ rhyolite calderas, and transported by the Waikato River. To the W of Kihikihi are the upstanding volcanoes of the Alexandra Volcanics Group of late Pliocene to early Pleistocene age (2.74–1.6 Ma), including Pirongia (959 m; Pirongia Formation: basalt and basaltic andesite), and smaller Kakepuku (449 m), and Tokanui (214 m).
From Otorohanga onward the road crosses limestone-dominated topography developed within Oligocene Te Kuiti Group. Waitomo Caves is located proximal to a major fault, the Waipa Fault.

Although not observed (except perhaps in a distant quarry), the day will traverse basement rocks of the Waipapa Terrane.

Route
SH1 to Wairakei; SH5 to Rotorua; SH5 to Tirau; SH1 to Cambridge (29.3 km); keep left to continue on Thermal Explorer Highway/Tirau Rd (2.5 km); at the roundabout, take the 1st exit onto Shakespeare St (0.7 km); at the roundabout, take the 2nd exit onto Cook St (0.4 km); at the roundabout, continue straight onto Pope Terrace (1.0 km); Cambridge Rd/Te Awamutu Cambridge Rd (76.1 km); at Te Awamutu take left to Golf Rd, left to Flat Rd, straight on to Rolleston Rd, right to Whitmore Rd, left to Church Rd and left to SH3; on to Hangatiki via Otorohanga; SH37 to Waitomo Caves Village.

STOP Huka Falls: on the Waikato River
STOP Wai-o-Tapu geothermal hot-springs
STOP Rotorua for lunch
STOP Waitomo Caves: participate in a cave tour

Day 4: Monday 3rd December: Waitomo to Kawhia: Murihiku….at last (Figs 10, 11, 12, 13)
240 km: 155 before lunch (92 km to Awakino; 60 km Awakino to Kiritehere); 85 km after lunch

Main geological objectives
To explore Jurassic and Late Triassic sequences within the Murihiku Supergroup, Murihiku Terrane. To travel through the Awakino Gorge at the southern end of the fault-controlled exposure of Mesozoic rocks within the Kawhia Regional Syncline. To examine the Norian–Rhaetian boundary sequence in coastal exposures at Kiritehere, and the Triassic–Jurassic boundary sequence exposed at Marokopa.

Route
SH3 to Te Kuiti and then SW to Awakino via Tanehopuwai, Arapae, Piopio, Paemako, Mahoenui. Turn right and head N up Manganui Rd to Waikawau and on past Moeatoa on Mangatoa Rd to Kiritehere, and then Marokopa. On towards Taharoa via Marokopa Rd through Awamarino and Te Anga, then turn left along Taharoa Rd, then visit a quarry; then turn right up Whakapirau Rd to Te Waitere and Lemon Point. Onwards to Kawhia via Kinohaku and then Harbour Rd via Waiharakeke, Pukeinui and Hauturu; then turn left on to SH31 to Oparau and Kawhia.

Geology
Drive S from Waitomo Caves to Te Kuiti.

Drive on towards Awakino via Piopio and Mahoenui, travelling mainly through Oligocene Te Kuiti Group (mainly limestones and calcareous siltstones).

Drive through (E–W) through the Awakino Gorge: traverse section down-sequence through Newcastle Group rocks spanning Early Jurassic to Late Triassic time and passing through a documented Triassic–Jurassic boundary sequence.

Drive N towards Kiritehere and Marokopa via the Manganui Valley, controlled by the Manganui Fault. The road criss-crosses the Manganui Fault which has significant apparent vertical throw juxtaposing east-dipping Early Jurassic Newcastle Group to the W against east-dipping older Late Triassic Newcastle Group to the E. North of Waikawau the Manganui Fault becomes the Whareorino Fault. Beyond Waikawau, the road climbs over the flanks of Mt Whareorino, an eroded (basalt) volcano within the Orangiwhao Intrusive Group (middle Pliocene; 3.9 Ma). The road then descends down Kiritehere Stream to Kiritehere beach with spectacular shore platform exposures to the S towards Spiriferina Point, and also N towards Marokopa, just a few kilometres away.

STOP Kiritehere: Norian–Rhaetian boundary within Late Triassic sequence
STOP Marokopa: Late Triassic–Early Jurassic sequence (Rhaetian–Hettangian–Sinemurian)

From Marokopa, the road follows the Marokopa River as far as Te Anga. Here it crosses the E–W oriented Marokopa Fault which is upthrown to the N.

STOP Taharoa road quarry: Pakau Formation, Kirikiri Group, Heterian (Oxfordian–Kimmeridgian). Drive up Whakapirau Rd: observe Giant Ammonite locality (*Lytoceras taharoaensis*; early Kimmeridgian)
STOP Lookout over Kawhia Harbour from a high point on Whakapirau Rd
STOP Lemon Point: Kinohaku Siltstone, Apotu Group, Ohauan (middle Tithonian)

Drive around Kawhia Harbour from S to N, passing conspicuous exposures of Kinohaku Siltstone between Kinohaku and Paparoa Point. The road then traverses very poorly exposed younger formations (Waiharekeke Conglomerate and Puti Siltstone, of middle Tithonian and late Tithonian respectively) for about 6 kilometres within the Toe Syncline. It then passes through Oligocene cover sediments of the Te Kuiti Group (mainly Aotea Formation) for about 7 km, and into much younger Alexandra Volcanics Group associated with the eruption of Pirongia (late Pliocene to early Pleistocene age; 2.74–1.6 Ma); proceed on through Oparau and on to Kawhia, crossing the Oparau Fault and around the N coast of Kawhia Harbour, passing through very poorly exposed Waiharakeke Conglomerate and conspicuous much better exposed Puti Siltstone within the Kawaroa Anticline, and then a belt of Te Kuiti Group (mainly Whaingaroa Formation). Kawhia is built on a tombolo of Pleistocene sands (Kaihu Group).

Day 5: Tuesday 4th December: Te Maika: chasing the Toarcian (Fig 14)
20 km by car; 10 km by boat; 7–8 km by foot

Main geological objectives
To explore the marine Ururoan and marginal marine to non-marine Temaikan (Toarcian–Kimmeridgian) Jurassic sequence preserved in the cliffs and shore platforms on the Te Maika coast, which is located on the south side of the entrance of Kawhia Harbour and is only accessible by boat.
Visit the best-exposed section through Ururoan (Toarcian) rocks in New Zealand.

Drive to Puti Point in the morning, back towards Oparau
STOP Puti Point: Puti Siltstone (Middle Tithonian)
Return to Kawhia
Drive to beach c. 5 kilometres W of Kawhia
STOP Te Puia Springs: a natural hot-water spring
Return to Kawhia
Travel by boat ("*Kotuku"*) in the late morning
STOP Te Maika: walk from N to S down-sequence through Temaikan and older Ururoan sequence, as far as the *Pseudaucella* shellbeds (basal Ururoan Stage)
Return to Kawhia by boat

Day 6: Wednesday 5th December: Kawhia to Tuakau: Huriwai Group (Figs 15, 16, 17)
175 km: 115 km before lunch (50 km to Raglan; 65 km to Nikau Cave); 60 km after lunch

Main geological objectives
To visit the youngest Jurassic sequence within the Huriwai Group, which is poorly exposed in the core of the Kaimango Syncline. This includes the fossiliferous Matira Siltstone which is in part lacustrine and in part marginal marine.

To visit the well-studied Huriwai Group coastal exposure at Port Waikato, at the very northern end of the Kawhia Syncline.

Route
Kawhia to Raglan along Raglan Rd via Makomako, Te Papatapu; then turn left onto Te Papatapu Rd to Te Mata and Te Mata Rd to Kauroa. Turn left on to SH23 to Raglan via Three Streams.

Back to the E along SH31, to Te Uku, then turn left up Ohautira Rd via Haroto Bay, Ohautira; then left again onto SH22 to Dunmore. Then right on SH22 to just beyond Jacobs Rd then left down Waimai valley Rd, and right onto Dixon Rd. Onwards to Matira Rd junction; turn right at Waikorea and then promptly left on to Richardson Rd, then left onto Waikaretu Valley Rd and find the Nikau Cave Cafe. After lunch, proceed onwards to W and then N up Waikaretu Rd to Limestone Downs and Port Waikato Rd to Port Waikato. From Port Waikato, head E along Port Waikato Rd up the S bank of the Waikato River through Tauranganui, Te Kohanga; cross the Waikato River and proceed to Tuakau located on the N side of the Waikato River.

Geology
From Kawhia, the road to Raglan snakes around the E side of Aotea Harbour, crossing Oligocene Te Kuiti Group and Pliocene Alexandra Volcanic Group (basaltic lavas and breccias of mainly Oteke Formation), relating to the eruption of the Karioi Volcano in latest Pliocene to early Pleistocene time (2.74–1.6 Ma).
From Raglan the road skirts around the E side of Raglan Harbour
STOP Raglan: coffee
STOP Dixon Rd: Matira Siltstone, Huriwai Group, within Kaimango Syncline
STOP Nikau Cave Café: lunch
STOP Port Waikato: Huriwai Group
Drive to Tuakau

Day 7: Thursday 6th December: Tuakau to Auckland: via Pakihi Island (Figs 18, 19)
110 km: 65 km from Tuakau to Kawakawa Bay; park vehicles in secure place; 45 km from Kawakawa Bay to Auckland Airport

Main geological objective
To visit Pakihi Island in the Hauraki Gulf, to explore a deep-marine chert and siliceous argillite sequence within Waipapa Terrane. Visit a well-documented Triassic–Jurassic boundary sequence.

Route
Tuakau to Pokeno and connect with SH1; drive over the Bombay Hill; drive for about 20 km, then take exit 458 to Papakura; Beach Rd (1.4 km), Settlement Rd (0.8 km); 1st exit onto Marne Rd (0.6 km); 2nd exit onto Clevedon Rd (2.0 km); continue on Papakura–Clevedon Rd (10.3 km); 2nd exit on to Clevedon–Kawakawa Rd (16.0 km).
Kawakawa Bay to Auckland Airport (45 km):
Head west on Clevedon-Kawakawa Rd toward Mihaka Rd (16.0 km)
1st exit on to Papakura–Clevedon Rd (1.5 km)
Turn right onto West Rd (4.1 km)
1st exit onto Brookby Rd/Pacific Coast Hwy (8.7 km)

1st exit onto Hill Rd/Pacific Coast Highway (1.0 km)
Turn right onto Grande Vue Rd/Pacific Coast Highway (0.1 km)
Keep right, follow signs for State Highway 1/Auckland/Motorway and merge onto SH 1 (2.0 km)
Take exit 449A-B for SH20 W toward Airport (1.0 km)
Continue onto SH20 (2.5 km)
Take exit 3 for Cavendish Drive towards Urban Route 30/SH20B/Puhinui Rd/Airport (0.4 km)
Keep right to continue toward Puhinui Rd/SH20B (0.3 km)
Keep left at the fork, follow signs for SH20B/Puhinui Rd/Airport (0.7 km)
Turn left onto Puhinui Rd/SH20B (3.9 km)
Turn left onto Puhinui Rd/SH20B (1.3 km)

Drive from Tuakau to Kawakawa Bay SE of Auckland
Travel by barge from Kawakawa Bay to Pakihi Island.
STOP Pakihi Island, also known as 'McCallum's Island'; privately owned by the McCallum Family.
Return by barge and drive from Kawakawa Bay to Auckland International Airport.

Australobuchia hochstetteri (Puaroan; Tithonian) Photo: Marianna Terezow, GNS Science.

FIGURES

Sixteen maps and three diagrams. Maps crafted by Donald MacFarlan; GIS data from LINZ, GNS Science and Google Earth.

