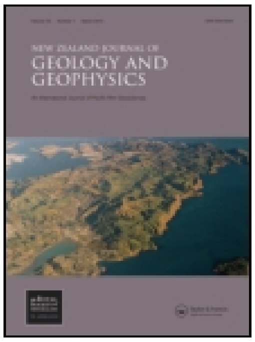

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Sedimentary structures in Quaternary ironsands at Waikato North Head, New Zealand

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ABSTRACT

Opencast mining at Waikato North Head, Franklin County, South Auckland, New Zealand, has exposed the sedimentary structures in Late Quaternary titanomagnetite ironsands of two units of the Kaihu Group: the Waiuku Blacksand Member (Hood Formation) and the Entrican Dune Member (Mitiwai Formation).

The Waiuku Blacksand Member consists of a series of alternating, steeply cross-laminated and horizontally laminated sand units, which are sometimes separated by units of mud. The very large scale of the cross-laminated sets (up to 12 m thick), their orientation, grain size and internal features suggest an eolian origin. Some of the horizontally laminated units are topset beds associated with the foresets of the cross-laminated units, whereas others are of either interdune stream–lake, or beach origin. Mud units may represent soils, loess, or interdune swamp and lake deposits.

The Entrican Dune Member consists of large migrating dunes which were stabilised in this area by afforestation in 1935. Internally, they are composed of large and very large sets of steeply inclined, cross-lamination (foresets) and large sets of horizontal lamination, or low angle cross-lamination (topsets).

INTRODUCTION

The New Zealand Steel Ltd. mine at Waikato North Head (Fig. 1) is situated in a particularly rich deposit of titanomagnetite ironsand underlying the Waiuku State Forest. The mine is open-cut (Fig. 2) and produces 900 tonnes of ironsand concentrate (58% Fe) per day. The concentrate is trucked 22 km to the Glenbrook steel mill and processed with scrap steel to produce 500 tonnes of steel billets per day.

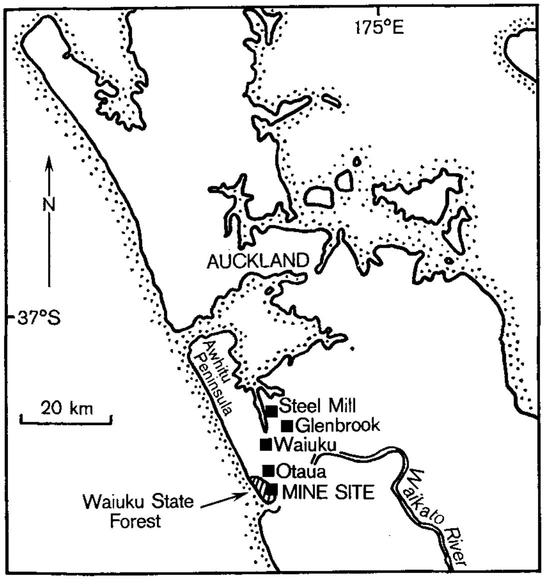

FIG. 1—Location of the New Zealand Steel Ltd. mine site at Waikato North Head, near Otaua, and the steel mill, near Glenbrook.

Previous work on the ironsands in the Waikato North Head area by Nicholson & Fyfe (1958), Kear (1962; 1965) and Schofield & Waterhouse (1974) is based mainly on drill hole information. This paper reports on the sedimentary structures and other sedimentological features exposed by the mining operations during the period March 1974 to August 1974. Concurrent with this study, Barter (1976) described the mineralogy and nature of weathering of some of the sand exposed in the mine as part of a study of the geology of the Awhitu Peninsula.

The sand and mud exposed in the mine is of Quaternary age and comprises three stratigraphic units of the Kaihu Group (Fig. 3). These units, the Entrican Dune Member of the Mitiwai Formation, the Waiuku Blacksand Member of the Hood Formation and the Awhitu Formation, were named and described from the South Auckland area by Kear (1962; 1965). Other stratigraphic units of the Kaihu Group are not represented.

Material from the Entrican Dune Member and the Waiuku Blacksand Member is mined and mixed before magnetic concentration at the site. The Awhitu Formation contains too little titanomagnetite to be mined economically and is left on the mine floor, therefore, only the upper part of this formation is exposed.

The three formations are easily distinguished in the field. The loose grey sand of the Entrican Dune Member slumps to the angle of rest in excavated scarps, whereas the reddish brown sand and mud of the Waiuku Blacksand Member holds up in cuts because of its weathered nature. The Awhitu Formation is represented

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FIG. 2—Aerial photograph of the New Zealand Steel Ltd. mine site at Waikato North Head, taken in January 1974.

(Reference: N.Z. Aerial Mapping Ltd., Hastings. No. A/2 S.N. 3386. Reproduced by courtesy of Murray-North Partners Ltd., Auckland, and New Zealand Steel Ltd.)

by a distinctive white tephra and a fossiliferous (N51/f1075, listed in Christie 1975) grey mud which are exposed only in patches on the mine floor.

The principal aim of this paper is to establish the depositional environment of the Waiuku Blacksand Member. This is accomplished by comparing it with the Entrican Dune Member.

NOMENCLATURE

The nomenclature used in this paper for primary sedimentary structures generally conforms to that suggested by McKee & Weir (1953). However, other sources are used for terms to describe the shape of cross-strata within a set (Fig. 4, modified after Allen 1968), and the scale of cross-stratified sets: small = less than 50 mm thick; medium = 50 mm to 2 m thick; large = 2 m to 8 m thick; and very large = greater than 8 m thick (after Conybeare & Crook 1968). Unless stated otherwise, all cross-lamination is steeply inclined, with foresets generally dipping at 30°.

The deformation structures found in the cross-laminated sand units are described using the classification of McKee *et al.* (1971) for the penecontemporaneous structures, and the classification of McKee *et al.* (1962) for the post-depositional structures.

The terms unit and sub-unit are used as a hierarchy of informal stratigraphic names. The term lithozone is also used as an informal stratigraphic name. It is of higher rank than a unit and these terms also differ in that a unit is a purely descriptive subdivision, whereas a lithozone is a grouping of units generally involving some inferred correlation.

