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Field Trip 5

27th November 2018

Structural Styles and Deformation Fabrics of an Emergent Accretionary Ridge, Hikurangi Margin, Southern Hawke's Bay:

from broken formation and dismembered units to tectonic mélange

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Cover image: View looking south along the Waimarama coast towards Red Island (middle distance) *(photo by Carolyn Boulton).*

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INTRODUCTION

Coastal cliff exposures in southern Hawke's Bay provide an opportunity to study structural styles and deformation fabrics within the emergent highest accretionary ridge forming the Hikurangi subduction margin forearc frontal wedge. Regional mapping indicates that the deformation fabrics reflect a complex interplay between fault movement, erosion, and deposition, and that over time, deformation migrates along multiple structures.

Within the coastal hill country and along-shore sections visited on this field trip (Figures 1 & 2), detailed field mapping of the mid-Cretaceous to late Neogene succession has delineated a NE–SW coast-parallel anastomosing network of five distinct thrust faults with accompanying shear zones composed of tectonic mélange. Locally, at Red Island, the tectonic mélange includes a number of Cretaceous-aged volcanic blocks with a pillow lava fabric interpreted as seamount derived.

Syn-tectonic erosional and depositional relationships display clear evidence for a temporal and spatial transfer of slip along en echelon and cross-cutting fault strands. The progressive westward (inboard-directed) younging of thrusts reflects the sequential imbrication in the hanging wall. The imbrication is linked to the structurally-driven growth of the submarine ridge and its associated Miocene-age Makara slope basin, situated to the west and on the inboard side of the coastal structural high. Locally, thrust duplex structures, footwall imbrication and out-of-sequence thrusts are also documented.

Between these thrust faults and associated tectonic mélange, the intervening fault-bounded blocks are stratigraphically truncated, complexly sheared, and tightly folded on a wide range of map scales. The deformation patterns reflect evolving structural complexity along the active margin during the Neogene. The scales and styles of deformation, which range from broken formation to dismembered units and tectonic mélange zones, including allochthonous blocks, are challenging to depict in maps and cross-sections. Yet, an understanding of the structural history of thrust faults within the margin, and of the length-scales at which deformation is accommodated, is integral to modelling margin evolution and seismicity along its active structures.

The principal objective of this field excursion is to demonstrate the structural styles and deformation fabrics characteristic of the emergent highest accretionary ridge in coastal southern Hawke's Bay. The emergent accretionary ridge (i.e., the Coastal High) is analogous to the thrust-dominated submarine ridges observed along the Hikurangi margin frontal slope accretionary wedge developing above the subduction interface. Our one-day field trip involves a 7–8 km hike extending along the coast from Red Island to Waimarama Beach (Figure 2). Along this traverse, deformation mechanisms operating along the outboard margin of the emergent basin and its bounding structures will be evaluated on the regional scale down to the grain scale. The spectacular exposures seen in the rolling hills and wave-cut rock faces will enable participants to visualize processes occurring offshore today in the seismically, structurally, and geomorphologically active accretionary prism.

Comment

This field guide has been compiled from data first recorded in 1975–78, and updated in 1982–83, 2015 and 2018 by the first author. However, rapid changes in sand cover over the shore platforms at inter-tidal to high-tide levels, as well as frequent cliff collapses, and weathering of the slake-prone lithologies means that some changes in the localities examined in detail may be necessary. Access to the coastal section is especially tide- (Table 1) and weather-dependent. The schedule below (Table 2) is planned to enable participants to complete the full traverse safely.

This field guide includes abridged and revised text and figures from a number of previous publications, including Pettinga (1980; 1982), Kobe and Pettinga (1984) and a previous Geological Society of New Zealand field guide to the Waimarama area (Pettinga, 1990). Additional photos are included in this field trip guide in Appendix B, which are referred to in text as "B1" etc.

Table 1: Tides, 27/11/2018

Tide	Time	Height (m)	Range (m)
High	09.24	0.87	1.62
Low	15. 42	−0.75	

Table 2: Target time schedule

	Arrive	Depart
Depart Napier	09.00 am	
Napier to Te Apiti Road Glenburn Farm	10.00 am	
Hike to stock yards on Glenburn Farm coastal hills	10.30 am	
Stop 1—lookout over coastal slopes and Red Island	10.40 am	11.00 am
Stop 2—Greensand locality on beach South of Red Is.	11.15 am	11.25 am
Stop 3—Red Island outcrop exposures and lunch stop	11.30 am	12.30 pm
Stop 4—First Bay N Red Island	12.40 pm	12.50 pm
Stop 5—N end of First Bay - Red Island related strata	13.00 pm	13.15 pm
Stop 6—Second Bay N of Red Island and overturned limb	13.30 pm	13.50 pm
Traverse mudflow south side Taingamata (tricky spot!)	14.00 pm	14.10 pm
South end Cray Bay	14.20 pm	14.30 pm
Mid Cray Bay stop	14.40 pm	14.45 pm
Stop 7—Te Wainohu Point southside stop and snack	14.55 pm	15.10 pm
Low tide at 15.42		
Rounding Te Wainohu Point	15.15 pm	15.20 pm
Stop 8—Rounding Te Ahua Point	15.30 pm	15.40 pm
Stop 9—Rounding Te Puku Point	15.45 pm	16.00 pm
Exposures to Ramp section	16.05 pm	16.15 pm
Stop 10—Transposition fabric to Whangai Bluff	16.20 pm	16.50 pm
Stop 11—Whangai Bluff and Melange Zone	16.55 pm	17.25 pm
Return to vehicles	17.30 pm	
Return to Napier (~50 min drive)	18.15 to 18.30 pm	

GEOLOGICAL SETTING

Since latest Oligocene time, the development of the imbricate accretionary wedge of the Australia–Pacific plate margin has driven the tectonic evolution of coastal southern Hawke's Bay. The onland exposure of the highest part of the accretionary slope provides an exceptional opportunity to examine in detail the structural/stratigraphic anatomy of an actively forming trench slope-structural ridge (the Coastal High) and an associated slope basin (the Makara Basin). In particular, the shore platform and coastal cliff exposures extending from Red Island to the south end of Waimarama beach provide insights into dynamic interactions between thrust faults, submarine ridges, and onlapping slope basin sequences.

Location of field trip area

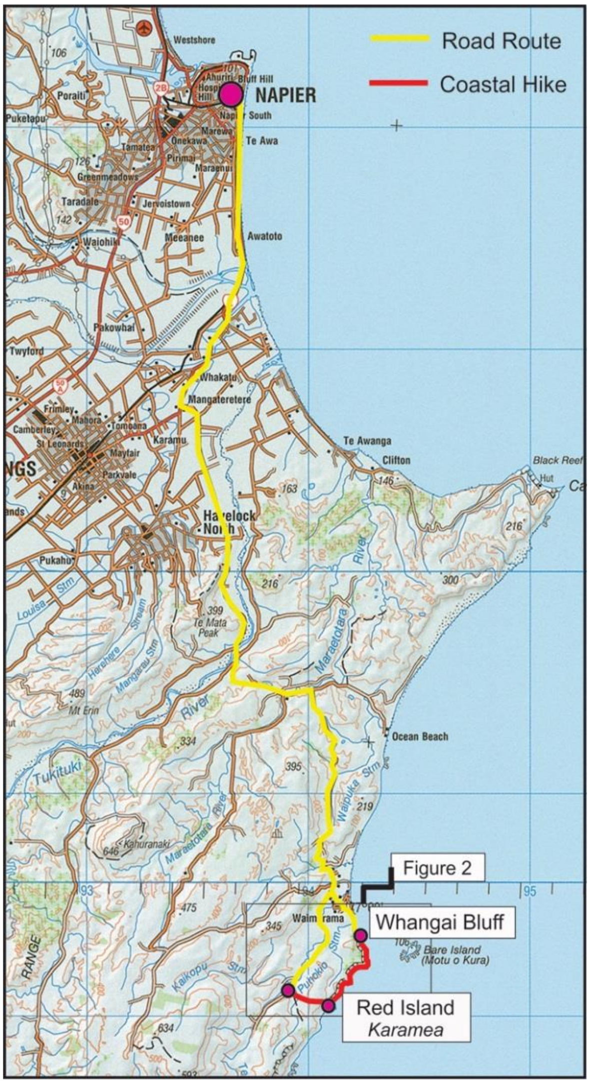

Figure 1 (left): Road route and field hike for the Red Island to Waimarama coastal excursion. (Map source: [NZ Topo Map] images sourced from [LINZ]).

Figure 2 (below): Google Earth image of the coastal area south of Waimarama township, southern Hawke's Bay, depicting the field trip hiking route of ~7.4 km. (source of map image Google Earth Pro – image dated 27/3/2018).

STRATIGRAPHIC FRAMEWORK

The stratigraphic succession within outcrop exposures in coastal southern Hawke's Bay include Late Cretaceous to Quaternary sedimentary strata. Pettinga (1980) adopted a 12-formation subdivision, but no formalized nomenclature was established. For the purpose of this field trip, the nomenclature for the stratigraphic succession used is based largely on the now formally published stratigraphic nomenclature (e.g., Lee et al. 2011), although some local, informal stratigraphic "member" terminology for the Glenburn Formation is retained from Pettinga (1980) to provide more detailed insights into structural deformation of the Late Cretaceous and early Paleogene sequence (Table 3). No detailed stratigraphic descriptions are presented here, but these may be found in Lillie (1953), Kingma (1971), Pettinga (1980), Moore et al. (1986), Moore (1988) and Lee et al. (2011).

Table 3: Informal "local" member subdivision, age correlations and brief lithologic descriptions for the Glenburn Formation, Waimarama District, southern Hawke's Bay (after Pettinga, 1980).

