Tectonic significance of Late Cretaceous Radiolaria from the obducted Matakaoa Volcanics, East Cape, North Island, New Zealand(MEMORIAL VOLUME TO THE LATE PROFESSOR TERUHIKO SAMESHIMA)

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Tectonic significance of Late Cretaceous Radiolaria from the obducted Matakaoa Volcanics, East Cape, North Island, New Zealand.

K. Bernhard SPÖRLI[1] and Yoshiaki AITA[2]

Abstract Radiolarian faunas from several localities in the Matakaoa Volcanics of the Mangaroa Range, North Island, New Zealand indicate Late Cretaceous (Campanian to Maastrichtian) ages. This contrasts with Late Paleocene/Early Eocene ages obtained from foraminifera approximately 3 km higher in the section. The radiolarian faunas are cosmopolitan and may have been deposited at mid to high latitude.

A new structural analysis indicates that the fossils occur in a sequence of intercalated pillow lavas, sediments and dolerites about 10 km thick equivalent of layer 2B of the oceanic crust. This great thickness implies that there has been much repetition by shortening deformation. Layering dips steeply; younging is generally to the north and the sequence is affected by km-scale steeply plunging folds associated with décollements. Structural development involved first formation of mélange, and subsequent refolding of these structures to give the present dextral, steeply plunging folds. It is not clear yet how another phase of deformation, steepening and overturning of layering in the Matakaoa Volcanics, relates to these two tectonic events.

Key words: Late Cretaceous, radiolaria, Matakaoa Volcanics, East Cape, New Zealand

INTRODUCTION

The present New Zealand micro-continent is the product of a long history of deformation on the margin of Gondwana until the Early Cretaceous, and subsequent rifting away from Gondwana until Early Tertiary (Spörli & Ballance 1989). In the Late Oligocene, during initiation of the present boundary between the Pacific and Australian Plates (Fig. 1A), a number of ophiolite massifs were obducted onto the continental crust of northern New Zealand, marking the onset of movement on the dextral Alpine Fault transform and of subduction at its northern end (Brothers & Delaloye 1982; Rait *et al.* 1991; Malpas *et al.* 1992). This resulted in rapid dextral rotation of large parts of eastern North Island from a NW-trending into a NE-trending structural trend (East Coast Deformed Belt) and the deformation of the New Zealand landmass into its present Z-shape (Lamb 1988; Mumme *et al.* 1989).

In Northland, the obducted ophiolites are represented by the Tangihua Volcanics, which are part of the Northland allochthon (Spörli & Ballance 1989). At the northern tip of the East Cape Peninsula (Fig. 1), Matakaoa Volcanics described in this paper form two prominent massifs and are part of the East Coast allochthon (Moore 1985). Further small slivers of pillow lavas in the east coast of the North Island, represented by Red Island and Hinemahanga Rocks in southern Hawke's Bay (Kobe & Pettinga 1984; Moore 1985; Moore *et al.* 1987), may be regarded as a disrupted continuation of the Matakaoa Volcanics. They are involved in subsequent deformation within the East Coast Deformed Belt (Fig. 1A). There is some question whether the Rip Volcanics, Tapuaeroa Valley (RV in Fig. 1; Pirajno 1979; Gibson 1986) also belong to this group of rocks. Pillow lavas and breccias are most common in these bodies of volcanics.

For reconstruction of the seafloor patterns and plate tectonics immediately prior to the obduction and for analysis of the subsequent tectonic history, it is important to have detailed information on the age of the ophiolites. Brothers & Delaloye

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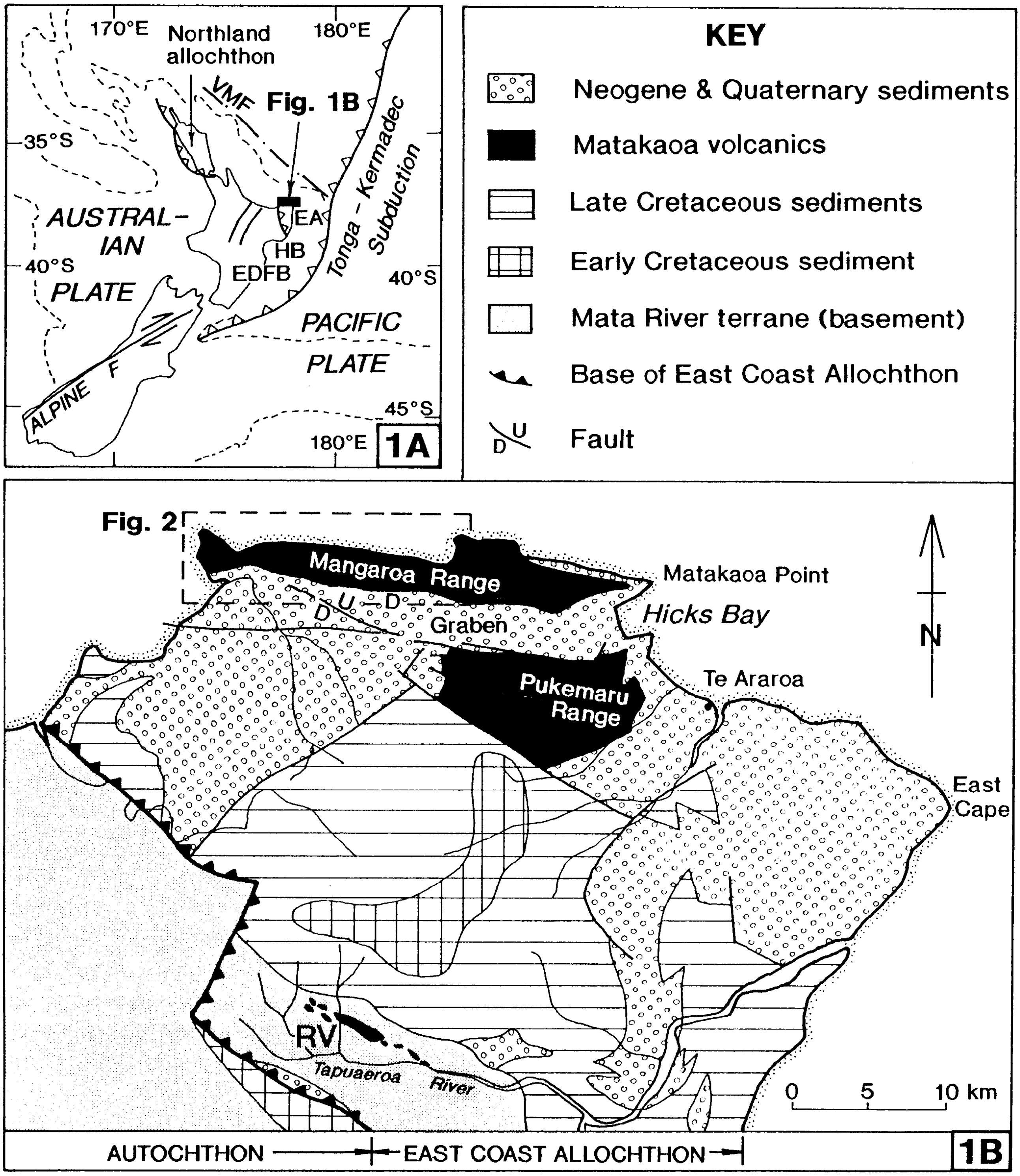

Fig. 1 Index map and tectonic setting of Matakaoa Volcanics within the New Zealand microcontinent.
1A: Relation of study area to present plate boundary and Late Oligocene allochthons. EA = East Coast allochthon. HB = Hawke's Bay. EDFB = East Coast Deformed Belt. VMF = Vening Meinesz Fracture Zone
1B: Regional geology of Matakaoa Volcanics. RV = Rip Volcanics of Tapuaeroa Valley (Pirajno 1979).
Note that part of the Tertiary and all of the Quaternary sequence onlaps onto the East Coast allochthon.