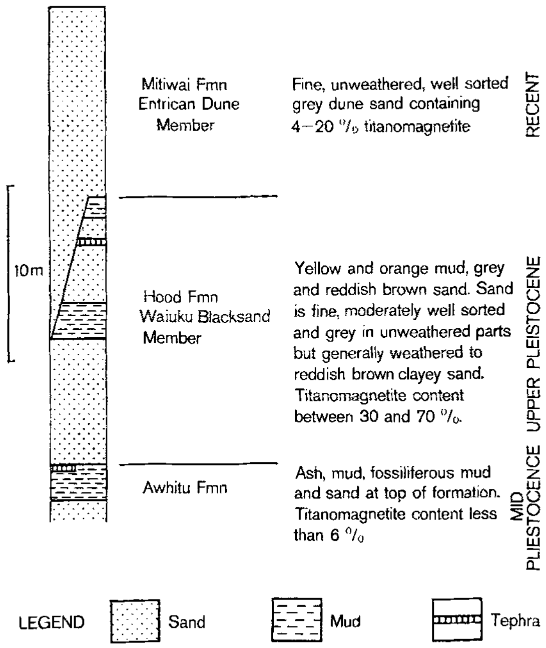

FIG. 3—Stratigraphic column for the sand and mud exposed in the Waikato North Head mine.

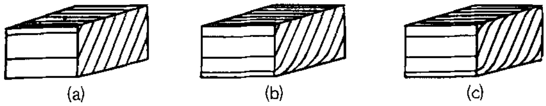

FIG. 4—The terms used to describe the shape of cross-strata within a set are: (a) inclined (foresets only); (b) tangential (foresets and bottomsets); (c) sigmoidal (topsets, foresets and bottomsets). The terminology and diagram are modified after Allen (1968).

GEOLOGY OF THE MINE SITE

Entrican Dune Member

The Entrican Dune Member consists of up to 50 m of recent wind-blown dune sand, stabilised by planting the Waiuku State Forest in 1935. The unweathered and unconsolidated sand contains up to 20% titanomagnetite. Texturally, sand from the dune foresets is fine, well sorted, near symmetrically skewed and mesokurtic (Table 1). Stratification is marked by alternating light (titanomagnetite poor) and dark (titanomagnetite rich) laminae, averaging 2 mm and 0·5 mm thick respectively.

The internal structure of the dunes is typical of that recorded from other eolian deposits by Thompson (1937), McKee (1957; 1966), Bigarella *et al.* (1969), Glennie (1970) and Bigarella (1972). It consists of approximately 4 m of low-angle cross-lamination and horizontal lamination overlying large and very large sets of steeply inclined cross-lamination. Most of the structures appear to belong to a single large transverse dune 15 m high (Fig. 5A). The low angle cross-lamination and horizontal lamination are the topsets and the steeply inclined cross lamination the foresets of the large dune. The sets of steeply inclined cross-lamination differ slightly in paleocurrent direction and are separated laterally by planar boundaries. These generally conform to the dip of the laminae of one of the sets of cross-lamination, but some cut across the lamination of both sets.

A diagram compiled from measurements of the dip directions of foresets of the Entrican Dune Member is given in Fig. 6. The derived vector mean or paleowind direction is identical to that measured from aerial photographs by Barter (1976) for the coastal dunes (his Group II dunes) in this area and as far north as Manukau Head.

The deformation structures observed in foresets of the Entrican Dune Member are listed in Table 2. Only penecontemporaneous structures were seen. They are typical of those reported from other eolian dunes by McKee *et al.* (1971) and are considered to form by the avalanching of sand down the lee slope of the dune.

Waiuku Blacksand Member

The Waiuku Blacksand Member at the mine site is up to 20 m thick and comprises titanomagnetite rich (up to 70% and seldom less than 30%) sand with a few thin mud layers. The richer sands are very clayey and have striking reddish brown colours due to weathering. The alteration, in the form of limonitisation, has caused some lithification so that the sands form vertical scarps when excavated. Sand from unweathered and undeformed foresets of the Waiuku Blacksand Member is fine, moderately well sorted, near symmetrically skewed and mesokurtic (Table 1). This sand is texturally very

TABLE 1—Grain size statistical parameters for samples of sand taken from the mine site. Values of all parameters listed for sand of the Waiuku Blacksand Member are very similar to those of modern dune sand of the Entrican Dune Member. The statistical parameters were calculated using the formulae of Folk & Ward (1957).

	Graphic Mean (phi units)	Inclusive Graphic Standard Deviation (phi units)	Inclusive Graphic Skewness	Graphic Kurtosis
Waiuku Blacksand Member				
12290	2.48	0.58	0.00	0.98
12291	2.47	0.54	0.07	1.02
12292	2.66	0.52	-0.01	0.95
Entrican Dune Member				
12293	2.59	0.46	0.04	1.12
12294	2.47	0.45	0.10	1.02