	Member	**Age (NZ)**	**Lithology and macrofossils**
Glenburn Formation	Huarau	*Mh–Mp*	Alternating thickly bedded to massive sandstones, minor siltstones and/or mudstone. Graded, laminated and cross-bedded. Pebbly mudstone and conglomerate lenses. Jarosite mineralisation is common. Coal lenses, plant fragments and pyrite also common. *Ostrea lapillicoli; Inoceramus matotorus(?); Inoceramus prisms*.
	Te Puku	*Mp*	Alternating thinly to medium bedded sandstones, siltstones and mudstones. Carbonaceous, graded, laminated, cross-bedded, convoluted. Rare conglomerate and grit lenses, elliptical concretions. *Inoceramus pacificus; Inoceramus australis*.
	Te Ahua	*Rt*	Alternating commonly sharply bedded carbonaceous sandstones, mudstones and/or siltstones. Sandstone beds are graded, laminated, convoluted and cross-bedded. Richly bioturbated beds are common. Occasional cone-in-cone concretions. Rolled mudstone clasts, conglomerates, concretionary beds. *Inoceramus opetius, Inoceramus nukeus.*
	Te Wainohu	*Rm*	Alternating thickly bedded carbonaceous sandstones–mudstones, with minor pyrite and jarosite mineralisation. Graded, cross-bedded, laminated, rarely convoluted. Large spherical concretions. Conglomerate and grit lenses and beds with indurated pebbles and *Inoceramus bicorrugatus*

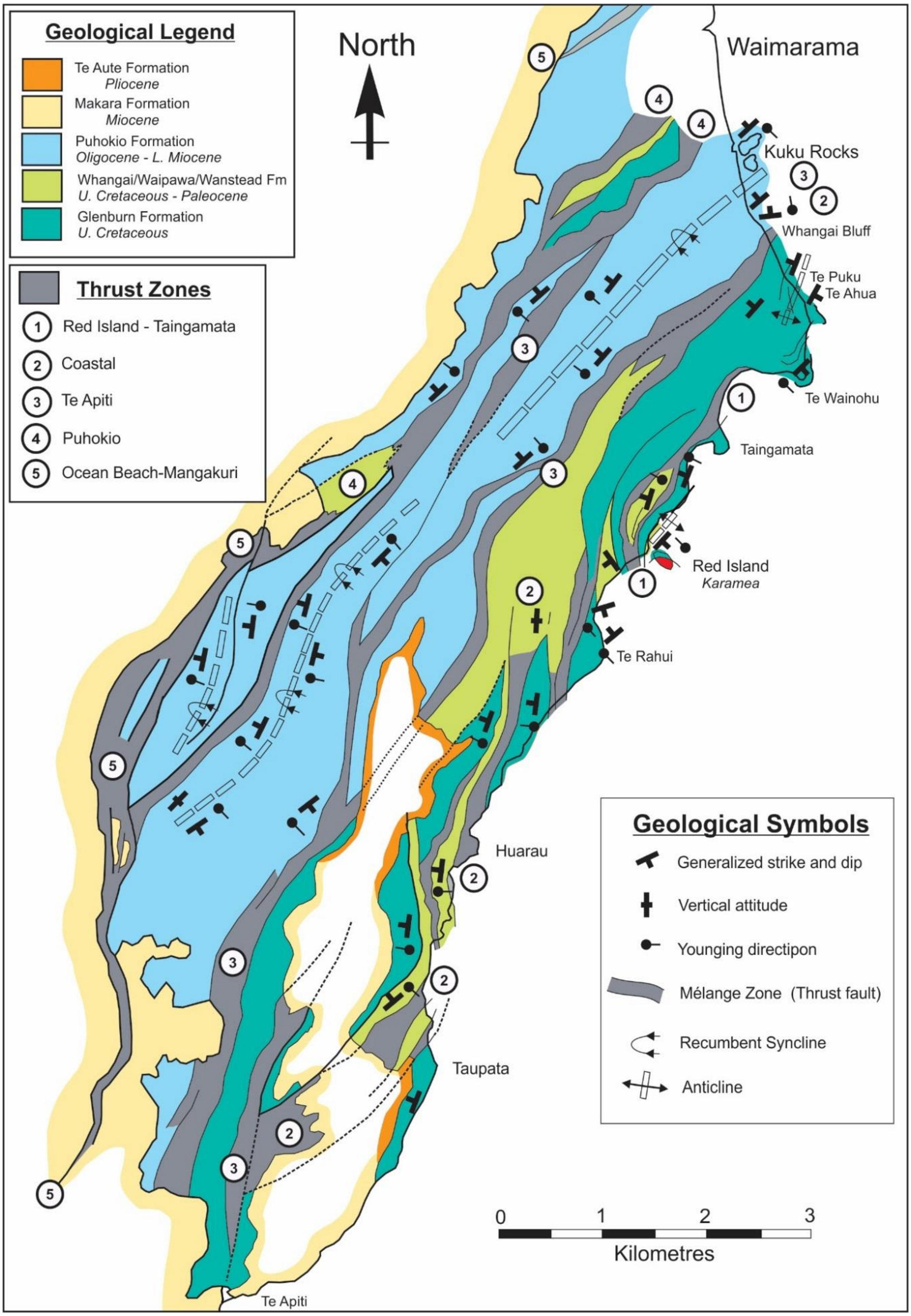

Figure 3: Structural domain map for the Coastal High from Waimarama to Te Apiti. This field trip will follow the coastal outcrop exposures from Red Island (Karamea) north to Waimarama. Figure modified from Pettinga (1980; 1982).

STRUCTURAL ANATOMY OF THE COASTAL HIGH

The Coastal High (Pettinga 1982) incorporates almost an entire stratigraphic succession from Late Cretaceous to early Miocene (Figure 3). Middle to late Miocene strata are also involved in the structural evolution of the high, but to a much lesser degree of complexity. Stratigraphically, plate boundary deformation is recorded in progressively younger units. Complexly deformed, often truncated Late Cretaceous to early Miocene successions are incorporated in the NE–SW trending structural ridge exposed onshore in the coastal hills south of Waimarama (Figure 3). The Cretaceous–Paleogene part of this incorporated succession formed a pre-existing passive continental margin sediment wedge prior to plate boundary propagation; in turn, it is now "basement" to the inboard trench slope sediments which onlapped the high (Lewis and Pettinga 1993).

At the south end of Waimarama Beach, the shore platform section reveals that early (early Miocene) ponded sediments were deposited in an accretionary slope basin (proto-Makara Basin) on the inboard side of the coeval coastal structural high. Subsequently, early Miocene sediments became part of the landward tilting flank of the structural high, and were strongly deformed via folding and thrust faulting. Younger (middle and late Miocene) accretionary slope basin sediments (Makara Basin) were deposited against the earlier basin succession with stratigraphic onlap that is locally strongly unconformable. The later Makara Basin sediments are not present at Waimarama Beach, but they can be mapped inland and to the north of the township (see Figure 3), as well as on Bare Island located immediately offshore from Waimarama, where a thin middle–late Miocene condensed succession is present.

Gross structural fabric in the Coastal High is dominated by a NE–SW trend (Figure 3). All pre- to early Miocene rocks have been tightly folded, faulted and imbricated by thrust faulting. Most thrust faults are accompanied by zones of tectonic mélange, broken formation and dismembered units (Figure 4) (Raymond 1984). Folding is related to the development of these thrust-driven tectonic mélange zones.

Five distinct thrust zones with associated development of tectonic mélange are mapped within the Coastal High (Figure 3). Several secondary branches occur with each of these zones, forming a complex braided network in map view. The thrust zones have formed sequentially from east (oldest) to west (youngest), indicating a hanging wall imbricate fault zone evolution for the Coastal High.

Internally, the thrust zones are intensely sheared. Mélanges within these thrust zones incorporate all but post-Miocene formations. Intensely sheared and slickenlined montmorillonite clays derived from the early Cenozoic Wanstead Formation are the most common matrix component in these zones, while more coherent blocks of all pre-Pliocene formations, ranging in size from less than 1 metre to several kilometres in length and hundreds of metres across, occur as lozenges, fault-bounded "floater" blocks, or fault-bounded "slabs". Internally, the larger blocks are also fractured and fragmented by connected networks of bedding-parallel shear zones and faults, leading to the progressive development of broken formation and dismembered units. The latter are structurally equivalent to the tectonic mélange zones, and form part of the same braided system of faults. From intersection with topography and coastal exposures, most thrust faults dip to the WNW to NW at angles ranging from less than 20° to near 90°.

As noted, the sequential development of the five major thrust zones with respect to each other has been established from map-scale cross-cutting relationships. The oldest zones are the Red Island–Taingamata Thrust Zone (Figure 3, thrust zone 1) and the Coastal Thrust Zone (Figure 3, thrust zone 2) (Stops 1,2, 4–7). Involvement of the mid-Cenozoic Waitakian Stage (Puhokio Formation) mudstones within both these zones yields a maximum age of development (Pettinga 1980; 1982). In coastal exposures near Huarau (for location, see Figure 3), south of the area visited on this field trip, the Coastal Thrust Zone reveals more complex internal structural relationships, with out-of-sequence thrusting and evidence for early-stage hanging wall imbrication and late-stage footwall imbrication.

The Te Apiti Thrust Zone (see Figure 3, thrust zone 3) forms an offshoot from the Coastal Thrust Zone near Waimarama, but at its southern end, it clearly cross-cuts the latter. The Te Apiti Thrust Zone delineates an important boundary between the late Oligocene–early Miocene clastic mass-flow succession of slope

basin affinity to the west, and the Late Cretaceous–early Cenozoic terrain to the east. The Waimarama Beach platform and coastal cliff exposures provide some of the most complete sections clarifying these relationships and their associated structural complexities (Stops 10, 11). Shore platform exposures at low tide on Waimarama Beach reveal a basal succession of debris flow units, inferred to have been derived locally from the Te Apiti Thrust Zone when it breached the paleo-seafloor and triggered slumps which gave rise to the mass flow units (Stop 11). Lithologies incorporated within these basal Puhokio Formation debris flow units appear to be locally derived from the mélange zones. The debris flows are interbedded with basal slope basin deposits of the proto-Makara Basin (detailed in Pettinga 1990).

To the west, and not exposed along the coastal traverse taken on this field trip, the Puhokio Thrust Zone (Figure 3, thrust zone 4) pre-dates the Ocean Beach–Mangakuri Thrust Zone (Figure 3, thrust zone 5). The last phase of thrust movement affecting the Coastal High and now exposed onland occurred along the Ocean Beach–Mangakuri Thrust Zone, and it involved late Miocene flysch. This thrust zone forms the western margin to the Coastal High in the district, although near Waimarama it is partly obscured by large landslides in Puhokio Valley. The best exposures of this thrust zone are in the coastal cliffs south from Ocean Beach, located ~7km north of Waimarama. The final phase of thrust-driven structural inversion of the Miocene Makara Basin succession is represented by the development of the Elsthorpe Anticline, located west of the Coastal High (refer to Lewis and Pettinga 1993, figure 11).

Stops 1 & 2: Red Island–Taingamata Thrust Zone Overview (Figures 5A and 5B)

The Red Island–Taingamata Thrust Zone extends from the NW side of Taingamata Peninsula to SW of Red Island. The thrust zone can be subdivided into three parts (see inset Figure 5A): (1) a western mélange belt; (2) a central inverted limb sequence; and (3) an eastern mélange belt—which includes Red Island.

