# The Geology of Waiheke Island, Auckland

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[*Communicated by Dr. R. N. Brothers and read before the Auckland Institute on September 12, 1955; received by the Editor, September 19, 1955.*]

### *Abstract*

THE rocks of Waiheke Island are mainly greywacke sandstones and argillites, interbedded with cherts, jaspilites, and fine-grained volcanic rocks with some pillow structures. These are named Waiheke Formation and belong to the Undifferentiated Jurassic-Triassic-Permian (9A) Group of Willett (1948). Over the greater part of the island the attitude of the bedding planes is fairly constant, with average strike 007° and dip usually west at about 50–60°. Sandstones and mudstones with intercalated pockets of sandstones and conglomerates containing macrofossils belong to the Waitemata Formation (Altonian, Lower Miocene) and occur at the western end of the island. Tertiary andesite breccias covered by boulders of Pleistocene basalt form a cap on the greywackes at Stony Batter in the north-east. Pleistocene deposits consist of sands, muds, and gravels forming valley flats and raised beaches which contain occasional shell layers

## INTRODUCTION

WAIHEKE Island, the largest of the islands immediately east of Auckland City, is hilly, and has few flat areas. The surface is finely dissected, and there is a general north-south disposition of the ridges and stream courses. From the highest point, Maunganui (759ft), situated near the southern coast between the heads of Awaawaroa and Te Matuka bays, a prominent line of hills, with average height of 600 feet, stretches to the north-east.

The coastline is mainly bounded by cliffs. The northern coast is exposed to the open sea and along it is developed a succession of long sandy beaches and steep, rugged cliffs. The southern coast is deeply embayed, with extensive mudflats and swamps filling the bay-heads and with occasional spits and bars across the mouths.

## PREVIOUS WORK

The first published account of the geology of Waiheke was by Hochstetter (1864) who, in describing "Paleozoic" formations in the Auckland District commented on the red jaspilite and associated manganese deposits near Te Matuka Bay. Subsequent accounts are mainly short reports devoted to mining (e.g., Cox, 1882).

In 1927, fossil beds were discovered near Oneroa, and Powell and Bartrum (1929) briefly described these basal Waitemata beds containing marine mollusca, giving the age of the beds as Hutchinsonian (Upper Oligocene, as then understood, *vide* Henderson, 1929). Later Powell (1938) described a new fossil locality near Church (Squadron) Bay. Finlay and Marwick (1948) included the Waitemata beds in the Altonian stage.

## STRATIGRAPHY

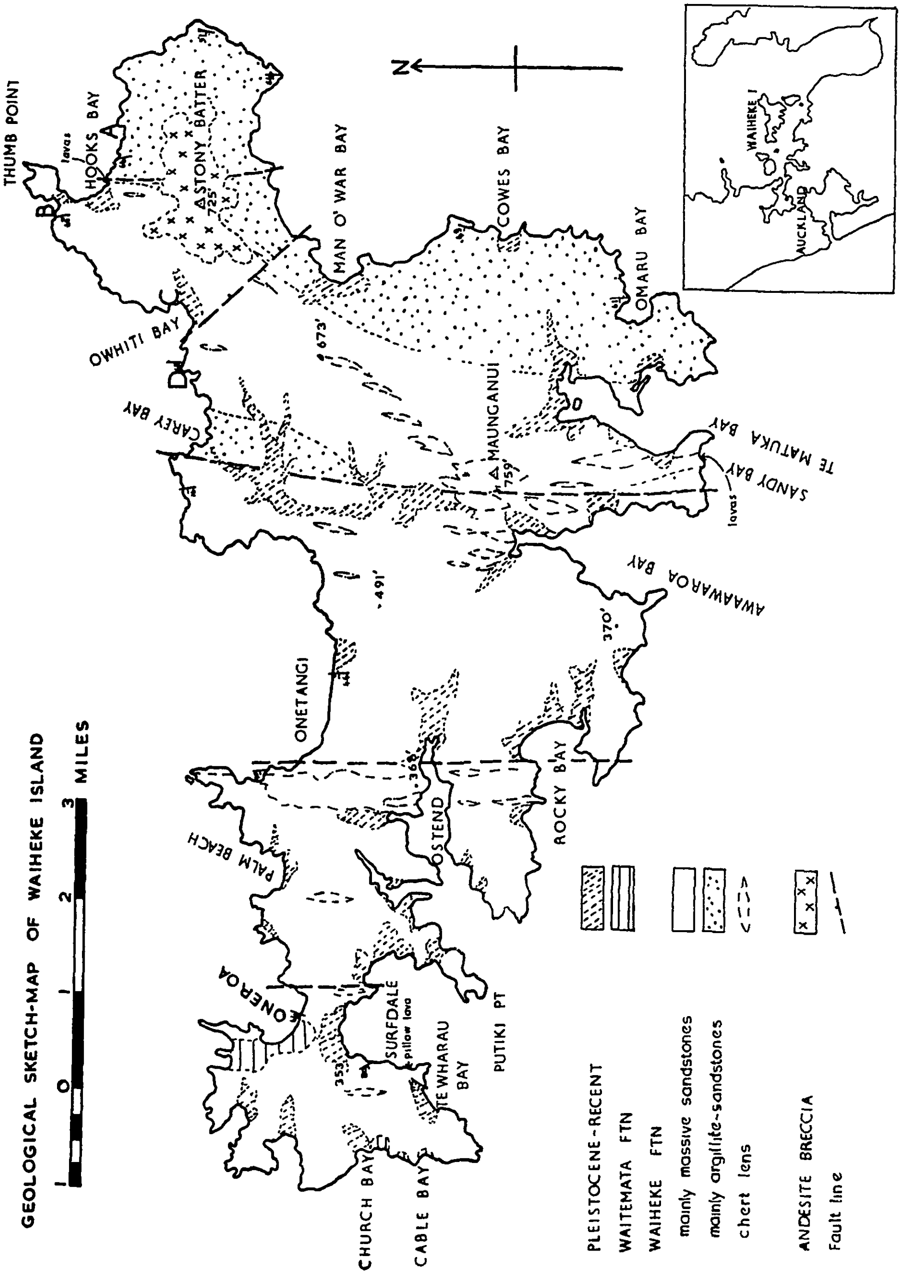
The greater part of the island is formed of indurated greywacke sandstone and argillite (*Waiheke Formation*) of probable Permian-Triassic age. Remnants of the covering strata occur as pockets of fossiliferous conglomerate and sandstone which are part of the basal beds of the *Waitemata Formation* (Altonian, Lower Miocene). *Andesitic breccia* outcrops on an isolated hill at the north-east end of the island *Pleistocene* deposits are restricted to valley and bayhead fillings which stand at a few feet above present sea level.

## Waiheke Formation

### *Lithology*

The lithology of the Waiheke Formation is typical of many other areas of "greywacke" in North Auckland—i.e., greywacke sandstones, argillites, cherts and jaspilites, and interbedded volcanic rocks.

*Greywacke Sandstones.* Dark grey, indurated sandstones are the most important sedimentary members at Waiheke, forming massive sequences 500 feet or more in




GEOLOGICAL SKETCH-MAP OF WAIHEKE ISLAND

thickness, or beds 10–40 feet thick separated by thinner argillite beds (Plate 13, Fig. 1). The sandstones are composed of quartz, feldspar, and rock fragments up to 2 mm in diameter set in a dark-coloured clayey matrix. Most of the sandstones are medium to fine-grained, but some show gradation to grits. Subaerial weathering has produced quantities of brownish-red limonite, which coats joint surfaces and extends in the rock to a depth of half an inch; inside this limonite zone the less weathered rock is orange, yellow, or light grey in colour. In places the harder limonitic portions project above the rest of the rock, giving a honeycombed appearance.

*Argillites.* The argillites vary in colour from light to dark grey and form thin layers 1in to 12in thick, between heavy sandstone beds. Occasionally, successions from 6 feet to 100 feet thick are composed dominantly of argillite beds with interbedded sandstone layers of varying thickness. (Plate 13, Fig. 2.) As a general rule, each argillite bed is a series of finer graded beds, the laminae ranging in size between 0 1 and 5 mm. Often there is a gradation in texture between sandstone and mudstone, the sandstone layer becoming finer upwards and passing into mudstone. In some places, the basal portion of a thicker sandstone overlying an argillite bed contains tabular fragments of the argillite up to 15 mm × 4 mm. Evidence of intraformational slumping is common, involving all thicknesses of beds from a single lamina to a layer 18 inches thick.