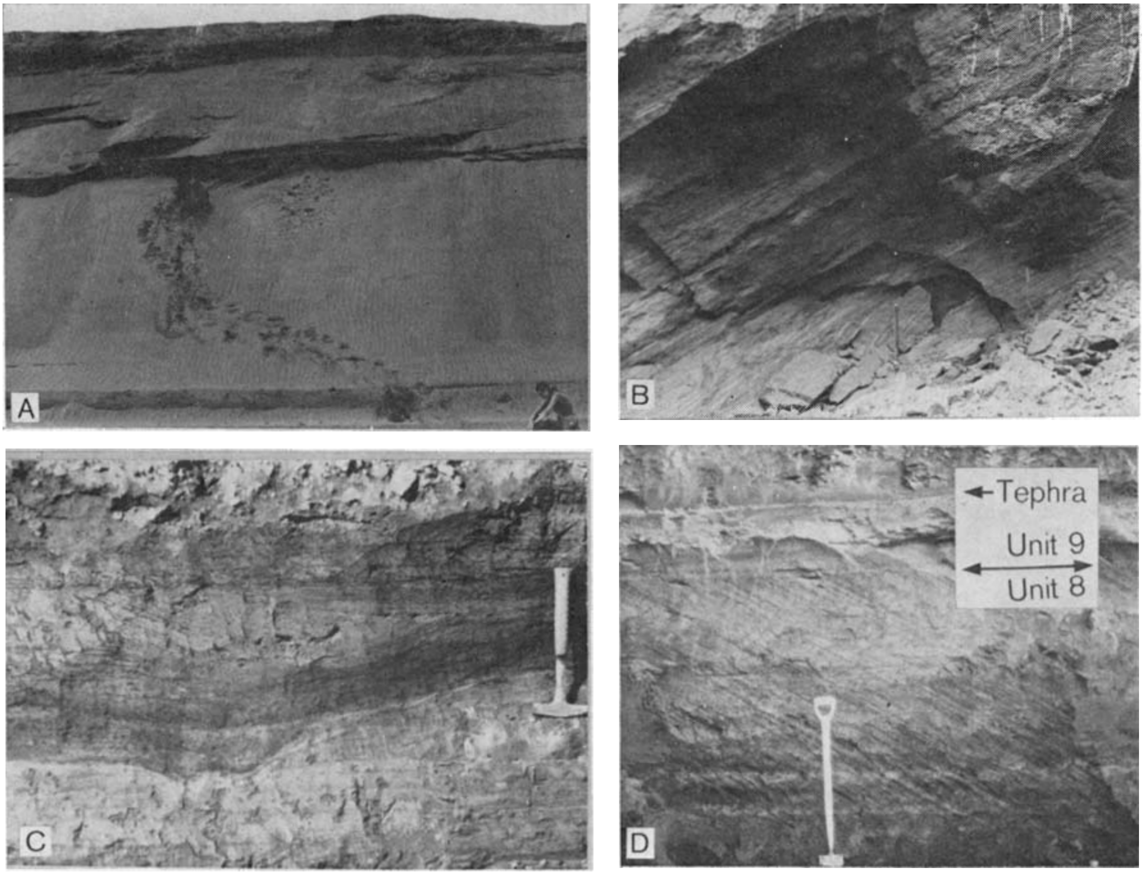

FIG. 5—Primary sedimentary structures. A—A section through the large dune of the Entrican Dune Member displaying topsets of low angle cross-lamination, overlying foresets of a very large set of cross-lamination. B—Foresets of unit 1 in the Waiuku Blacksand Member. The handle of the shovel is 0·5 m long. C—Channel structures of unit 9c in the Waiuku Blacksand Member. D—A composite set (unit 9) overlying a large solitary set of tangential cross-lamination (unit 8) in the Waiuku Blacksand Member.

similar to dune sand taken from foresets of the Entrican Dune Member. Sand from other sedimentary structural types is too weathered for meaningful grain size analysis. Stratification is distinct in the less weathered sand with alternating titanomagnetite poor (grey) and titanomagnetite rich (black) laminae, averaging 2 mm and 1 mm thick respectively.

The Waiuku Blacksand Member has been divided into units which are described in Table 3 and illustrated in Fig. 7. Two sections are described: sand and mud exposed in the western part of the mine (Fig. 7B) is considered separately from that in the eastern part of the mine (Fig. 7C). The intervening material (yellow and brown mud: unit 17), complicates the evaluation of the relationships of the sections on either side because of poorly exposed contacts with the adjoining sands.

The sedimentary structures of the Waiuku Blacksand Member consist of at least six medium, large, or very large sets of cross-lamination, separated vertically or laterally predominantly by horizontally laminated sand or by units of mud. These units have been grouped into six lithozones (Fig. 8). Lithozone 1 consists of a very large solitary set of cross-lamination (unit 1, Fig. 7B, Fig. 5B) which underlies most of the other units in the western part of the mine. It is up to 12 m thick and is the largest single structure exposed in the mine. Foresets of the structure grade vertically into topsets to the north, but are truncated by horizontal lamination (unit 2, Fig. 7B), probably also topsets, to the south. A foreset dip direction diagram for lithozone 1 is given in Fig. 9A.

Lithozone 2 comprises the three units of mud that overlie lithozone 1 and separate it from the overlying laminated sand units of lithozones 3 and 4. The contacts between lithozone 1 and the mud units of lithozone 2 are gradational, and show an increase in limonitisation and loss of lamination in lithozone 1 with increasing proximity towards the mud units. A transitional stage of laminated sand lenses in mud occurs between lithozone 1 and the mud of unit 3.

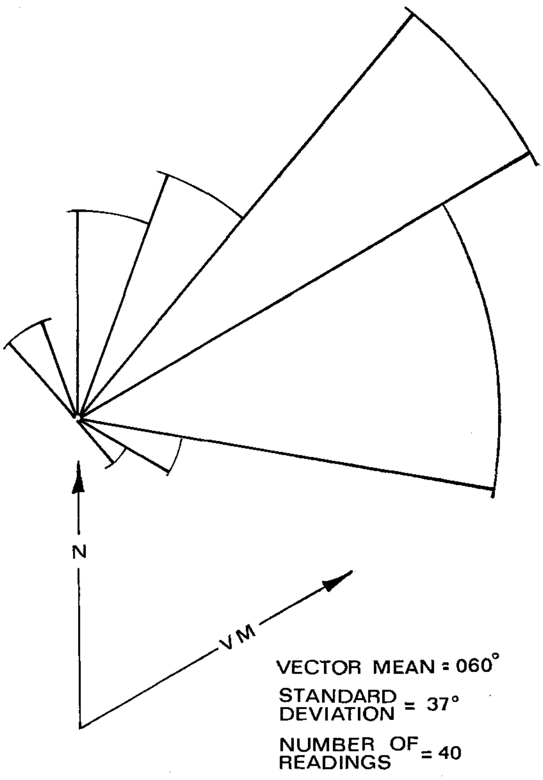

FIG. 6—A foreset dip direction diagram compiled from measurements from the medium, large, and very large sets of cross-lamination of the Entrican Dune Member.

Two of the mud units (3 and 4, Fig. 7B) display complex sequences of different coloured mud sub-units, some thinly laminated, and both contain fossiliferous sub-units. Unit 4 forms a plateau in the north-western corner of the mine (Fig. 7A) and has a richly fossiliferous sub-unit containing logs and twigs in a net-like matrix of woody fragments (N51/f1076, listed in Christie 1975). Unit 3 overlies the southern exposure of lithozone 1 and contains a few scattered twigs or roots in its top sub-unit. The third mud unit (unit 5, Fig. 7B) cuts across the northern boundary of lithozone 1, separating it laterally from several other solitary sets of cross-lamination (lithozones 4 and 5).

Lithozone 3 comprises a large solitary set of cross-lamination overlain by a composite set, predominantly containing sets of horizontal lamination, but also containing small sets of trough cross-lamination. This sequence occurs separately in both parts of the mine (units 6 and 7 in the north-western part of the mine; Fig. 7B, and units 8 and 9 in the eastern part of the mine, Fig. 7C). Both sequences overlie fossiliferous mud units: unit 3 in the north-western part of the mine, and the Awhitu Formation in the eastern part of the mine. The sequences differ in that the composite set in the eastern part of the mine also contains sets of ripple drift cross-lamination (unit 9b), channel structures (unit 9c, Fig. 5C), sigmoidal cross-lamination (unit 9d), and a tephra horizon (Fig. 5D). Also, in the eastern part of the mine, the contact between the large sets of cross-lamination and the overlying composite set is nearly horizontal, whereas that in the western part of the mine is in the form of a trough, in an east-west section, with a depth of 1 m and width of 60 m. These contacts are erosional and indicate that the large cross-laminated sets were planated prior to the deposition of the composite sets. Their original thickness was larger than the preserved thickness noted here.