The first part, the western mélange belt, may be subdivided into two mélange components bearing a cross-cutting relationship to each other (Figure 5B, cross section C–D). The basal contact of the early stage mélange dips steeply westward, near-parallel to stratification in the adjacent inverted Glenburn Formation sequence (to the east). The distribution of the Wanstead Formation-derived montmorillonite clays forming the highly sheared mélange matrix is complex. Thrust fault bounded wedges of these matrix clays clearly wedge-out downward, dipping steeply to the west (Figures 5C, cross section A–B). Successive wedges occur along-strike, but their basal thrust contacts dip less steeply in the later (structurally higher, cross-cutting) wedges to the west. The mélange zone units between these wedges are composed primarily of the Late Cretaceous Glenburn Formation (Te Puku member) and Paleogene strata (Wanstead and Whangai Formations). The later-phase mélange is overthrust onto the early-phase, truncating it (Figure 5B, cross section C–D). The lower part of this late thrust mélange near Red Island displays internal mesoscopic zig-zag type folding. Also incorporated into this western mélange belt is a large “slab” of a more coherent latest Cretaceous to early Paleogene stratigraphic succession.

An inverted sequence of Glenburn Formation strata (Te Wainohu member) constitutes the second, central, part of the Red Island–Taingamata Thrust Zone. This overturned limb is traceable from west of Red Island northward to Taingamata Peninsula, forming this promontory. The limb is internally more coherent, with the dominant deformation being represented by transposition fabric development (for an explanation refer to Appendix A) and zones of broken formation. Structural fabric analysis indicate that the direction of separation is generally to the NNE. At Taingamata, the limb is folded into a north-plunging antiform. The complex core of the antiform is exposed on the southern side of the promontory. Structurally beneath the inverted limb, a further mélange zone trending NNE–SSW is exposed at Red Island and forms the edge of the first headland to the north. This mélange separates Red Island structurally from the mainland but remains poorly exposed.

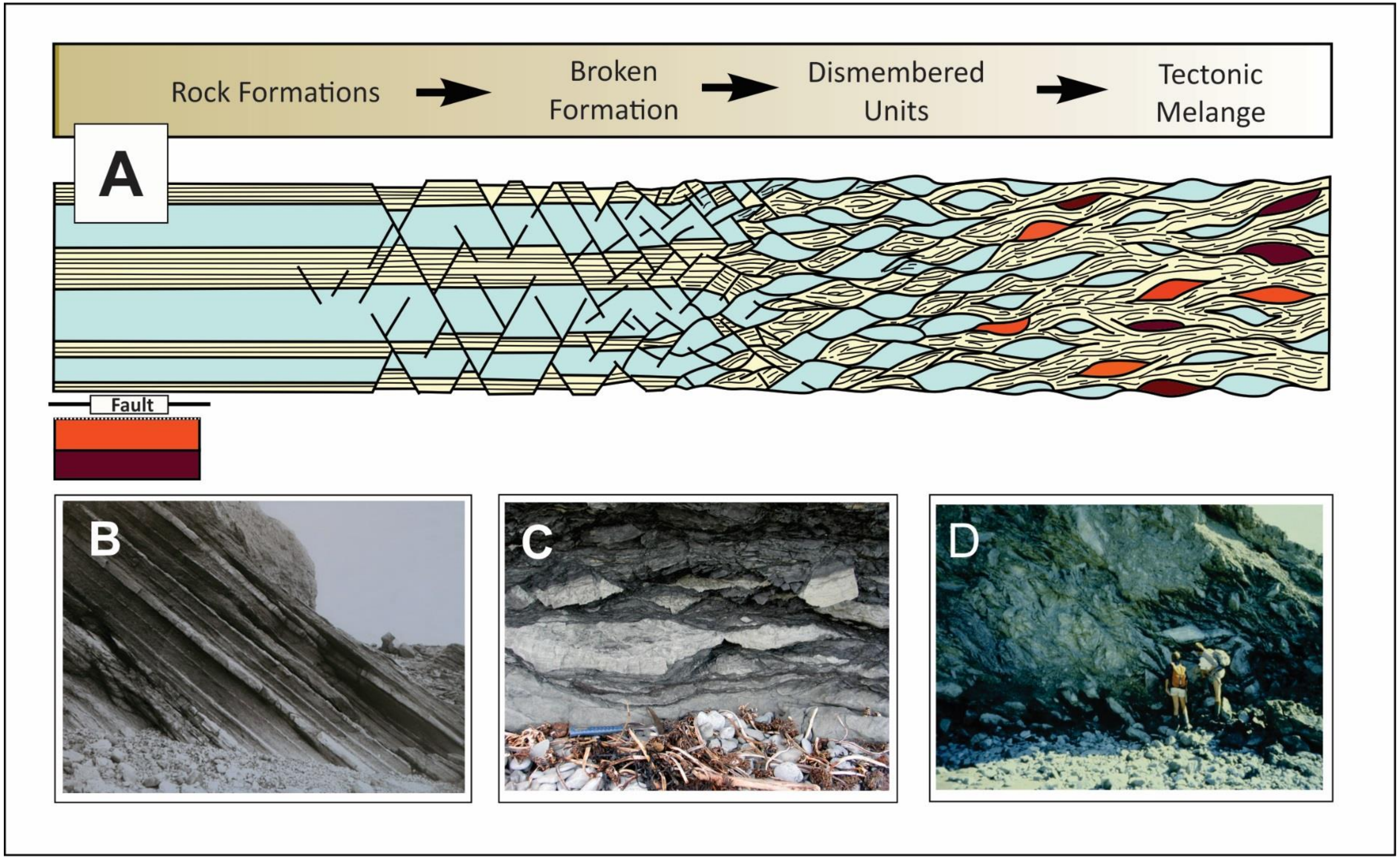

Figure 4: The classification of rock formations ranging from intact, coherent units to faulted broken formation and dismembered units to tectonic mélange (A is modified from Raymond, 1984). **A:** schematically depicts the progressive fragmentation and disruption of alternating sandstone–mudstone strata leading ultimately to tectonic mixing of units (mélange). **B:** intact strata of the Glenburn Formation Te Ahua member at Te Ahua Point, south of Waimarama Beach; **C:** dismembered strata of the Glenburn Formation Te Wainohu member, north Cray Bay; and **D:** tectonic mélange at south end of Waimarama Beach.

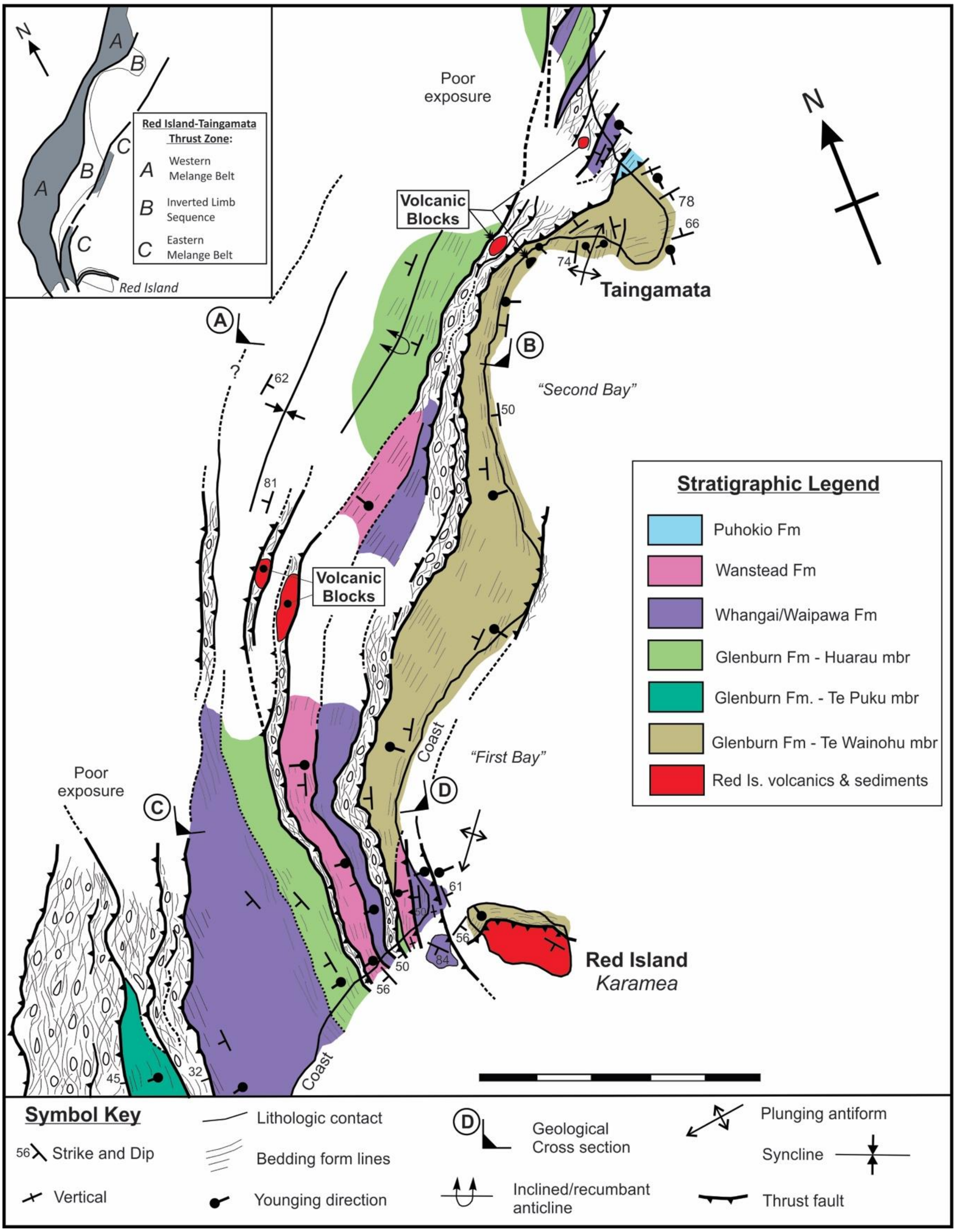

Figure 5A: Geological map of the Red Island–Taingamata Thrust Zone. Inset: Depicts internal subdivision of the thrust zone. Note the east–west trending thrust fault at the base of the Red Island volcanic succession. See Figure 5B for cross sections A–B and C–D. Figure modified from Pettinga (1980; 1982).