At four localities (Hooks Bay, Surfdale, Sandy Bay and Rocky Bay) red argillites are associated with interbedded volcanics and are continuous along the strike with cherts and jaspilites. They are dark brownish-red in colour and form beds ½in to 2in thick in sequences of 1 to 10 feet. They appear to be normal argillites stained with ferric iron. A green argillite at Owhiti Bay has a similar setting, but is so greatly contorted and lineated, with slickensiding along the bedding planes, that it has the appearance of a greenschist or mylonite.

Most of the argillites are variable in colour, and finely graded sequences usually show alternation of narrow dark and broader light-coloured bands. Compressed and shattered argillites are dark grey or black, with transgressive quartz veins. On weathering, they become light brown, yellow, or white in colour.

For the purposes of description, the thick sequences of thinly bedded argillites and alternating sandstones will be referred to as the *argillite-sandstones* and the thickly bedded and more massive greywacke sandstones as the *sandstones.*

*Cherts and Jaspilites.* The cherts and jaspilites are composed of dense cryptocrystalline silica traversed by fine quartz veins; the rocks are extremely hard and tough, breaking with a splintery fracture. These siliceous rocks contain irregular veins and nests of black manganese oxides.

The cherts and jaspilites are usually in beds 1in to 6in thick, which are often closely folded and crumpled. Colours vary from black through grey, green, red, and orange to white, with the weathered rock a light orange in colour.

*Igneous Rocks* A pillow lava is exposed in the shore platform near Surfdale. The lava is at least 35 feet thick, with pillows 1 to 5 feet in diameter. A dark-green, fine-grained flaky argillaceous rock fills spaces between the pillows. The lava is very fine-grained and contains no phenocrysts, vesicles or amygdules, but some of the pillow surfaces show variolites up to 2 mm diameter (Plate 13, Fig. 3).

The pillows are dark grey in colour with narrow greenish margins and sometimes, red-tinted centres. Calcite forms irregular veins cutting through the pillows and also occurs between the pillows as interstitial limestone; epidote fills joints in the lava and adjacent country rocks. Some pillows contain radial cracks, but all are closely jointed and sheared. Underlying the pillow lavas is a dark-red, dense, fine-grained lava which shows no pillow structures and is apparently interbedded with adjacent greywackes. It is strongly jointed and contains veins of epidote.

At Sandy Bay and Hooks Bay fine-grained lavas, interbedded with greywackes, are orange to dark-red in colour and require microscopic examination before they can be recognised as lavas. A finely bedded tuff occurring with the lavas at Hooks Bay is green in colour and has an argillaceous appearance.

## Stratigraphy of the Waiheke Formation

Thick successions of argillite-sandstone are confined to the eastern part of Waiheke Island. In a section normal to the strike along the northern coast from Kauri Point to Carey Bay, argillite-sandstone sequences appear three times, perhaps due to repetition by faulting. The portion between Kauri Point and Hooks Bay consists almost entirely of argillite-sandstones; these are overlain by massive sandstones for 1⅓ miles to Owhiti Bay, where argillite-sandstones reappear, and are again followed by sandstones to Carey Bay, where there are again sequences of argillite-sandstone At Hooks Bay, Owhiti Bay, and Carey Bay, argillite-sandstone closely underlying the massive sandstones have suffered intense folding and shearing. In the section along the southern coast there is only one major argillite-sandstone sequence. Tight folding is restricted to the top of this sequence, and contortion of beds is generally less intense than at the northern localities.

The massive sandstones constitute the major portion of the Waiheke Formation. Occasional bedding planes are present and only rarely are thin argillite-sandstone sequences intercalated within the massive sandstone sequences.

A conspicuous feature at Waiheke is the abundance of thick lenses of cherts and jaspilites which have strong topographical expression as sharp ridges. They occur at a number of different horizons within sandstones and argillite-sandstones. The horizontal contacts between cherts and sandstones are sharp, but there is often lateral gradation from chert to clastic sediment by a decrease in colloform silica in the cherts and an increase in detrital material. This is combined with a thinning out of the lenses, which often terminate along the strike as a series of chert nodules within the argillites or sandstones.

Most of the chert lenses do not exceed 500 feet in thickness, but the total thickness of the lenses underlying Puke Range and the hills east of Ostend is between 2,000 and 3,000 feet. It is likely that these are compound lenses, consisting of a number of thinner sequences separated by thin argillite and sandstone beds not sufficiently resistant to outcrop in the inland localities.

At two places the stratigraphic relations of interbedded lavas and cherts are visible. At Sandy Bay, the lavas overlie a sequence of chert 500 feet thick, but at Hooks Bay one type of rock gives place to the other along the strike

The apparent thickness of the whole formation is 49,000 feet. However, there is probably much repetition of strata by strike faults, so that the true thickness is likely to be much less.

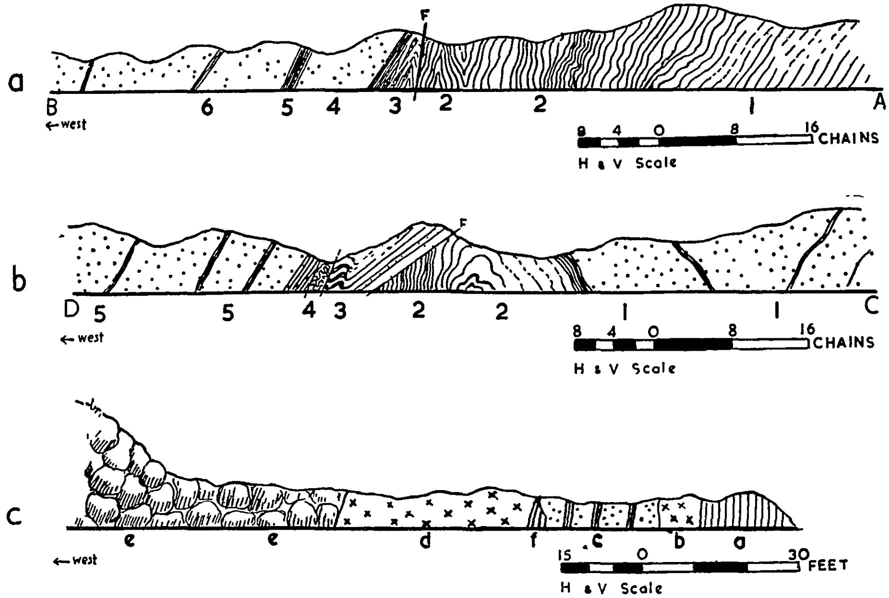
*Section at Hooks Bay.* (See Text-fig. 2a, and between A and B on the map.)

1. *Thinly bedded argillite-sandstones* (5 500ft). These beds dip to the west, steeply in places, but show no small-scale folds. The thickness of the sandstone members decreases westwards until beds ½ to 3 inches thick separate argillite beds up to 12 inches thick. Small folds. often broken along the axial planes by minor thrust faults become common.

2. *Highly deformed thinly-bedded argillite-sandstones* (1,000 ± feet). These beds have been compressed and strongly sheared. As a result the sandstone members are broken into boudins and the argillites greatly crushed. Quartz segregations follow the bedding planes and cross joints. The quartz is lineated by slickensiding perpendicular to the strike of the beds. The dip of the beds is variable, but is usually vertical.

Sharply separating (2) and (3) is a narrow 3in to 6in zone of dark, finely crushed rock marking a fault of unknown magnitude.

