Field Trip Guide to Oligocene Limestones and Caves in the Waitomo District

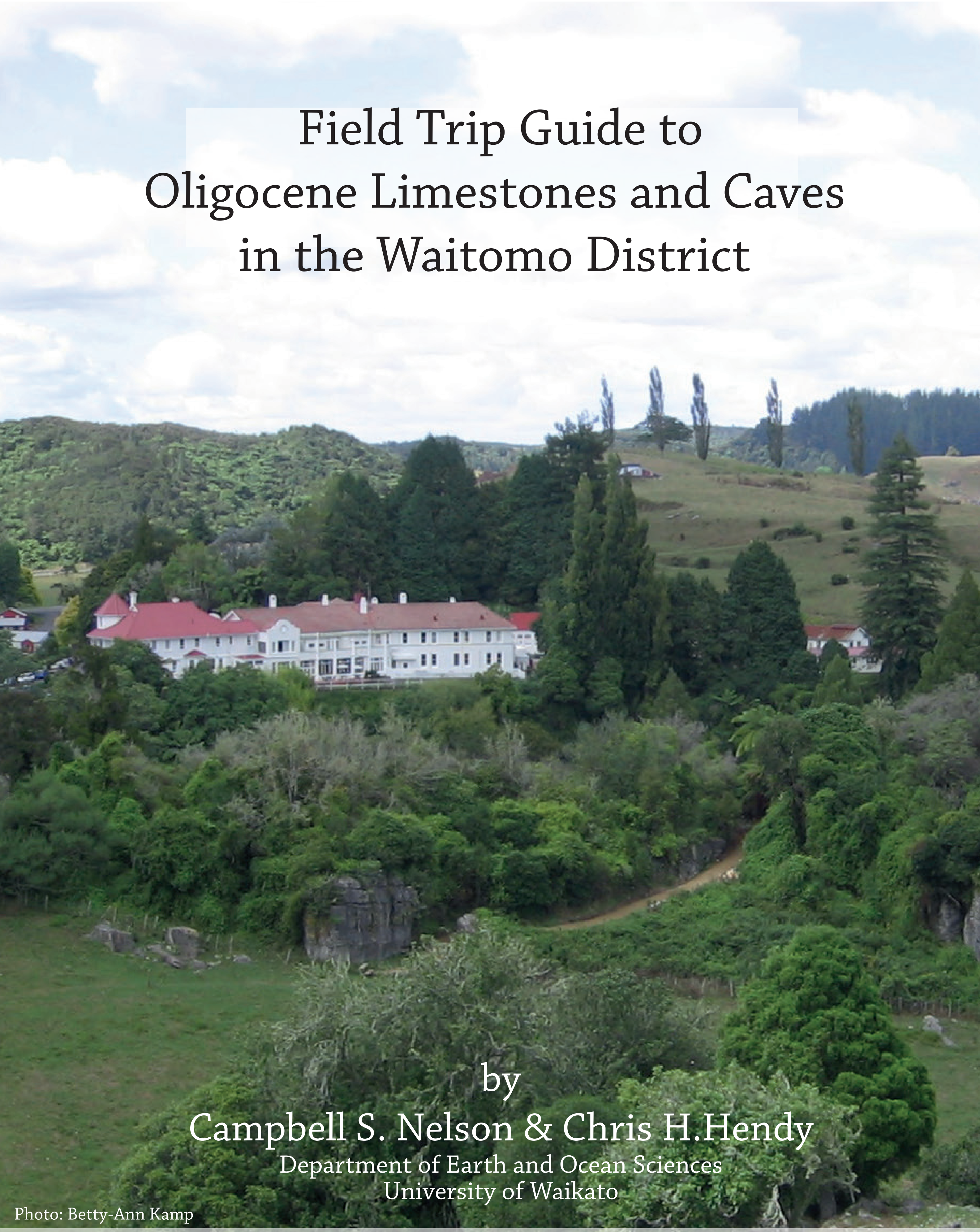

Photo: Betty-Ann Kamp

by

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Title **Field Trip Guide to Oligocene Limestones and Caves in the Waitomo District**

Operator

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Date 2013

Summary The field guide runs from Hamilton to Waitomo to Te Anga and return in limestone-dominated country developed in transgressive sedimentary deposits of the Oligocene Te Kuiti Group – a world class example of a temperate shelf carbonate depositional system. Attention focuses on the nature, distribution and paleoenvironmental controls of the main limestone facies and some of the mixed terrigenous-carbonate facies in the Group. Along the way features of the Waitomo karst landscape are noted and the trip concludes by going underground in the Ruakuri Cave to discuss cave origins and the evidence for paleoenvironmental changes locked up in speleothems.

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Frontispiece: *Karst landscape formed on Otorohanga Limestone west of Waitomo, with numerous sinkholes separated by irregular limestone ridges (Photo CN33080/11 taken by D.L. Homer as Fig. 11 in Edbrooke 2005).*

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1. HEALTH AND SAFETY

Certain hazards will be encountered on this field trip. General information is mentioned below and some more specific matters are given in Appendix 3.

Weather in summer is typically warm and sunny, occasionally wet, while conditions in winter are often cool, wet and/or windy. Sturdy, enclosed, shoes or boot-like footwear are required and eye protection (e.g. glasses or sunglasses) is desirable. A sunhat and sunscreen is recommended, as is a waterproof and/or windproof jacket. Participants must carry any personal medications for allergic reactions (e.g. insect stings, pollen or food allergies).

An average level of fitness and mobility is required for this trip. Participants must be surefooted enough to walk up to several hundred metres on farm or bush tracks, and be able to walk up and down moderately steep tracks and grassed hilly paddocks exposing rock outcrops. Underfoot conditions will include gravel or bush tracks, roadside curbs, grass slopes, wooden walkways and stepped rock outcrops.

Caution must be exercised when examining rocks at the base of roadside, natural or quarried cliffs and banks, due to the risk of rock fall from above and, in the case of road exposures, also from passing traffic. If you hammer rocks, wear eye protection and pay special heed to the safety of other participants. High-visibility vests and hard hats are essential at quarry and roadside stops. A hammer and hand lens are useful but not essential, but a camera to record your trip is!

2. FIELD TRIP SYNOPSIS

This geological report is an adaptation of one prepared for a one-day field trip in conjunction with the Annual Conference of the Geoscience Society of New Zealand held at the University of Waikato in Hamilton in late November 2012 (Nelson & Hendy 2012). The intention here is to make the field trip guide more readily accessible to a wider geosciences audience, including those in related georesources and petroleum and engineering industries.

The field trip runs from Hamilton to Waitomo to Te Anga and return in limestone country developed in transgressive sedimentary deposits of the Oligocene Te Kuiti Group – a world class example of a temperate shelf carbonate depositional system. Attention focuses on the nature, distribution and paleoenvironmental controls of the main limestone facies and some of the mixed terrigenous-carbonate facies in the Group. Along the way features of the Waitomo karst landscape features are noted and the trip concludes by going underground in the Ruakuri Cave to discuss cave origins and the evidence for paleoenvironmental changes locked up in speleothems.

3. ROUTE MAP

The route map and planned stops for the trip are shown on Fig. 1 (p. 3). The main stops, involving some time and walking, are at 2, 3, 6, 8, 9 and 12. The other stops are briefer ones and can be treated as optional depending on time. Grid references are approximate and based on the 1:50,000 NZ 260 Topomap Series, while equivalent newer Topo50 grid references are shown in italics.

4. FIELD TRIP STOPS

Hamilton to Te Awamutu to Otorohanga

The drive south affords excellent scenic views of the Hamilton Basin (or graben) landscape and the bounding horst blocks of uplifted Mesozoic basement rocks to the west (Hakarimata Range) and east (Cambridge hills and Rangitoto Range). The main Hamilton-Otorohanga highway (SH3) mainly follows the summit of a series of low hills developed on early to middle Pleistocene tephras and alluvium including the Hamilton Ash Formation, Kauroa Ash Formation, Karapiro Formation and Puketoka Formation. The flat surface surrounding the low hills is the Hinuera Surface, the maximum aggradational level of the ancestral braided Waikato River system during the late Pleistocene (c. 40-12 ka). The alluvial deposits, known as the Hinuera Formation, consist of profusely cross-bedded rhyolitic gravelly sands derived from active erosion and silicic volcanism in the Central Volcanic Region of North Island during the Last Glacial period. In the Holocene, extensive (now drained) peat swamps developed on poorly drained parts of the Hinuera Surface, including the Rukuhia Swamp west of the highway on leaving Hamilton and the Tuatuamoana Swamp east of the highway near Ohaupo.

STOP 1 - Gateway to Otuiti Lodge, south of Ohaupo (S15/136597; *BE33/034981*)

Overview of geomorphology and geology of Hamilton Basin and surrounds, noting some of the features mentioned above. Here, and nearer Te Awamutu, excellent views to the W-SW of the NW-SE aligned andesitic and basaltic composite cones of Karioi (756 m), Pirongia (959 m), Kakepuku (450 m) and Te Kawa (214 m), all part of the Alexandra Volcanic Group (2.74-1.6 Ma). To the east is the andesitic-dacitic cone of Maungatautiri (797 m; 1.8 Ma).

Otorohanga to Waitomo

At the south end of Otorohanga township turn west onto highway 31 (to Kawhia) and, soon after crossing the Waipa River, south into Waitomo Valley Rd. The road closely follows the trace of the Waitomo Fault that separates uplifted Mesozoic basement rocks capped by Oligocene Te Kuiti Group rocks forming the hills to the west from mudstones of the early Miocene (Otaian) Mahoenui Group to the east. Typically, up to several metres of yellow-brown weathered Quaternary tephra blankets all these deposits.

STOP 2 - Waitomo Valley Rd Quarry (S16/960294; *BE33/858677*)

Discussion points

1. *Regional lithostratigraphy of the Te Kuiti Group*
2. *Immediate geological succession and landscape (include faulting, basement relief, karst features)*
3. *Nature of formation contacts and facies*
4. *Depositional paleoenvironments*
5. *Flaggy limestone development*

Lithostratigraphy

Te Kuiti Group rocks crop out extensively in central western North Island from Waikato River mouth in the north to Awakino in the south (Fig. 2, p. 4). Due especially to considerable lateral variability

Fig. 1 Route guide and approximate locations of field trip stops.

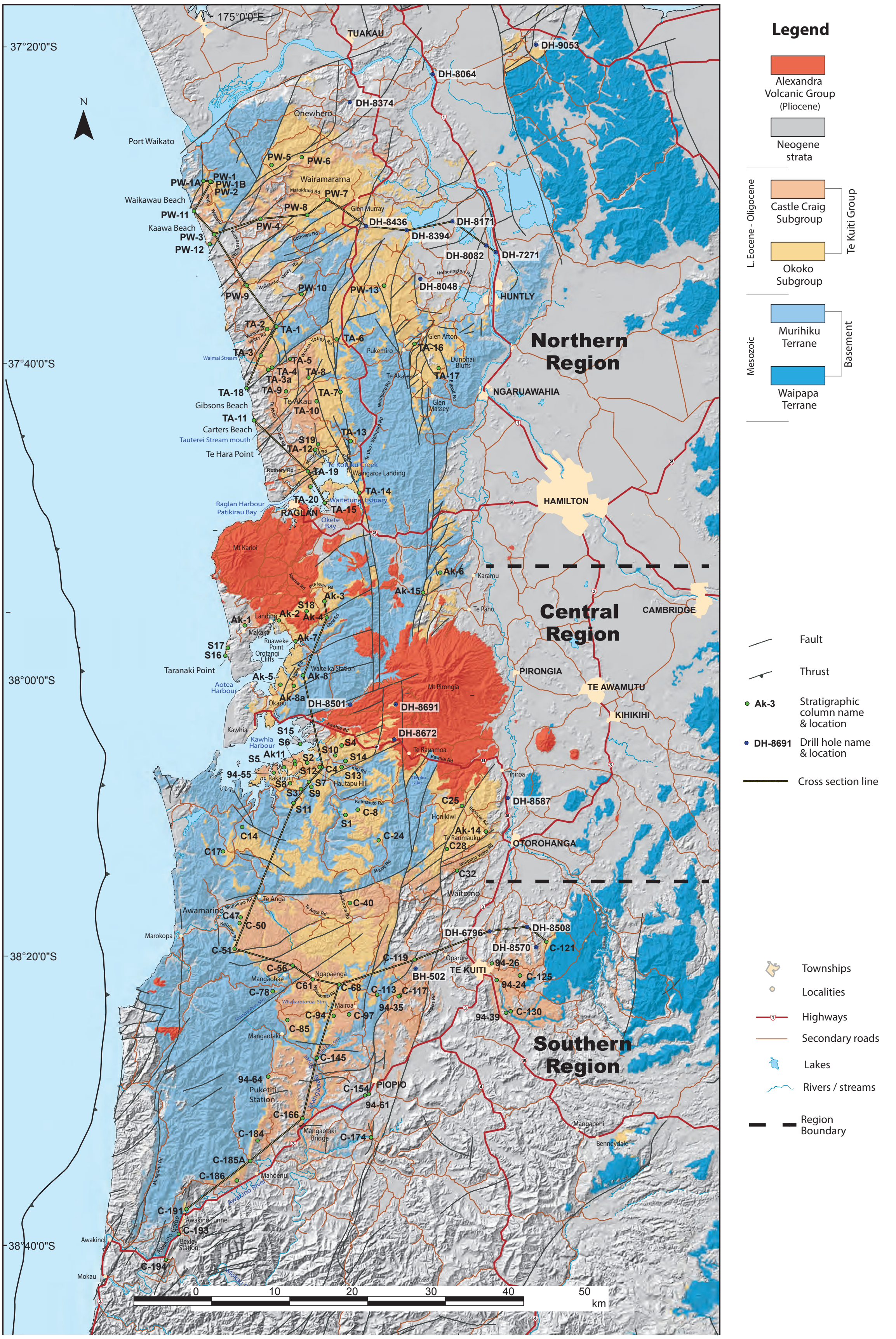

Fig. 2 Simplified map of the outcrop geology of central-western North Island between Port Waikato in the north and Awakino in the south showing the distribution of Mesozoic basement rocks (blue), Te Kuiti Group (Okoko and Castle Craig Subgroups, yellow-fawn colours) and Neogene and Quaternary strata (grey) and volcanics (red). Map from Kamp et al. (2008) after Edbrooke (2005).

in facies, the lithostratigraphic naming of the Oligocene rocks has had a long and rather confusing history, not yet fully resolved (e.g. Kear & Schofield 1959, Nelson 1978; White & Waterhouse 1993; Tripathi 2008; Kamp et al. 2008). A lithostratigraphic compilation by Tripathi (2008) for the full N-S outcrop extent of the Te Kuiti Group in central western North Island is shown in Fig. 3 (p. 6). The scheme recognises six major unconformity-bound depositional sequences (TK-1 to TK-6) and places the Te Kuiti Group within a suggested large-scale sequence stratigraphic framework (see also Dix & Nelson 2004). The limestone-dominated upper part of the Te Kuiti Group (TK-5 & -6) belongs in the Castle Craig Subgroup, with all underlying mixed carbonate-siliciclastic sediments and basal non-calcareous and coal measure deposits in the Okoko Subgroup (Tripathi 2008). For the limestone formations in the wider Waitomo region Nelson (1973, 1978) established also a finer stratigraphic subdivision involving members and beds (Table 1, below).

Bio/chronostratigraphy

The Te Kuiti Group rocks regionally range in age from late Eocene to earliest Miocene (Ab-Lw), but are mainly Oligocene (Lwh-Lw). Ages derive principally from foraminiferal bioevents (Fig. 4, p. 6), supported by some strontium isotope absolute dates (Nelson et al. 2004).