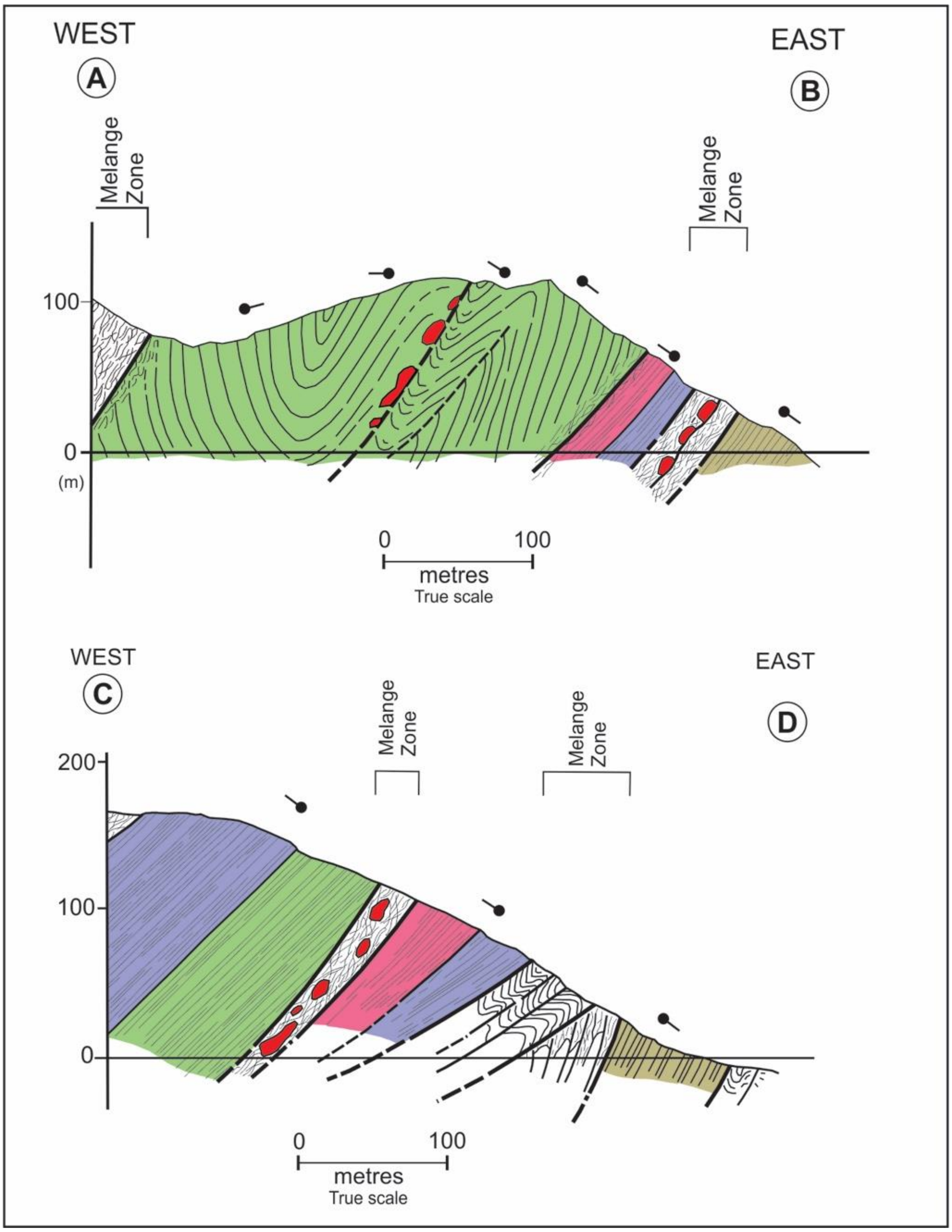

Figure 5B: Cross sections of the Red Island–Taingamata Thrust Zone. For section locations refer Figure 5A. Figure modified from Pettinga (1980; 1982).

Movement directions from the inverted sequence, as inferred from separation plots, indicate northward-directed deformation. Micro- and macro-structure data from Red Island indicate a similar movement, overprinted by a west-to-east event. Small-scale fold axes also indicate two deformation events, directed from S to N and from W to E.

At a number of localities within the Red Island–Taingamata Thrust Zone, "floater" blocks of the mid-Cretaceous Red Island volcanics are mapped, the largest block forming Red Island itself, which lies within the eastern mélange belt. Again, an antiform is inferred to structurally separate Red Island from the mainland, and the core of this fold was sheared out along the eastern mélange zone.

Stop 3: Red Island Volcanics and Submarine-Exhalative Mn–Fe Mineralisation (Figures 6 & B1)

The Red Island volcanic and volcano-sedimentary rocks are very restricted in occurrence. The maximum stratigraphic succession forms Red Island itself and is less than 50 m in total stratigraphic thickness. Other minor outcrops occur along the coast near Red Island, immediately offshore from Kairakau Beach 10 km south of Red Island and at one locality inland, in the core of the Elsthorpe Anticline. Age determinations based on micro- and macro-fossils are uncertain, but a late Albian (Motuan Stage) seems probable (CP Strong pers comm. ~1977).

Kobe (1976) and Kobe and Pettinga (1984) describe the Early Cretaceous series of fossiliferous limestones enclosing the four basaltic pillow lava units of Red Island, characterized by either pillow or disjunction fracture fabric, their associated and pervasive zeolitization and partial cover by a "blanketing" deposit of ferriferous–siliceous beds (see Appended Figures B1/A–C). The latter contain strong concentrations of Mn oxide at their base and is interpreted as an exhalative submarine hydrothermal deposit. The intercalated and sequence-topping fossiliferous bedded pink limestones also contain Mn oxide nodules. The field relations, mineralogy and fabrics indicate a syn-diagenetic concentration of Fe and Mn in a volcanic–sedimentary submarine environment.

Most of the outcrop occurrences of the Red Island volcanics and related deposits are as allochthonous "floaters" within tectonic mélange zones (see Figures 5A & B). However, on the first headland north of Red Island some boulders of Glenburn Formation conglomerate (Mangaotanean age, Te Wainohu member) contain clasts of Red Island volcanics with associated red chert and pink limestone (see appended Figures B1/D & E). On the tip of the headland, outcrop exposures also include interbedded and sheared pink argillaceous limestone and mudstones similar to those recorded from the basal sequence on Red Island, suggesting a sedimentary relationship.

Stops 4–6: First Bay and Second Bay North from Red Island

The coastal cliff and shore platform outcrops leading north from Red Island to Taingamata Peninsula are currently generally disappointing in terms of exposures. Apart from the headland at Red Island, the shoreline section is entirely within the overturned limb of Glenburn Formation (Te Wainohu member). Several outcrops reveal that the sequence is dominated by moderately to thickly bedded sandstones with thin, interbedded carbonaceous siltstones and mudstones. The beds are spectacular in terms of mass flow related sedimentary structures (grading, cross bedding, laminations and convolutions). On the headland between First and Second Bays (Figure 5A), there are grit beds exposed, which include clasts derived from the Red Island lavas and pink limestone sequence (see appended Figures B1/D & E). The sequence is also fossiliferous, with fragments and rarely whole *Inoceramus bicorrugatus* indicating a Mangaotanean age.

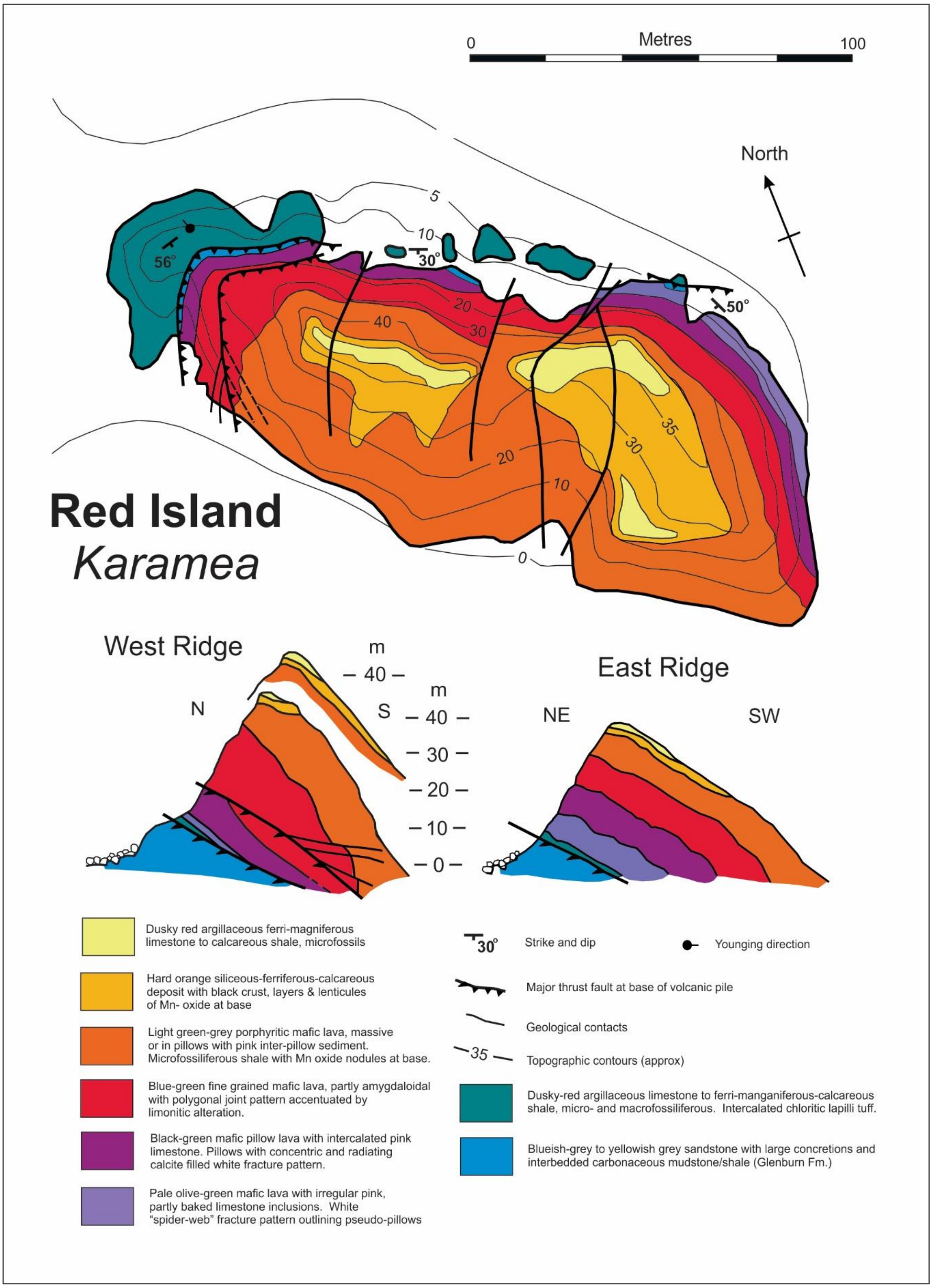

Figure 6: Geological map and cross-sections of Red Island (Karamea). Geology after Kobe (1976) and Kobe and Pettinga (1984).

