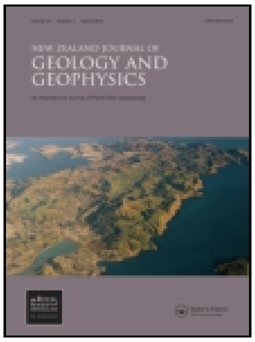

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SEDIMENTATION OF THE ALTERNATING GREYWACKE AND ARGILLITE STRATA IN THE PORIRUA DISTRICT

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Summary

The Lower Mesozoic alternating greywackes and argillites in the Porirua district exhibit graded bedding, lamination, convolute lamination, cross lamination, mud flakes, and current markings.

The sediments, rapidly derived from a plutonic terrain, were rapidly transported and deposited by turbidity currents in the New Zealand Geosyncline. The orientation of cross lamination and current markings suggests that the turbidity currents flowed north-north-east, sub-parallel to the present regional tectonic trend.

At Porirua, sedimentation was in deep water, a considerable distance from the supplying land mass, and not far from the axis of the geosyncline.

INTRODUCTION

The Lower Mesozoic rocks of the Wellington Peninsula are predominantly unfossiliferous well indurated greywackes and argillites, with local occurrences of intraformational conglomerates, autoclastic breccias, and submarine spilitic lavas associated with red and green tuffaceous argillites, radiolarian jaspers, and grey cherts (Reed, 1957). In the Porirua district (Fig. 1), the rocks are mainly well indurated

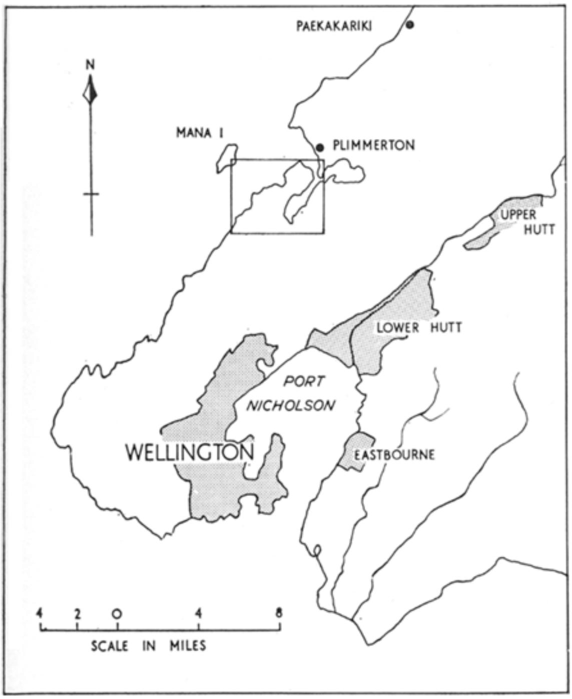

FIG. 1.—Map showing location of the Porirua district.

alternating greywackes and argillites, evenly bedded, intensely fractured, and with few fossils (Fig. 2). The rocks, apart from those exposed along the actively retrograding west coast, are affected by weathering.

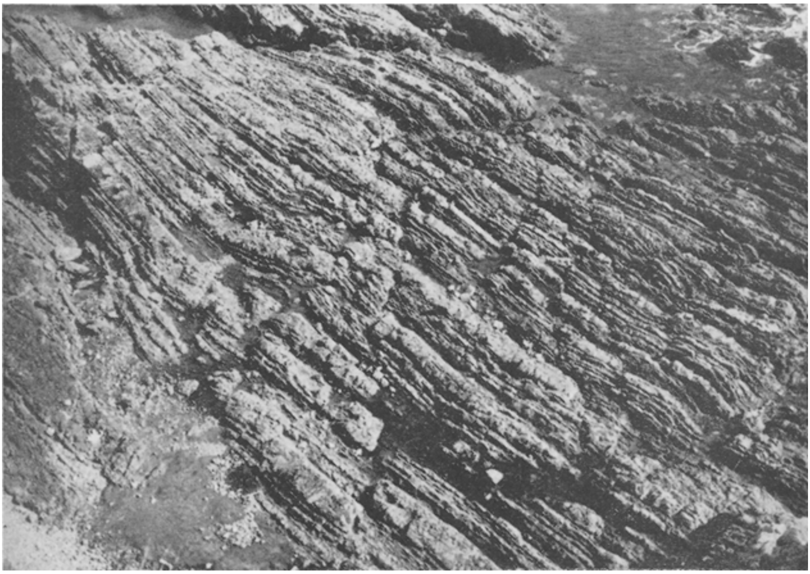

FIG. 2.—An outcrop of thinly bedded alternating strata near Titahi Bay. Note the regular bedding and the small-scale faulting. The strata shown are 100 ft thick.

The unweathered rocks on the coastal strip north-east and south-west of Titahi Bay were examined in detail (Fig. 3).

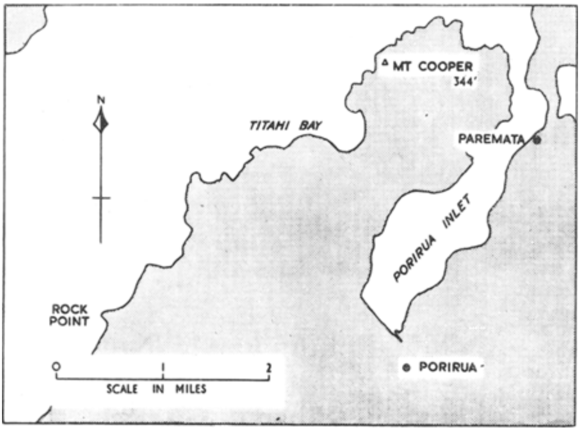

FIG. 3.—Locality map of the Porirua district.