List of figures

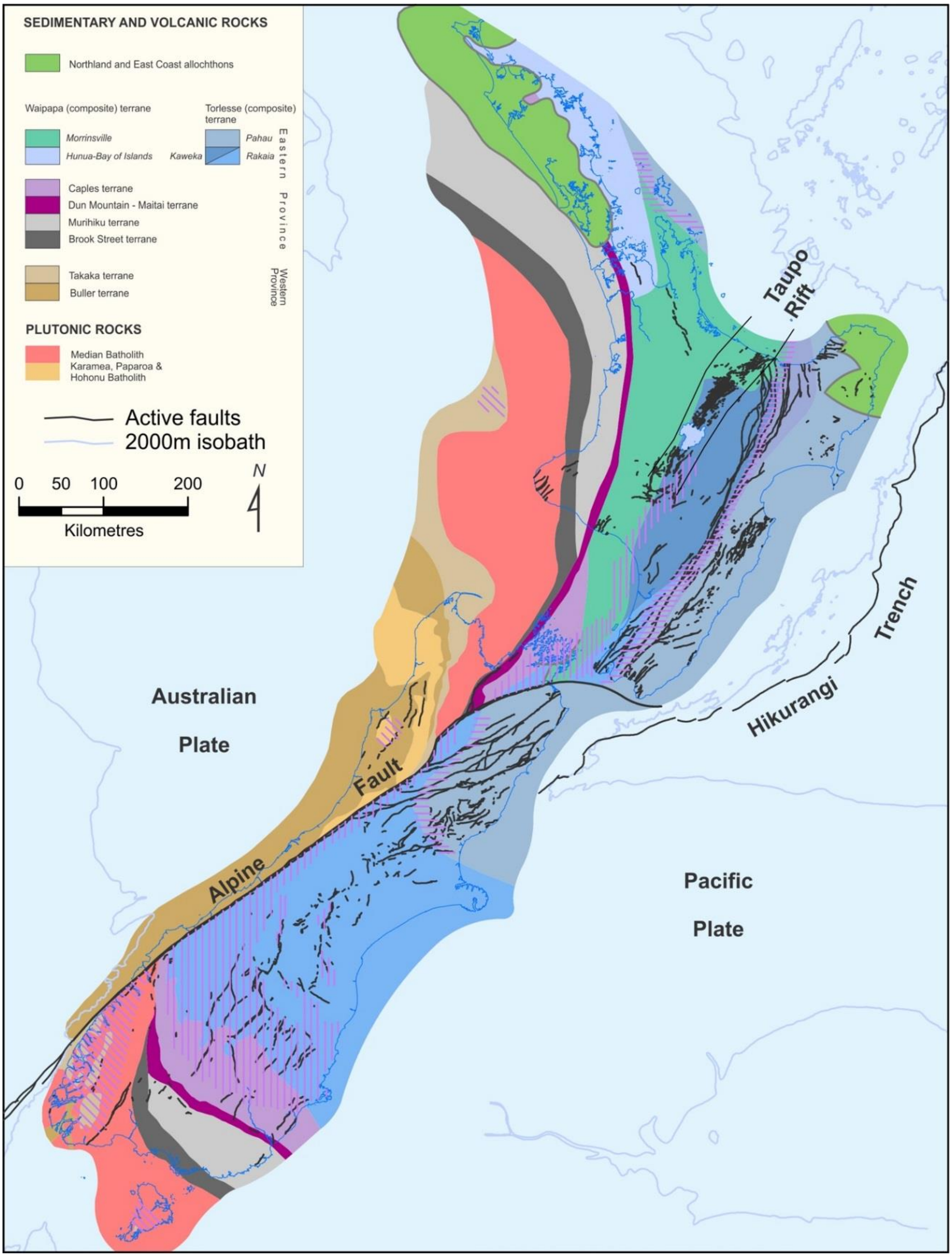

Fig 1: Pre-Cenozoic basement rocks of New Zealand showing tectonostratigraphic units, including Kaweka, Murihiku and Waipapa terranes, and batholiths (Townsend et al. 2017).

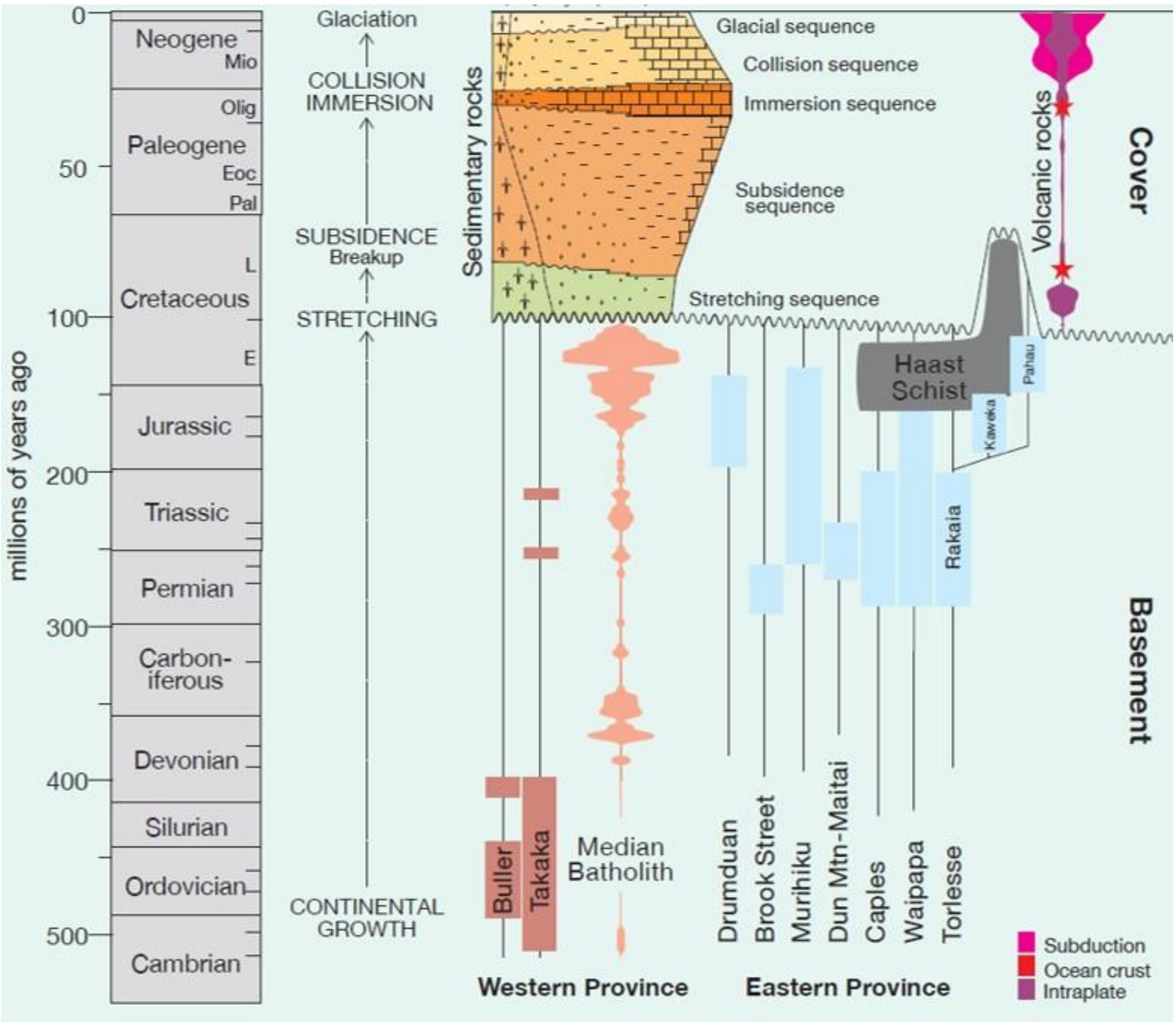

Fig 2: Geology of New Zealand in terms of basement and cover (Mortimer et al. 2014).

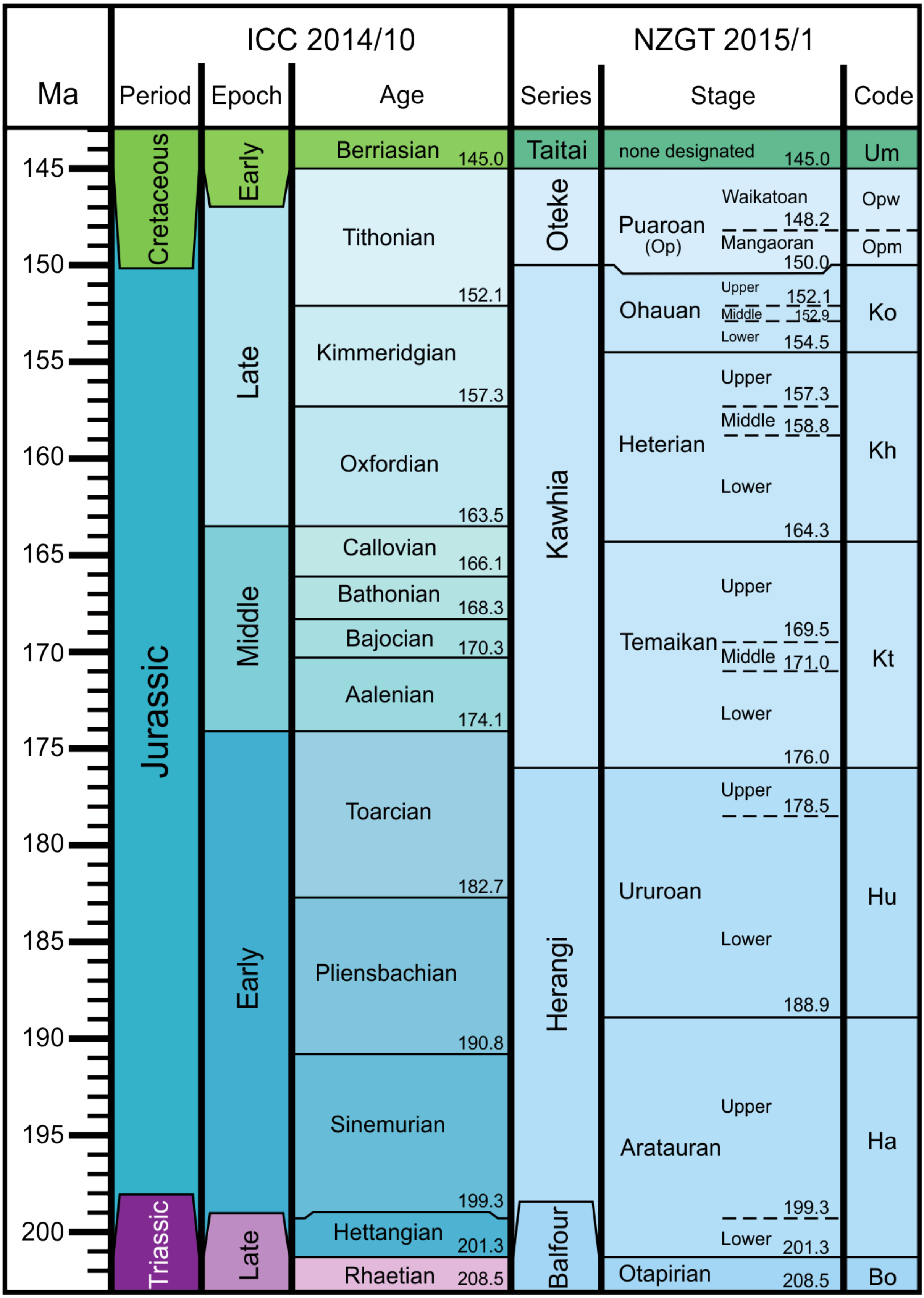

Fig 3: New Zealand Geological Timescale: Jurassic (Raine et al. 2015).