3. *Interbedded lavas, green tuffs and red argillites* (230ft). These rocks are interbedded in lenses of various thicknesses, and occasionally there seems to




TEXT-FIG. 2.—*a,* Section at Hooks Bay. *b,* Section at Owhiti Bay. *c,* Section of pillow lavas and associated rocks at Surfdale. The height of the cliffs is exaggerated for diagrammatic purposes. See text for explanation of figures.

be gradation between one type and another. The lavas are orange-yellow in colour, and in the field have the appearance of a weathered greywacke. The green tuffs have an argillaceous appearance and interfinger at the top of the sequence with thinly bedded red argillites. Within the latter there are streaks of green tuff, traces of manganese oxides and fine sandstone boudins. All the rocks have been sheared and shattered. Bartrum and Turner (1928) describe a similar sequence of rocks associated with pillow lavas in the Whangakea Series at Spirits Bay, North Cape, and explain the intermixture of igneous and sedimentary material in a part of their section as a result of moderately acute shearing. The fine-grained green material at that locality is intensely shattered crushed basalt, and part of the red rock is sedimentary in nature.

Overlying this sequence at Hooks Bay there is a 15-foot bed of undeformed argillite sandstone. The contact between these and the underlying rocks is obscured by sand and vegetation.

4. *Sandstone* (380ft), with occasional thin beds of argillite.

5. a. *red argillite* (8ft).

b. *green tuff* (6ft). Both of these are similar to the rocks described before.

6. *Massive sandstone* (1,300 + ft). Following upon the coloured rocks is 20 feet of argillite sandstones, followed by thick sandstones with occasional thin sequences of argillite-sandstone.

*Section at Owhiti Bay.* (Text-fig. 2b, between D and C on the map; Text-fig. 1).

1. *Massive sandstones* (800 + feet), which are apparently continuous with (6) of the Hooks Bay section. These beds dip east at the eastern end of the section, but it is not known if they are overturned.

2. *Argillite-sandstone* (approximately 500 feet). At the south-west end of Owhiti Bay, the beds are folded into an assymetrical anticline trending 170° and carrying conaxial folds which are broken by minor ac or bc faults. To the west the rocks are more thinly bedded and the degree of shearing and shattering

increases; strikes and dips are irregular, although the general dip is towards the west. Quartz segregations with slickensided surfaces are common.

Near the top of this succession a thrust with strike 170° and dip 28° W., and marked by a silicified crush zone, cuts across the argillites.

3. a. *argillite-sandstones* (3ft). This overlies the crush zone.

b. *coarse sandstone* (35ft). This bed dips to the west and the sandstone becomes finer in that direction, eventually grading into argillite-sandstones. Immediately to the east of (4) these fine beds are folded into a narrow asymmetrical anticline whose axis is parallel to the regional strike of 007°.

4. *Green mylonite* (70–90ft). This occurs within a steeply dipping fault zone The rocks are closely contorted by minute folds which strike parallel to the fault zone at 130°. Shearing and stretching has broken interbedded thin sandstones into boudins, but thicker beds form large angular horses. Slickensiding on the bedding planes has produced a lineation at a high angle to the strike. Included within this rock are rounded nodules of reddish chert up to 18 inches in diameter.

5. *Greywacke sandstones* (4,000ft). Thick sandstones with thin argillite bands. Adjacent to the fault zone the beds are crumpled, but the overlying rock is little deformed and dips consistently west. At Carey Bay another group of argillite-sandstones is closely folded in places, with minor shearing and segregation of quartz along the bedding planes.

*Section at Surfdale* (Text-fig. 2c).

1. *Greywacke sandstone* (260ft).
2. *Siliceous greywacke* (4–6ft), contained within 30 feet of argillite-sandstones.
3. *Greywacke sandstone* (approximately 750ft).
4. *Pillow lavas and associated rocks* (110 + ft).

a. *red argillite* (10+ft). Mainly composed of thin beds, ½in to 3in thick, of alternating very fine and slightly coarser material.

b. *red lavas* (7ft).

c. *greywacke* (20ft), with bedding and imperfect boudinage structures.

d. *red lavas* (35–65ft). The lava encloses streaks of sediment and normally shows a sharp but uneven contact against the underlying greywacke, but this contact is absent or obscure in places, particularly where the lava and sediments interdigitate.

e. *pillow lavas* (35+ft). A lens-shaped mass of pillows has formed partly within and partly on top of the red lavas. The lens pinches out to the north, and the southern and upwards extension of the lavas is obscured.

f. *green albitised chert* (3ft by 15ft along strike), occurring as a small lens between the red lavas and bedded greywacke.

5. *Massive sandstones* (2,000+ft), with minor interbedded argillite-sandstones and siltstone. Red cherts outcrop as hillside boulders 700 yards to the north of the pillow lavas and lie about 500 feet above the lava horizon.

In the Surfdale section all the beds dip to the west at an average of 60°, and there is no evidence for overturning.

## Structure of the Waiheke Formation

Because of the lack of distinctive marker beds and the common obliteration of internal structures by shattering, jointing and weathering, it is difficult to determine structures within the Waiheke Formation. Local zones of intense shear complicate the regional pattern.

Although the strike of the bedding planes varies locally, a regional strike of 007° is obvious. The beds usually dip steeply west at about 50°–60°, and easterly dips are generally confined to local areas of disturbance.

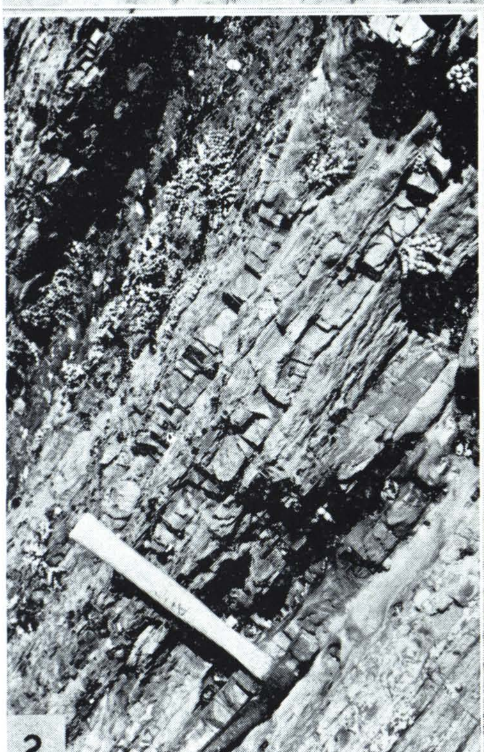


FIG. 1.—Sandstone beds separated by thin argillite beds folded into a small asymmetrical anticline overturned to the east, and with incipient faulting along the synclinal axis. Owhiti Bay. FIG. 2.—Thinly bedded alternating argillites and sandstones. Man O' War Bay. FIG. 3.—Pillow lavas at Surfdale. Photo: Dr. R. N. Brothers.