PREVIOUS GEOLOGICAL WORK

Crawford (1869) recognized impressions of "plants and carbonized substances" in almost vertical strata on the shores of Porirua Harbour. According to McKay (1888), these "plant bearing beds extend through the hills to the shores of Port Nicholson between Ngauranga and Petone".

THE SEDIMENTS

Definition of Terms

The basic terms used in this description are defined as follows:

Stratification is the kind of rock-layering formed during deposition by changes of some kind in the materials being deposited or in the conditions of deposition, and a *stratum* is a layer so formed (Dunbar and Rogers, 1957, p. 97).

Bed and *bedding* are applied to any stratum or stratification of thickness greater than 1 cm (McKee and Weir, 1953, p. 384).

A *graded bed* is distinguished by a gradation in grain size, from coarse to fine, upward from the base to the top of a bed.

Lamina and *lamination* are applied to any stratum or stratification 1 cm or less in thickness (McKee and Weir, *loc. cit.*).

Convolute lamination is the corrugation of depositional lamination within individual beds of a regular stratified sequence (ten Haaf, 1956, p. 188). It has also been termed convolute bedding, contortions, crinkled bedding, intraformational corrugations, penecontemporaneous or subaqueous deformation, syn-sedimentary folds, and slumping.

Cross lamination is the small-scale current ripple lamination within individual beds of a regular stratified sequence. It has also been termed micro-current bedding.

Mud flakes are fine grained mudstone (or argillite) fragments embedded in a coarse grained (greywacke) matrix within individual beds of a regular stratified sequence.

Current markings is a general term that includes both drag marks and flute casts.

Drag marks are "long, even ridges" on the base of individual beds of a regular stratified sequence (Kuenen, 1957a, p. 243).

Flute casts are "sharp subconical welts" on the base of individual beds of a regular stratified sequence (Crowell, 1955, p. 1359).

Bed facing is the direction of younging as inferred from top and bottom criteria (Moore, 1957, p. 122).

Bedding

MEGASCOPIC CHARACTERS

An individual bed consists of a coarser, lower unit of greywacke, which either grades into, or is in direct contact with, a finer, upper unit of argillite. It is separated from an overlying bed by an abrupt contact (Fig. 4).

The thickness of individual beds varies from 1 in. to more than 30 ft. A total of 290 beds were measured (N 160/392449, 109 beds; N 160/386437, 106 beds; N 160/388446, 75 beds), grouped into bed thickness classes and plotted in a histogram (Fig. 5A). The histogram is symmetrical about a maximum in the 0·5 to 1·0 ft range. Cumulative bed thickness frequencies plot on logarithmic probability paper as a straight line (Fig. 5B), and thus have a logarithmic normal distribution (Pettijohn, 1957, p. 160). The symmetry of the histogram is also an expression of this logarithmic normal distribution. The significance of the log normal bed thickness variation is uncertain. Pettijohn (*loc. cit.*, p. 161) noted that some graded bedded and current bedded sequences show log normal bed thickness variations.

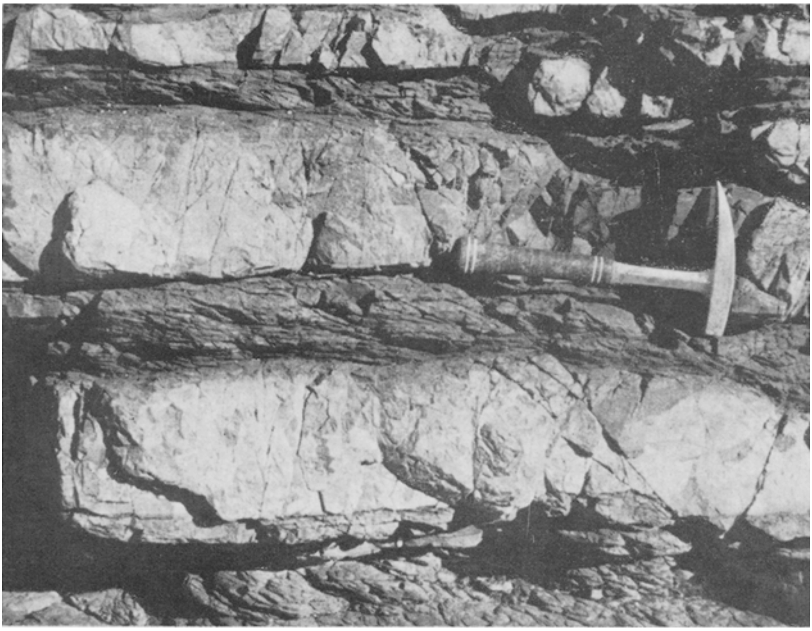

FIG. 4.—Detail of two graded beds in abrupt contact along the line of the hammer handle. Note the intense fracturing particularly in the upper argillite units.

The chief variations in grading of beds, observed in the field, are summarized in Fig. 6. Many transitions between the varieties figured have, however, been found. The various types of beds in the figure are placed in order of decreasing field occurrence.