Foreset dip direction diagrams (Fig. 9B and C) for the two large sets of cross-lamination (units 6 and 8) show that they have generally similar paleocurrent directions. A similar paleocurrent direction (Fig. 9D) is shown by a large solitary set of cross-lamination (unit 10, Fig. 7B) overlying the third mud unit of lithozone 2, in the north-western part of the mine. This indicates that these sets were deposited under similar conditions and their relative stratigraphic positions suggest that they may have been deposited at approximately the same time.

The tephra (Fig. 5D) present in unit 9 was found to be unsuitable for dating by the fission track method (Seward pers. comm. 1975).

Lithozone 4 is a large solitary set of cross-lamination (unit 11, Fig. 7B) with a bimodal paleocurrent direction (Fig. 9E). It occurs in the northern exposure of the western part of the mine and does not appear to correlate with any of the other units observed. Foresets of the structure dip at an average angle of 13°, in contrast with the 28–31° average foreset dips of the cross-laminated sets in the other lithozones (Table 3).

Lithozone 5 consists of medium solitary sets of cross-lamination (unit 12, Fig. 7B; unit 13, Fig. 7C). They have similar paleocurrent directions (Fig. 9F and G) and occur near the top of both sections exposed in the different parts of the mine.

Lithozone 6 comprises units of mud occurring stratigraphically at the top of the Waiuku Blacksand Member in both parts of the mine (units 14, 15, and 16, Fig. 7B; unit 18, Fig. 7C; unit 17, Fig. 7B and C).

In summary, the Waiuku Blacksand Member displays a sequence of cross-laminated structures separated vertically or horizontally by composite sets or by units of mud (Fig. 8). Each successive cross-laminated structure is generally of smaller size than its predecessor and there is a general change in paleocurrent direction from east-trending in the largest structure at the base of the sequence, to north-west-trending in the smallest structures near the top of the sequence.

Foreset dip direction diagrams compiled from the different sets of cross-lamination mentioned previously are given in Fig. 10. These diagrams show that the Waiuku Blacksand Member has a similar paleocurrent pattern to that of the Entrican Dune Member (Fig. 6).

Table 2 lists the occurrence of deformation structures in the cross-laminated sand units. The penecontemporaneous structures, with the exception of the impact struc-

TABLE 2—Occurrence of penecontemporaneous and post-depositional deformation structures in the cross-laminated sands at the mine site.

	Waiuku Blacksand Member							Entrican Dune Member
Unit number	1	6	8	10	11	12	13	
Exposure in square metres *	4000	400	1200	200	150	30	35	6000
Deformation Structures								
(a) Penecontemporaneous †								
1. Rotated plates or blocks								
2. Stairstep or monoclinal folds and normal faults						very common		rare
3. Stretched laminae		rare				very common		
4. Warps or gentle folds	rare	rare				very common		rare
5. Drag folds and flames	very rare	rare				very common		
6. High angle assymetrical folds								
7. Overthrusts and overturned folds		rare						rare
8. Break apart laminae and breccia		rare						
9. Fadeout laminae						very common		rare
10. Impact structures ‡	single structure		single structure					
(b) Post-Depositional §								
1. Irregularly contorted beds	rare	common	very common					
2. Intraformational recumbent folds		common	very common					
3. Convolute bedding			very common					
4. Intraformational thrust structures			very common					

*The occurrence of deformation structures in each unit is unrelated to the amount of exposure.
†The terminology used in the first nine classes is after McKee *et al.* (1971).
‡The term "impact structures" is the author's.
§The terminology used is after McKee *et al.* (1962).

TABLE 3—Description of units illustrated in Fig. 7.

Unit	Maximum Exposed Thickness (m)	Lithology	Sedimentary Structures*	Average Dip of Foresets	Notes†	Vertical Section Exposure‡ (m^2)
1	12	Sand	Very large solitary set of cross-lamination.	31°	Sample Nos. 12290, 12291, and 12292.	4 000
2	1.5	Sand	Horizontal lamination.			20
3	2	Mud			Fossiliferous	40
4	2	Mud			Fossiliferous. Fossil Record No. N51/f1076.	50
5	1.5	Mud				100
6	7	Sand	Large solitary set of cross-lamination.	29°		400
7	1.2	Sand	Composite set containing small sets of trough cross-lamination, medium sets of tangential cross-lamination and horizontal lamination.			40
8	3	Sand	Large solitary set of tangential cross-lamination.	31°		1 200
9	2	Sand	Horizontal lamination containing tephra and horizons of small sets of trough cross-lamination.		Tephra Sample No. 12298.	420
9b	0.6	Sand	Ripple drift cross-lamination with high rate of climb.	Bedding planes dip 30°	Similar to Jopling & Walker's (1968) Type A and Lamda cross-stratification of Allen (1963).	9
9c	0.4	Sand	Channel structures.		"U" shaped and generally symmetrical in cross-section.	6
9d	0.6	Sand	Medium solitary sets of cross and sigmoidal cross-lamination.	29°		10
10	6	Sand	Large solitary set of cross-lamination.	30°		200
11	5	Sand	Large solitary set of cross-lamination.	13°		150
12	1.5	Sand	Medium solitary sets of cross-lamination.	31°		30
13	1	Sand	Medium sets of cross-lamination.	28°		35
14	2	Mud				200
15	>1	Mud				70
16	5	Mud				200
17	>1	Mud				50
18	2	Mud				500

*Foreset dip direction diagrams for the sets of cross-lamination are given in Fig. 9.

†Reference samples are lodged at the Department of Geology, Victoria University of Wellington.

‡The exposure in square metres refers to exposure in vertical section only (Fig. 7B and C). It does not include the plan exposure (Fig. 7A).