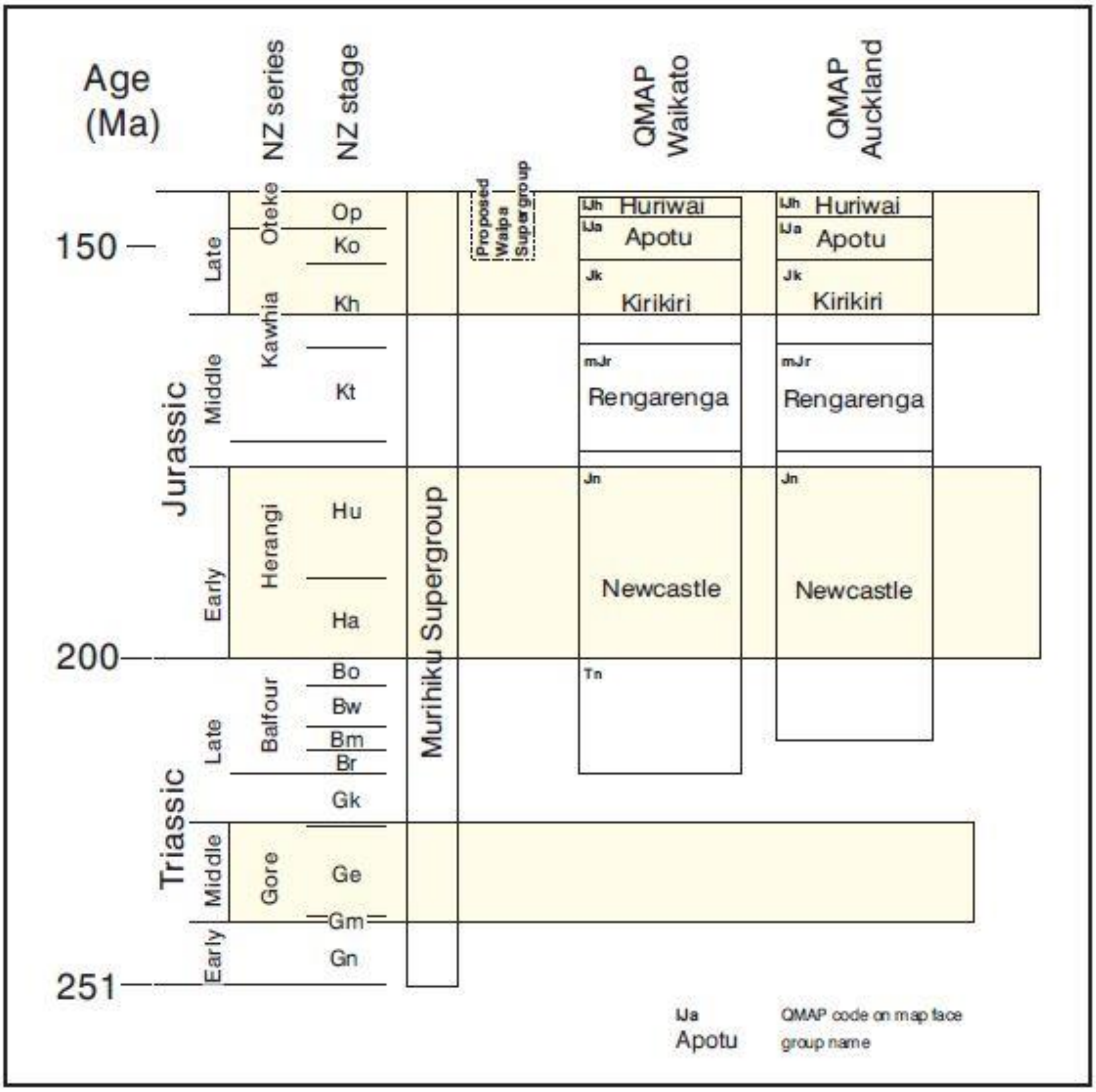

Fig 4: Lithostratigraphic subdivision of Murihiku Supergroup rocks, Murihku Terrane, as mapped in the Kawhia Regional Syncline, North Island of New Zealand (Edbrooke 2005).

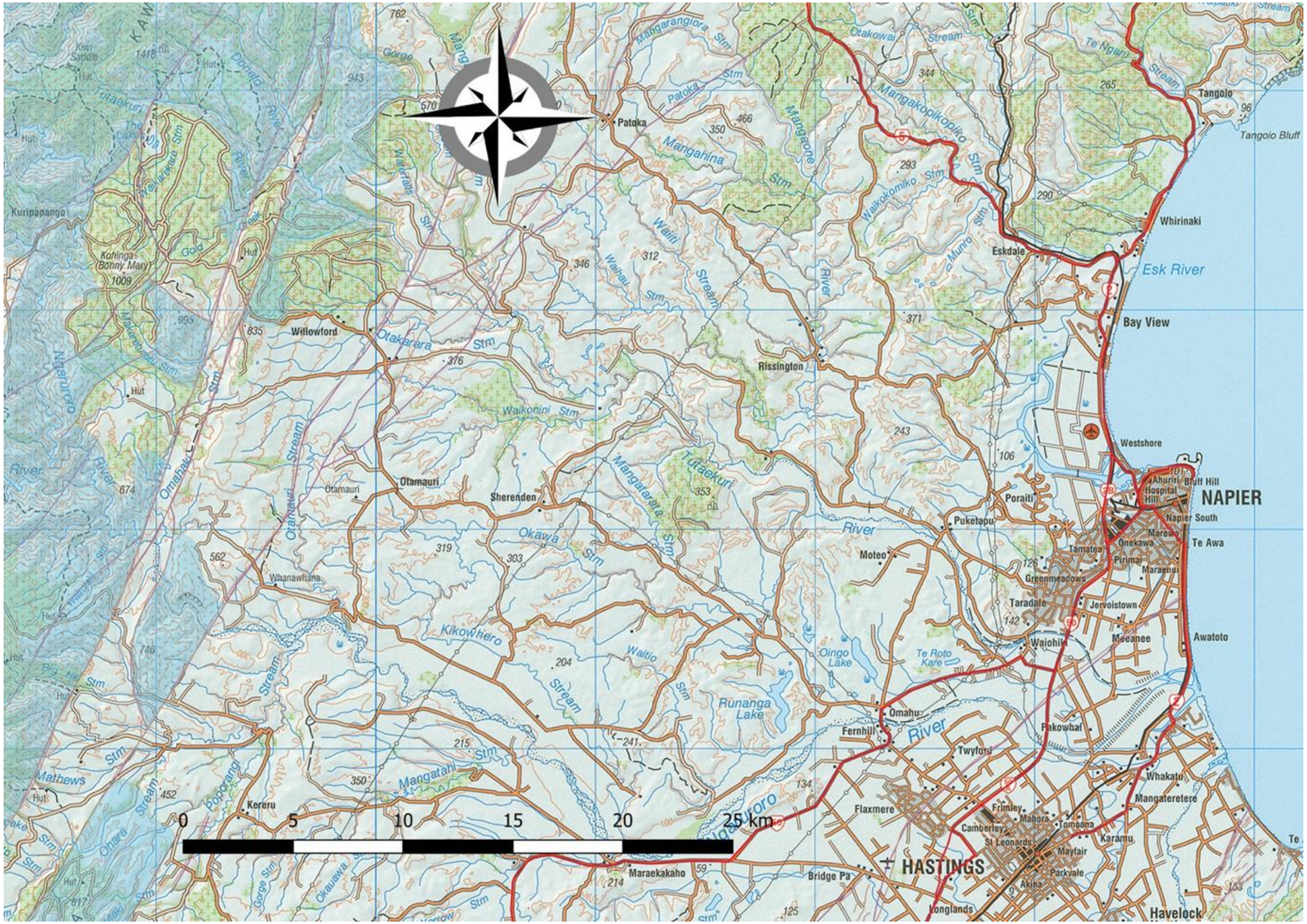

Fig 5: Day 1: Napier to Kuripapango, showing the distribution of basement rocks (shaded).

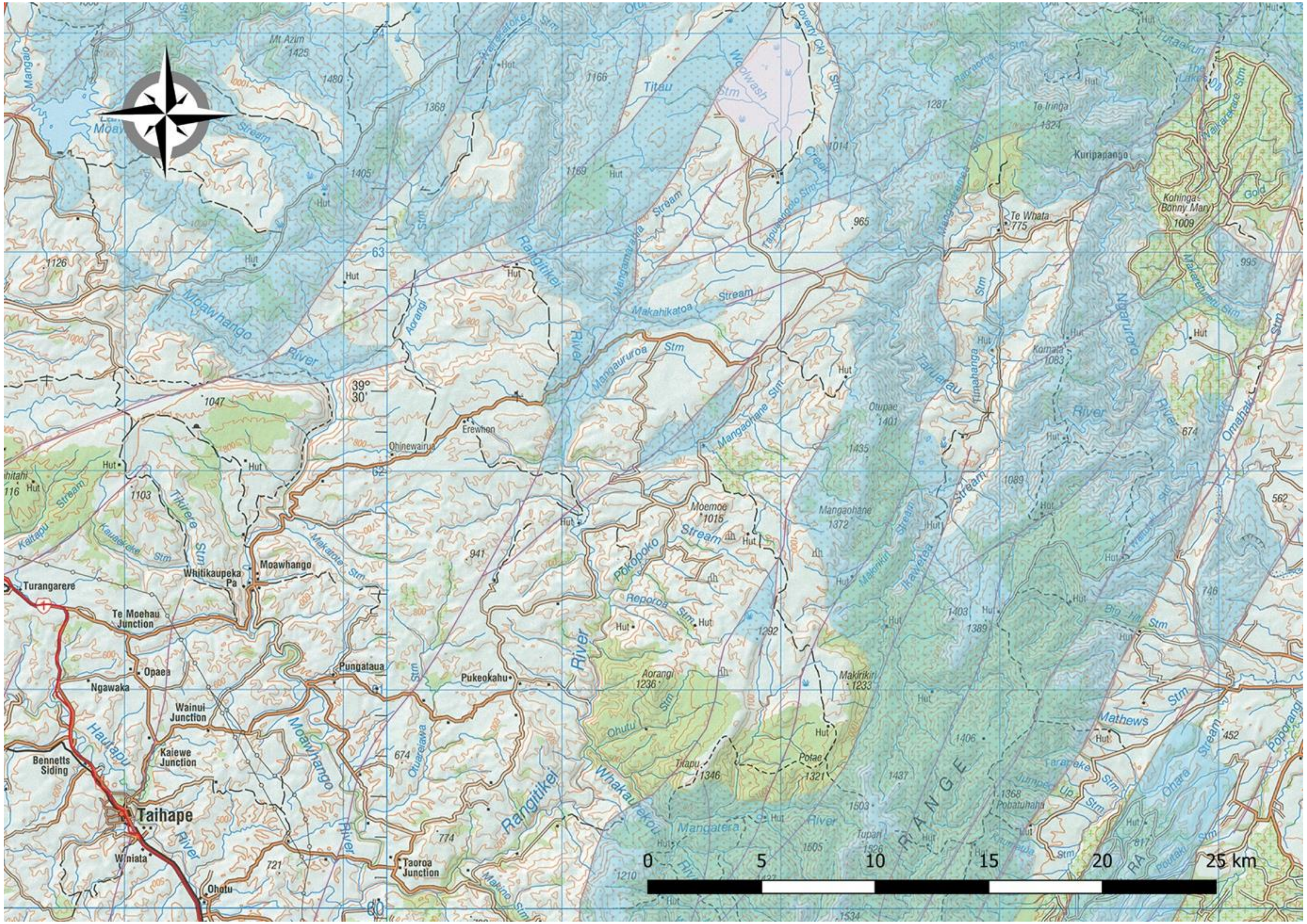

Fig 6: Day 1: Kuripapango to Taihape, showing the distribution of basement rocks (shaded).