Table 1: *Lithostratigraphic subunits in the main Te Kuiti Group limestone formations (After Nelson 1978a).*

Subgroup	Formation	Member	Beds
Castle Craig (old Upper Te Kuiti)	Otorohanga Limestone (Ot)	Piopio Lst (OtC)	2. Argillaceous Limestone 1. Upper Flaggy Limestone
		Waitanguru Limestone (OtB)	3. Open Knobbly Limestone 2. Packed Knobbly Limestone 1. Blocky Limestone
		Pakeho Limestone (OtA)	3. Irregularly Seamed Limestone 2. Lower Flaggy Limestone 1. Basal
	Waitomo Sandstone (Wt)		
	Orahiri Limestone (Or)	Te Anga Limestone (OrB)	7. Coquinite 6. Limestone-in-Limestone 5. Fossil-hash 4. Massive Sandy Limestone 3. Semiknobbly Limestone 2. Oyster 1. Flaggy Limestone
		Mangaotaki Limestone (OrA)	6. Pebbly Micritic Limestone 5. Bimodally-Sandy Limestone 4. Upper Banded Sandstone 3. Massive Sandy Limestone 2. Glauconitic Limestone 1. Basal

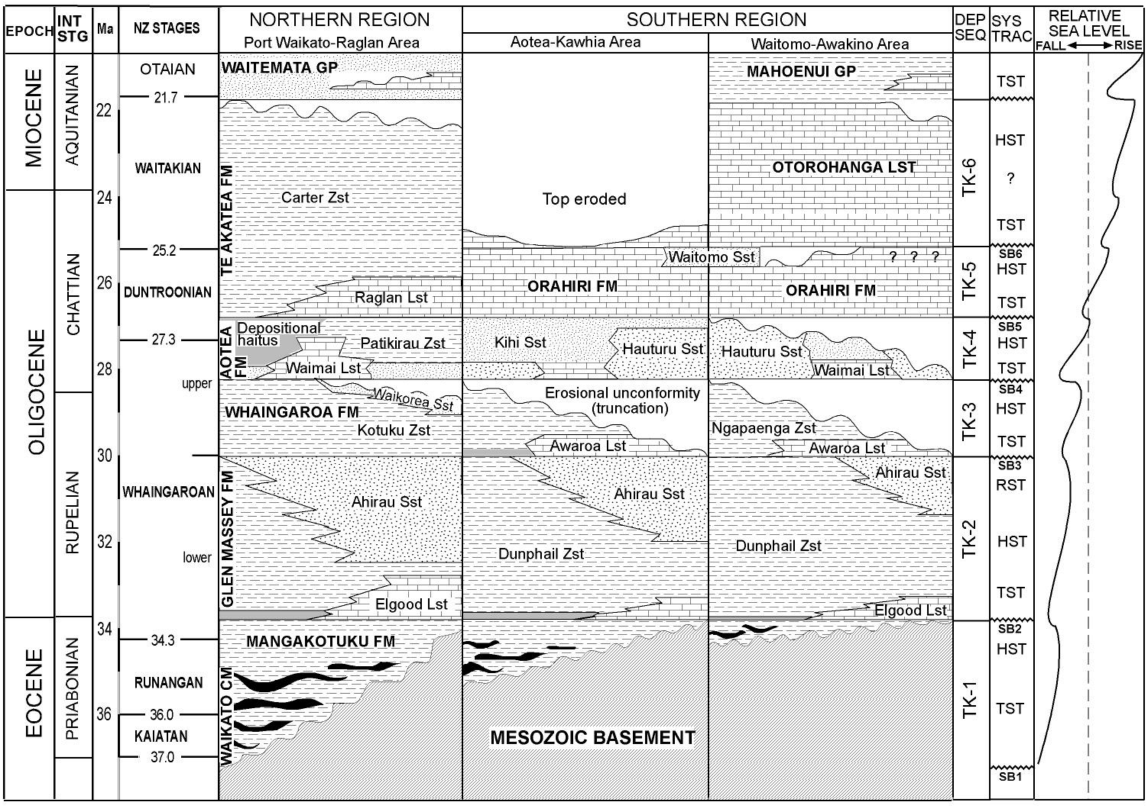

Fig. 3 *N-S lithostratigraphy of Te Kuiti Group formations and members. From Tripathi (2008).*

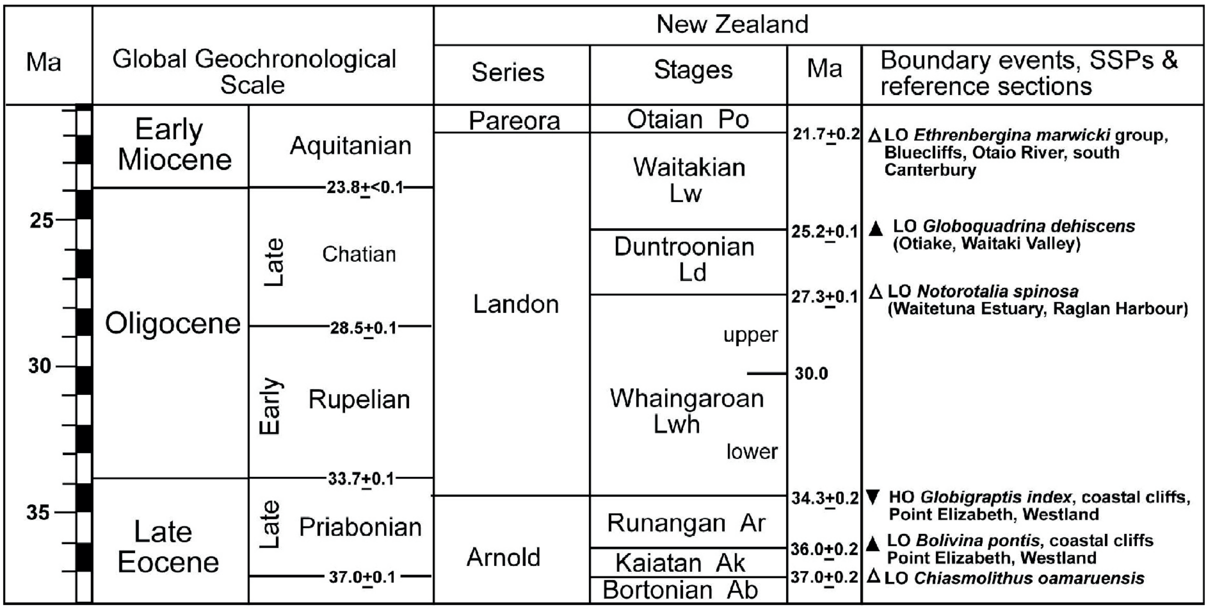

Fig. 4 *New Zealand Stages and boundary events for the Oligocene. From Cooper et al. (2004).*

Stratigraphic column

The stop introduces participants to the main Oligocene Te Kuiti Group formations in the immediate Waitomo area, these being from bottom to top the Aotea Formation, Orahiri Limestone/Formation, Waitomo Sandstone and Otorohanga Limestone. This now disused Waitomo Valley Rd quarry site is the type locality for the last three named formations (Nelson 1978). A stratigraphic column for the site (C32) is reproduced in Fig. 5 (p. 8-11), along with some photo images tied to the column (Kamp et al. 2008).

Facies characteristics for the various limestones and mixed carbonate-siliciclastic sandstones and siltstones in the Castle Craig Subgroup, along with possible paleoenvironmental interpretations, are noted in Appendix 1 (Kamp et al. 2008). The facies codes are recorded against the stratigraphic columns in the field guide.

Geomorphic expression

Where fully developed, the succession of formations in the Te Kuiti Group typically crop out with a characteristic geomorphic expression, related to carbonate content (Table 2, below), well seen here at Waitomo Valley Rd. The high carbonate (70-100%) limestones form steep and stepped or vertical faces with excellent exposure, while the moderate carbonate (40-60%) calcareous muddy sandstones and mudstones erode to give more subdued sloping grass or bush covered topography with mainly sporadic outcrop (e.g. image 7 in Fig. 5D, p. 11).

Limestone composition

Compositional aspects of the Te Kuiti Group rocks are fully described in the theses of Nelson (1973) and Tripathi (2008), and summary information is provided by Nelson & Hume (1987). The carbonate fraction is dominated by the fragmental remains of a wide variety of invertebrate skeletons, principally bryozoans, echinoderms, foraminifera (benthic and planktic), and epifaunal bivalve molluscs, but also infaunal bivalves, calcareous red algae, brachiopods, and serpulids (Nelson 1973; Nelson et al. 1988b; Hayton et al. 1995). Overall, whole fossils are rare (Nelson 1978). Siliciclastic material includes quartz, plagioclase and potash feldspar, volcanic and sedimentary rock fragments, and clay minerals (smectite, chlorite, illite, and kaolinite). Pelletal glauconite is ubiquitous, sometimes abundant, and rare limonitised pyrite spheres occur. The rocks are strongly cemented most commonly by granular and syntaxial rim calcite spar or microspar, and locally by micrite (very fine-grained calcite). Except for local marine cemented horizons associated with some unconformities or persistent high energy current conditions (Nelson & James 2000), the cements are mainly of burial origin as evidenced from the widespread development of pressure-dissolution features in the limestones, such as dissolution seams, stylolites, and microstylolites, so that rock fabrics are tight and rock porosity values are very low or zero (Nelson et al. 1988a; Hood & Nelson 1996).

Table 2: *Average calcium carbonate-siliciclastic sand-siliciclastic mud contents for some of the Te Kuiti Group formations (From Nelson 1973).*

Formation	**%$CaCO_3$**	**% Siliciclastic sand**	**% Siliciclastic mud**
Otorohanga Lst	91.0	3.7	5.3
Waitomo Sst	46.6	37.2	16.2
Orahiri Limestone	76.2	18.5	5.3
Aotea Fm (Sst)	44.7	43.3	12.0
Whaingaroa/Glen Massey Fm (Zst)	54.1	9.6	36.3

Stratigraphic Column No: *C32* **Grid Reference:**

Region: King Country/Waitomo

Location: Abandoned limestone quarry, northeast of Waitomo

E: 2696320 - 2696142

N: 6329200 - 6329388

NZMS 1 Sheet: S16

Page 1 *of* 2 **Author:** C. Nelson

Modified: A. Tripathi

NZMS 260 S16

C-32

1 of 4

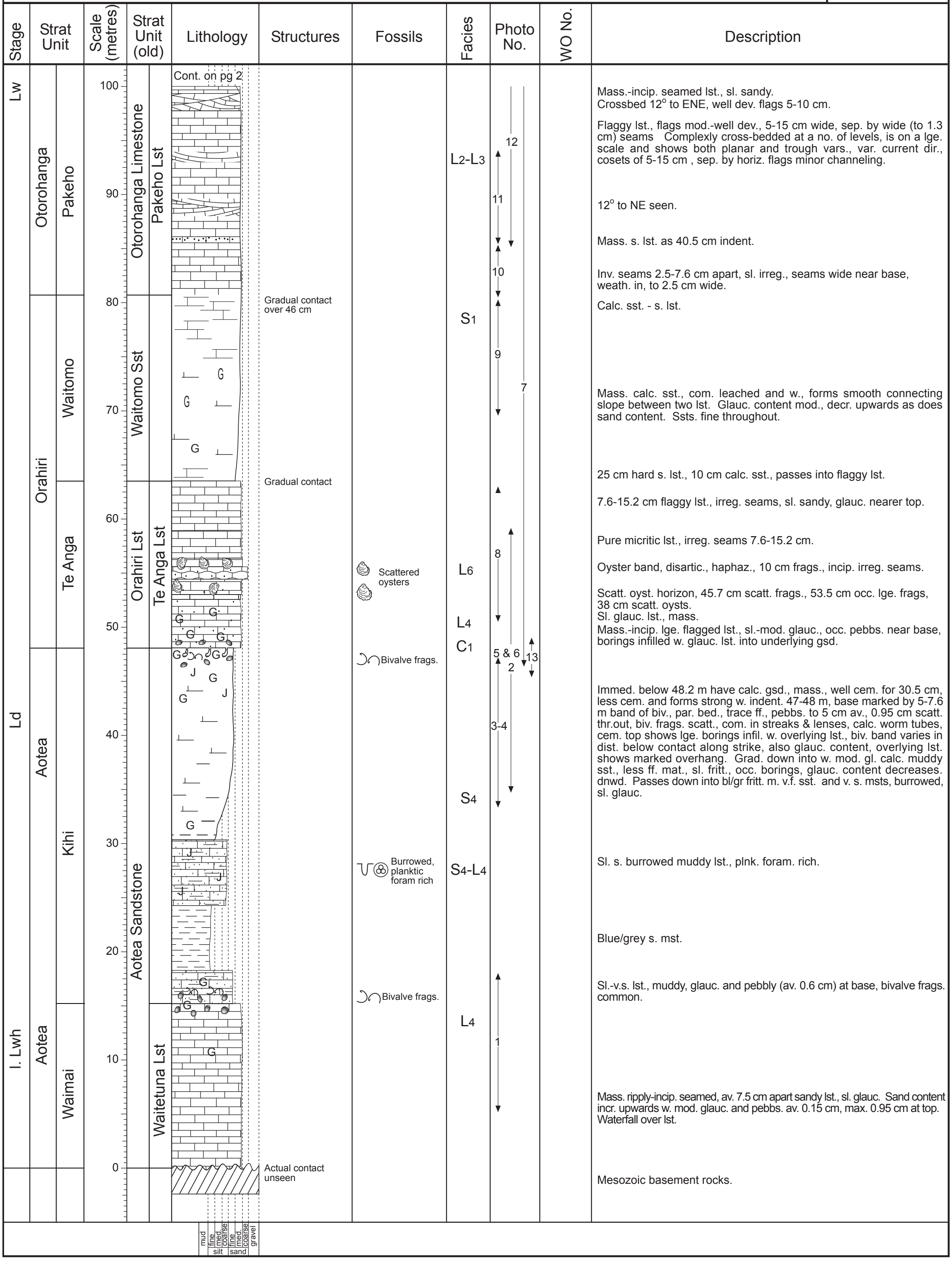

Fig. 5A Stratigraphic column C32, Waitomo Valley Rd. Facies codes are defined in Appendix 1. Photo numbers refer to those shown in Figs. 5B, C and D (From Kamp et al. 2008).

Stratigraphic Column No: *C32* ***Grid Reference:***

Region: King Country/Waitomo

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E: 2696320 - 2696142

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Page 2 *of* 2

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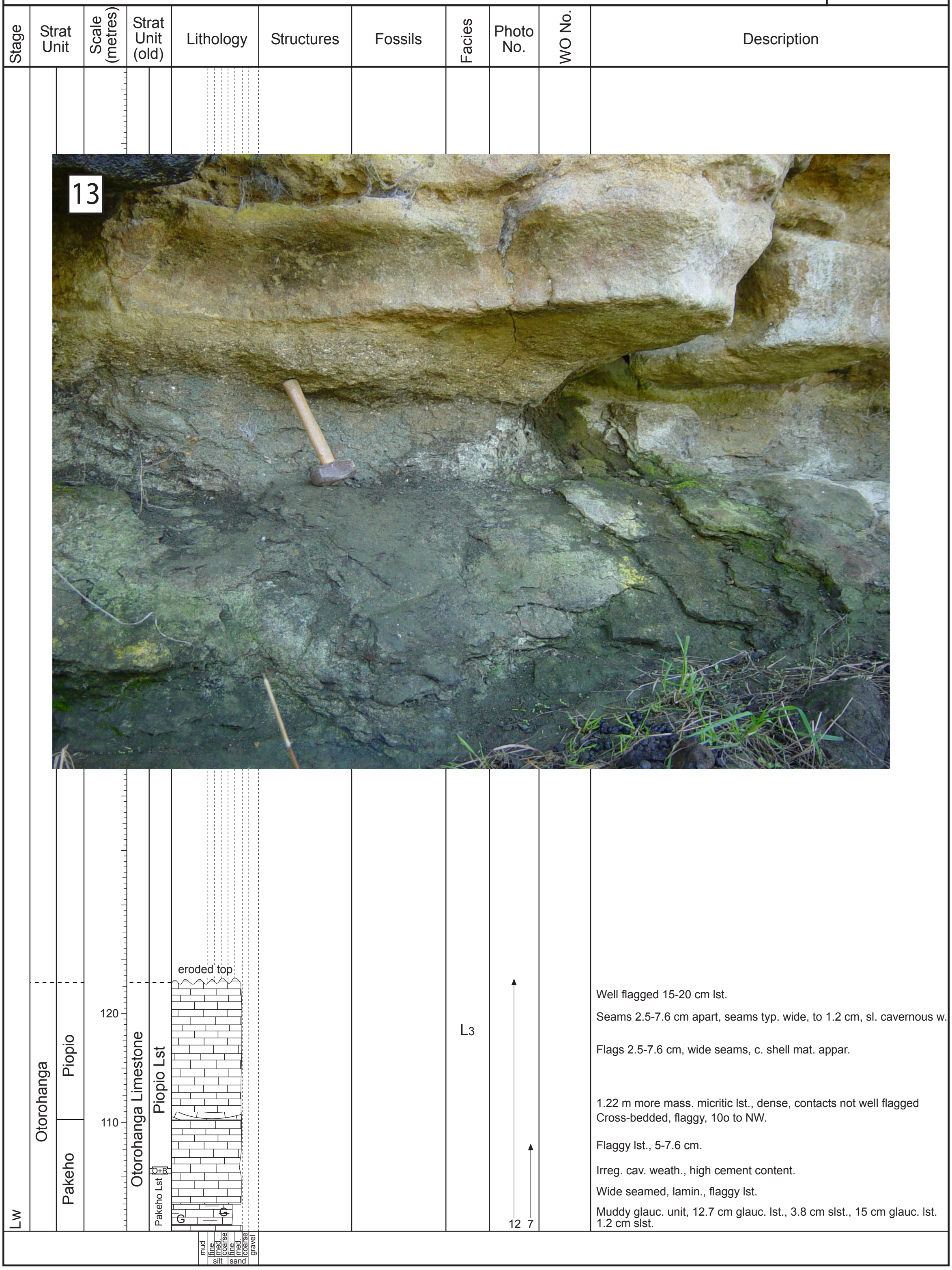

Fig. 5B *Stratigraphic column and field photo of locations at C32 identified on Fig. 5A.*

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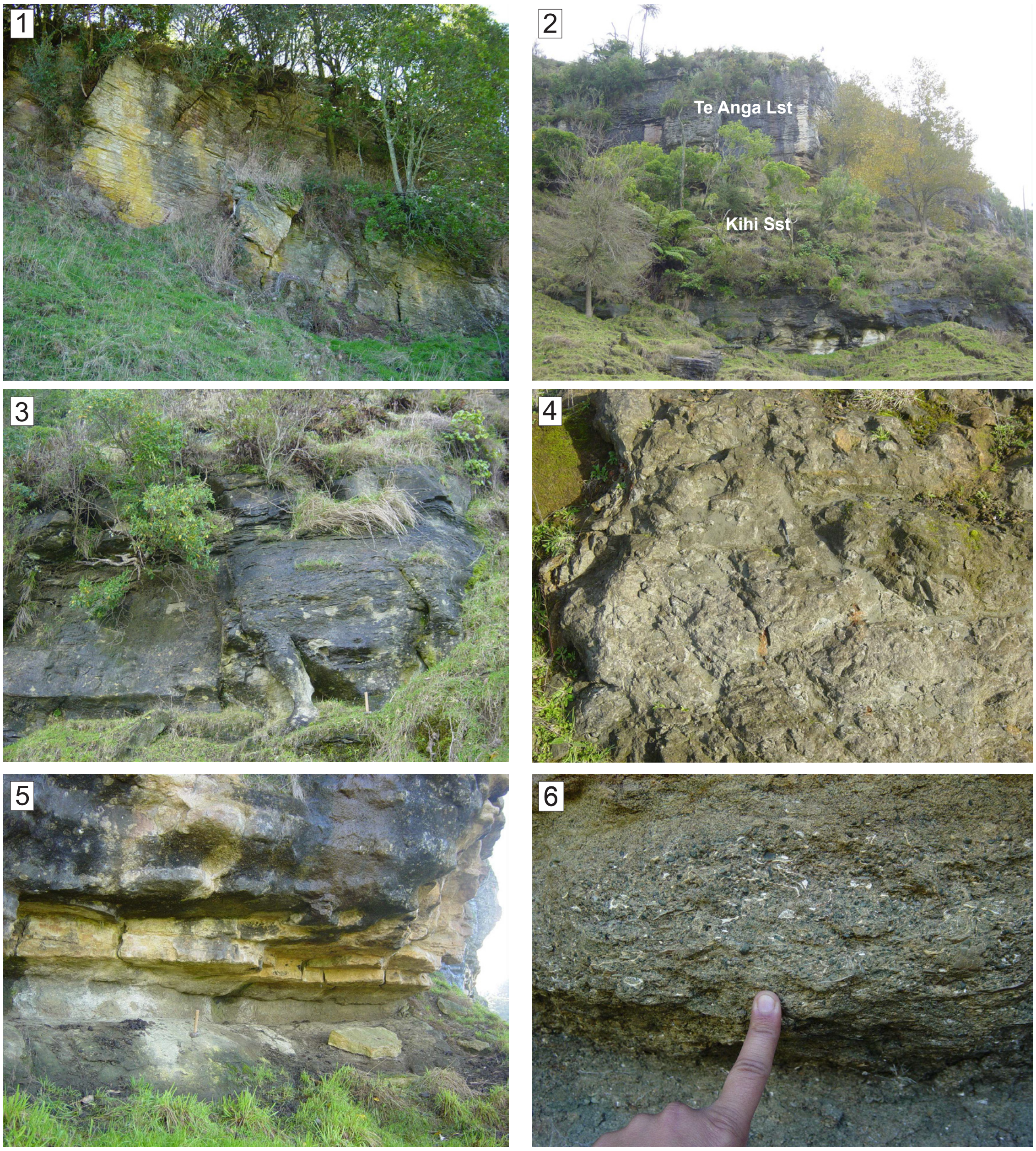

Fig. 5C *Field photos of locations at C32 identified on Fig. 5A.*

Fig. 5D *Field photos of locations at C32 identified on Fig. 5A.*

Using Folk's (1962) petrographic classification for carbonate rocks the Te Kuiti limestones are biosparites and biosparudites, less commonly biomicrites and biomicrudites, while Dunham's (1962) scheme would have them as predominantly skeletal grainstones and rudstones, or occasionally packstones (Fig. 6, p. 13).

