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A Petrological Study of the Kaiwhata Sill, Ngahape, East Wairarapa, New Zealand

By R. H. GRAPES
Victoria University of Wellington

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Abstract

THE Kaiwhata Sill intrudes Upper Cretaceous (Piripauan) sediments and is made up of two injections now dipping at 50° north-north-west. South of the Kaiwhata Stream the sill is 25–30 feet thick and composed of fine-grained olivine and augite dolerite. Variation of rock types in this part of the sill is probably the result of flow differentiation aided by gravity. North of the stream the sill (average thickness 70ft) is made up of coarse-grained albite dolerite. It crystallised as a homogeneous mass, residual liquids being displaced upwards during consolidation.

The Kaiwhata Sill and other igneous rocks near Ngahape, including teschenite, olivine dolerite, and variolitic basalt flows farther south, probably form a consanguineous suite derived from a parent alkali olivine–basalt magma. It is proposed to call this suite of rocks the " East Wairarapa Igneous Complex ".

INTRODUCTION

THE Ngahape area is hilly but not rugged except in the Brocken Range and farther east towards the coast. The hills are essentially free of scrub and the sill outcrops are readily mapped.

TABLE I.—Stratigraphic column for the Ngahape–Brocken Range area.

NEW ZEALAND				
	STAGES	SERIES	LITHOLOGY	
Sa	Altonian	Southland	Siltstone and graded sandstone	MIOCENE
D	Undifferentiated	Dannevirke	Graded bedded sandstones and siltstones with greensands (2,800')	EOCENE PALEOCENE
Mh Mp	Haumurian Piripauan	Mata	Siltstone and sandstone with greensands and conglomerate bands (3,300')	CRETACEOUS
R	Teratan Mangaotanean Arowhanan	Raukumara	Graded bedded sandstones and siltstones (1,500')	
Cn Cm Cu	Ngaterian Motuan Urutawan	Clarence	Graded bedded sandstones and siltstones (c. 9,000')	

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A. McKay (1883) visited the East Coast district and reported on the igneous rocks he found there. He described "syenitic and porphyritic" boulders in the Kaiwhata River but could not locate their outcrop. Later W. A. McKay (1889) recorded igneous rocks and tuffs in the bed of the Kaiwhata River about half a mile below the junction with Bismark Creek (Fig. 1).

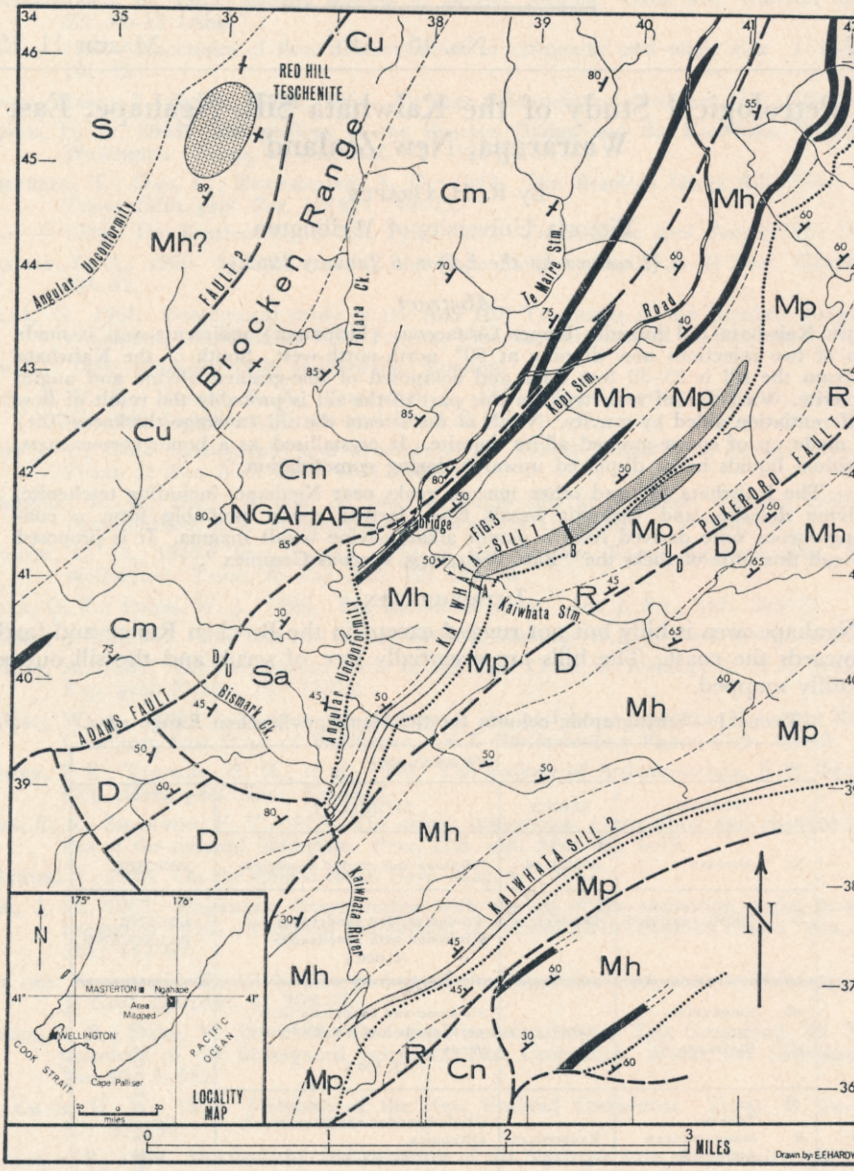

Fig. 1.—Geological sketch map of the Ngahape–Brocken Range area showing location of igneous rocks (after P. Wellman and the writer). Thickness of Kaiwhata Sill and basalt flows have been slightly exaggerated.

Black, variolitic basalt flows; fine dots, olivine dolerite; coarse dots, albite dolerite; cross hatching, Red Hill teschenite. Faults are shown by thick dashed lines, stratigraphic boundaries shown by thin dashed lines. Dotted lines indicate conglomerate bands.

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In 1941 D. Brown found an additional intrusion that crosses the Kaiwhata Stream about 40 chains upstream from the bridge at Ngahape. He named this the Kaiwhata Sill, but traced only part of the exposures.

Hutton (1943) examined specimens collected from the sill by Brown, and thought that the sill might have been gravitationally differentiated.

Recently P. Wellman (in press) has mapped the Ngahape area, and Fig. 1 has been drawn essentially from his material.

FIELD RELATIONSHIPS OF THE SILL (Fig. 1)

A sill (25-30ft. thick) of hard, crystalline dolerite is cut through by the Kaiwhata Stream about 40 chains upstream from the bridge at Ngahape. In the ridges to the north the sill stands out as a hard erosion-remnant concordant with the softer Piripauan sandstones and mudstones, striking at 285° and dipping at 50° NNW, following the inclined V-shaped profile of the valley. Alongside the bridge at Ngahape, pillow lavas, which are here considered to be comagmatic with the sill, dip at the same angle as the sill and follow the strike of the country rocks. They thus add further evidence of the concordant nature of the intrusion.

On both sides of the stream the sill is weathered into cuboidal blocks. A striking character is the marked change in composition and texture along the strike of the sill to the north and south of the Kaiwhata Stream. The exact point at which this change occurs has not been seen, but it presumably lies where the stream now intersects the sill. There is no gradational change in fabric or composition on either side of the stream, and so the contact is inferred to be sharp.

North of the stream the sill, at least 90ft thick, is made up of albite dolerite and is admirably exposed as a prominent buttress, which in places has been weathered to a brick-red soil. The rocks are coarse-grained, having long prismatic crystals of feldspar and pyroxene which increase in size towards the upper contact. The base of the sill is nowhere exposed, although its position can be located within a margin of 2–3ft. The top of the intrusion is marked by a chilled phase which contains sporadic concentrations of calcite, epidote, and zeolite. The overlying sediments have a spotted appearance a short distance from the contact with the sill. About three-quarters of a mile along this northern extension from the stream an outlier of albite dolerite is found. Its physical, mineralogical, and petrographic features are found to be identical with those of the main sill, and so the outlier is here considered to have been formed at the same time. It is probably a bifurcation that joins the main sill at depth or is similar in form to that described by Jones and Pugh (1949) for a laccolithic series of albite dolerites in central Wales.