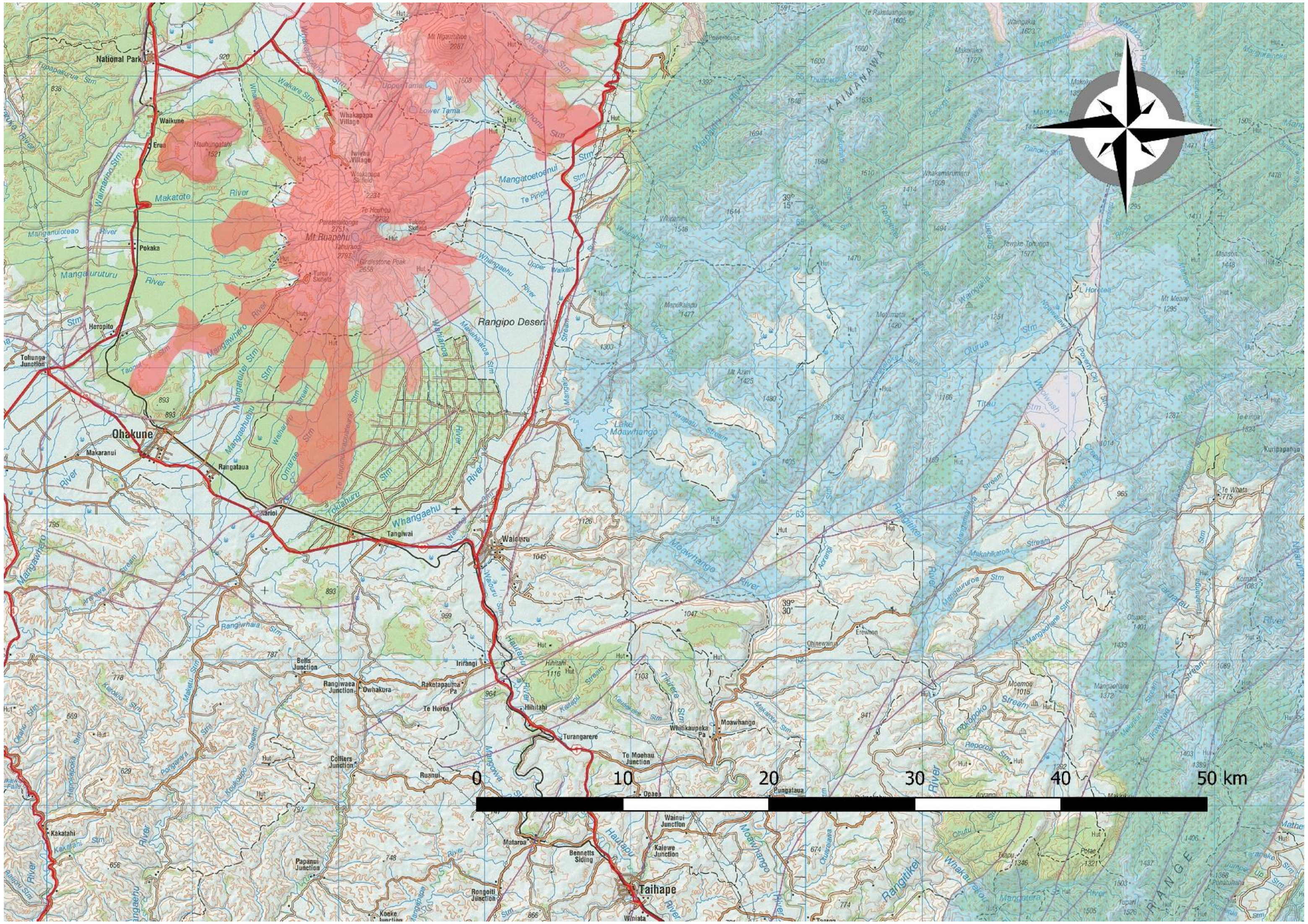

Fig 7A: Day 2: Taihape to Taupō. (A) Taihape to Ruapehu and (B) Ruapehu to Taupō showing distribution of basement rocks (mainly Kaweka Terrane; shaded), and volcanics: andesite (red), dacite (orange) and rhyolite (purple) lava flows and/or domes.

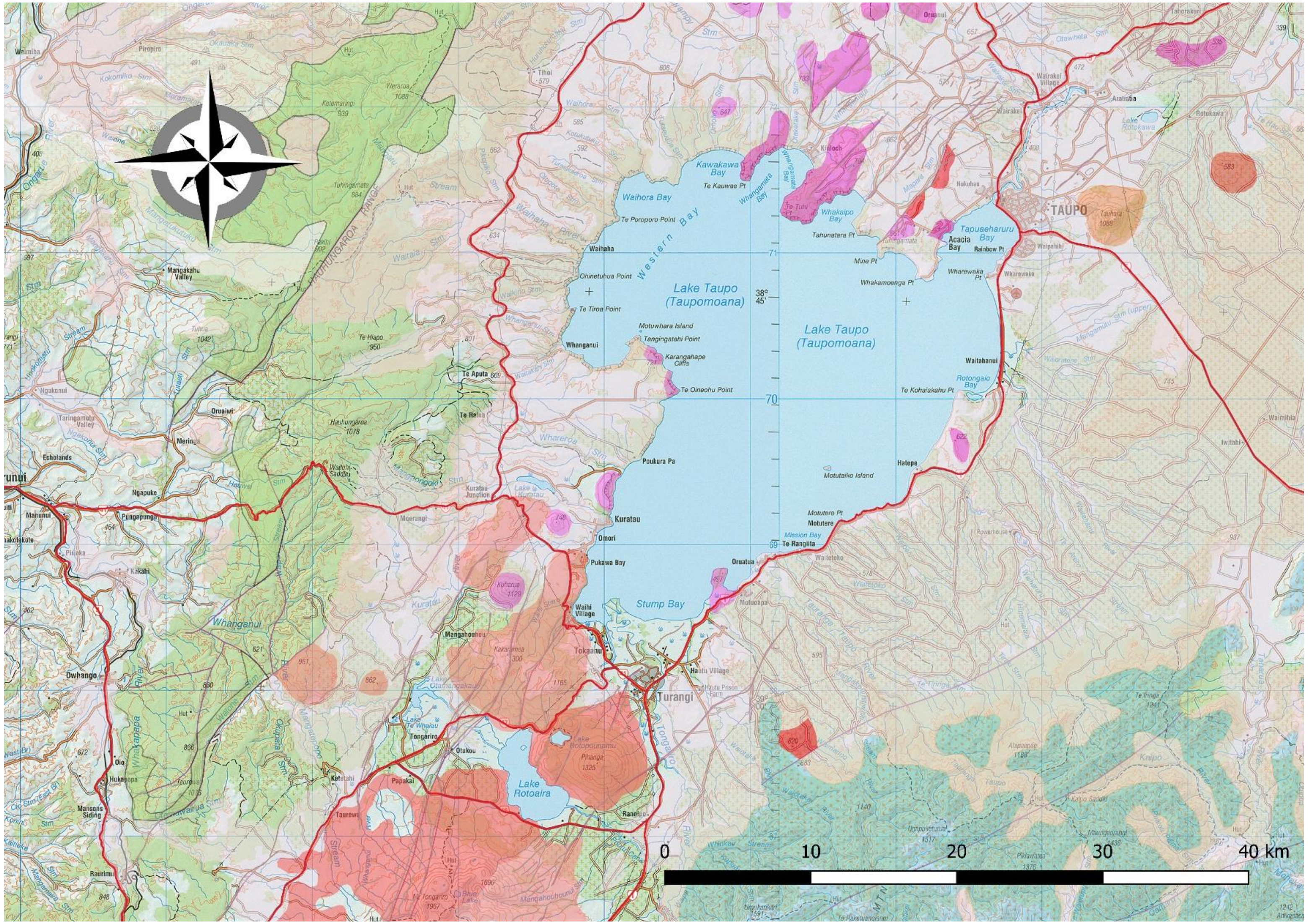

Fig 7B: Day 2: Taihape to Taupō. showing distribution of basement rocks (mainly Kaweka Terrane; shaded), and volcanics: andesite (red), dacite (orange) and rhyolite (purple) lava flows and/or domes.

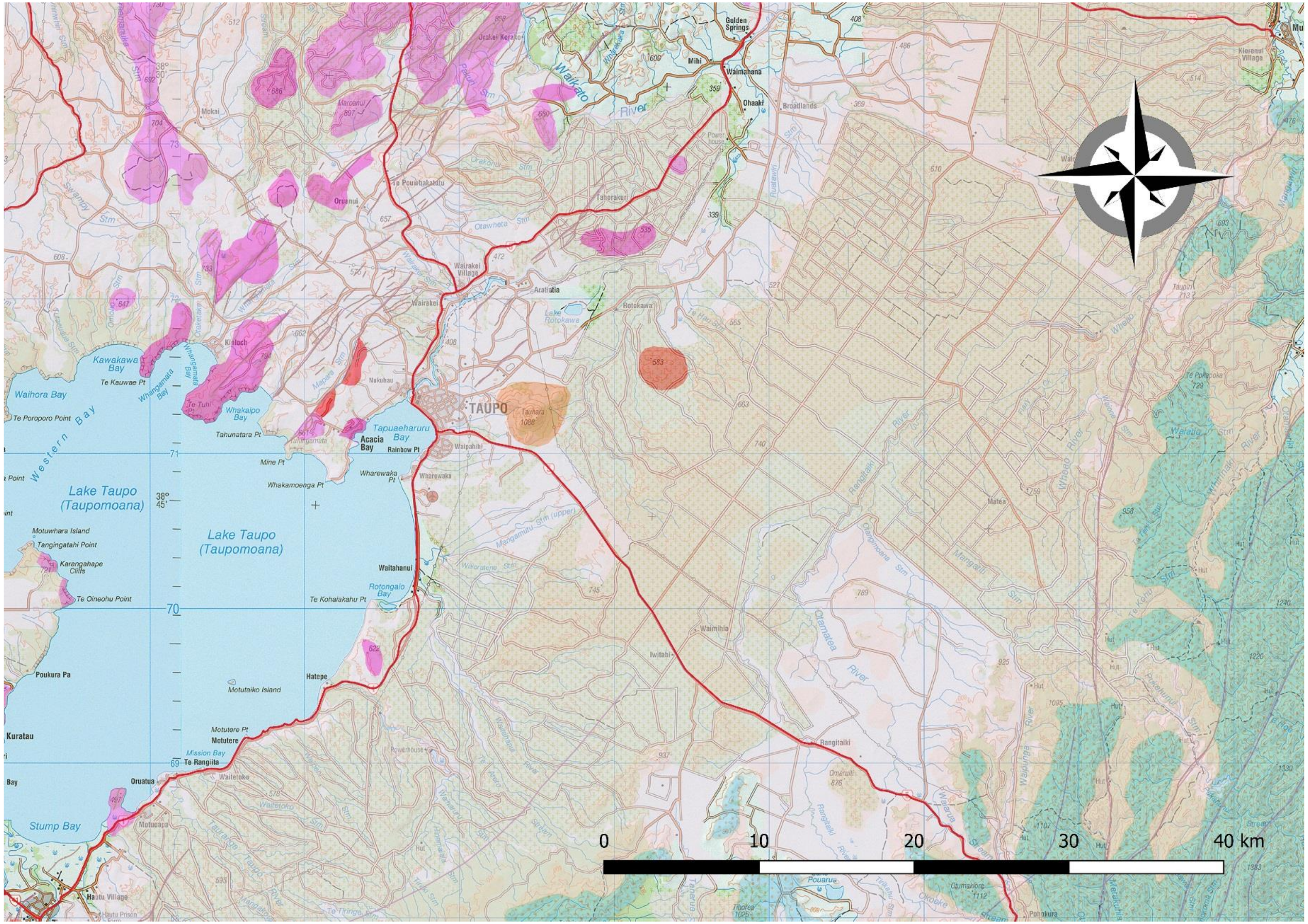

Fig 8A: Day 3: Taupō to Rotorua showing dacite (orange) and rhyolite (purple) lava flows and/or domes, and known faults.