Interestingly, sedimentary structures indicate that this succession is overturned. In the Te Aute Bulletin, Kingma (1971) mapped this coastal section and described the strata, but he failed to recognise the structural overturning—he noted that the sedimentary structures were indicative of an eastern source region, clearly an untenable proposition!

At the north end of Second Bay, we will negotiate around several large boulders of Red Island volcanics, which have been emplaced by recent debris flows from their previous *in situ* location within the Western Mélange Belt of the Red Island–Taingamata Thrust Zone (see Figure 5A) exposed on the adjacent higher slopes. This location is potentially a difficult point to negotiate around and we will aim to pass here about 2.00 pm, within 90 minutes of low tide.

Stop 7: Cray Bay to Te Wainohu Point

At the south end of Cray Bay and extending northward along the cliffs and across deeply dissected slopes at the back of the beach, we can observe the partly exposed Red Island–Taingamata Thrust Zone with its tectonic mélange and its complex relationship to the allochthonous stratigraphic successions examined in coastal exposures both to the south and to the north end of the bay (Figures 5A & 5B). Stop 7 is located along the northern side of this bay, where we will examine some excellent outcrop exposures of dismembered strata of the Glenburn Formation Te Wainohu member (see Appendix Figures B2/A & B). The exposure reveals an intensely bedding-parallel sheared carbonaceous mudstone "matrix" with sandstone beds that have been stretched and pervasively fractured by brittle faulting. In close-up examination of the sandstone "blocks" we can observe these are cross-cut by a network of thin grey-black cataclastic shears forming a 3D-web structure within the sandstone blocks. There is also evidence for multiple episodes of shear disruption of the sandstone strata.

From Stop 7 to Te Wainohu Point, the sequence becomes progressively less deformed and represents a useful local reference section for the Te Wainohu member. Macrofossils, *Inoceramus bicorrugatus* indicate a Mangaotanean to Teratan age. The lower stratigraphic contact is not exposed at Te Wainohu Point. The member includes thickly bedded alternating non-calcareous sandstones (up to 4–6 m thick), often with lenses and beds of conglomerate and thin carbonaceous siltstones and mudstones. Some graded sandstones contain basal conglomerate lenses. Large spherical concretions in the thickly bedded sandstones, reaching diameters up to 3.5 metres, are common especially west from Te Wainohu Point.
Outcrop exposures north from Te Wainohu Point are generally poor, with significant landsliding encroaching across the coastal section. We will traverse on to Te Ahau Point. The shore platform section from Cray Bay to Te Ahua again has several difficult locations requiring low tide for ease of access.

Stop 8: Near Te Ahua Point

At this locality, the Glenburn Formation Te Ahua member is composed of thinly to thickly bedded carbonaceous flysch. Lower and upper stratigraphic contacts are comformable with other members of the formation. Within the siltstone–mudstone beds at Te Ahua Point, richly fossiliferous beds with *Inoceramus opetius* and *Inoceramus nukeus* are common. There are a wealth of well-exposed, mass flow-related sedimentary structures and intensely bioturbated beds in this sequence.

Stop 9: Te Puku Point to the "Ramp" (Figures 7A & B; Figure B3/A to D)

At Te Puku Point and north to Whangai Bluff (refer to Stop 10), the Glenburn Formation strata are assigned to the informal Te Puku member. Strata are exposed in outcrops along the lower cliffs and on the shore platform (Figure 7A & B; Figure B3), and are generally thinly bedded alternating sandstone–siltstones/mudstones with macro-fossiliferous horizons. Beds contain a range of excellent sedimentary structures again indicative of a mass-flow origin.

At the "Ramp" locality, there is a sharp bedding parallel thrust fault contact between broken formation and dismembered strata, with a more coherent interval below this contact disrupted by a well-developed transposition fabric (Figure B3/A & C). To the south (see Figure 7B), the cliff-tops reveal shears forming a braided network isolating larger and smaller blocks or "floaters" of more coherent strata. Observed at this scale, the structural–lithological relationships highlight the difficulties involved in establishing stratigraphic continuity in such tectonic settings. It is possible that the intensely sheared zone at this locality may be structurally correlated to the Red Island–Taingamata Thrust Zone, but outcrop exposures preclude confirmation of this.

Between Te Puku Point and Whangai Bluff (Figures 7A & B), typical Te Puku member strata are intensely deformed and a pervasive transposition fabric is present at a range of outcrop scales. Several major thrust faults (see Figure 7B, shears I–V) confirm southeast-directed overthrusting. Note the development of structural "horizons" with metres-scale transposition fabric and the development of a bedding-parallel shear fabric within the black carbonaceous mudstones, with the transposed fabric and boudinage structures associated with sandstone–siltstone beds. The overall deformational fabric ranges from broken formation to dismembered units (Figures B3 & B4). Within this complex, several overprinted shear phases are present (Figure B3/B–D; B4/B), and earlier thrust shears are crenulated and folded (see Figure 7B, shear IV). The overprinting of shear fabrics has led to the earlier formed broken formation/dismembered units being incorporated in a later shear zone with a well-developed transposition (or lozenge) fabric (Figure B3). Between stops 9 and 10, several spectacular exposures of the structural deformation and consequent fault fabric overprinting are present.

Stop 10: Whangai Bluff (Figures 7A & B; B5)

Latest Cretaceous and early Cenozoic strata assigned to the Whangai and Waipawa formations are represented by a transposed "floater" block at the north end of the coastal cliff section (stop 10), immediately south of the amalgamated Coastal and Te Apiti thrust zone (thrust zones 2 & 3) mélange.

At this locality, Pettinga (1980) described the Whangai Bluff exposures of the Whangai Formation as the best in the district. The truncated sequence is characterised by the distinctive thinly bedded light and dark-coloured argillites (Figure B5/B). Moore (1988) included this calcareous sequence in his newly named Porangahau Member, while Kingma (1971) described the succession here as the "zebra beds". These "argillites" grade up into alternating greensands and dark-brown to black mudstones now tentatively assigned to the Waipawa Formation. Moore (1988) established a Teurian age for the basal part of the Whangai Bluff sequence. The argillites are highly bioturbated and parallel laminated. Rare, interbedded thin greensands are present, lensing markedly in outcrop. Several clastic dykes have been injected at a high angle to bedding through the argillite sequence. It is possible that this sequence contains the K–Pg boundary!

The Waipawa Formation beds are composed of a truncated sequence of alternating thickly and thinly bedded greensands with parallel and convolute laminations. The beds are graded and cross-bedded and alternate with mid-brown to brown-black mudstone resting conformably on Whangai Formation strata. Occasional, thin indurated calcareous argillite beds are interbedded within what appears to be a transitional facies. The base of the sequence at Whangai Bluff is represented by a major 5–10 m-wide fault zone located on the south side of the bluff. Adjacent to the fault, sheared and intensely fractured strata of the Glenburn Formation Te Puku member are well exposed.

To the north of Whangai Bluff, a fault marks the contact between Waipawa and Wanstead formations. North of this fault contact, Wanstead Formation greensands and dark-brown mudstones are almost indistinguishable from the Waipawa Formation beds below the fault.

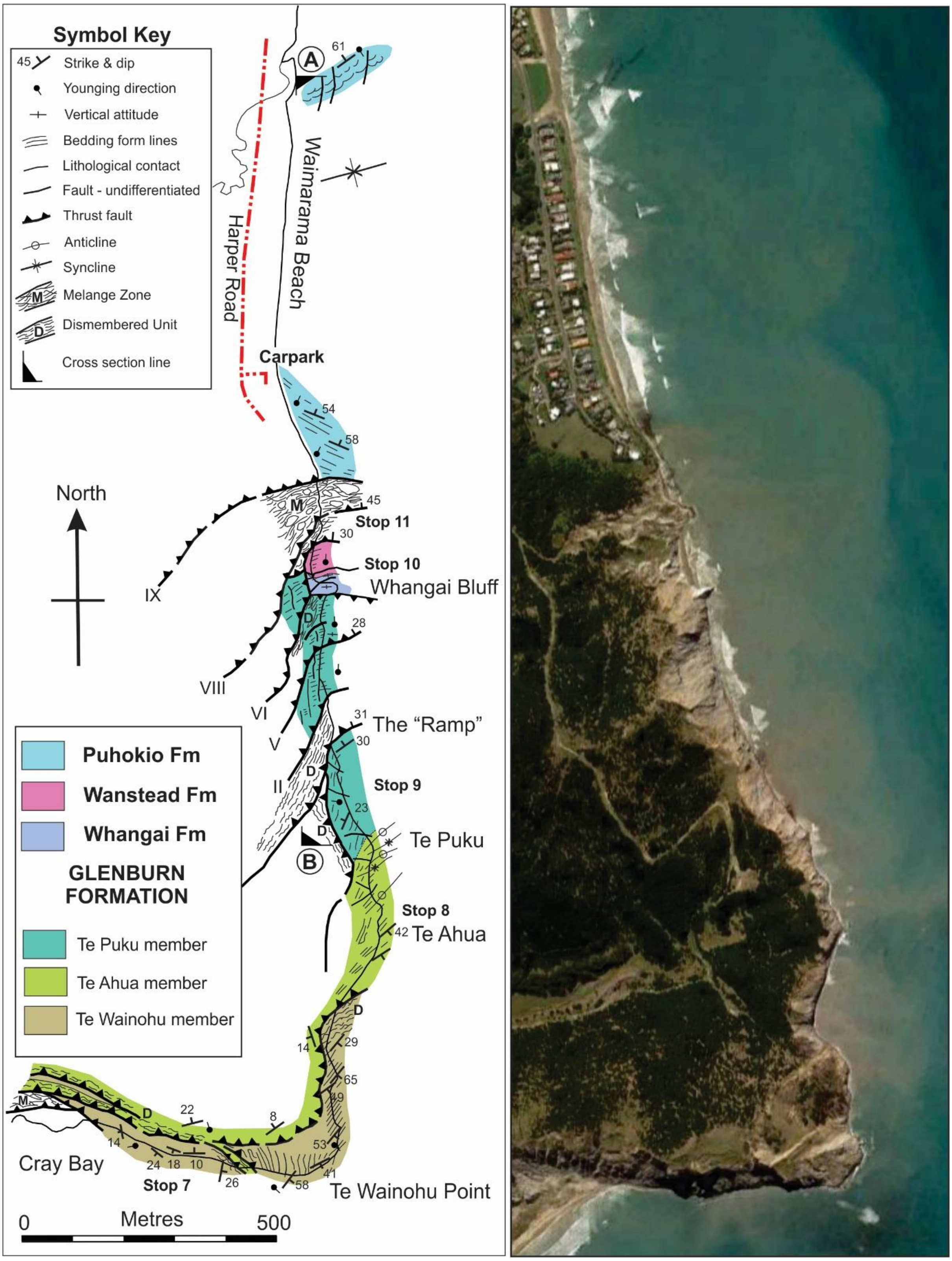

Figure 7A: Detailed geological map of the coastal cliff section extending from the Kuku Rocks reef on Waimarama Beach, southward to the north end of Cray Bay. The position of cross-section line A–B is shown, and presented in Figure 7B. Note the mélange zone represents the combined Coastal and Te Apiti Thrust zones (thrust zones 2 & 3, refer Figure 3). *Source of right side image is Google Earth Pro, image dated 13/9/2018.* Map is modified from Pettinga (1980; 1982; 1990).