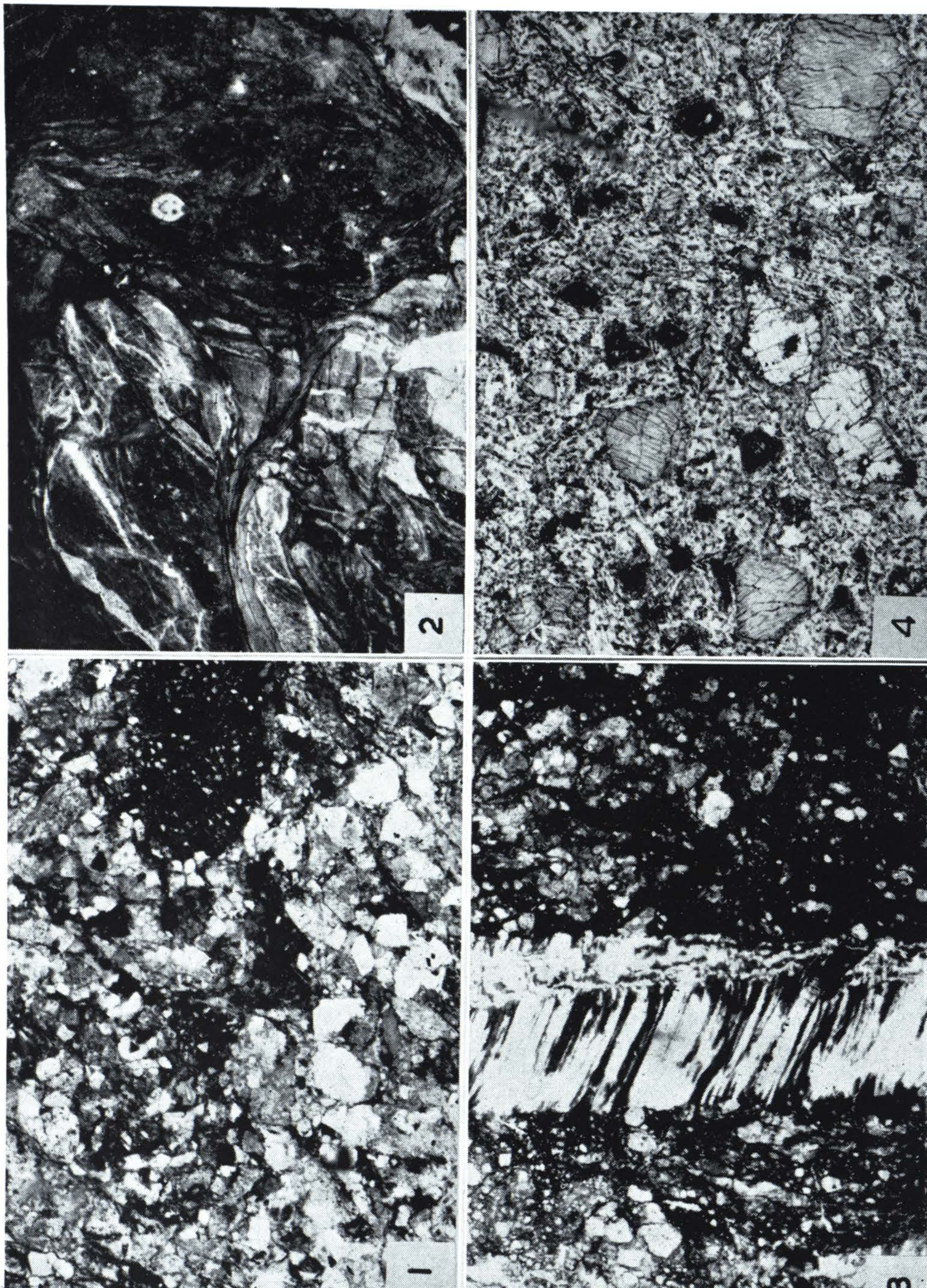
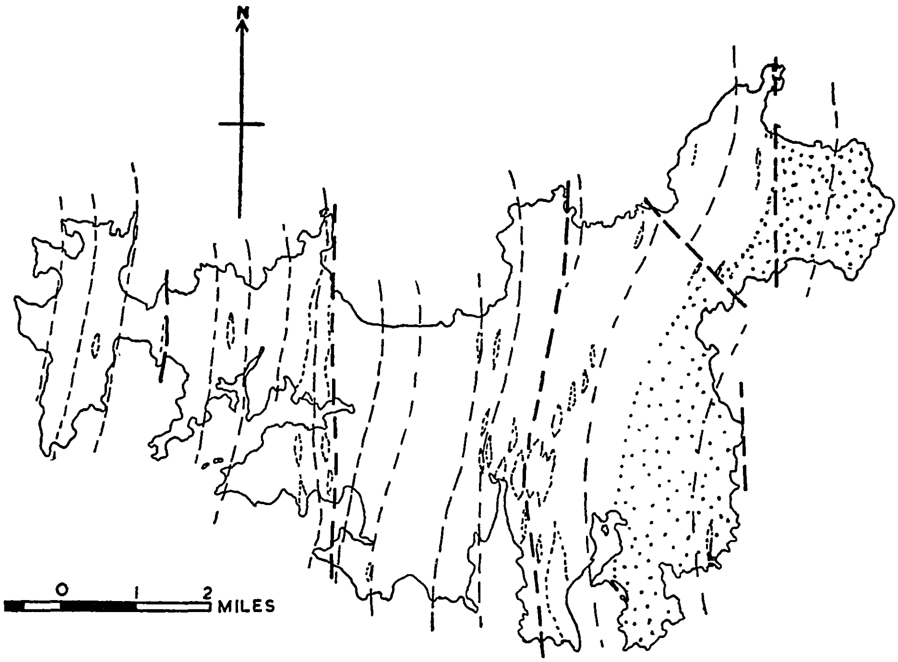


FIG. 1.—Greywacke sandstone composed of angular quartz (white), saussuritised feldspar (grey) and argillite fragments set in a fine clay matrix. × 12. FIG. 2.—Green mylonite from Owhiti Bay containing quartz veins cut by movement along bedding planes, chlorite veins and a radiolarian. × 15. FIG. 3.—Quartz vein in greywacke sandstone. The dark patches in the vein are chlorite. × 15. FIG. 4.—Pleistocene basalt from a boulder at Stony Batter. Large augite phenocrysts with smaller, resorbed olivine crystals are set in a fine groundmass of feldspar laths, augite, and iron ore. × 15.




TEXT-FIG. 3.—Sketch map showing swings in the regional strike of the Waiheke Formation.

As the main structure is homoclinal, the area probably represents a portion of a major fold. This regional structure is varied by minor folds whose axes are more or less parallel with the regional strike, and by strike faults of unknown magnitude. A swing in the regional strike from north-north-west to north-north-east and back to north-north-west may be traced from south to north across the island. This swing in strike results from local irregularities in the fold axis, but the regional trend is nevertheless constant in a north-south direction (Text-fig. 3).

An asymmetrical anticline overturned towards the east appears in cliff sections between Oneroa and Palm Beach. This is the only complete large fold recognised within the whole structure. Minor folds are common, both symmetrical or isoclinal, but the commonest structures are asymmetric folds slightly overturned to the east.

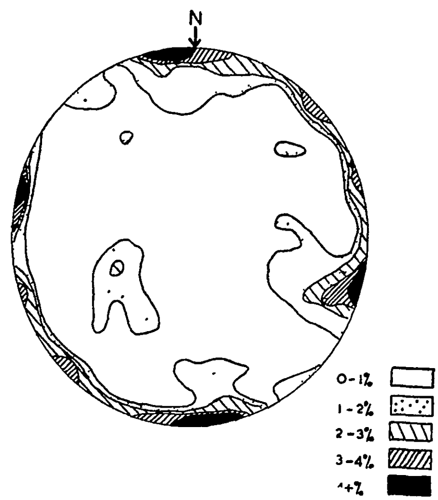
A common feature of Paleozoic and Mesozoic greywacke sequences is the numerous strike faults whose traces are seldom expressed topographically. Recognition is generally based on narrow zones of shear, tight folds and disturbance of the rocks. The only definite evidence at Waiheke for such faults is found in the Hooks Bay and Owhiti Bay sections where zones of intricate folding are accompanied by narrow belts of mylonitisation However, other local zones of intense deformation can often be matched between the north and south coasts. They probably represent localisation of shearing stress, with the development of true faulting in some places and complex deformation of the strata in others. Because of the lack of marker beds and the massive nature of most of the rock, it is likely that many faults of this type are not obvious.

A major fault oriented obliquely to the regional fold axis is indicated by contiguous zones of mylonitisation at Owhiti Bay and a point 40 chains north-east of Man-o'-War Bay. The crush belt at Owhiti Bay strikes 138° and seems to be the north-western extension of a dislocation zone that is marked on the east coast by discordant strike patterns, minor faults, and shear planes. The existence of such a fault, with a downthrow to the north of 1,250 feet, would account for the dislocation of a chert lens and for the contact of argillite-sandstones against massive sandstones. (A warm spring in the creek bed at Owhiti lies on the trace of this suggested fault line.)

Minor faults with small throw and no accordance of strike are very common throughout the whole formation; narrow crush zones line many of the planes.

*Joints.* All rock types in the Waiheke Formation carry planes which have been recorded as joints. Within the sandstones the joints are most prominent as regularly spaced cleavages continuous over some distance. Generally, two nearly perpendicular sets of joints occur, with smooth, flat surfaces which in rare cases are cemented together by quartz.

Within the argillites, the joints are, as a rule, not well-developed. The large joints are widely spaced and irregular and the sets are ill-defined. The smaller joints are closely-spaced hair-like partings which extend for no more than a few feet, but usually in quite well-defined sets. These may be tension cracks. The cherts are closely and evenly jointed in two or three directions, the joints forming facets on brick-shaped cleavage fragments.