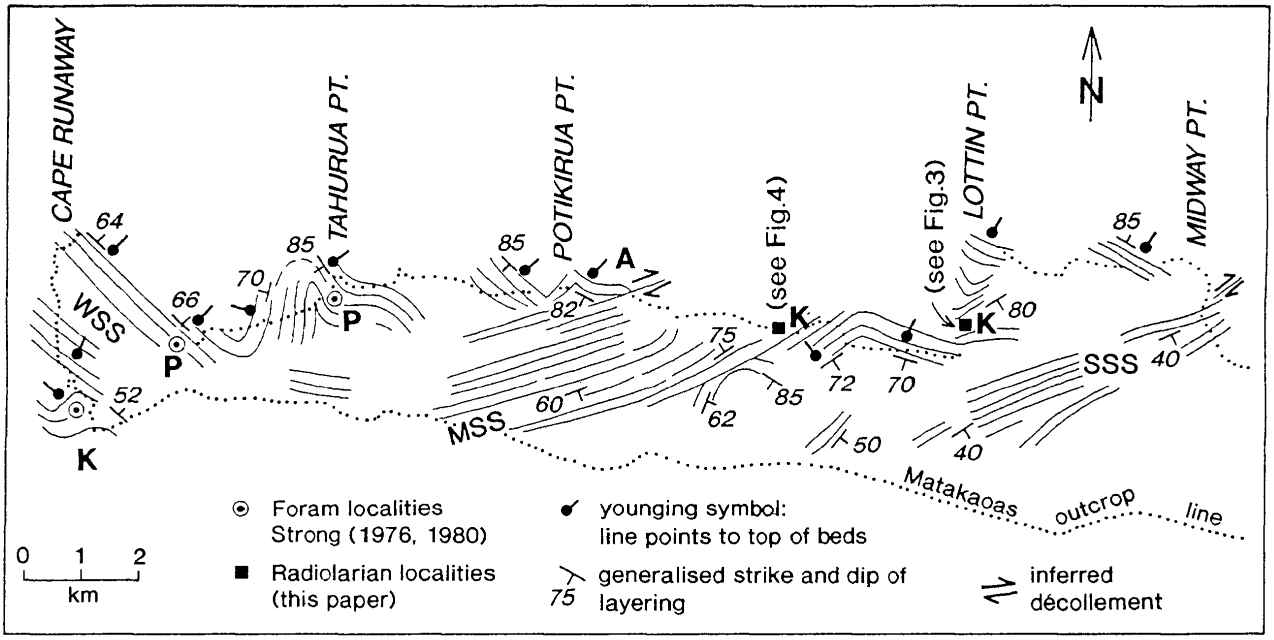

Fig. 2 Form line map of the western part of Mangaroa Range (location see Fig. 1B) and position of fossil localities. K = Cretaceous, P = Paleocene. A = zone of complex dextral folding, indicating décollement. Note widespread overturning along northern coastline. SSS, MSS, WSS = southeastern, middle and western straight section respectively.

(1982) attempted a programme of K-Ar age determinations, which however produced a wide scatter, possibly associated with deformation of the ophiolites. Fossil ages from sedimentary rocks intercalated with the pillow lavas are scarce and widely separated. In Northland, Brook (1989) reports Late Cretaceous ages for some of the northernmost Tangihua Massifs. A well preserved fauna of radiolarians at Camp Bay, Northland, indicates a late Early to Late Paleocene age (*Buryella tetradica* Zone of Hollis 1993) of the Tangihua Volcanics at that locality (Hollis & Hanson 1991).

In the Matakaoa Volcanics of East Cape, an older group of Cretaceous (Albian) ages was reported from the western end, near Cape Runaway (Strong 1976), and Strong (1980) has described good foraminiferal faunas of Late Paleocene / earliest Eocene age from the central part of the northern coast line (locations see Fig. 2, this paper). Submarine volcanic sequences at Red Island and Hinemahanga Rocks in southern Hawke's Bay have yielded foraminiferal ages of Albian age (Moore *et al.* 1987).

In this paper, we describe Radiolaria from the Lottin Point area which complement and refine the age determinations of Strong (1980) and discuss their tectonic significance.

LITHOLOGY

Lithological descriptions mainly follow those of Rutherford (1980), but have been supplemented with observations by the authors.

Igneous rocks

Extrusive rocks consist of augite basalt and (in the western part of the area shown in Fig. 2) of minor plagioclase megaphyric basalt. These rock types are mainly in the form of pillow lavas and pillow breccias, but include some massive lavas. The feldspar-phyric basalts are often amygdaloidal and are sometimes oxidized to red colours. Foliated basalt is present SE of the tip of Cape Runaway (Rutherford 1980, Fig. 2-6a) and may represent an early shear zone.

Intrusive rocks include basaltic dikes, dolerite sills, dikes and subvolcanic masses, gabbro intrusions and minor alkaline intrusions, particularly represented by the picrite-teschenite-dolerite intrusions south of Lottin Point (Fig 3).

The igneous rocks have a predominantly low-K tholeiitic chemistry, but there are minor alkaline components. The rocks have been affected by sub-sea metamorphism, mostly of zeolite facies but locally grading to low-grade greenschist facies (Rutherford 1980). This situation is similar to that in the Tangihua volcanics of Northland (Malpas *et al.* 1992). Rutherford (1980) interprets

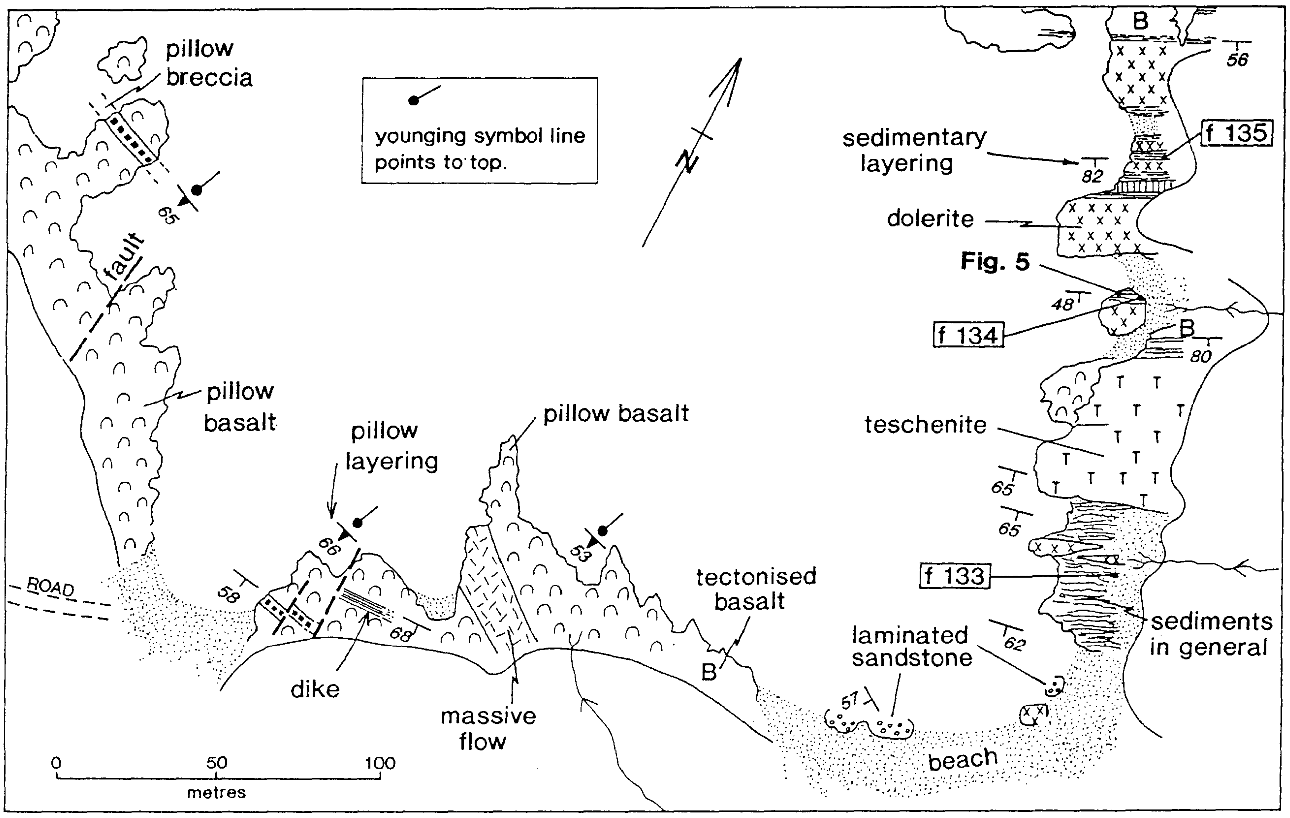

Fig. 3 Radiolarian fossil localities south of Lottin Point (for location see Fig. 2). Map based on Rutherford (1980). Numbers pre-fixed with "f" are New Zealand fossil record numbers referenced to the 1:50,000 S260 series map sheet Y 14.

the Matakaoa volcanics as a product of volcanism at a mid-oceanic spreading centre with some later addition of seamount volcanism.

