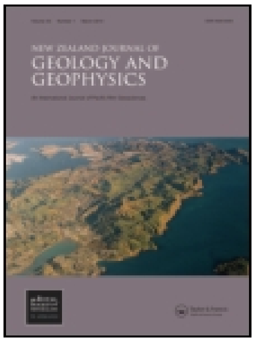

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Upper Cenozoic structural history, coastal Southern Hawke's Bay, New Zealand

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Abstract The structural high (Coastal High) trending northeast along coastal Southern Hawke's Bay comprises Upper Cretaceous to Miocene successions that have been complexly folded and thrust-faulted. Major tectonic melange and crushed zones are associated with thrusts.

The high developed in Late Oligocene time in conjunction with a slope basin to the west. Continued deformation led to westward growth of the high by incorporating older basin-fill sequences. A thick wedge of flysch subsequently accumulated within the landward-migrating slope basin. The progressively tilted margins shed cohesive debris flows which interdigitate with the flysch. On the high, sedimentation is typified by a greatly condensed mudstone succession with local unconformities and onlaps which disappear basinwards.

An earlier Oligocene deformation resulted from northward movement of an allochthonous gravity slide sheet, recognised by local east–west-trending structures, inverted sequences, and northward transposition. Overprinting by the subsequent phase of imbricate thrusting led to the present NNE–SSW to northeast–southwest structural fabric of the region.

West of the Coastal High, the Elsthorpe Anticline propagated as an offshoot during Quaternary time. Deformation of the basin-fill tectonically thickened the western limb by a series of en echelon bedding thrusts. Quaternary tensional faulting affecting the Coastal High reflects major gravitational collapse. There is no evidence for major transcurrent faulting.

Petroleum source and reservoir beds are known throughout the East Coast region. However, substantial traps may prove difficult to locate because of the intensity and type of deformation. The numerous seeps in the area reflect voiding of trap structures.

Keywords tectonics; Cenozoic; structure; Hawke's Bay; East Coast Deformed Belt; thrusts; melange; imbrication; convergent margin; accretion; slope basins; flysch

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INTRODUCTION

The presence of hydrocarbon accumulations in the East Coast region of the North Island, New Zealand, are well exemplified by the numerous gas and oil seepages recorded (de Caen 1970). However, to date, exploration for economically viable fields has been unsuccessful. A description of previous exploration is given by Leslie & Hollingsworth (1972), though further offshore surveys have since been completed (Dean 1975).

A vital key to the outcome of regional prospecting is the tectonic setting and structural framework model adopted. Recently, plate tectonic interpretations have polarised into 2 apparently incompatible hypotheses with respect to regional structure, namely, the Tectonic Erosion Hypothesis (Katz 1974a; Katz & Wood 1980) and the Tectonic Accretion Hypothesis (Pettinga 1977; Walcott 1978a, b; Lewis 1980; Spörli 1980; van der Lingen & Pettinga 1980; Cole & Lewis 1981).

The purpose of this paper is to present factual field relations established from detailed mapping in coastal Southern Hawke's Bay. Based on this, a structural-tectonic history for the region is discussed, and the existing hypotheses are evaluated. The impact on hydrocarbon accumulations is then outlined.

LOCATION AND GEOLOGICAL SETTING

The area described is located on the southeast coast of Hawke's Bay (Fig. 1). It forms one-fifth of the Te Aute Subdivision (Kingma 1971).

The region is situated in a geologically complex zone variously referred to as the East Coast Fold Belt (Katz 1974a), Axial Tectonic Belt (Walcott 1978a, b) and the East Coast Deformed Belt (Spörli 1980). The last term is adopted here because it most accurately describes the structural style of the region. This complex zone is characterised by active compressional teconics with a pronounced northeast–southwest structural grain (Walcott 1978b; Spörli 1980).

Two prominent structures, the Coastal High and the Elsthorpe Anticline, are mapped and described, and both form an integral part of this belt. These, and the intervening shallow synclines and other major regional structures in the study area, are shown on Fig. 2.

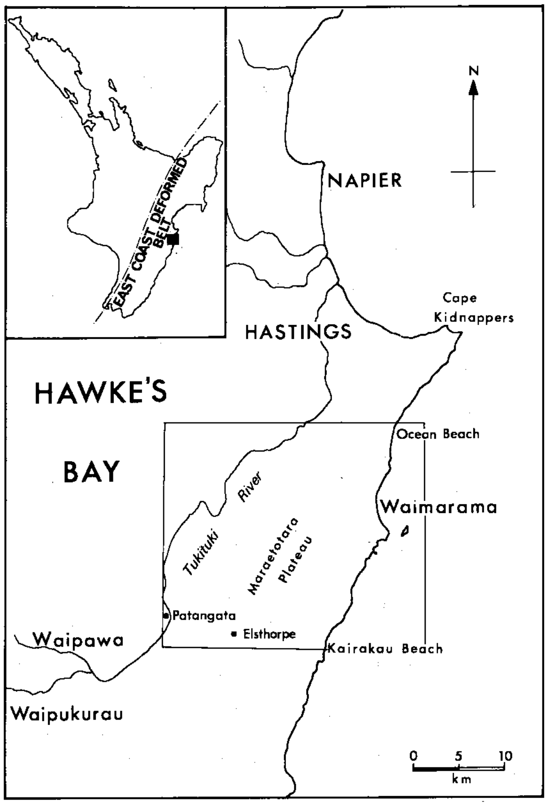


Fig. 1 Location of area studied within the East Coast Deformed Belt.

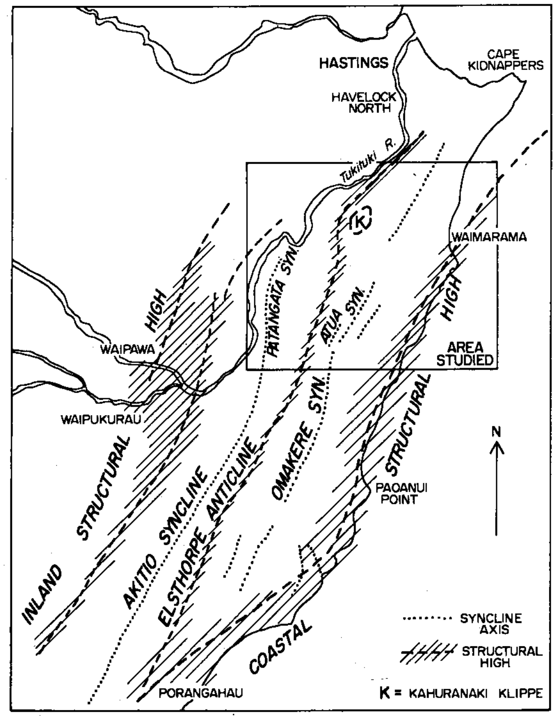


Fig. 2 Main structural elements of the Southern Hawke's Bay Land District (based on Lillie 1953; Kingma 1971; and Pettinga 1980).

STRATIGRAPHIC FRAMEWORK: COASTAL SOUTHERN HAWKE'S BAY (Fig. 3)

Within the area, a succession of Upper Cretaceous to Quaternary sedimentary strata are mapped. A 12-formation subdivision was adopted (Pettinga 1980), but for the purpose of this paper these are not presented. Rather, the stratigraphic succession is divided into 7 distinct sedimentation phases (Table 1).

Phases 1–4: Upper Cretaceous–Paleogene

Following the Rangitata Orogeny, much of the present-day New Zealand area and neighbouring submarine ridges and plateaux comprised part of a substantial landmass (Stevens & Speden 1978). This landmass presumably formed the continental borderland of Gondwana with the Pacific region (Molnar et al. 1975; Ballance 1976; Ballance & Spörli 1979; Spörli 1980).

During Early Cretaceous time, transgression commenced in the Raukumara Peninsula area and Northland (Speden 1973, 1975; Stevens & Speden 1978). The succeeding Upper Cretaceous and Paleogene stratigraphy of the entire East Coast Deformed Belt and Northland is remarkably similar (see Kingma 1960; Stevens & Speden 1978; Ballance & Spörli 1979).

Phase 1

The oldest marine sedimentary sequences comprise carbonaceous flysch (mass-flow deposits). Similar facies are recorded fom Northland, Raukumara Peninsula, Wairarapa, and Kaikoura, and an excellent summary is given by Stevens & Speden (1978).

Sedimentation appears to have taken place along a subsiding continental borderland. The influx of carbonaceous detritus is thought to reflect the response of the New Zealand (or Gondwana) Pacific margin to the tectonic activity preceding and accompanying the opening of the Tasman Basin from 80 to 60 m.y. ago (Hayes & Ringis 1973; Weissel & Hayes 1977). Depths of deposition are uncertain, but shellbeds of *Inoceramus* suggest shelf to upper slope conditions prevailed.

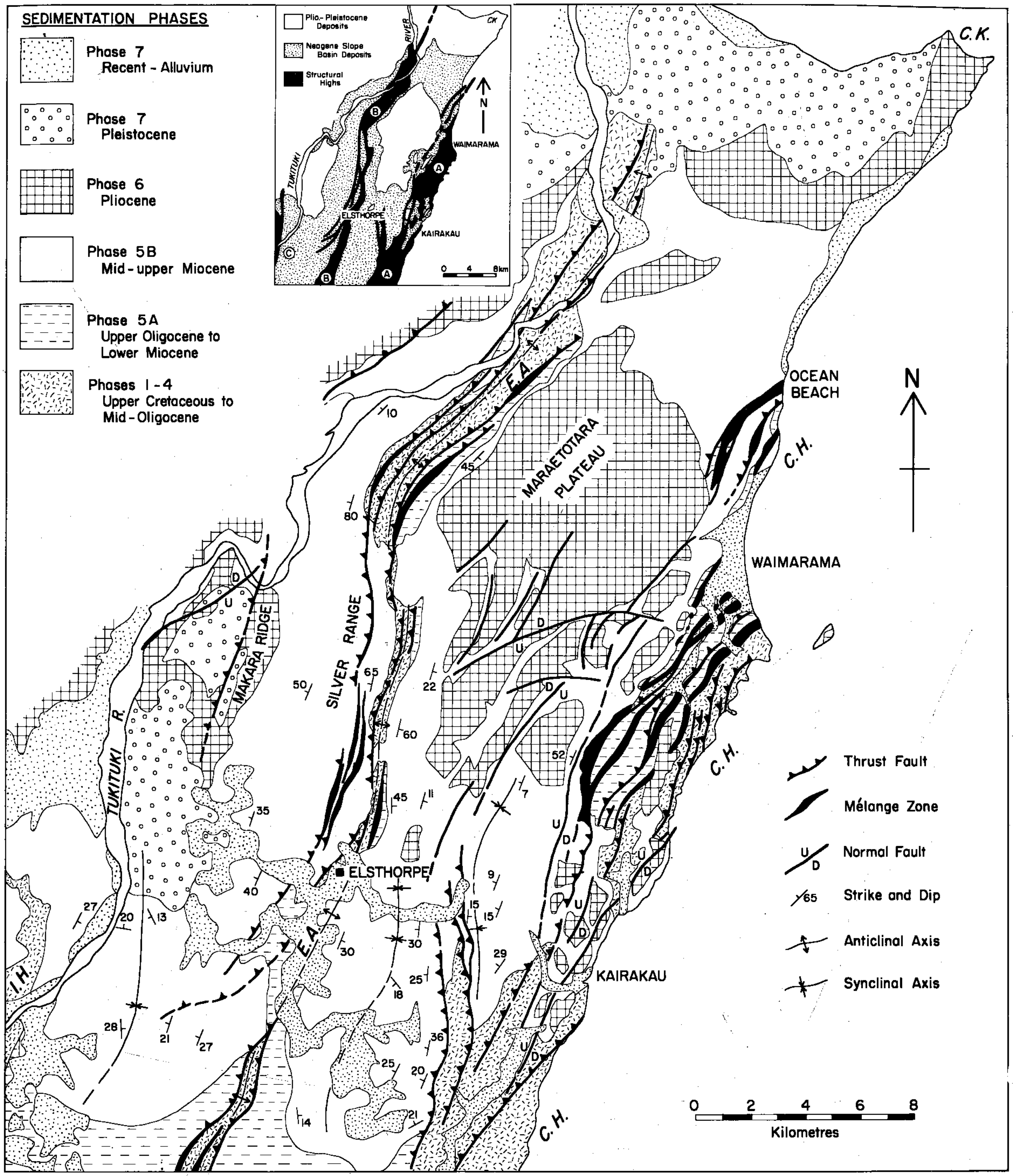


Fig. 3 Generalised geological map of the area studied. For brief description of sedimentation phases (1–7) refer to text. *Inset*: generalised structural entities (highs) and upper Cenozoic sediment groupings. C.H. (A, inset) = Coastal High; E.A. (B, inset) = Elsthorpe Anticline; I.H. (C, inset) = Inland High.

Phase 2

The Tapuwäeroa Facies of Piripauan–Haumurian age represents a change in sediment supply. Glauconite became a major component in mass-flow deposits, while finer grained carbonaceous matter dominated mudstone and shale facies. Also included in this phase are the various lithotypes of the Whangai Facies. This Late Cretaceous to early Tertiary unit is widespread throughout the East Coast Deformed Belt. It is highly variable in sediment type, but at its type area is composed of a light-grey siliceous argillite (Lillie 1953; see also Stevens & Speden 1978 and Suggate et al. 1978).

The change from coarse clastic sequences of Raukumaran time (Phase 1) to the widespread Whangai and Tapuwaeroa Facies reflects the culmination of a major change in the tectonic environment to one of relative stability (Lillie 1953; Kingma 1971; Stevens & Speden 1978).

Phases 1 and 2 sediment types have long been recognised as the most likely source rocks for hydrocarbon accumulations in the East Coast region.

Table 1 Upper Cretaceous, Tertiary, and Quaternary sedimentation phases.

NZ Series		Phases
Upper Wanganui-Hawera *(Pleistocene-Holocene)*	7	Shallow marine and non-marine gravels; lake beds
Lower Wanganui *(Pliocene)*	6	Limestones; sandstones
Landon-Taranaki *(Oligocene-Miocene)*	5	Mass-flow deposits (turbidites; debris flows); massive mudstones and sandstones; tuffaceous beds.
Arnold *(Upper Eocene)*	4	Bentonitic marls; calcareous mudstones
Dannevirke *(Paleocene-Lower Eocene)*	3	Alternating bentonitic mudstones and sandstones
Mata-Dannevirke *(Uppermost Cretaceous-Lowermost Tertiary)*	2	Argillites, glauconitic flysch, carbonaceous mudstones, shales
Raukumara-Mata *(Upper Cretaceous)*	1	Carbonaceous flysch

Phase 3

A progressively fining-upward sequence characterises the Paleocene to Lower Eocene. Flysch of this phase is composed of fine-grained glauconitic sandstones and dark carbonaceous siltstones, with montmorillonitic mudstones representing hemipelagic (background) sedimentation. Terrigeneous detrital constituents are much reduced, and glauconite is a major component. Total stratigraphic thickness is small, indicating a sediment-starved, tectonically quiescent environment. Depositional environment was probably deep water, continental slope, as judged from micropaleontologic evidence.

Phase 4

Although no clear unfaulted stratigraphic sequence is recorded in Southern Hawke's Bay, it appears that a continuous succession from montmorillonitic mudstones (bentonite) to calcareous mudstones (marls) is present. The Oligocene marls are represented by the widely mapped Weber Formation (Ongley & Williamson 1931; Lillie 1953). Conditions were similar to those of Phase 3. Similar sediments characterise sequences at Raukumara Peninsula, while to the south and west, shelf(?) limestones (Amuri Limestone) accumulated (Waterhouse & Bradley 1957; Prebble 1976, 1980; see also Ballance & Spörli 1979).

Phases 5–7: Neogene–Quaternary

The upper Cenozoic geology and development of the East Coast Deformed Belt directly reflects the development of the accretionary sediment prism in the arc-trench gap of the New Zealand obliquely convergent plate margin (Pettinga 1980; van der Lingen & Pettinga 1980; Spörli 1980; Ballance et al. in press).

Phase 5 (A and B)

This phase records the onset of active continental slope sedimentation during Late Oligocene and Miocene times. Thick flysch sequences composed of mass-flow deposits (especially turbidites and debris flows) are characteristic; they are frequently separated and enclosed by thin condensed mudstone successions. Local angular unconformities and disconformities, rapid lateral facies changes, and rapid thinning of strata also occur.

Sedimentation was controlled by a major growing anticlinal submarine ridge, presently represented by the Coastal High in the area studied. This structural (thrust) ridge (see later) ponded sediment on the continental slope in a small basin. Several pulses of tectonism (growth) are recognised (see later). Many such basins are now recognised onland in Southern Hawke's Bay, Wairarapa, and northeast Marlborough.

The Upper Oligocene and Lower Miocene sediments (Phase 5A) so ponded were themselves subsequently (during Middle Miocene time) strongly deformed and incorporated into the submarine (thrust) ridge, and a new basin (Makara) was created. The fill of this basin is of Middle–Late Miocene age (Phase 5B) and has been the subject of considerable research by Kingma (1958a), van der Lingen (1968, 1969), and more recently by Pettinga (1980) and van der Lingen & Pettinga (1980).

Airfall ash, subsequently settled through the water column, and redeposited tuffaceous units are incorporated in both Upper Oligocene and Lower–Upper Miocene basin-fill sequences, indicating contemporary volcanism.

Paleontologic and sedimentologic data suggest Late Oligocene–Early Miocene basin fill accumulated in a deeper water environment (mid to outer slope) than the Late Miocene Makara Basin fill (van der Lingen & Pettinga 1980). The former is depicted as Phase 5A and the latter as Phase 5B on Fig. 3.

Phase 6

Widespread abrupt shallowing to shelf conditions mark the commencement of deposition of the Te Aute Formation limestones and calcareous sandstones during Pliocene time (de Caen 1968b; Beu et al. 1980). Local variations in the thickness of the limestone sheet indicate the possible control of sedimentation by tectonic warping and faulting. Uplift, however, was widespread throughout the East Coast district. The uplift is of different age in different parts of the East Coast Deformed Belt (Lillie 1953; Kingma 1971; Katz 1973; Johnston 1975). Within the area studied the limestones are diachronous from east to west (Grant-Taylor & Hornibrook 1976; Beu et al. 1980; Pettinga 1980).

Phase 7

Marine sedimentation ceased over much of the region during Late Pliocene. During Pleistocene time, following emergence, the district acquired many of the gross morphologic features of the present-day landscape. Castlecliffian gravels, sands, and lake deposits accumulated in local structural depressions. Major depressions to the west of the coastal districts, such as the Ruataniwha–Heretaunga Depression, continued to receive marine massive mudstones and intercalated shelf limestones during the early Pleistocene (Kingma 1971; Clark 1976). They were followed by widespread greywacke gravels of late Pleistocene (Castlecliffian) age, derived from the west, reflecting an increase in the tectonic tempo that accompanied uplift of the axial ranges.

Mid-Cretaceous volcanics (Red Island)

Volcanic and volcano-sedimentary rocks are very restricted in occurrence. The maximum stratigraphic succession forms Red Island and is less than 50 m in total thickness. Other minor outcrops occur along the coast near Red Island and at 1 locality in the core of the Elsthorpe Anticline. Age determinations based on micro and macrofossils are uncertain, but a Motuan age seems probable (C. P. Strong pers. comm.). Kobe (1976) describes the petrography of various mafic pillow lava units, pink limestones, and exhalative submarine hydrothermal deposits.

All occurrences of the volcanics and related deposits are as "floaters" within melange zones (see later).