Nontropical (or temperate or cool-water) limestones

The birthplace of shallow-water or platform limestones has traditionally been regarded to be in the warm shallow seas of tropical regions (Table 3A, p. 14). However, we now know that modern shelf carbonate sediments can also be widespread in cool to cold waters beyond the tropics, and there is growing awareness that extensive tracts of shelf limestones in the geological record probably also originated in cool waters at more temperate latitudes (Nelson 1988a). The paleoenvironmental interpretation of shelf carbonate rocks is consequently not always so straightforward, and the geologist requires criteria that can help distinguish this broad spectrum of carbonate facies types.

Despite the tectonically active setting of New Zealand, presently at 35-45°S latitude, modern cool-water skeletal carbonates are common on those shelf sectors where terrigenous sediment supply is low (Table 3B, p. 14). Moreover, skeletal limestones that are fossil analogues of the modern deposits are widespread at times during the Tertiary, when the New Zealand subcontinent was drifting northwards (60-40°S paleolatitudes) out of the Southern Ocean, away from Antarctica (Nelson 1978b). The carbonate facies in the Oligocene Te Kuiti Group exemplify all the characteristics of such a nontropical or temperate or cool-water shelf carbonate regime (Nelson 1973; Anastas et al. 1997, 2006; Tripathi 2008), as do all NZ occurrences of Tertiary age limestones (Nelson 1978b; Table 3C, p. 14).

STOP 3 - Overview of Waitomo Caves area (S16/943249; *BF33/841632*)

Travel south to end of Waitomo Valley Rd and right into major Waitomo Caves Rd (highway 37) that enters Waitomo village. Just after the Waitomo Caves entrance way, park on the right (north) side of road behind the Glowworm Caves portacom building. Toilets are available across the road at the Waitomo Caves reception area. We will climb the hill (Owner C. Dimond) adjacent to the car park up through the Otorohanga Limestone, noting its outcrop characteristics at close quarters. At the summit, discuss features of the surrounding landscape, including larger scale controls on karst development. Note that the major N-S trending Waipa Fault which separates Murihiku and Waipapa Terrane rocks in western North Island, lies just to east of this locality (Fig. 2, p. 4).

STOP 4 - Ahuroa Ignimbrite (S16/918251; *BF33/816634*)

Continue west along Waitomo-Te Anga Rd where road climbs up though poorly exposed slope mudstone of the Early Miocene Mahoenui Group (Taumatamaire Formation, Otaian (Po) age) that everywhere overlies the Otorohanga Limestone in the wider Waitomo area. Above the Mahoenui Group are occasional road side outcrops Mokau Group shelf muddy sandstones and mudstones, in places laminated, carbonaceous, jarositic and fossiliferous, of Early Miocene age (Altonian, Pl). Note the implied major tectonic shifts in relative sea level between the Te Kuiti, Mahoenui and Mokau Group deposits.

Brief roadside stop to view Ahuroa Ignimbrite (1.18 Ma), one of several old (1.68-1.00 Ma) Pakaumanu Group ignimbrites that are widespread in the King Country, sourced from the Mangakino caldera, 50 km distant from here (Edbrooke 2005). The Ahuroa Ignimbrite is a partially welded ignimbrite with inverse thermal zonation that is characterised by development of columnar jointing throughout much of its thickness, includes conspicuous flattened pumice clasts (weathered lenticulite of Marwick 1946), and can have a prominent bedded airfall ash deposit named Unit D

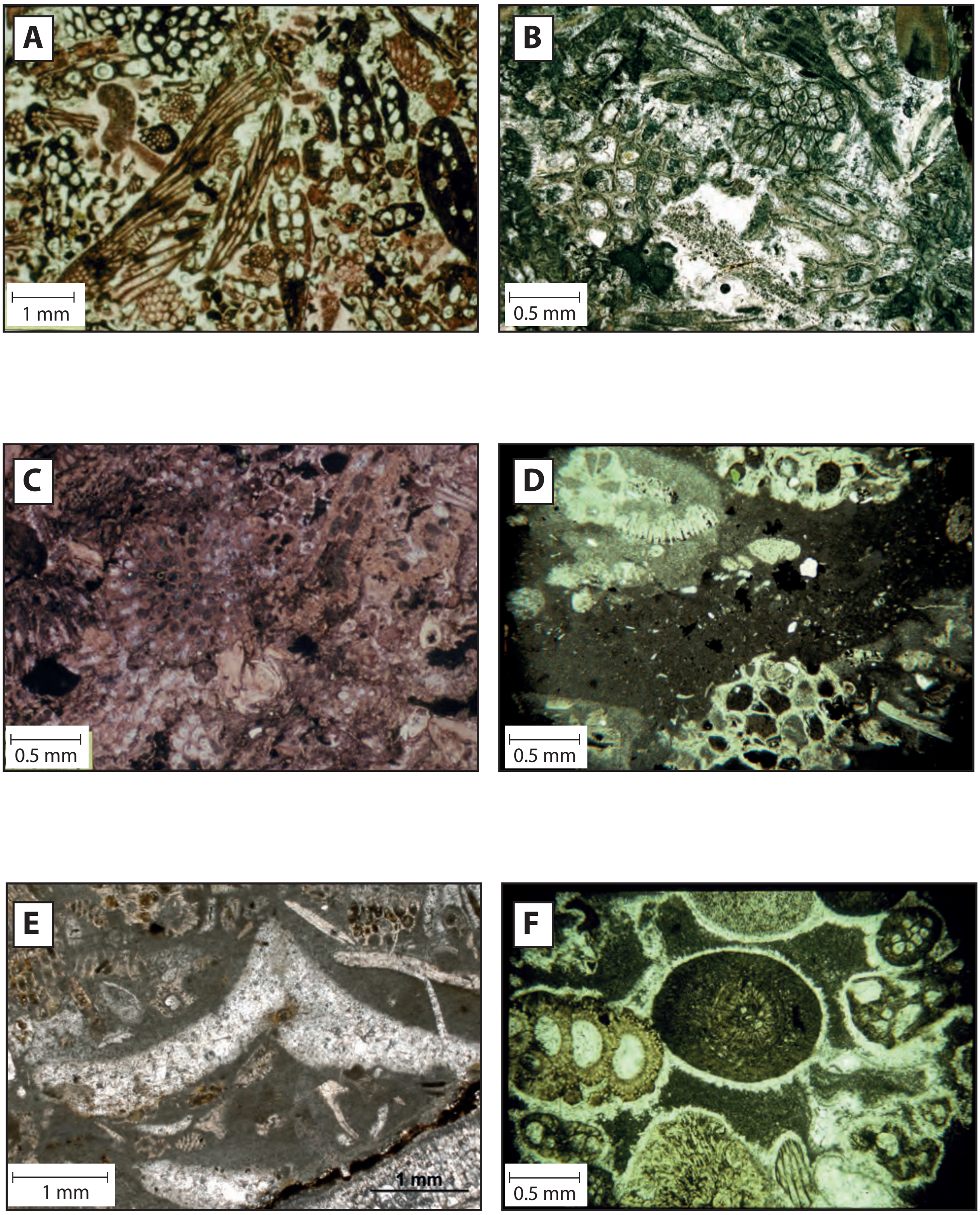

Fig. 6 *Photomicrograph examples from Otorohanga (A-C) and Orahiri (D-F) Limestones. Dominant types in both limestones resemble images B & C (bryozoan biosparites/grainstones), having moderately to tightly pressolved fabrics. Open fabric bryozoan biosparite/grainstone in A. D & E have micritic matrices (biomicrites/packstones) typical of many of the oyster-bearing units. Spar filled biomolds of former aragonite bivalve fragments evident in E, although never in the more widespread biosparites (e.g. A, B, C). Spar cement fringes evident in F, followed by infiltered detrital micrite, a "marine cement" fabric evident in some units associated with unconformities and high energy.*

Table 3: *Comparison of tropical shelf carbonate model (A) with New Zealand modern (B) and Cenozoic (C) carbonate deposits (Adapted from Nelson 1978b, 1988b).*

Environmental or facies parameter	A. Tropical shelf carbonate model	B. New Zealand modern shelf carbonates	C. New Zealand Cenozoic shelf limestones
Latitude	From 30°S to 30°N	From 49°S to 33°S	From 60°S to 35°S
Depositional setting	Shallow rimmed shelves and platforms	Deeper open shelves, ramps and platforms	Open shelves, platforms and seaways
Marine climate zone	Tropical-warm subtropical	Warm-cool temperate	Warm-cool temperate
Sea-water temp. (mean)	Above 23°C	13-19°C	Below 20°C
Sea-water temp. (min.)	About 14°C	9-12°C	About 5°C
Sea-water salinity	Normal-hypersaline	Normal	Normal
$CaCO_3$ saturation at/in sea bed	Highly supersaturated	Mildly supersaturated to ?locally undersaturated	Infer mild supersaturation to local undersaturation
Water circulation	Restricted-open	Open, strongly storm- and tide-dominated	Open, storm- and tide-dom. shelves/seaways
Tectonic regime	Stable, slow subsidence	Stable-unstable	Stable-unstable
Shelf gradient	<0.5 m/km	0.25-2 m/km	>0.5 m/km
Reef structures	Common (especially coral/ coralgal)	None (some oyster banks)	Rare (oyster banks; bryozoan mounds)
Sedimentation rates	10-1000+ cm/ky	1-15 cm/ky, often relict	<5 cm/ky, many diastems
$CaCO_3$ content	>90%	50-100%	50-100%
Siliciclastic grains	Rare	Rare-abundant	Rare-abundant
Glauconite	Rare	Common, especially in skeletal chambers	Common, pelletal and in skeletal chambers
Dolomite and evaporite minerals	Common-rare	Absent	Absent (locally rare late diagenetic dolomite)
Non-skeletal carbonate grains (e.g. ooids, pellets)	Common-abundant	Absent	Absent
Major skeletal grain types	Calcareous green algae Corals (hermatypic) Benthic foraminifera Molluscs generally Coralline algae	Bryozoans Molluscs, mainly bivalves Forams, mainly benthic Echinodems Barnacles Coralline algae Serpulids Brachiopods Corals (ahermatypic) Sponges	Bryozoans Molluscs (epifaunal bivs.) Forams, mainly benthic Echinoderms Barnacles Coralline algae Brachiopods
Main skeletal assemblages (Hayton et al. 1995 Sed. Geol. 100: 123-141)	Chlorozoan Chloralgal	Bryomol Bimol (Nannofor)	Bryomol, Echinofor Barnamol, Rhodechfor Bimol (Nannofor)
Algal mats/stromatolites	Common	Absent (or not preserved)	Absent
Overall diagenetic regime	Constructive	Destructive	Destructive
Carbonate mud	Common-abundant	Absent-rare, flushed and by-passed offshore	Absent-rare, locally as matrix, increases offshore
Main origins of carbonate mud	Disintegration calc. green algae and inorganic pptn.	Physical abrasion, bioeros. & maceration of skeletons	Skeletal abrasion and bio-erosion; nannofossils
Primary sediment mineralogy	Aragonite > HMC > IMC > LMC	LMC+IMC > HMC ≥ aragonite	LMC+IMC > HMC ≥ aragonite
Main envir. of alteration of metastable carb. grains	Subaerial/meteoric	Beginning submarine	Submarine to shallow burial, rarely subaerial
Environment of major lithification	Submarine and subaerial/ meteoric	Unlithified	Subsurface burial, rarely subaerial/meteoric
Timing of cementation	Mainly early diagenetic	-	Rarely early, mainly later diagenetic
Major carbonate cements	Aragonite and HMC	-	Rare IMC, mainly LMC (often ferroan)
Major sources of cements	Sea water and dissolution of aragonite grains	-	Pressure-dissolution of calcitic skeletons
Carbonate petrography	Mud-, wacke-, pack-, rud-, grain- and boundstones	Grain- and rudstones	Grain-, pack- and rudstones

(1.2 Ma) at its base from a large-scale phreatomagmatic eruption. Other pyroclastic flow deposits in the Pakaumanu Group include the Ngaroma (1.55 Ma), Ongatiti (1.21 Ma), and Rocky Hill (1.00 Ma) ignimbrites.

STOP 5 - View thin Waitomo Sandstone (R16/860234; *BF32/758617*)

Continue west along Te Anga Rd and pause only in vans on roadside about 1 km west of Waipuna Rd to observe a small cliff face (part of now overgrown Mac's Quarry) exposing the Orahiri Limestone (some oysters visible), Waitomo Sandstone (bushed "ledge") and basal beds of the Otorohanga Limestone. In particular, note that the Waitomo Sandstone has thinned considerably (c. 1 m) from Stop 2 on Waitomo Valley Rd, which is only about 10 km away to the NE. South and west from here the Waitomo Sandstone rapidly thins into a prominent disconformity between the Orahiri and Otorohanga limestones (Fig. 7, p. 16).

STOP 6 - Orahiri Limestone at Kokakoroa Rd (R16/819242; *BF32/717625*)

Continue west along Te Anga Rd to Kokakoroa Rd where turn north (right). Travel about 2 km to Gate 183 (Owners D & T Townsend), where enter and drive up hill to presently disused farm house and beyond onto air field. This is a possible lunch and toilet stop. Weather permitting, drive southwards across paddock towards hillock with trig that exposes Aotea Sandstone at the base, a full thickness of Orahiri Limestone with prominent oyster beds (Fig. 8, p. 16) and some pebbly horizons (Fig. 9, p. 16), and some Otorohanga Limestone at the top. Column C40, from nearby this locality, portrays the general stratigraphic succession, along with some field images tied to the column (Fig. 10, p. 17-19).

Field trip participants can explore at their leisure as much of the outcrop as they feel comfortable to undertake. The main aim is to observe the Orahiri Limestone at close quarters and to make some comparisons with what was seen at earlier stops for the overlying Otorohanga Limestone. Some W-E cross sections through the Te Kuiti Group are shown in Fig. 11 (p. 20) which demonstrate that Oyster Bed (OrB2) development in the Orahiri Limestone in the Oligocene (Ld) was thickest in the vicinity of C40 (see also Fig. 12, p. 21).

STOP 7 - Te Kuiti Group on basement (R16/786235; *BF32/684618)*

Return to Te Anga Rd and continue west. Most of the immediate country along this stretch of road is in Okoko (or Lower Te Kuiti) Subgroup rocks, namely calcareous sandstones (Hauturu Sandstone of Aotea Fm) and calcareous mudstones (Dunphail/Ngapaenga Siltstone of Glen Massey/Whaingaroa Fm) (Fig. 3, p. 6). Local limestone can occur at the base of each of these formations (Fig. 3, p. 6). Note that intensive leaching of the calcite cement from the Hauturu Sandstone leads first to hard residual sandstone slabs in a soft sandstone "matrix" (referred to as Banded Sandstone Beds (Ao-5) by Nelson 1978) and ultimately into a soft friable sand otherwise appearing like "Quaternary sands".

Park at roadside area immediately beyond Marae Rd. Walk single file for about 200 m along south (left) side of Te Anga Rd observing the occasional roadside outcrops. In particular, note the nature of the Mesozoic basement rocks (here Late Jurassic; Ko – Ohauan, *Inoceramus haasti*) and the basal facies of the onlapping Te Kuiti Group (= C42 of Nelson 1977).