South of the stream the sill is essentially made up of fine-grained olivine dolerite. In the section of the sill exposed on the south side of the stream a vertical change in texture can clearly be seen. The basal part is a hard, crystalline dolerite, which grades into rocks rich in calcite veins and amygdales, with xenoliths near the centre of the sill. Towards the top there is a fine-grained variolitic phase, heavily charged with amygdales. The contacts with the surrounding strata show signs of baking, as the rocks are indurated for a few inches from the sill. Farther to the south the sill is difficult to follow owing to the paucity of outcrops. The only evidence of its existence are loose blocks in the grassy surface, and the red-weathered dolerite seen within a westward-flowing tributary of the Kaiwhata River.

McKay (1889) has mentioned an intrusion crossing the Kaiwhata River one mile below its junction with Bismark Creek, which Brown (1943) has suggested may form the southern continuation of the Kaiwhata Sill. The writer was able to trace the sill exposures to this outcrop and found that it also was composed of olivine dolerite, with similar textural changes to those seen in the section 40 chains upstream from the bridge at Ngahape. Farther to the south an outlier of olivine dolerite concordant with the main sill is present. Both the outlier and the sill may be cut off by a fault (Fig. 1), but if so this is concealed by scrub cover.

Structural Relationships and Age Correlation

The Kaiwhata Sill is composed of two injections, olivine dolerite and albite dolerite, which are now adjacent to each other along the strike of the sill. Post-intrusion strike faulting has duplicated the olivine dolerite in a fault block south-east of the main sill (Fig. 1).

It has not proved possible to locate the source of the Kaiwhata Sill or the variolitic basalt flows of the Ngahape region with any certainty. In the opinion of Gardiner (1965) the Red Hill teschenite in the Brocken Range (Fig. 1) was the conduit of a submarine volcano from which the sill and flows originated. Recently Coles (1968) has postulated on geophysical evidence, however, that the teschenite is a thin (80–90ft. thick) surficial saucer-shaped body dipping at a low angle to the east, of no great extent and discordant with the surrounding vertical sediments. The teschenite body appears therefore to have no direct structural relationship with the igneous rocks of the Ngahape area.

The stratigraphic position of the Kaiwhata Sill indicates a post-Piripauan age. Chemical evidence (Hutton, 1934: 363) indicates that the olivine dolerite part of the sill can probably be related to a variolitic basalt flow in the Haumurian. If this correlation is correct then the association of the basalt flow with the Whangai shale (Wellman, 1959) indicates a geosynclinal environment.

Table II.—Age relationships of the "East Wairarapa Igneous Complex".

	Age	Flatpoint (H. Van den Heuvel)	Mount Adams (J. Eade)	Ngahape - Brocken Range
Tertiary	Dw			Basalt flows
	Dt		Teschenite sills	
Cretaceous	Mh		Basalt flows	Basalt flows ? Red Hill teschenite
	Mp			Kaiwhata Sill
	Rt		Dolerite sills	
	Rm	Dolerite sills	Dolerite sills	
	Ra			
	Cn	Dolerite sills		
	Cu			Basalt flows
	Tk			
	Tm	Basalt flows	Basalt flows	

Several sills and basalt flows have been recorded by Van den Heuvel (1960) in the Flat Point area and by Eade (1966) in the Mount Adams area to the south. They have similar mineralogy and textures to those at Ngahape and include teschenites, olivine dolerites, and basalt flows. Table II shows the stratigraphic relationship of the igneous rocks in all three areas, and it is proposed to call this suite of rocks the "East Wairarapa Igneous Complex" (Fig. 2). The strong genetic correlation between all the igneous rocks suggests that they are a consanguineous suite and their stratigraphic correlation based on the basalt flows indicates that there were at least four phases of igneous activity, the first in the Mokoiwian, the second in the Motuan, the third in the Haumurian, and the fourth in the Waipawan stage. The first two episodes are early Cretaceous and may represent a different phase of activity, unrelated to the late-Cretaceous–early-Tertiary igneous activity.

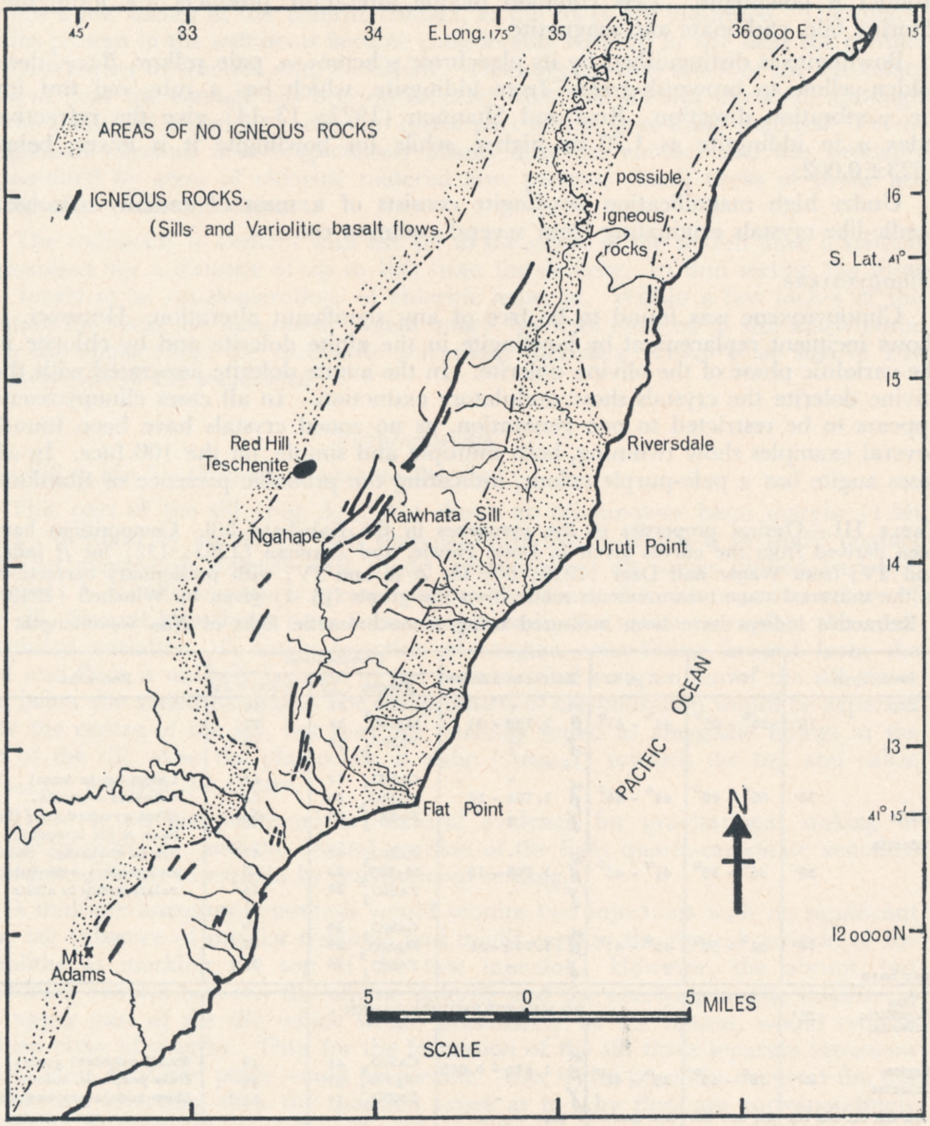

FIG. 2.—Map showing the areal extent of the "East Wairarapa Igneous Complex".