TEXT-FIG. 4—Equal-area projection of the poles of 437 joint planes contoured according to percentage density per 1 per cent. area.

The poles of the measured joint planes have been plotted on equal-area projections and contoured according to percentage density per 1 per cent. area. The contour diagram (Text-fig. 4) represents the total of 437 joints recorded from 174 localities on the island, and indicates the presence of two major joint sets. One set strikes almost parallel to the regional strike, and the other approximately at right angles to it. Both sets may be regarded as of tensional origin, produced by stretching across folds and along them due to plunging (Nevin, 1949, p. 152). It is also thought that those parallel to the strike may represent release after compression of the rocks (Billings, 1942, p. 125). There is no evidence to show that the two major sets of joints in the system differ either in magnitude or in age.

Two minor joint sets, which strike between 155° and 230°, may be shear joints.

*Boudinage.* This is a common feature within the argillite-sandstone sequences, especially when the thickness of sandstones is equal to or less than that of the interbedded argillites. During stretching of the beds the competent sandstone layers have broken across and the finely-sheared incompetent mudstones have flowed around the sausage-like sandstone fragments The sandstone boudins in the Waiheke Formation are usually cut by quartz-filled cross joints. Although the enclosing argillites show intense shearing the sandstone is less deformed with only minor granulation of the mineral components, and with smaller quantities of such crystalloblastic minerals as chlorite and epidote.

Along zones of deformation, bedding planes and cleavage planes show slickensiding, and the movement planes are usually covered by a thin film of finely lineated quartz and chlorite. The direction of slickensiding is nearly always normal to the strike of the strata and seldom oblique to it—i.e., the lineation is perpendicular to *b*.

## PETROGRAPHY

*Greywacke sandstones* (Plate 14, Fig. 1). The greywacke sandstones are composed of mineral and rock fragments, with an average size 0·25 mm set in a very fine-grained clay matrix. Saussuritised plagioclase feldspar constitutes the greatest proportion of mineral fragments. Quartz makes up 15 to 30 per cent. of the clastic grains as very angular, sliver-like fragments. Undulatory extinction is common, and fracturing and granulation has modified the outlines of most grains. Closely interlocking mosaics of strained quartz grains form occasional composite fragments. Chlorite in crystalline, fibrous, and vermicular form commonly occurs in large patches, probably replacing original detrital ferromagnesian minerals. Ilmenite, partially altered to leucoxene, and some small fragments of pale green hornblende make up a small fraction of the rocks.

Fragments of sedimentary and igneous material form an important part of the lithic content in the sandstones. The sedimentary types represented are siltstones, argillite, and minor chert. Igneous rocks are mainly rounded grains of a volcanic flow rock with trachytic texture, with small laths of feldspar doubtfully determined as oligoclase. Other minerals in the groundmass are indeterminate and have been largely replaced by chlorite, epidote, and iron ore. Only one determinable phenocryst of highly altered sodic plagioclase was found. Vermicular chlorite occurs as pseudomorphs after ferromagnesian phenocrysts, the shape of one pseudomorph suggesting that the original mineral was augite. Several fragments of micropegmatite are also present in the sandstones.

The clay matrix of the sandstones consists of minute shreds of quartz, feldspar, epidote, chlorite, sericite, and iron ore.

The mineral assemblage and texture of the sandstones is close to that defined for the subzone Chl 1 (Turner 1935; Hutton, 1940), and therefore these rocks may be placed in that grouping.

*Graded argillites*. The graded argillites are extremely fine-grained, and most of the material is indeterminable. Tiny fragments of quartz and feldspar are set in a clay matrix of chlorite and sericite shreds with epidote, iron ore, and other dust-like material.

*The Owhiti greenschist or mylonite* (Plate 14, Fig. 2). This very fine-grained rock is composed of strained and granulated quartz, chlorite, epidote, and sericite, with grains and flakes of iron ore. The chloritic material is usually aligned parallel to the bedding planes. Macroscopically, the whole of the rock gives evidence of strong crushing, and intercalated thin beds have been closely crumpled and contorted. Between the beds and cutting across them are shear planes filled by irregular veins of sheaf-like yellowish green chlorite with strained and granulated quartz.

Included within the rock are several siliceous micro-organisms which show remarkably little distortion considering the amount of deformation the rock has suffered. Mr. N. de B. Hornibrook, New Zealand Geological Survey, has kindly examined these fossils and considers that they are radiolarians. The largest is little more than 0 2 mm in diameter.

*Hooks Bay green tuff*. This rock appears to be a fine-grained argillite in the field, but under the microscope it has the texture of a medium-grained crystal tuff which has been broken down into a fine-grained argillaceous material by crushing. A number of highly saussuritised sodic plagioclase crystals are present, mainly altered to water-clear albite and sericite. Chlorite and sericitic mica are common in a fine-grained groundmass along with numerous grains of iron ore. Fibrous chlorite often occurs as alteration products of ferromagnesian minerals and as vein fillings.

*Red argillites.* The red argillites are usually extremely fine-grained and contain a mineral assemblage similar to that of the normal argillites except that the material is largely obscured by a dense stain of ferric oxide. The argillite from Hooks Bay contains fragmentary organic material similar in nature to the Owhiti mylonite. The rock from Omiha (Rocky Bay) contains numerous irregular rounded bodies which range in diameter from 0·01 to 2 mm. These bodies may represent altered organic remains; they are composed of fine grained epidote with chlorite and quartz.

*Cherts and jaspilites.* These rocks are microcrystalline aggregates of quartz in which the individual grains display strain polarisation. In some cherts the groundmass is obscured by dense granular and flaky aggregates of hematite. A few cherts contain detrital quartz grains. In thin section the cherts are seamed by a series of quartz veinlets and a few of chlorite. The quartz veins are filled in several distinctive ways: with equidimensional quartz grains, by crystals oriented perpendicular to the vein wall, or by fan-shaped and spherulitic aggregates of fibrous quartz. These veins weld the rock into a very resistant mass.

Green chert which forms a small lens under the pillow lavas at Surfdale contains much granular epidote and chlorite. Veins in the rock are filled almost entirely by laths of low temperature albite. The crystals show little regular orientation except for a tendency some have to grow in radiating sheafs. The crystals are twinned on the albite and Carlsbad laws.

*Igneous rocks.* The pillow lavas at Surfdale have a variolitic texture with minute, partially altered feldspar needles and dark ferromagnesian material which has been replaced by chlorite, sericite, and epidote. Most of the feldspar appears to be albite, although there are a few laths of labradorite. Euhedral and granular pyrite, often partly altered to limonite, is fairly common. Phenocrysts of ferromagnesian minerals are altered to chlorite, sericite, and iron ore.

Small vesicles have been filled by felt-like crystals and spherulitic aggregates of pale green chlorite, or by calcite. Occasionally chlorite and calcite occur together, and, rarely, albite or quartz fills a vesicle. Irregular veins and cracks cutting the rock are filled mainly by calcite, with minor sericite and chlorite. Near the pillow surfaces the lava tends to be glassy and the variolitic texture disappears. Streaky lenses of pale green and colourless chlorite appear along the contacts between the lava and the interstitial limestones. Sperulitic chalcedony and pyrite are common within the lava and the limestone.

The interstitial limestones are composed of large anhedral interlocking calcite crystals with rare pale green chloritic and chert-like material filling irregular veins. There are no traces of organic matter. The mineralogy, texture, and field appearance of these lavas indicates that they are spilites of the type defined by Dewey and Flett (1911) and by Hatch, Wells, and Wells (1949).

Other inter-bedded lavas show no pillow structures and variolitic texture is not so well developed. Minute crystals of feldspar are arranged in fan-shaped, plumose, and arborescent clusters, and in places the texture tends to be hyalopilitic. The feldspars are almost completely altered, but appear from the extinction angles, perpendicular to *a,* to be sodic plagioclase. Original ferromagnesian minerals have been altered to dark patches of chlorite and sericite. Much of the groundmass is obscured by a dense stain of ferric oxide. Pyroxene phenocrysts are rare and are completely replaced by epidote, chlorite, iron ore, and chalcedony.