INTERNAL STRUCTURE OF THE COASTAL HIGH

Introduction

The Coastal High is a structurally complex terrain forming the coastal borderland to the eastern part of the area (Fig. 4). The high is a direct northward continuation of the Porangahau–Pourerere Anticlinal Complex described by Lillie (1953).

Previous workers

Lillie (1953) summarised the complex geology of the coastal areas of Southern Hawke's Bay, describing features such as thrust (reverse) faulting and tight folding. Despite intense shearing, the "bentonites" were considered as part of a mappable Wanstead Formation of early Tertiary age. Along the coast the "bentonites" are contained in what Lillie described as Tectonic Slices; these are equivalent to the melange zone thrust wedges involving bentonite described in this paper.

Kingma (1971) mapped the coastal belt in detail. He described the Cretaceo-Tertiary sediments as having been "fault involved with Lower Tertiary bentonites" (Kingma 1971, p. 131), and concluded that the extreme complexity encountered was due to interference folding and that faulting was mostly normal, with some reverse. No transcurrent faults were observed, but he considered the entire area to have been affected by dextral shear. Haw (1960) and de Caen (1968a) came to similar conclusions.

Outline of major structures (Fig. 4)

The Coastal High incorporates almost the entire stratigraphic succession from mid Cretaceous to Lower Miocene, except for some Lower–Middle Oligocene formations, which, although not recognised, may be present as thin, very condensed

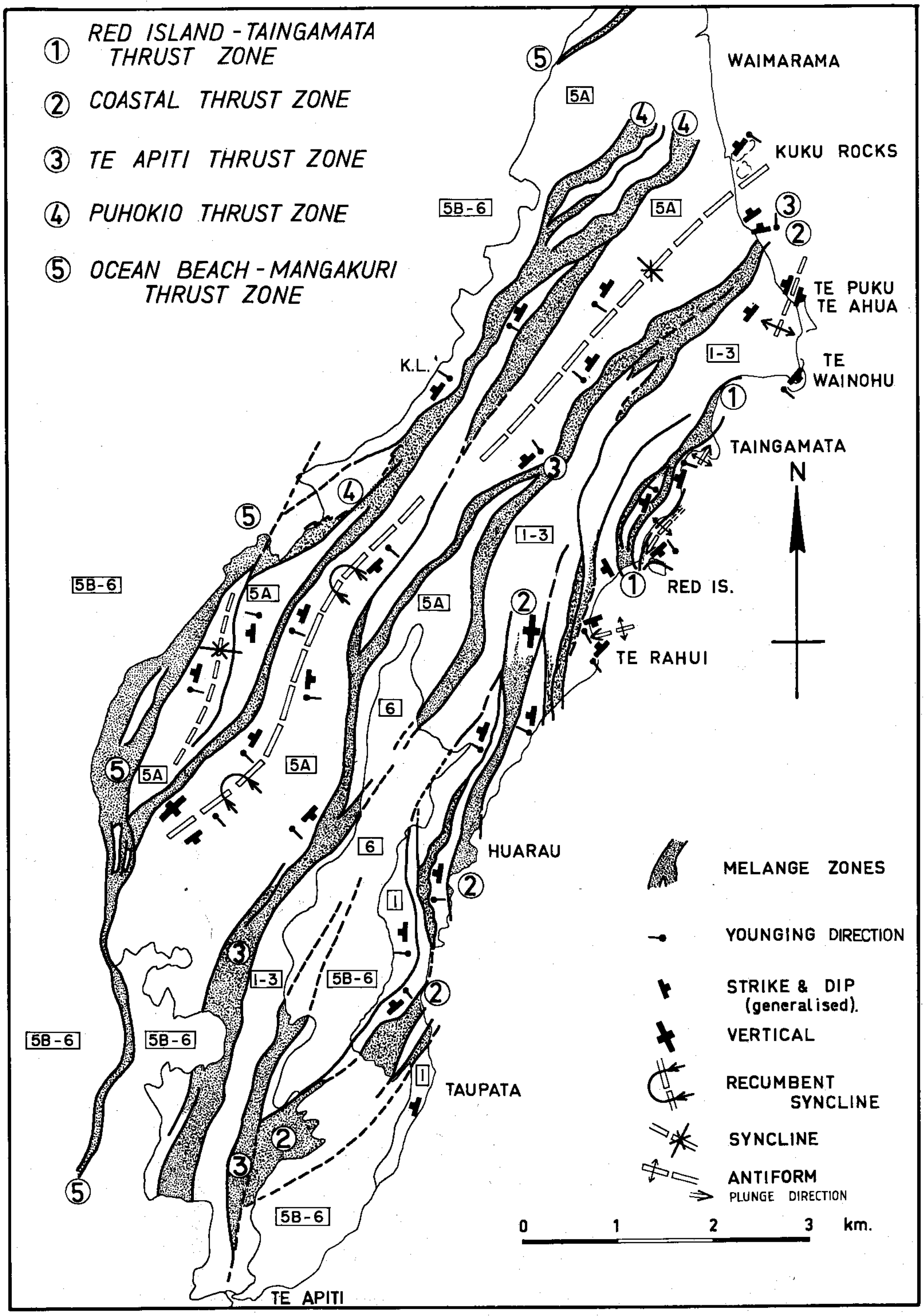


Fig. 4 Structural-tectonic map of the Coastal High from Waimarama to Te Apiti. Various sedimentation phases are shown in boxes.

Fig. 5 Typical bentonitic melange zone exposure, south Waimarama Beach (N142/404979: NZMS1). Note shear fabric in bentonite and numerous "encased exotic floaters" within the bentonitic matrix. Photo view looking westward.

sequences obscured by the overall complexity of the area. Middle–Upper Miocene strata are also involved in the structural development of the Coastal High, but to a much lesser degree of complexity.

The gross structural fabric of the high is dominated by a northeast–southwest to NNE–SSW trend. All pre- to Middle Miocene sequences have been tightly folded and imbricated by thrust faulting. Most thrust faults are accompanied by **melange** (here defined as tectonically mixed formations—see Hsu 1968, 1974) or **crushed zones** (tectonically disrupted zones involving only 1 formation). Folding is related to the development of these zones.

Five distinct thrust zones are mapped within the Coastal High: (1) Red Island–Taingamata Thrust Zone; (2) Coastal Thrust Zone; (3) Te Apiti Thrust Zone; (4) Puhokio Thrust Zone; and (5) Ocean Beach–Mangakuri Thrust Zone. Several secondary branches or "offshoots" occur with each of these zones.

Internally, thrust zones exhibit an intense shear fabric (Fig. 5). Melange accompanying these thrusts incorporate all but post-Miocene formations. "Bentonitic" clays derived from lower Tertiary formations are a most common gouge or matrix component in these zones, and more coherent blocks of varying sizes of all pre-Pliocene formations occur as "floaters" or fault "pips". These blocks may be internally brecciated. From intersection with topography and unambiguous exposures, it is clear most thrust faults dip to the northwest, with angles ranging from less than 20° to near 90° in attitude.

Generally the thrust zones conform in trend with the northeast–southwest to NNE–SSW structural grain of the district. However, a notable exception to this occurs at Red Island and immediately onshore from there. A thrust fault accompanied by bentonitic fault gouge at Red Island strikes east–west. Onshore, the Red Island–Taingamata Thrust Zone swings noticeably from a NNE–SSW strike at Taingamata to NNW–SSE around the southern tip of Red Island (see Fig. 20.).

A sequential development of the thrust zones to each other has been established from crosscutting relationships. The oldest zones are the Red Island–Taingamata and Coastal Thrusts. Involvement of Waitakian (Oligocene) mudstones within both zones places a maximum age of development on these. The Te Apiti Thrust forms an offshoot from the Coastal Thrust near Waimarama, but at its southern end it clearly crosscuts the latter. It delineates an important boundary between the Oligocene–Lower Miocene clastic mass-flow succession to the west, and the Upper Cretaceous–lower Tertiary terrain to the east. To the west, the Puhokio Thrust Zone predates the Ocean Beach–Mangakuri Thrust Zone.

The last phase of thrust movement affecting the Coastal High onland occurred along the Ocean Beach–Mangakuri Thrust and involved Upper Miocene flysch strata. This thrust zone extends through the entire length of the study area and forms the western margin to the Coastal High, although it is partly obscured by Pliocene limestones and the Kaiwhakapiripiri Landslide.

The other thrust zones (1–4) situated to the east all ceased to be active from the Middle Miocene onward, as shown by the unconformable onlap of massive mudstones of Miocene age. No Pliocene Te Aute Limestone was involved in thrust faulting on or adjacent to the Coastal High. This is in sharp contrast to the Elsthorpe Anticline situation (see later).

Thrust faulting and folding of the Cretaceous and lower Tertiary sequence of the Coastal High appears to have been more severe than that of the Oligocene strata. Folds within the Cretaceous formations are recognised from the presence of thin, severely sheared, inverted sequences imbricated within the melange zones, and these sequences are thought to form the very much attenuated lower limbs of fold nappes (see later). In particular, 3 such structures are recognised, 1 with the Red Island–Taingamata Thrust Zone and 2 with the Coastal Thrust Zone. Further to the west, folding in conjunction with the Te Apiti and Puhokio Thrust Zones has been less intense, and overturned beds only occur adjacent to the thrust zones due to drag caused by the faulting. Folds are tight and inclined or recumbent.

The southern part of the Coastal High has been affected by considerable downfaulting to the east associated with the development of a major regional slump in latest Pliocene and Quaternary times (see later). Maximum recorded vertical offset is approximately 500 m.

The continental margin offshore from the Hawke's Bay land district is subject to major submarine slumping (Lewis 1971). All such slumps are relatively shallow seated slide sheets never exceeding tens of metres in thickness. In contrast, the regional slump is a much deeper seated structure. Its exact geometry has not been adequately defined, but recently obtained seismic profiles from the offshore continental shelf suggest it extends to at least the shelf-slope break and possibly beyond into the Motukura Trough (see Fig. 25) (Pettinga in press).

Analysis of deformation episodes based on mesoscopic and macroscopic structures

Detailed field mapping has revealed 3 distinct episodes of deformation (based on crosscutting relationships) within the Coastal High. These are summarised in Table 2.

EPISODE 1

This episode includes the oldest structures recognised but infrequently developed. Their overall effect is minor, and time of formation uncertain. They clearly predate Episode 2 structures, but may genetically be closely related in time. No further discussion of Episode 1 is presented here.

EPISODE 2

Separation and movement direction analysis (see Appendix 1 and Fig. 33) indicates within this

Table 2 Episodes of deformation, Coastal High, Southern Hawke's Bay.

Deformation Episode	Structures recognised	Age
Episode 1	Minor thrust and reverse faulting; bedding slides; micro- and mesoscopic folds *(Compressional Regime)*	Undetermined
Episode 2	Bedding plane shears; conjugate faults; development of lozenge and/or transposed fabric; thrusting: formation of melange and crushed zones; micro-, meso- and macroscopic folds *(Compressional Regime)*	Mid Oligocene–uppermost Miocene
Episode 3	Normal faulting *(Extensional Regime)*	Pliocene–Quaternary

episode there is an *early* set of structures indicative of movement directed to the north and northwest, and a *later* set of similar structures indicative of movement directed to the east and southeast. Structures of both the early and late Episode 2 deformation events are similar in style and geometric relationships, and they can be subdivided into 4 types. These are labelled here 2a–2d, but it must be emphasised that all 4 develop together and are associated with both early and late events of Episode 2. Movement reversals and scale variations locally further complicate interpretations.

Bedding shears (2a): Typically shears have formed along the sandstone–mudstone interface in bedded sequences or along discrete planes within the shale or mudstone horizons. They are recognised in all formations up to the Early Miocene, but are difficult to detect in less-deformed well-bedded successions. They are invariably associated with structures such as microfaults, folds, and variations in bedding attitude (Fig. 6 and 7).

Fig. 6 Thinly bedded, finely laminated carbonaceous sandstone/siltstone (sedimentaton phase 1) near Te Puku (N142/407975: NZMS1) (for location refer Fig. 4). Note typical lozenge fabric development by combined movement on dominant conjugate faults and bedding shears (refer also Fig. 33A). The inferred movement direction is from right to left across top of photo and reflects stretching of the succession.

Fig. 7 Lozenge (transposition) fabric developed in sedimentation phase 1 flysch near Te Wainohu Point (N142/401965) (for location refer Fig. 4). Note the considerable bedding shear accommodated by the dark carbonaceous mudstone beds. Inferred movement direction is approximately from left to right across top of photo.

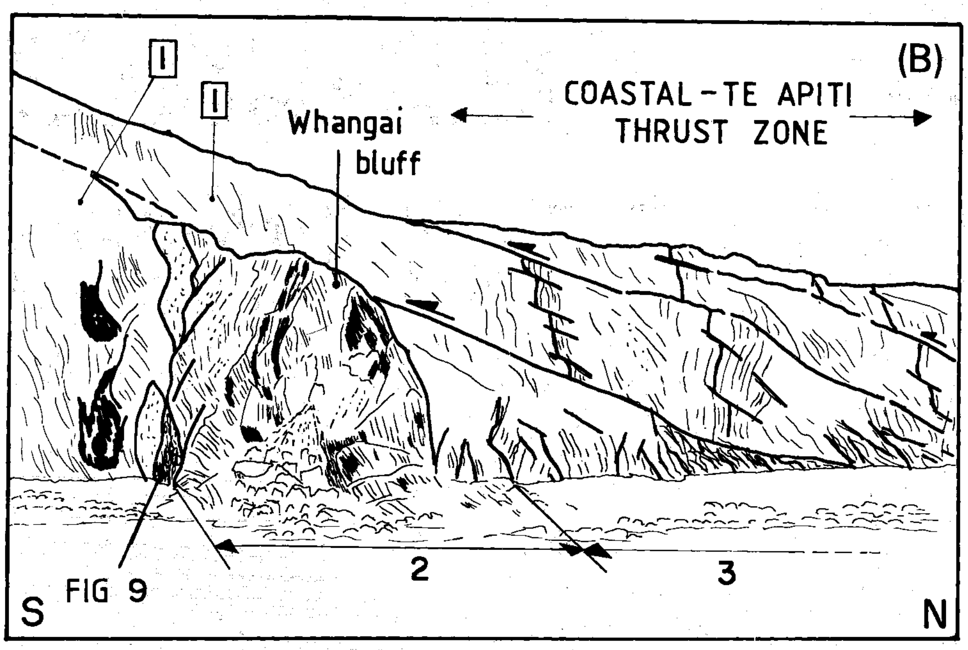


Fig. 8 Photoview to west (A) and corresponding line drawing (B) at Whangai argillite bluff, south Waimarama Beach (N142/404978). Melange zone of Coastal and Te Apiti Thrust Zones to north (right) side. Fault contact south side of bluff detailed in Fig. 9. Note the Whangai Facies block is a large floater in melange zone. Note also the large-scale transposition fabric depicted. Sedimentation phases present are indicated (1, 2, 3).

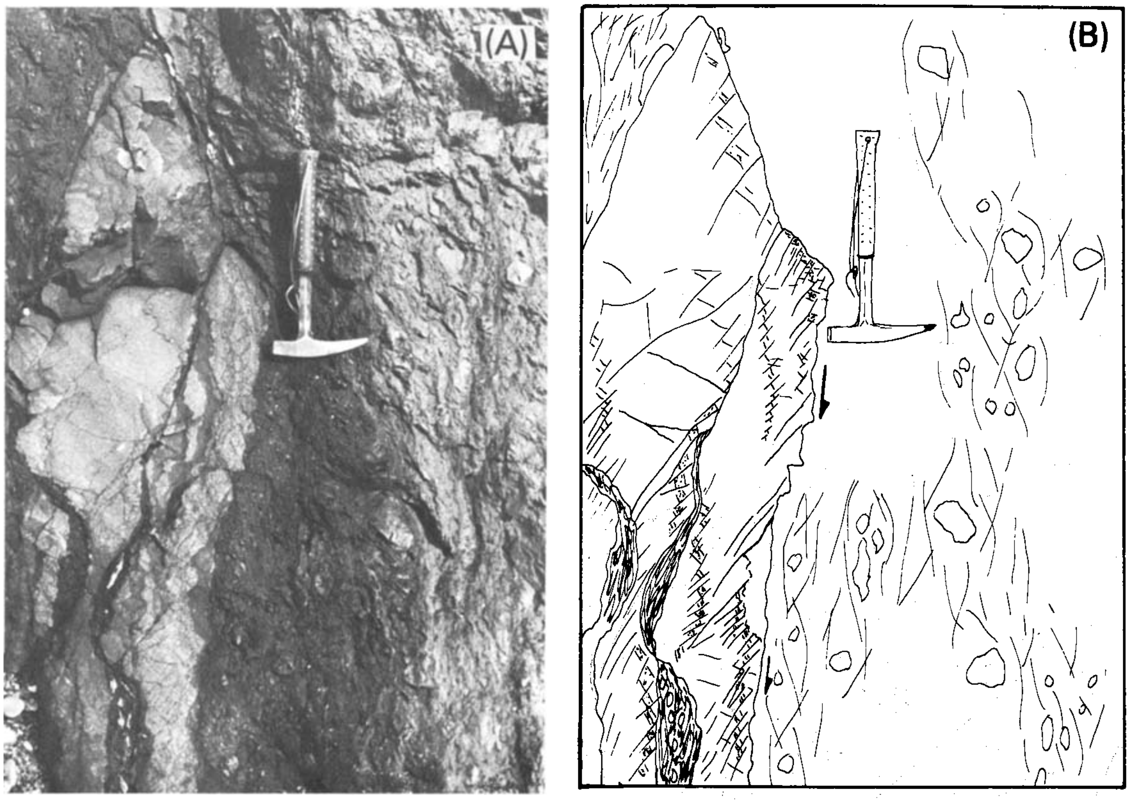


Fig. 9 Detailed photo view (A) and line drawing (B) of fault contact, south side of Whangai argillite bluff. Note the movement direction indicated by transposition fabric is downward and hence to the north, almost directly opposite to movement directions determined from bentonitic matrix material in adjacent melange zone (refer Fig. 8).

Conjugate faults and shear lozenges (2b): Normal conjugate faulting and bedding shears are frequently associated. Commonly, 1 of the shears of a conjugate couple is dominant, and in combination with bedding shears lead to development of a lozenge fabric (Fig. 6 and 7). When developed to the extreme, complete transposition results. The scales at which lozenges and transposition develop are also variable (Fig. 8 and 9).

Stereonet plots of conjugate faults extension–compression axes and separation plots of poles to bedding (bedding shears) and associated normal faults (dominant conjugate faults) are summarised and presented for key localities (see Fig. 16, 20, and 25).

Mesoscopic and small-scale folds (2c): Small-scale folds (Fig. 10) and larger asymmetric folds (see Fig. 4) are related to major shears. Most folds either verge NNW over SSE or south over north and movement direction is normal to fold hinge. (see Fig. 16, 20, and 25).

Thrust faulting and development of melange and crushed zones (2d): The 5 major thrust faults are accompanied by the development of crushed zones and melange zones (Fig. 4). Generally, melange zones have a distinct cross-sectional geometry. Basal shear surfaces frequently dip less steeply to the west than their upper surfaces (Fig. 11). Thus, these zones are seen to "wedge" where exposed. Crushed zones are more variable in geometry, but are most frequently westward dipping. The best exposures of melange and crushed zones occur along the cliffs south from Waimarama Beach (Fig. 8; see Fig. 17) and near Huarau (Fig. 12 and 13).

The common "matrix" component within melange zones are the sheared mudstones of Paleogene age ("bentonites"). Typically these exhibit several fabrics which are indicative of movement direction (or slip line) within these zones and also the relative movement of their upper and lower contacts. These features include: internal major shear surfaces; fold structures; lineations; and lozenge geometry.