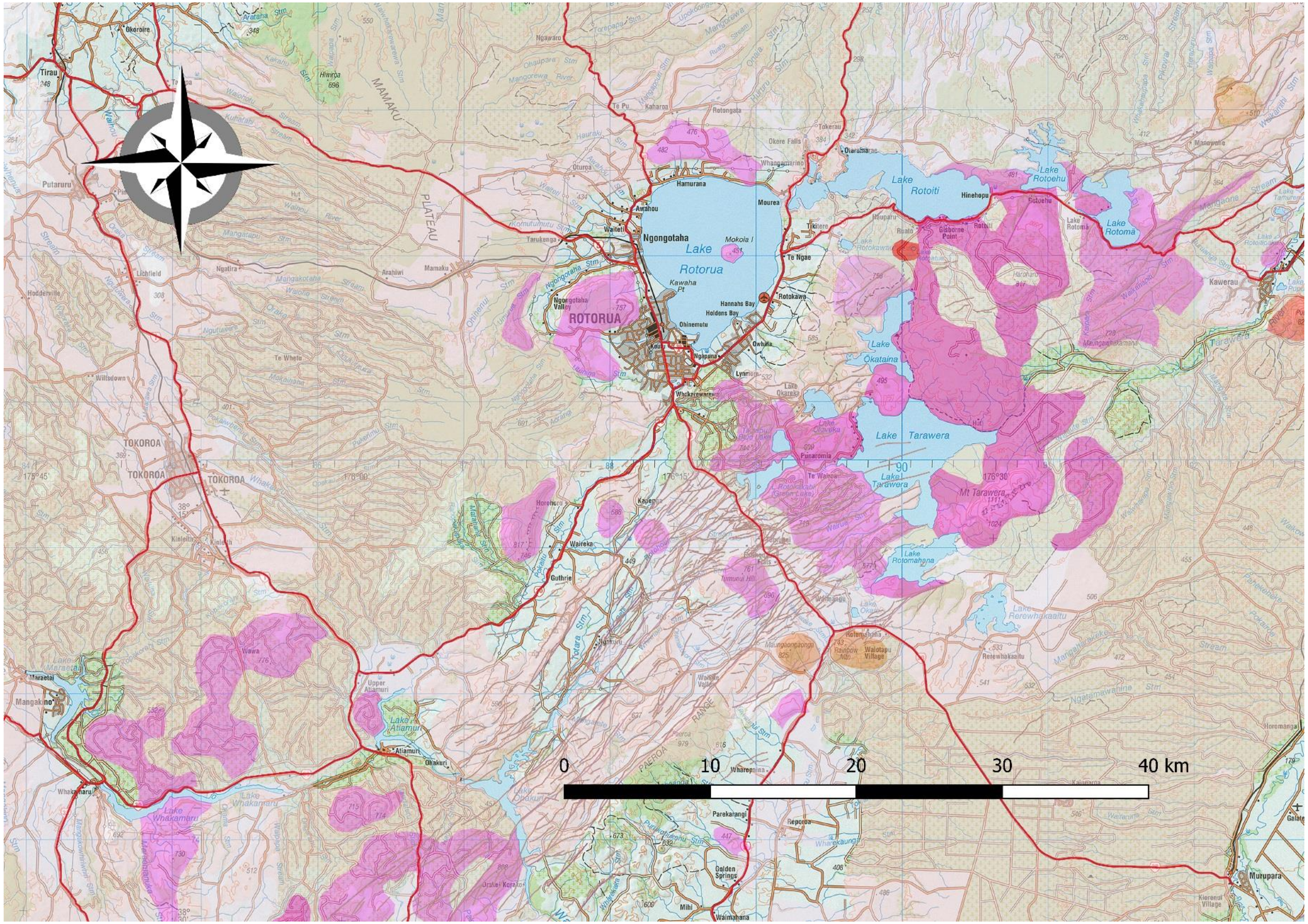

Fig 8B: Day 3: Taupō to Rotorua showing dacite (orange) and rhyolite (purple) lava flows and/or domes, and known faults.

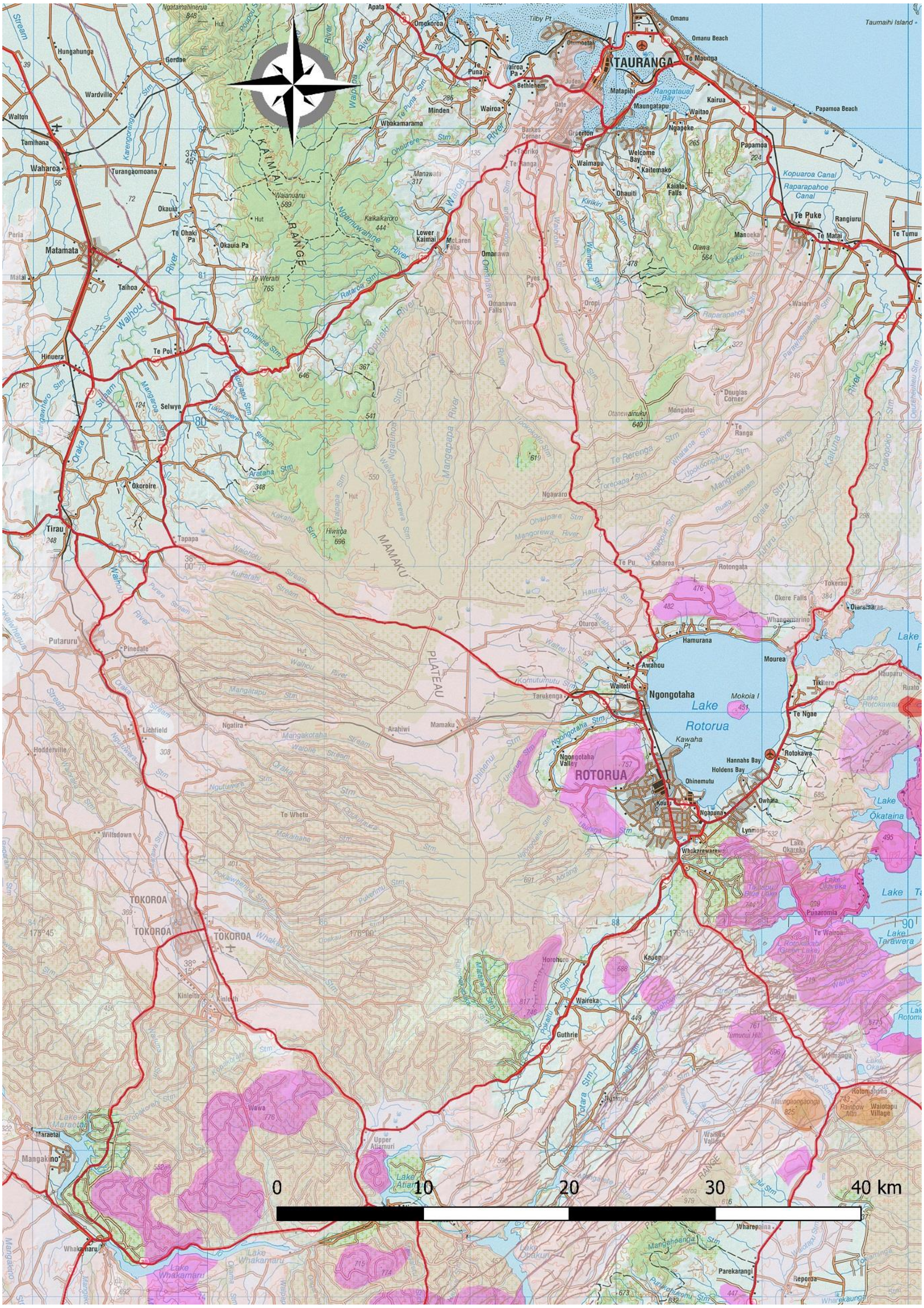

Fig 9A: Day 3: Rotorua to Waitomo Caves, showing distribution of basement rocks (mainly Waipapa Terrane; green), and volcanics: andesite (red), dacite (orange) and rhyolite (purple) lava flows and/or domes.

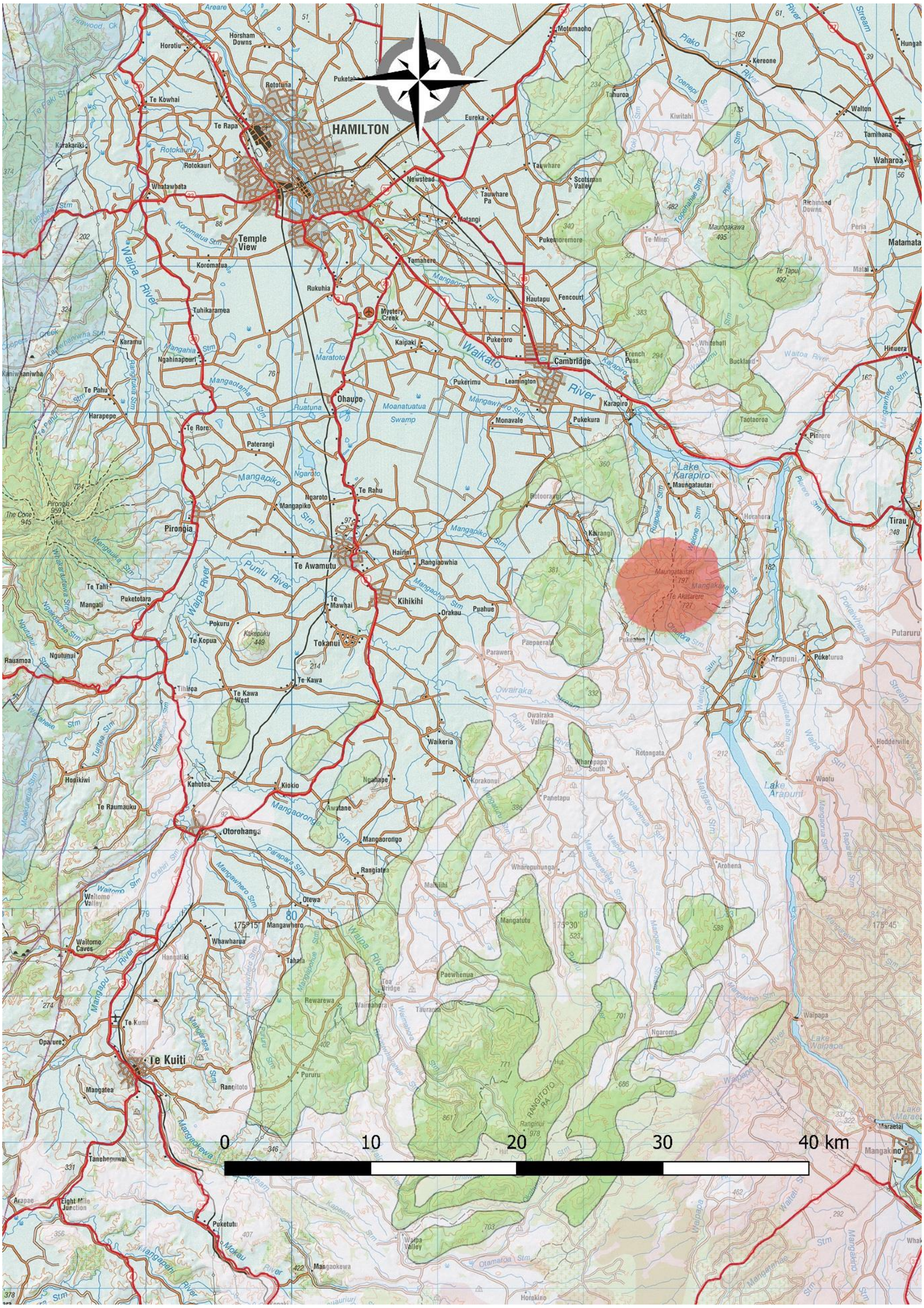

Fig 9B: Day 3: Rotorua to Waitomo Caves, showing distribution of basement rocks (mainly Waipapa Terrane; green), and volcanics: andesite (red), dacite (orange) and rhyolite (purple) lava flows and/or domes.

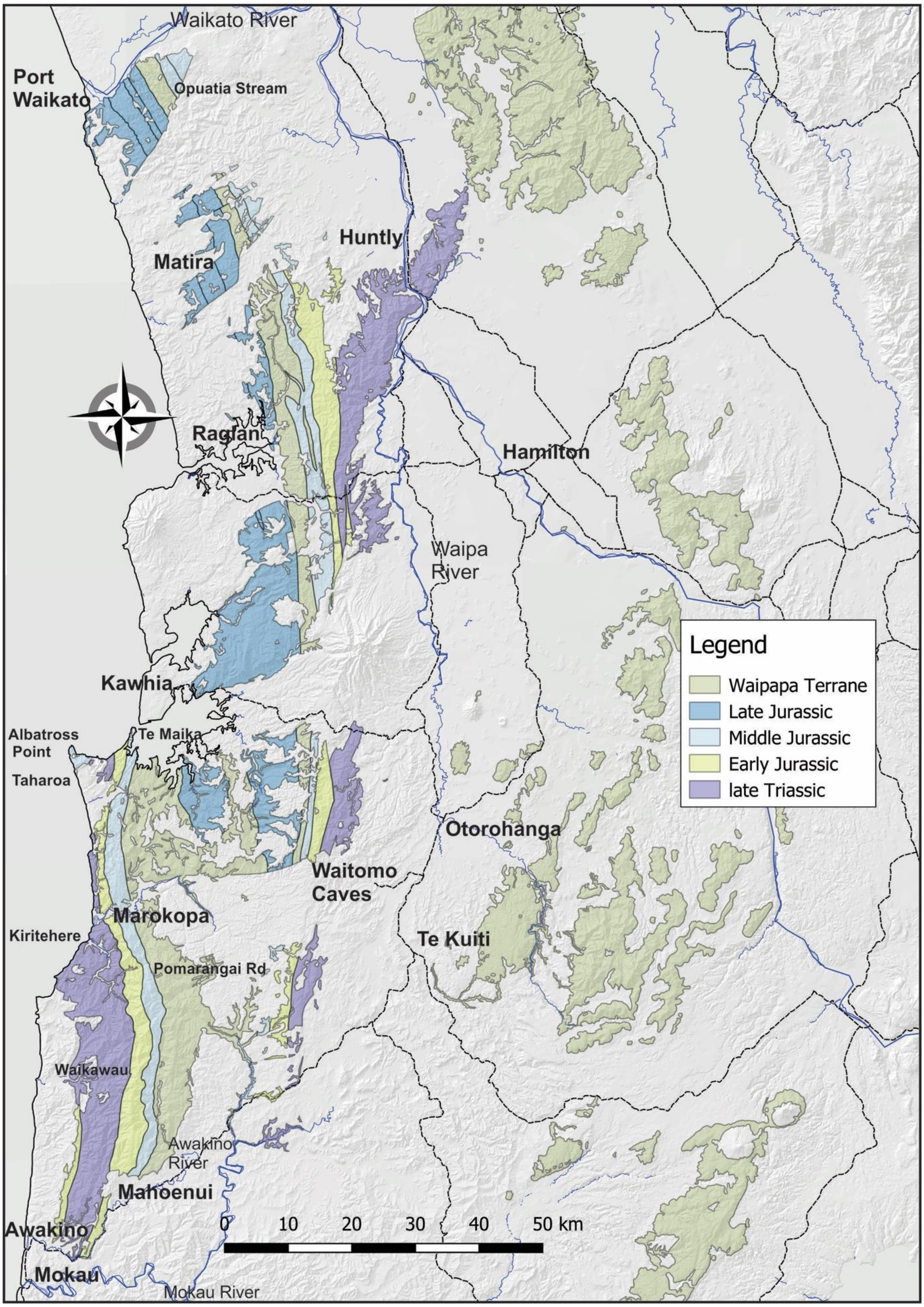

Fig 10: Days 3, 4, 5, 6: Waitomo Caves, Awakino, Marokopa, Kawhia, Port Waikato: showing distribution of basement rocks, including Waipapa Terrane. Late Triassic and Early, Middle and Late Jurassic rocks are shown within the Murihiku Terrane as mapped within the Kawhia Regional Syncline.