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Kingma (1959) states that the igneous rocks of Marlborough can be correlated with those of the Ngahape–Brocken Range area, but the writer agrees with Challis (1960), who has shown that the Marlborough igneous rocks cannot be correlated on either mineralogical or chemical evidence. Challis, however, notes that the Inland Kaikoura–Awatere River intrusions could be correlatives of the Cape Palliser rocks, but thinks that the Ngahape–Brocken Range rocks are younger. The East Wairarapa Igneous Complex thus seems to represent an isolated example of igneous activity in the East Coast Geosyncline during Cretaceous–Tertiary times.

MINERALOGY

Olivine

There is no fresh olivine in any slide examined, and the most common alteration product is bowlingite. Less common olivine alteration products are iddingsite, chlorite, talc, carbonate and magnetite.

Bowlingite is distinguished by its pleochroic scheme—α, pale yellow, $\beta=\gamma$, deep golden-yellow to brownish-green—from iddingsite, which has a ruby red tint for the γ vibration direction. Ross and Shannon (1925: 13–14) give the refractive index α in iddingsite as 1.70 or higher, while for bowlingite it is lower, being 1.623 ± 0.002.

Under high magnification bowlingite consists of a mass of radially arranged needle-like crystals originating from several common centres.

Clinopyroxene

Clinopyroxene was found to be free of any significant alteration. However, it shows incipient replacement by bowlingite in the albite dolerite and by chlorite in the variolitic phase of the olivine dolerite. In the augite dolerite associated with the olivine dolerite the crystals show undulatory extinction. In all cases clinopyroxene appears to be restricted to one generation, as no zoned crystals have been found. Several examples show twinning, both multiple and simple, on the 100 face. In all cases augite has a pale-purple colour, indicating the probable presence of titanium.

TABLE III.—Optical properties of the pyroxenes in the Kaiwhata Sill. Compositions have been derived from the curves given in Deer, Howie, and Zussman (1965: 132) for β index and 2V; from Wager and Deer (1939: 80) for Z∧c and 2V; with preliminary corrections to the universal stage measurements made from the graph (pl. 1) given by Winchell (1949).

Refractive indices have been measured using monochromatic light of Na_D wave-length.

Rock Type		2V	Z ∧ C	Refractive Index	Composition: β index + 2V	Composition: Z ∧ C + 2V	Remarks
Albite Dolerite, Top	70'	56° - 59°	44° - 47°	α - β 1.709 - 11 γ -	$CaSiO_3$ 47 $MgSiO_3$ 24 $FeSiO_3$ 29	44 17 39	
Albite Dolerite	50'	56° - 60°	44° - 46°	α - β 1.708 - 10 γ -	$CaSiO_3$ 47 $MgSiO_3$ 25 $FeSiO_3$ 28	45 22 33	Large (up to 4mm) euhedral crystals. Often cracked near the base of the intrusion due to shearing. Shows an ophitic - subophitic relationship to albite
Albite Dolerite	30'	56° - 59°	41° - 45°	α - β 1.708 - 10 γ -	$CaSiO_3$ 47 $MgSiO_3$ 25 $FeSiO_3$ 28	47 27 26	
Albite Dolerite, Near base	10'	54° - 57°	43° - 47°	α - β 1.705 - 06 γ -	$CaSiO_3$ 45 $MgSiO_3$ 29 $FeSiO_3$ 26	39 27 34	
Top Variolitic Dolerite	25'	NO MEASUREMENTS TAKEN					
Augite Dolerite	20'	52° - 59°	39° - 42°	α - β 1.694 ± 0.003 γ -	$CaSiO_3$ 46 $MgSiO_3$ 37 $FeSiO_3$ 17	45 45 10	Small euhedral grains. Pale purple in colour. Show undulatory extinction.
Olivine Dolerite	16'	50° - 53°	44° - 46°	α - β 1.695 - 97 γ -	$CaSiO_3$ 42 $MgSiO_3$ 36 $FeSiO_3$ 22	32 32 36	Granules of titanaugite occur in subophitic texture with plagioclase. Some glomeroporphyritic clusters occur
Xenolithic Zone	11'	54° - 56°	44° - 45°	α - β 1.695 - 98 γ -	$CaSiO_3$ 45 $MgSiO_3$ 35 $FeSiO_3$ 20	40 30 30	
Olivine Dolerite	5'	51° - 54°	43° - 45°	α 1.690 β 1.695 - 97 γ 1.701	$CaSiO_3$ 44 $MgSiO_3$ 36 $FeSiO_3$ 20	37 37 26	
Contact Dolerite Base	1'	52° - 53°	43°	α 1.680 β 1.687 - 90 γ 1.695	$CaSiO_3$ 44 $MgSiO_3$ 41 $FeSiO_3$ 15	38 42 20	Small granules (0.2 mm) of colourless augites

It is non-pleochroic to very weakly pleochroic; $\alpha = \beta$, pale lilac-brown; γ, light violet.

Throughout the olivine and augite dolerites and the albite dolerite augite is characterised by its euhedral crystal habit.

Optical determinations on the clinopyroxene are shown in Table III.

Feldspar

Plagioclase: This occurs as prismatic crystals varying from 0.02mm in contact

TABLE IV.—Optical properties of the feldspars in the Kaiwhata Sill. Readings taken off α-normal sections wherever possible. Compositions derived from curves given by Tobi (1963).

Rock Type		Refractive Index	2V	Composition	Zoning Centre	Zoning Periphery	Twinning	Remarks
Albite Dolerite (Top)	70'	α 1.532 - 3 β 1.535 - 7 γ 1.542 - 3	$79^\circ(+)$	An_{8-11}	-	-	Albite +	Albite shows replacement by analcite. Orthoclase rims are not replaced.
	50'	α - β 1.537 - 8 γ -	$79^\circ - 82^\circ(+)$	An_{9-12}	An_{10-12}	An_{3-5}	Pericline +	Plagioclase often has a rim of orthoclase with the following properties:- 2v = $70^\circ - 71^\circ$ (-); r > v. α = 517 - 18, β = 1.523 - 24, γ = 1.526 - 28.
	30'	α - β 1.536 - 7 γ -	$81^\circ(+)$	An_{10}	-	-	Carlsbad	Plagioclase crystals are tabular-prismatic in habit and altered to sericite and kaolin.
(Near base)	10'	α - β 1.540 ± 0.002 γ -	$81^\circ - 83^\circ(+)$	An_{10-14}	An_{10-14}	An_3		{010} = Twin plane, (001) = Twin Axis
Variolitic Dolerite (Top)	25'	α - β - γ -	-	An_{38-44}	-	-	Carlsbad + albite	Fine branching needle-like crystals.
Augite Dolerite	20'	α - β 1.555 - 57 γ -	-	An_{38-44}	-	-	"	Slender prisms (0.5 - 0.8 mm). Show cervicorn structure. Cleavage trace often ‖ to twin plane.
Olivine Dolerite	16'	α 1.556 β 1.562 ± 0.002 γ 1.567	$76^\circ(+)$	An_{54-59}	An_{54-59}	An_{45-46}	Carlsbad + pericline + albite	Prismatic crystals (0.5 - 1 mm in length). Twinning axis ≠ composition plane. Twinning axis ⊥ to (001) with {010} equal to the twin plane.
Xenolithic Zone	11'	α - β 1.565 ± 0.002 γ -	$82^\circ - 84^\circ(+)$	An_{55-62}	-	-		Large tabular crystals (3 mm x 3 mm) occur in the xenolithic olivine dolerite.
Olivine Dolerite	5'	α 1.557 β 1.561 ± 0.002 γ 1.567	$76^\circ - 77^\circ(+)$	An_{53-58}	An_{53-58}	An_{46}		
Contact Dolerite Base	1'	α - β - γ -	-		-	-	Carlsbad + albite	Very small microliths (0.1 mm in length). Form a pseudo-variolitic pattern.

rocks to an average of 1.5mm × 0.5mm in the olivine and augite dolerites and a maximum of 6mm in the albite dolerite. In both injections albite, carlsbad, and pericline twin laws were the only ones noted. Alteration products of plagioclase are varied. In the olivine and augite dolerites mesostasic material occurs along cracks and cleavage planes. In the albite dolerite kaolinisation, sericitisation, and analcite and bowlingite replacement are common.