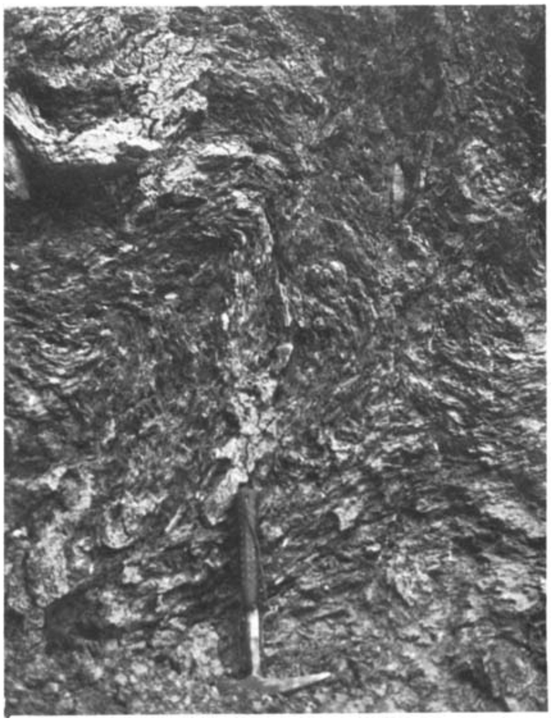


Fig. 10 Small-scale mesoscopic fold structures within bentonitic melange in bay to south side of Huarau (N142/370911). Note the sheared fabric of bentonite.

Internal major shear surfaces are of 2 types:

1. Those near-parallel to basal and upper shears of individual melange zones (Fig. 13; see also Fig. 24). These may be visible as clear-cut shear surfaces or be enhanced by colour changes. Fault "pips" or "floaters" of more competent (brittle) lithologies involved within the melange are frequent and often align at a specific horizon along-strike (see Fig. 23 and 24).
2. Those that are more complex, with successive phases of melange formation and later zones crosscutting earlier ones. Best examples are from the Red Island–Taingamata and Coastal Thrust Zones where 2 distinct phases are recognised (see following).

Fold structures within the bentonitic melange are of 2 types:

1. Mesoscopic reclined zigzag-type folds are recognised. Axial planes are near-parallel to basal shear surfaces and fold axes are near-horizontal (see Fig. 21) trending parallel to the thrust zones.
2. Small-scale folds (Fig. 10). These are more common than the larger zigzag folds and are frequently located over bounding thrust fault planes and internal shear surfaces.

Lineations on shear surfaces are also present within the bentonitic melange and are presumed to parallel movement direction. The more reliable, regularly directed lineations occur on basal shear

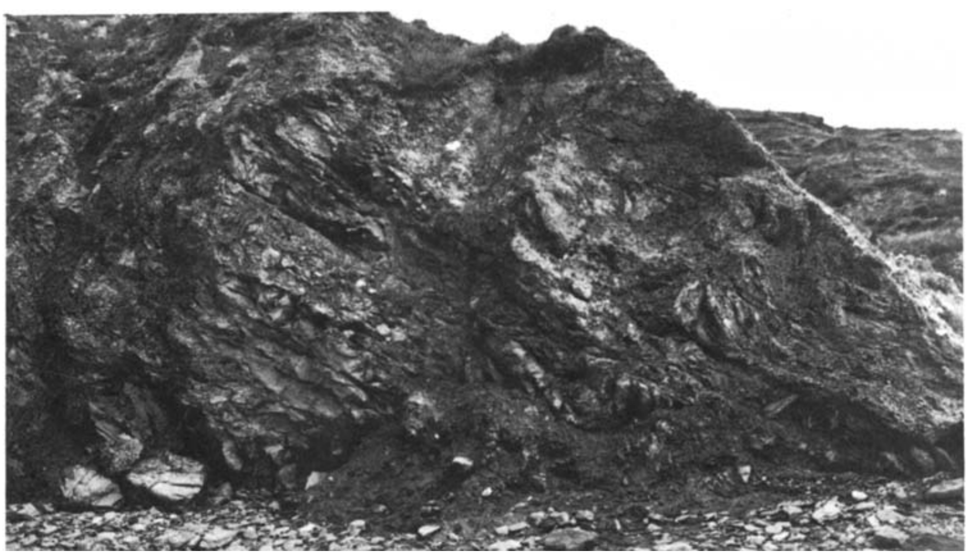


Fig. 11 Combined Coastal–Te Apiti Thrust Zone melange, south Waimarama Beach. Note the distinct shear fabric with numerous exotic floaters within a bentonitic matrix. Several major planar internal shear surfaces are visible dipping from left to right. Note wedged appearance of zone. Photo view to west.

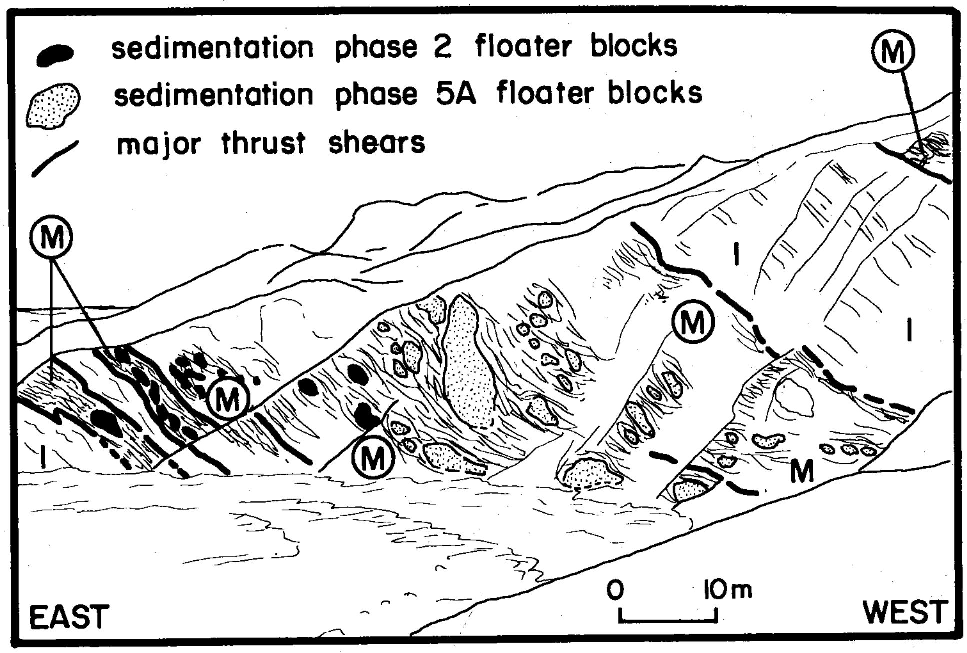


Fig. 12 Line drawing of exposure from bay to north side of Huarau (N142/373913). Note bentonitic melange zone (M) with Late Oligocene sedimentation phase 5A floaters and phase 2 (Whangai) floaters. Sedimentation phase 1 (Piripauan) succession rests over (west of) the melange zone. Refer also Fig. 24B, cross section L–M.

surfaces (Fig. 14). Less reliable information may be obtained from the irregular internal shear surfaces (Fig. 15).

Key areas

A combined geometric analysis of associate structures (2a–2d) has been attempted at several select locations. Data were collected at Waimarama Beach South, Red Island–Taingamata, and Huarau (for locations refer Fig. 4).

Coastal and Te Apiti Thrust Zones near Waimarama Beach South: Shore platform and coastal cliff exposures south from Waimarama Beach are shown in Fig. 16 and 17. This area provides a section of the complex amalgamated Coastal and Te Apiti Thrust Zones.

South of the melange belt the Cretaceous succession (sedimentation phase 1) has been complexly deformed. Major structures reflect southeast-directed overthrusting accompanied by the development of large-scale lozenge and/or transposition fabric and crushed zones (Fig. 18; refer also Fig. 8 and 9). Within the complex, several shear phases are present, some earlier thrust shears having been crenulated and folded. Crushed zones pass gradually into more coherent transposed strata.

Uppermost Cretaceous and lower Tertiary formations (sedimentation phases 2 and 3) are represented by a transposed block immediately to the southern side of the melange zone (refer also Fig. 8). The faulted contact on the southern side of this block reflects an earlier phase deformation directed to the north (see Fig. 9). Similar evidence for earlier phase, north and northwest directed deformation (early Episode 2) has been established elsewhere along the cliff section (Fig. 19) using normal conjugate fault couplets and lozenge fabric. Crosscutting relationships are clear.

The melange zone abruptly truncates the older sedimentary succession. Internally it is characterised by major shears (Fig. 11) and transposed fabric (Fig. 8). Floater blocks within the melange are locally derived and include Oligocene mudstones (sedimentation phase 5A).

Locally derived cohesive debris flows (basal sedimentation phase 5A) onlap the melange zone. The debris material in the flows, including some matrix, is identical to that of the melange, suggesting coeval development. The contact zone between the melange and debris flows is, however, also sheared. The less-deformed phase 5A sediments to the north of the melange are folded into a tight inclined syncline.

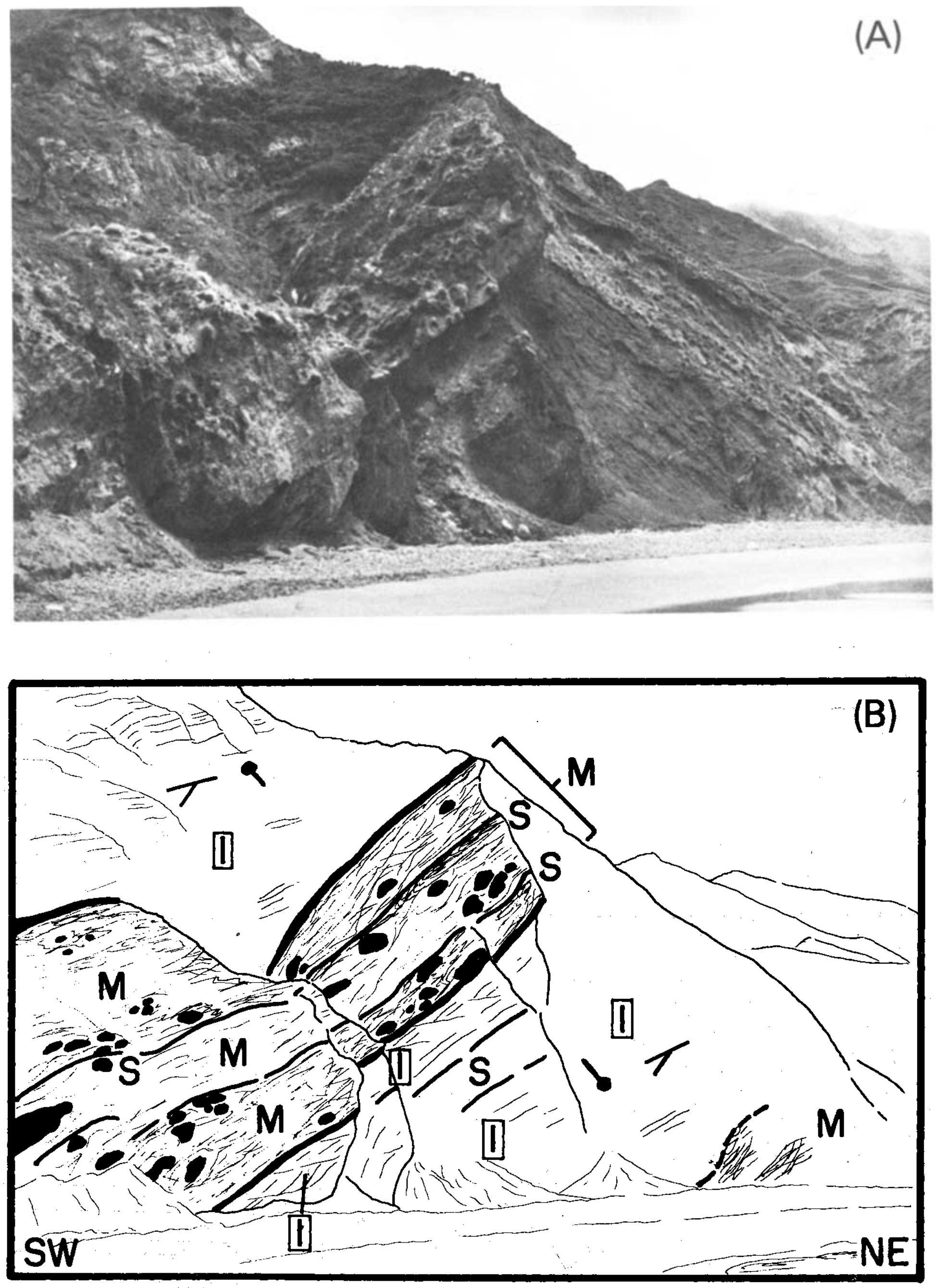


Fig. 13 Photo view (A) and line drawing (B) of exposure from bay to south side of Huarau (N142/370910). Note bentonitic melange zone (M) visibly wedging in outcrop. Note several major internal shears (S) and floaters of exotic lithologies (blackened). Also overturned limb above or west of thrust zone. Sedimentation phases are indicated in boxes.

Fig. 14 Lineations on basal thrust plane of bentonitic melange zone south of Huarau (N142/368904).

Fig. 15 Te Apiti and Coastal Thrust Zone bentonitic melange, south Waimarama Beach (N142/404979). Note the intensely sheared bentonitic clay with slickensides and encased exotic and intraformational floaters (lower right). *(Photo: N. Trustrum, MWD)*

Red Island–Taingamata Thrust Zone (Fig. 20 and 21): This zone stretches from the northwestern side of Taingamata to immediately onshore southwest of Red Island. It may be subdivided into 3 entities: (1) a western melange belt; (2) a central inverted sequence (sedimentation phase 1); and (3) an eastern melange belt and Red Island.

The western melange belt may in turn be subdivided into 2 melange components bearing a crosscutting relationship to each other. The basal contact of the early melange dips steeply westward, near-parallel to bedding in the adjacent inverted sequence (to the east side). The distribution of the bentonites is complex. Thrust-bound wedges of bentonitic clays clearly wedge downward, dipping steeply to the west (Fig. 22). Successive wedges may occur along near-parallel trends, but generally basal thrust contacts dip less steeply in later (crosscutting) wedges to the west. The melange material between wedges is composed primarily of older formations (sedimentation phases 1 and 2). The later-phase melange is overthrust onto the early phase, truncating it (see Fig. 21; section T–U). The lower part of this late thrust melange near Red Island displays mesoscopic zigzag-type folding.

Incorporated into this western melange is a large floater of a more coherent stratigraphic succession (sedimentation phases 2 and 3).

An inverted sequence (sedimentation phase 1) constitutes the central part of the Red Island–Taingamata Thrust Zone. This overturned fold limb is traced from west of Red Island northward to Taingamata, forming the latter promontory. The limb is internally coherent with the dominant deformation being represented by lozenge fabric (Episode 2b). Direction of separation is to the NNE. At Taingamata the limb is refolded into an antiform, the complex core of which is exposed on the southern side of the promontory.

Structurally beneath the inverted limb, a further melange zone trending NNE–SSW is exposed at Red Island and on the headland to the north. This melange separates Red Island structurally from the mainland.

At 4 localities within the Red Island–Taingamata Thrust Zone, "floater" blocks of mid-Cretaceous Red Island Volcanics are mapped, the largest block forming Red Island. Another antiform is inferred to separate Red Island from the mainland structurally, the core of this fold having been sheared out along the melange zone.

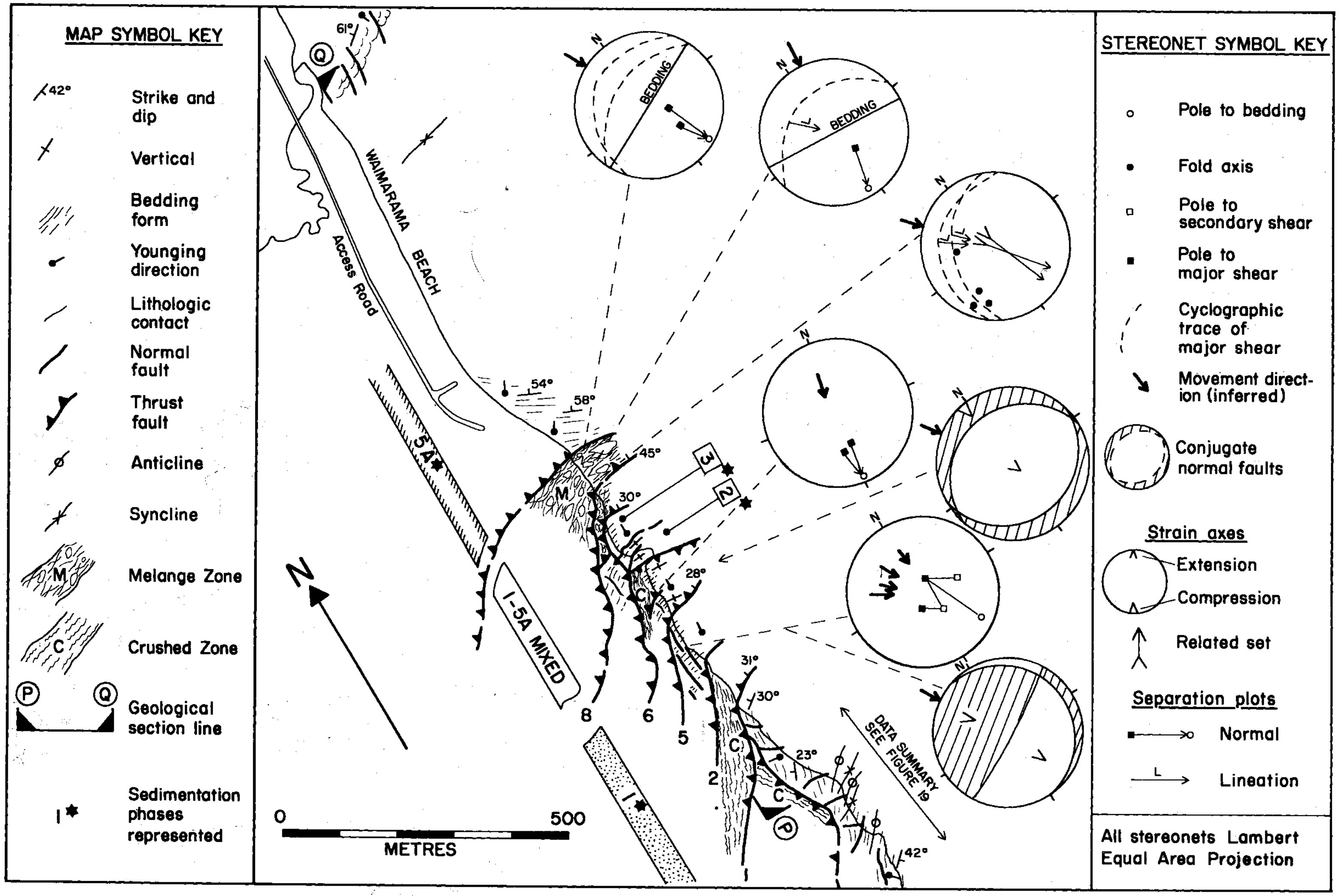


Fig. 16 Detailed geological map of south Waimarama Beach. Note melange represents the combined Coastal and Te Apiti Thrust Zones (see also Fig. 5, 8, and 11). Note also the northward-directed thrust located below thrust 6; the northward movement represents the early Episode 2 event. For a more detailed view of the latter relationship refer Fig. 9. For cross section P–Q see Fig. 17.