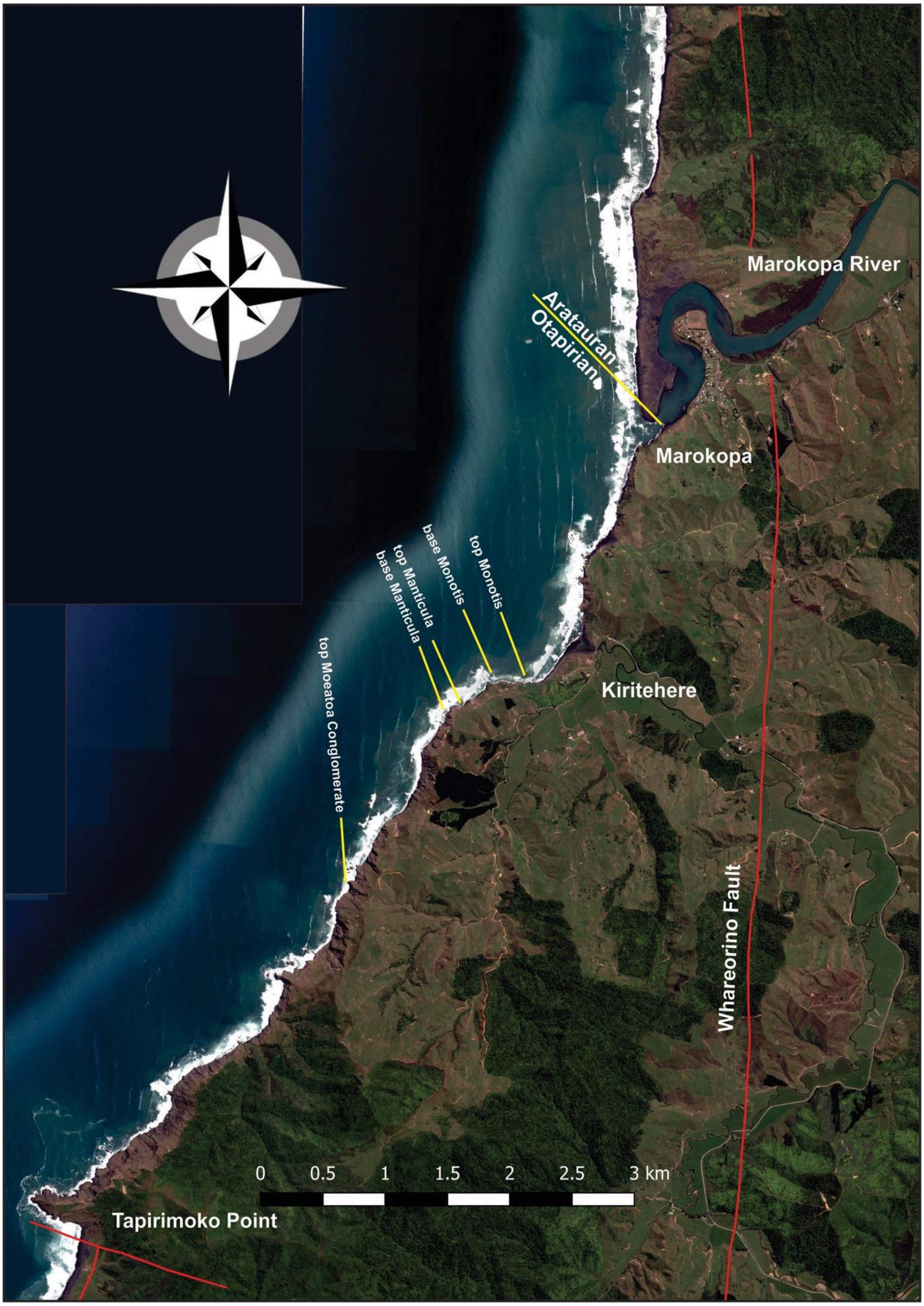

Fig 11: Day 4: Kiritehere and Marokopa: Late Triassic–Early Jurassic sequence within Murihiku Terrane, showing location of key fossil datums.

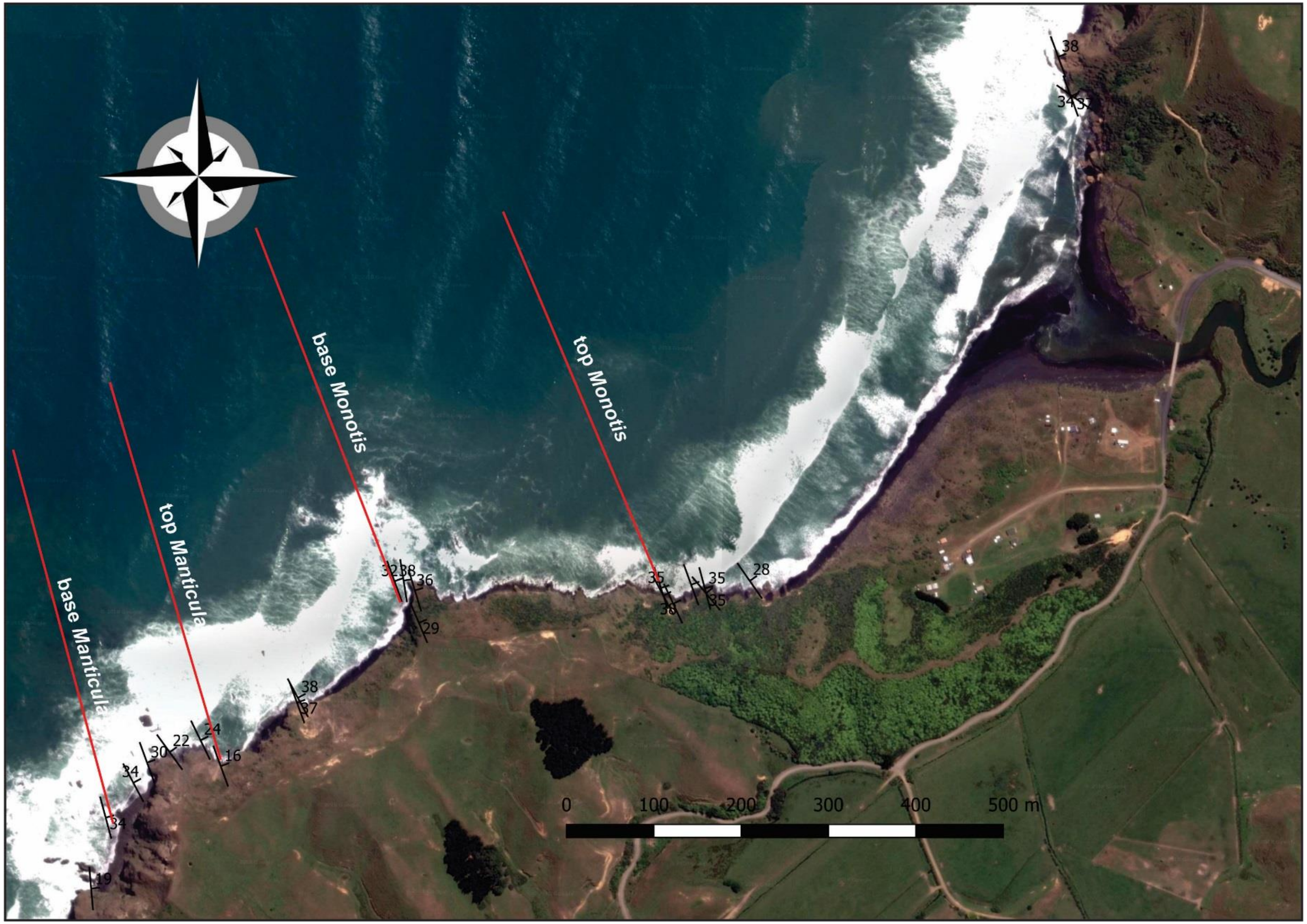

Fig 12: Day 4: Kiritehere: key Late Triassic–Early Jurassic fossil datums and strike/dip measurements of strata.

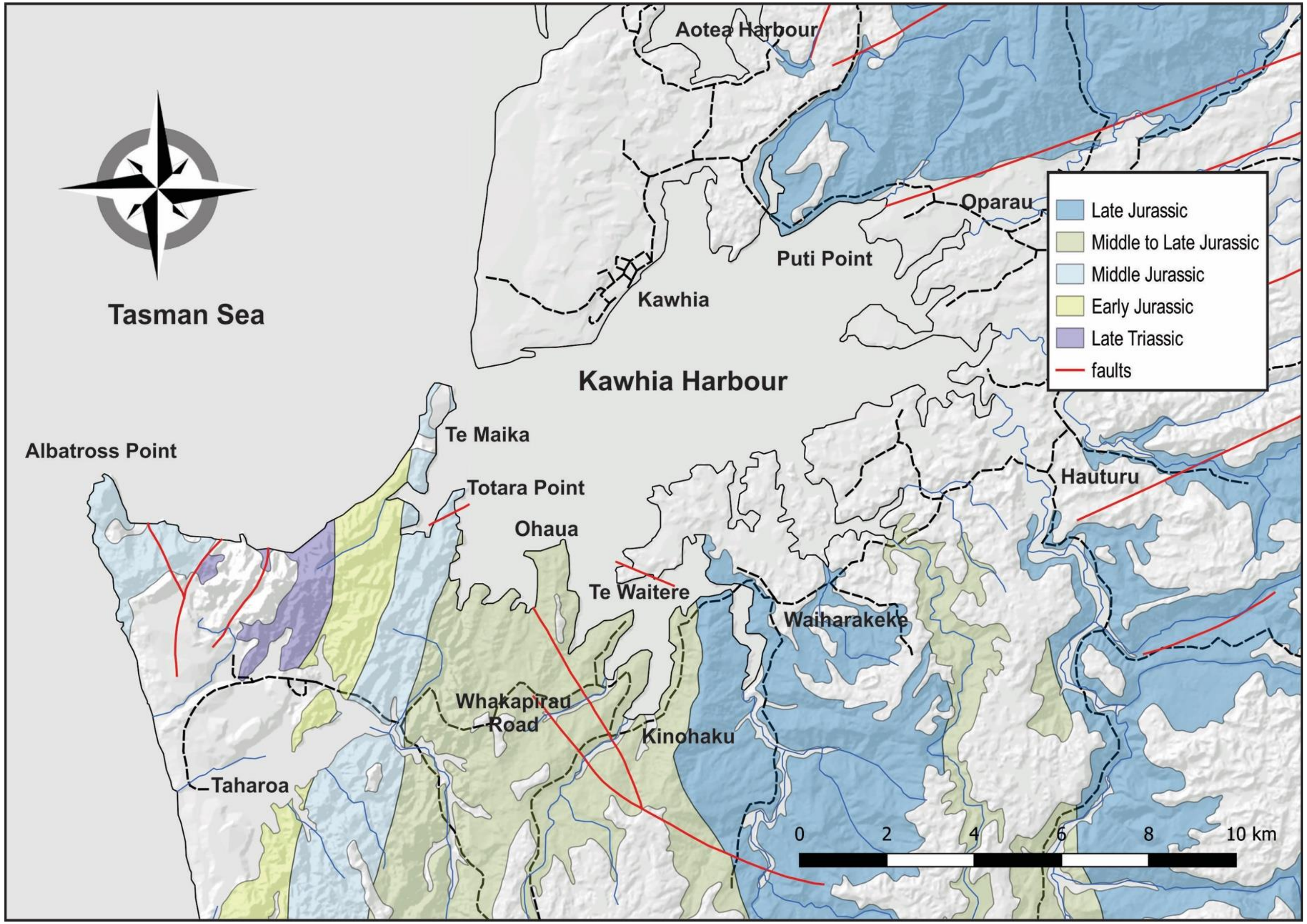

Fig 13: Days 4, 5: Kawhia Harbour showing Whakapirau Rd, Te Waitere (Lemon Point), Kihohaku, Oparau, Puti Point, Kawhia, Te Maika.