MICROSCOPIC CHARACTERS

Two different methods were used to study microscopically representative graded beds. In one, thin sections were cut to include the whole of two consecutive thin graded beds (A and B), and the maximum grain size, under a high power objective, was measured at 1 mm intervals. Bed A is separated from bed B by an abrupt contact. Both beds show a definite, though fluctuating, upward decrease in maximum grain size (Fig. 7). The fluctuations of maximum grain size are larger in the upper limits of each bed. The larger fluctuations in bed A (the upper 4 cm of bed A) coincide with lamination and convolute lamination, and in bed B (the upper 2 cm of bed B) with lamination.

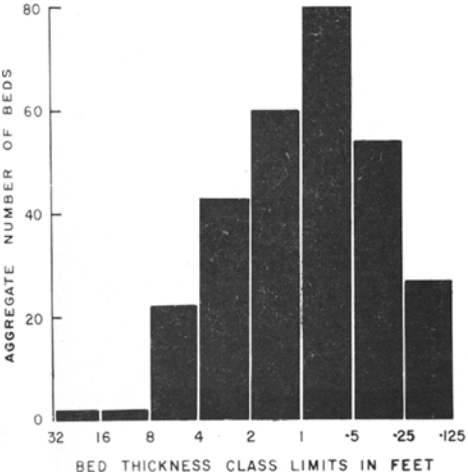

FIG. 5A.—Histogram of bed thickness frequencies.

The above results and further microscopic study of random samples indicate that a typical bed has a maximum grain size approximately 0·5 mm at the base and less than 0·01 mm at the top. Usually the maximum grain size near the base is coarser in the thicker bed, than in the thinner bed.

In the other method three thick graded beds, C (92·4 cm), D (45·7 cm), and E (134·3 cm) were each sampled at five equally spaced intervals. Thin sections of the samples were analysed microscopically with a graticule eyepiece for the volume percentage coarser, and finer, than 16μ grain size. The value of 16μ was taken as an arbitrary division between coarse and fine. The progressive decrease in the volume percentage coarser than 16μ shows grading from the bottom to the top of the individual beds, apart from a small anomaly near the base of bed E (Fig. 8). A striking feature of the results is the very high volume percentage finer than 16μ, even near the base of each bed.

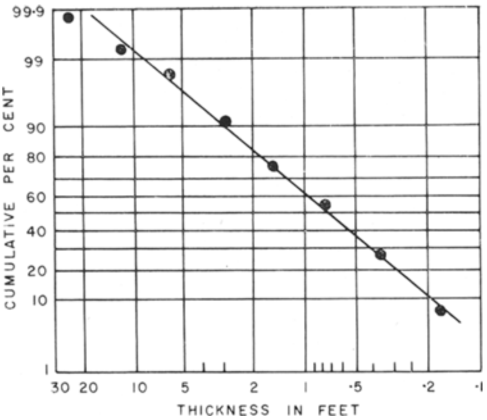

FIG. 5B.—Bedding thicknesses plotted on logarithmic probability paper.

Lamination

Lamination (Fig. 6 B and C), a common sedimentary feature in the Porirua argillites, is parallel to bedding except where affected by convolutions or current rippling. The thickness of each lamina varies from 0·5 mm to 10 mm. Some laminae exhibit micro-grading (Fig. 11).

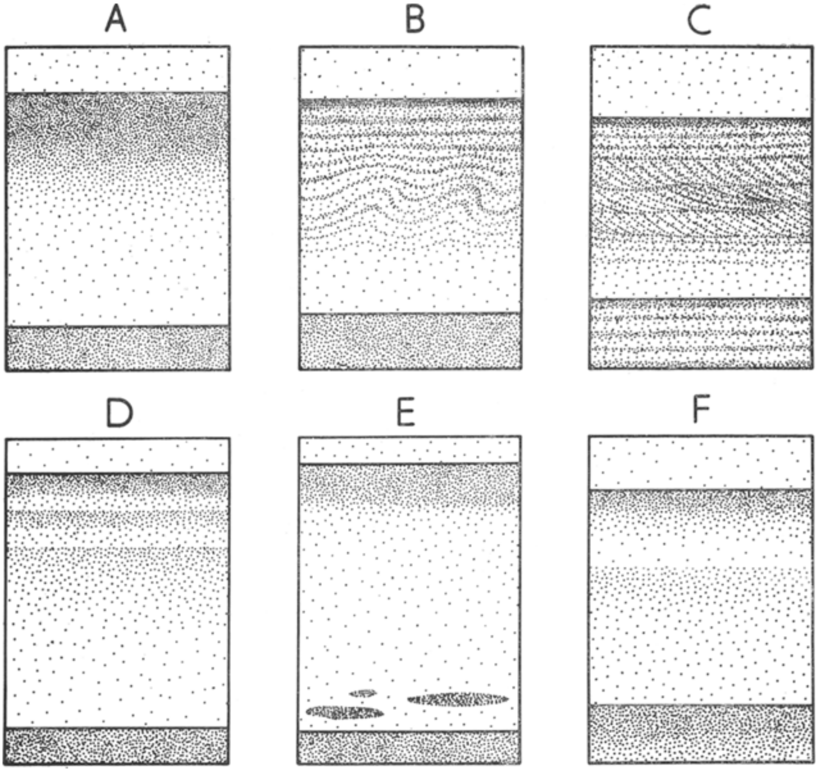

FIG. 6.—Types of graded bedding. A: graded bed without sedimentary structures. B: graded bed with convolute lamination and lamination. C: graded bed with cross lamination and lamination. D: composite graded bed with a thick primary, and thinner secondary and tertiary beds. E: bed with mud flakes near the base, and an abrupt contact between greywacke and argillite units. F: composite graded bed with a relatively fine grained primary bed which is truncated by a coarse, well graded, secondary bed. (Not to scale.)