Alkali Feldspar: Orthoclase is found only in the albite dolerite, where it occurs as peripheral zones surrounding the plagioclase. Unlike the plagioclase it is typically free of any alteration.

Optical determinations on the feldspars are shown in Table IV.

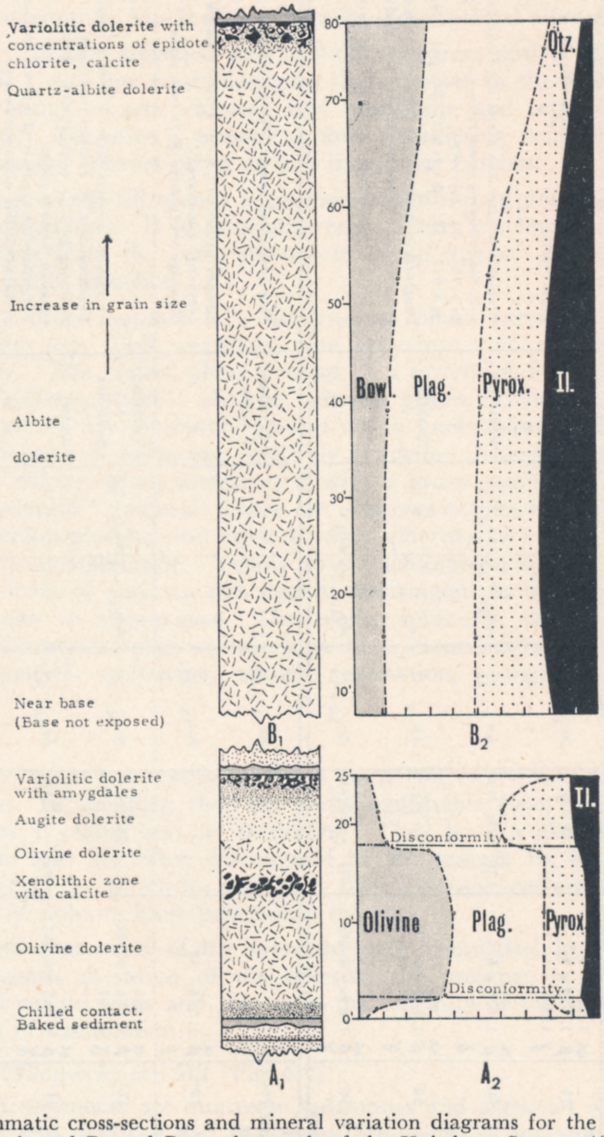

Fig. 3.—Diagrammatic cross-sections and mineral variation diagrams for the Kaiwhata Sill, A_1 and A_2 to the south and B_1 and B_2 to the north of the Kaiwhata Stream 40 chains upstream from the bridge at Ngahape. Cross-section localities shown in Fig. 1.

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Opaque Minerals

Observations in reflected light show that ilmenite is the common opaque mineral in both injections· Magnetite is present but consists only of granules which result from the alteration of olivine. Equigranular titanomagnetite crystals are found in the albite dolerite. Ilmenite occurs as ragged rods in the olivine dolerite and shows the beginnings of a dendritic form in the augite dolerite, which is greatly accentuated in the chilled variolitic margins of both injections. In the albite dolerite the size of ilmenite crystals is greatly increased and well-developed skeletal crystals are particularly prominent. Alteration of the ilmenite to leucoxene is common, giving a weak reflection pleochroism. A chemical test for titanium with sulphuric acid solution of phenol gave a positive reaction, with the formation of a brick-red colour.

PETROGRAPHY

The Sill to the South of the Kaiwhatu Stream

Basal Contact Dolerite (Fig. 4B) : In hand specimen these are dense, fine-grained rocks. No individual minerals can be seen, but small veins and amygdales of calcite are present and stand out in relief against the rest of the rock.

The rocks are holocrystalline, though extensively metasomatised. The olivines at this chilled margin are in part euhedral, though many are corroded. They average 0.2–0.3mm in diameter. All the olivines are altered to carbonates and are frequently pseudomorphed by ?iddingsite and powdery magnetite.

Plagioclase occurs as simple-twinned acicular microlites averaging 0.2mm in length. Because of their small size no suitable sections could be found to determine their composition. The plagioclase needles commonly radiate from centres, approaching a fine variolitic texture. They are commonly altered along cracks and cleavage planes by an indeterminable mesostasis.

A few crystals of augite (0.2mm in diameter), with an extinction angle of 43°, are present. No glomeroporphyritic clusters of augite are present, but olivine sometimes occurs in aggregates.

Circular vesicles filled with calcite and lined with ilmenite and chlorite commonly occur. Calcite is also present as ragged, " wisp-like " crystals arranged in a variolitic pattern with plagioclase.

Ilmenite occurs as blob-like masses and ragged rods and commonly has, especially near the contact with the sediments, a feathery dendritic structure. It is extensively leucoxenised, having a patchy white appearance in reflected light. A more advanced stage of alteration is probably indicated by a light-brown replacement mineral, with the trigonal symmetry of ilmenite, which is emphasised by the white (leucoxenised) parallel bars arranged in three dirctions across the replacement mineral. Ilmenite is often associated with calcite-filled amygdales, but in several examples surrounds altered olivine.

Olivine Dolerite (Fig. 4C) : In hand specimen these are hard, dense rocks characterised by a crystalline appearance on a fractured surface. The olivine imparts a distinct greenish hue. The rocks are fine-grained and it is difficult to distinguish the individual grains without the aid of a lens. Veins and irregular masses of calcite, with xenoliths, are located near the centre of the sill within the olivine dolerite.

Microscopically the olivine dolerite is holocrystalline with a decided granular texture. All the rocks are somewhat altered, but clearly show subophitic–intergranular texture.

Plagioclase occurs as interpenetrating prisms, the edges of which are somewhat ragged. Many tabular crystals are also present. The plagioclase shows no variolitic growth pattern as in the contact rocks, which is the result of its larger crystal size, reaching 2.5mm in length, the majority averaging from 0.5 to 1.0mm in length.

In the zone of calcite masses and veins with xenoliths near the centre of the sill, large tabular crystals of plagioclase occur (3–4mm in diameter) and often poikilitically enclose small euhedral crystals of augite and, to a lesser extent, olivine. The plagioclase is twinned on the albite, carlsbad, and pericline laws and has been identified as labradorite ($An_{53\text{-}62}$). More tabular crystals show normal progressive zoning from a labradorite core to an andesine periphery (Table IV).

Clinopyroxene occurs as small equidimensional crystals ranging from 0.2 to 0.5mm in diameter. It was identified as pleochroic pale-lilac titanaugite (Table III) with $\alpha=\beta$, pale lilac-brown, and γ, light violet. The pyroxene has a poikilitic–subophitic relation with plagioclase and also commonly occurs as glomeroporphyritic clusters.

Olivine has been altered to bowlingite, but whether all the bowlingite present is formed by the alteration of olivine could not be determined. The bowlingite pseudomorphs after olivine are commonly euhedral. Near the centre of the sill olivine is altered to carbonates associated with masses of bowlingite and iddingsite (possibly partial pseudomorphs after olivine). In some cases bowlingite is rimmed with limonite associated with green chlorite and grains of powdery magnetite which may indicate the decomposition of the mineral itself.

Ilmenite is generally accessory and occurs as ragged rods, although rare granular and dendritic grains are present. The rods range up to 2.0mm in length, but most of them are commonly less than 1.0mm. Partial alteration to leucoxene has been noted. The bars of ilmenite are aligned in two directions across the slide intersecting at oblique angles—a fabric similar to that described by Dana (1890) in the olivine basalts of Hawaii, and by Campbell, Day, and Stenhouse (1932: 353) in some teschenites of the Braefoot Outer Sill, Fife.