Sedimentary rocks

Vari-coloured argillaceous, tuffaceous and cherty rocks, and conspicuous limestone lenses predominate. The argillaceous rocks include red mudstone, purple-maroon mudstone, manganiferous shale, and grey-green mudstone. There are lenses and thin layers of red, green and yellow chert. The limestones are usually micritic and pink to grey in colour. Some display mm-scale "pseudo-bedding" formed by closely spaced stylolite surfaces which produce open kink folds associated with carbonate veining. Rutherford (1980) interprets all of these rocks as deep sea sediments.

At three localities in the Lottin Point area and at one on the west coast south of Cape Runaway localities (Rutherford 1980, p. 27), there are grey, well indurated moderately to poorly sorted, fine-grained quartzo-feldspathic sandstones, possibly derived from a cratonic source (Rutherford 1980; see also Fig. 5, this paper).

Mineralisation

The Matakaoa Volcanics contain a number of localities with manganese or sulphide type mineralisation (Rutherford 1980; Pirajno 1980).

Overall distribution of rock types

In the section from Cape Runaway to Lottin Point, sedimentary layers intercalated with the igneous rocks are common (Rutherford 1980). In contrast to this, the section to the east of Lottin Point contains only a few seams of sediments (Gifford 1970) and consists dominantly of pillow lavas and some gabbros, with a considerable volume of basalt/dolerite breccia at the eastern end.

STRUCTURE

Tectonic setting

The Matakaoa Volcanics are preserved in two massifs, a northern, E-W elongated body stretching from Cape Runaway to Matakaoa Point (Mangaroa Range of Strong 1980), and a southern body, located south of Hicks Bay (Pukeamaru Range of Strong 1980), which is more isometric in plan (Fig. 1). It is likely that the two massifs are part of a formerly continuous body (e.g. Pirajno 1980), now separated by an E-W trending graben filled by Cenozoic sediments (Wharekahika Graben of Kingma 1974). The E-W elongation of the northern massif represents a pre-Alpine Fault structural trend, which is in contrast to the pervasive rotation to NE-trends in the rest of the East Coast Deformed Belt (Lamb 1988; Mumme *et al.* 1989).

The massifs structurally overlie a complex assemblage of Cretaceous and early Tertiary sedimentary rocks (Fig. 1), with which they form the East Coast Allochthon of Moore (1985). The allochthonous sediments in turn overlie the complexly deformed but presumably autochthonous greywacke basement (Torlesse of older authors, Mata River terrane of Aita & Spörli 1992).

The fossil localities relevant to this paper (Figs. 2, 3 and 4) are in the northern massif (Mangaroa Range). The western and eastern terminations of this massif seem to be purely erosional. The northern and southern edges, however, have more structural significance, the southern edge probably being mostly formed by late extensional faults, whereas the northern edge may be parallel to a rather short, shallow, E-W trending and north-dipping root a short distance offshore of the present coast (Gillies 1983).

Large scale internal structure of the northern massif

In general, attitudes of pillow layering and bedding in intercalated sediments are steep (60° to vertical and 80° overturned, with a few 40° dips). Younging directions (mainly based on pillow structures) are to the N or NE, even if the layering is dipping south. This overall younging to the north appears to be supported by the age of the fossils (Fig. 2). The main sections of overturned layering are along the north coast (Fig. 2). It is interesting that such overturning is also seen at Red Island, southern Hawke's Bay (Moore *et al.* 1987). Whether this is of regional significance or is purely a coincidence requires further investigation.

We have constructed form lines (Fig. 2) based on sedimentary and pillow lava layering from the maps of Rutherford (1980). The main strike trend is ENE to NE, distinctly discordant to the northern and southern boundaries of the massif. A major swing to NW-SE strikes occurs at the western end, in the peninsula incorporating Cape Runaway.

The changes in strike indicate the presence of large scale, steeply plunging folds with approximately north-south trending, steep axial planes (Fig. 2). For example, a large scale syncline/anticline couple with a wave length of about 2 km is present between Cape Runaway and Tahurua Point. The syncline, which lies in the west, has the shape of a chevron fold. The anticline, as exposed, is almost isoclinal, possibly representing the pinched core of a flexural slip fold. Kink-like km-scale chevron folds (an anticline-sycline couple) can also be detected between the two radiolarian fossil localitiesm (Fig. 2).

In several areas, the form lines reveal major discordances in strike trends. These probably represent shear surfaces accommodating disharmonic movement, where a certain amount of décollement has taken place. The association of chevron and isoclinal folds with décollements indicates an overall regime of flexural slip or parallel folding for these steeply plunging folds. Asymmetry of the folds is mostly dextral.

Within the overall form line pattern, there appear to be at least three areas with patterns of straight, parallel form lines. A southeastern straight section strikes out to sea on the east-facing coast south of Midway Point (SSS in Fig. 2). A middle straight section (MSS in Fig. 2) intersects the coast halfway between Potikirua Point and Lottin Point. A western straight section (WSS in Fig. 2) is represented by the NW-trending structure of the Cape Runaway peninsula.

Taking account of the the changes in dip across the strike (Busk construction, for example see Badgley 1959) the following thicknesses are obtained for the three areas of straight layering: southeastern straight section, 2.9 km; middle straight section, 3.6 km; Cape Runaway, 3.9 km.

In two of the straight sections, there is a tendency for dips to shallow from the north to the south (vertical to 40° in the Lottin Point cross section; 66° to 52° in the Cape Runaway section). In all three straight sections, there are local changes in dip (including dip reversals) with no change in strike. This indicates the presence of folds with subhorizontal axes which, because of their geometry, must represent a phase of deformation different from that producing the steeply plunging folds described earlier. The form line pattern gives no indication about the relative age of the steeply plunging and the horizontal folds.

Structure at the fossil localities

South of Lottin Point: (Figs. 2 and 3): The rocks here are strike NE to ENE and are part of the eastern flank of a relatively major steeply plunging kink fold (see Fig. 2). If the younging from pillow lavas can be transferred to the sedimentary rocks, the whole section is overturned, with dips ranging down to 45° (the inverted sequence of basalt/chert/mudstone and sandstone in Fig. 5 may be a disrupted stratigraphic section, confirming this overturning). In this area, there are relatively regular alternations of zones of high deformation with dominant sedimentary rocks and zones dominated by erosion-resistant igneous rocks (Fig. 3).

A typical contact between igneous and sedimentary rocks is shown in Fig. 5. The sedimentary rocks show an initial (Phase I) disruption into a méange, indicating west-over-east shear (in the present orientation) followed by east-over-west dextral folding (depending on where in this sequence

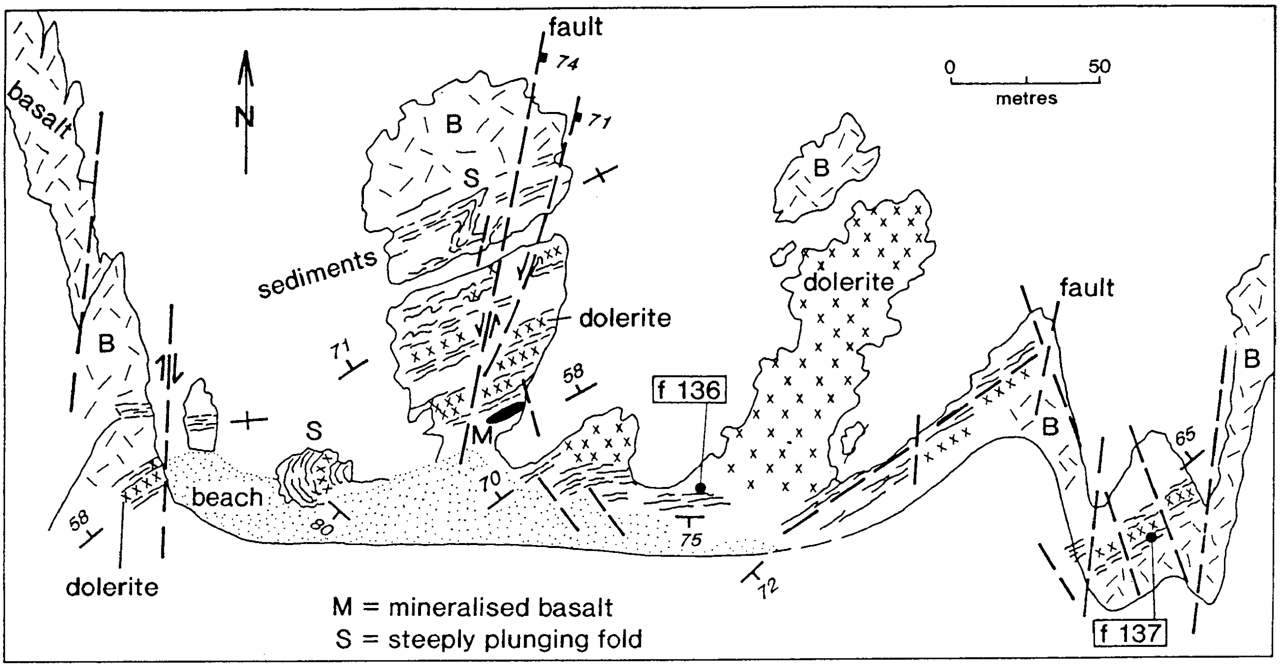

Fig. 4 Western radiolarian fossil localities (for location see Fig. 2). Map based on Rutherford (1980). Numbers prefixed with "f" are New Zealand fossil record numbers referenced to the 1:50,000 S260 series map sheet Y 14. Note dextral vergence of northern steeply plunging fold. Strike and dip measurements were taken from sedimentary layering. Dashed lines are faults.

the steepening and overturning of the layers fits in, this is phase II (as indicated in Fig. 5) or phase III (see Fig. 8)). Extensional faults (phase IV) are the latest structures seen at this locality. They are equivalent to the larger scale cross faults seen in Figs. 3 and 4.