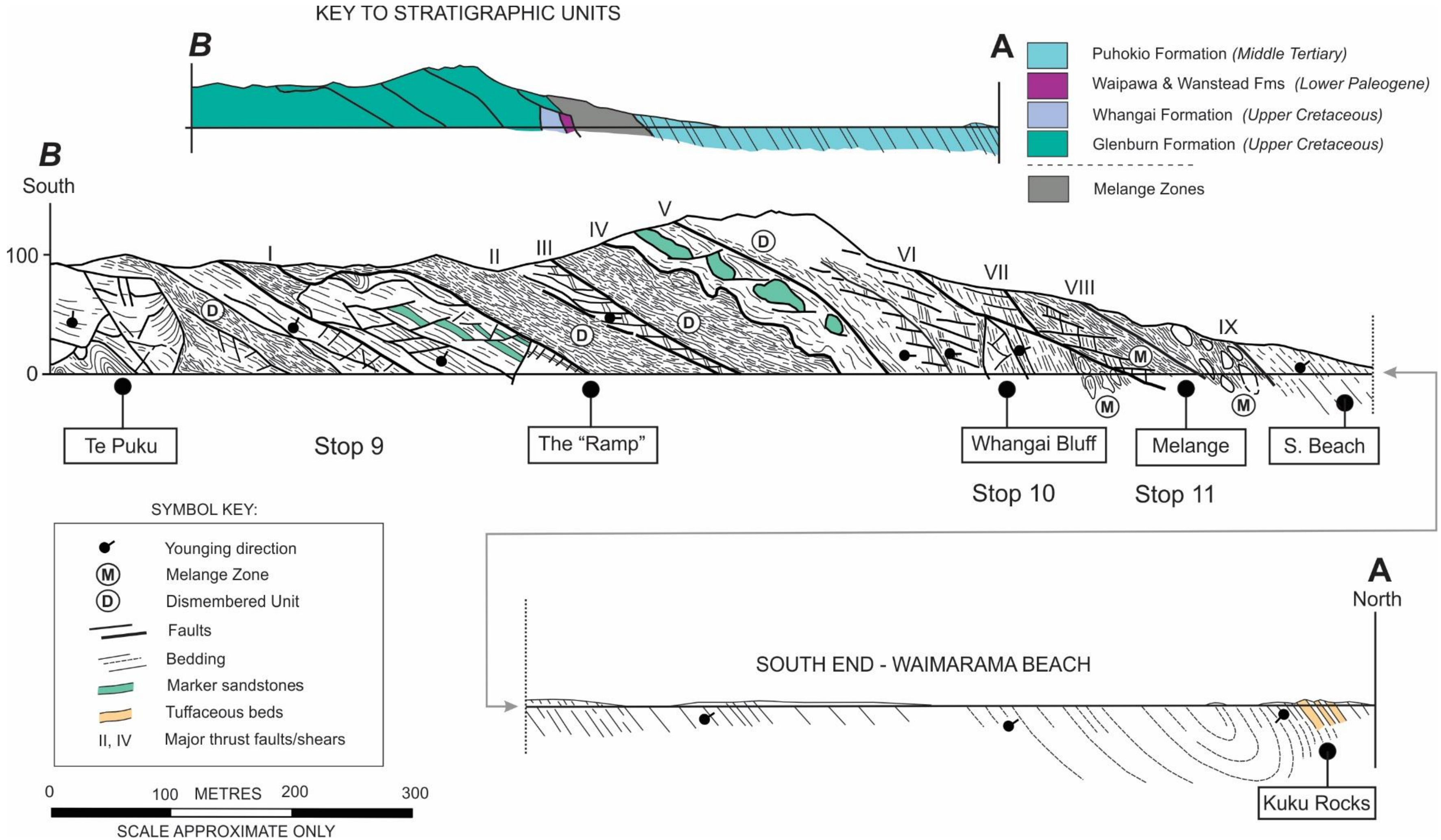

Figure 7B: Cross-section A–B (for location see Figure 7A) extending from Kuku Rocks on Waimarama Beach to Te Puku Point. Figure modified from Pettinga (1980; 1982).

However, the distinction between units is based on the presence of interbedded light bluish-green to greenish-grey montmorillonitic clays within the mudstones. These mudstones are always highly sheared and northward grade into the mélange of the amalgamated Coastal and Te Apiti Thrust zones. Again, sedimentary structures within the thickly and thinly bedded sandstone beds are indicative of a mass flow (turbidite?) origin for this succession. The light-coloured swelling clay mudstones/claystones represent distinctive background hemipelagic sedimentation.

The Whangai Bluff sequence is abruptly truncated in the slopes above by a major low-angle thrust (shear VI; Figures 7A & B; 5B/A). This thrust corresponds to the basal shear plane of the mélange zone present at beach level to the north. In the slopes above Whangai Bluff, Waipawa Formation and late Cretaceous Glenburn Formation lithologies are present, and stratal continuity is disrupted by a meso-scale transposition fabric. This contrasts sharply with the vertical fault zone contact seen on the south side of the bluff, where micro- and meso-scopic deformation fabrics indicate a north side-down sense of motion, interpreted by Pettinga (1982) as representative of an early phase northwest-directed deformation. The cross-cutting relationship between structures at this locality is clear.

Stop 11: Amalgamated Mélange Zone (Figures 7A & B; B6/A–C)

The mélange zone at this locality represents the amalgamated Coastal and Te Apiti Thrust zones (Figure 3, thrust zones 2 & 3). Internally, the zone has several major shears (Figures B6/A & B) and a meso-scale transposition fabric. “Floater” blocks within the mélange are derived from a number of discrete formations, which are all of locally exposed formations, including some of the Oligocene massive mudstones and turbidites (proto-Makara basin sequence). The mélange matrix is a pervasively sheared clay containing abundant montmorillonite, illite and other clays (claystone/mudstone derived) with excellent slickenlines. The matrix clays are derived from the Paleogene Wanstead Formation. The sheared “matrix” clays were referred to incorrectly as "bentonites" in earlier literature covering East Coast region. Outcrop geometry and the attitude of the major shears indicates the mélange zone wedges (narrows) at depth—something better exposed further south along the Waimarama coast. The amalgamated mélange zone reveals a variety of deformation fabrics that are indicative of movement directions, as well as relative movement of the upper and lower contacts. These features include internal major shear surfaces, fold structures, lineations, and transposition fabrics. Generally, the inferred movement direction is from NW to SE.

The remaining ~200m of our coastal traverse is unlikely to offer much by way of outcrop exposures. During winter months, a low-level shore platform does reveal an onlapping slope basin fill succession assigned to the mid-Cenozoic (Waitakian Stage) Puhokio Formation. The basal beds include some spectacular coarse debris flows interpreted to be locally derived debris from the adjacent tectonic mélange zones, which was mobilized from the structural ridge into the adjacent basin succession. An inclined syncline is mapped (see Figure 7A & B) with a series of overturned tuffaceous beds well exposed at Kuku reef along Waimarama Beach, approximately 800m to the north.

Our coastal traverse will conclude at the first carpark area above the seawall, south end of the beach.

Acknowledgments:

The authors thank Anna McKay (Glenburn Farm) for advice and granting access to property in order to reach the coastal section visited on this field trip.

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APPENDIX A—TRANSPOSITION FABRIC