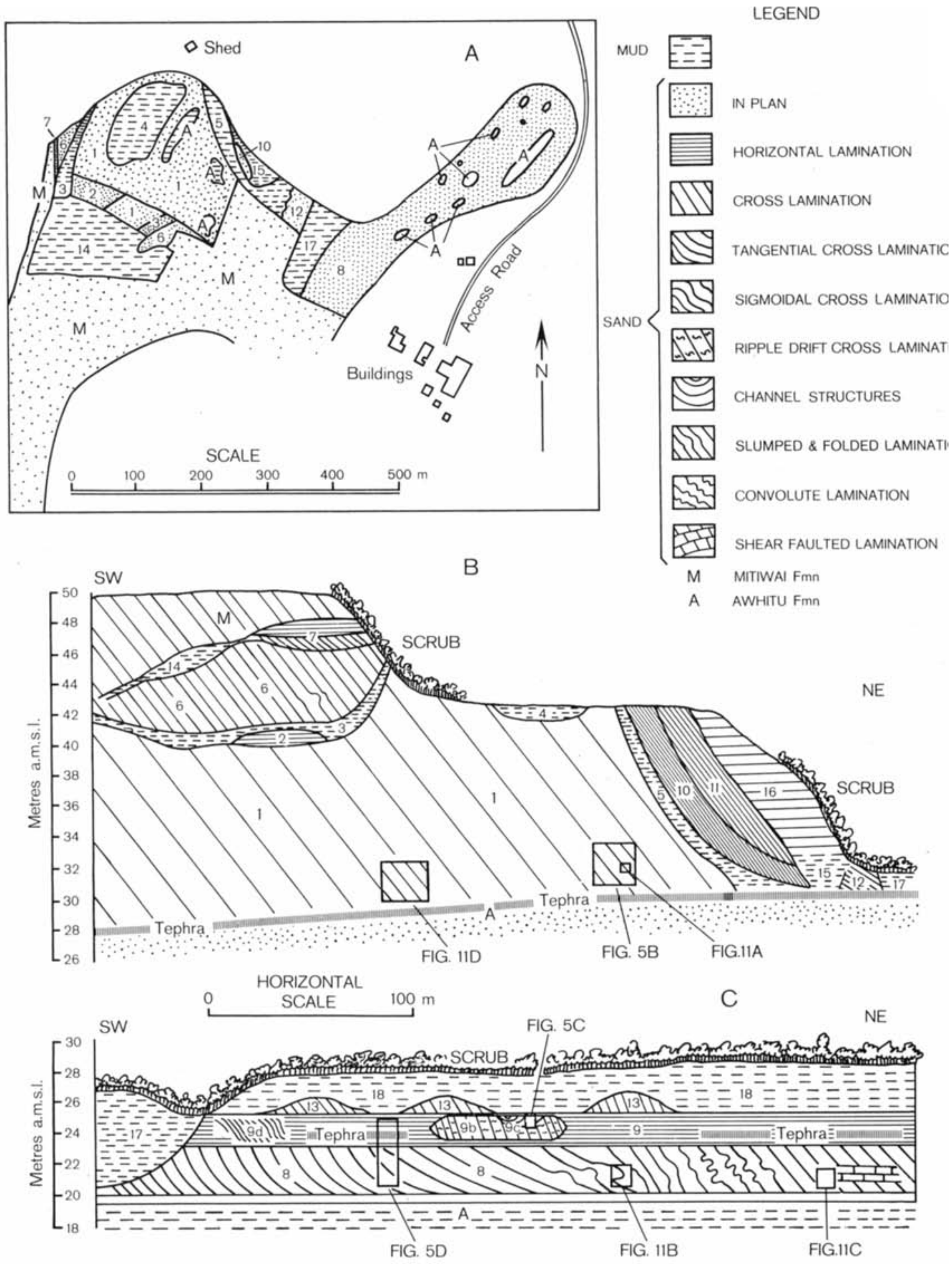

FIG. 7—Map (A) and diagrammatic cross-sections (B—western, and C—eastern) showing the various units exposed in the mine site. A short description of these (numbered) units is given in Table 3, and they are discussed further in the text. The horizontal scale is only approximate, because of the diagrammatic nature of the cross-sections.

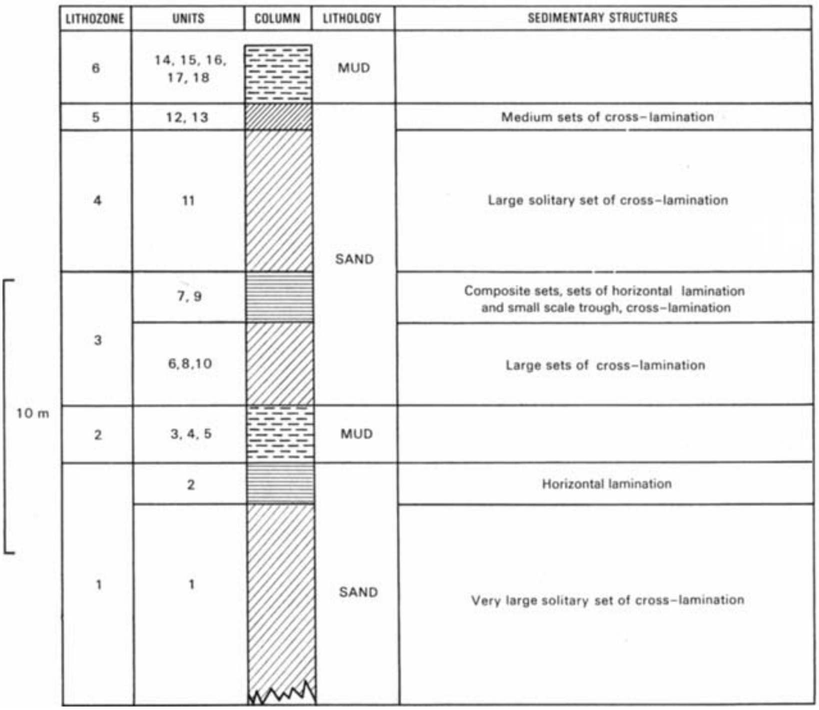

FIG. 8—Column showing the grouping of the various units of the Waiuku Blacksand Member into a sequence of lithozones.

tures, are typical of those found in eolian dunes as exemplified by the Entrican Dune Member. The impact structures (Fig. 11A) were named because of their similarity in appearance to horse-hoofprint structures reported by Van der Lingen & Andrews (1969), although the latter are three times the size. Their origin is unknown. The post depositional deformation structures occur irregularly throughout units 1 and 6, but are in a recognisable sequence in unit 8: undeformed foresets (Fig. 5D) grade down dip into bent, slumped, folded (Fig. 11B) and finally low angle shear faulted foresets (Fig. 11C). The irregularly contorted beds and intraformational recumbent folds of unit 6 are similar to those of unit 8; however "kinked lamination" structures (Fig. 11D) were the only irregularly contorted beds seen in unit 1. The deformation in units 6 and 8 occurred prior to the deposition of the overlying composite sets because the intervening contacts are undeformed.