Convolute Lamination

Convolute lamination (Figs 6 B and 9), common in the Porirua district, is usually situated near the middle of a graded bed and commonly along the transition between the greywacke and the argillite units. Occasionally it affects the whole bed. The thickness of the convoluted zone varies from 1 in. to 18 in. The maximum grain size in the convoluted zone, determined from four thin sections, is reasonably uniform, varying from 48μ to 58μ.

The shapes of convolutions range from gently undulating symmetric forms that are distinguishable from ripple marks only by the uneven distances between corrugations, to complex asymmetric contorted forms. Convolute laminae are seldom truncated by erosion in crests or troughs. In a bed the intensity of convolution gradually increases upward from greywacke to a maximum, and then decreases in the argillite. In the plane of bedding the convolutions have the appearance of small alternate oval domes and basins, as described by Kuenen (1953, p. 1056), ten Haaf (1956, p. 191), and Kingma (1958, p. 14).

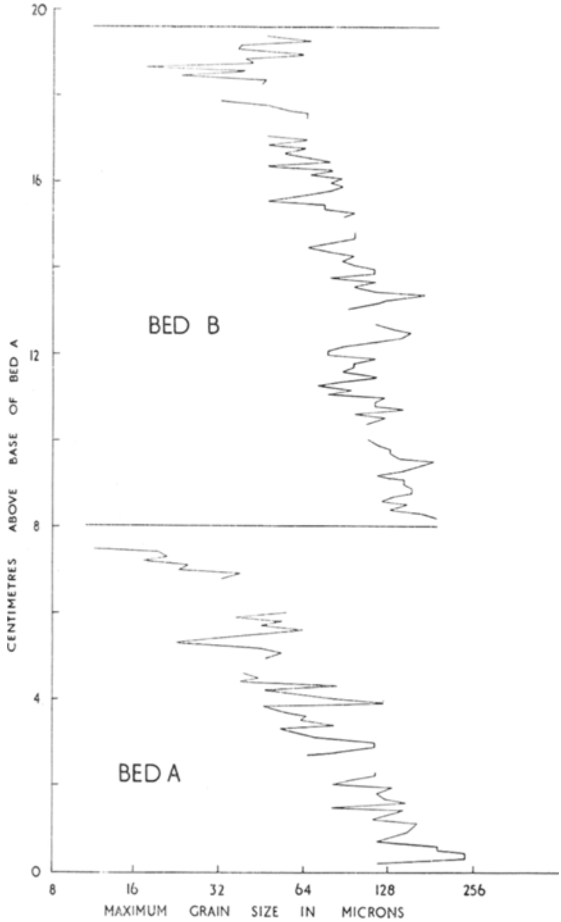

FIG. 7.—Variation in maximum grain size across two consecutive thin graded beds (A and B). Small gaps between successive thin sections shown by breaks in the line joining maximum grain size plots.

Current Ripple Marks and Cross Lamination

Current ripple marks are sparse and usually ill-defined in the Porirua district. In a single bed, they are slightly asymmetric with rounded crests and troughs, and have a constant wavelength (distance between crests) and amplitude. The wave length ranges from 7·5 cm to 25 cm, and the amplitude from 1·0 cm to 2·0 cm.

Kuenen (1950, p. 290) considered that a current flow of between 25 cm and 100 cm per second is required to develop ripples in sand and fine gravel. The sediments at Porirua are finer, and presumably required a current flow somewhat less than 25 cm per second.

Current ripple marks commonly occur in the same part of the bed as cross lamination. Prentice (1956) emphasized their genetic relationship by showing in a diagram, how cross lamination could develop by scour and fill from current rippling.

Cross lamination (Figs 6 C, 10, and 11) usually occurs within thin fine grained beds. Less frequently it occurs in the medial or upper parts (i.e. fine greywacke or argillite) of thicker beds. The thickness of cross lamination varies from 1·5 cm to 15 cm. Laterally the cross laminated part of an individual bed retains a uniform thickness as far as it can be traced. The maximum grain size of cross laminated sediments, as seen in thin sections, varies from 100μ to 60μ. The coarsest grains are from the thickest laminae.

Both cross and convolute lamination were seen in three beds. In one, cross lamination overlies convolute lamination, in the others the order is reversed.