Smaller scale structures are represented by the limestone sample shown in Fig. 6. An early, steep pressure-solution cleavage, subparallel to the large scale lithological layering, has been folded into dextral folds, probably corresponding to Phase II in Fig. 5. Subsequent development of carbonate filled joints parallel and perpendicular to the axial plane of the F_2 folds (AB and AC joints) indicates uplift and/or hydrofracturing with high fluid pressures under approximately the same regime of shortening that produced the dextral folds.

Western Radiolarian localities (Fig. 4): This area shows the same disruption within the alternating sedimentary and igneous rocks as at Lottin Point. Relatively large steeply plunging folds (several tens of metres half wave length) were already mapped by Rutherford (1980). The northern fold in Fig. 4 clearly shows dextral vergence, has a similar axial orientation and therefore can probably be correlated with the dextral folding (phase II) seen at Lottin Point. Late cross-faults are prominent in this section.

RADIOLARIAN FAUNAS

Material and methods

Twenty nine samples of chert, limestone and shale were collected from two areas south and west respectively of Lottin Point (Figs. 3 and 4). Radiolarians were extracted from cherts and shales by soaking samples in dilute HF acid (3 to 5%) for 24 hours. Limestone samples were broken into 1 cm pieces and dissolved in diluted HCl (5 to 10%) with a small amount of hydrogen peroxide (10%). Residues were washed over a 63 μm mesh sieve. After examining dried residues, selected samples were picked for study by stereo and scanning electron microscope. Five chert samples were productive. These are discussed below.

Faunas and estimated ages

In the area 2 km directly south of Lottin Point (Fig. 3), three chert samples collected from within red and green argillite matrix associated with sheared igneous rocks yielded moderately well to poorly-preserved radiolarians as listed in Table 1. The most diverse and abundant fauna was obtained from sample LO9 (New Zealand Fossil Record Number (N.Z.F.R.N. hereafter) Y14/f 135) which was taken from a small green chert lens 15 cm long. The fauna (Plates 1 and 2) is characterised by abundant nassellarians such as *Amphipyndax stocki, Stichomitra asymbatos, Dictyomitra* spp. and *Theocapsomma* spp. Common spumellarians include *Stylosphaera pusilla,*

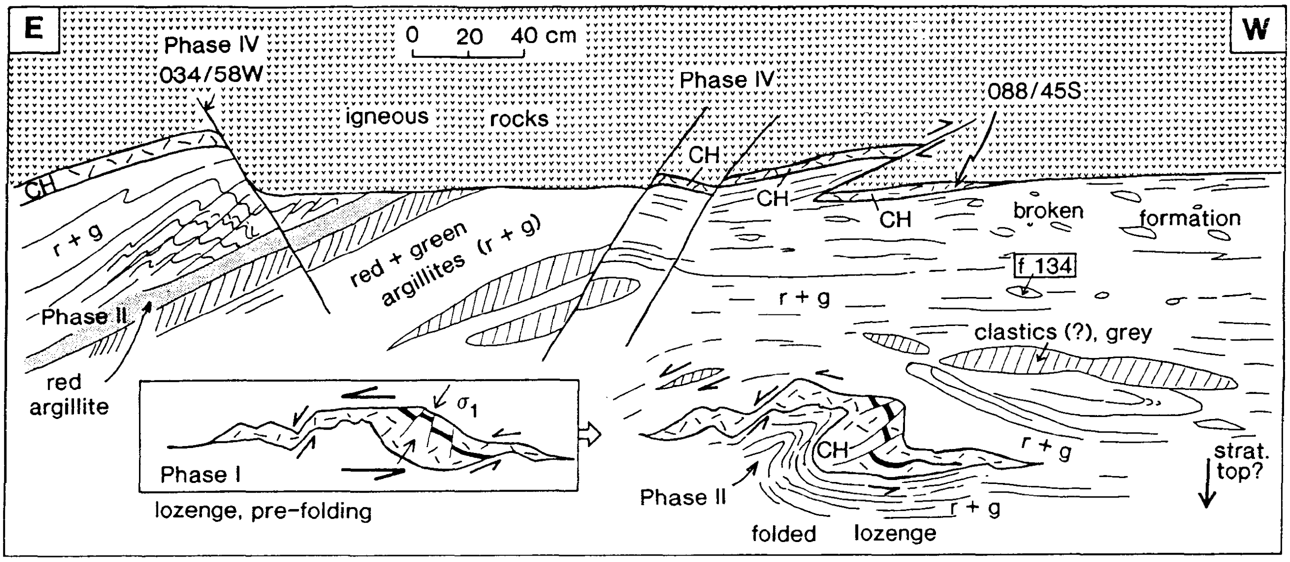

Fig. 5 Multiphase structures, in an outcrop with mèlange, near fossil locality Y14/f134 south of Lottin Point (for location see Fig. 3). Exposure is gentle slope to north. Axes of lozenges and of dextral folds are approximately perpendicular to page and plunge to the south in the plane of the layering.
Note change from sinistral to dextral shearing indicated in chert lozenge (first phase reconstructed in box). Small scale faults in the chert lozenge have acted as conjugate Riedel shears during phase I sinistral shearing.

Amphisphaera privus, and rare *Lithomespilus mendosa* (Plate 1, Figs. 5, 6 and 1). In terms of faunal composition, this fauna is very similar to the late Maastrichtian assemblages from Amuri Limestone Group in eastern Marlborough, South Island, New Zealand (Hollis 1993). Samples LO9 and Sample LO4 (N.Z.F.R.N. Y 14/f 133) can be correlated with late Campanian to Maastrichtian *Lithomelissa ? hoplites* Zone of Hollis (1993) based on the presence of *L. ? hoplites* and the absence of Paleocene index species. Hollis's study showed that many Cretaceous species range to Paleocene, making it difficult to distinguish Late Cretaceous from Early Paleocene assemblages. Although it was earlier suggested (Aita & Spörli, 1992) that the Lottin Point green chert may be of Early Paleocene age, based on the presence of *Stylosphaera goruna*, subsequent detailed study could not confirm the presence of this species. The absence of *Dictyomitra duodecimcostata*, which is present in sample LO 26 (see below), indicates that the age of these samples is Maastrichtian (upper part of *Amphipyndax tylotus* Zone of Foreman 1977).

The assemblage in sample LO7 (N.Z.F.R.N. Y14/f 134) is meagre and of low diversity. It contained *Amphipyndax stocki*, *Dictyomitra multicostata* and forms of the *Theocapsomma comys* group. This fauna is considered to be of a very similar age to that described in the previous paragraph.

The other fossil localities lie 4 km west of Lottin Point (Figs. 2 and 4). Two red chert samples yielded poorly preserved radiolarians of low diversity. Faunas in samples LO26 and LO29 (N.Z.F.R.N. Y14/f 136 & f 137), consist predominantly of *Amphipyndax stocki* and *Dictyomitra* spp. and *Theocapsomma* spp. The presence of *Dictyomitra duodecimcostata* s.s. indicates a Campanian to Early Maastrichtian age (Foreman 1977, 1978).

Overall faunal similarities between the Lottin Point chert samples and those obtained from siliceous limestones in Marlborough (Hollis 1993) are striking. *Amphipyndax tylotus* Foreman has never been recorded in assemblages of East Cape, nor in assemblages of the latest Cretaceous of Marlborough (Hollis 1993), at DSDP site 275 near New Zealand (Pessagno 1974), or at ODP sites 698A and 700B in the subantarctic South Atlantic (Ling 1991). A single record of *A. tylotus* in relatively high southern latitude was reported by Ballance *et al.* (1989) in a dredge sample from the Tonga Trench (42°S in paleolatitude) although no illustrations were given. It seems that the late Cretaceous Lottin Point faunas may have also originated in southern high latitudes. This is compatible with the fact that low latitude species such as *Alievium* and *Pseudoaulophacus* (Empson-Morin 1984) were not observed from the Lottin Point samples.