STOP 8 - Mangapohue Natural Bridge (R16/763253; *BF32/661636*)

Continue west along Te Anga Rd and stop at Mangapohue Natural Bridge Scenic Reserve car park. Toilet within reserve. A clockwise loop walk initially follows the Mangapohue Stream (which

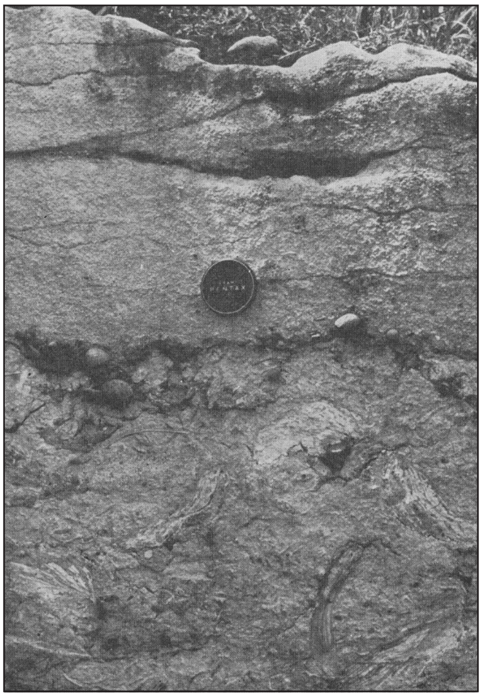

Fig. 7 *Sharp disconformable contact between pebbly and macrofossil-rich Orahiri Limestone (below) and flaggy Otorohanga Limestone (above) at Ngapaenga, south of Waitomo.*

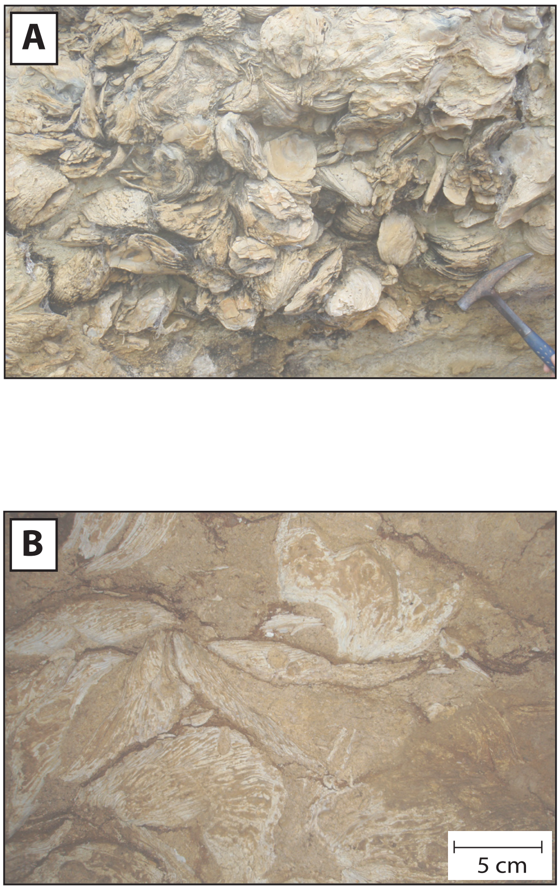

Fig. 8 *Packed and haphazardly oriented giant oyster valves (A) and shell borings (B) in Oyster Bed facies (OrB2) of the Orahiri Limestone, Waitomo.*

Fig. 9 *Pebble band separating the Mangaotaki and Te Anga Limestone Members of the Orahiri Limestone (Table 1) at Ngapaenga, south of Waitomo.*

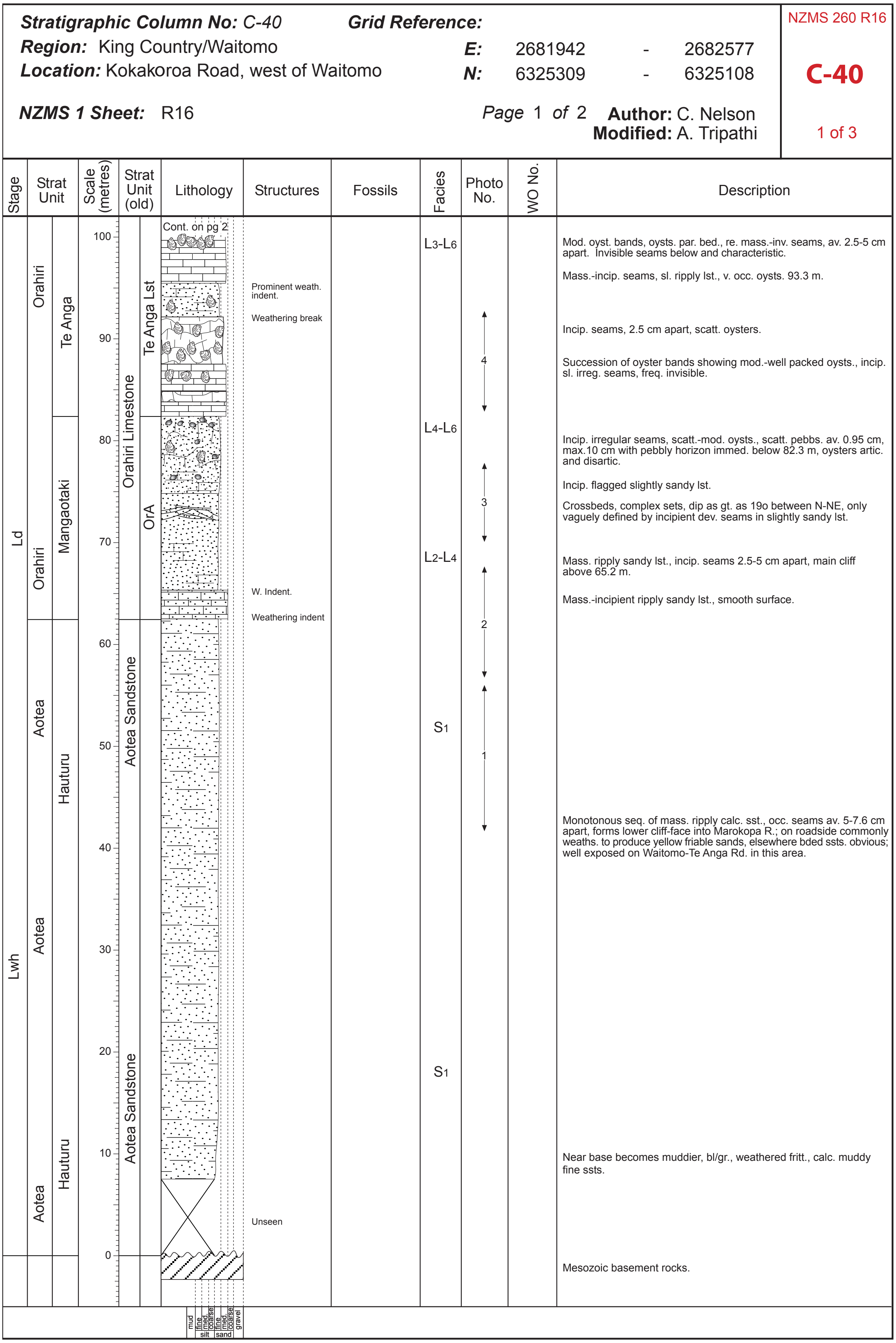

Fig. 10A Stratigraphic column C40, Kokakoroa Rd. Facies codes are defined in Appendix 1. Photo numbers refer to those shown in Fig. 10C (From Kamp et al. 2008).

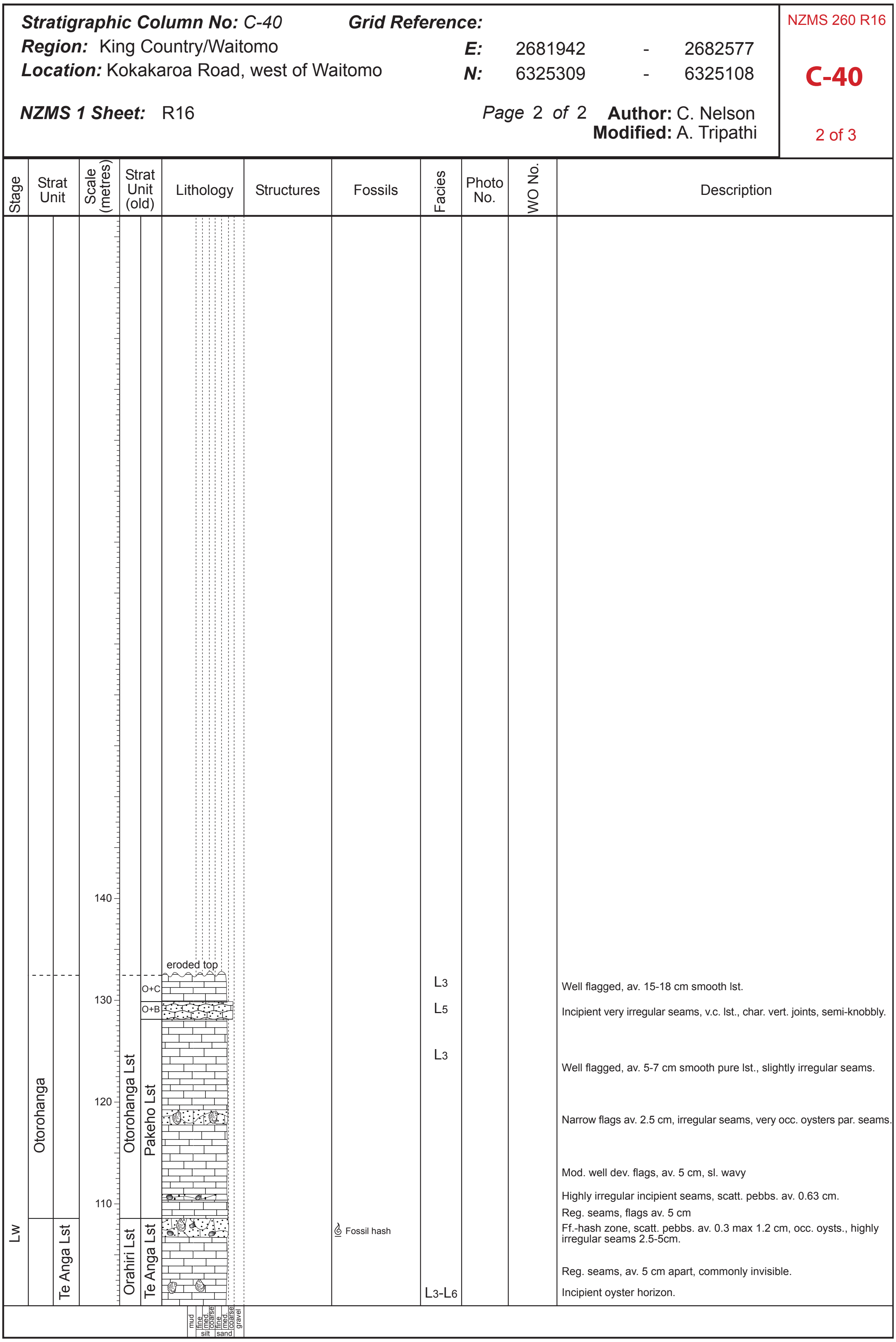

Fig. 10B *Stratigraphic column C40 continued.*

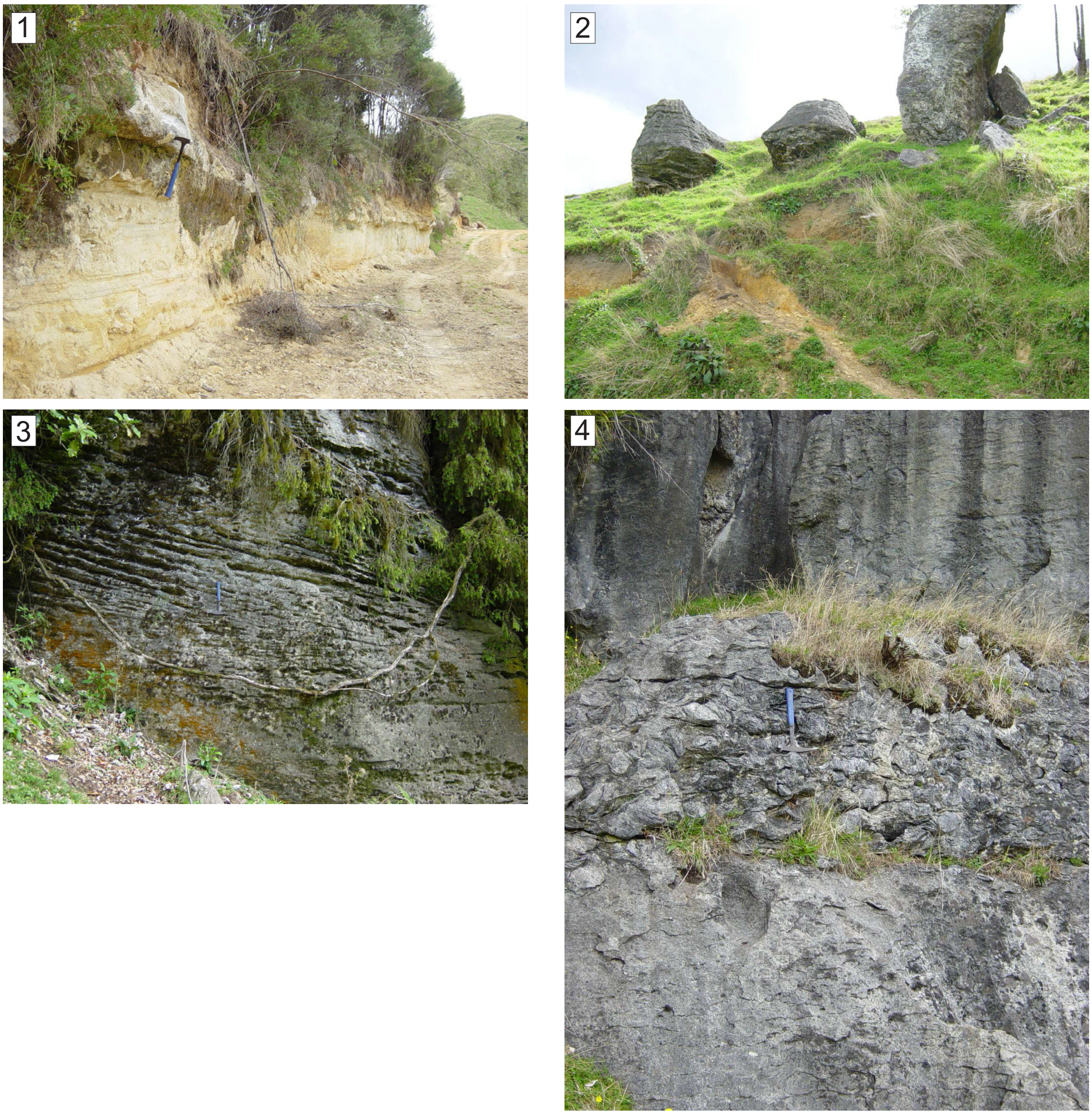

Fig. 10C *Field photos of locations at C40 identified on Fig. 10A.*

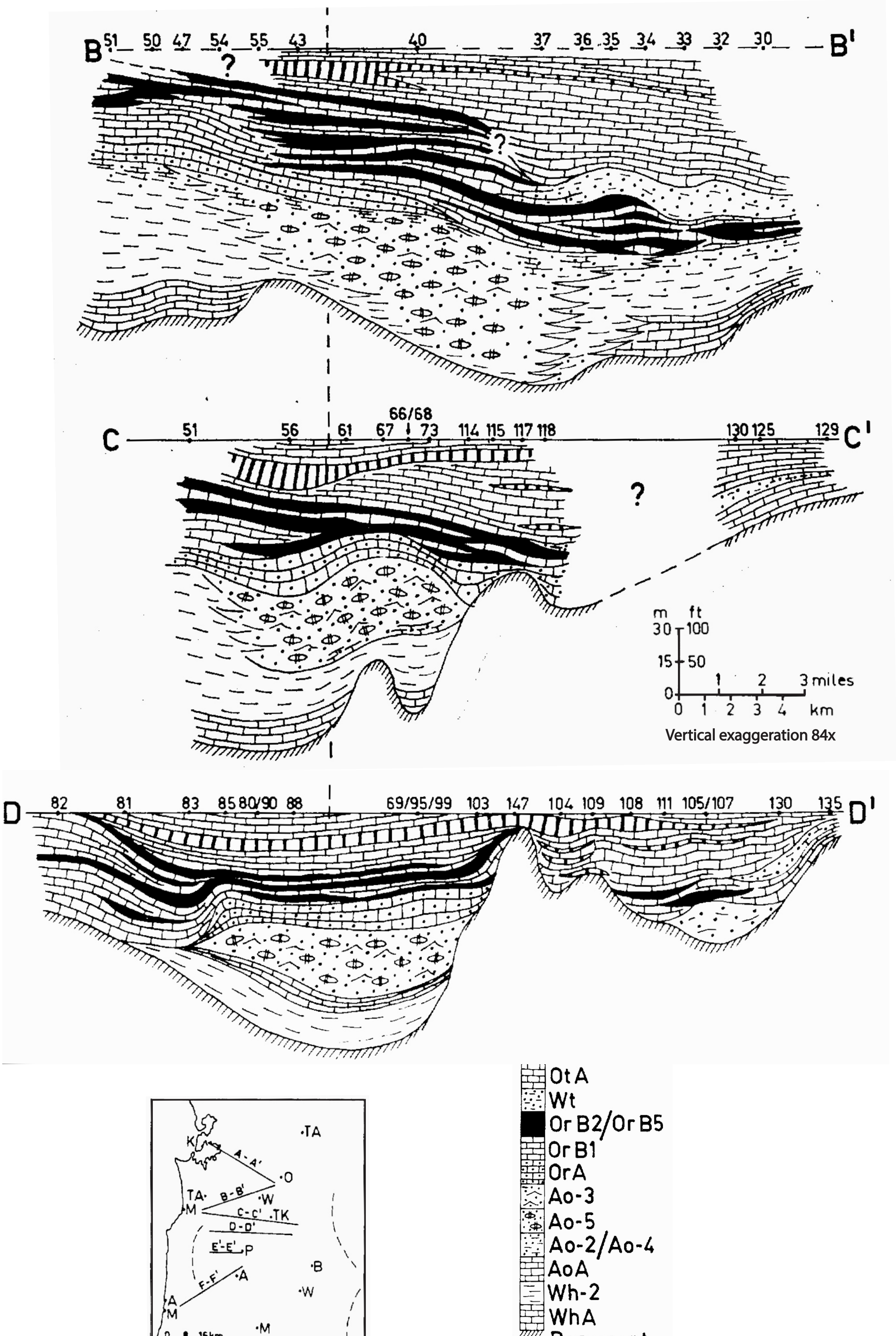

Fig. 11 *Schematic W-E sections from Nelson (1978a) through the Te Kuiti Group showing lateral relations between several of the main rock units in the wider Waitomo region.*