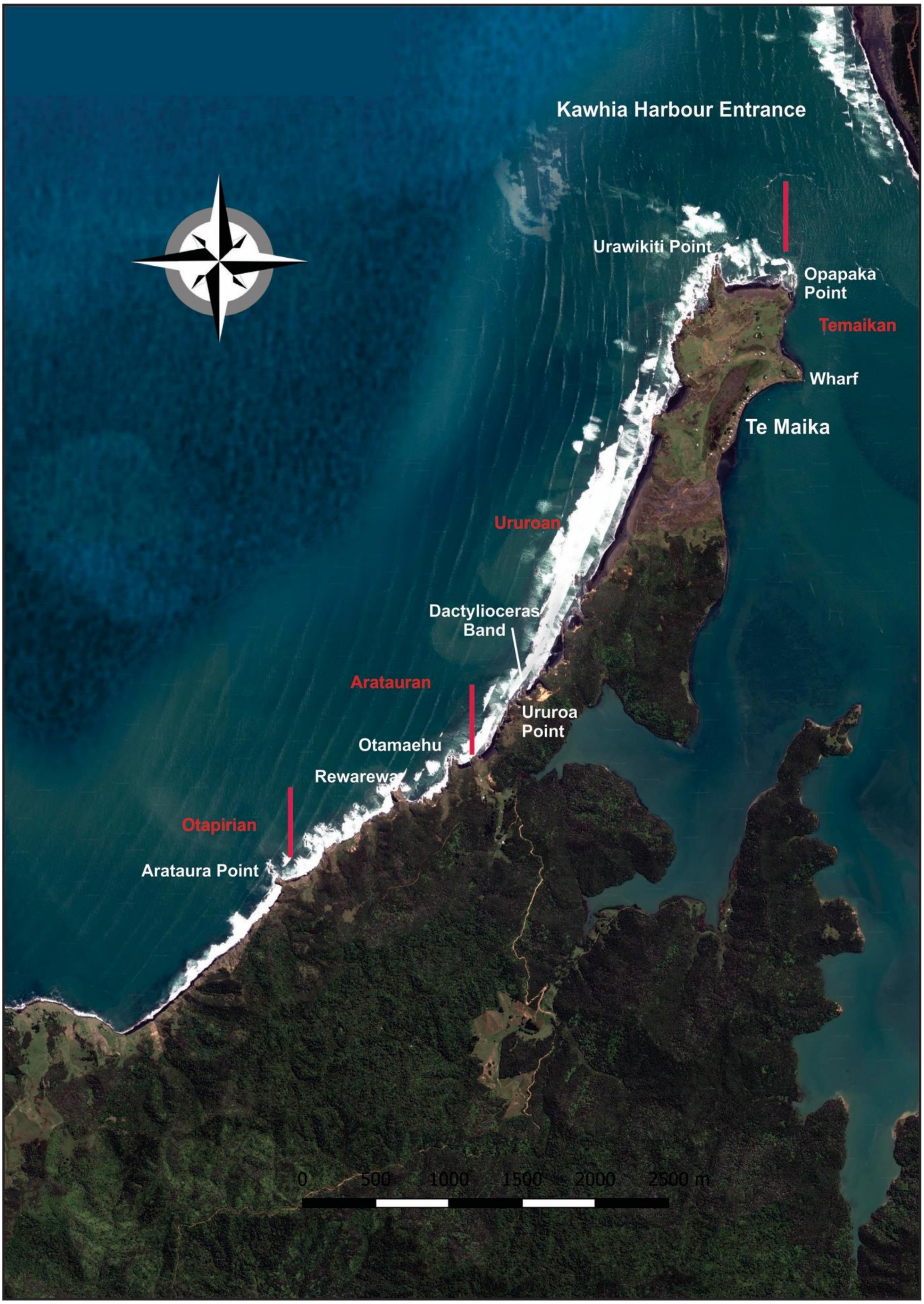

Fig 14: Day 5: Te Maika.

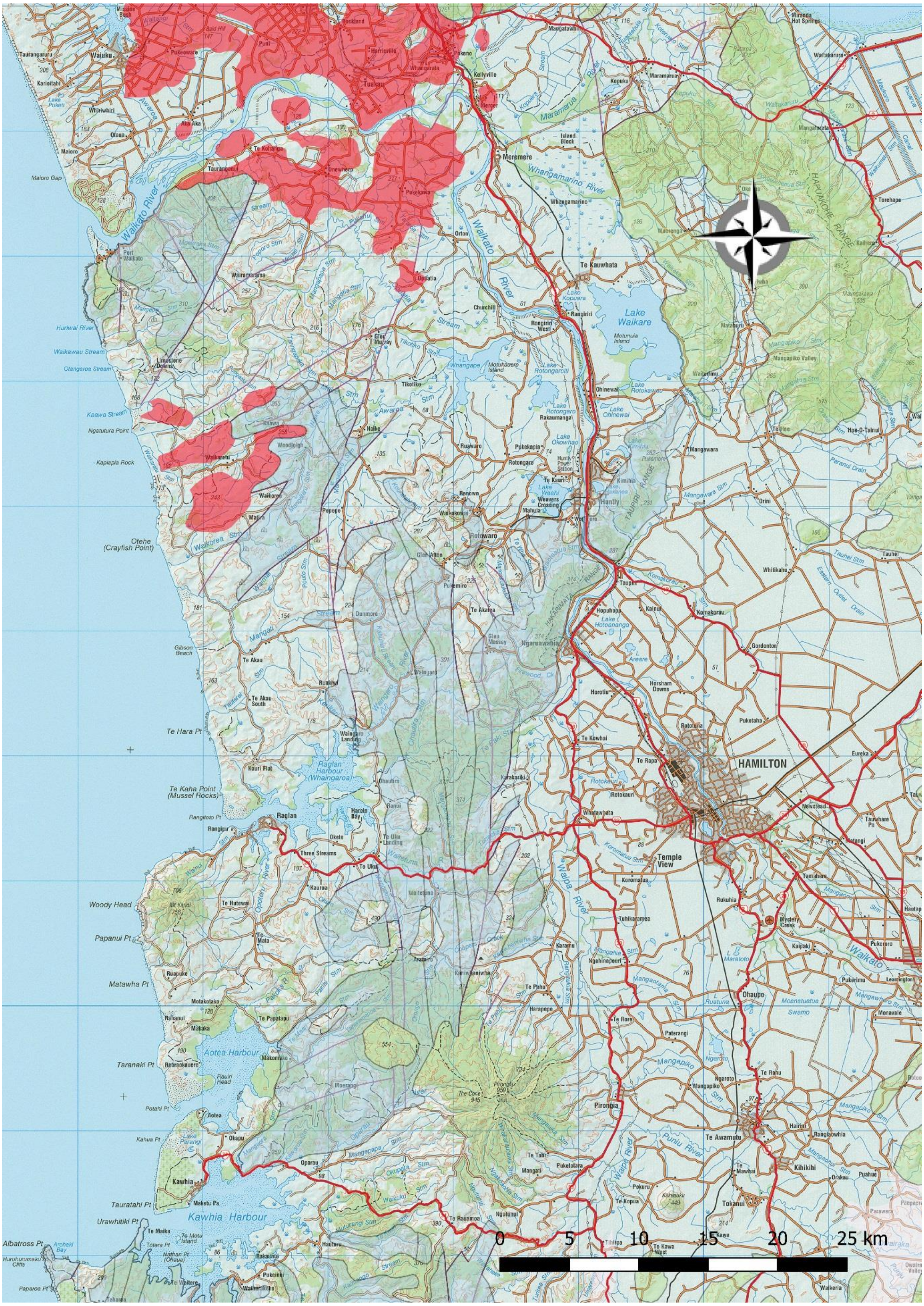

Fig 15: Day 6: Kawhia to Tuakau showing South Auckland Volcanics (red).

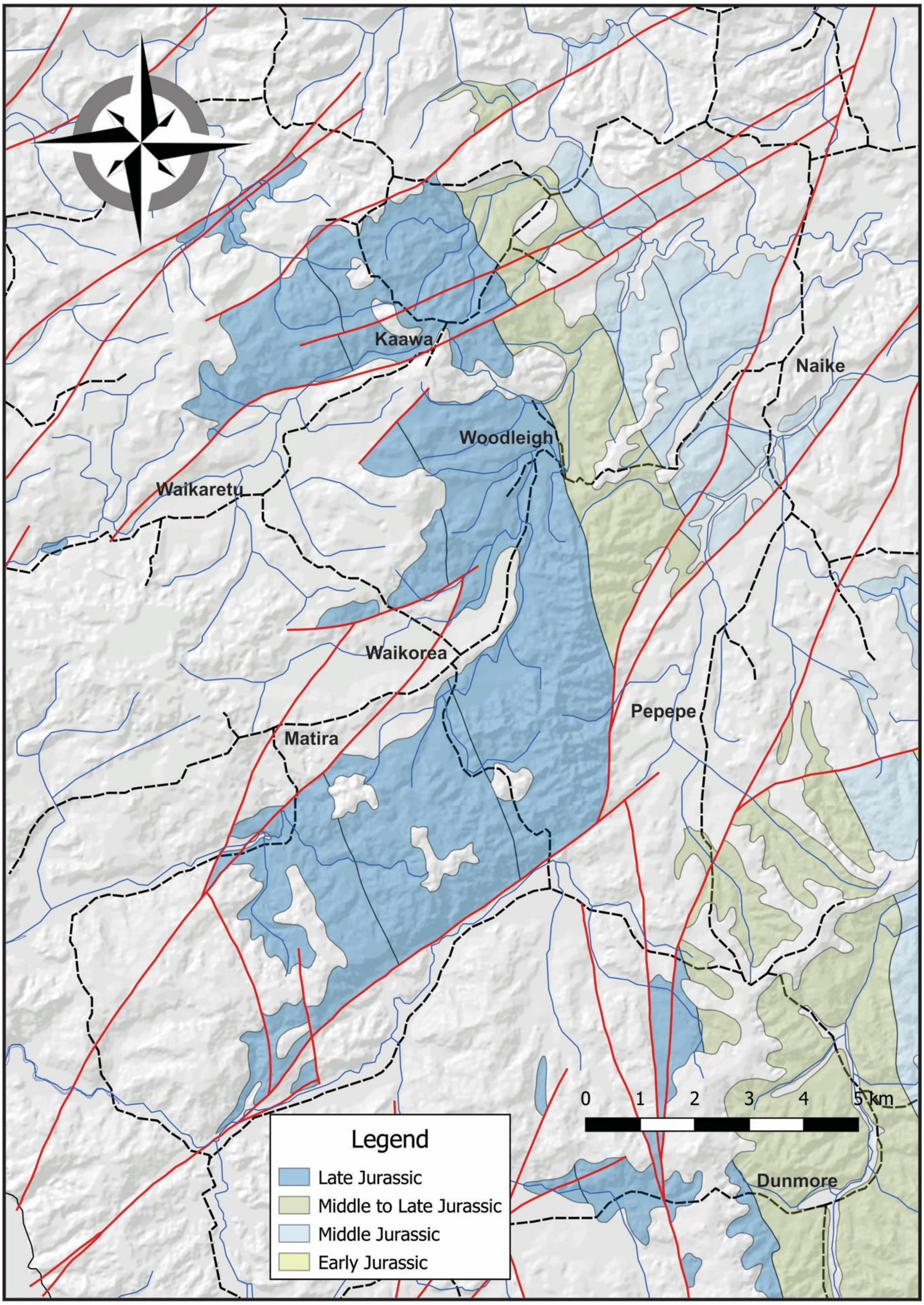

Fig 16: Day 6: Matira.