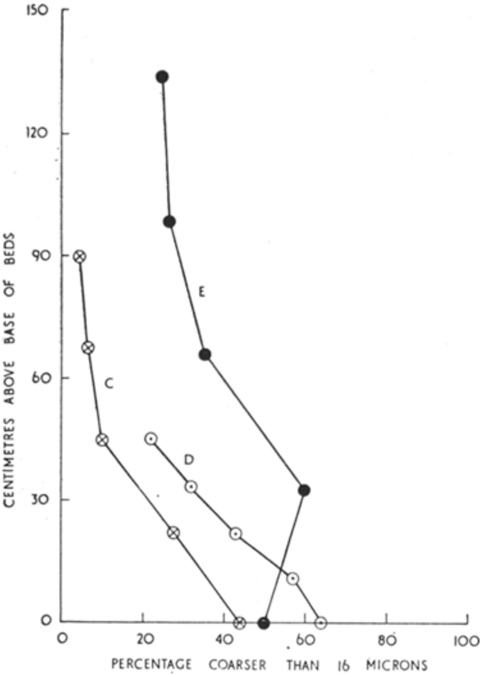

FIG. 8.—Relation of volume percentage coarser than 16μ grain size to the thickness of three individual beds (C, D, and E).

Mud Flakes

Mud flakes are angular to sub-rounded, elongated (or rarely curved), lenticular flakes or pellets from 0·1 cm to 20 cm long. They are usually only present in thick beds and are aligned subparallel or parallel to bedding. The flakes are largest and most abundant near the base of a bed (Fig. 6 E), but occasionally a bed exhibits successively smaller flakes grading upward. In two exposures small mud flakes were seen near the middle of a bed within coarse argillite.

Mud flakes were previously described in the Wellington Peninsula as intraformational conglomerates by Brodie (1953, p. 209) and Reed 1957, p. 30).

Current Markings

Two distinct types of current markings were observed on the base of a few graded beds, namely drag marks and flute casts.

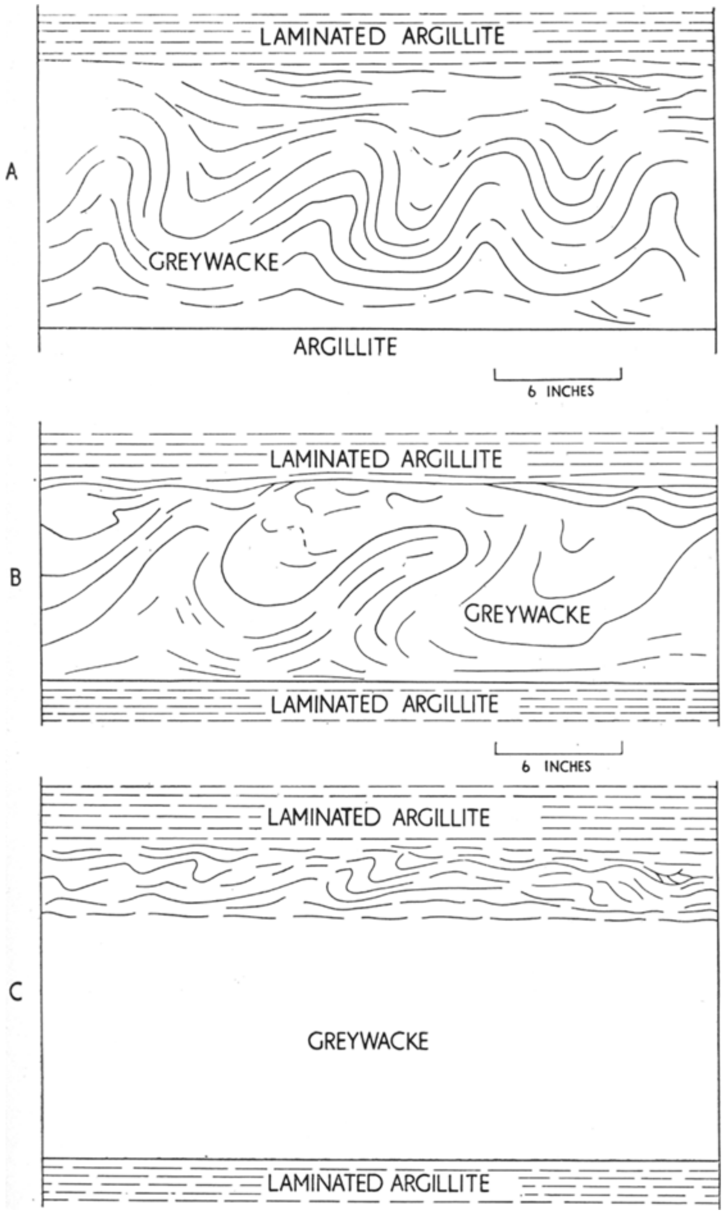

Fig. 9.—Convolute lamination in three beds (drawn from field sketches). A: large regular convolutions in the greywacke unit of a bed. B: large asymmetric convolutions with heeling crests, in the greywacke unit of a bed. C: small asymmetric convolutions in fine greywacke between greywacke and argillite units of a graded bed.

Drag Marks

Drag marks (Fig. 12), exposed along the coast south of Titahi Bay (N 160/383438), are straight, parallel to sub-parallel shallow ridges from 2 mm to 3 cm wide and up to 5 mm high, which represent infillings of grooves cut in the top of the underlying bed. They vary widely in cross-section, but individual drag marks retain the same section along their length.