The interbedded lavas from Sandy Bay and Hooks Bay tend towards a variolitic texture, but more often the texture is hyalopilitic with some flow banding. The minute feldspar laths are of the composition oligoclase-andesine, and one or two phenocrysts of partially saussuritised oligoclase-andesine are present.

*Quartz and epidote veins.* Most of the greywackes and argillites examined carry up to five distinct sets of epidote and quartz veins which vary in width from 0·05 to 4 mm. In epidote veins the crystals are usually in thick sheaves arranged parallel to or radiating from the vein walls. Quartz with a little chlorite is usually present, forming up to a quarter of the material by volume. In sheared argillites the epidote veins are parallel to the bedding surfaces.

The quartz veins are from 0 05 to 3 mm wide, and show much variation in their form. Simple, narrow veinlets contain equidimensional quartz crystals showing slight undulatory extinction. Radiating nests of tiny epidote crystals, some fibrous chlorite, and rarely a little apatite line parts of the vein walls. In the wider, more complex veins the quartz occurs as an interlocking mosaic of elongated crystals with a lining of much smaller crystals along the vein walls (Plate 14, Fig. 3). Usually the long axes of the crystals are normal to the vein walls, and they show strong undulatory extinction. Chlorite occurs in long streaks parallel to the vein walls, but individual fibres are at right angles to the walls. Small amounts of epidote are also present in these veins.

## ORIGIN OF THE ROCKS OF THE WAIHEKE FORMATION

The abundance of plagioclase feldspar fragments, with subordinate sharply angular and strained quartz grains, in the sandstones of the Waiheke Formation indicates that the clastic materials were derived from a mixed igneous and metamorphic land-mass (Pettijohn, 1949). The presence of detrital apatite, zircon, garnet, hornblende, and iron ores in heavy mineral concentrates, and a few fragments of micropegmatite and polygranular quartz also points to a mixed igneous-metamorphic derivation.

Detrital epidote and ferromagnesian minerals indicate that at least a part of the source area was composed of intermediate to basic igneous rocks. Part of the epidote may have been derived from crystalline metamorphic rocks or sedimentary rocks.

Fragments of andesitic material are ubiquitous in rocks of this type in the Auckland Province (Allen, 1951) and show that vulcanicity was also widespread in the parent land. Fragments of argillite, siltstone, and chert indicate sedimentary provenance, but many of these fragments are likely to be of intraformational origin. The large proportion of clay in the greywacke matrix also suggests that shale formed a part of the parent rock association (Dapples, Krumbein, and Sloss, 1953).

The parent rock material probably suffered little chemical weathering, as the quartz concentration is fairly low. The complete lack of rounding of the quartz grains and the freshness of some of the plagioclase feldspar indicates that the sediments have been transported no great distance by normal agents of sedimentation. Indeed, much of the alteration of the feldspar is probably diagenetic.

It is generally believed that the land mass supplying the material for the Late Palaeozoic and Mesozoic sediments of New Zealand lay to the west (Benson, 1923; Wellman, 1952). The sediments were probably rapidly deposited under geosynclinal conditions, debris of the Waiheke type being deposited close to the axis of the geosynclinal trough.

*Conditions of deposition.* The sandy nature of the greywackes, especially when thinly bedded with mudstones, points at first to deposition in shallow water, estuarine, or beach environments. However, Bailey (1930, 1936) and others believe that the deposition of most graded sediments takes place in deep water, and Kuenen and Carozzi (1953) claim a depth of at least a few hundreds of metres for most beds of this kind.

The rocks of the Waiheke Formation contain no structures of shallow-water type, such as local unconformities, true conglomerates, or cross bedding. Similarly, there is no evidence of sorting or reworking of sediments except for minute ripple marks. On the other hand, the greywackes and argillites show many of the internal structures attributed to redeposition from turbidity currents. Graded beds are common among the argillites and most of the sandstones. Among the argillite-sandstones are structures indicating that the passage of turbidity currents had, at times, disrupted the topmost portions of the unconsolidated muds on the sea floor, incorporating the fragments in the lowermost portion of the new sandstone layer, thus forming intraformational conglomerates. In addition, the presence of finely graded laminae of great lateral extent indicates that deposition took place in deep water rather than shallow water where wave base and the activities of organisms would have destroyed fine layering.

The earliest deposited beds in the formation are the thinly bedded sandstones and argillites which outcrop on the eastern coast. They were probably deposited in deep water in the subsiding geosyncline, where normal deposition of fine-grained materials proceeded very slowly. However, turbidity currents carrying small volumes of sediment periodically flowed over the sea-floor, depositing thin beds of graded muds and sands. The surface of deposition had some notable slope, since intraformational slumping under load and convolution of the graded beds is quite common.

The thinly bedded sediments pass quite quickly up into thickly bedded and massive sandstones, which form the major part of the Waiheke Formation. The change in lithology was probably caused by oversteepening at this locality, followed by a greater influx of debris.

Uplift of the parent land mass, possibly accompanied by an eastward shift of the geosynclinal axis, greatly increased the volume and average particle size of the detrital material and the rate at which it was deposited on the continental shelf. The deposition of sediments under these conditions led to unstable conditions on the continental shelf, so that slumping, once initiated, involved large volumes of coarse material, which was carried out to deep water as turbidity currents. In this way thick beds of unsorted, graded sands were produced. Occasionally the turbidity currents carried material of finer grade, so that some thin sequences of alternating sands and muds are contained by the massive sandstones.

At least three times in the course of deposition basic and intermediate volcanic lavas were poured out on the sea-floor, and the lavas of at least one of these eruptions contains important quantities of albite. Bedded cherts were also deposited at a number of horizons.

*Cherts within the Waiheke Formation.* Thick lenses of chert and jaspilite containing iron and manganese oxides are characteristic of the Waiheke Formation and are common in similar rocks throughout New Zealand. The lenses of bedded chert at Waiheke are inter-bedded with marine sandstones and argillites. The bedding planes between the two rock types are sharp, although one may grade laterally to another, or interdigitate with each other. There is no evidence to suppose that the cherts are not primary, sedimentary in origin, and syngenetic with the surrounding rocks.

The Waiheke cherts are of marine origin and have been deposited in moderately deep water. The association of many cherts with sandstones has led to the belief that they are formed in a shallow water environment (e.g., Davis, 1918; Pettijohn, 1943). However, other writers using in part the same evidence, believe that cherts are characteristic of deep water or abyssal conditions (Bailey, 1936; Krumbein and Sloss, 1951). The association of cherts with manganiferous red argillites which may represent red abyssal clays also points to a deepwater origin. Present day red abyssal clays containing manganese pellets are often associated with sands, graded sands, and muds (Ericson, Ewing, and Heezon, 1952). The red argillites at Waiheke are often continuous along the strike with cherts and usually contain manganese oxides.

If the theory of redeposition by turbidity currents is accepted then one must assume at least a moderately deep water origin for the Waiheke cherts. The problem of depth of origin is linked with the problem of the origin of the silica. It is believed by some writers that the silica forming large chert deposits is carried by rivers in a colloidal state and thrown down by electrolytes on reaching the sea (Moore and Maynard, 1929; Twenhofel, 1939). On the other hand, recent tests indicate that the silica carried by rivers is in ionic solution, probably as the silicate ion $SiO_3^-$ and it will not precipitate out as a pure siliceous sediment unless the solution becomes supersaturated; furthermore, the solution will not precipitate as a result of coming into contact with electrolytes (Roy, 1945). Even granting that deposits could be so formed by precipitation of colloidal silica, either on the continental slope or the shelf, they would, according to the theory of redeposition, be destroyed by slumping, and the material disseminated through the redeposited sediments.

It is not likely that ordinary sea water would provide enough silica and iron to form ferruginous chert deposits, as the proportion of dissolved silica in sea water is minute. It has been shown that flocculation in sea water of extremely diluted silica sols is impossible, so that "the inorganic origin of siliceous deposits in the sea water under normal conditions must be excluded" (Rankama and Sahama, 1950, p. 216 and p. 555).