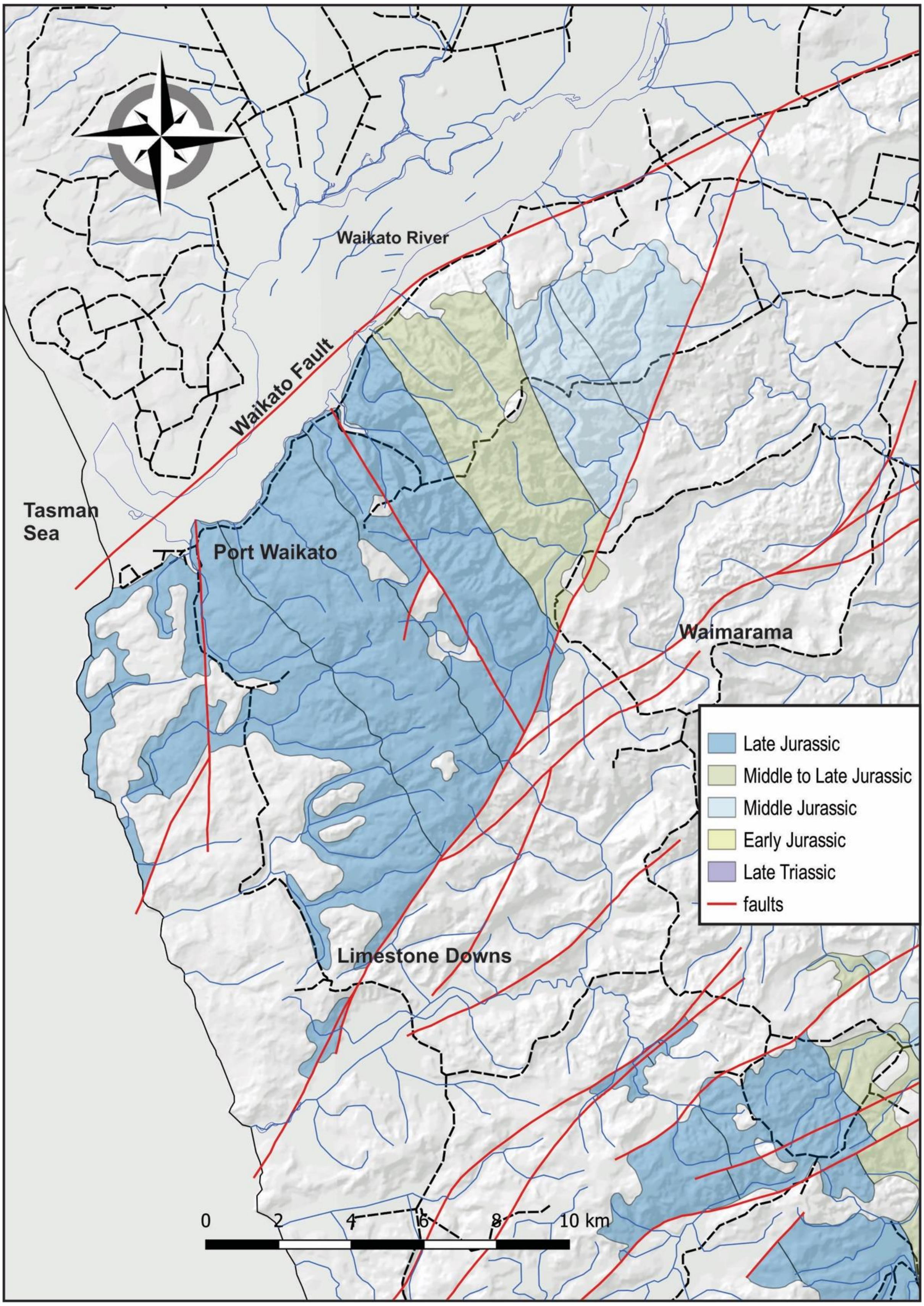

Fig 17: Day 6: Port Waikato.

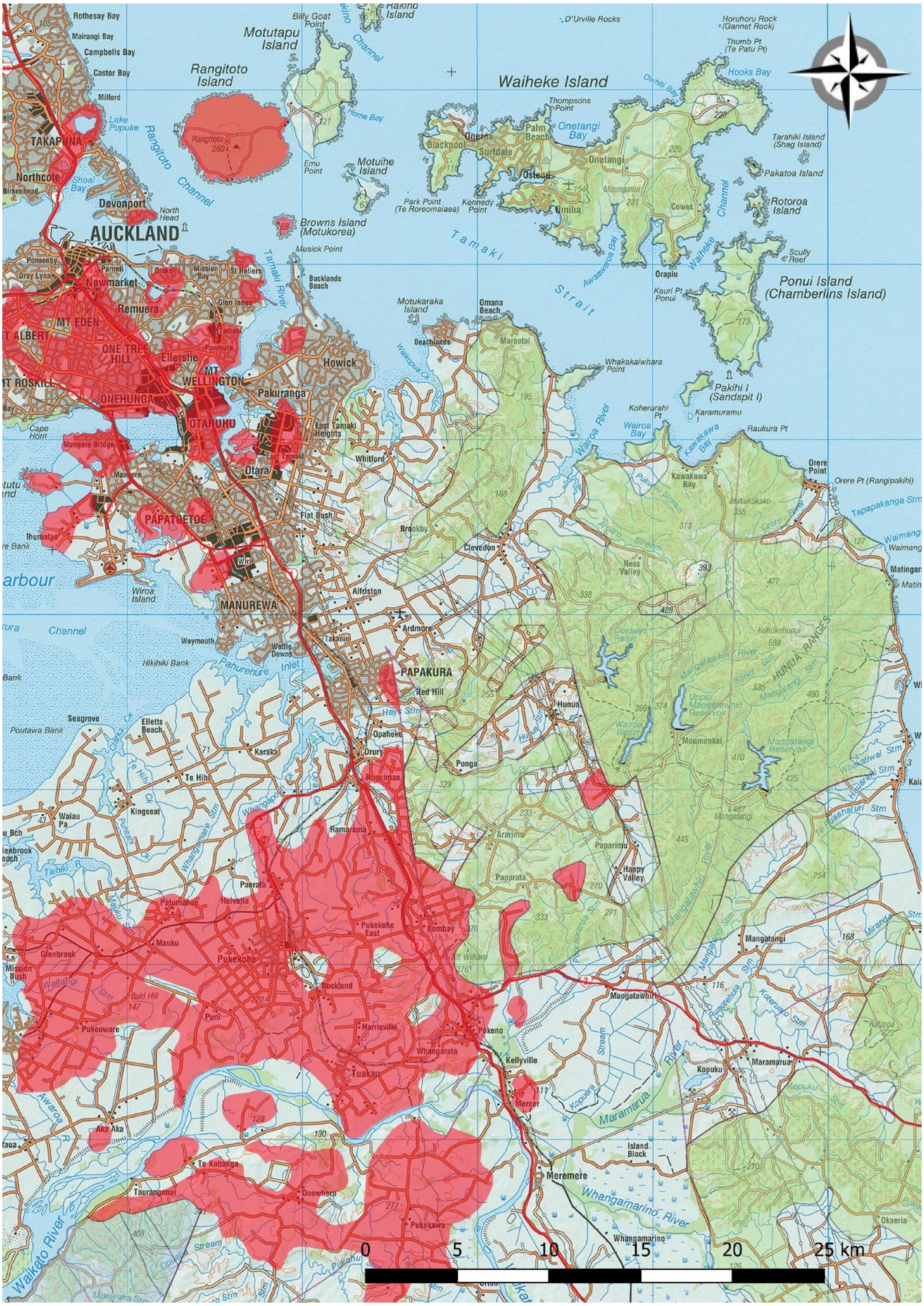

Fig 18: Day 7: Tuakau to Auckland. Triassic–Jurassic basement rocks shown include Waipapa Terrane (bright green) and Murihiku Terrane (dull green). Also shown are Pleistocene–Recent basaltic volcanics of the Auckland and South Auckland volcanic fields (red).

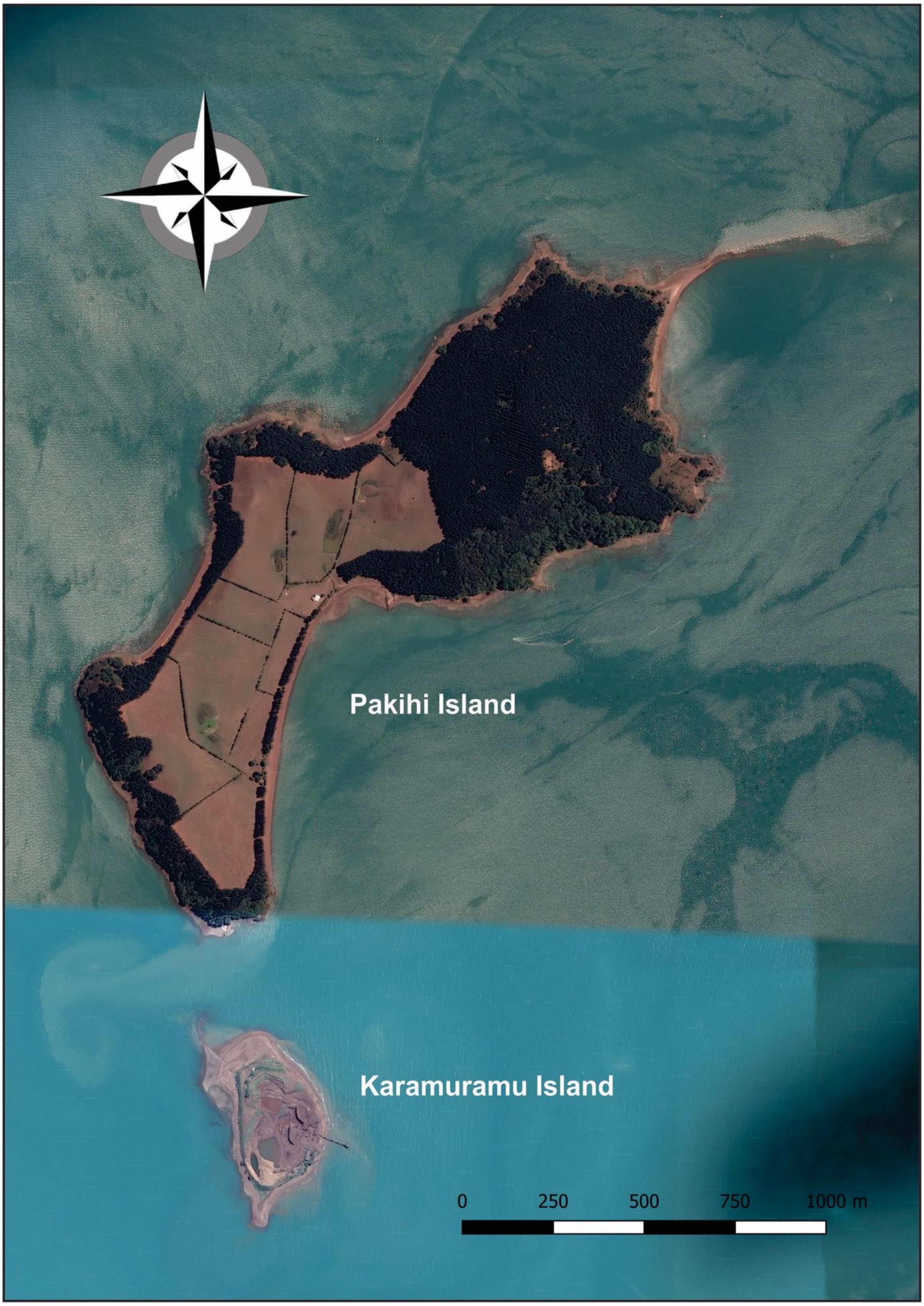

Fig 19: Day 7: Pakihi Island.