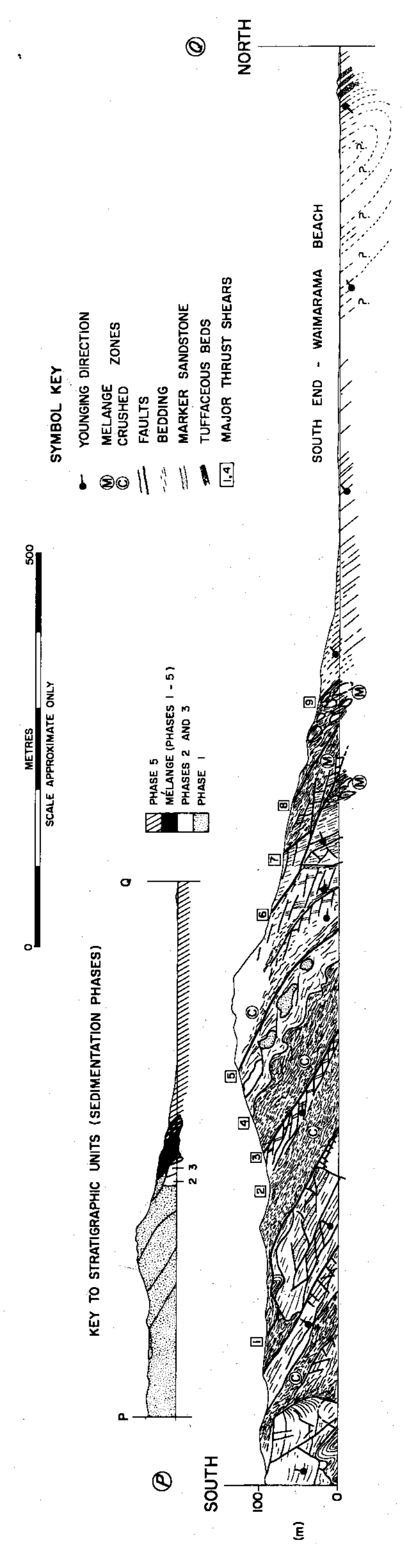


Fig. 17 Cross section P–Q, south Waimarama Beach. For location see Fig. 16.

Movement directions from the inverted sequence, as inferred from separation plots, indicate northward-directed deformation. Micro and macrostructure data from Red Island indicate a similar movement, overprinted by a west-to-east event. Small-scale fold axes also indicate 2 deformation events, directed from south to north and from west to east.

Coastal Thrust Zone near Huarau: This area provides the clearest cross section of a melange zone. Exposure is good and relationships can be traced over a considerable distance.

The main elements comprising the Coastal Thrust Zone are depicted in the inset of Fig. 23. Although schematically the whole zone can be considered as a melange, several discrete relatively coherent stratigraphic successions are included. One such succession is inverted and its repetition by overthrusting from the southwest is clear.

The dominant melange matrix component is the bentonitic clay. Many major internal shears are mapped, and "floater" clasts of locally present formations are aligned along parallel trends (Fig. 24; section N–O) (see also Fig. 13). The youngest included floaters are of latest Oligocene age (sedimentation phase 5A) and are recorded at several distinct structural levels within the melange (refer Fig. 12). The unconformable onlap of Middle Miocene massive mudstones over the thrust zone complex constrains its development to Early Miocene time.

The downward wedging of individual melange elements is also well exposed. In the area immediately to the west of Huarau, a gradational change from melange to crushed zone is recorded, thus emphasising their genetic similarity.

Internal detailed structural information on movement directions is indicated by small-scale folds associated with major shears and lineations on major shears. Again, 2 directions are apparent, but no crosscutting relationships were recorded.

Synthesis

Stereographic analysis of Episode 2 structures (2a–2d) has established 2 movement directions. The early Episode 2 event involved a north or northwest-directed translation, whilst a subsequent late Episode 2 deformation was directed to the east or southeast. Best evidence for the crosscutting relationship of these 2 events was taken from the Waimarama Beach South area. The significance of these and other major structures (such as the inverted fold limbs) are discussed later.

Much of the detailed information collected during fieldwork is omitted for clarity, and the reader is referred to Pettinga (1980) for a more complete treatment.

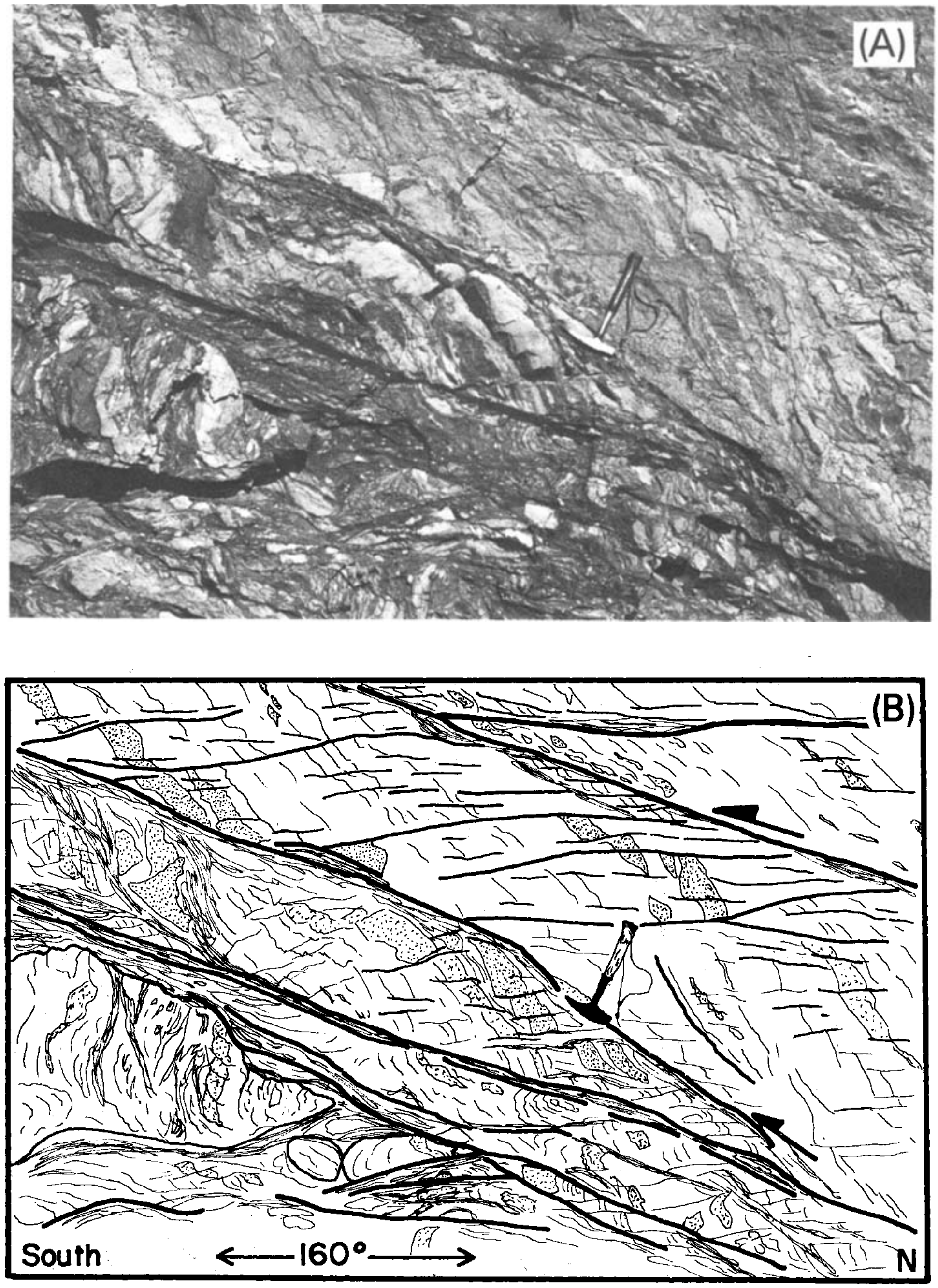


Fig. 18 Photo view (A) and line drawing (B) of lozenge fabric (transposed bedding) developed between 2 major shears south of Waimarama Beach (N142/405978). Locality is situated below thrust 5 illustrated in Fig. 17. Crushed zones visible top right and bottom left. Note large floater block in crushed zone lower left; also note that transposed beds have undergone a previous deformation expressed by lozenge formation accompanied by pervasive bedding shear. The inferred movement direction is from right to left.

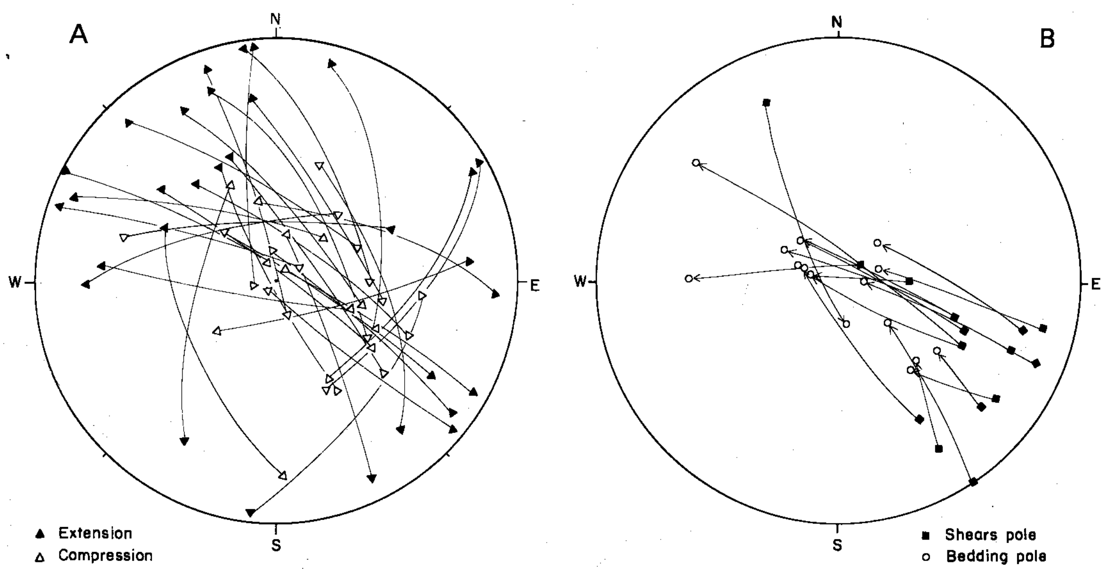


Fig. 19 **A** Cumulative extension-compression axes plot of normal conjugate fault couplets (Episode 2b structures). For location of data collection see Fig. 16. Partial great circle connecting axes represents a movement plane at right angles to intermediate axes (or intersection line) of conjugate set. Approximate average movement direction is indicative of northwest–southeast extension. Note the fanned distribution of extension of axes in the northwest quadrant is indicative of direction of movement to there, representing a stretching of the stratal succession. Lambert equal area projection, lower hemisphere.

B Cumulative separation plot of lozenge fabric (Episode 2b structures). For location of data collection see Fig. 16. Symbol convention is as shown in Fig. 33B and 33C. Averaged overall direction of separation to the northwest.

EPISODE 3

The Pliocene–Holocene deformation of the Coastal High contrasts sharply by being extensional only. Many steeply dipping normal faults trending NNE are present. Recent fault traces delineate several small horst and graben. The tensional faulting is related to a major regional slump (Pettinga 1980, in press) involving blocks up to 20 km in length. Faults cut all previous structures and are shown only schematically in Fig. 25.

Possible theories for a history of structural development of the Coastal High

In proposing various hypotheses and testing them on the geometric development and present disposition of structures, several constraints immediately become apparent. They include:

(1) Inverted sequences within the Red Island–Taingamata and Coastal Thrust Zones.
(2) The plunging fold structures at Taingamata, Red Island, and Te Rahui.
(3) The east–west-striking, south-dipping thrust fault at Red Island.
(4) Episodes (1, 2, and 3) of structures identified, and the 2 respective directions of separation (movement) obtained for Episode 2.
(5) The crosscutting sequence of the major thrust zones mapped.
(6) The unconformable onlap of Upper Miocene and Pliocene formations over the thrust zones.

Two hypotheses are proposed here. The Red Island–Taingamata area is used to test each hypothesis, and discussion is then extended to include other areas.

Hypothesis 1: Inversion due to early Episode 2 structures overprinted by late Episode 2 structures

Early development of north-facing fold nappes and thrust faults comprising a first deformation is followed by the northeast-trending, eastward-directed overthrusting, comprising a later, dominant phase of deformation.

The development of fold nappes (large-scale recumbent folds) facing northward (Fig. 26) provides a possible mechanism for forming the inverted sequences present, all of which are remarkably continuous, but much attenuated, along-strike. As this early phase structure developed and the inverted limb was attenuated, northward-directed overthrusting became dominant and was accompanied by the development of melange. These melange zones appear to wedge with depth, and a

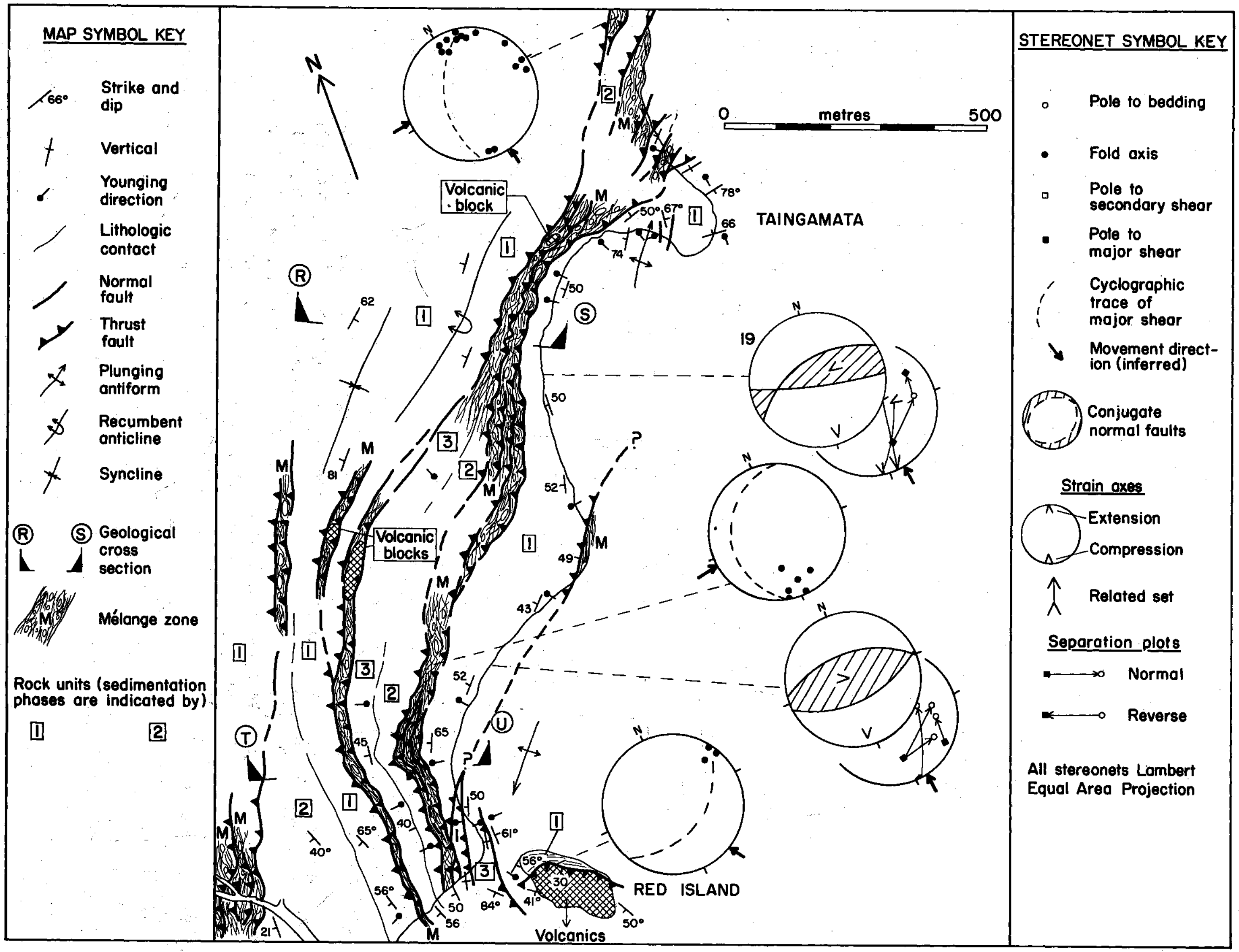


Fig. 20 Detailed geological map of Taingamata to Red Island. Note the melange accompanying the Red Island–Taingamata Thrust Zone. Also note the east–west-trending thrust at the base of the volcanic sequence of Red Island. For cross sections R–S and T–U see Fig. 21A and 21B.

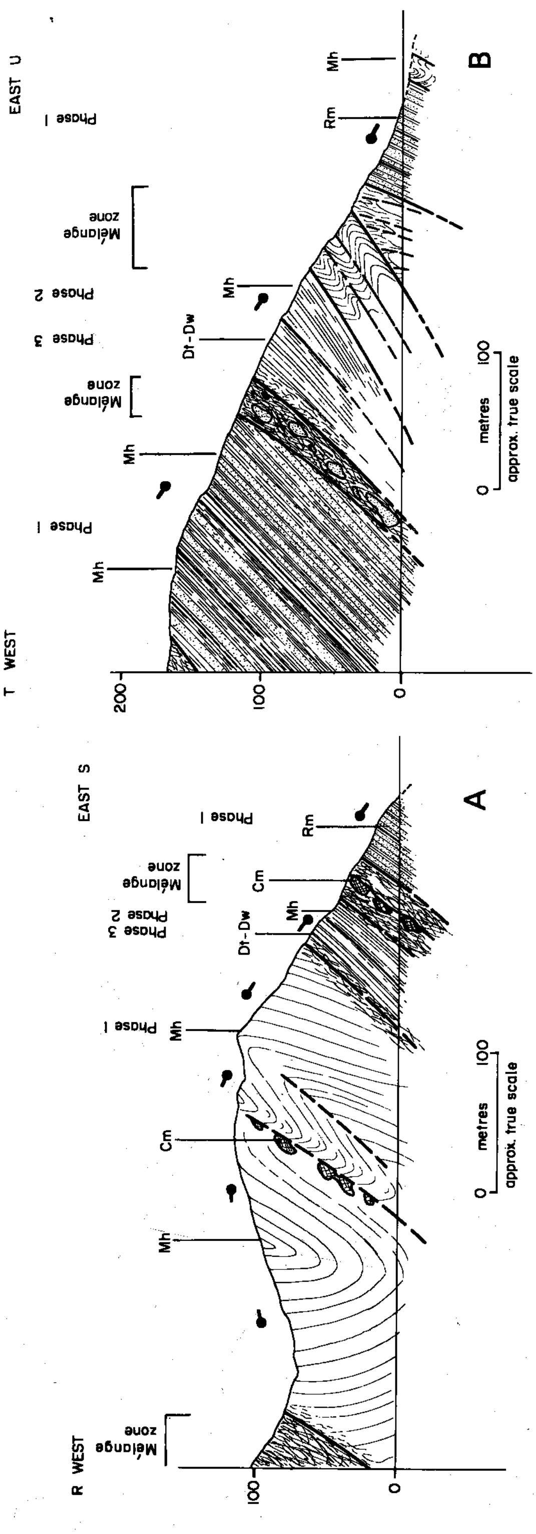


Fig. 21 Cross sections R–S and T–U, Red Island–Taingamata Thrust Zone. For location refer Fig. 20.

possible mechanism in explanation of this is incorporated in Fig. 26B.