It is noteworthy that common *Cornutella californica* and *Bathropyramis* sp. are present in the assemblage of sample LO9. Both genera are known as having a cosmopolitan and deep water dwelling distribution (Casey 1971).

Table 1 Occurrence of Late Cretaceous radiolarians from cherts within the Matakaoa Volcanics south and west Lottin Point, East Cape.

Samples	LO 4	LO 7	LO 9	LO 26	LO 29
New Zealand Fossil Record Number	Y14/f133	Y14/f134	Y14/f135	Y14/f136	Y14/f137
Lithologies	maroon chert	green chert	green chert	red chert	red chert
Abundance; F: few, R: rare, C: common, A: abundant	F	R	A	R	C
Preservation; P: poor, M: moderate	P	P	M	P	P
Acanthocircus ellipticus (Campbell & Clark)			X		
Amphisphaera privus (Foreman)			X		
Amphisphaera sp.	X		X		
Lithomespilus mendosa (Krasheninnikov)	X		X		X
Phaseliforma sp.			X		X
Protoxiphotractus sp.	X	X	X		
Spongosaturnalis sp.			X		
Stylosphaera ? pusilla Campbell & Clark	X		X		X
Stylosphaera sp.			X		
Amphipyndax stocki (Campbell & Clark)	X	X	X		X
Amphipyndax sp.	X	X	X		X
Archaeodictyomitra sp.				X	X
Bathropyramis sp.			X		
Calocyclas? sp.			X		
Cornutella californica Campbell & Clark			X		
Dictyomitra andersoni (Campbell & Clark)			X		X
Dictyomitra duodecimcostata s.s. (Squinabol)				X	
Dictyomitra multicostata Zittel group	X	X	X		X
Dictyomitra spp.	X	X	X	X	X
Ectonocorys? sp.			X		
Lithocampe sp.	X		X		
Lithomelissa ? aff. amazon Foreman			X		
Lithomelissa ? heros Campbell & Clark			X		
Lithomelissa ? hoplites Foreman	X		X		
Lithomelissa ? sp.		X	X		
Lophophaena sp. A	X		X		
Mita regina (Campbell & Clark)					X
Myllocercion cf. acineton Foreman	X	X	X		
Neosciadiocapsa sp.			X		
Schadelfusslerus cf. echtus Empson-Morin			X		
Schadelfusslerus spp.	X	X	X		
Stichomitra asymbatos Foreman	X		X		
Stichomitra aff. marinae (Gorbovetz)			X		
Stichomitra warzigata (Empson-Morin)			X		
Stichomitra sp. B of Dumitrica			X		
Stichomitra spp.	X	X	X		
Theocampe altamontensis (Campbell & Clark)			X		X
Theocampe cf. vanderhooi (Campbell & Clark)			X		
Theocampe spp.			X		
Theocapsomma amphora (Campbell & Clark)			X		
Theocapsomma comys Foreman group	X	X	X		X
Theocapsomma erdnussa (Empson-Morin)			X		
Theocapsomma spp.	X	X	X		X

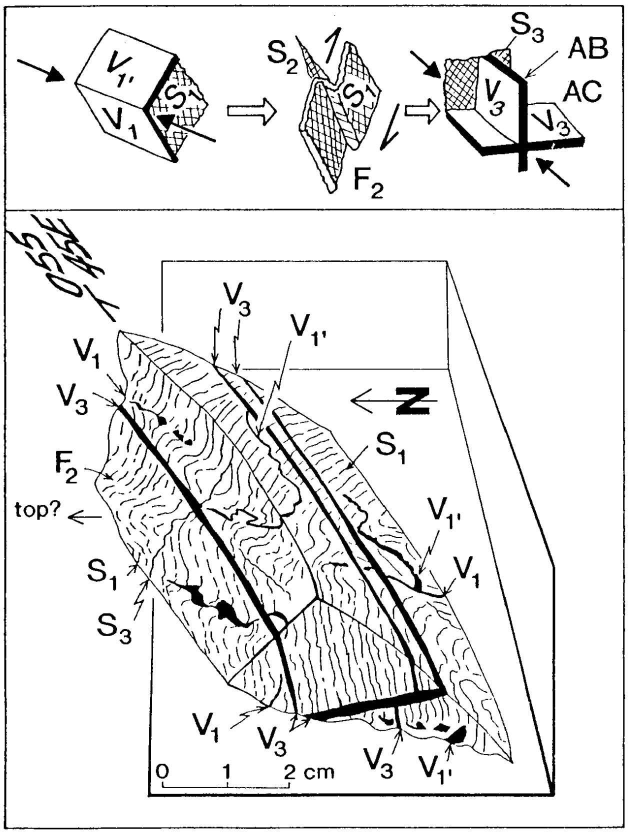

Fig. 6 Deformation shown in a hand specimen of red micritic limestone, south of Lottin Point (collected near fossil locality f135, Fig. 3), shown in an oriented, slabbed specimen. A subvertical, mm-spaced pressure solution cleavage (S_1) associated with orthogonal carbonate veins (V_1 and V_1') has been folded by dextral folds (F_2). S_2 is the axial surface of the F_2 folds but is not developed in the form of any cleavage surface. Another orthogonal carbonate vein system and isolated S_3 pressure solutions surfaces subsequently formed approximately in the AB, AC and BC joint orientation of the F_2 folds (sequence of deformations is illustrated in schematic block diagrams at top of figure).

DISCUSSION

Implication of rock types

The western part of the Mangaroa Range consists of pillow lavas, basaltic flows, some dolerites, with minor gabbro and swarms of dikes. Zones of sheared sedimentary rocks are present throughout the area. The volcanics are all considered to be of ocean floor derivation (Rutherford 1980), the majority having been generated at a spreading ridge, with minor alkaline rocks attributed to seamount volcanism. From the rock descriptions, it is clear that the levels of oceanic crust represented in the Mangaroa Range must be the uppermost two layers (seismic layers 1 and 2A, see Hussong *et al.* 1979; White *et al.* 1992). Minor layer 2B may be represented by some of the dolerites. Possibly, more of layer 2B is present at the eastern end of the Mangaroa Range.

Large scale structure

The structural style of the Matakaoa Volcanics differs from that of the Tangihua Volcanics in Northland in that the attitude of layering is significantly steeper and that large scale steeply plunging disharmonic folds are present.

Because of the steep dips and the uniform younging direction, the form line pattern between Cape Runaway and Midway Point (excepting the southeastern straight section (SSS) with its low dips) can be viewed more or less as a structural profile of the steeply plunging structures (Fig. 2). Because of the absence of younging indicators, it is not certain whether the southeastern straight section (SSS, Fig. 2) can simply be regarded as a portion of such a structural profile or has to be excluded, because it is the southeast flank of a subhorizontal anticline, repeating the sequence further to the NW by folding along this anticline which would have an axial trace trending NE through Midway Point (Fig. 2).

There are at least two possible interpretations of the structural profile for the steeply plunging structures (Fig. 7):

The conservative intepretation (Fig. 7A) regards the change in strike between Cape Runaway and the rest of the massif as the major fold structure in the area, in the form of a kink fold, with the disharmonic steeply plunging folds in the north representing geometric adjustments during this folding. If a hypothetical additional fold is introduced 2 km west of Potikirua Point (Loc. M, Fig. 7), to keep inferred thicknesses to a minimum, the thickness of layer 2B material involved in the whole structure would be about 10.2 km (allowing for an average dip of 60°). Shortening would be only about 4.8 km or 11%.

In such a structural interpretation, the Cretaceous radiolarian fossil localities and the Cretaceous foram locality would lie approximately at the same structural (or even stratigraphic) level, while the Paleocene foram localities would be positioned about 3 km higher.