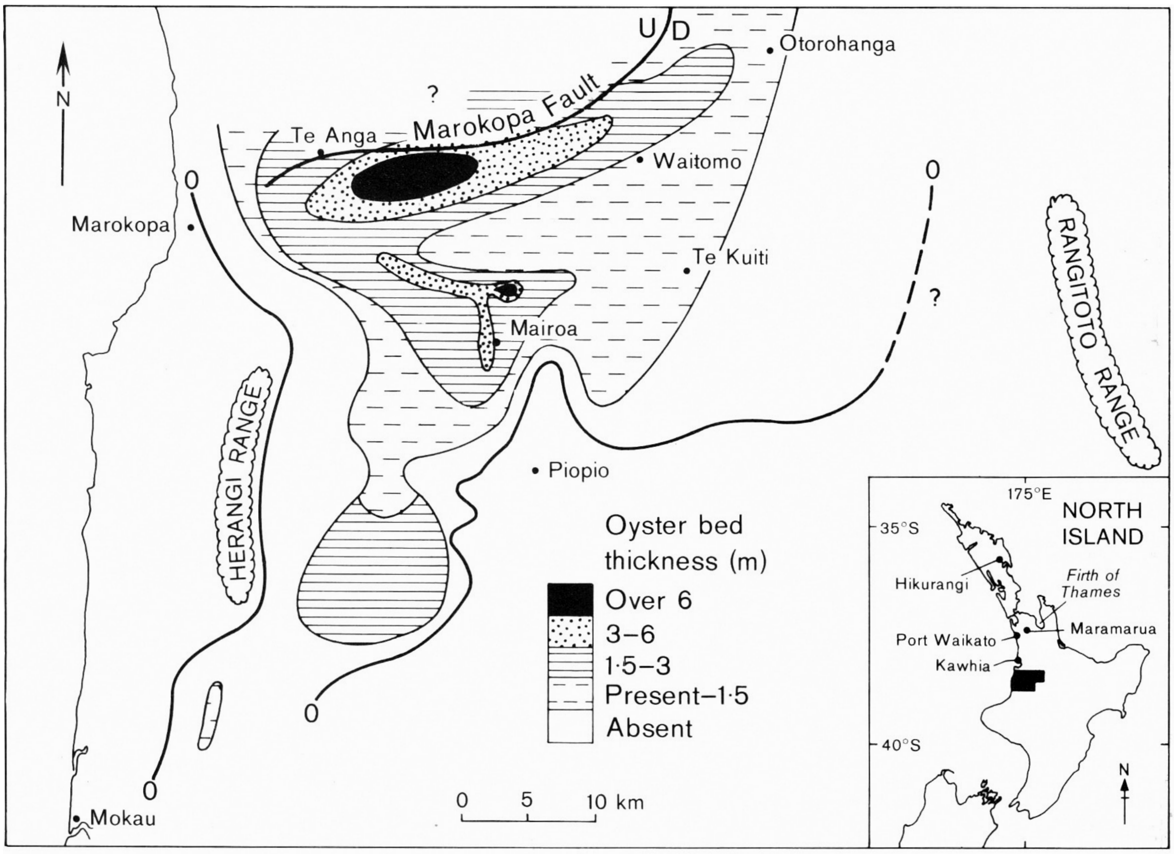

Fig. 12 Total thickness map of the Oyster Bed facies (OrB2) in the Orahiri Limestone in the wider Waitomo region (from Nelson et al. 1983).

feeds into the Marokopa River) in a collapsed cavern developed in the Orahiri Limestone. Massive (OrA3/5), flaggy (OrB1) and oyster-bearing (OrB2) beds comprise the limestone at this locality. Locally the cavern walls show secondary tufa deposits. The spectacular Natural Bridge is formed from an intact 20 m section of the cavern roof which supports (epitrophic) speleothems.

Beyond the Bridge the track loops around uphill through excellent exposures of the oyster-bearing Orahiri Limestone (OrB2). OrB2 facies are thickest in this general area (Fig. 12, p. 21). Despite several past suggestions, the oyster genus involved remains unknown, but they are most typical of the tribe Flemingostreini Stenzel (Nelson et al. 1983). Carbon and oxygen isotope values, and associated sedimentological and petrographic evidence, support development of the oyster banks in a fully marine, tideswept seaway, in water depths of 25-50 m and bottom temperatures in the vicinity of 12-15°C. Apart from the much larger size of the Oligocene oysters, the proposed setting is reminiscent of the modern oyster (*Tiostrea lutaria* Hutton) accumulations in Foveaux Strait off southern New Zealand (Fleming 1952).

To the north of this site the Mesozoic basement rocks with residual Okoko (Lower Te Kuiti) Subgroup successions are upthrown on the Marokopa Fault (Fig.12, p. 21), a roughly WSW-ENE bearing normal fault that ultimately links north of Waitomo Caves into the major N-S trending Waipa Fault separating the Murihiku and Waipapa Terranes (Fig. 2, p. 4).

STOP 9 - Marokopa Falls (R16/720255; *BF32/618638*)

Continue west along Te Anga Rd to the Marokopa Falls car park. The falls have developed over a thick, well lithified conglomerate and coarse sandstone bed within siltstones of the Mesozoic basement rocks (here Late Jurassic; Op – Puaroan, *Buchia plicata*). This location is roughly at the centre of the regional N-S trending Kawhia Syncline developed in Murihiku Terrane rocks (Late Triassic-Late Jurassic) in western North Island. Low positive Oligocene paleorelief associated with the resistant basement interval at Marokopa Falls is onlapped by basal limestone and calcareous sandstone of the Glen Massey or Aotea Formation, seen above and south of the falls from the lookout point down the bushwalk track below the car park.

STOP 10 - Basal Te Kuiti Group limestone (R16/714255; *BF32/612638*)

Continue west along Te Anga Rd, pausing on the descent down to Te Anga settlement to note the character in fallen roadside blocks of basal limestone of the Te Kuiti Group (either Waimai or Elgood Limestone Member of Aotea or Glen Massey Formation; Fig. 3, p. 6). Not uncommonly, such on-basement transgressive (TST) limestones include conspicuous calcareous red algal and/or rhodolith clasts (Nalin et al. 2008), skeletal types otherwise mainly rare or absent in the main Te Kuiti Group limestone formations.

STOP 11 - Te Anga limestone bluffs (R16/695257; *BF32/593640*)

Immediately after Te Anga turn south at the T-intersection on to Marokopa Rd (to the north Taharoa Rd leads to the Taharoa ironsand mining site and beyond to Kawhia Harbour). Travel a short distance to the second roadside pull over spot with gravel piles and a small quarry in Mesozoic basement rocks of Late Jurassic sandstone on the opposite side of the road. View to the east across the Marokopa River the impressive bluffs of Orahiri Limestone above Glen Massey Formation, in turn overlying an irregular paleosurface upon Mesozoic basement rocks (Fig. 13, p. 23-25). The Castle Craig Subgroup (Table 1, p. 5) derives its name from the cliff face having this name, just visible on the skyline to the south of this stop. Note the occurrence in images 7 & 8 in Fig. 13C (p. 25) of some prominent pebble bands in the Orahiri Limestone at this site.

STOP 12 - Ruakuri Caves (S16/920240; *BF33/818623*)

Return to Waitomo back east along Te Anga Rd. At the roundabout just before Waitomo Caves, turn south into Tumutumu Rd and proceed to the junction with Ruakuri Rd, where vehicles will park and await instructions for entering the Ruakuri Cave from Travis Cross (Cave Environmental Officer, Tourist Holdings Ltd) or some other official cave guides.

Overview

This field trip demonstrates the relationship between cave development and regional geomorphology, especially where this in turn is influenced by glacio-eustatic sea-level fluctuations. Participants will be guided through Ruakuri Cave (Appendix 2), one of the most pristine and accessible caves in New Zealand, with an opportunity to observe speleogenesis, environmental concerns associated with tourist activities in caves, and scientific opportunities offered by caves.

History

Ruakuri Cave, which literally means two dogs, has been known to the Maori for many centuries with a small high entrance above the original main entrance being used as a burial cave which is Waahi Tapu - "a sacred place". Ruakuri Cave was first opened to visitors in 1904 by James Holden, an ancestor of the family that still owns much of the land above the cave system.

It was the second cave in the region to be opened as a visitor attraction and was quickly announced by early visitors to be visually impressive and an experience that was almost spiritual.

The Government claimed ownership of Ruakuri Cave and the attraction was then operated by

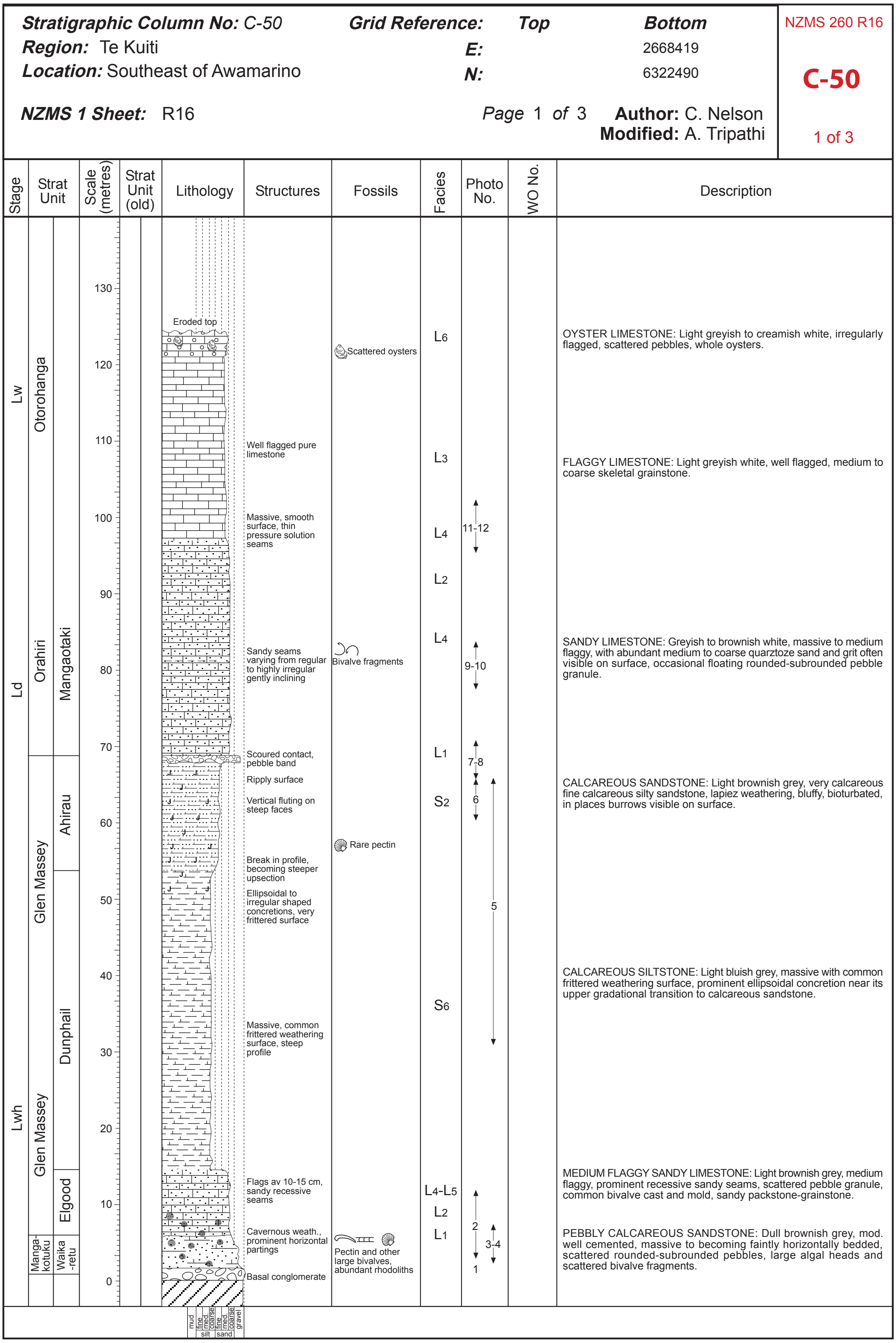

Fig. 13A *Stratigraphic column C50, south of Te Anga. Facies codes are defined in Appendix 1. Photo numbers refer to those shown on Figs. 13B and C (From Kamp et al. 2008).*

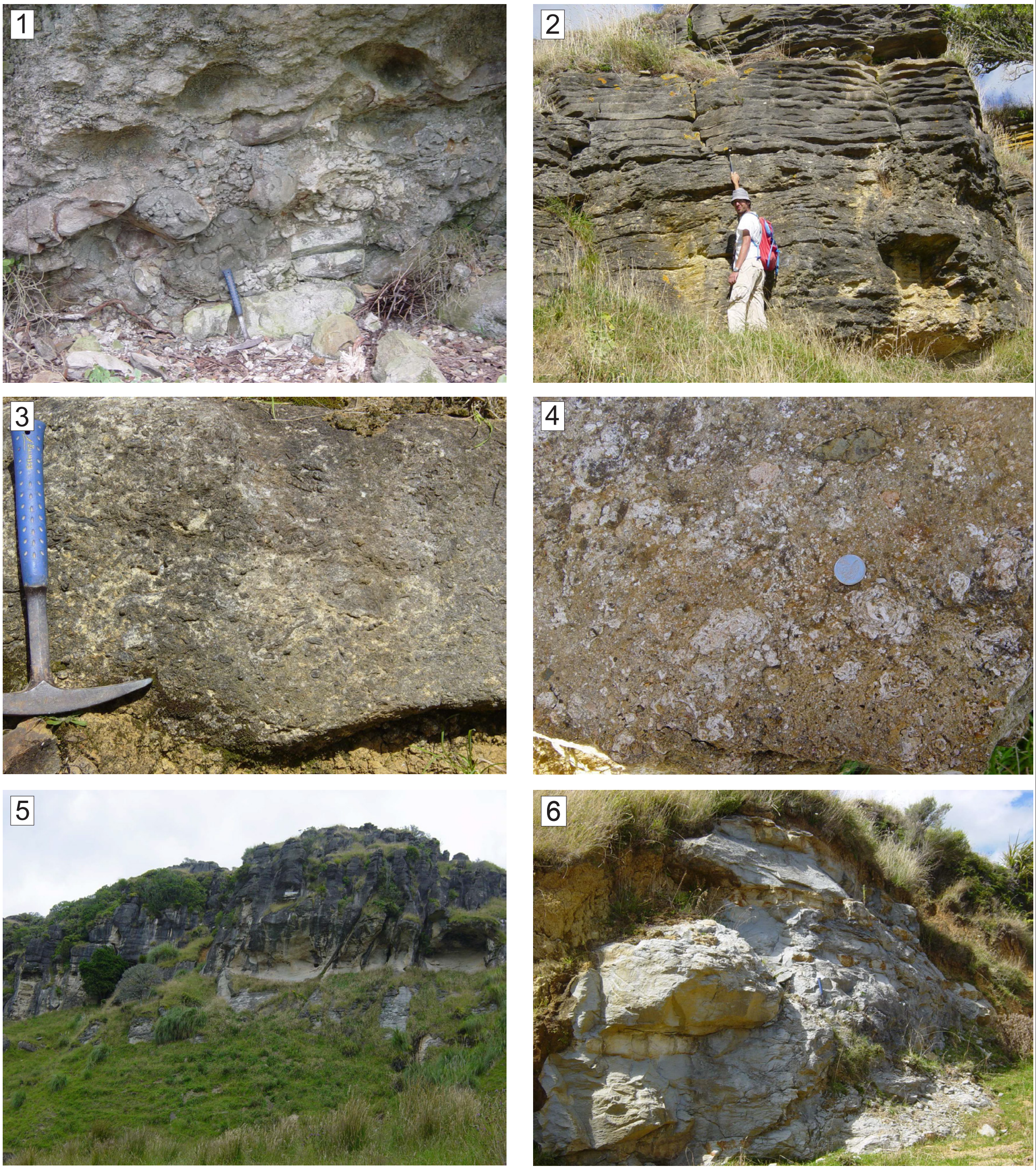

Fig. 13B Field photos of locations at C50 identified on Fig. 13A.