At Red Island this overthrusting emplaced the volcanics as floaters within the melange core of the original fold nappe. Early phase overthrusting from the south also accounts for northward-directed lozenge fabric in the overturned sequence near Red Island and the northwest-directed lozenge fabric developed near Waimarama. The early phase melange recognised onland and located structurally above the inverted sequences of the Red Island–Taingamata Thrust Zone may also be related to this overthrusting. The parallel arrangement of bedding, thrust planes, and melange suggests these structures all developed at originally low angles.

The early phase inversion was followed by a later phase of eastward-directed overthrusting along a NNE trend. The early phase fold nappes, thrusts, and melange, were imbricated by this later overthrusting (see, e.g., repetition of structures near Huarau, Fig. 23) The early melange zones were also remobilised during this later phase. The en echelon plunging folds associated with the Red Island–Taingamata Thrust Zone may have formed by drag with this later overthrusting (but another explanation for these folds is their early development with the northward-directed thrusting). Again, thrusts initially appear to have developed at low angles, but with continued imbrication the tectonically stacked sequence became progressively more tilted westward, and crosscutting relationships developed accompanied by large-scale transposition fabric.

A south-facing fold nappe structure as an alternative possibility appears unlikely (see below).

Discussion: Fold nappes (see definitions in Hills 1972; Hobbs et al. 1976) may have formed by a number of possible mechanisms, 2 of which are described as part of Hypothesis 2 (see below). A third is outlined here.

Gravity tectonics is an accepted mechanism of fold nappe development (de Sitter 1964; Hills 1972; de Jong & Scholten 1973; Hobbs et al. 1976). The development and preservation of a middle "inverted" limb is to some extent dependent on the extent of fold development. The greater the horizontal transportation, the greater will be the thinning of the middle limb. In thrust nappes no inverted limb is formed (see de Sitter 1964, fig. 190). The gravity collapse structures described by Harrison & Falcon (1936) in Iran are similar to fold nappes.

The concept of gravity glide structures is not new to East Coast, North Island, geology. The early work of MacPherson (1946) and Lillie (1951) was followed by that of Stoneley (1962, 1968) and Ridd (1968, 1970). Stoneley interpreted complex structures in the East Cape–Gisborne area to have slid

Fig. 22 Crosscutting bentonitic melange thrust wedges (outlined) in part separated by melange of Upper Cretaceous and lower Tertiary lithotypes; Red Island–Taingamata Thrust Zone (N142/395955). Note the thrust wedges bifurcate, are crenulated, and wedge or pinch-out downward. Note also exotic clasts visible in melange matrix lower left. Photo view to southwest.

from a northwest–southeast-trending high formed over the central Raukumara Peninsula. Both Stoneley and Ridd suggest decollement had occurred at depth coinciding with the lower Tertiary bentonitic formations. More recently, I. G. Speden (1976, pers. comm.) has mapped similar structures in the northern and central parts of the Raukumara Peninsula.

On a much larger scale, Ballance & Spörli (1979) have suggested that gravity glide emplaced the Northland Allochthon, which may possibly extend to East Cape (as originally suggested by Brothers 1974), and further suggested its southward extension, possibly to Kaikoura.

Hypothesis 2: Inversion due to folding associated with NNE-trending structures

For this hypothesis it is envisaged that the development of steeply plunging folds and fold nappes occurred as a response to dextral slip along a NNE-trending direction. This phase was subsequently followed by eastward-directed overthrusting.

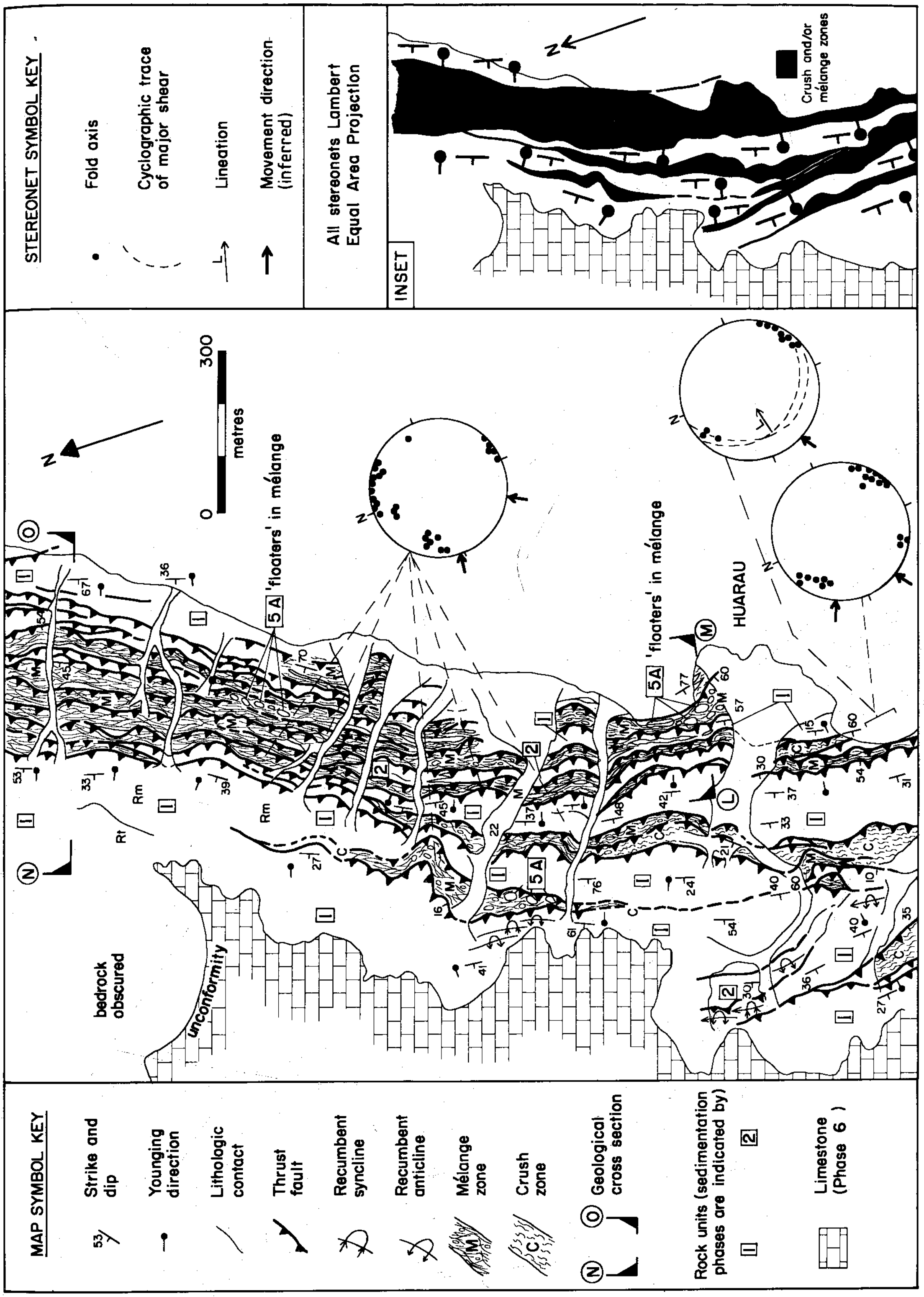


Fig. 23 Detailed geological map of Huarau area. Note the melange accompanying the Coastal Thrust Zone. Dual movement directions are indicated by small-scale folds axial trends on stereonets. For cross sections N–O and L–M see Fig. 24A and 24B. The inset map simplistically outlines the primary structural elmements including fold limbs and melange crush zones. Note repetition of inverted sequence.

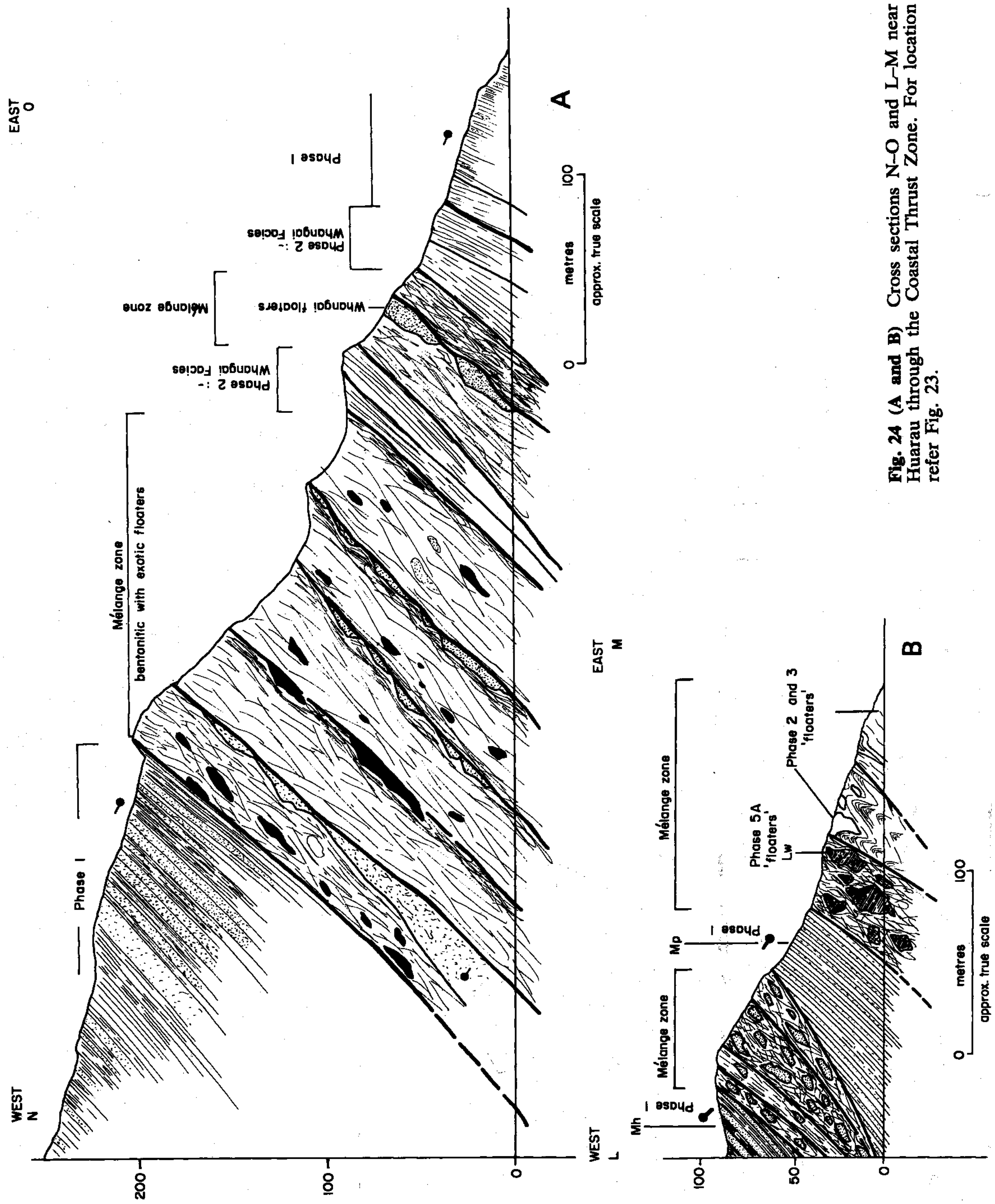


Fig. 24 (A and B) Cross sections N–O and L–M near Huarau through the Coastal Thrust Zone. For location refer Fig. 23.

One immediate requirement is the early development of the fold and inverted sequence at Red Island. It appears unlikely that the development of steeply plunging folds adjacent to a single major (dextral) transcurrent fault could give rise to the situation mapped at Red Island.

Two possible mechanisms that could develop the early recumbent and/or fold nappes by transcurrent faulting are proposed.

1. This alternative hypothetical development is based on Ridd (1964, fig. 7). He showed the development of decollement, with overthrusting and en echelon transcurrent faulting developing in response to major basement transcurrent faulting. A recumbent or fold nappe may form associated with the overthrusting. De Sitter (1964) noted, however, that inverted limbs do not in general form with overthrusting, only with gravity glide (see also discussion in Hobbs et al. 1976).

2. The hypothetical concept of folding in relation to 2 en echelon transcurrent (dextral) shears is outlined by de Sitter (1964) (see also Kingma 1958b). Spörli (1980) relates the development of north–south-trending en echelon folds in the Wairarapa district of the East Coast Deformed Belt to major dextral transcurrent faults in basement. However, it is difficult to envisage the development of the structural setting at Red Island as a consequence of transcurrent (dextral) shear. Pettinga (1980) presents further discussion on this.

Discussion: The most reliable evidence documented in support of transcurrent faulting along the East Coast of the North Island comes from south of the Dannevirke district (Ridd 1967; Lensen 1968; Neef 1974; Johnston 1975). Katz 1974b speculated on possible Miocene dextral shear along the Wairarapa Fault Zone, to the west of the study area, near Lake Poukawa, basing this interpretation on drillhole data. Although evidence of transcurrent faulting in Wairarapa seems well substantiated by fieldwork, Lillie (1953) did not consider transcurrent faulting to be a feature of the Dannevirke district.

Kingma (1958b) considered that the narrow complex structural highs, typical of the East Coast district, represented "piercement structures" developed in response to (dextral) transcurrent faulting. These "faults" are frequently arranged en echelon and are sinuous along-strike. Small sedimentary basins developed between and along fault zones in response to lateral shear (Kingma 1958b, fig. 2). Kingma (1971, p. 133) states that, of the coastal belt:

> "Transcurrent faults have not been observed, but transcurrent movement affecting the area as a whole has certainly taken place".

Indeed, there is little field evidence to support transcurrent offset, and none shown on maps accompanying the Te Aute bulletin (Kingma 1971). However, the possibility that major dextral shears exist at depth in the basement rock should not be discounted. Cross fold (east–west) structures, such as those proposed by the model of Ridd (1964), could be expected. These could have formed part of an early phase deformation, developing such structures as the east-west-striking thrust contact and inverted sequences at Red Island. A subsequent phase of eastward-directed overthrusting could have destroyed all field evidence of the en echelon wrench faults. To counter this argument it could be said that the inverted sequences are too continuous to have developed as part of an en echelon east–west overthrust and recumbent folding regime in relation to northeast–southwest-trending transcurrent faults, and the lack of steeply plunging folds may support this criticism.

The hypothesis of Kingma (1958b) that transcurrent faulting has had a long, continuous history in the district is clearly difficult to prove or refute. Yet, at the present day, and probably from Late Miocene onward, the dominant deformation has been eastward-directed overthrusting, and not transcurrent (dextral) shear.

Synthesis: A favoured hypothesis (Fig. 27)

Of the 2 hypotheses proposed, the author favours the first. The lack of any conclusive evidence for transcurrent faulting, or related steeply plunging folds, and the presence of long, continuous, inverted sequences, all argue against Hypothesis 2.

The inversion of sequences occurred during the early Episode 2 event, and this was directed to the north and northwest (based on separation plots, fold axes, and overthrust directions recorded).

Timing of this event is difficult to pinpoint. Sedimentation to the west in the region of the Elsthorpe Anticline (see later) continued through to Early Miocene time apparently uninterrupted. However, no Lower Oligocene and Upper Eocene rocks have been recorded in the coastal area. The Waitakian and lowermost Miocene strata within the coastal belt do not appear to have been involved in this early phase, and it is thus probable the fold nappe development occurred during Late Eocene–Late Oligocene (Waitakian?) times. The Episode 2 second (later) phase of thrust faulting (and melange development) along the northeast–southwest trend is considered to have, in part, accompanied and followed deposition of the earlier slope basin sediments (Phase 5A, Table 1, Fig. 3), from latest Oligocene time onward. The regional northeast–southwest fabric developed during this phase, and thrusting continued through the Late Miocene,

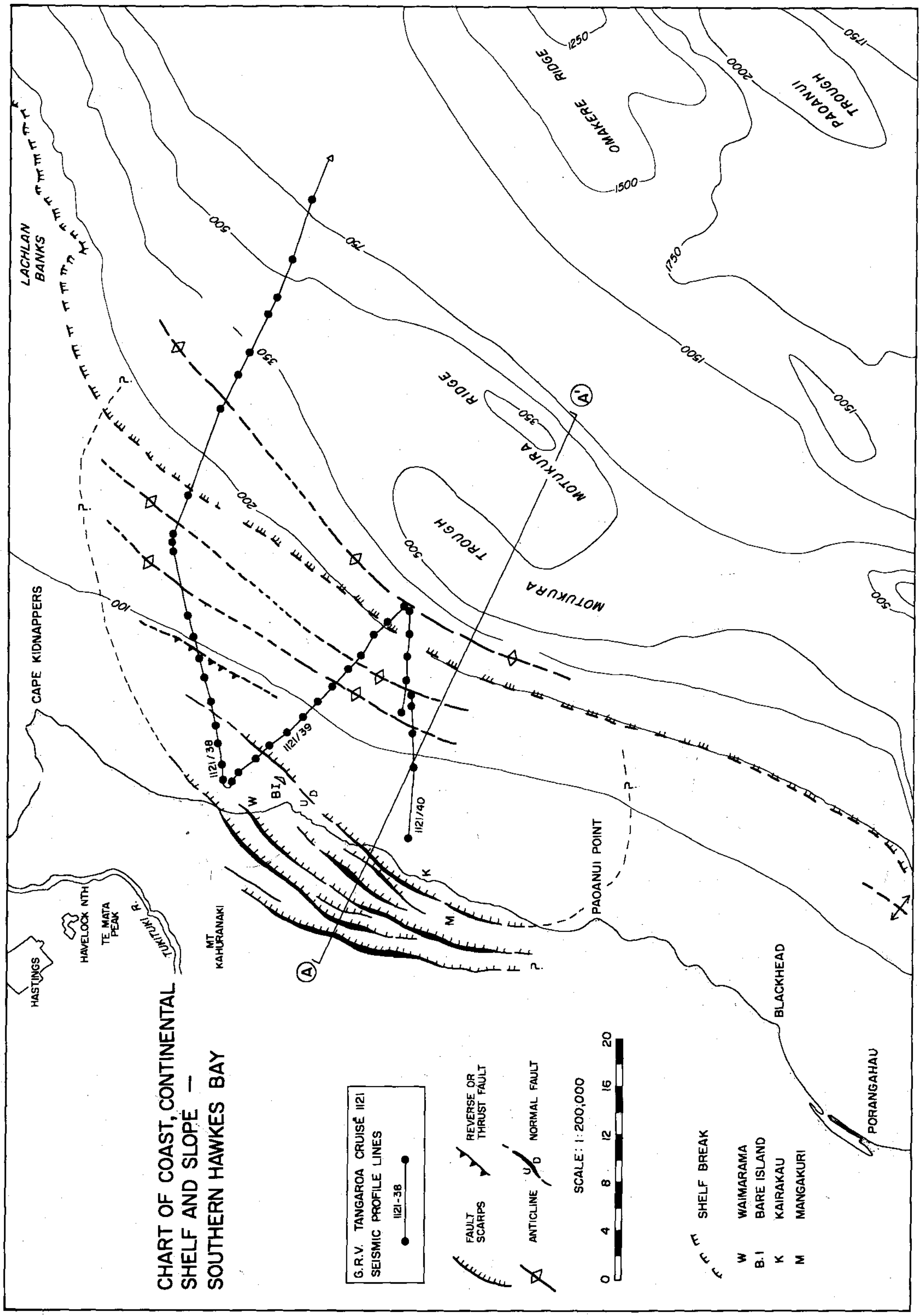


CHART OF COAST, CONTINENTAL SHELF AND SLOPE — SOUTHERN HAWKES BAY
G.R.V. TANGAROA CRUISE 1121 SEISMIC PROFILE LINES
1121-38
FAULT SCARPS
REVERSE OR THRUST FAULT
ANTICLINE
NORMAL FAULT
SCALE: 1:200,000
0 4 8 12 16 20
SHELF BREAK
W WAIMARAMA
B.I BARE ISLAND
K KAIRAKAU
M MANGAKURI
HASTINGS
HAVELOCK NTH
TE MATA PEAK
TUKITUKI R.
MT KAHURANAKI
CAPE KIDNAPPERS
PAOANUI POINT
BLACKHEAD
PORANGAHAU
LACHLAN BANKS
MOTUKURA RIDGE
MOTUKURA TROUGH
OMAKERE RIDGE
PAOANUI TROUGH
1121/38
1121/39
1121/40

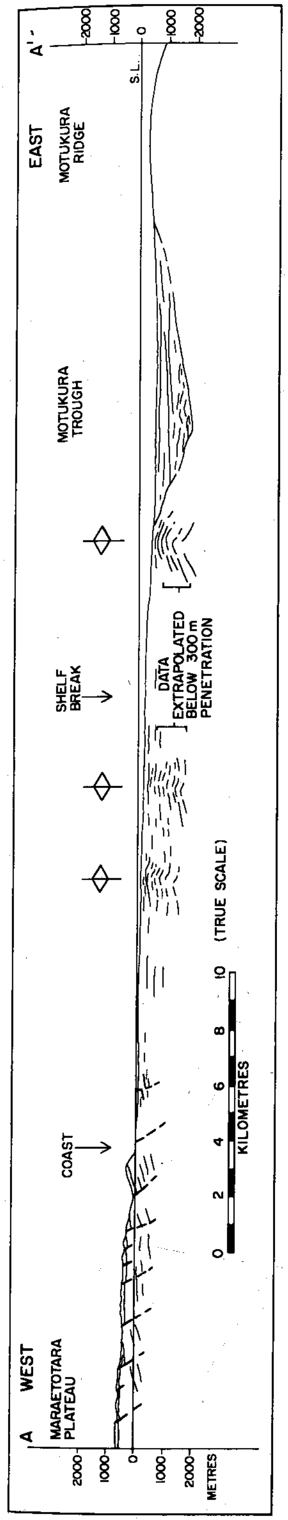


Fig. 25 *(above and opposite)* Schematic summary map of regional slump, coastal Southern Hawke's Bay. Onshore normal faults represent the head zone of the slump. Offshore compressional structures taken from subsurface seismic reflection data obtained on NZOI 1981 RV *Tangaroa* Hikurangi Margin Cruise. Maximum depth penetration of approximately 500 m (Pettinga in press). Generalised bathymetry shown.