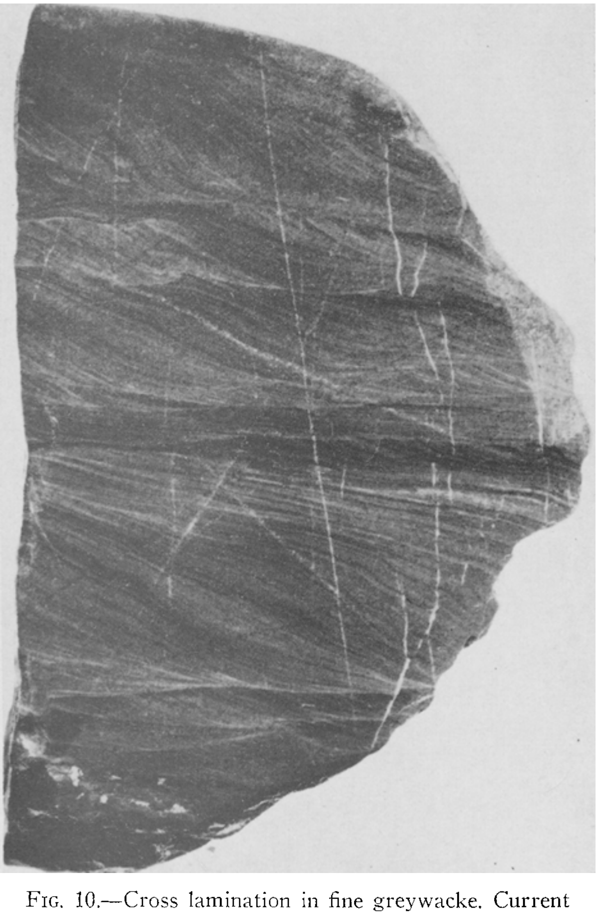

FIG. 10.—Cross lamination in fine greywacke. Current flow from left to right (×1).
—*M. D. King, photo*

Flute Casts

Small, aligned, tapering protuberances from 2 cm to 8 cm long and up to 3 cm wide were seen on the base of a few graded beds, and probably represent flute casts.

Bed Facing Criteria

The field criteria for determining bed facing in the Porirua district are, in order of decreasing importance: (1) graded bedding, (2) individual beds consisting of greywacke at the bottom, convolute zone in the middle and argillite at the top, (3) cross lamination, (4) mud flakes near the base of individual beds, and (5) current markings on the base of individual beds.

Directional-Current Structures

The original orientation of cross lamination and current markings was determined by the method of Kuenen and Sanders (1956, p. 656), modified to allow for the tectonic plunge at Porirua (Webby, 1959). The method was as follows:

A rectangular notebook was placed on the bedding plane with the long edge parallel to the plunging fold axis. A pencil was fastened to the notebook, parallel to the current structure to be measured. The notebook was rotated about the long edge parallel to the fold axis until its short edges were horizontal. Then the notebook was rotated to horizontal about a short edge, and a compass bearing was taken on the pencil alignment.

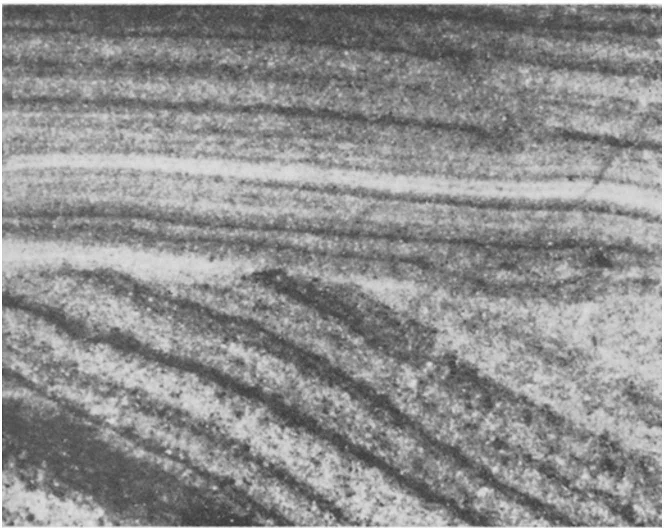

FIG. 11.—Detail of cross lamination, showing micro-grading of individual laminae and an abrupt contact between cross laminated and laminated units (× 5).
—*M. D. King, photo.*

Cross lamination is a good indicator of the general direction of current flow, accurate to about 45°. Eight observations of cross lamination indicate that currents flowed north to north-east (Table 1). The orientation of drag marks (3 observations) indicates a north-south current lineation, and the flute casts (3 observations), a north-north-east direction of current flow. More recently, the writer measured the orientation of current structures at ten additional localities in the Wellington Peninsula, and found that the north-north-east to north-east direction predominates.

Petrography

The rocks in the Porirua district are mainly greywackes and argillites. An arbitrary boundary of 0·06 mm grain size is selected to separate greywacke and argillite.

TABLE 1.—Current Orientations in Alternating Strata at Titahi Bay (N 160).

Sedimentary structure	Grid reference	Number of observations	Direction of current flow
Flute casts	388446	3	035°
Drag marks	382438	2	000°*
Drag marks	383438	1	007°*
Cross lamination	392449	4	010°–030°
Cross lamination	388446	2	020°–045°
Cross lamination	386436	2	000°–020°

*The sense of current direction could not be determined from drag marks, and from the flute cast and cross-lamination directions is inferred to be 000° and 007° rather than 180° and 187°.

TABLE 2.—Modal analyses of three greywacke samples.