SEDIMENTARY ENVIRONMENT OF THE WAIUKU BLACKSAND MEMBER

The Waiuku Blacksand Member can be subdivided into three facies: a cross-laminated sand facies (units 1, 6, 8, 10, 11, 12, and 13); a horizontally laminated sand facies (units 7, 9, 9b, 9c, and 9d); and a mud facies (units 3, 4, 5, 14, 15, 16, 17, and 18).

The cross-laminated sand facies has sets ranging in thickness from 1 m to 12 m, however, a common origin is indicated by the following features. (1) All the sets except unit 11 have average foreset dips of 30° ± 2° (Table 3). Unit 11 has an average foreset dip angle of 13°. (2) Although there is a progressive change in paleocurrent direction up the sequence of lithozones, sets within the same lithozone have similar vector means (Table 4). (3) All the sets except unit 11 have similar paleocurrent patterns, with standard deviations about the vector means of less than 30° (Table 4). A standard deviation of 50° for unit 11 is caused by a bimodal paleocurrent pattern (Fig. 9E) and if each mode is treated separately, standard deviations of 28° and 15° are calculated. (4) The sets containing penecontemporaneous deformation structures have similar types of these structures.

TABLE 4—Statistical parameters for the foreset dip direction diagrams of Fig. 9.

Unit	Designation in Fig. 9	Vector Mean	Standard Deviation	Number of Readings
1	A	092°	22°	134
6	B	022°	27°	41
8	C	048°	13°	19
10	D	032°	16°	28
11	E	071°	50°	15
12	F	346°	17°	6
13	G	327°	30°	6

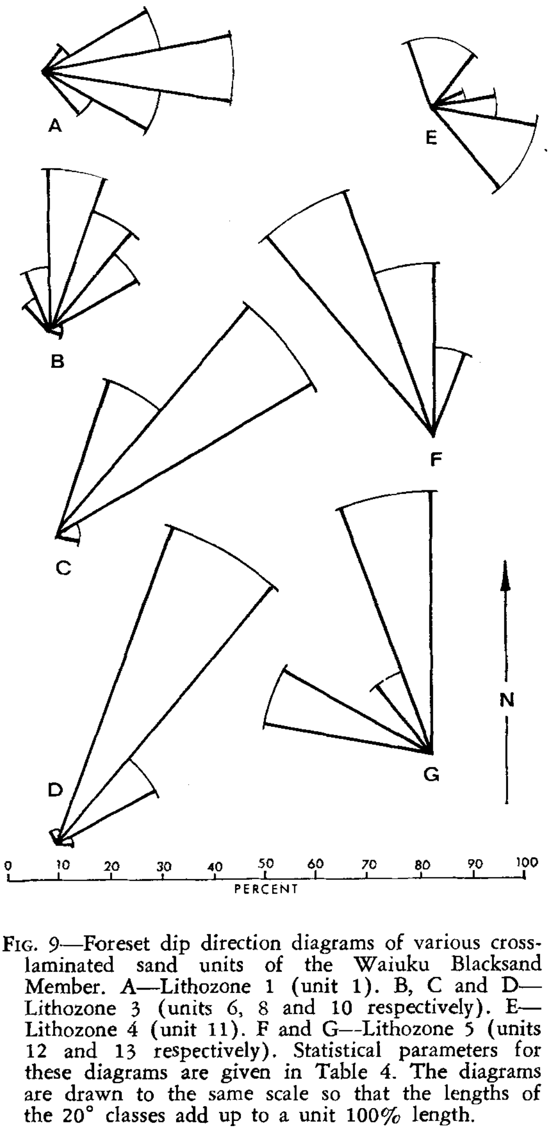

FIG. 9—Foreset dip direction diagrams of various cross-laminated sand units of the Waiuku Blacksand Member. A—Lithozone 1 (unit 1). B, C and D—Lithozone 3 (units 6, 8 and 10 respectively). E—Lithozone 4 (unit 11). F and G—Lithozone 5 (units 12 and 13 respectively). Statistical parameters for these diagrams are given in Table 4. The diagrams are drawn to the same scale so that the lengths of the 20° classes add up to a unit 100% length.

Although unit 11 differs from the other sets by having a smaller average foreset dip angle, the general appearance and stratigraphic position of this unit suggest an identical origin to the adjacent cross-laminated sand.

Medium and large cross-laminated sets can form in a number of different environments, but very large sets have been recorded only from eolian dunes, although they are believed to form subaqueously as tidal current ridges (cf. Houbolt 1968) and marine deltas (cf. Collinson 1968, Gradstein & Van Gelder 1971). The formation of the very large cross-laminated set at the mine site in either of these subaqueous environments is precluded by features such as the absence of marine fossils, and the direction, texture, steep inclination, scale, and penecontemporaneous deformation structures of the foresets. These features are consistent with an eolian origin and, therefore, the very large set is believed to be an eolian dune. Similarly, the sets of medium and large cross-lamination are considered to have an eolian origin. Therefore, the cross-laminated sand facies is concluded to be eolian.

The cross-laminated sands of the Waiuku Blacksand Member have been deformed predominantly by small scale folding after deposition (Fig. 11B), although small scale faulting (Fig. 11C) has also occurred in one of the units.

Experimental work by Rettger (1935) showed that waterlogged sand deformed by flowage and folding, whereas dry sand deformed by faulting. Therefore, most of the deformation at the mine site must have occurred under moist or saturated conditions. Mud units underlie all of the post-depositionally deformed cross-laminated units and these may have provided unstable bases for the dunes or formed perched water tables within the dunes aiding the deformation.

The down-dip succession of deformation structures in unit 8 (Figs 11B and 11C) displays a transition from folding in the south-west to faulting in the north-east. This succession may reflect the proximity of the structures to the lee face of the dune, with wet conditions prevailing within the dune and dry conditions near the lee face.

Earthquakes have been postulated as the stimulus for deformation of water saturated sand in examples described by Kiersch (1950), Kuenen (1958) and Greensmith (1965), and such a mechanism may have initiated the deformation in the Waiuku Blacksand Member.

The second facies contains an association of horizontal lamination with some, mainly small-scale, cross-lamination (trough, ripple drift, and sigmoidal) and channel structures. Sets of trough cross-lamination and ripple drift cross-lamination are formed by the migration of subaqueous current ripples (Allen 1968). Although Sharp (1963) showed that foreset laminae may be rarely present in the internal structure of individual wind ripples, the bedding produced from the migration of these ripples is horizontally laminated sand (Reineck & Singh 1973, pp. 43–44). It is concluded that this second facies was deposited subaqueously.