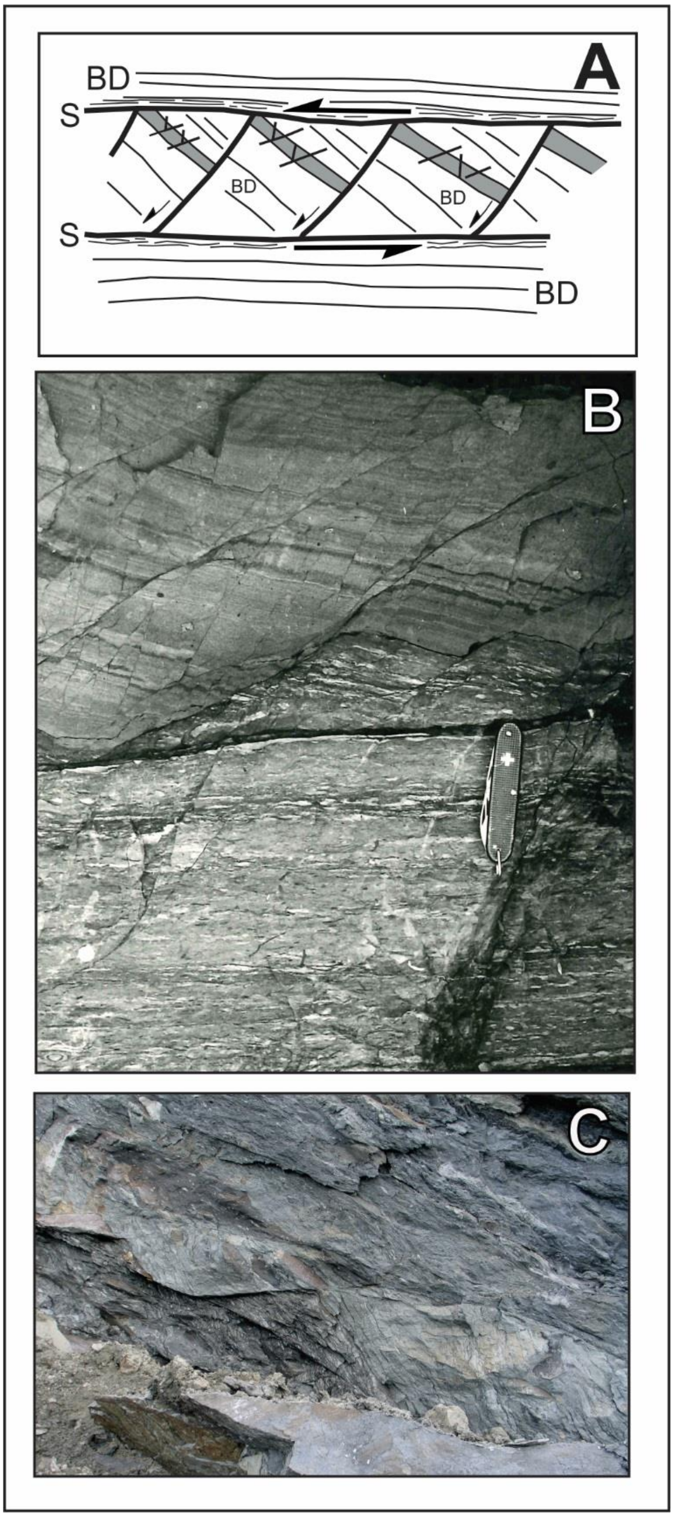

Figure A1: Throughout this field guide, we discuss transposition (or lozenge) fabrics formed at shallow crustal levels in the accretionary wedge. Processes responsible for fabric formation are evident in the stratified, anisotropic Late Cretaceous and Paleogene sandstones and mudstones. During thrust faulting, bedding-parallel slip within the frictionally weak, clay-rich mudstones places interbedded, brittle, frictionally strong sandstones in extension, which is accommodated by normal faulting (i.e., conjugate normal faults and R_1 shears). Brittle faulting of the sandstone beds leads to thinning, block rotation, boudin formation, dismembered units and/or mélange. This pervasive transposition fabric, in which bedding orientations are transposed by fault-related slip, is especially helpful in determining the kinematics of deformation. **A:** The line drawing presented here represents the basic geometry of the transposition fabrics observed in the field along the Red Island–Waimarama Traverse (BD: bedding; S: bedding parallel shears); **B–C:** Two representative outcrop photographs are also included as examples.

For a more detailed structural deformation analysis see Pettinga (1980; 1982).

APPENDIX B—ADDITIONAL REPRESENTATIVE FIELD PHOTOS

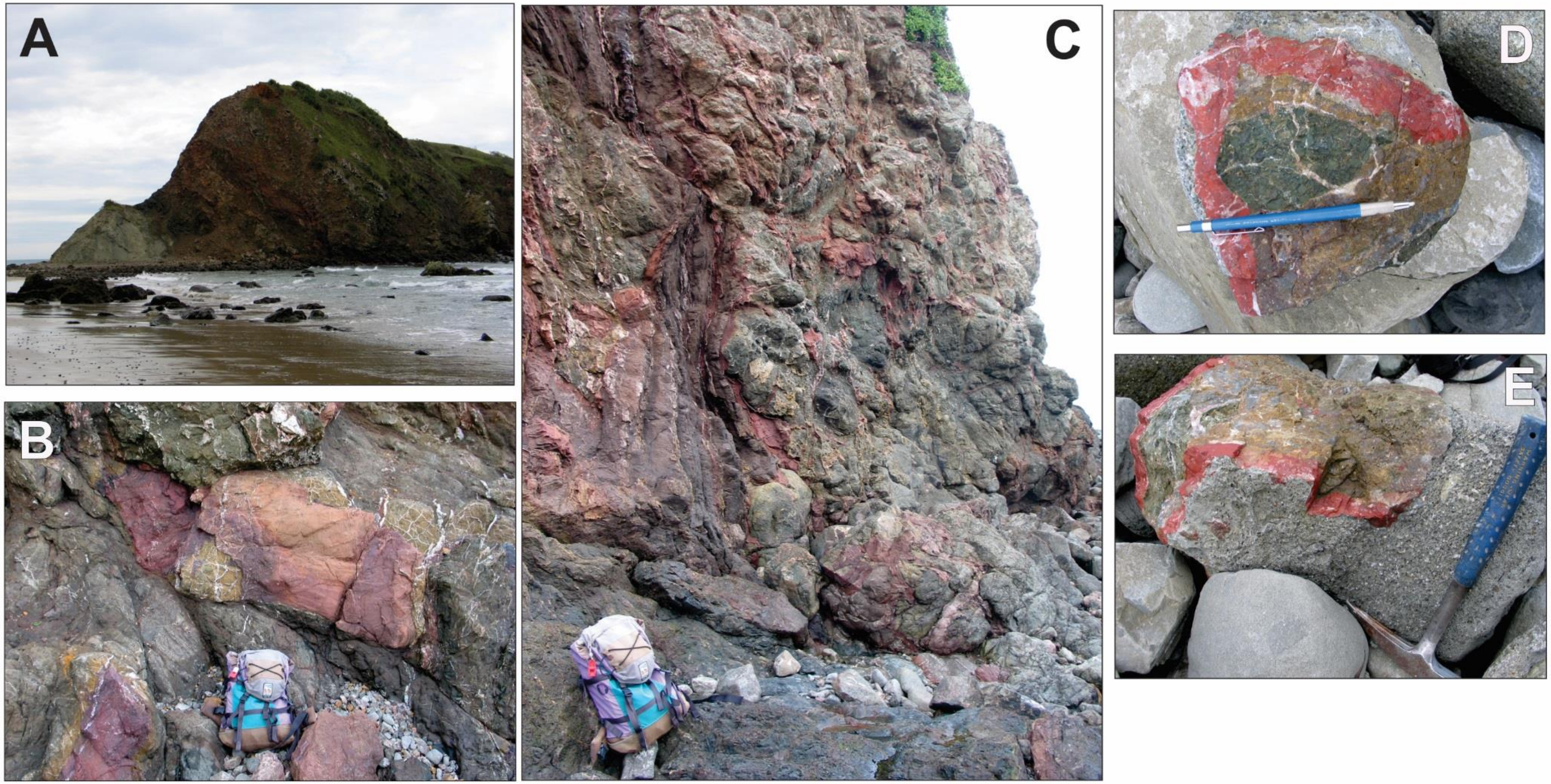

Figure B1: Red Island (Karamea) field photos. **A:** Red island viewed from SW. **B & C:** Pale olive-green to dark-green pillow lava with red-baked limestone inclusions and polygonal fracture pattern with zeolite mineralisation; **D & E:** Conglomerate clasts of Red Island lavas incorporated into grit and conglomerate beds of the Glenburn Formation Te Wainohu member (Rm) at first headland north of Red Island (refer Figure 5A).

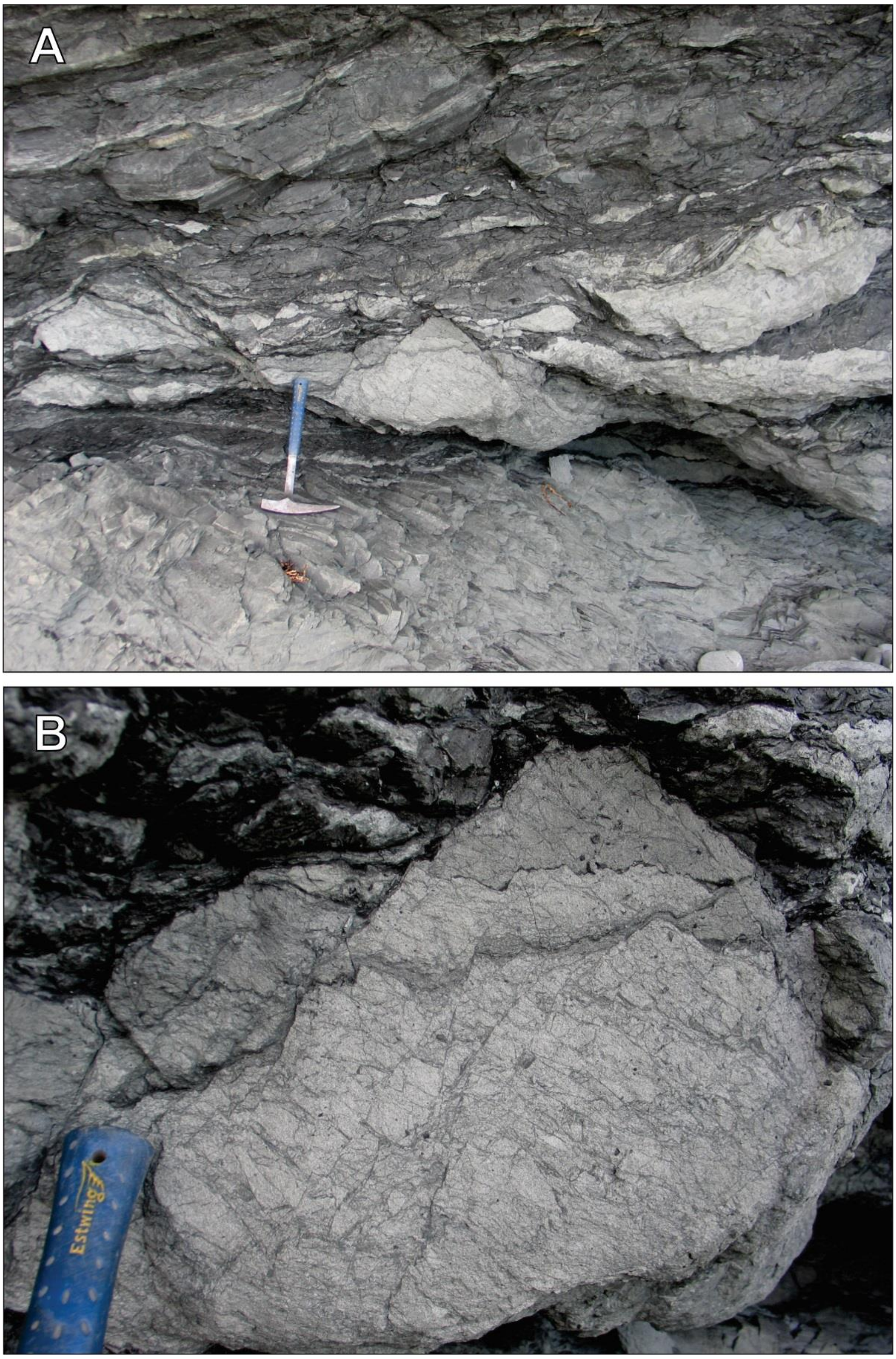

Figure B2: Dismembered strata assigned to Glenburn Formation Te Wainohu member, outcrop exposure located at north end of Cray Bay. **A:** Note the pervasive bedding-parallel shear accommodated within the more “ductile” carbonaceous mudstones “matrix”, versus the “brittle” sandstone beds that are intensely fractured and faulted, leading to both asymmetric and symmetric (extensional) “boundinage” structures. **B:** Enlarged image of central sandstone “boudin” depicted in photo A. Note the network of thin, cross-cutting grey-black cataclastic shears forming a 3D-web structure within the sandstone blocks.