Calcite is only a minor constituent except near the centre of the sill, where it occurs as veins and large masses up to 5in. in diameter. Its origin is probably due to xenolith assimilation. In thin section calcite occurs as small crystals interstitial to plagioclase, pyroxene, and olivine, but occasionally fills small vesicles about 0.5mm in diameter. These calcite vesicles are usually surrounded and partly invaded by a rim of fine crystalline material, similar to that figured by Baily, Clough, *et al.* (1924: 151) for a pillow lava at Ben Fhada, Mull. This rim consists of minute crystals of plagioclase, limonite, ilmenite, and bowlingite, often associated with small crystals of quartz. The adjacent feldspars, as they enter the rim, subdivide into radiating smaller prisms, while the large rods of ilmenite disappear and smaller ones take their place. This change does not always occur, but when larger feldspar prisms reach the boundary of a vescicle they are commonly tangential to the wall, possibly an effect of surface tension.

Mesostasis is always a constant accessory and is composed of a finely crystalline mass of bowlingite and ilmenite associated with microlitic plagioclase, giving a pseudo-variolitic texture. The mesostasis commonly penetrates plagioclase twin planes, especially those twinned on the carlsbad law.

Augite Dolerite (Fig. 4D): The augite dolerite which overlies the olivine dolerite in the sill is distinguished by its finer grain size, by a subvariolitic growth pattern of the plagioclase, and by a greater percentage of augite.

Plagioclase ($An_{38\text{-}44}$) occurs as thin ragged prisms about 0.5–0.75mm in length arranged in a subvariolitic growth pattern and showing a marked dendritic–cervicorn habit. Such a fabric has caused bending and the plagioclase is commonly broken where bending is extreme. The individual crystals typically branch out from several centres throughout the slide. Plagioclase is unaltered, although uncommon tabular crystals typically have an unaltered periphery surrounding an altered centre.

Augite occurs as small equidimensional granules about 0.1–0.2mm in diameter which are typically idiomorphic in habit. It has a pale-purple colour and is very

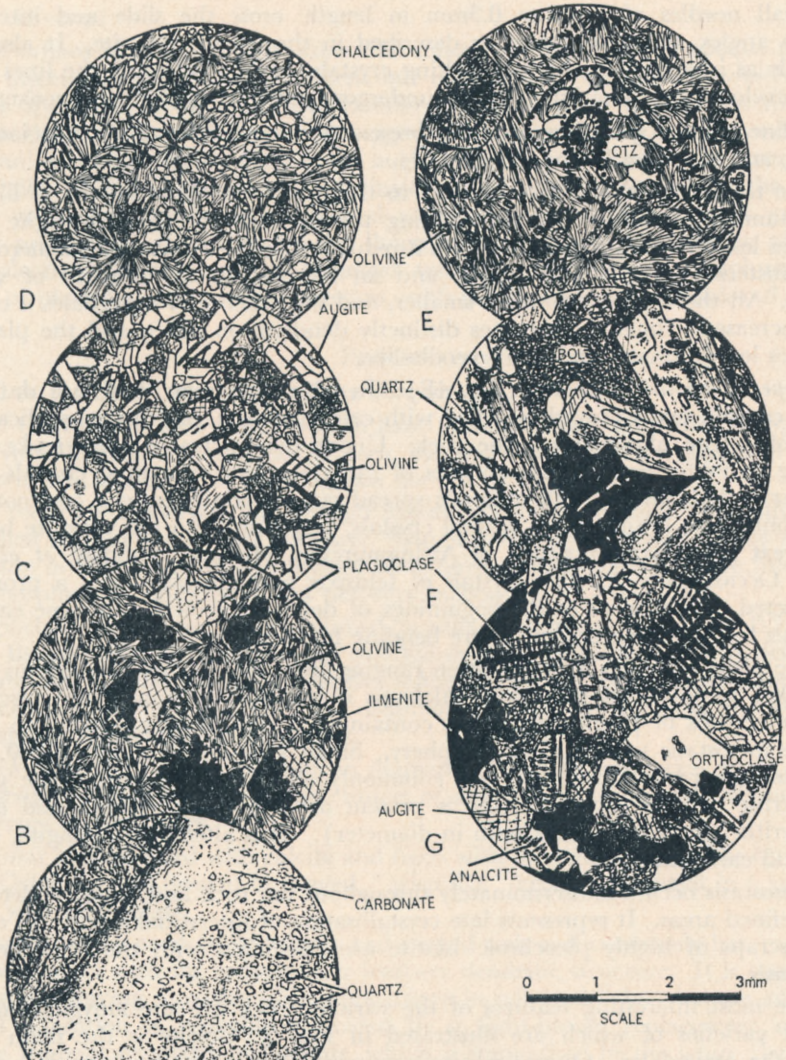

FIG. 4.—Textural diagrams drawn from a microprojector to illustrate the rock types present in the Kaiwhata Sill.

A, contact of sill with underlying sediments; B, basal contact dolerite; C, olivine dolerite; D, augite dolerite; E, top variolitic dolerite; F, quartz-albite dolerite; G, albite dolerite. (C, calcite; Bol, bowlingite; Ol, olivine; Qtz, quartz.)

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weakly pleochroic. Nearly all the crystals have undulating extinction which makes the precise determination of $Z \wedge c$ difficult. The mineral shows an intergranular relationship with plagioclase and although generally evenly distributed it sometimes occurs as glomeroporphyritic clusters.

Olivine has a larger grain size than augite (0.3–0.5mm) and typically forms glomeroporphyritic aggregates. It has been altered to chlorite, carbonate, and bowlingite, and is often rimmed with iddingsite.

Small needles of ilmenite 0.3mm in length cross the slide and intersect at oblique angles, the same fabric as described in the olivine dolerite. It also occurs typically as irregular, feathery-branching crystals, closely following the lines of feldspar development. The ilmenite has undergone some alteration to leucoxene.

A fine-grained green mesostasis is present as interstitial patches associated with calcite, and may possibly be chlorite.

The transition from augite dolerite to the upper variolitic dolerite is illustrated by a number of slides. On approaching the variolite the normal augite dolerite becomes less obviously crystalline, with a reduction in the number of glomeroporphyritic clusters of augite and olivine and an increase in the amount of variolitic matrix. All the crystals are much smaller, and the number of amygdales is considerably increased. Ilmentite becomes distinctly dendritic in habit, and the plagioclase becomes less prismatic and more needle-like.

Upper Variolitic Contact (Fig. 4E): In hand specimen these are dark rocks, which contain many amygdales filled with calcite, quartz, and hydrous silica. Small veins of calcite also transect the rock. Under the microscope the rocks have a striking variolitic texture that consists of radiating and branching crystals of both feldspar and ilmenite. Both minerals spread out sectorially from a common centre by a continuous branching of several crystals, very similar to the variolite basalts of the Great Ben Hiant intrusion of Ardnamurchan (Richey, Thomas, *et al.,* 1930: 171). Occasionally acicular crystals of feldspar and ilmenite show a pronounced constricted development at the beginnings of dendritic growth. In some cases both minerals have become broken where bending has been severe.

The plagioclase has a composition ranging from $An_{38\text{-}44}$ and ranges up to 1mm in length, although its maximum thickness is less than 0.1mm. Very rarely small tabular crystals of plagioclase occur containing a central area filled with indeterminate mesostasis with a clear periphery. Small granules of augite 0.1–0.2mm in diameter are present, but they are commonly altered to chlorite. Rare glomeroporphyritic clusters occur. Olivine is present as both single crystals and glomeroporphyritic aggregates (0.2-0.3mm in diameter). It is altered to iddingite, chlorite, talc, and carbonate.

Mesostasis occurs indiscriminately throughout the rock and is not collected into well-defined areas. It represents late crystallisation of interstitial liquid. In one slide small scraps of highly pleochroic biotite are associated with the cryptocrystalline mesostasis.