The two rocks from Waiheke which contain radiolarian-like bodies are continuous along the strike with cherts. It may be inferred that these rocks are formed on the margins of a basin where silica was deposited by the agency of radiolaria, and that their tests were not preserved in the cherts because of subsequent recrystallisation of the latter. However, since there is so little available silica in sea water, another source must be found which can account for the periodic development of large numbers of such siliceous organisms. Taliaferro (1933) pointed out an almost constant association of cherts with inter-bedded volcanic lavas, and he believes that siliceous emanations from the lavas will provide the silica required by the organisms. However, many writers are of the opinion that the presence of siliceous organisms within cherts is merely accidental. The Waiheke cherts contain no obvious organic remains, and the writer believes that contributions, if any, of silica from radiolarians is secondary to that from other sources.

It is thought by many that silica can be directly precipitated from solutions produced by inter-action between sea-water and submarine volcanic lavas and from the accompanying hydrothermal solutions; such activity is likely to provide most of the iron and silica necessary for the formation of ferruginous cherts (Davis, 1918; Sampson, 1923; Sargent, 1929; Ruedemann and Wilson, 1936; Bruce, 1945). Of the three sets of volcanic rocks within the Waiheke Formation, two are associated with cherts; one overlies a chert sequence and the other is replaced along the strike by cherts Most of the chert lenses at Waiheke have no obvious relationship with lava flows, but since the Waiheke Formation was deposited in an active orogenic environment, it is possible that the lava flows are more numerous and of greater extent within the sedimentary members than is known at present It is likely that the cherts of the Waiheke Formation were formed from silica and iron derived from lavas and hydrothermal solutions. There is no direct evidence for secondary alteration of normal sandstones and argillites.

Crumpling and contortion of bedded cherts appears to be a universal feature. These structures are probably due to subaqueous slumping soon after deposition whilst the chert was still in a gel-like condition (Pettijohn, 1943; Spencer and Percival, 1952), or because they showed less resistance to folding than the surrounding rocks (Davis, 1918).

*Manganese.* The cherts, jaspilites, and red argillites of Waiheke are characterised by the presence of nests and stringers of manganese oxides and hydroxides. Although some secondary concentration in lenses and along joints and bedding planes has taken place in the cherts and jaspilites, it seems most likely that the manganese oxides are syngenetic with the host rock. There is no evidence that the oxides have formed in any kind of terrestrial environment.

Nodules of manganese are commonly formed on the ocean floor at great depths, usually in association with red abyssal clays. According to various authors (e.g., Rankama and Sahama, 1950, p. 648) the deep-sea formation of manganese may be due to biological extraction from the sea water, chemical extraction, or the adsorption of manganese on volcanic dust. The content of manganese in sea water is very low. In this case, the manganese cannot be totally derived from sea water alone, and it is believed that submarine volcanic eruptions are probably the main source of manganese on the sea floor. In this way, it is not absolutely necessary to have abyssal conditions for the formation of manganese. If ferric hydroxide and manganese hydroxides are brought together they will flocculate by virtue of their opposite charges; if large quantities of silica are present, a ferruginous chert with manganese will result.

## Age and Correlation of the Waiheke Formation

Since no index fossils have been found in Waiheke Formation, the rocks have been assigned on a lithological basis to the petrographically similar Undifferentiated Jurassic-Triassic-Permian of Willett (1948).

The Waiheke Formation shares a common structural line with similar rocks in North Auckland which have been called "Waipapa Series" (Bell and Clarke, 1909). Recent fossil discoveries near Whangaroa and Russell have led to the series being placed in the Upper Permian. The lower portion of the Waiheke Formation (rapidly alternating argillites and sandstones) may be correlated with the "Waipapa Series". Similarly, the rocks of the Waiheke Formation are comparable with the Coromandel pre-Jurassic Moehau and Tokatea Series of Fraser and Adams (1907), but they cannot be separated into two such series on the presence or absence of inter-bedded volcanics.

In the hand specimen, the rocks may be placed with the Upper Sub-Schists (Upper Triassic) of Harpers Pass (Wellman, Grindley, and Munden, 1952) which have been dated on the presence of rare *Monotis richmondiana*.

## Waitemata Group (Altonian Stage, Lower Miocene)

Fossiliferous argillaceous sandstones with basal greywacke conglomerates occur in small pockets half a mile north-east of Oneroa and immediately south of Church Bay (Squadron Bay of Powell, 1938). Similar but unfossiliferous beds are exposed in two bays south of Church Bay, and probably belong to this group. The total area covered by these sediments is not more than one-third of a square mile, and the thickness is only about 50 feet. The fossils are marine molluscs and broken plant debris enclosed in conglomerates and sandstones.

*Typical sediments.* The conglomerate is evenly bedded in layers 1 to 2 feet thick, and rests unconformably on the greywacke basement. It is composed of slightly rounded pebbles, with diameter ½in to 8in in a silty matrix. The rock fragments are chiefly greywacke with occasional fragments of soft sandstone of the same lithological type as the overlying sandstone. Parts of the conglomerate are highly weathered and seamed by calcite, and in some places films of ferric oxide coat the rock fragments and fill cracks.

At Oneroa the rock fragments become finer upwards and pass into material of sand grade; the thickness of the conglomerate here is 12 feet. At Church Bay, the conglomerate is about 20 feet thick, and there is a sharp contact between conglomerate and sandstone. The overlying sandstone is soft, grey, and silty, and the component particles are not well sorted although poorly defined bedding planes are present. South of Church Bay, at Cable Bay and Te Rere, small patches of greywacke conglomerate rest unconformably on the greywacke basement. At Te Rere the sediments are affected by minor faults and folds.

The basal Waitemata conglomerate rests unconformably on the greywacke basement. The beds dip inwards towards the middle of each bay, and the overlying sediments follow this trend so that they appear to be flexed downwards. The manner in which the beds overlap on to the greywacke basement, with dips little less than that of the surface of contact, suggests that the synform structure is due to compaction.

*Origin of the sediments.* The Waitemata sediments occurring at Waiheke were deposited in "small sheltered pocket-like hollows" (Powell and Bartrum, 1929) close to a lower Miocene shoreline. The basal deposits were subangular greywacke chips with plant debris and shell fragments. Variations in the source of supply occurred from time to time and sandstone fragments were worn from "adjacent lithologically similar sediments of Tertiary age" (Powell and Bartrum, 1929). The size of the rock fragments supplied to the hollows gradually decreased, and sands with much silt completed the succession. The finer grades were deposited quickly in quiet waters, as shown by the poor sorting, the lack of well defined bedding planes, and the absence of the alternating sandstones and mudstones which characterise Waitemata sediments elsewhere near Auckland.

Following compaction and consolidation, the Waitemata sediments were uplifted and slightly deformed by faulting and folding.

*Age and Correlation of the Waitemata Group.* Correlation of the Waitemata sediments at Waiheke with Altonian horizons in other parts of New Zealand is difficult, partly because the fauna is of a rare littoral and shallow-water type and partly because a great number of new forms are present. Powell and Bartrum (1929) placed the Oneroa beds in the Hutchinsonian stage (Upper Oligocene, *vide* Henderson, 1928) on the molluscan fauna. Powell (1938) described new species from the Church (Squadron) Bay beds and the Oneroa beds.

In their revision of the New Zealand Upper Cretaceous and Tertiary stage divisions, Finlay and Marwick (1947, 1948) indicated that Waitemata beds, including those at Waiheke, are Lower Miocene in age and should be included in the Altonian stage.

## TERTIARY VOLCANICS

At the north-east corner of Waiheke, a dissected, dome-like hill, Stony Batter, rises to 725 feet above sea level and is capped by a highly weathered andesite breccia which is very similar in general appearance to the Altonian Manukau Breccia of the Waitakere Hills, west of Auckland. The breccia covers an area of little more than 1½ square miles, and scattered over the surface are numerous large boulders of comparatively fresh basalt.

The andesite breccia is a deeply weathered mass of rounded to sub-angular pebbles and boulders from 1in to 3ft in diameter seated in a heavy yellow to orange clay-like matrix. The rock fragments are altered porphyritic andesite with large zoned plagioclase phenocrysts in all stages of decomposition, set in a dark, fine-grained groundmass of minute feldspar laths, granular pyroxene, and magnetite. Smaller phenocrysts of hypersthene, with some augite, are numerous.