Sample No.	1	2	3
Quartz	21·4	32·9	43·4
Total feldspar (potash feldspar in brackets)	13·0 (5·6)	21·2 (7·7)	26·8 (8·0)
Biotite, muscovite, and accessories	7·5	5·3	1·3
Fine matrix	50·7	33·3	22·9
Rock fragments	7·2	7·3	5·6
Total	99·8	100·0	100·0
Number of counts (from automatic point counter)	1407	919	1032

1. Sample from the base of a graded bed, south of Titahi Bay (N 160/383438).
2. Sample from the base of a graded bed, north of Titahi Bay (N 160/390448).
3. Coarse grained sample from a composite graded bed, north of Titahi Bay (N 160/392449).

GREYWACKE

Microscopic examination of representative greywackes reveals angular, poorly sorted clastic grains embedded in a slightly chloritized and sericitised clay matrix (Fig. 13). The clastic grains and matrix are not well differentiated, but to facilitate description an arbitrary value of 16μ is taken as the lower limit for clastic grains.

The clastic grains are quartz, feldspar, rock fragments, and biotite. Quartz grains form between 21% and 43% of the rock volume (Table 2). They commonly display undulose extinction and not infrequently contain inclusions.

Both potash and plagioclase feldspars are present in the rocks. Potash feldspars are orthoclase and less plentiful microline. Orthoclase is

FIG. 12.—Large and small sub-parallel aligned drag marks on the base of a bed. Note the worm tracks between the hammer head and the large drag mark in the upper part of the photograph.

usually cloudy or less commonly clear. Occasionaly orthoclase exhibits Carlsbad twinning. Plagioclase feldspar is twinned or untwinned, the former being more common. Numerous extinction angle measurements of twinned plagioclases indicate a general range from oligoclase to andesine (An 25 to 40). Perthite also occurs. Table 2 shows that feldspar varies from 13% to 25% in the three greywacke modal analyses. By a staining technique (Chayes, 1952) potash feldspar was calculated as representing 30% to 45% of the total feldspar. Intergrowths of quartz and feldspar are recognized, and include graphic and myrmekitic forms.

Flakes of biotite form less than 6% of the rocks. Sericite was also observed. Rock fragments, present in varying amounts up to 7%, are fine grained siltstones and mudstones, and possibly hornfels. The matrix forms 23% to 50% of the volume in the three samples analysed (Table 2).

Accessory minerals, observed in thin sections, are muscovite, sphene (including twinned varieties), epidote, pink garnet, and zircon. None of these minerals appears to be authigenic.

A heavy mineral separation was prepared from sample 1 (Table 2). The heavy minerals in the 125μ to 250μ size range represent $1 \cdot 5\%$ by weight of the total sample. The dominant heavy mineral is biotite.

Garnet (pink variety often with tiny globular inclusions some of which may be zircon), sphene, epidote, chlorite, zircon, and iron ore are less abundant. Apatite and rutile are rare. Microscopic observations indicate that the most abundant and varied heavy mineral assemblages are in greywacke that contains a high percentage of matrix.

FIG. 13.—Photomicrograph of greywacke from north of Titahi Bay (Table 2, sample 3), showing the angularity of clastic grains and poor sorting. Note the clastic grains of quartz, plagioclase feldspar, orthoclase, and microline set in a fine grained matrix. Polarised light, × 58.

—*R. H. Clark, photo.*

The Porirua greywackes ("Alpine Facies" of Wellman, 1952) were compared with a greywacke sample collected from Puoroan strata at South Head, Port Waikato (N 51/235941) ("Hokonui Facies" of Wellman, 1952). The Port Waikato greywacke has: (1) a much higher percentage of rock fragments that are mainly volcanic, (2) more feldspar, a greater proportion being plagioclase, (3) less quartz, and (4) some detrital calcite.

ARGILLITE

In texture the argillites are fine grained equivalents of greywackes, with a larger percentage of fine matrix. Reed (1957, p. 27) indicated that in chemical composition the argillites differ from greywackes in having a lower silica content, a higher alumina content, and in being potassic rather than sodic.

RADIOLARIAN JASPER

Radiolarian jasper fragments, from a Pleistocene solifluction deposit (N 160/413394), are pale red in colour. They consist of cryptocrystalline quartz and a small amount of finely disseminated hematite.

Paleontology

Tubes of *Terebellina* (*Torlessia*) *mackayi* (Bather) were found in place on the coastal strip north-east of Mt Cooper (N 160/402458), and from a large locally derived boulder immediately north of Titahi Bay (N 160/388448). *Terebellina* (*Torlessia*) *mackayi* may indicate a Triassic or Lower Jurassic age (Bather, 1906; Jaworski, 1915) for the rocks of the Porirua district.

Titahia corrugata, an annelid described by Webby (1958), was found throughout a 250 ft thick overturned sequence at Rock Point. The sequence is composed of thin beds underlain by a few thick beds. *T. corrugata* is confined to the argillite unit of a bed, and particularly near the abrupt contact with the greywacke unit of the overlying bed.

Worm tracks were observed in association with drag marks on the base of one graded bed (Fig. 12), south of Titahi Bay (N 160/382440).

Crawford (1869) and McKay (1888) reported plant remains in the rocks on the shores of Porirua Harbour. Although no plant remains were found, just south of Paremata (N 160/417435) an unusual argillite contains fine, dark, aligned mudstone fragments which are slightly carbonaceous.

The red jasper fragments contain imperfectly preserved Radiolaria (Spumellaria variety) with diameters of 90μ to 180μ.