The association of sedimentary structures in the horizontally laminated sand facies is most commonly found in alluvial or beach backshore (above high tide) deposits (cf. Reineck & Singh 1973), but noting the encompassing eolian sand and the widespread preservation of a tephra layer in unit 9, an interdune stream–lake type of environment seems more appropriate. Raised beach deposits and marine terraces are common in the south-west Auckland coastal region (cf. Chappell 1970; Barter 1976) and, therefore, a beach origin may also be possible for this facies. There is evidence more adequately explained by a marine transgression, for example, the horizontal planation of the underlying dune sand (unit 8) in the eastern part of the mine. Therefore, this facies may be of either beach, backshore, or interdune stream–lake origin.

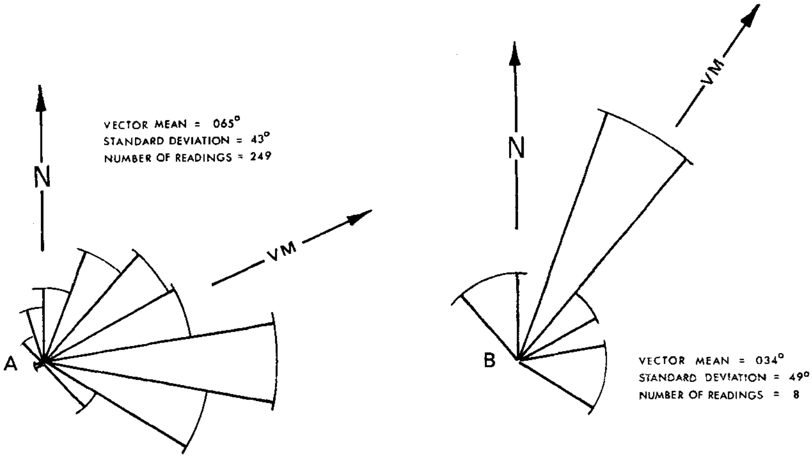

FIG. 10—Foreset dip direction diagrams for the medium, large, and very large sets of cross-lamination in the Waiuku Blacksand Member. A is calculated from all measurements, whereas only the vector means of the various sets were used to calculate B.

The mud units comprising the third facies could be interdune swamp and lake deposits, loess, or soils. The floral assemblage present in unit 4 can be reconciled with interdune swamp and lake, or soil deposits (Christie 1975)*, although the thickness of this particular unit (2 m) indicates that a soil origin is unlikely. Unit 5 drapes up the lee face of the large dune of lithozone 1 with a dip of approximately 20°, precluding an interdune swamp or lake origin. The remaining mud units are compatible with all the aforementioned environments.

The microfloral assemblage in one of the fossiliferous muds lying above lithozone 1 (unit 4) represents a full coastal or lowland forest situation during an interglacial stage (Mildenhall pers. comm. 1975). If the dune building phases are considered to be a result of an increase in the supply of sand due to a falling sea level (Kear 1964), then the dune-mud-dune succession (lithozones 1, 2, and 3 respectively) could represent a glacial-interglacial-glacial cycle.

An appraisal of the three facies present in the Waiuku Blacksand Member and their stratigraphic organisation suggests that the following events occurred at the mine site.

1. A dune building stage forming the very large set of cross-lamination (foresets) and horizontal lamination (topsets) of lithozone 1.

2. A stage when the dunes were fixed and the mud units of lithozone 2 were formed as interdune swamp or lake deposits, loess deposits or soils.

3. A second dune building stage forming the large cross-laminated sets of lithozone 3. These dunes advanced into interdune swamps or lakes and were subsequently internally deformed.

4. An interdune stream–lake or marine transgressive stage, or stages, planing the tops of the large sets of cross-lamination and depositing the composite sets of lithozone 3.

5. A third and perhaps fourth dune building stage forming the large solitary cross-laminated set of lithozone 4 and the medium cross-laminated sets of lithozone 5.

The dune, interdune stream–swamp–lake environment envisaged for the Waiuku Blacksand Member occurs at present along the coast of the Awhitu Peninsula and similar systems occur at Kawhia (Pain 1976) and Foxton (Cowie 1963).

The suggested eolian origin for most of the sand of the Waiuku Blacksand Member at the mine site contrasts with previous interpretations of this deposit (Kear 1962; 1965; Schofield & Waterhouse 1974) in which it was suggested to be a beach deposit. Schofield & Waterhouse (1974) based their interpretation in part on the assumption that a high level of titanomagnetite implied a marine origin. For example, they stated "most of the local dune sand contains less than 20% titanomagnetite concentrate and where the concentration is greater than this, it is considered to be of marine origin". This is not a valid argument, for Barter (1976) has shown that the high titanomagnetite concentration in the Waiuku Blacksand Member is not a primary feature, but is due to the leaching out of the less resistant minerals during weathering and diagenesis, relatively enriching the concentration of titanomagnetite.

The topography of the top surface of the Waiuku Blacksand Member and a coincidence of titanomagnetite concentration at certain depths in drill holes led Schofield & Waterhouse (1974) to postulate a number of marine terraces and a complex history of marine transgressions and regressions. The exposure at the mine site shows that this correlation of titanomagnetite concentrations corresponds to observable units in the excavated

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*The unit numbering is different in this paper to that in Christie (1975) so that unit 4 is designated as unit 13 of fig. 41A in the latter. Other units can be correlated by comparing Figs 7B and 7C of this paper with figs 41A and 41B of Christie (1975).