The most interesting features of the variolite rock are the amygdale minerals, several varieties of which are illustrated in Fig. 5. Calcite is the main mineral filling the amygdales. Quartz is also commonly present and occurs as aggregates of unaltered crystals. In rare cases it is seen in graphic intergrowth with feldspar, perhaps indicating a eutectic mixture, and is often surrounded by a rim of chalcedony. Several varieties of silica are present, and of these chalcedony is the most common. It is found as aggregated and spherulitic fibrous crystals. Extinction is parallel to the length of the fibres, and although many are length fast, the fibres in concentric zones have alternatively fast and slow elongation directions. In some amygdales chalcedony has a banded structure while in others a typical "salt and pepper" aggregate of tiny crystals is seen. Pale-yellow to colourless opal is another form of silica present. It commonly shows an alternate layer structure with limonite inside the amygdales. Limonite is a fairly common accessory and occurs either as blobs or as "rosette" structures typically associated with opal. Rarely fibrous zeolite is found partially filling amygdales.

The Sill to the North of the Kaiwhata Stream

Albite Dolerite (Fig. 4F and 4G): In hand specimen these are coarse-grained rocks with a greenish hue. They are crumbly and composed of interpenetrating

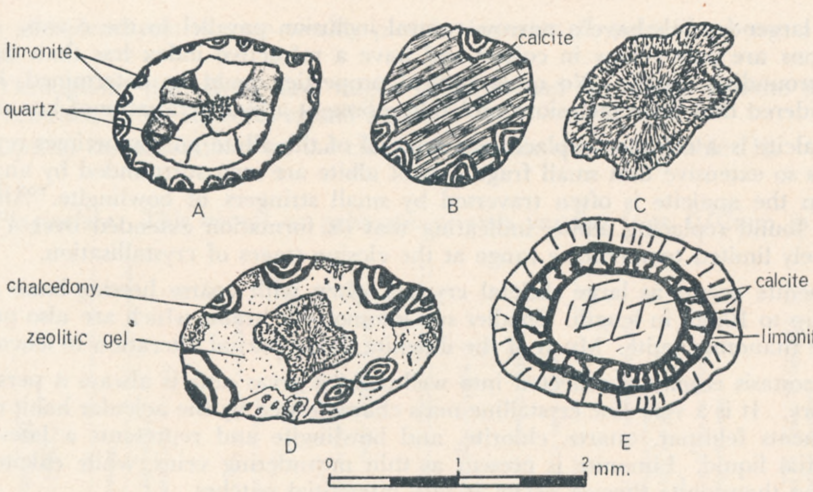

FIG. 5.—Some amygdale structures from the top variolitic dolerite of the Kaiwhata Sill. A, quartz filling with central nucleus of chalcedony; B, calcite filling bordered by limonite; C, chalcedony filling in distinctive banded units; D, ?zeolitic gel with limonite and a centre of chalcedony; E, calcite centre and periphery interlayered with limonite.

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prisms of greasy-grey feldspar, often with a central bluish zone parallel to the length of the crystal, and clinopyroxene. Feldspar is in excess of pyroxene. The dimensions of the crystals are approximately the same, about 3–8mm, but rarely ranging up to 30mm in length. Some specimens collected near the margins of the sill show signs of shearing.

Microscopically the rocks are holocrystalline showing ophitic–subophitic texture. The plagioclase, unlike that in the olivine and augite dolerites, occurs as large euhedral prisms, about 2–6mm $\times$ 1–2mm in size, twinned on the albite, carlsbad, and pericline laws. Near the base of the sill plagioclase is 1mm $\times$ 0.5mm in size. It has been identified as oligoclase-albite (Table IV). Many of the crystals show zoning from an oligoclase centre to an albite periphery. Albite is commonly surrounded by a border of orthoclase, which is free of any alteration. The plagioclase has a " dusty " appearance due to kaolinisation and sericitisation and often contains inclusions of clinozoisite, epidote, and limonite. The cracks and twinning planes have often been penetrated by bowlingite. Crystals affected by shearing are heavily cracked, often granulated and bent.

Augite occurs as large euhedral crystals up to 4mm in diameter, but smaller, averaging 1.5mm, near the base of the sill. They have a pale-purple colour with slight or no pleochroism. In contrast to the plagioclase, augite shows little or no alteration. Shearing has caused granulation, and the cracks are invariably filled with bowlingite. The augite appears to have separated from the magma at the same time as plagioclase, and often ophitically encloses that mineral. Growth of the clinopyroxene crystal faces has, in some cases, been clearly governed by the positioning of the feldspars and may represent eutectic crystallisation of the two minerals.

Bowlingite is a common constituent and is found as interstitial masses which increase in areal extent toward the top of the sill. These masses consist of agglomerations of fine radiating crystals which are uniaxial-negative and pleochroic from pale yellow to a greenish-gold colour. The habit of this bowlingite suggests that it is not a pseudomorph after original olivine.

Apatite is present as needles from 0.3mm–3mm in length and is a fairly common accessory. Many of the slides are crowded with minute acicular apatite rods. Some of the larger crystals have a narrow central inclusion parallel to the c axis. Such inclusions are pale yellow in colour and have a refractive index less than that of the surrounding apatite. No other optical properties could be determined, but it is considered that these inclusions probably represent a hydroxyapatite of late origin.

Analcite is a common replacement mineral of the albite and sometimes replacement is so extensive that small fragments of albite are seen surrounded by analcite. In turn the analcite is often traversed by small stringers of bowlingite. Analcite is only found replacing albite, indicating that its formation extended over a comparatively limited temperature range at the closing stages of crystallisation.

Ilmenite occurs as large skeletal crystals, often with coarse herring-bone structures, up to 10mm in length. Smaller sub-idiomorphic grains which are also present may be titanomagnetite. Much of the ilmenite shows partial alteration to leucoxene.

Mesostasis is mainly collected into well-defined areas and is always a persistent accessory. It is a very fine crystalline mass characterised by the acicular habit of the constituents feldspar, quartz, chlorite, and bowlingite and represents a late-phase interstitial liquid. Limonite is present as thin meandering veins, while calcite and radiating thomsonite sheaves occur as rare interstitial patches.

Near the top of the sill quartz is present as allotriomorphic water-clear crystals up to 2mm in diameter. It is associated with albite, bowlingite, and ilmenite—a notable exception from the rock mineralogy being augite. These rocks are here termed quartz-albite dolerites.

The upper chilled contact is a fine-grained phase extensively weathered for 6–12in. from the top. This weathered zone may represent an original glassy skin of the intrusion. The chilled phase consists of a matrix of fine plagioclase needles (composition indeterminable), chlorite, altered grains of augite, bowlingite, and ilmenite. Amygdales are commonly present which under high power are seen to be filled with aggregates of radiating, positively elongated sheaves of bowlingite. They are lined with calcite, often interlayered with a green mineral which may be an iron-rich " celadonitic " mineral. There are also concentrations of calcite associated with chlorite, chlorophaeite, and epidote, with spherules of zeolite, indicating late-stage (deuteric) crystallisation. Yellow to pistachio-green epidote is found inter-bedded in a matrix of chlorite and weakly birefringent to isotropic chlorophaeite, which is granular in appearance. The zeolite spherules, consisting of sheaf-like aggregates of sharply acicular crystals, have been identified as thomsonite with the following properties: colourless, straight extinction, elongation parallel to β, $2V=66° \pm 2°$.

Xenoliths

Xenoliths of quartzose sandstones have been collected from the centre of the olivine dolerite. In the field they are indistinguishable from the normal olivine dolerite and are revealed only by sectioning. They have a glassy selvage of fine-grained dolerite and are often discoloured at the margin by limonite. Veins of calcite occur within the xenoliths, and many show extensive carbonate metasomatism where tongues of dolerite have penetrated the rock.

It is probable that many of the xenoliths were assimilated in the magma. The extensive carbonate alteration of the dolerite, the presence of some chalcedony amygdales, and calcite veins and masses in the vincinity of the xenoliths may indicate the effects of assimilation.