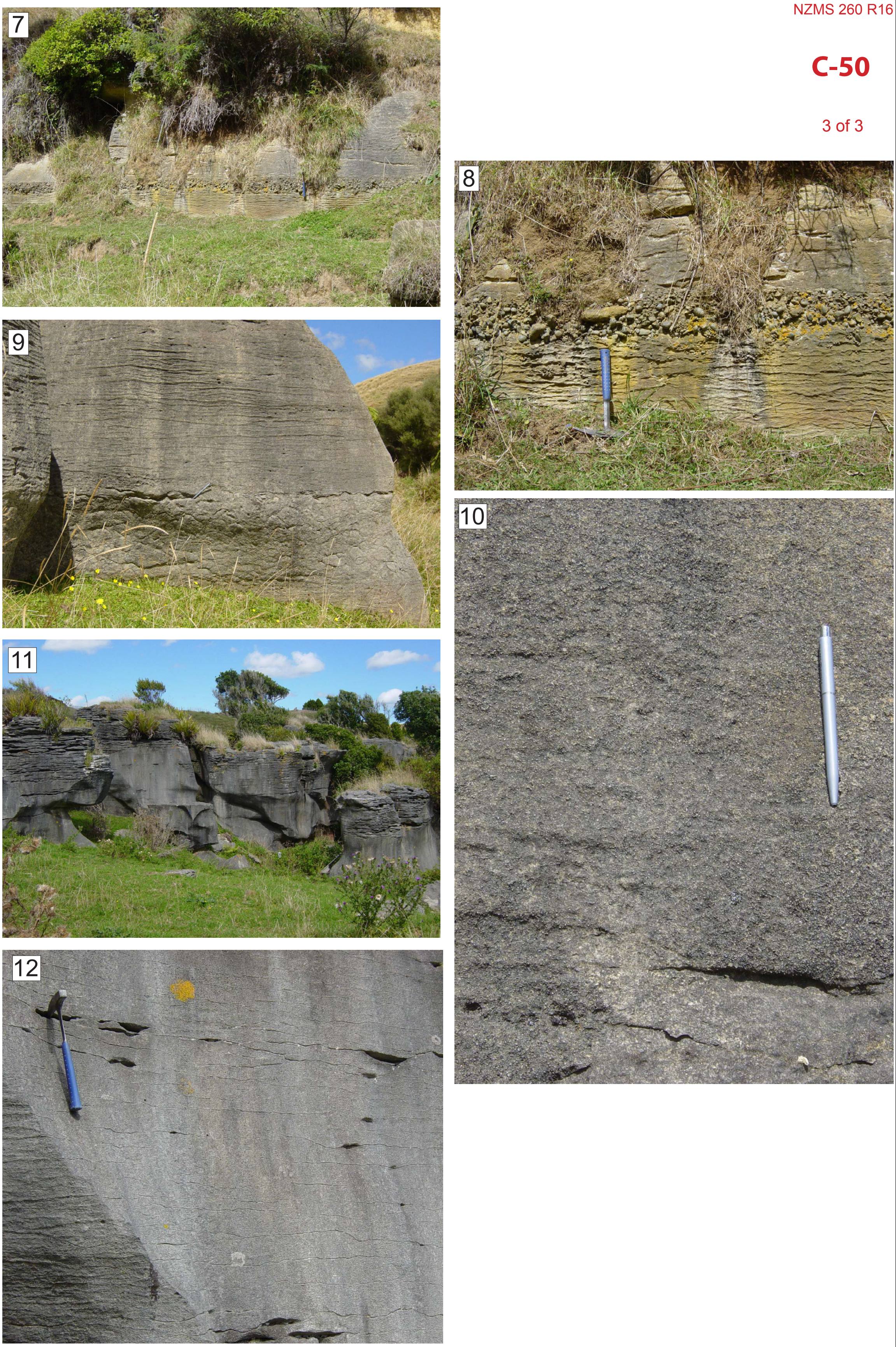

Fig. 13C *Field photos of locations at C50 identified on Fig. 13A.*

the former Tourist Hotel Corporation until February 1988, when a legal and financial dispute forced its closure.

Ruakuri Cave was closed for over 18 years and was officially re-opened for underground guided walking tours by the New Zealand Prime Minister in July 2005. This followed extensive redevelopment by Tourism Holdings Limited and an agreement with the Holden Family Trust of Waitomo. The re-opening marked the culmination of 18 months of underground construction work on walkways, bridges and a new spiral entrance way to avoid the Waahi Tapu, the source of much of the original strife between cave operators and descendants of the original land holders.

Geomorphology

In common with much of lowland North Island, the combination of 100,000 year glacio-eustatic sea-level fluctuations and easily eroded sedimentary rocks has resulted in valleys with steep walls and broad gently sloping valley floors. At times of low sea levels, the last about 18,000 years ago, the valleys were probably incised to grade to the then coast line. With post-glacial sea-level rise the valleys have infilled to grade to modern high sea level. This effect is visible looking north down the Waitomo Valley Road from Waitomo Village. Fluctuating sea levels impact on cave development as most of the cavernous weathering takes place at stream level and gives rise to multiple passageways. Where the landscape is also undergoing slow tectonic uplift, old high sea-level passages are raised above the regional groundwater table between successive high sea levels resulting in four or more abandoned high level passages. We will enter through one of the upper passages and descend progressively to stream level.

Karst geochemistry

Plants expire large quantities of CO_2 from their roots raising the PCO_2 of the soil atmosphere to several % of an atmosphere. Water passing down through the soil will dissolve this CO_2:

$$H_2O + CO_2 = HCO_{3^-} + H^+$$

When this solution comes into contact with the limestone the hydrogen ions attack the carbonates

$$H^+ + CaCO_3 = Ca^{2+} + HCO_{3^-}$$

which results in solution of calcium ions and a disturbance of the chain of equilibria:

$$H_2O + CO_2 = HCO_{3^-} + H^+$$

$$HCO_{3^-} = CO_{3^-} + H^+$$

$$CO_3^{2-} + Ca^{2+} = CaCO_3$$

If the soils are shallow, as CO_2 is removed from solution through attack on $CaCO_3$ more is replaced from the soil atmosphere (open system). However, if the soils are deep and plant roots are isolated from the limestone, the P_{CO_2} will drop substantially, and the pH will rise as the water passes into the limestone (Fig. 14, p. 27).

When the solution re-emerges in a cave the PCO_2 will readjust to achieve equilibrium with the cave air. If it is higher than the cave air CO_2 will be lost from solution forcing carbonates to be precipitated.

$$Ca^{2+} + 2HCO_{3^-} = CaCO_{3(calcite)} + H_2O + CO_2$$

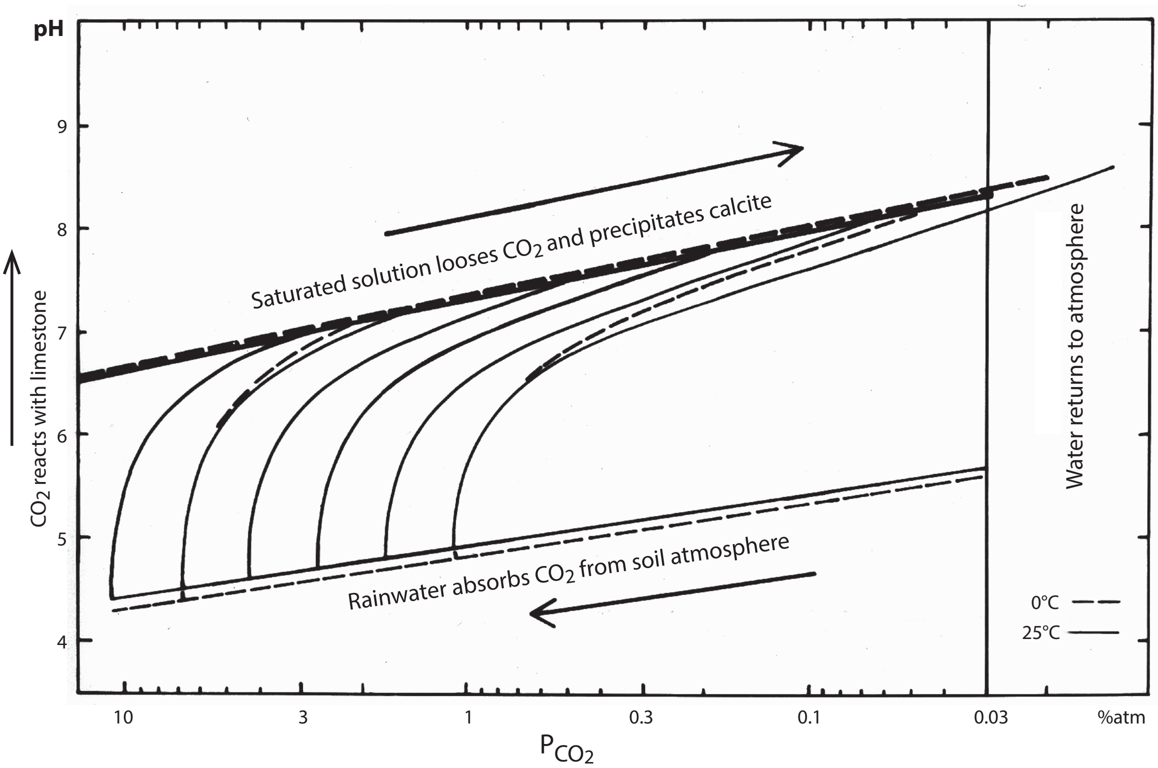

***Fig. 14** Changes in in P_{CO_2} and pH in speleothem genesis.*

But if it is lower than the cave atmosphere the reverse will occur and further solution of calcium carbonate will take place. Where calcium carbonate is precipitated, formations known as "speleothems" will be deposited, such as stalactites, stalagmites and flowstone. Both of these effects occur in Ruakuri Cave.

A special problem can arise when large numbers of people occupy small or poorly ventilated caves. As people respire CO_2, the partial pressure rises in the cave atmosphere and can exceed that of the drip waters causing speleothems to redissolve. Other deposits can also occur as a result of the loss of CO_2 (and rise in pH) for example deposits of black MnO_2 (pyrolusite) in the form of cave varnish on stones, and "cave leather". These are precipitated by:

$$Mn^{2+} + H_2O + ½\, O_2\ +\ MnO_{2\,(pyrolusite)} + 2H^+$$

as the pH rises and oxygen is readily available.

Evaporation also causes precipitation of carbonates and sulphates.

$$Ca^{2+}\ +\ SO_4^{2-}\ =\ CaSO_4.2H_2O_{(gypsum)}$$

This leads to deposits with a crumbly appearance as water moving by capillary attraction is not as constrained by gravity. Examples of "Cave Coral" can be found in many caves, including Ruakuri.

Lampenflora

The waters seeping into limestone caves are typical ground waters (other than for the effects of their exposure to limestone). In this respect they will carry similar concentrations of nutrients such as phosphate and nitrate, especially if they originate under pasture or cultivated land. All they lack to grow plants is light. When light is available to these waters, such as in tourist caves, a wide range of low light tolerant plants will grow giving rise to lampenflora. Careful management of lighting (reduced intensity and duration, spectral shifting, etc. can reduce this effect in tourist caves, but often chemical control with bleaching agents is also required). In Ruakuri Cave the growth of lampenflora is suppressed by using LED lights with low output and limiting the duration of illumination.

Geochemical research in Ruakuri Cave

In order to prevent respired carbon dioxide from damaging speleothems the Department of Conservation require the cave operators to keep PCO_2 below 2400 ppm. However the upper Drum Passage regularly exceeds this value when outside temperatures are greater than cave temperatures (Fig. 15, p. 29). Under these conditions it appears that air cools on contact with the limestone and gradually sinks into the upper levels of the cave bringing with it high PCO_2 air from an epikarst region above Drum Passage. When outside air temperatures are colder than cave temperatures the airflow reverses bringing low PCO_2 air up from the many low level entrances into the cave (Fig. 16, p. 29).

Development of the new Drum Entrance and its graduated walkway required excavation of silt and rockfall infill in two locations (near the Drum Entrance – off to the upper right in the map, and a short section marked "no connection" in the map). During both of these excavations buried and broken stalagmites were recovered. Some of these are still in the cave near the Drum Entrance, but several were removed and used by Tom Whittaker as part of his PhD research (Fig. 17, p. 30). Tom determined the age of these by using the decay of natural uranium, which is present in the speleothems in concentrations of typically 100 ppb. Uranium-234 has a half life of 250,000 years and decays to form thorium-230 with a half life of 80,000 years. By measuring the ratio of both isotopes you can determine ages up to about 400,000 years. Two stalagmites (RK05-3 & RK05-4) buried by silt near the Drum Entrance were dated (Figs. 18, 19, p. 31) as were two buried beneath the rockfall between Holden's Cavern and the mirror pool (RK05-1 & RK05-2).

RK05-4 from near the base of the silt infill started growing 102,000 years ago and stopped 73,000 years ago.

RK05-3 started about 53,000 years ago but finished about 7000 years ago. Unfortunately the depth from which this stalagmite was recovered was not recorded. From the dates it was likely to have formed on top of the silt bank.

RK05-1 started 60,000 years ago and stopped 51,000 years ago while RK05-2 was modern. Again the depths at which these speleothems were recovered during the excavation process was not recorded, but shows that the rockfall cannot be more than 50,000 years old.

However, Tom's thesis was aimed at looking for a record of changing climate rather than cave development (Fig. 20, p. 32). This was done by investigating changes in the ratios of oxygen isotopes ^{16}O and ^{18}O (driven by changes in temperature, global ice volume and weather patterns), and changes in the ratios of carbon isotopes ^{13}C and ^{12}C, which was suggested to be driven by whether the overlying soil is saturated with water or dry and friable. The technique was first developed in New Zealand using stalactites from Gardners Gut Cave, about 1 km from Ruakuri Cave, and Waipuna Cave, also in the Waitomo district (Hendy & Wilson 1968).

The results of Tom's analyses of the three suitable Ruakuri stalagmites agreed with stalagmites he collected from the West Coast of the South Island and from cores taken in the Pacific Ocean to the east of the South Island (Fig. 20, p. 32). These all show cold dry periods between 75,000 and 60,000 years and again between 30,000 and 18,000 years. Both these times were marked by extensive glaciations in the South Island.