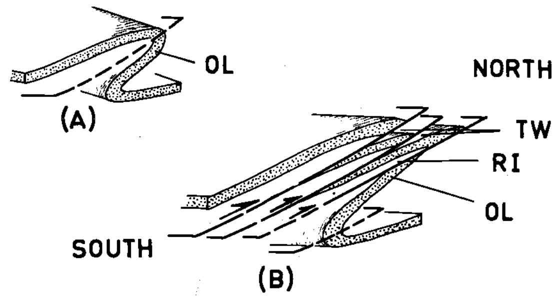


Fig. 26 Early Episode 2 deformation; hypothetical development of east–west structures near Red Island and the formation of overturned sequences there and near Huarau by fold nappes.

A Development of northward-verging recumbent fold or fold nappe; inversion or overturned limb (OL), and basal thrust shears.

B Further development of structures in (A) with attenuation (flattening) of inverted limb. Overthrusting becoming predominant, accompanied by development of melange zone thrust wedges (TW) containing exotic floaters above thrust shears. The hypothetical location of Red Island (RI) in relation to thrust shear is shown.

(probably spasmodically), culminating in the vicinity of the Coastal High during the latest Miocene to earliest Pliocene. To the west, later thrusting formed the Elsthorpe Anticline during Late Pliocene and Pleistocene time. It is clear that the Red Island–Taingamata and Coastal Thrust Zones were still active during and/or following the deposition of Phase 5A flysch and mudstone, because floaters of these materials occur within the melange of both zones. However, the unconformable onlap of Waiauan massive mudstones over the Coastal High (Fig. 3 and 4) indicates these zones had locked by late Middle Miocene. Thrusting, however, clearly continued to the west along the line of the Ocean Beach–Mangakuri Thrust Zone.

Red Island—its structural implications

The presence of the Red Island Volcanics and associated pink limestones of Motuan age in Southern Hawke's Bay provides something of an enigma. Their structural position as floaters within a melange zone clearly discounts any possiblity of this being the site of local volcanism. Two explanations are proposed here.

1. Red Island pillow lavas and associated limestones represent part of the subducted Pacific plate, scraped off and accreted onto the continental margin under the present regime.
2. Red Island pillow lavas and associated limestones represent part of an allochthon (fold nappe) formed prior to the present accretion system. More recently, Ballance & Spörli (1979)

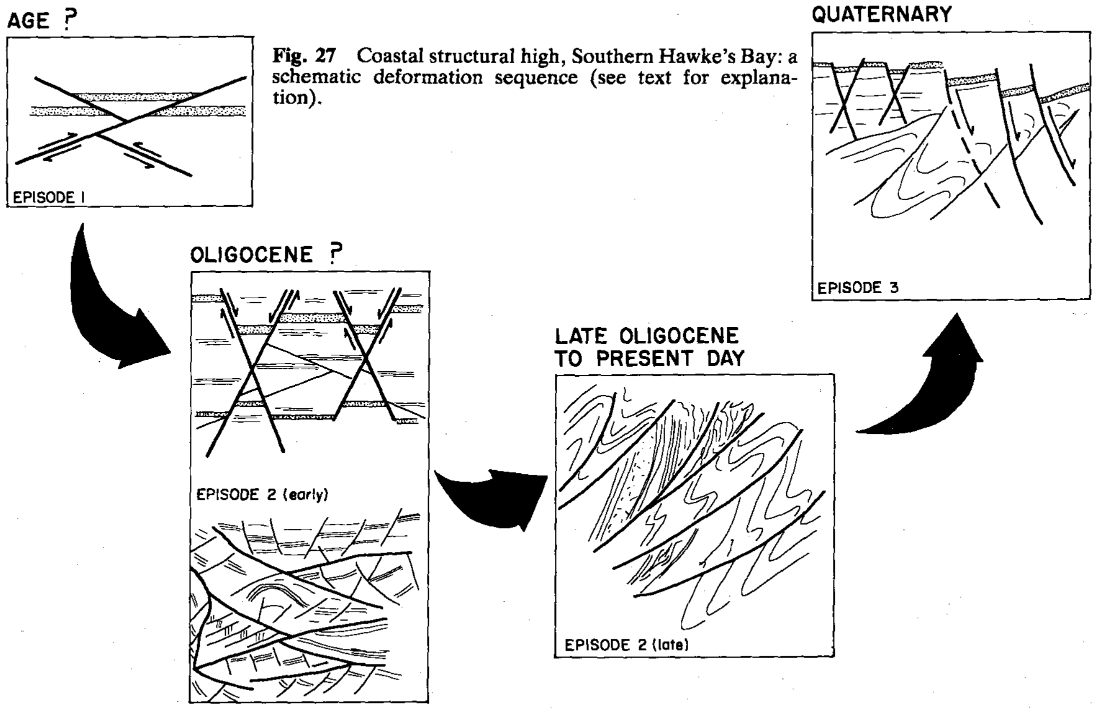


Fig. 27 Coastal structural high, Southern Hawke's Bay: a schematic deformation sequence (see text for explanation).

have suggested the Northland Allochthon may extend to as far south as Kaikoura in the East Coast Deformed Belt. The similarity of the Tangihua and Matakaoa Volcanics as suggested by Brothers (1974) has been further extended recently by the inclusion of the Red Island Volcanics (K. B. Spörli, pers. comm.). Ages are problematic (see discussion in Ballance & Spörli 1979; Katz 1976; Strong 1976a, b). If a similar argument is adopted, the Red Island Volcanics may have been part of the new oceanic crust formed by rifting, as suggested by Ballance & Spörli's model, north and northeast of the East Coast Deformed Belt. Its emplacement as part of an allochthonous sheet may thus be related to that of the Northland Allochthon. The present location of the volcanics within a melange zone reflects their subsequent involvement in the present imbricate thrust regime.

The second of the alternatives is favoured here.

THE ELSTHORPE ANTICLINE AND ASSOCIATED STRUCTURES

Introduction

The Elsthorpe Anticline is a major structural element of the East Coast Deformed Belt. The narrow, linear core is mapped northward from west of Porangahau, where it is an offshoot of the Porangahau-Pourerere Anticlinal Complex (Lillie 1953)—a southward extension of the Coastal High described here—to the east of Havelock North, where it plunges beneath a Pleistocene and Holocene cover (refer Fig. 2 and 3) (see Kingma 1971). The northern part of the anticline traverses the area studied and is the most conspicuous structure (Fig. 2 and 3).

The narrow core zone contains complexly faulted and folded Eocene and Oligocene strata. Elongate fault-bounded inliers of Cretaceous and Tertiary formations are offset west of the core. Faults are generally steep and indicate a predominance of overthrusting from the west.

The limbs of the anticline are formed of the Miocene Makara Formation—Phase 5B (Kingma 1971; Pettinga 1977, 1980). The western limb is substantially thicker than the eastern limb. This is considered due to thrust faulting combined with a lateral facies change and the original Miocene basin geometry (see later, also Pettinga 1980).

Both limbs of the anticline are flanked by Pliocene limestones of Te Aute Formation. The western limb forms the Kohinurakau Range to the north, near Mount Erin, and the Makara Ridge south of the S-bend in Tukituki River. The eastern limb forms the western margin of Maraetotara Plateau.

The Elsthorpe Anticline developed in Late Pliocene and Pleistocene times. It is certainly post-Miocene, based on the lack of, or small amount of, angular discordance between the Makara and Te Aute Formations. The probable emplacement of Mt Kahuranaki as a gravity glide block, from the crest of the anticline onto its eastern limb, further lends support to a Pleistocene age (Spörli & Pettinga 1980).

Recent tectonic movements associated with the Elsthorpe Anticline have been extensional. Recent fault traces are numerous and all are normal; many are parallel to bedding. Dextral transcurrent offsets are localised in occurrence near Mt Kahuranaki (see Spörli & Pettinga 1980). Maraetotara Plateau to the east of the Elsthorpe Anticline has been affected by block faulting giving rise to both graben and fault-angle depression structures.

Previous work

Walpole (1940) first mapped the Elsthorpe Anticline in a regional reconnaissance survey, and interpreted it as a complex thrust zone. Lillie (1953) mapped the southern sector in the Dannevirke Subdivision and concluded it is related to major reverse faulting involving basement. Kingma (1971) mapped the northern part in the Te Aute Subdivision and related the anticlinal core zone to major dextral shear.

Major thrust structures on the western limb of the Elsthorpe Anticline

Two major en echelon thrust zones have thickened the stratigraphically lower part of the western limb of the anticline (Fig. 28). The McKenzie Thrust is a southward extension of the Tarui Thrust Zone (cf. Tarui piercement structure, Kingma 1971). The latter is located adjacent to the anticlinal core north of the prominent bend in the anticlinal axis near Mt Kahuranaki. It appears from field evidence that the McKenzie Thrust "dies out" southward before reaching the Hawea Stream, but that its continuation is en echelon along the complex Ryans Ridge Thrust Zone (Fig. 28 and 29). Further major thrust faulting has occurred within the axial core zone, where the Elsthorpe Thrust is most prominent, forming a steeply dipping zone accompanied by melange and associated folding to the east.

A speculative attempt is made here to determine the gross structure of the western limb (Fig. 30) and thus establish stratigraphic correlation between limbs, and a possible hypothesis for the development of the Elsthorpe Anticline as a whole (see later).

Comparison of eastern and western limb thickness

All previous workers in the district have noted the considerable disparity of limb thickness of the Elsthorpe Anticline between the Mt Kahuranaki area and the Elsthorpe settlement (see Fig. 3 and 28). If the Miocene Makara Formation is taken as reference, the western limb totals in excess of 2600 m in thickness, and the eastern limb is barely 1400 m (ignoring the Te Aute Formation). Kingma (1958a, fig. 21) considered this to be a result of basin geometry and an associated lateral facies change.

A schematic cross section (Fig. 30C) shows the obvious difference in limb thickness, and illustrates how it can be accounted for by tectonic imbrication due to thrust faulting of the western limb.

Age of the Elsthorpe Anticline

This has been a subject of some conjecture. Lillie (1953) considered the anticline to be post-Miocene, and probably largely Pleistocene in age. Kingma (1971) concluded that the anticline had been in existence since at least the middle Tertiary, and had a complex history of emergence coupled with erosion and submergence with onlap, such movements being controlled by transcurrent faulting. He suggested (Kingma 1971, p. 134) that the anticline was folded prior to deposition of the limestones of the Te Aute Formation. This conclusion is based on the recognition by Kingma of an angular unconformity between Miocene and Pliocene formations along the western escarpment of the Maraetotara Plateau.

Although a high angular discordance characterises the Te Aute–Makara Formation contact near the coast, there appears little field evidence to support major angular discordance between these formations on either limb of the anticline. The sharp change in lithology appears to coincide with a sedimentation break (Kapitean fauna are generally absent). The contact on the western limb, best exposed at the eastern entrance to the Makara River Gorge, is disconformable and typically highly bored. A similar relationship is recorded elsewhere along-strike. The eastern limb relationships are much the same. It is reasonable, therefore, to postulate the major folding phase of the anticline occurred in Late Pliocene and/or Pleistocene times.

Thrust faulting affecting the western limb is of post-Miocene age. The basal Makara Formation members mapped over the core zone have been folded and faulted in congruence with the anticline, and flysch onlap relationships, such as occur at the western margin of the Coastal High, are not recorded. Exposure within the core zone, however, is generally too poor to provide more detailed information.

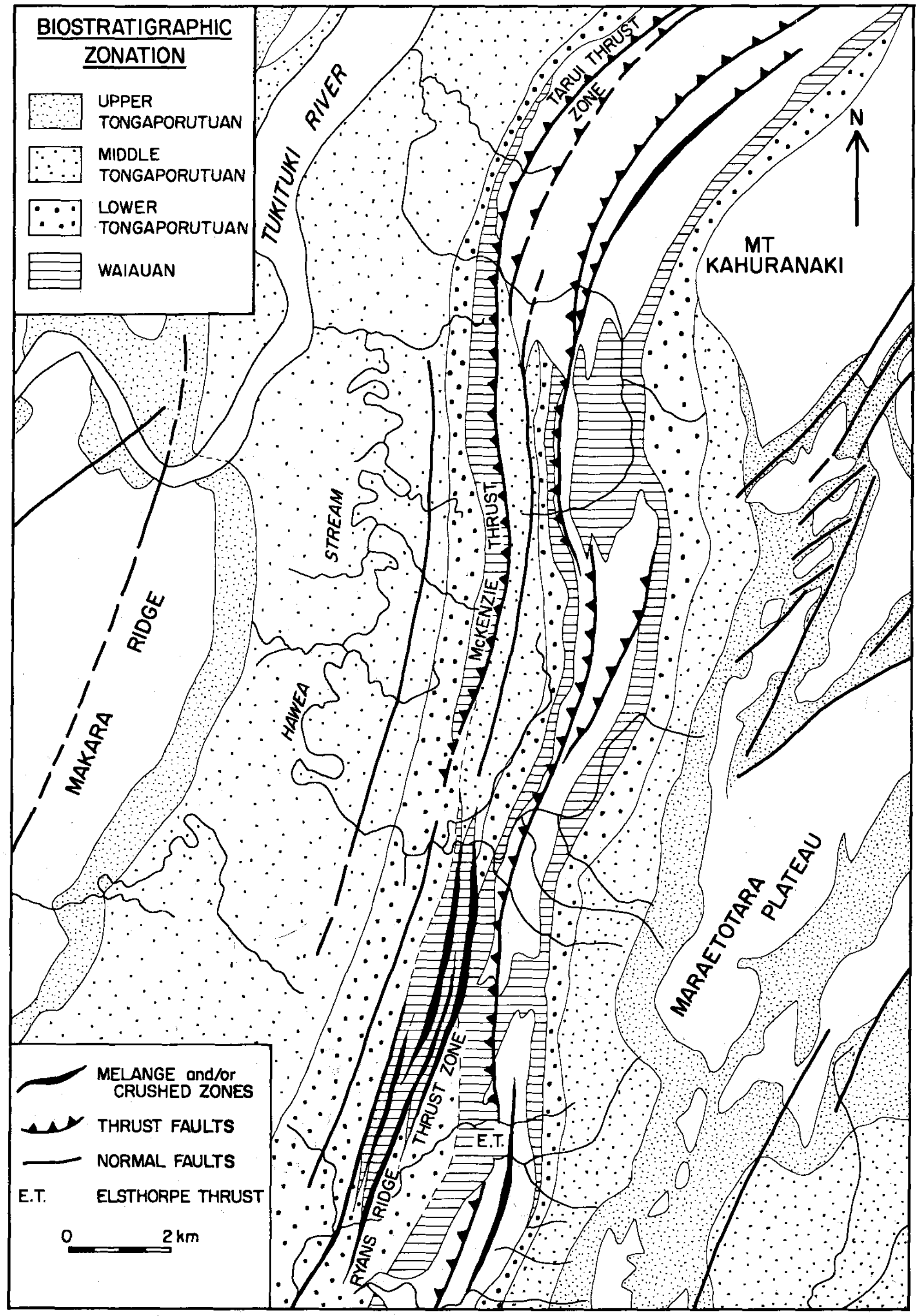


Fig. 28 Generalised biostratigraphic zonation map of Late Miocene Makara Formation (sedimentation phase 5B) comprising part of the Elsthorpe Anticline limbs. Blank areas including the Makara Ridge, Mt Kahuranaki, and Maraetotara Plateau are formed on Pliocene Te Aute Limestone; within the anticline core, blank areas are formed on pre-Miocene lithologies.