Contact Effects Shown by the Sill (Fig. 4A)

The contact sediments are quartzose sandstones and siltstones cemented by carbonate and siliceous material and show very little signs of metamorphism. This is probably the result of the injection of the sill into wet, unconsolidated sediments. Because of the high specific heat of water, as the sill cooled much of the heat given off would be used to vaporise the water held in the sediment after which there was insufficient heat left to cause any widespread alteration of the intruded sediments.

The sill to the south of the Kaiwhata stream has caused baking of the sediment within a few inches of the dolerite contact, as the rocks are indurated. The quartz grains present in the sediments become considerably reduced in size near the contact perhaps owing to reaction with carbonate. This suggests that much of the carbonate present near the contact has been introduced when the sill was intruded, although in the unaltered sediment carbonate forms part of the cementing material. Ferro-magnesian minerals are conspicuously absent near the contact and are probably represented by areas of chloritic material now present. Small flecks of pyrite are found at or near the contact.

The sediments in contact with the sill to the north of the stream have a spotted appearance for a distance of up to 10ft from the dolerite. In thin section the spots are found to be conglomerations of chloritic material. Within a few inches of the contact the rocks are indurated. Again quartz becomes reduced in size and volume near the contact and the carbonate percentage increases. There is no sign of any adinolisation of the sediments.

PETROGENESIS

The Sill to the South of the Kaiwhata Stream

This part of the sill (Fig. 3A_1, A_2) shows an olivine-poor basal margin (1.5ft thick) overlain by an olivine rich dolerite (17ft thick) which is in sharp contact with an augite-rich dolerite (4ft thick) extending to an upper chilled variolitic margin. A xenolithic zone is present within the olivine dolerite near the centre of the sill. Several hypotheses have been considered by the writer to explain this compositional variation. A single injection of magma crystallising inward from the roof and floor is unlikely because of the asymmetrical composition of the sill above and below the xenolithic zone. The last products of crystallisation would be expected near the centre of the sill, but they are partially found as amygdale fillings at the top of the sill. Also the plagioclase is sodic ($An_{38\text{-}44}$) towards the top and calcic ($An_{56\text{-}62}$) towards the centre.

There is no compositional or textural evidence for gravitational sinking of olivine or pyroxene, and the central position of the light quartz-carbonate xenoliths would be difficult to explain by gravitational settling.

A multiple-intrusion hypothesis would require two injections with no significant time lag (absence of interior chilling) and might explain the central position of the xenoliths as marking the top of the first injection. However, the abrupt, but unchilled, contact between the olivine dolerite and the overlying augite dolerite in the upper part of the sill, which would presumably be the hottest, would require a third pulse of magma. Thus for the formation of the sill three separate intrusions in the same time and place would be needed. Also, if the xenoliths occur at the top of the first injection, then the question arises as to why they are correspondingly absent in the upper part of the sill. These difficulties make the multiple-intrusion hypothesis unlikely.

The small amount of olivine/augite phenocrysts in the chilled margins and the abrupt discontinuity between the olivine and augite dolerite in the upper part of the sill suggest a fourth alternative, that of flow differentiation (Bhattacharji and Smith, 1964) aided by gravity (Bhattacharji, 1965; 1967). This hypothesis is based on the movement of particles away from the margins towards the centre of the sill, the area of low shear gradient, a mechanism which has a definite explanation by way of experimental approach. Petrographic evidence suggests that this alternative was at least the *primary* mechanism that produced the compositional variation shown in the sill. Bhattacharji (1965; 1967) has produced the pattern shown in

Fig. $3A_2$ in scale-model experiments. Crystals of olivine and augite in the chilled margins indicate that the magma already contained these minerals when it was intruded. By analogy with experiments using viscous fluids and solids of different densities, sizes, and shapes simulating the properties of olivine (Fo_{40-85}), pyroxene, and plagioclase (labradorite–bytownite) it is suggested that during intrusion these minerals were influenced by the combined effect of flow concentration and gravity and moved in the lower two-thirds of the sill as a crystal mush. The concentration of crystals within this mush seems to have been high enough to cause grain interference, inhibiting any gravity segregation of individual minerals or crystal orientation. Such an environment would also be favourable for the formation of glomeroporphyritic clusters of olivine and augite. The interstitial liquid in this viscous mush is now represented by the fine-grained interstitial masses of bowlingite, ilmenite, and plagioclase. Flow concentration may have caused the central concentration of xenoliths where they are associated with large (3–4mm in diameter) crystals of poikilitic labradorite.

The lower transitional discontinuity between the olivine-poor basal margin (3–7 per cent olivine) and the overlying olivine dolerite (30–40 per cent olivine) was probably caused by a combination of rapid chilling, inhibiting crystal settling, and the tendency for the crystals to move away from this area of high shear gradient during flowage. The top of the olivine dolerite would essentially be the interface between the crystal mush and overlying liquid, gravity and flow concentration producing the abrupt discontinuity shown in Fig. $3A_2$. Above this discontinuity small euhedral crystals of augite and the subvariolitic growth pattern of the plagioclase indicate that this liquid crystallised fairly rapidly after intrusion. Lateral flow of the magma combined with rapid consolidation may have caused the undulatory extinction shown by most of the augites in this part of the sill. A few glomeroporphyritic clusters of olivine probably represent crystals caught in the liquid overlying the discontinuity and " frozen " in place by rapid consolidation.

The composition of the plagioclase (An_{38-44}) in the augite dolerite and variolite indicates an upward increase in soda. The clinopyroxenes (Table III) show a slight increase in calcium above the upper discontinuity and an increase in iron in the olivine dolerite.

The presence of calcite veins and rounded amygdales in the variolite containing calcite, limonite, zeolite, chlorite, and varieties of silica suggest that these are late phase products, probably combined with silica and calcite liberated from xenolith assimilation. This material was carried upwards by the separation of a gas phase through the consolidating magma to condense as amygdales.

The Sill to the North of the Kaiwhata Stream

The albite dolerite adjacent to the first injection of olivine dolerite was formed by a second injection of magma.

Subophitic-ophitic texture between pyroxene and plagioclase probably indicates that these two minerals crystallised together. Crystals of both minerals occurring near the margins are commonly cracked and granulated, which suggests that they were sheared when the magma was intruded. Irregular interstitial masses of bowlingite indicate that it is not a pseudomorph after olivine, and thus olivine probably did not crystallise in this part of the sill. Apatite, ilmenite, and quartz were precipitated later.

Analcitisation, kaolinisation, and sericitisation of plagioclase, alteration of ilmenite to leucoxene, and the replacement of analcite by bowlingite provide evidence for the activity of residual solutions. A late-stage alkali-silicate water environment was responsible for the formation of bowlingite, thomsonite, orthoclase rims around albite, minor biotite, and the growth of large skeletal ilmenite crystals.

An important question arises as to the primary or secondary origin of albite. The presence of cracked and granulated crystals of albite may imply that the plagioclase was already albite when the magma was injected, and thus it would be of primary origin in the sill. It may be assumed that if a more basic plagioclase was changed to albite after intrusion a great deal of the original cracking would have been masked out. One of the main objections to the primary character of albite has been its ophitic intergrowth with pyroxene, for the physical chemistry of the problem is against it. Battey (1956: 103), however, has suggested that partly metastable pyroxene could be rapidly precipitated along with plagioclase in a water-rich environment. This environment would be favourable for free diffusion, allowing the plagioclase to become more soda rich by continuous reaction. Some crystals in the sill show slight zoning from a sodic oligoclase core to an albite periphery. The coarse-grained nature of the rocks, especially in the upper part of the sill, suggests a high water content, which would prolong crystallisation to lower temperatures. If it be assumed that the pyroxene was in part metastable, the release of the anorthite molecule from the continuously changing plagioclase may have been partly taken up by the pyroxene (Table III). Calcium also would be needed for the formation of epidote, chlorite, and calcite concentrated at the top of the sill, sericite and clinozoisite associated with the albite, the Na-Ca zeolite thomsonite, bowlingite, and apatite.

The absence of albite-filled vesicles and veinlets, remnants of more basic plagioclase replaced by albite, and adinolisation of the surrounding sediments suggest that the albite in the sill was not formed by soda metasomatism.