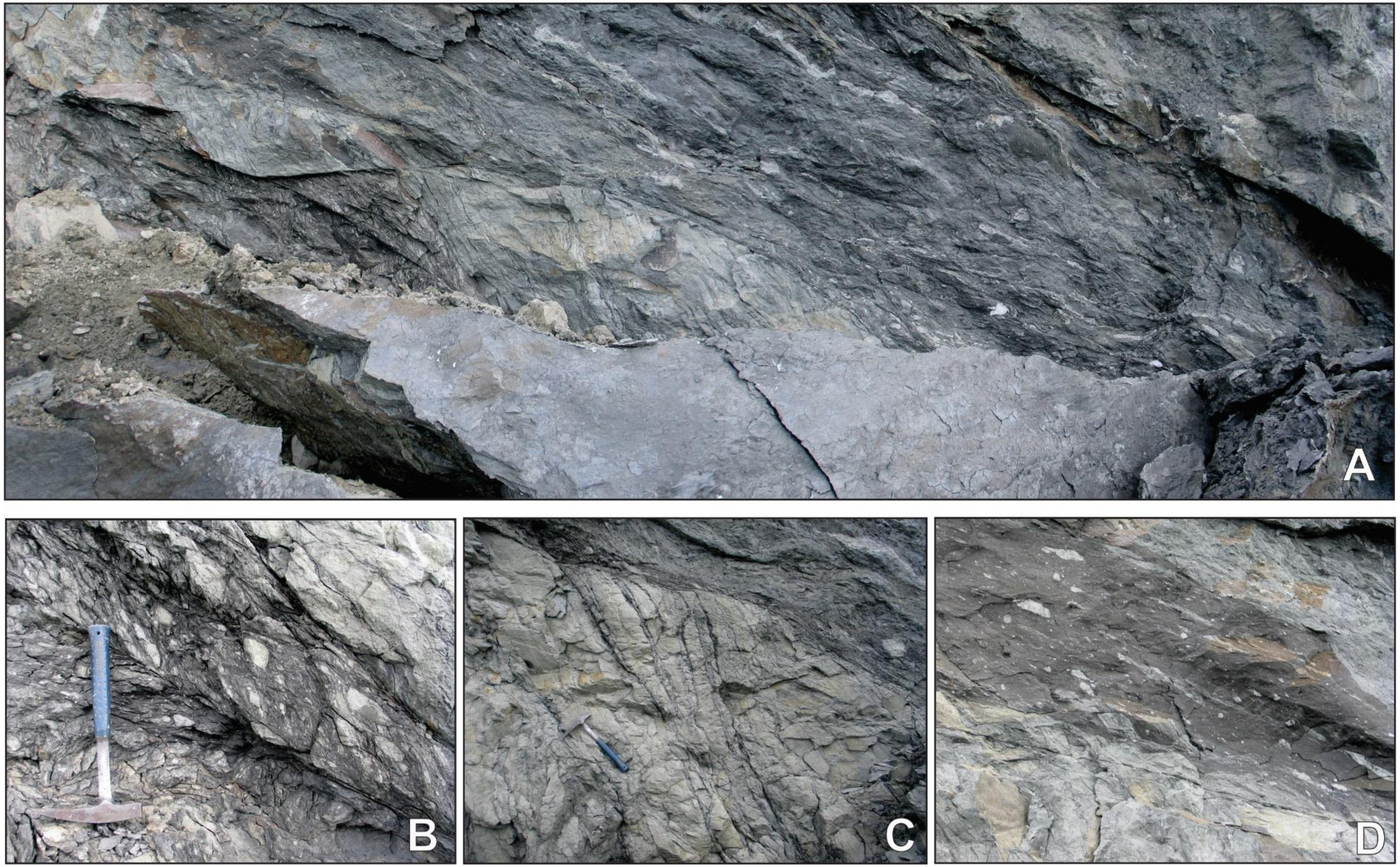

Figure B3. A: Approximately 12 m-wide base of cliff outcrop exposure adjacent to "the Ramp" locality (refer Figure 7A &7B). This exposure reveals a dismembered and pervasively sheared rock fabric formed by a bedding-parallel thrust interval within Glenburn Formation. Note the sharp bedding-parallel thrust fault contact (centre in photo) above a thin strongly transposed bedded sandstone interval. **B:** Close-up photo of the intensely sheared and dismembered strata below the transposed interval. Note that individual sandstone clasts document multiple phases of shear deformation; **C:** Close-up view of one of the sandstone dominated "lozenges" within the transposed horizon; and **D:** Close-up view of the pervasively sheared matrix above the transposed package.

Figure B4/A: An example of Glenburn Formation Te Puku member broken formation strata, adjacent to "The Ramp" location (see Figure 7A & B).

Figure B4/B: Detail of overprinted shear fabric in dismembered strata, Glenburn Formation Te Puku member at "The Ramp" locality.

Figure B5/A (above): View to south of Whangai Bluff (mid-view) and Te Puku Point (to far left in view). The light-coloured Whangai Formation strata are truncated part way up slope by a low-angle thrust fault with Glenburn Formation strata outcropping on the higher slope above the fault contact.

Figure B5/B (left): Detailed outcrop exposure of the alternating light- and dark-coloured Whangai Formation argillites, south side of Whangai Bluff.

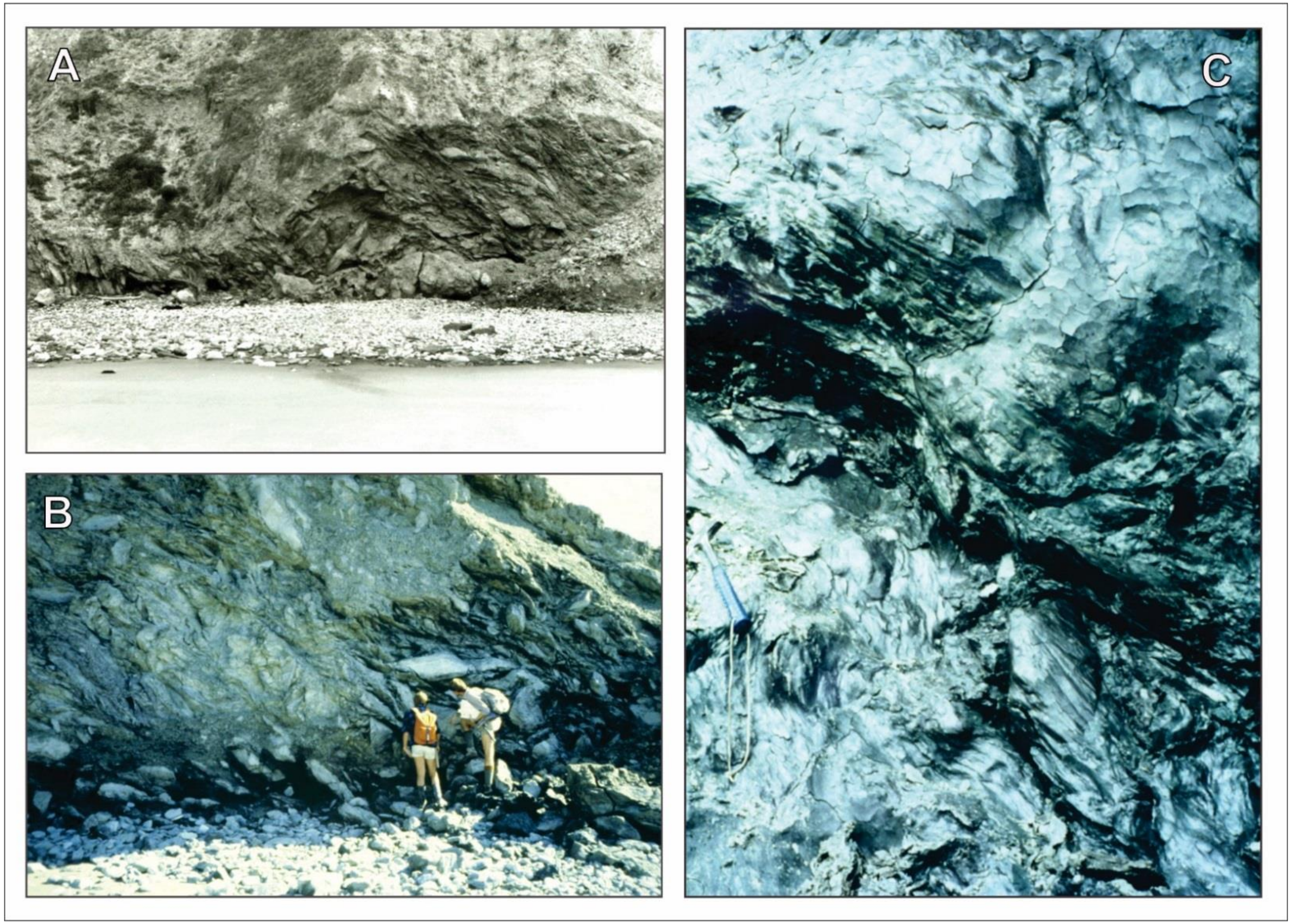

Figure B6/A–C: Outcrop exposures of the amalgamated Coastal and Te Apiti Thrust Zones (2 & 3), south end of Waimarama Beach (Stop 11). **A & B:** Depict the mélange zone matrix shear fabric developed preferentially in the swelling clays derived from the Paleogene Wanstead Formation. The sandstone blocks or "floater" clasts are derived from a range of formations and are chaotically embedded within the sheared clay matrix of the mélange zone. *(Photo by M Laird).* **C:** More detailed view of the intensely sheared and slickenlined swelling clay matrix of the mélange zone. Note clay-encased 'floater" clast lower right in photo. *(Photo by N Trustrum).* Photos A and C previously published in Pettinga (1982).