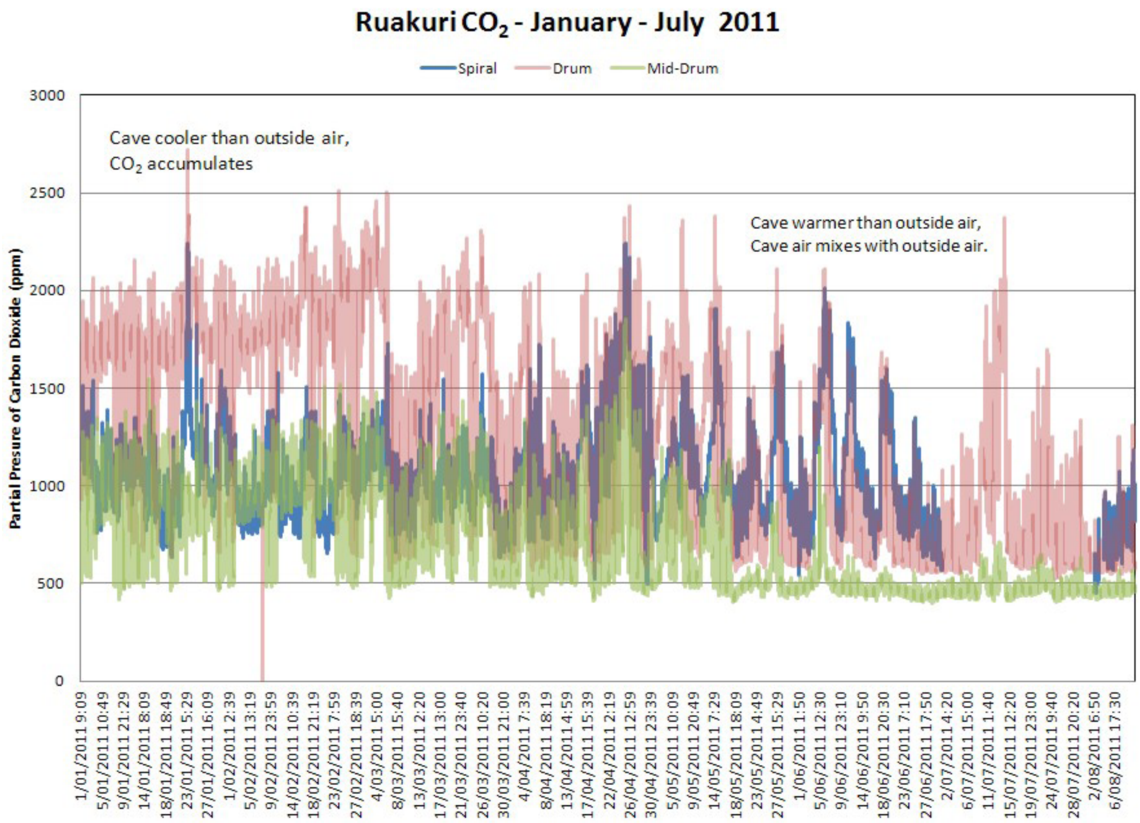

***Fig. 15** Changes in P_{CO_2} in Ruakuri Cave during 2011.*

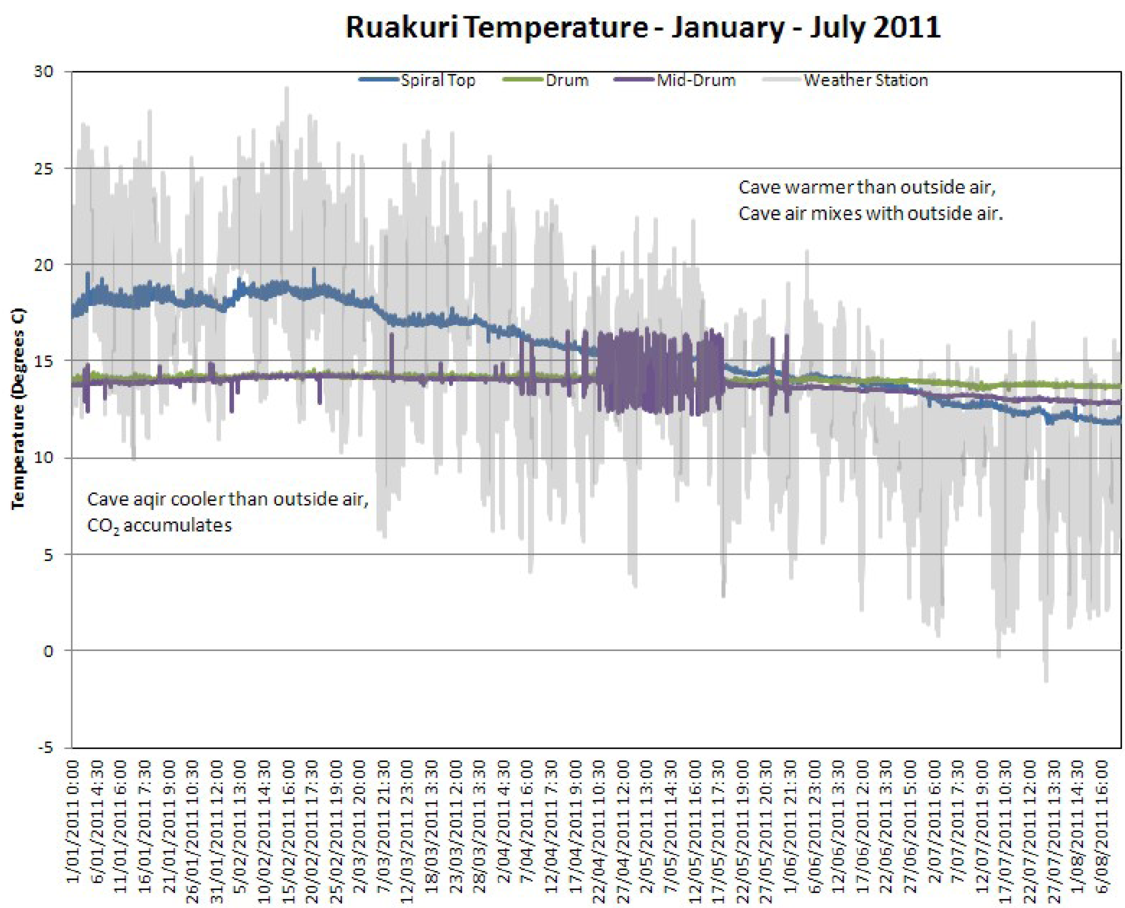

***Fig. 16** Changes in temperature in Ruakuri Cave during 2011.*

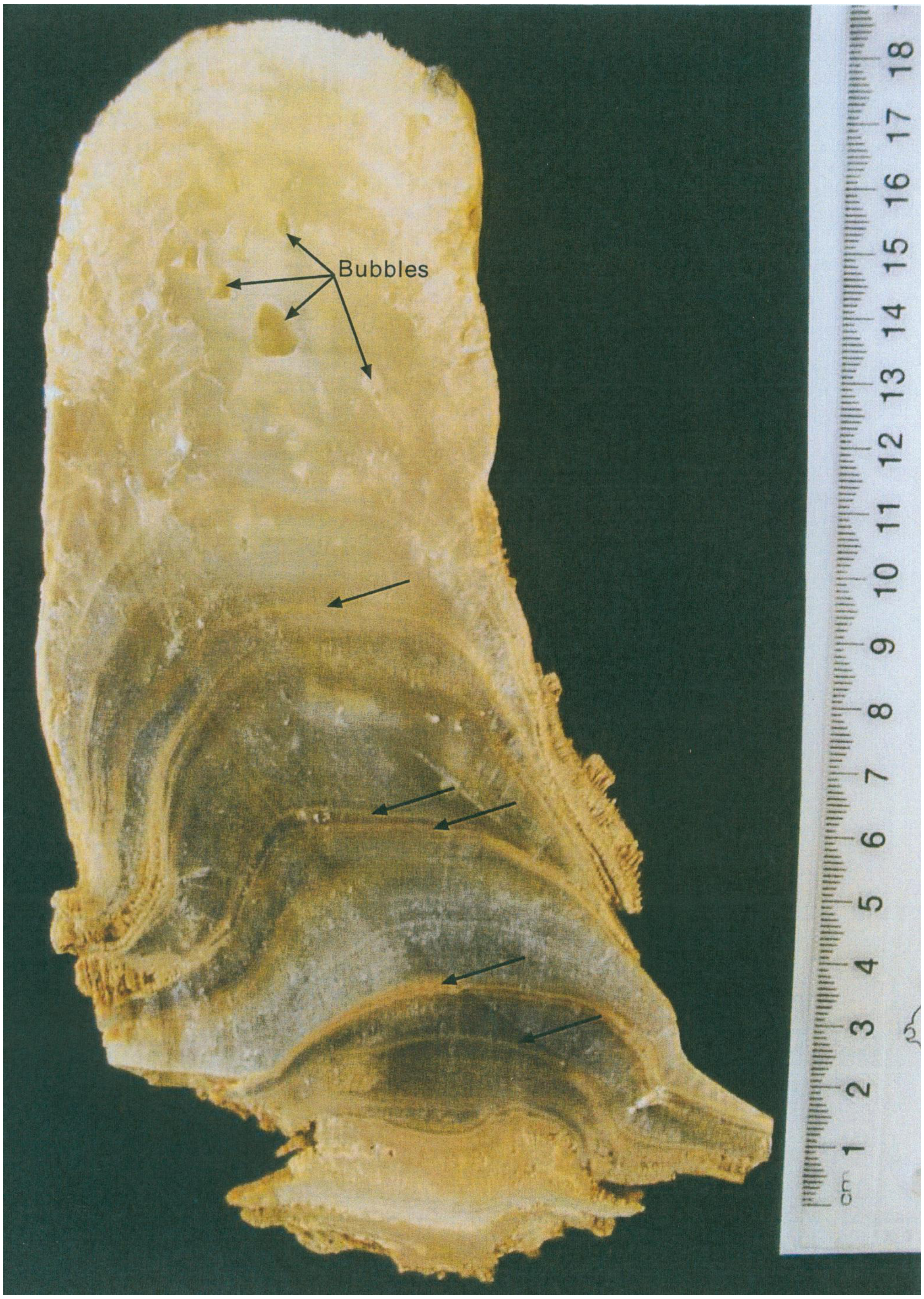

Fig. 17 *Section through stalagmite RK05-4 from Ruakuri Cave. Five mineral-rich laminae shown by arrows. From Whittaker (2008).*

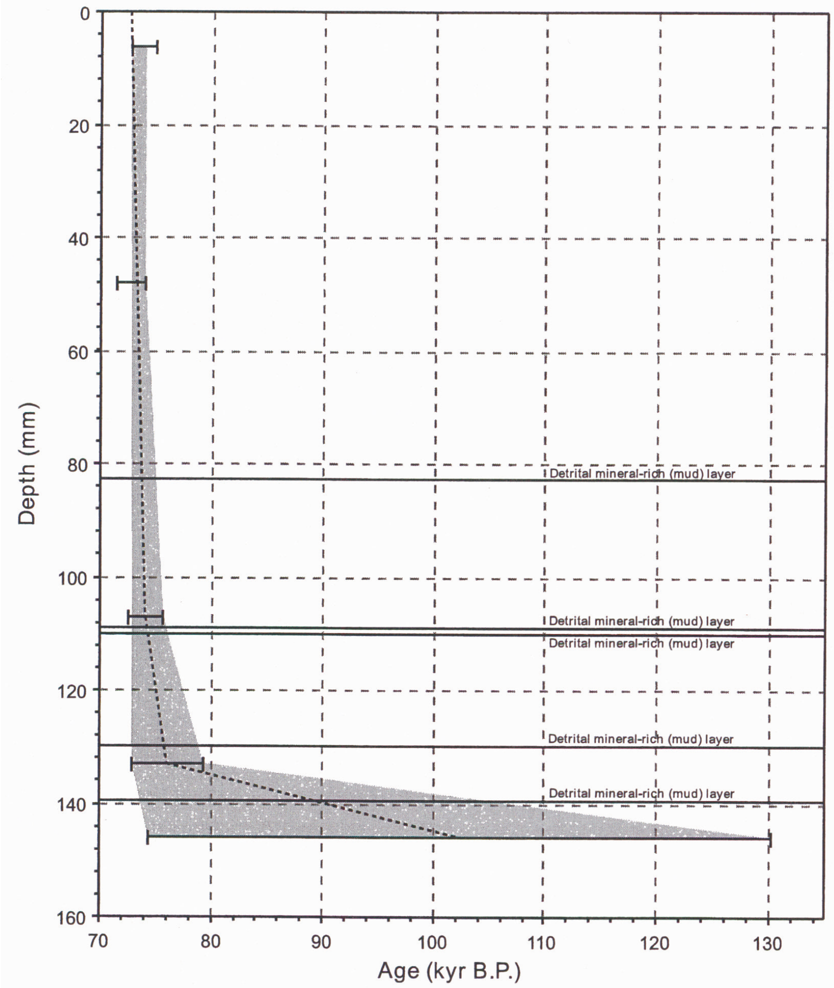

Fig. 18 *Age vs depth for Ruakuri Cave stalagmite RK05-4 (±2σ errors). Dashed line is age model used for plotting stable isotope ratios. Mud-rich layers are also noted. From Whittaker (2008).*

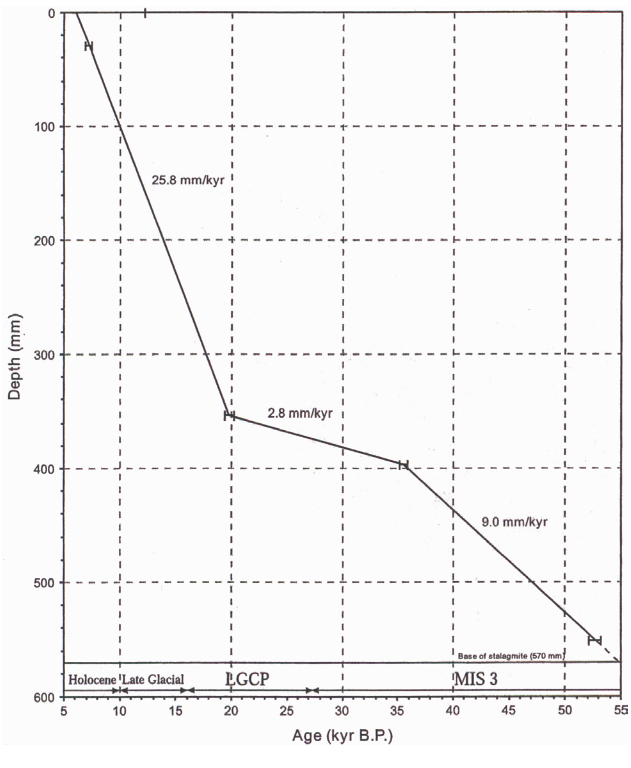

Fig. 19 *Age vs depth for Ruakuri Cave stalagmite RK05-3 (±2σ errors). Average growth rates are shown on the diagram. From Whittaker (2008).*

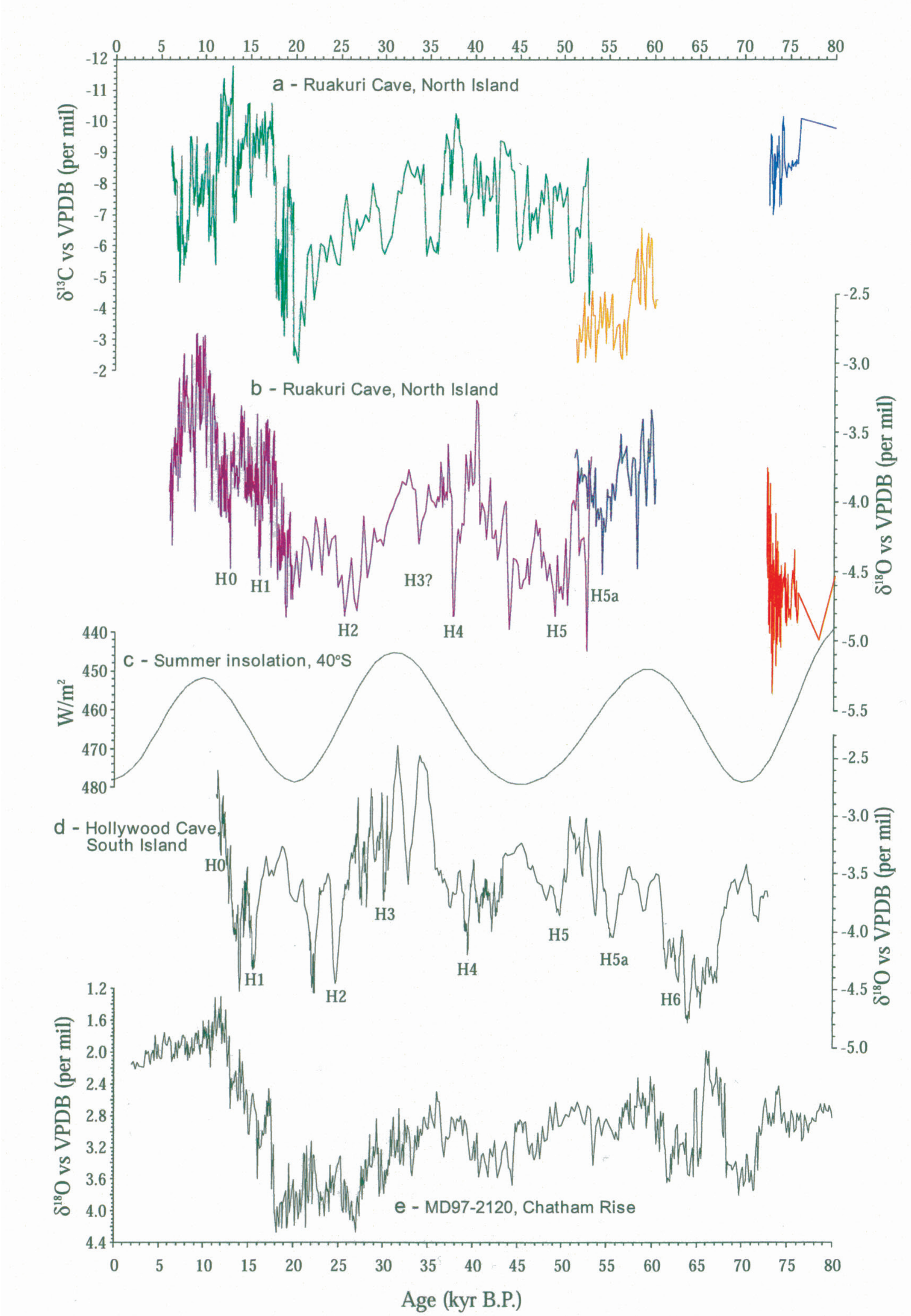

Fig. 20 *Stable isotope and paleoenvironmental summaries from the Ruakuri Cave stalagmite data in comparison to some other New Zealand sites. From Whittaker (2008).*

STOP 13 - Mahoenui Group mudstone (S16/933247; *BF33/831630)*

Stop briefly at the entrance to Kaimanawa farm to view a small roadside exposure of light blue-grey massive mudstone of the Taumatamaire Formation, typical of the Mahoenui Group in the Waitomo area (Fig. 3, p. 6). Of early Miocene (Otaian, Po) age, this slope depth mudstone accumulated during rapid subsidence and marks the cessation of limestone deposition (Otorohanga Limestone) in the region. Away to the north of Hamilton the contact between the Te Kuiti and Mahoenui Groups is strongly unconformable, with uplift and significant erosion of the Te Kuiti Group deposits, but in the King Country the contact is abrupt to rapidly gradational as a consequence of subsidence and drowning. The event corresponds to the full tectonic effects associated with the propagation of the Pacific-Australian convergent plate boundary through Zealandia at this time. Note that north of Hamilton through Auckland and on to Northland, the lateral equivalent of the Mahoenui Group is the Waitemata Group including widespread vocanogenic and mass flow deposits.

STOP 14 - Waitomo Caves Discovery Centre (S16/947248; *BF33/845631)*

Celina Yapp, Managing Director of the Waitomo Caves Discovery Centre, invites you to visit the Centre and see the displays related to the caves and history of the Waitomo district. Some archived fossil specimens from the region may also be able to be viewed, including recent fossil whale and fish vertebrate finds.

4. ACKNOWLEDGEMENTS

We thank the Waitomo area land owners for kindly allowing access on to their property to view and discuss the geology on the original Geosciences Society of New Zealand field trip in November 2012, but it is emphasised that individuals or groups subsequently following this field guide must again seek permission to enter privately owned farmland. In particular, contact is required with Ross and Viv Roberts (Stop 2), Trevor and Jodie Murchie (Stop 2), Cristen Dimond (Stop 3), and David and Toni Townsend (Stop 6).

The stratigraphic columns forming Figs. 5, 10 and 13 (p. 8, 17, 23) come from Nelson (1977) but were redrawn and included within the stratigraphic column compilation by Kamp et al. (2008) from where they have been copied into the present field guide. Travis Cross (Cave Environmental Officer, Tourist Holdings Ltd) is thanked for facilitating the original visit into Ruakuri Cave, as is Celina Yapp (Managing Director of the Waitomo Caves Discovery Centre) for kindly allowing access to the Waitomo Caves Discovery Centre.

The support of Steven Hood and Peter Kamp (University of Waikato) in the preparation of this field trip is acknowledged, as is the cartographic input by Betty-Ann Kamp (University of Waikato) who assembled the original field trip guide notes and this report into a coherent whole. A special thanks for the long time support given by John Ash (Waitomo) for all things geological in the Waitomo region.

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6. APPENDIX 1 – Lithofacies characteristics in the dominant limestones and other mixed carbonate-siliciclastic deposits of the Castle Craig Subgroup of the Te Kuiti Group (from Kamp et al. 2008).