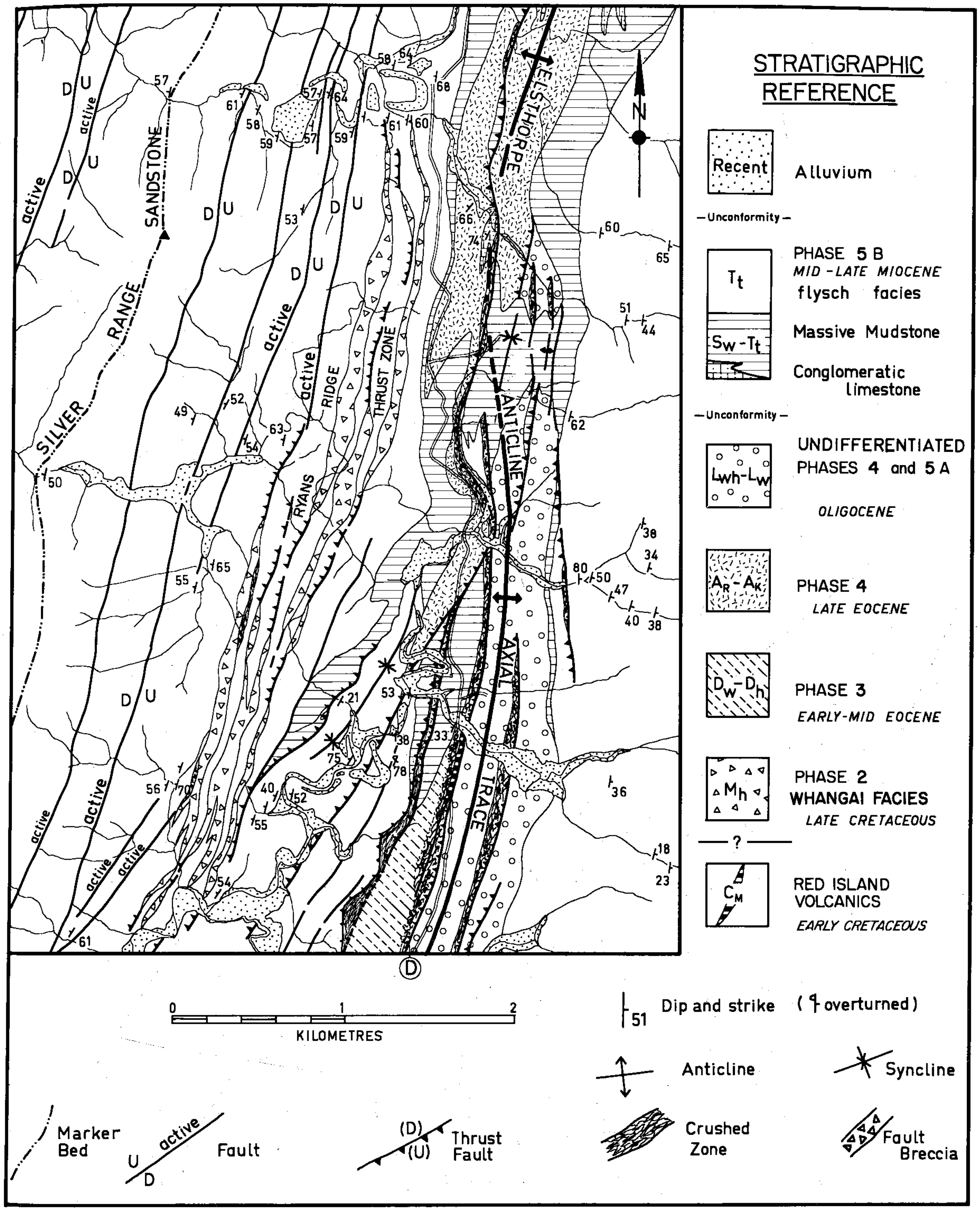


Fig. 29 Geology of the Ryans Ridge Thrust Zone and adjacent Elsthorpe Anticline core, north of Elsthorpe settlement. D = Elsthorpe Thrust.

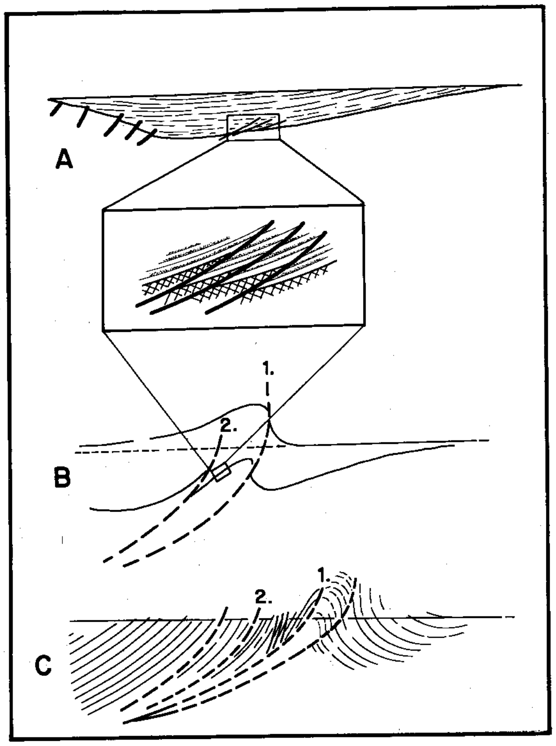


Fig. 30 Schematic developmental history of the Elsthorpe Anticline. **A** Makara Basin hypothetical cross section view, Late Miocene time (refer also Fig. 31E). **B** Development of the Elsthorpe Anticline with major thrust faulting (Late Pliocene and/or Pleistocene times). 1 = Elsthorpe Thrust, 2 = McKenzie Thrust. Boxed areas in A and B show very low angle imbricate thrust faulting (gravity glide?). Hypothetical early development of the Ryans Ridge Thrust Zone. **C** Present-day situation, tectonically thickened, west limb of the Elsthorpe Anticline, symbols as for B.

The postulated emplacement of Mt Kahuranaki, composed of Pliocene Te Aute Limestone, as a gravity glide block (or klippe) from the crest of the anticline further supports its Late Pliocene and/or Pleistocene development (Spörli & Pettinga 1980).

The Patangata Syncline

The Patangata Syncline forms the northward continuation of the very prominent Akitio Syncline mapped to the south in the Dannevirke Subdivision by Lillie (1953) (Fig. 2). The syncline is mapped on the evidence of poorly exposed Makara Formation flysch. Folding is not clearly reflected by the Te Aute Limestone.

South of the area studied, the syncline forms a broad open fold. This is in contrast to the sharp-crested and much faulted adjacent Elsthorpe Anticline. The syncline is thought to have had a 2-phase development, the eastern limb forming as part of the Elsthorpe Anticline during post-Middle Pliocene folding; the western limb appears to have formed earlier in conjunction with folding and faulting of the adjacent Inland High (Fig. 2). This is borne out by evidence southwest of the study area, where upper Tongaporutuan strata overlap onto Waiauan mass-flow limestones (see Kingma 1971, pp. 125–126).

The Atua Synclinorium

A broad open fold structure, similar to the Patangata Syncline, occurs east of the Elsthorpe Anticline and is known as the Atua Syncline (Kingma 1971). It forms the northward extension of the prominent Omakere Syncline of the Dannevirke Subdivision (Fig. 2).

The synclinal structure as described by Kingma (1971) is a simplification of what has been mapped as a synclinorium. Several en echelon folds exist, flanking and separated by the northward extension of a thrust zone, forming an offshoot from the Coastal High south of the area studied, and named the "Clareinch High" by Lillie (1953).

The synclinal structure is further enhanced by the progressive tilting which accompanied sedimentation of the Makara Basin flysch sequence adjacent to the Coastal High. Strata were tilted gradually, and a distinct onlap relationship of flysch with the actively growing high was developed during Miocene time (see van der Lingen & Pettinga 1980, fig. 3 and 11). This onlap was first described by Kingma (1958a).

The northward extension of the Atua Syncline beneath the Pliocene limestone cover of Maraetotara Plateau is probable. The latter, however, is not folded in congruence, because westward tilting of the Makara Formation adjacent to the Coastal High predates deposition of the limestone, whereas folding of the western limb occurred with the development of the Elsthorpe Anticline, following deposition of the Te Aute Limestone. This is a similar development as that suggested for the Patangata Syncline, indicating these shallow synclines are consequential structures related to the thrust fault development of the structural highs.

Mud volcanoes

It has been frequently reported that marl diapirism associated with faulting is manifested at the surface as mud volcanoes (Lillie 1953; Stoneley 1962; Ridd 1968, 1970; de Caen 1969; Kingma 1971; Katz 1974a). Indeed, within the study area, numerous such mud volcanoes occur.

It would appear, however, that the importance of true "diapirism" has been overemphasised. The montmorillonitic mudstones of early Tertiary age, when sheared, become soft, incompetent clays, commonly referred to as bentonite, and in association with major thrust faulting (melange zones) they may act as a tectonic lubricant. There also seems little doubt that these bentonitic clays in near-surface conditions may be remobilised by the combined effects of groundwater and litho- and hydrostatic pressure, to be erupted as mud volcanoes. The volcanoes are most active during and immediately after major earthquakes (see Henderson 1933; Lillie 1953; Ridd 1970; Kingma 1971) and at other times remain relatively quiescent. The sites of volcanoes are also typified by escaping methane gases.

It is suggested here that mud volcanoes, such as those mapped within the core of the Elsthorpe Anticline, do not necessarily represent true diapiric upwelling, but are small surface manifestations of the "tectonic pressure" along major thrust fault zones, in which bentonitic clays are distributed as "fault gouge". As outlined earlier, sheared "bentonitic" mudstones are frequently incorporated in thrust zones as inliers or slivers.

Possible theories for the development of the Elsthorpe anticlinal structure

The early phase deformation considered to have affected pre-Middle Miocene formations of the Coastal High are equally likely to have affected the same strata exposed in the core zone of the Elsthorpe Anticline. However, insufficient mapping combined with restricted outcrop and poor exposure prevent a similar interpretation from being attempted. Accordingly only post-Miocene deformation is discussed here. Two hypotheses are proposed.

Hypothesis 1: Post-Middle Pliocene development of the Elsthorpe Anticline by eastward-directed imbricate thrust faulting.

Thrust faulting has already been shown to have played a major role in the development of the Coastal High to the east of the Elsthorpe Anticline. Three possible causes of thrust faulting should be considered.

1. *Gravity glide with possible decollement on basement.* This alternative appears unlikely, largely because the anticline is a linear feature, propagated as an offshoot from the Coastal High near Porangahau (Fig. 2). The latter forms parts of a structurally complex linear belt traced almost the entire length of the East Coast Deformed Belt from Wairarapa to Hawke Bay. If gravity glide was responsible, the outcrop pattern would be more arcuate (see, e.g., Stoneley 1968).

The Ryans Ridge and McKenzie Thrust Zones have substantially thickened the western limb and may have developed prior to, or during, fold movements which formed the anticline. Their subparallelism to bedding suggests early development (Fig. 30A). Accordingly, their formation by gravity gliding should not be discounted. This would more easily account for the en echelon arrangement of the thrusts. These early thrusts were subsequently incorporated into the anticlinal structure. One point to counter their development by gravity glide is that the eastern limb does not appear to be affected by thrust faults subparallel to bedding and causing biostratigraphic repetition (Fig. 28).

2. *Deep-seated underthrusting associated with regional compressional tectonics.* This alternative is favoured here, (Fig. 30). It follows that the anticline, as an offshoot from the Coastal High, marks a westward shift in the loci of thrusting associated with the development of the gross regional structural fabric which is dominated by the northeast–southwest trend. This conclusion is further supported by the lack of evidence for post-Middle Pliocene thrust faulting of the Coastal High.

3. *Transcurrent faulting in basement and associated cover decollement.* This alternative is not favoured because of the continuity and linearity of major structures. The model, as proposed by Ridd (1964), would require a discontinuous and/or en echelon structure, and, for the Elsthorpe Anticline, transcurrent faults trending east–west are considered to be most improbable. A drag fold structure, developed as a cover decollement in response to transcurrent faulting, has been proposed by Prebble (1980) for the Kekerengu area in northeast Marlborough. Although a WSW-trending fold structure affecting Oligocene formations west of Mt Kahuranaki may be similar to that described by Prebble, the necessary conclusion would be pre-Middle Miocene transcurrent faulting along the line of the Elsthorpe Anticline, because the Upper Miocene succession rests unconformably on the fold structure. The possibility of transcurrent faulting during pre-Middle Miocene time is not able to be assessed further here, but is considered unlikely, as no other similar fold structures occur exposed in the core of the anticline, and no evidence for transcurrent faulting has been established from elsewhere in the study area.

Hypothesis 2: Transcurrent faults controlling structures such as the Elsthorpe Anticline.

This possibility was first proposed by Kingma (1958b) (see also Kingma 1971). Although this hypothesis is not favoured here it is examined below.

Kingma's hypothesis attempted to explain 2 characteristic features of East Coast geology: (1) rapid facies changes with the presence of thick flysch sequences separated and enclosed by thin condensed mudstones; and (2) the presence of numerous local unconformities.

Kingma's hypothesis explains these by the development of small local basins arranged adjacent to major transcurrent faults, and by the occurrence along these faults of "piercement structures" (see Kingma 1958b, fig. 1 and 2). Kingma (1971, p. 134), in examining the area northwest of Mt Kahuranaki, concludes that

> "... the piercement was already moving and eroding in Waitakian time immediately earlier, and that consequently the transcurrent fault zones were then active".

This conclusion was based on the incorrect assumption that the lower Haumurian part of the piercement was covered by Waitakian sediments in this area. Field mapping indicates this to be incorrect and that the Waitakian in fact comprises a thrust wedge.

The development of the Elsthorpe Anticline by post-Miocene dextral shear along the anticline core is countered by a number of arguments. Firstly, neither the Te Aute or Makara Formations show any sign of dextral (or sinistral) offset of facies across the anticlinal core. Secondly, the mapping of what Kingma termed "piercement structures" was simplistic. Detailed field mapping has shown that both the Ryans Ridge and McKenzie Thrust Zones (and the northward continuation of the latter into the Tarui Thrust Zone) contain several thrust slices or inliers, with thrust fault contacts near-parallel to bedding (refer Fig. 28 and 29). Thirdly, it would be difficult to envisage the development of imbricate geometry of the western limb by incorporating the effects of transcurrent shear (see Fig. 30).

Recent faulting—why tensional?

The 1931 Napier earthquake served to emphasise that thrust faulting is still continuing. It involved major overthrust along a northeast–southwest-trending fault located west of the study area (Henderson 1933; Walcott 1978b). East–west shortening associated with this rupture was about 2–3 m (Walcott 1978b). No active thrust faults are identified in the study area. All recent faults are normal, with few showing minor dextral shear components also.

Three possible explanations are advanced to account for the normal faulting.

1. The influence of the proposed regional slump may extend inland beyond (west of) the eastern margin of Maraetotara Plateau.
2. The area could be under surface tension due to uplift and arching, faulting along bedding being indicative of surface adjustments only (favoured here).
3. Walcott (1978b), using geodetic data, showed that prior to the 1931 earthquake, the Hawke's Bay district shear strains had a large component of compression normal to the regional northeast–southwest structural grain, and, following the earthquake, a large component of extension. He suggested that: (1) the compressional stage resulted from locking of the subduction thrust with plate movement accumulating as an elastic strain; (2) the earthquake was caused by rupturing of the locked zone; and (3) the following extension was a relaxation and gravitational spreading within the lithosphere above the thrust.

Recent fault traces all trend NNW–SSE to northeast–southwest. None showed renewed offset during the 1931 earthquake, with the exception of those at the northeast tip of Mt Kahuranaki. It may be that these have recorded a local gravity settling of Mt Kahuranaki.

SUMMARY

A schematic sequential development history (Oligocene to present day): Coastal High and Makara Basin–Southern Hawke's Bay

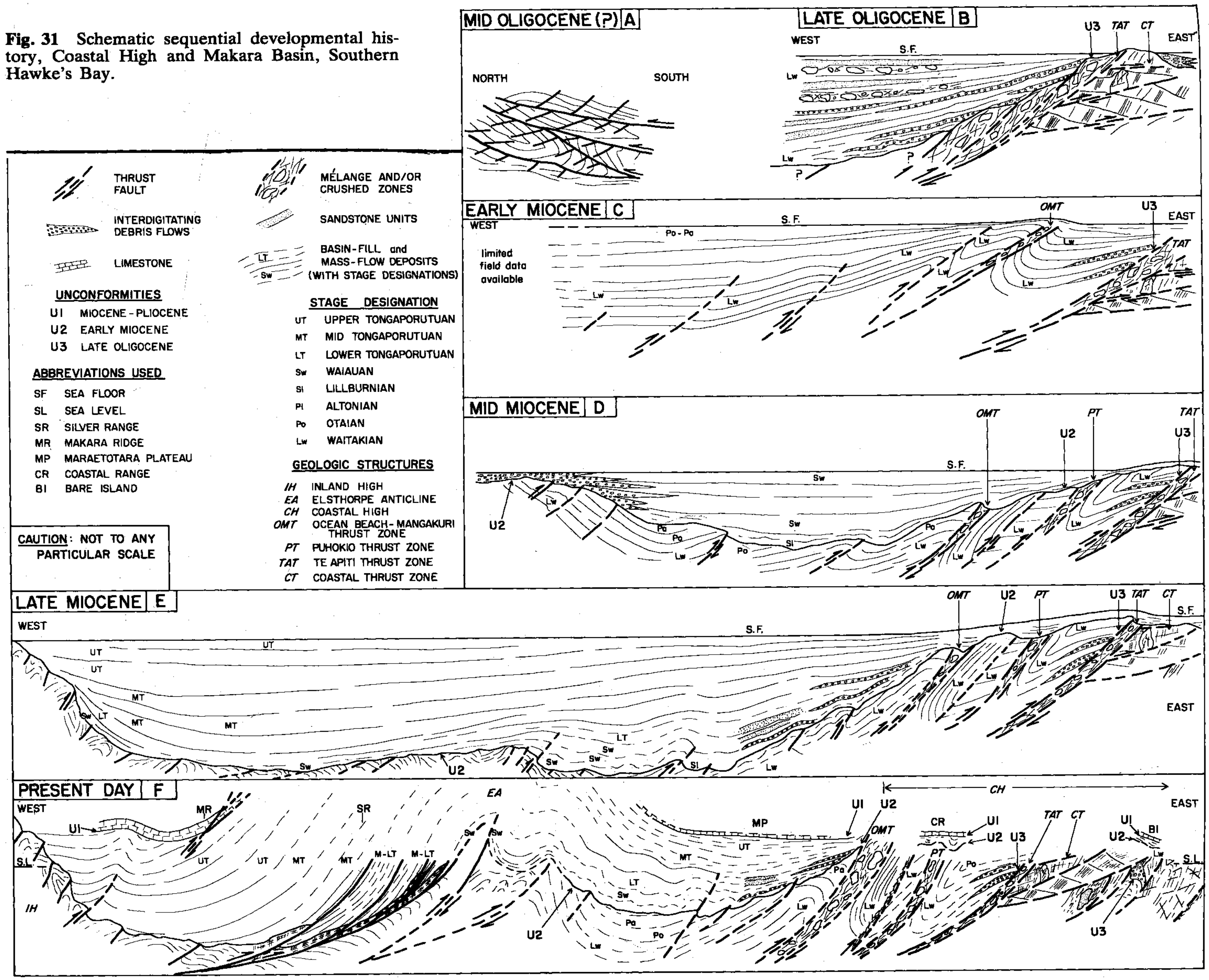
The following summary relates to Fig. 31. This figure is highly schematic and attempts to show all pertinent field relationships recognised in the area studied. Accordingly, it does not represent a detailed cross-sectional summary along any 1 particular line, but rather is a representative view of the area and likely structural-stratigraphic relationships to be encountered.

Middle Oligocene(?)

Northward-directed gravity glide fold nappes (early Episode 2) are recognised from the Upper Cretaceous and Paleocene sequences incorporated in the Coastal High. This is borne out by the presence of: (1) inverted-attenuated sequences imbricated within early phase melange and crushed zones; (2) northward-directed lozenge and transposition fabric at both mesoscopic and microscopic scale; and (3) northward-verging minor folds and lineations associated with shears.

The regional extent of the allochthonous sheets is impossible to determine from present data. However, the apparently similar gravity slide sheet described by Stoneley (1968) is not very extensive, although regionally many such "sheets" are now recognised (I. G. Speden pers. comm.) and their relation to the very extensive Northland Allochthon is as yet uncertain. It seems more probable that individual sheets are of the order of several hundred square kilometres only.

Fig. 31 Schematic sequential developmental history, Coastal High and Makara Basin, Southern Hawke's Bay.



This early Episode 2 deformation reflects the onset of regional tectonism, possibly widespread broad warping with the consequent development of allochthonous slide sheets. The tectonism may reflect the propagation of the Indian–Pacific plate junction through the New Zealand region (see Walcott 1978a; Ballance et al. in press).