The breccia forms a superficial capping on the greywacke and has a maximum thickness of 300 feet, but in most places it is considerably less than 200 feet thick. The boulders are not sorted, but show rough bedding.

*Age and Correlation of the Breccia.* In hand specimen and thin section the breccia at Waiheke is similar to the other Tertiary andesite breccias in North Auckland. Petrographically there is a close resemblance to the hypersthene and hornblende andesites of the First Period volcanics at Coromandel (Fraser and Adams, 1907). The rounded and subangular shapes of the rock fragments, together with the rough stratification of the breccia, suggests that it was deposited under water. There is no evidence pointing to the nearby existence of a volcanic vent, but it is possible that the breccia at Waiheke represents a marginal portion of the Coromandel volcanic accumulations.

The basalt boulders are scattered over the surface of the ground and range in size from 18 inches to 15 feet or more in diameter. The rock is porphyritic in texture, with large olivine and augite phenocrysts in subequal amounts set in a fine-grained holocrystalline groundmass of plagioclase feldspar laths, small grains of augite, magnetite, ilmenite, and apatite (Plate 14, Fig. 4). In coarser varieties of the basalt spherulitic and fan-shaped masses of fibrous calcite fill elongated vesicles.

The boulders show little sign of decomposition and decay except in thin shells on the surface, but they are being broken down by spalling and by development of solution channels. A most striking feature is the development of lapiez or fluting on the surfaces of some of the larger boulders. Similar forms in basalt blocks have been recorded by Bartrum and Mason (1948) at Hokianga. Here also the fluting is almost exclusively confined to stable blocks which are greater than 5 feet in diameter, and it is developed usually on steep surfaces.

*Age and Correlation of the Boulders.* The basalts forming the boulders at Waiheke resemble in most respects the Pleistocene to Recent basalts of North Auckland. Pleistocene deposits on the nearby shore contain fragments of the andesitic breccia, but the basalts are contained only in modern beach deposits. These Pleistocene deposits may represent a period of deposition when sea level was 40 to 60 feet above the present day level, and the basalts therefore, were probably erupted after that time.

No clear evidence was seen of a volcanic vent in the vicinity of Stony Batter, but the distribution of boulders and the topography suggest that the centre of the eruptions was situated near or at the summit of the hill. The isolated flow was small in area, so that a thin layer of lava covered the soft, unconsolidated andesite breccia. Subsequent breaking along joints and undermining of the basalt flow by the headward erosion of streams seated in the soft breccia caused its breakdown into large boulders. The rounding of the boulders may have been developed partly by subsurface spheroidal weathering and partly by further physical weathering after exposure.

## Quaternary Sediments

Pleistocene and sub-Recent sediments at Waiheke are confined to small littoral and alluvial deposits along the coast: they are gravels, conglomerates, sands, and muds, sometimes with included shell and plant debris.

Hooks Bay is flanked by cliffs a little more than 50 feet in height in which are exposed water-laid gravels, sands, and muds. The base of the sequence is formed by an andesitic conglomerate which has been derived from the breccia capping Stony Batter. The conglomerate is overlain by a pumiceous bed 4 feet thick and a fine blue-grey mud containing carbonised plant remains. The rest of the sequence is composed mainly of angular fragments of greywacke and chert in a silty matrix. In Te Wharau Bay, near Surfdale, similar sediments containing bands of limonite are exposed in a 50-foot cliff, but no derived igneous conglomerate and few plant remains are present. Nearer Surfdale, there is a small exposure of a soft, pumiceous, very friable sandstone similar to the pumiceous bed at Hooks Bay. Putiki Point, between Surfdale and Ostend, is capped in places by water-laid gravels extending up to 50 feet above mean sea level. The sediments at all these localities are soft, poorly consolidated, and highly weathered None of the beds contain shell debris and therefore they are classed as fluvial in origin. They may be correlated with the "40ft to 60ft" erosion surface of Turner and Bartrum (1928).

Several terrace remnants 20 feet high and 25 feet above sea level are carved in the alluvium by the stream running into Man O' War Bay, and an alluvial flat at Anita Bay may be correlated with the "10ft to 20ft" erosion surface of Brothers

(1954). Water-laid muds and gravels with plant debris, but lacking shell beds, appear along the north-east coast, and along the southern shore there are littoral deposits of gravels with pockets of shell debris. These various deposits may also be correlated with the "10ft to 20ft" erosion surface as their surface is usually a little higher than 12ft to 15ft above sea level.

Raised beaches and mudflats up to 6ft in height, the result of a sub-Recent lowering of sea level, are very common on the coast. Usually they consist of water-laid gravels partly cemented by ferruginous material, and muds with included pockets of shell debris. The lower beds are mainly fine grey silty muds with carbonised remains of sedges, rushes, and mangrove roots.

## The Geological History of Waiheke Island

During the late Paleozoic and most of Mesozoic times the Waiheke area formed part of the floor of a large geosyncline extending from south of New Zealand far to the north. Great quantities of clastic sediments derived from an ancient land-mass lying to the west were deposited, mainly by turbidity currents, on the floor of the geosyncline. From time to time small quantities of basic lava were erupted on the sea-floor, and sometimes conditions allowed the deposition of almost pure siliceous sediments.

This long period of deposition was closed by a late Paleozoic or early Mesozoic orogeny. In the Waiheke area, the rocks were probably folded into a large anti-clinorium, slightly overturned to the east, with major faulting along the eastern limb. Most of the evidence at Waiheke indicates that fold movements were directed from the west. Notwithstanding the fact that a great thickness of sediment accumulated in this area, there is no trace of progressive load metamorphism in the older rocks.

The Waiheke area apparently remained above sea-level until early Miocene times, when a new transgression of the sea allowed deposition of sands and muds of the Waitemata Group over much of the Auckland district. The western portion of Waiheke formed a part of the lower Miocene shoreline, and littoral sediments with included shell and plant debris were deposited in sheltered bays and hollows.

During the Miocene period some andesite fragmental material was deposited subaqueously at the eastern extremity of Waiheke Island. It is likely that the andesite breccias were derived from contemporaneous volcanic eruptions in the Coromandel area. There is no evidence that the Waiheke area was again submerged until post-Tertiary times.

By the late Pliocene, the Kaikoura orogeny had reached its climax as a period of major block-faulting. In the Auckland district the main fault lines strike roughly north-south and east-west, and it is probable that faults with these trends blocked out the outlines of Waiheke Island.

Subsequent to the Kaikoura orogeny, there was extensive erosion of the Auckland area, followed by a series of positive and negative changes in relative sea level in Pleistocene times. The remnants of an old peneplaned surface stand about 550 feet above sea level (Brothers, 1954). At Waiheke, the successive changes in sea level are not clearly recorded by erosion surfaces and sediments. Towards the end of Pleistocene time gravels, sands, and muds were deposited in earlier-formed river valleys and along the seashore. About the same time, a small amount of basaltic lava was erupted near the eastern extremity of Waiheke, the flow covering the earlier andesitic breccias and protecting them from further erosion.

When the sea level dropped until it stood at 150 feet to 200 feet below the present level, the streams and rivers were rejuvenated and vigorously cut down toward the new base level, forming deep, trench-like valleys. At this time Waiheke and the Hunua area, south-east of Auckland city, were probably joined by land.

The last major rise in sea level submerged the land until sea level stood at a few feet above the present day level. River valleys were flooded to form a deeply embayed coastline, and Waiheke became an island. In sub-Recent times a fall of sea level of the order of 3ft to 8ft was responsible for the formation of raised beaches in the majority of bays and other sheltered portions of the coastline.

Since the last rise in sea level (Flandrian transgression) strong marine erosion on the north coast has driven back the headlands for some distance to form lines of high cliffs and broad sandy beaches. The south coast is deeply embayed by estuaries which at present are being progressively filled by gravels and muds

## Acknowledgments

The above account is based on work submitted as a thesis for the Master's Degree. Grateful acknowledgment is made to Professor A. R. Lillie and Dr. R. N. Brothers for advice and criticism in the field and in the preparation of this paper. Thanks are due also to Dr. C. R. Laws for advice regarding the fossil localities. The writer is deeply indebted to those residents of Waiheke Island who supplied both accommodation and local information.

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