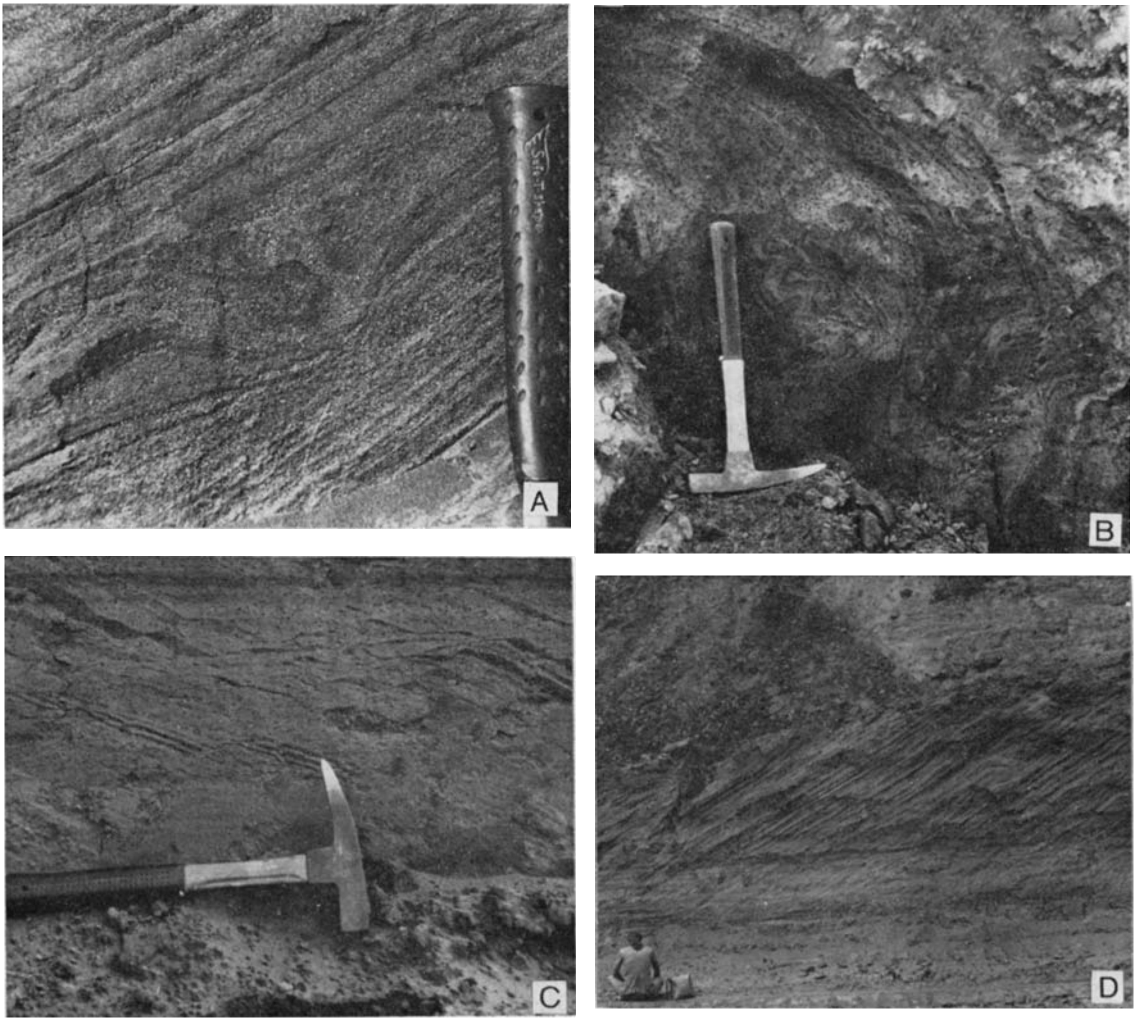

FIG. 11—Deformation structures in the cross-laminated sand of the Waiuku Blacksand Member. The impact structure (A) is considered penecontemporaneous, whereas the structures shown in B, C, and D are post-depositional deformation structures. A—"impact structure" in unit 1. B—Folded foresets in unit 8. C—Sheared foresets of unit 8 (classified as *intra-formational thrust structures* in Table 2). D—Kinked laminated structures (irregularly contorted beds of Table 2) in foresets of unit 1 (right hand side of the photograph).

site. For example, in fig. 3 of Schofield & Waterhouse (1974), the drill holes 66/10, 66/3, 65/93 and 66/15 have histogram peaks lying between 43 and 52 metres, corresponding to units 6 and 7 of this paper, whereas the lower portions of these histograms correspond to unit 1. Therefore, most of the transgressive and regressive episodes proposed by Schofield & Waterhouse are based on what is now interpreted as eolian sediment, apart from the two waterlaid deposits at 21–27 m and 46–48 m (units 9 and 7 respectively).

SEA LEVELS AND UPLIFT RATE

Barter (1976) described a series of thallassostatic terraces on the Awhitu Peninsula occurring between the heights 60–70 m, 35–45 m, 18–24 m and 8–10 m. He correlated these terraces with those of similar heights described from Te Akau by Chappell (1970) and from South Kaipara by Brothers (1954) assigning, to the Awhitu Peninsula, the same rate of uplift, 0·3 mm/year, that Chappell (1975) calculated for south-west Auckland.

If the composite sets in the Waiuku Blacksand Member lying at 46–48 m (unit 7) and 21–27 m (unit 9) above sea level are beach deposits, they may be correlated with Barter's 35–45 m terraces and 18–24 m terraces respectively. This implies an uplift rate of approximately 0·3 mm/year for the mine site area and ages of 120 000–125 000 and 105 000 years respectively for the composite sets. Alternatively, both composite sets could have been formed during the one high sea level stage (120 000–125 000 years), while the lower deposit was formed by a stillsand during the marine regression. Both alternatives are consistent with the Oturian age assigned to the Hood Formation by Barter (1976).

TIME SPAN OF DEPOSITION

Estimates of the time period required for the deposition of the Waiuku Blacksand Member succession at the mine site depend on the environmental interpretation of the composite sets (lithozone 3). If they are beach deposits, they may have been deposited by two separate marine transgressions, one at 120 000–125 000 years and the other at 105 000 years ago. Using Chappell's absolute sea level curve (Chappell 1975), the time between the first dune building phase, during a glacial stage, and the last dune building phase, in another glacial stage, is approximately 60 000 years. A single marine transgression, at 120 000–125 000 years ago, depositing both sets would require only 40 000 years for the complete Waiuku Blacksand Member sequence.

Alternatively, the composite sets could be interpreted as interdune stream–lake deposits, in which case a considerably shorter time period could be postulated. In fact a series of large dunes migrating over their adjoining interdune swamps and lakes could probably deposit the sequence in a few hundred years, although a longer time period would be necessary for soil development if any of the mud units were formed by this process.

CONCLUSIONS

The sedimentary structures, paleocurrent direction, paleocurrent pattern, and texture of the sand of the Waiuku Blacksand Member are very similar to those of the Entrican Dune Member and suggest an eolian origin for most of the deposit at the mine site. The eolian sand is considered to represent three or four dune stages.

Water-laid sand of interdune stream–lake or beach origin makes up a small proportion of the Waiuku Blacksand Member and separates two of the dune stages. If this sand is of beach origin it may record 120 000–125 000 year and 105 000 year sea-level maxima and imply an uplift rate of 0·3 mm/year for the mine site area.

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