The radical interpretation (Fig. 7B) is one of dextral shear, producing imbricated shortening structures analogous to thrust sheets. Such a structure would be compatible with the tight dextral steeply plunging fold at A east of Potikirua Point in Fig. 2 (see also Rutherford 1980). A semi-balanced section (Fig. 7B) indicates that the lithological column involved would be about 9.4 km thick (allowing for an average dip of 60°), excluding the southeastern straight section. There are two major fault surfaces, one just east of Potikirua Point and the other just east of Midway Point. A minor décollement lies near the western

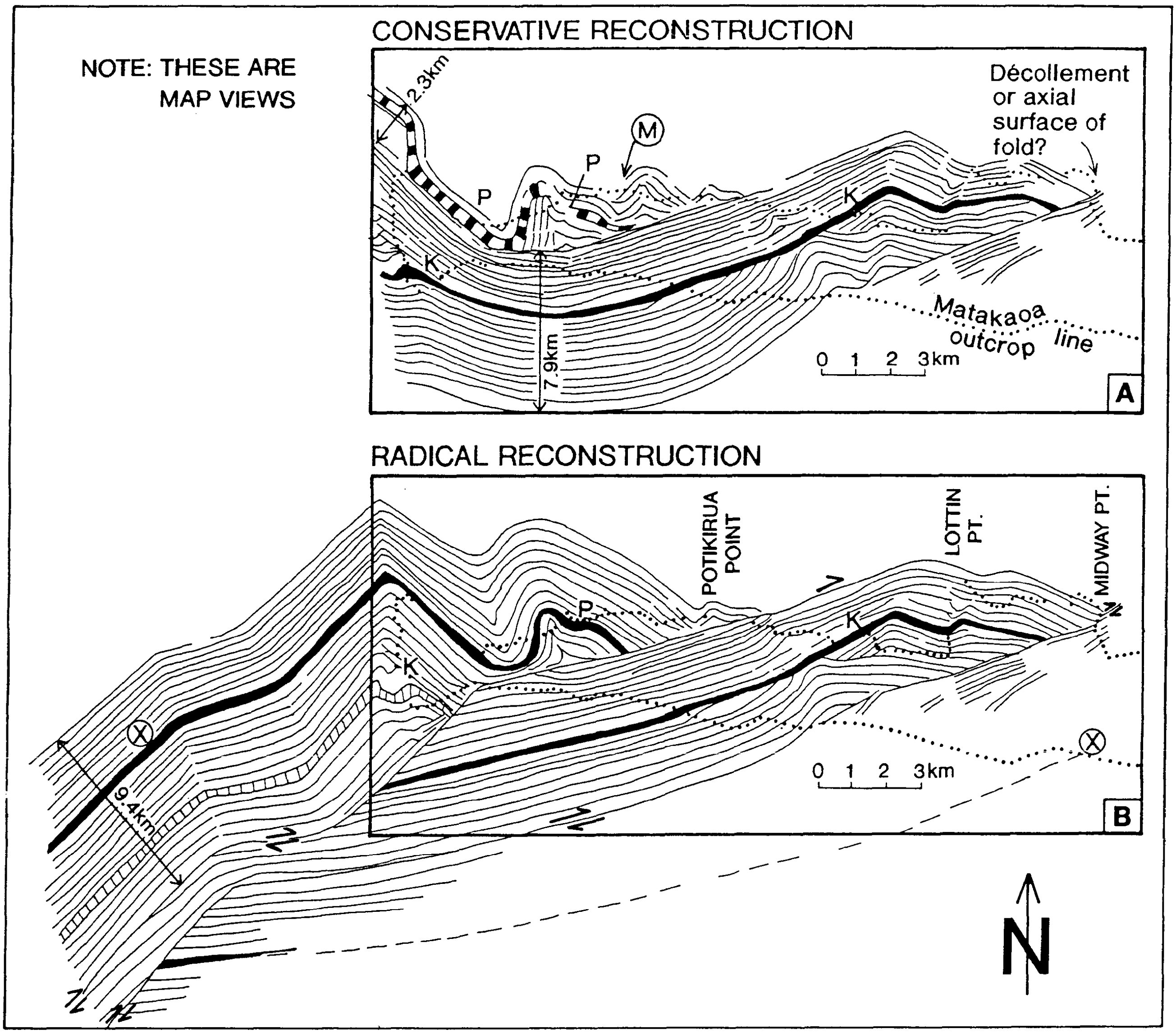

Fig. 7 Two possible map sketch reconstructions of the form line patterns of steeply plunging folds. Both are semi-balanced. Hypothetical markers including the fossil localities are shown in solid black or with patterns (K= Cretaceous, P= Paleocene). Straight lines with double arrows indicate location of thickness estimates, thicknesses indicated are corrected for an average 60° dip. Dotted line traces outline of the Matakaoa outcrop within the Mangaroa Masssif; rectangle is frame of Fig. 2. (x)-marks in B were used to estimate shortening. M = locality where hypothetical fold was added to obtain estimate of minimal thickness.

radiolarian localities. Total shortening in this profile would be about 38 km (or 60%). At present it cannot be determined whether these shortening structures were formed as dip slip west-over-east thrusts before tilting of the sequence to steep dips, or whether they were formed as dextral strike slip structures after steepening (see below).

In this reconstruction, the Paleocene foram localities and the late Cretaceous radiolarian localities would have been approximately at the same level before imbrication, while the Cretaceous foram locality lay about 3 km lower in the section and now would be positioned in the core of a hanging wall anticline over a ramp. This implies that in this case, iso-chronological surfaces would be oblique to lithological layering, a situation which could be expected in rocks formed on a moving oceanic plate. Since the upper marker horizon in Fig. 7B would become younger towards the west, the western parts of the Mangaroa massif would have been closer to the generating spreading ridge than the eastern parts.

It is interesting to note that there is only about 1 km difference between thicknesses estimated in the two reconstructions. In the future, it should be possible to considerably refine these reconstructions and to establish their relative merit, with further collection of microfossils and structural analysis.

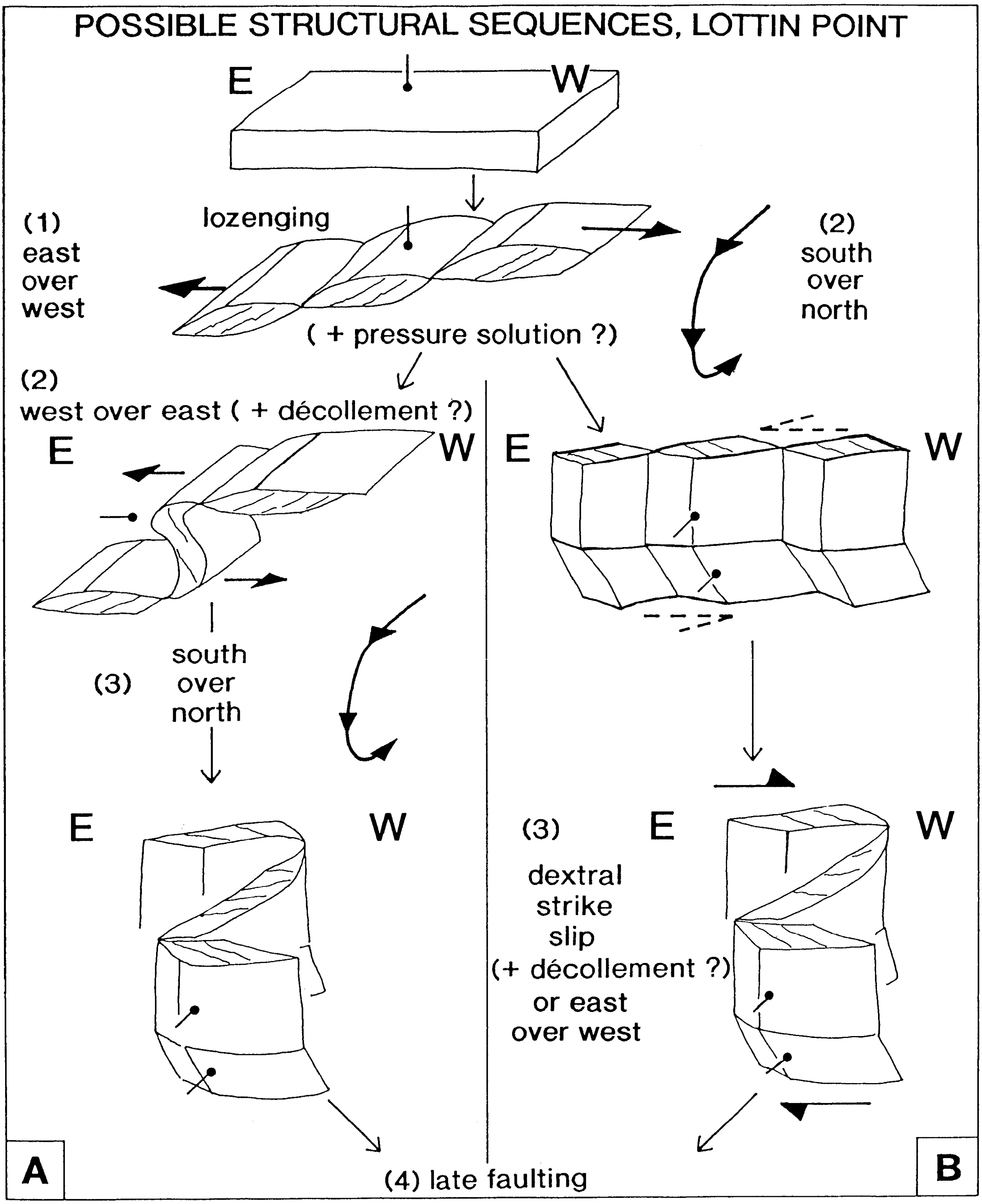

Fig 8 Schematic representation of structural sequence at Lottin Point. "Décollement" refers to large scale, now steeply plunging structures shown in Figs. 2 and 7. Curved arrows represent over turning on subhorizontal east-west axes. Phase (1) may consist of several different events. At least part of this sequence may be typical of the entire massif.