The timing of gravity sliding is difficult to pinpoint; however, it predates late Waitakian sedimentation and is hence inferred to have occurred in Mid–Late Oligocene times. This is approximately coincident with events in the East Cape–Gisborne region (see Stoneley 1962, 1968; Ridd 1968) and Northland (Ballance & Spörli 1979).

Late Oligocene

By Late Oligocene time, slope basin sedimentation had commenced in a proto-Makara Basin, located west of a major structural high (Coastal High). The inferred depositional environment is mid–outer slope, based on paleontologic evidence. Waitakian and Otaian mass-flow deposits (turbidites, debris flows, and conglomerates) have an onlap relationship onto this structural ridge. Chaotic debris flows shed from the latter are incorporated within the basal part of the sequence (at Waimarama Beach). The constituents of these debris flows are identical to those of the adjacent melange zone, and it appears from field relationships that the melange developed coevally with the debris flow units. It is concluded, therefore, that the melange material was exposed on the seafloor on the western or inboard side of the thrust ridge. Periodically, material slumping from the actively growing ridge generated the debris flows. During this period, the Coastal and Te Apiti Thrust Zones developed with a crosscutting relationship as shown.

While thick mass-flow deposits were accumulating in the adjacent basin, thin, condensed, massive mudstones accumulated on the ridge. Some of this mudstone has subsequently become incorporated within the melange zones.

Flysch accumulated in the basin to the west with a predominance of southward-directed current indicators, suggesting sediment was fed longitudinally along the basin axis.

Early Miocene

Early Miocene successions are rare in Southern Hawke's Bay. This is thought to be indicative of an increased tectonic tempo and the destruction of the slope basin trough, with sediment being funnelled to other depocentres on the slope. During this period, the earlier slope basin-fill sediments were strongly deformed and accreted onto the western margin of the structural high. Both the Puhokio and Ocean Beach–Mangakuri Thrust Zones were active during this period and are now recognised as major structural entities of the Coastal High.

Subsequent sedimentation associated with the Middle–Upper Miocene Makara Basin displays angular discordance with the older deformed succession.

Middle Miocene

The Makara Basin came into existence by Middle Miocene time. The early depocentre appears to have been located east of the future line of the Elsthorpe Anticline. A substantial pulse of conglomeratic limestone debris flows entered the basin from the west. Other chaotic debris flows were derived from the structural high to the east.

Late Miocene

The Makara Basin by Late Miocene time (Tongaporutuan) was at its greatest extent. The depocentre had shifted westward and a thick flysch succession accumulated within the basin. The flysch passed laterally into very condensed massive mudstones resting unconformably on the high. The inferred depositional environment is mid- to upper slope, possibly outer shelf by the close of the Tongaporutuan Stage.

The older basin fill (Lillburnian–Waiauan) was progressively deformed during subsequent sedimentation. This deformation was most pronounced near the bounding structural highs. Adjacent to the Coastal High gradual tilting, minor folding, and unconformities are more apparent with depth through the succession (see also Fig. 32C). Chaotic debris flows are commonly interdigitated with the flysch sequence and were derived from the eastern high.

Field relationships on the Coastal High clearly indicate that most of the thrust zones had "locked-up" by Late Miocene time, except for the westernmost Ocean Beach–Mangakuri Thrust Zone which not only incorporates Tongaporutuan mudstone as blocks and matrix gouge in melange, but is also locally overthrust by melange.

During this period, the eastern limb of the Atua Synclinorium and western limb of the Patangata Syncline developed. The former is expressed primarily in the basal basin-fill succession of Lillburnian–Waiauan age.

Present day

The last phase of thrusting formed the Elsthorpe Anticline during Late Pliocene and Pleistocene times. Complex steeply dipping thrust relationships are recorded in and adjacent to the core of the anticline. The Makara Basin fill is more simply folded over this core zone into an asymmetric anticlinal structure. The disconformable relationship of the Pliocene Te Aute Limestone and Miocene Makara Formations clearly indicates the anticline is of Plio-Pleistocene age. To the east, over the Coastal High, the same units are separated by a sharp angular discordance.

Tectonic thickening of the western limb of the anticline is considered to be related to the deep-seated thrusting which subparallels bedding within the flysch. Bedding provided planar (anistropic) weaknesses along which major movement could be readily accommodated.

The present-day offshore structural development, with its growing (anticlinal) thrust ridges and ponding of flysch sediments in individual basins, is described by Lewis & Kohn (1973) and Lewis (1980) and provides a close analogue for Miocene sedimentation as described in this paper (see also van der Lingen & Pettinga 1980).

Some implications for a regional tectonic synthesis

The interpretations by Molnar et al. (1975) of seafloor magnetic anomalies indicate that no subduction zone existed in the New Zealand region during Cretaceous and early Tertiary time. Other interpretations are also possible (see Weissel et al. 1977; Oliver et al. 1979). It appears, however, that a westward-directed phase of subduction was propagated southward through the New Zealand region following a major shift in the position of the pole of rotation about 21 m.y. ago at approximately the Oligocene–Miocene boundary (Molnar et al. 1975; Ballance 1976; Walcott 1978a; Ballance & Spörli 1979; Spörli 1980; Ballance et al. in press). This plate junction (between the Indian and Pacific plates) presently trends along the Kermadec–Hikurangi margin and onto the Alpine Fault (Walcott 1978a; Spörli 1980). The developmental history of the Kermadec–Hikurangi margin through Oligocene and late Cenozoic times has been outlined by Ballance (1976) with further refinements by Ballance & Spörli (1979), Walcott (1978a), Spörli (1980), van der Lingen & Pettinga (1980), Lewis (1980), and Ballance et al. (in press). A variation on this model is given by Cole & Lewis (1981).

The upper Cenozoic geology and development of the East Coast Deformed Belt directly reflects the development of the accretionary sediment prism in the arc-trench gap of this obliquely convergent plate margin.

Over the last decade, 2 opposing apparently incompatible hypotheses have developed describing the tectonic evolution of the East Coast Deformed Belt.

1. *Tectonic erosion hypothesis:* This model is based on the work by Katz (1974a) (see also Katz & Wood 1980) and is characterised by extensional tectonics. Large vertical movements in the overriding (continental margin) plate lead to extensive subsidence and development of a continental borderland (horst-graben) terrain. Katz attributed this fragmentation to the special conditions which prevail where a subducting plate passes from a transition zone into an intercontinental shear belt (the New Zealand Alpine Fault system).

2. *Tectonic accretion hypothesis:* This model is advocated by workers for many of the active tectonic regions of the world and incorporates the concept of an accretionary sediment prism on the lower continental slope formed from sediments scraped off the oceanic plate, trench-fill sediments, and slope basin-fill material (the subduction complex). The accretionary prism is typified by outward growth (seaward accretion) and landward understuffing (the imbricated rising stack). The most recent proponents of this theory for the Hikurangi margin evolution include Pettinga (1977), Walcott (1978a, b), Spörli (1980), Lewis (1980), van der Lingen & Pettinga (1980), and Cole & Lewis (1981).

The fundamental implication from the detailed onland information presented in this paper indicates that the region as a whole conforms more closely to the second (accretionary prism) hypothesis. Clearly, westward-directed underthrusting and tectonic imbrication have played a major role in the Cenozoic structural development of the Hawke's Bay sector of the East Coast region.

Since initiation of the plate boundary, the interpreted depths of deposition (based on sediment characteristics and paleontologic evidence) show a gradual shallowing with the Eocene–Oligocene phases of sedimentation reflecting a mid- to outer(?) slope setting. The Miocene basin fill is more characteristic of upper slope–outer shelf depositional environments. Shallow water Pliocene limestones followed. This sequential upper Cenozoic (Neogene) shallowing is widely recorded throughout East Coast districts.

However, the East Coast Deformed Belt is not a typical subduction complex such as described by Seely et al. (1974), Karig & Sharman (1975), Moore & Karig (1976), and Seely (1979). This is because a typical subduction complex is comprised of abyssal plain, trench, and slope sediments together with ophiolite suites and/or metamorphics. These are normally associated in thrust sheets, isoclines, and melange zones. Within the East Coast Deformed Belt, oceanic plate ophiolites are absent, as are the abyssal plain sediments. Instead, almost the entire exposed subduction complex appears to be composed of continental shelf and slope sediments. These are inferred to be part of a major sediment wedge of Cretaceous–Paleogene age, accumulated adjacent to and on the New Zealand continental block, probably in a passive margin setting (Suggate et al. 1978; Stevens & Speden 1978). With propagation of the plate boundary along the Hikurangi margin, this thick sediment prism became gradually deformed, reflecting the regional obliquely compressive regime associated with deep-seated underthrusting. The Neogene sediments merely reflect that active continental margin sedimentation continued on the gradually deforming (imbricating) older sediment wedge. This process continues to the present day.

Little direct information is as yet available from offshore areas (continental slope—Hikurangi Trough). However, it is very probable that oceanic material is being incorporated within the lower slope subduction complex frontal ridge, which is particularly prominent offshore from Hawke's Bay. Recently gathered seaborne magnetic surveys and seismic reflection profiles have delineated several nearly and completely subducted guyots in this region (Lewis & Bennett in press). The scarcity of igneous ocean-floor material onshore indicates that the accretion and uplift process accompanying tectonic imbrication on the lower slope is as yet not sufficiently developed, and is masked by the extensive pre-existing sediment wedge. Deformation recorded onland involves only this sediment wedge that adjoined the New Zealand continental block.

Recently obtained seismic profiles from the mid- and lower slope regions of the Hikurangi margin (Lewis & Bennett in press) clearly indicate that this part of the subduction complex is developing in accordance with the models proposed by Seely et al. (1974), Karig & Sharman (1975), Moore & Karig (1976), and Seely (1979). However, the structural development of the Coastal High detailed in this paper indicates that in addition to the "understuffing" on the seaboard side of structural highs, a considerable amount of thrust deformation occurs on the inboard side. This allows for landward accretion of earlier slope-basin fill sediments onto the structural high. A progressive landward shift of the loci of thrusting may ensue and this can also account for accretionary uplift and shallowing conditions of deposition. Uninterrupted underthrusting on the seaboard side of the high may also continue. This more complex development of a structural high within the subduction complex is hinted at by Seely (1979, fig. 5).

The apparent conflict between the 2 proposed tectonic hypotheses outlined earlier may be resolved in the light of other information. That accretion and imbrication have occurred continuously and since Late Oligocene time is evident from the data presented herein. During Quaternary time, a major gravitational collapse structure (the regional slump) developed, affecting the coastal land district south of Cape Kidnappers. Its offshore extent is uncertain but is the subject of more recent investigation (Pettinga in press). In a tectonically very active, rapidly rising region, the development of such major deep-seated slump structures is perhaps not unexpected, and similar structures may occur along the Hikurangi margin. Already well-documented examples include: (1) the Agulhas slump on the sheared continental margin off Southeast Africa (Dingle 1977) which is comprised of an allochthonous mass some 750 km long, 106 km wide, and up to hundreds of metres thick; and (2) the Bassein Slide associated with the Sunda Arc Subduction Zone, Northeast Indian Ocean, with a total estimated volume of 900 km^3 and covering an area of almost 4000 km^2 (Moore et al. 1976).

HYDROCARBON PROSPECTS

The intense deformation, poor overall reservoir conditions (including unfavourable facies), disruption of migration paths by structural dislocation, and low regional heat flux combine to indicate that the region is discouraging for hydrocarbon exploration.

However, petroleum source and some reservoir beds are known throughout the East Coast Deformed Belt. The numerous seeps in the area provide some evidence of generation, but may also reflect voiding of trap structures. However, potential hydrocarbon accumulations are also certainly present, and the location and exploitation of these, in this structurally most complex area, provides the exploration industry with a great challenge.

Trap settings

Six possible model trap settings associated with slope basins are recognised from the field relationships in Southern Hawke's Bay. All are influenced to some degree by the active structural development of the basin-ridge association. Three stratigraphic trap types and 3 structural traps are depicted in Fig. 32.

Some salient points relating to hydrocarbon exploration in the East Coast Deformed Belt

1. The belt is located in an obliquely convergent plate margin setting and comprises the accretionary complex.
2. Upper Cretaceous and lowermost Tertiary organic-rich source beds are widespread onland and are likely offshore. Numerous gas and oil seeps indicate maturation has occurred.

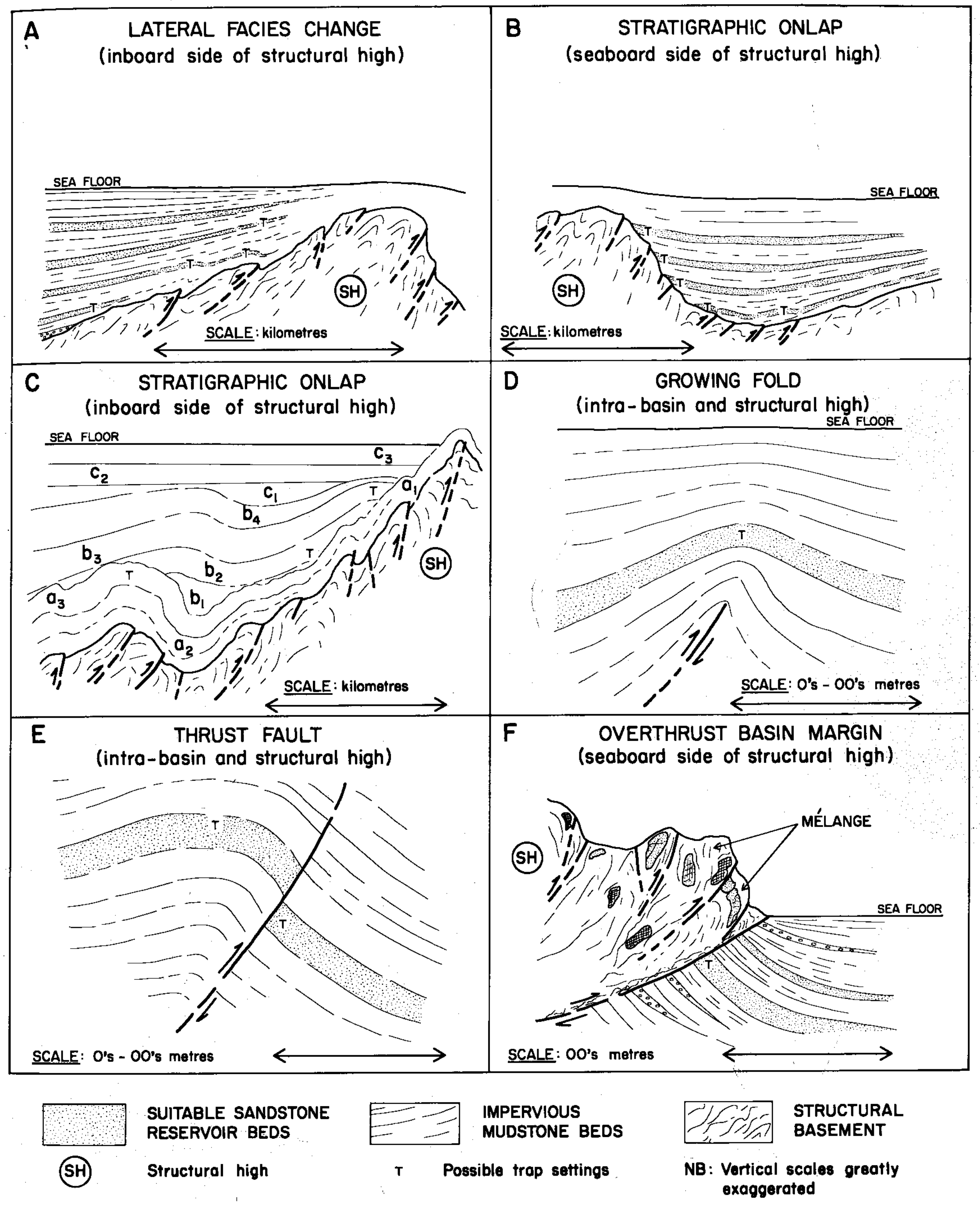


Fig. 32 Possible hydrocarbon trap settings associated with trench-slope (accretionary) basins.

3. Stratigraphic and structural traps in Cenozoic rocks are present, as are conduits and reservoir lithofacies.
4. Dominant Cenozoic lithofacies, however, are mudstones and siltstones of low porosity and permeability and are unsuitable as reservoir beds.
5. Tectonically, the region is still active and has been progressively deformed since Oligocene time. Structural dislocation and overall complexity is intense, with older rocks having been deformed to a greater extent than younger rocks.

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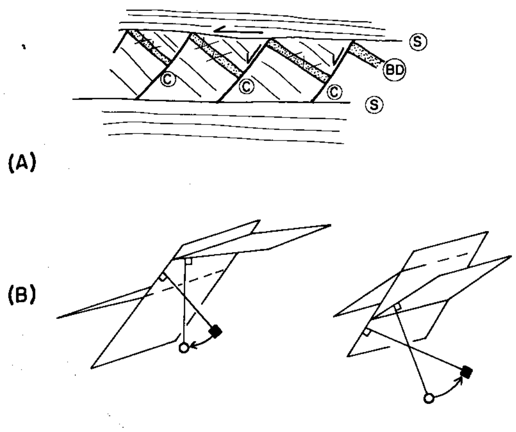
APPENDIX 1

Separation directions (Fig. 33)

The bedded "soft-rock" lithologies constitute an anisotropic medium for deformation, as both stress and strain are channelled by the primary stratification. Frequently, 1 fault of a conjugate set is dominant. In conjunction with bedding shear a **lozenge** or **transposition** fabric develops (Fig. 33A). Separation plots (modified from Spörli & Lillie 1974) are particularly useful for analysing the anisotropic deformation (Fig. 33B). **Separation directions** may be obtained from the separation plot construction of lozenge geometry, this direction is normal to the intersection line of bedding fault (Fig. 33C). Separation directions are plotted around the periphery of the lower hemisphere equal area stereonet projection, for convenience. Lozenge and/or transposition fabric reflects a stretching of the overthrust sedimentary pile, hence movement (separation) directions are inferred.



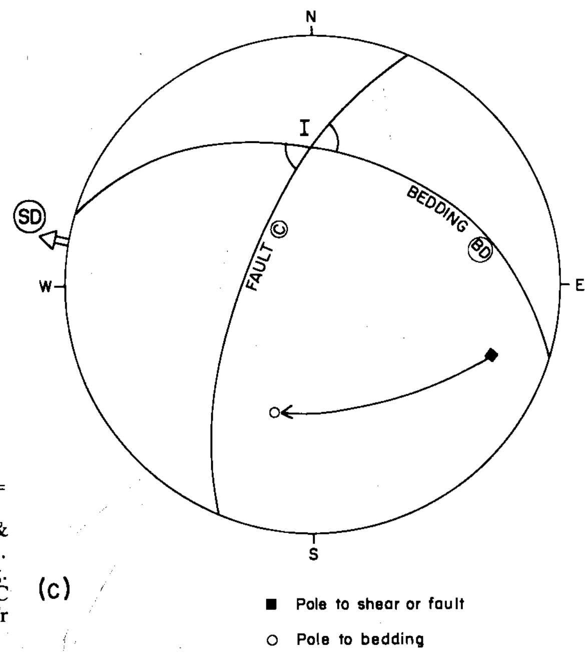


Fig. 33 **A** Lozenge shear fabric. BD = bedding; C = conjugate fault (dominant); S = bedding shear.
B Separation plot convention (modified from Spörli & Lillie 1974). Arrow in direction of hanging wall movement.
C Stereonet separation plot (for convention see Fig. 33B). I = intermediate axis; SD = separation direction; C = conjugate fault (dominant); BD = bedding. Lower hemisphere equal area projection.