INTERPRETATION

The alternating greywacke and argillite strata of the Porirua district belong to a "marine geosynclinal association" (Reed, 1957), and are a part of the "Alpine Facies" deposited along and to the east of the axis of the New Zealand Geosyncline (Wellman, 1956).

Two recent hypotheses have been suggested to explain the origin of alternating strata in geosynclines and "geosynclinettes" (Kingma, 1958, p. 24): the redeposition theory by turbidity currents (Kuenen and Migliorini, 1950), and the basin and bar theory (Kingma, *loc. cit.*). Although Kingma's theory explains the mode of deposition in a "geosynclinette", it does not satisfactorily account for the mode of deposition of thick and extensive alternating strata of the New Zealand Geosyncline. It depends on a fine adjustment between depth and bar conditions, but such an adjustment is unlikely to be maintained in time and place in a geosyncline. In contrast, turbidity currents can be expected over a wide range of conditions in both geosynclines and "geosynclinettes". As the theory of redeposition by turbidity currents is in accord with all the known facts, it has been adopted by the writer as the preferred hypothesis for the origin of the alternating strata in the Porirua district.

Origin of the Sedimentary Features

Kuenen and Migliorini (1950, p. 91) invoked that "turbidity currents of high density . . . supplied the sediment and deposited it in graded beds". Well *graded beds* (Fig. 7, bed A) are deposited from turbidity currents charged with an even range of grain sizes. More commonly, beds are non-graded in their lower parts and well graded in their upper parts (Figs 4 and 6 A). These beds may be formed from turbidity currents charged with similar coarse grains and an even range of finer grains.

Two types of composite graded bed are recognized. One type consists of a thick primary bed overlain by thin, and on the average finer secondary and tertiary beds (Fig. 6 D). It probably originated by a turbidity current flowing along the sea floor, splitting into a large high density primary suspension and slower moving less dense secondary and tertiary suspensions. The other type of composite graded bed is produced when a turbidity current creates unstable conditions at its point of origin, and a second turbidity current is generated which follows and plunges beneath the tail of the first (Kuenen and Menard, 1952, p. 92). This results in a composite bed composed of a primary bed truncated by a well graded secondary bed (Fig. 6 F).

Kuenen (1953, p. 1050) interpreted *lamination, current ripple marks,* and *cross lamination* as the product of traction accompanied by sorting, of a load along the bottom in a turbidity current. Alternatively, lamination and cross lamination may be formed by wave-like pulsations in a turbidity current as suggested by Hills and Thomas (1954, p. 127).

Innumerable hypotheses attempt to explain the origin of *convolute lamination.* Ten Haaf (1956) reviewed the various theories of origin, and suggested that "most of the characteristic properties of convolute lamination can be accounted for by the general hypothesis that in a growing hydroplastic bed, slight differential forces—probably in most cases current rippling as suggested by Kuenen—can effect a corrugation of the laminae which grows into exaggerated forms after being buried, both by accelerated deposition in the troughs and expulsion of excess water through the crests" (p. 194).

Mud flakes include angular and curved forms which were clearly plastic when deposited. Only the cushioning effect of a turbid suspension satisfactorily explains the transportation and deposition of unconsolidated mud flakes. Brodie (1953, p. 209) stated that fragments were not transported far and can sometimes be seen in the process of disruption. Short transport may apply in many instances, but where large flakes grade up into smaller flakes within a graded bed longer transport is implied, enabling sorting of the suspended mud flakes in the turbidity current.

Drag marks (groove casts) are interpreted by Prentice (1956, pp. 43–45) as infillings of parallel striations which appear to have been cut into the surface of the mud below, by sharply pointed fragments dragged along by a turbidity current. Kuenen (1957a, p. 241) considered that *flute casts* were formed by scouring of the underlying mud by a sediment-laden turbidity current.

The comparative rareness of current markings is almost certainly due to the bedding plane faulting that is associated with strong folding of the Porirua rocks.

Provenance and Dispersal

Reed (1957) stated that the greywackes and argillites were derived "from a plutonic terrain of granite, gneiss, and metamorphic rocks, the erosion of which was marked by little chemical decomposition; rapid or short transport as indicated by the angularity of the clastic grains; and rapid deposition as implied by the poor sorting of the rocks". This statement is consistent with the evidence assembled in the present study.

The fact that the north-north-east direction of current flow at Porirua is sub-parallel to the tectonic trend suggests that the turbidity currents transported sediment along the axial belt of the geosynclinal trough. Kuenen (1957b) cited numerous overseas examples of depositional current directions coinciding with tectonic trends.

Depositional Environment

The freshness of the feldspar indicates predominantly rapid mechanical disintegration of the Lower Mesozoic landmass. With such rapid mechanical erosion it is probable that a great quantity of coarse material would accumulate immediately offshore. In contrast, fine material (Porirua greywacke less than 0·5 mm maximum grain size) would be deposited a considerable distance from this landmass, and because a continuous bottom slope is required for the transportation of sediment (whether by turbid suspension or traction), deposition is necessarily in deep water. A deep-water origin is supported by graded bedding and the absence of features typical of shallow water deposition.

A notable absence of benthonic faunas, apart from annelids, suggests an unfavourable environment for bottom dwellers, perhaps due to the combined effect of deep water, poor circulation, and the turbidity current mode of deposition.

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