Deformational sequence

Structural analysis has not progressed far enough to arrive at a unique movement sequence for the Matakaoa Volcanics. However, two possible sequences of events for the Lottin Point area (Fig. 8) can give an indication of the scenarios that may be involved. If the overturning in this area is reversed, the phase I broken formation shear indicates east-over-west movement (Fig. 8, No 1). Pressure solution cleavages in limestones (see Fig. 6) may be part of the same deformation. Timing of the steepening and overturning in relation to the steeply plunging dextral folds is uncertain. If the overturning postdates dextral folding, the latter originally represented west-over-east thrusting (Fig. 8A, No. 3); if overturning took place earlier, the dextral folds probably originated in a dextral strike slip regime (Fig. 8B).

Any general emplacement model for the Matakaoa Volcanics would require some overthrusting from the north. The only structures that could be related to such an event would be those belonging to the steepening and overturning phase (Fig. 8A, No. 3; Fig. 8B, No. 2), since they are the only structures indicating major folds with E-W trending horizontal axes. However, because of the northward younging and overturning along the northern rim of the Mangaroa Massif (Fig. 2), the sense of movement (south over north) implied by this geometry is opposite to what would be expected, unless the whole of the massif is interpreted as one giant overturned limb of an even larger south and downward facing recumbent fold (which is unlikely, considering the 10 km thickness of the section). Alternatively, these structures could represent backthrusting (over a ramp?) during southward emplacement.

According Fig. 8A, the large folds, which now plunge steeply would have originated as structures with subhorizontal axes (thrust sheets in the radical reconstruction of Fig. 7). According to Fig. 8B, these structures could have formed in a strike-slip regime without necessity of vertically stacking large thicknesses of rocks. The model of Fig. 8A would involve low angle thrusting movements parallel to the continental margin, whereas the model in Fig. 8B implies dextral strike-slip parallel to this margin.

At the moment there is no way to determine which of the two versions of structural sequence is more correct. However, the sequence of Fig. 8B seems fractionally more likely, because it does not require that a great thickness of rock has to be stacked vertically. Such vertical stacking should have caused noticeable gradients in metamorpism and intensity of deformation, which cannot be detected in the massif. Also, late dextral strike-slip would be more compatible with events taking place along the margin of the New Zealand microcontinent at that time. Such strike-slip could be an expression of movement on the Vening Meinesz Fracture zone (Fig. 1A and Spörli & Ballance 1989), a fundamental tectonic feature in the development of that margin.

It should be noted that there is actually a third possible sequence of events. It involves steepening as the first phase, followed by lozenging in a sinistral strike slip regime and turn dextral strike-slip shearing. Any early steepening would indicate that the Matakaoa Volcanics were part of a persistent strike slip fault zone which may have first acted as a sinistral slip (dextral offset) transform fault on the ocean floor and subsequently as a dextral strike slip fault, as it became incorporated into the continental margin. However, there is as yet no detailed information on whether particular structures in the Matakaoa Volcanics were formed on the ocean floor or later (either during or after emplacement of the Matakaoa Volcanics onto the continental margin).

Both reconstructions of the overall geometry of the western Mangaroa Range (Fig. 7) are compatible with the three movement sequences discussed above.

Significance of thickness of volcanics.

The straight sequences in the Mangaroa Range corresponding to layer 2A are thick compared with the 0.34 km thickness of that layer in normal Pacific Basin crust or the 1.3 to 1.5 km thickness in the oceanic plateaux (Hussong *et al.* 1979). If we add layer 2B (dolerites) from Hussong *et al.* (1979) to the comparison, the interval 2A/2B from the Pacific Basin becomes 1.2 km and that from the plateaux 4 to 4.6 km. Thicknesses of Matakaoa Volcanics straight sequences then are of the same order of magnitude as those of the oceanic plateaux, but the 10 km or so total thicknesses for the Matakaoa Volcanics estimated from the reconstructions (Fig. 7) are much larger than any of those of the plateaux. Rather, they are on the same order of magnitude as geophysical estimates of thickness of the entire oceanic crust (White *et al.* 1992), which indicates that there must be much tectonic repetition within the Matakaoa Volcanics in addition to those that we have described in this paper. These repetitions may eventually be revealed by closer sampling for microfossils.

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Plate 1

Scanning electron micrographs of latest Cretaceous (Maastrichtian) radiolarians from green chert at south of Lottin Point, East Cape, New Zealand. All specimens are from sample LO9 (New Zealand Fossil Record Number Y14/f135). Scale bar = 100 μm on left upper corner applies to all other specimens without scale bar. Four digit number identifies specimens in Y.A. collection.

1. *Lithomespilus mendosa* (Krasheninnikov)
   LO9, 8603.
2. *Amphisphaera* sp.
   LO9, 8604.
3. *Stylosphaera* sp.
   LO9, 8608.
4. *Protoxiphotractus* sp.
   LO9, 8609.

5-6. *Amphisphaera privus* (Foreman)
   5: LO9, 8611; 6: LO9, 8610.

7, 12. *Dictyomitra andersoni* (Campbell & Clark)
   7: LO9, 8598; 12: LO9, 8770, scale bar =100 μm.

8-9. *Amphipyndax stocki* (Campbell & Clark)
   8: LO9, 8786; 9: LO9, 8593.

10. *Stichomitra asymbatos* Foreman
   LO9, 8596.

11. *Stichomitra warzigata* (Empson-Morin)
   LO9, 8778, scale ba = 100 μm.

13. *Stichomitra* aff. *marinae* (Gorbovetze)
   LO9, 8765, scale bar = 100 μm.

14. *Stichomitra* sp. B of Dumitrica (1973)
   LO9, 8734, scale bar = 100 μm.

15-16. *Stichomitra* sp.
   15: LO9, 8762; 16: LO9, 8597.