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
Limestone association						
L_1 Pebbly grain-stone -pack-stone.	Common to abundant subrounded pebbles and cobbles may occur as pebble bands, or fabric supported by bioclastic silty fine sandstone, usually massive in appearance	Moderate (50-60%)	Medium to coarse grainstone-rudstone, occasional large shell fragments, poorly to moderately sorted; very abraded	Fragmented pectinids, oysters, echinoderm, clasts occasionally encrusted by calcareous red algae, including rhodoliths	Common near the lower contact with basement, and/or mark erosional contact with the underlying formation; up to tens of centimetres thick. "Basal Beds" (OrA1/ OtA1 of Nelson 1978a)	Near shore to inner shelf adjac-ent to rocky shore-line
L_2 Cross-stratified grain-stone	Sigmoidal to tabular cross-beds are low (< 10^0) to moderate angle (10^0-25^0); occur as 0.3-4.5 m thick cross-sets traceable laterally for few tens of metres; base and tops of sets are sharp and discordant, cross-beds are generally 2-15 cm thick	High (91-96%)	Medium to very coarse grainstone, rare small pebbles and granules. Siliciclastic particles in bedding planes are generally of fine sandstone to siltstone, moderately abraded, poorly to moderately sorted	Bryozoans, echinoderms, benthic foraminifers, occasional bivalves, coralline red algae, rare planktic foraminifers	Developed locally in the lower, mid and upper parts of Orahiri Formation and Otorohanga Limestone.	High energy inner to mid shelf domin-ated by strong off-shore-directed storm and or tidal induced currents

APPENDIX 1 (continued)

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
L_3 Horizontally bedded grainstone	Beds typically well developed, averaging 2-10 cm; well developed flagginess is characteristic	High (81-99%)	Medium to very coarse grainstone, abraded, poorly to moderately sorted	Bryozoans, echinoderms, benthic foraminifers, and occasional bivalves and calcareous red algae; planktic foraminifers rare or absent	Comprises most of the Orahiri Formation and Otorohanga Limestone. "Flaggy Limestone Beds" (OrB1, OtA2, OtC1) of Nelson 1978a	Inner to mid wave dominated shelf
L_4 Sandy grainstone-packstone	Commonly varying from massive to tabular bedded units, bedding plane (0.1 - 1.5 cm) rich in siliciclastic material is obvious in places	Moderate to high (42-87%)	Coarse to very coarse grainstone, common medium to coarse quartz sand grains, abraded, and poorly to moderately sorted	Echinoderm, large benthic foraminifers (*Amphistegina*), bryozoans, and occasional bivalves and calcareous red algae; planktic foraminifers rare or absent	Comprises most of the Mangaotaki Limestone Member mainly in western areas. "Sandy Limestone Beds" (OrA3, OrA4, OrA5, OrB4) of Nelson 1978a.	Inner to mid shelf
L_5 Massive to irregularly bedded, fossiliferous rudstone-grainstone	Massive to irregularly bedded, occasionally well bedded 20-100 cm thick beds, commonly develops "knobbly" to blocky weathering feature, frequently cavernously weathered	High (98-100%)	Medium to coarse grainstone, common large skeletal fragments, abraded, poorly to moderately sorted	Bryozoans (up to 80 %), echinoderms, benthic foraminifers, common bivalves and gastropod moulds and occasional calcareous red algae	Comprises most of the Waitanguru Limestone Member (Otorohanga 'B'). "Blocky and Knobbly Limestone Beds" (OtB1, OtB2, OtB3) of Nelson 1978a	Bryozoan mound buildup indicating high energy inner-mid shelf depths

APPENDIX 1 (continued)

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
L_6 Pebbly-oyster float-stone-pack-stone.	Massive to irregularly bedded, tens of centimetre thick; beds laterally traceable for few metres	High (77-97%)	Medium to very coarse with pebbles (<2 cm), clasts and matrix supported, poorly sorted	Articulated / disarticulated, randomly orientated oysters (*Flemingo-strea sp.*), bryozoans, echinoderms, benthic foraminifers, bivalves and occasional calcareous red algae, solitary corals (*Flabellum*)	Comprises most of the Te Anga Limestone Member. "Oyster and Fossil Hash Beds" (Or B2, OrB5) of Nelson 1978a	Oyster reefs com-monly associ-ated with sandy grain-stone -pack-stone, high energy tide swept inner-mid shelf
L_7 Con-glom-eratic limestone	Bedded units 0.5-3 m thick with abundant clasts of limestone, calcareous sandstone and rounded-subrounded basement pebbles, which are frequently profusely bored	Moderate to high	Coarse to very coarse sparry grainstone with 1-10 cm size clasts, poorly sorted	Bryozoans, echinoderms, benthic foraminifers, oysters and occasional calcareous red algae encrusting basement pebbles	Occurs as conspicuous unit within Orahiri Formation near Awakino Tunnel. "Limestone in Limestone Beds" (OrB6) of Nelson 1978a	Inter-preted as carbon-ate debrite/ mass em-placed unit - deposit-ed at shelf depths in re-sponse to tilting

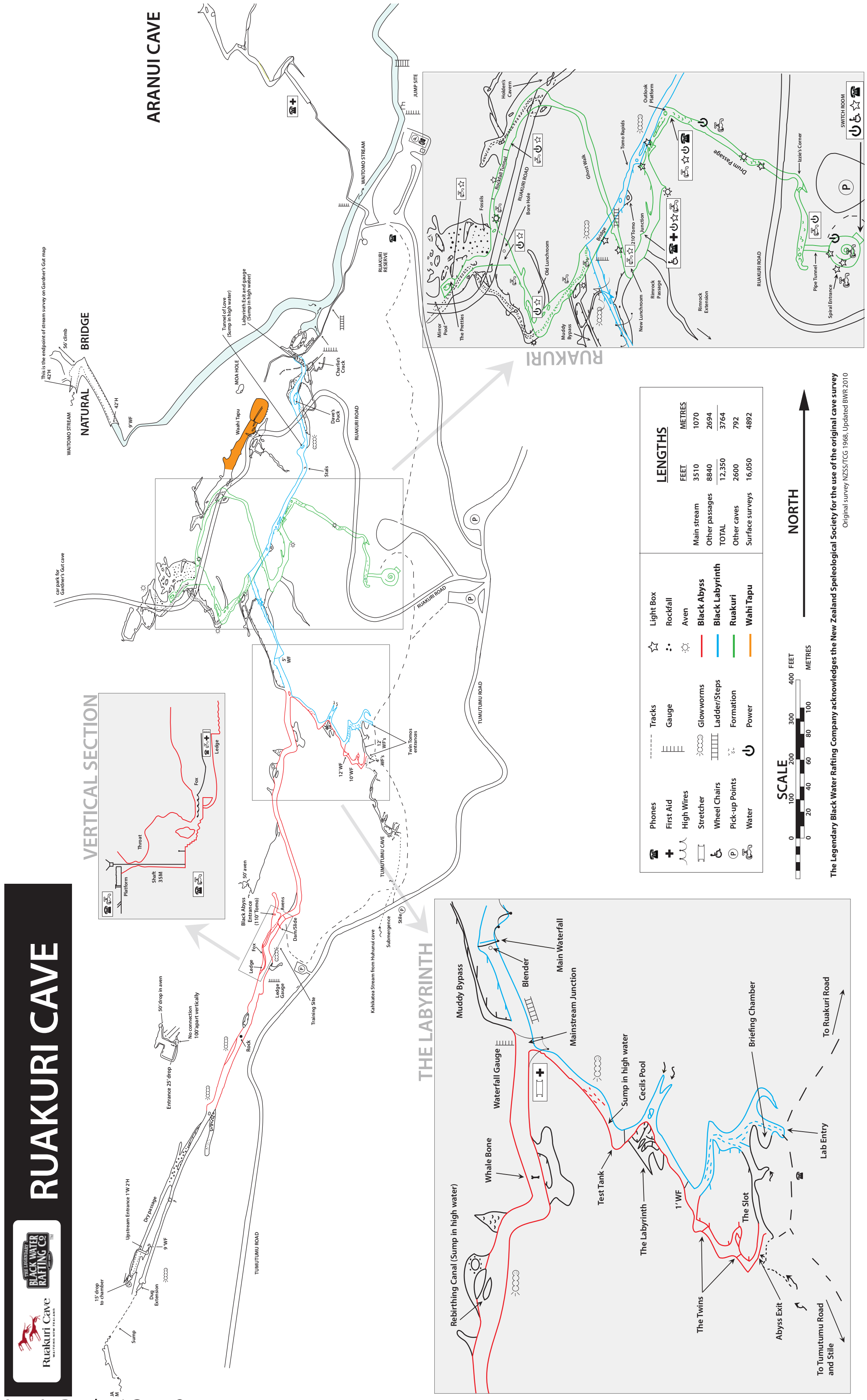
APPENDIX 1 (continued)

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
Mixed carbonate-siliciclastic sandstone association						
L_8 Massive to horizon-tally bedded skeletal pack-stone-wacke-stone	Massive to well bedded (2-25 cm) with prominent sub-horizontal to bifurcating thin (0.5 -1.5 cm) silty interbeds	Moderate to high (59-89%)	Predominantly micritic with scattered whole and fragmented bivalves (pectinids) and echinoderms, poorly to moderately sorted	Moderate to abundant planktic foraminifera with subequal proportions of echinoderms, benthic foraminifers and bivalve fragments, occasional whole well preserved echinoderms. Bryozoans and calcareous red algae are absent or present in traces	Comprises most of the Raglan Limestone Member in the northern region; also occurs as a transition facies near the upper contact with Mahoenui Group. “Argillace-ous Limestone Beds” (OtC2) of Nelson 1978a	Outer shelf to slope
S_1 Massive glauco-nitic muddy sand-stone	Typically massive with smooth weathering profile, poorly to moderately cemented, and bioturbated	Low to moderate (20-60%)	Fine to very fine sandstone, poorly sorted	Echinoderms, bryozoans and benthic foraminifers with rare presence of calcareous red algae and bivalves.	Most common in the Waitomo Valley area. “Waitomo Sandstone Formation” of Nelson 1978a)	Mid to outer shelf
S_2 Fossilif-erous silty sand-stone and sandy siltstone	Massive, dull brownish grey, moderately cemented, occasional hard concretionary glauconitic sandstone bands, bioturbated	Moderate (38-62%)	Fine silty sandstone with scattered large bivalve and skeletal fragments, poorly sorted	Oysters (*Flemingo-strea sp.), Athlopecten athleta, Lentipecten hochstetteri, Panopea worthingtoni, Dosinia* sp., solitary corals (*Flabellum* sp.), abundant *pectinid fragments* and benthic foraminifers	Mostly forms the top part of the limestone (Orahiri Formation/ Otorohanga Limestone) at inland Kawhia Harbour area	Mid-outer shelf above storm wave base

APPENDIX 1 (continued)

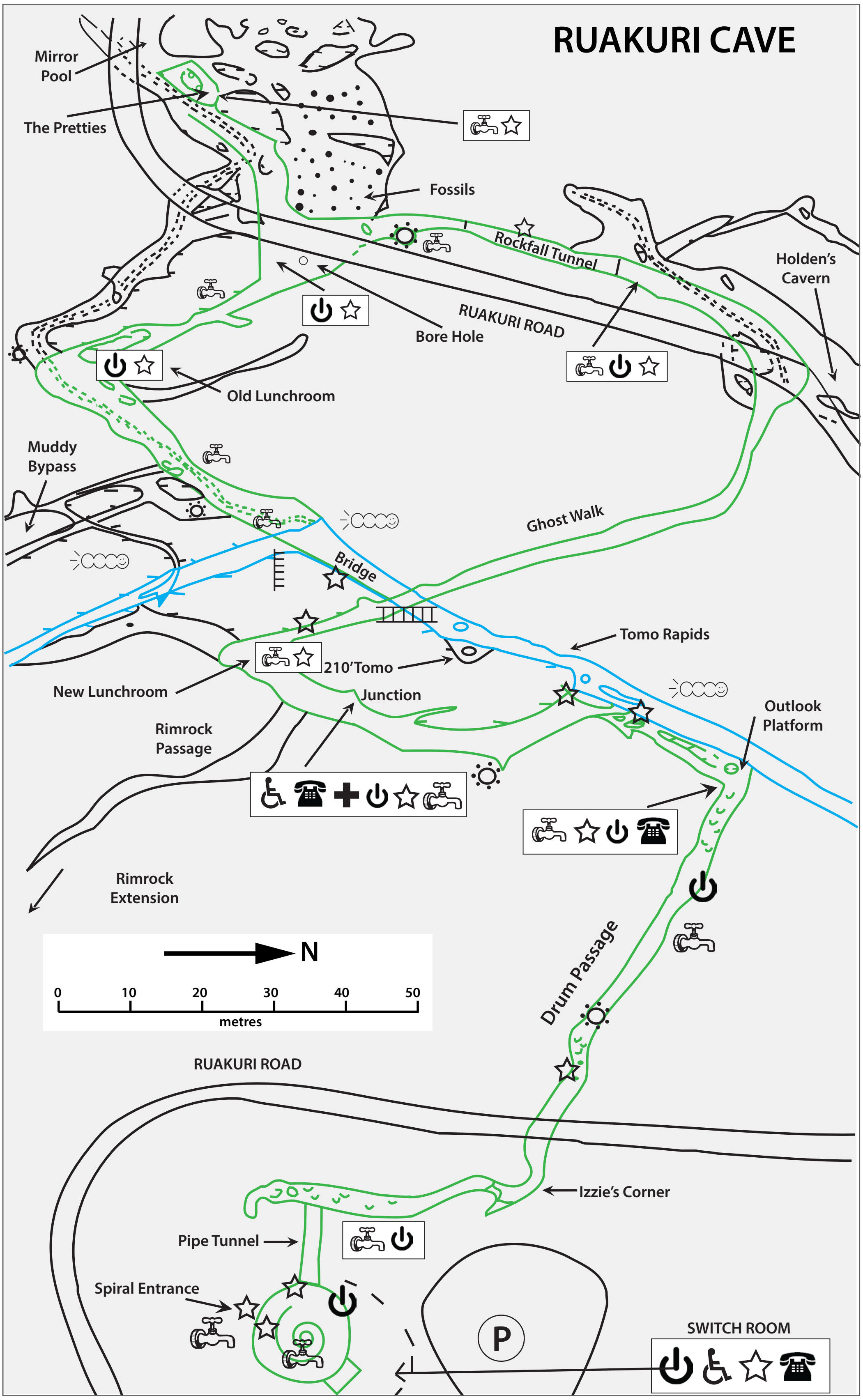
Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
Mixed carbonate-siliciclastic siltstone association						
Z_1 Medium bedded calcar-eous siltstone	Light grey to creamy yellow, moderately to well bedded (10-50 cm), occasional glauconitic in-filled burrowed horizons (10-30 cm) locally present	Moderate (51-75%)	Medium to coarse siltstone, occasional whole bivalves, gastropods and echinoderms, poorly to moderately sorted	Dominated by planktic foraminifers with variable proportion of benthic foraminifers, echinoderms and bivalves, bryozoans	Common in the lower part of Carter Siltstone Member	Outer shelf to upper bathyal
Z_2 Massive calcar-eous siltstone	Massive, light bluish grey to brownish grey, characteristic conchoidal fracture when fresh, weathers into a finely frittered surface	Low to moderate (24-73%)	Predominantly medium to coarse siltstone, however admixture of very fine to fine sand grains may be observed locally, fine-sand sized planktic foraminifera commonly recognisable, poorly to moderately sorted	Bioclasts are dominated by planktic foraminifers with minor proportion of benthic foraminifers, echinoderms and bivalve whole shell fragments	Wide-spread in the northern region forming most of the Carter Siltstone Member	Outer shelf to upper bathyal

7. APPENDIX 2 Maps of the wider Ruakuri Cave system (A) and the tourist section of Ruakuri Cave (B). (Kindly supplied by the Black Water Rafting Co. 2010).



Map A: Ruakuri Cave System

Appendix 2B Map of Ruakuri Cave.



Map B: Ruakuri Cave

8. APPENDIX 3 Stop specific potential hazards and mitigation for Waitomo field trip

These Stop specific notes supplement the Health and Safety information given on page 1, which must be read.

Emergency agency: Phone 111

Healthline: Phone 0800 611116

First aid: Vans to carry appropriate first aid kits

Illness: Advise trip leaders immediately if any health or other problems arise during the trip

Drinks: No alcohol or recreational drugs during the field trip Stops 1 to 14.

Smoking: No smoking in vehicles during the trip

Stop 1: Gateway to Otuiti Lodge, south of Ohaupo
Hazard: Traffic
Mitigation: Do not wander on to main road; wear fluoro vests

Stop 2: Waitomo Valley Quarry (disused)
Hazard: Falling rock debris; slippery grass slopes
Mitigation: Keep away from cliff faces; use geological hammers appropriately and wear safety glasses; wear fluoro vests and hard hats; take care ascending/descending grass slopes

Stop 3: Overview of Waitomo Caves area
Hazard: Slippery grass slope
Mitigation: Take care ascending/descending grass slopes; optional participation

Stop 4: Ahuroa Ignimbrite
Hazard: Traffic
Mitigation: Do not wander on to road; only cross road if instructed; wear fluoro vests; use geological hammers appropriately

Stop 5: View thin Waitomo Sandstone
Hazard: Traffic
Mitigation: Do not wander on to road; wear fluoro vests

Stop 6: Orahiri Limestone at Kokakoroa Rd
Hazard: Falling rock debris; slippery grass slopes
Mitigation: Keep away from cliff faces; use geological hammers appropriately and wear safety glasses; wear fluoro vests and hard hats; take care ascending/descending grass slopes

Stop 7: Te Kuiti Group on basement

Hazard: Traffic; falling rock debris

Mitigation: Do not wander on to main road; use geological hammers appropriately and wear safety glasses; wear fluoro vests and hard hats

Stop 8: Mangapohue Natural Bridge

Hazard: Traffic; slippery grass slopes and muddy track

Mitigation: Do not wander on to main road; wear fluoro vests and solid foot wear; use stiles provided to cross fence lines

Stop 9: Marokopa Falls

Hazard: Traffic; slippery muddy bush track

Mitigation: Do not wander on to main road; wear fluoro vests and solid footwear

Stop 10: Basal Te Kuiti Group limestone

Hazard: Traffic; slippery grass slopes

Mitigation: Do not wander on to main road; only cross road if instructed; wear fluoro vests and solid footwear

Stop 11: Te Anga limestone bluffs

Hazard: Traffic

Mitigation: Do not wander on to main road; wear fluoro vests

Stop 12: Ruakuri Cave

Hazard: Slipping on wet walkway floor

Mitigation: Wear solid footwear; take time; follow directions of Cave Environmental Officer

Stop 13: Mahoenui Group mudstone

Hazard: Traffic

Mitigation: Do not wander on to main road; wear fluoro vests

Stop 14: Waitomo Caves Discovery Centre

Hazard: Traffic

Mitigation: Do not wander on to main road