Plate 1

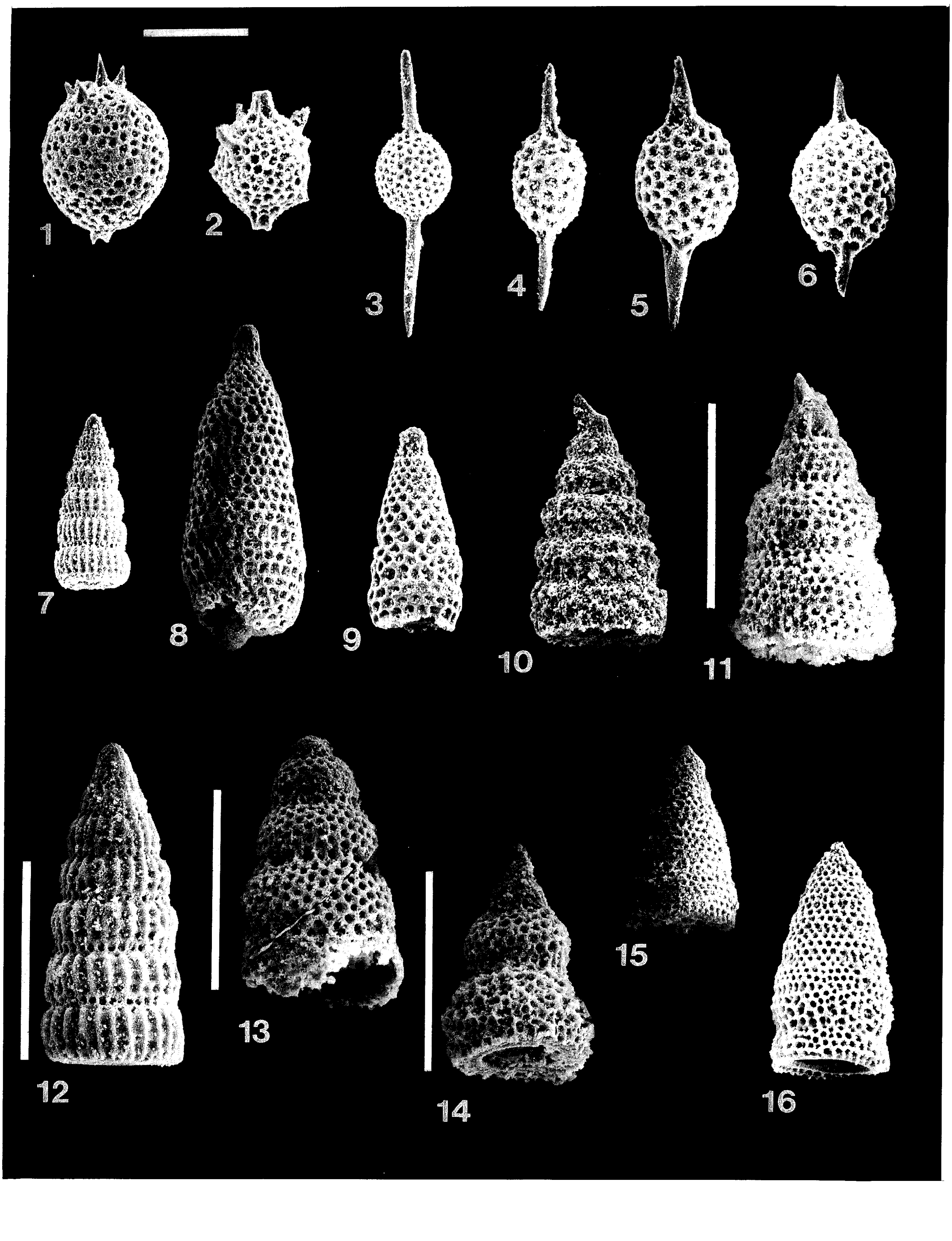

Plate 2

Scanning electron micrographs of latest Cretaceous (Maastrichtian) radiolarians from green chert at south of Lottin Point, East Cape, New Zealand. All specimens are from sample LO9 (New Zealand Fossil Record Number Y14/f135). Scale bar = 100 μm on right upper corner applies to all other specimens without scale bar. Four digit number identifies specimens in Y.A. collection.

1. *Lithomelissa*? *hoplites* Foreman
   LO9, 8789, scale bar = 100 μm.
2. *Theocampe altamontensis* (Campbell & Clark)
   LO9, 8733.
3. *Lithomelissa*? *heros* Campbell & Clark
   LO9, 8616.
4. *Ectonocorys*? sp.
   LO9, 8618.
5. *Theocampe* cf. *vanderhooi* (Campbell & Clark)
   LO9, 8752.
6. *Theocampe* sp.
   LO9, 8613.

7-8. *Myllocercion* cf. *acineton* Foreman
   7: LO9, 8751; 8: LO9, 8753.

9. *Theocapsomma erdnussa* (Empson-Morin)
   LO9, 8743, scale bar = 100 μm.
10. *Calocyclas*? sp.
    LO9, 8745.
11. *Schadelfusslerus* sp.
    LO9, 8749.
12. *Schadelfusslerus* cf. *echtus* Empson-Morin
    LO9, 8747.
13. *Theocapsomma amphora* (Campbell & Clark)
    LO9, 8736, scale bar = 100 μm.
14. unnamed nassellaria
    LO9, 8748.

15-16. *Theocapsomma* sp.
   15: LO9, 8750; 16: LO9, 8742.

Plate 2

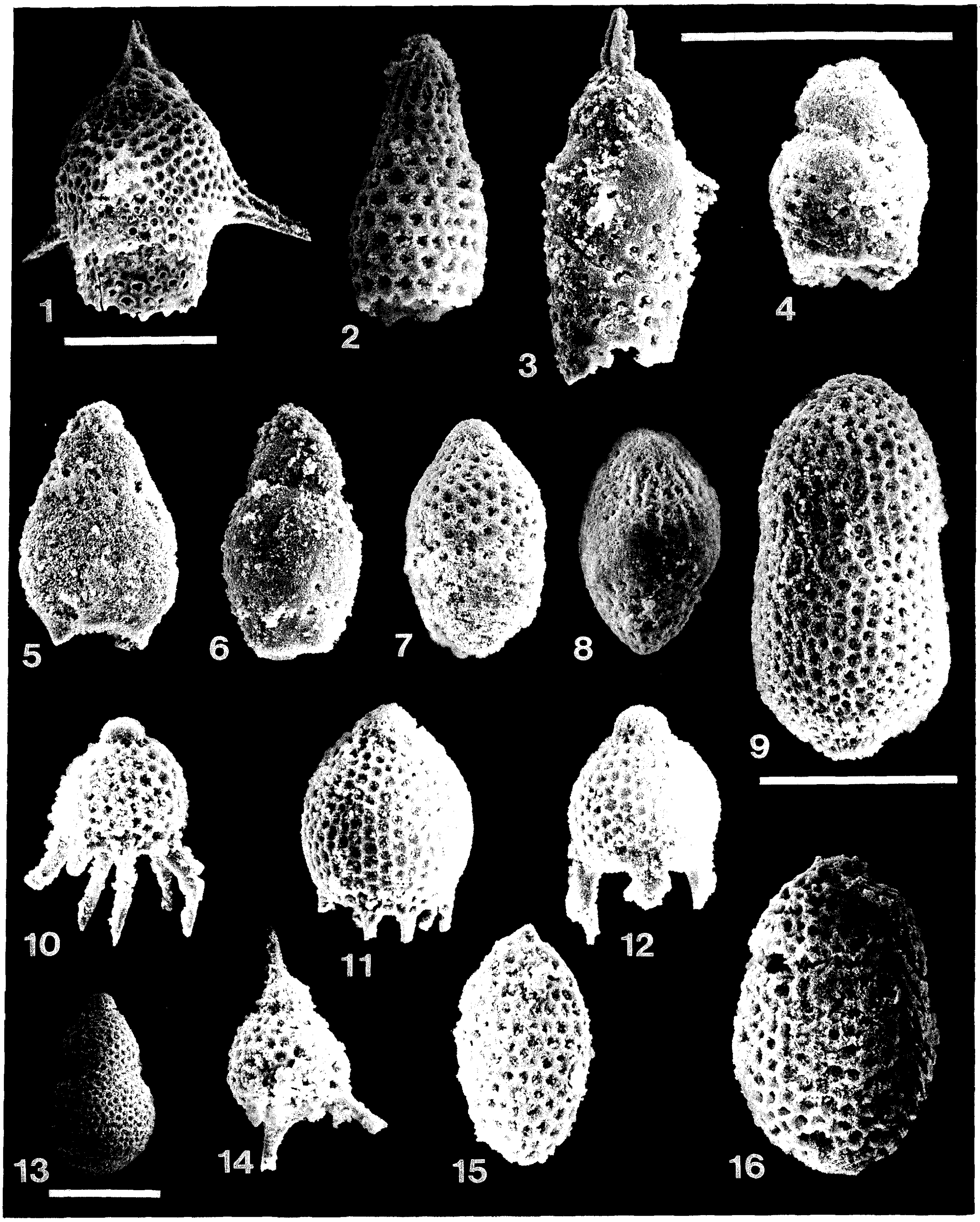

Plate 3

Scanning electron micrographs of Late Cretaceous radiolarians from chert at west of Lottin Point, East Cape, New Zealand. All specimens are from sample LO29 (New Zealand Fossil Record Number Y14/f137) except the specimen of figure 4 from LO9 (New Zealand Fossil Record Number Y14/f135). Scale bar = 100 μm on left upper corner applies to all other specimens without scale bar. Four digit number identifies specimens in Y.A. collection.

1-2. *Amphipyndax stocki* (Campbell & Clark)
1, 2: LO29, 8842, 8845.
3. *Amphipyndax* sp.
LO29, 8844.
4. *Lophophaena* sp A.
LO9, 8754, scale bar = 100 μm.
5. *Archaeodictyomitra* sp.
LO29, 8856.
6-7. *Dictyomitra multicostata* (Zittel) group
6: LO29, 8853; 7: LO29, 8887.
8. *Dictyomitra andersoni* (Campbell & Clark)
LO29, 8854.
9. *Stichomitra* sp.
LO29, 8875, scale bar = 100 μm.
10. *Theocampe altamontensis* (Campbell & Clark)
LO29, 8884, scale bar = 100 μm.
11. *Schadelfusslerus* sp.
LO29, 8883, scale bar = 100 μm.
12. *Stichomitra* sp.
LO29, 8877.
13-14. *Dictyomitra* sp.
13,14: LO29, 8886, 8858.

Plate 3