On the above evidence it would seem that the plagioclase was already sodic when the sill was intruded and that it was formed by continuous reaction in a water-rich environment associated with metastable pyroxene in the magma chamber and/or during intrusion.

Petrographic evidence suggests that after the formation of a chilled selvage the sill solidified *in situ* as an essentially homogeneous mass from one magmatic injection. The residual liquids were displaced upwards during consolidation, resulting in a progressive upward coarsening in grain size. The upward decrease in pyroxene,

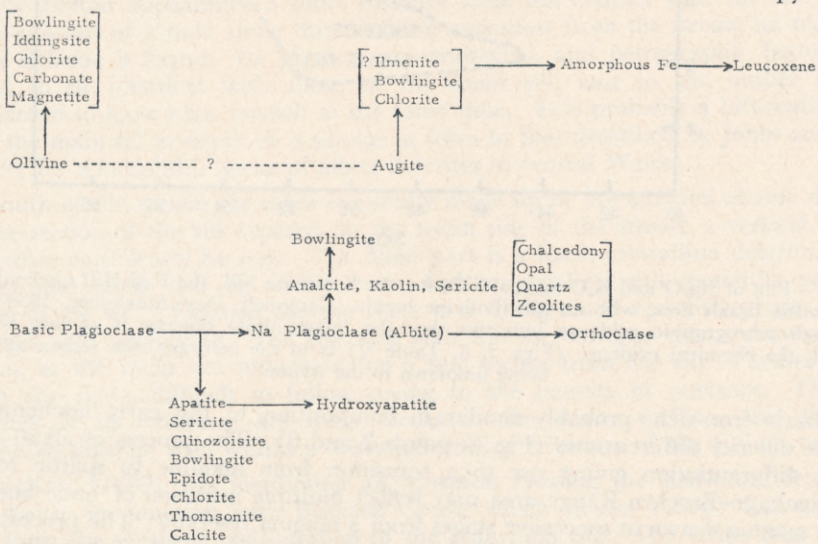

FIG. 6.—Reaction series shown by the rocks of the Kaiwhata Sill. The upward-pointing arrows indicate replacement of lower mineral by the upper ones. The downward arrow indicates precipitation of the lower minerals while the one above is changing during the course of crystallisation.

balanced by the increasing amount of plagioclase and bowlingite (Fig. $3B_2$), suggests that the augite ceased to crystallise before plagioclase. There is no appreciable evidence for gravitational sinking of pyroxene, and the retardation of such sinking was probably the result of high viscosity, shown by the high SiO_2 values given in Table V, aided by crystal interference between pyroxene and plagioclase already in the magma.

Regional Petrogenesis

If Na_2O, K_2O, and SiO_2 analyses of the rocks from the Kaiwhata Sill, the Red Hill teschenite in the Brocken Range, and a variolitic basalt flow at Nghape (Hutton, 1943: 368) (see Table V) are plotted on an alkali/silica diagram (Fig. 7), the rocks fall into the alkali basalt field, and show a strong increase in $Na_2O + K_2O$ with increasing silica in the albite dolerites. Fig. 7 suggests that the teschenite–olivine dolerite–variolitic basalt series and the albite dolerite series are "conjugate magmas" derived from an alkali–olivine basalt parent, similar to that quoted by Campbell, Day and Stenhouse (1932: 349). Fig. 8 shows that the parent magma

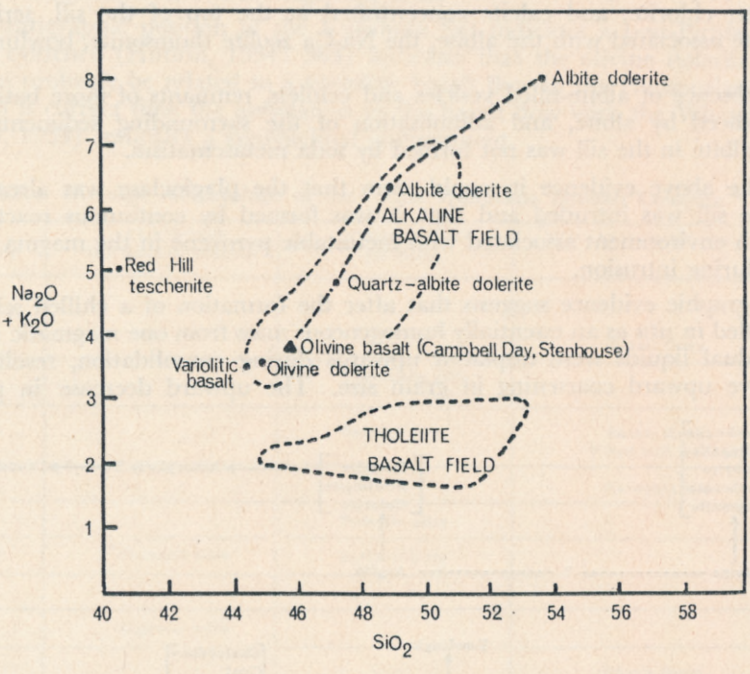

Fig. 7.—Plot of Na_2O and K_2O against SiO_2 for the Kaiwhata Sill, the Red Hill teschenite, and a variolitic basalt flow, with an alkali-olivine basalt (Campbell, Day, Stenhouse, 1934: 349). Although petrographic evidence indicates that the quartz-albite dolerite is of late origin in the sill, the chemical evidence (Figs. 7, 8, Table V) is to the contrary, the reason at present being unknown to the writer.

was fairly iron-rich, probably similar in composition to the early teschenite and olivine dolerite differentiates (Fig. 8, points 2 and 6). The process of alkali–olivine basalt differentiation giving rise to a transition from alkaline to spilitic rocks in the Ngahape–Brocken Range area may reflect multiple intrusion of basic and more silicic magma drawn at successive stages from a magma reservoir. The process would be complicated, probably involving assimilative reaction with geosynclinal sediments associated with alkali/volatile transfers in the magma, which would have been helped by the removal of early-formed olivine, pyroxene, and basic plagioclase in the early teschenite, olivine dolerite, and variolitic basalt differentiates.

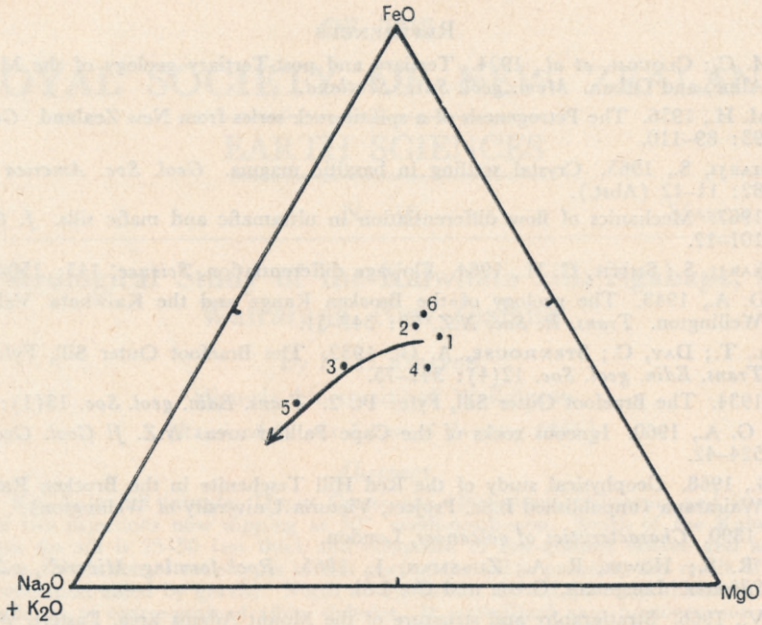

FIG. 8.—Plots for FeO–MgO–(Na_2O +K_2O) showing the differentiation trend of the Kaiwhata Sill magma. 1: Parent alkali-olivine basalt (Campbell *et al.*, 1934: 349); 2: Olivine dolerite; 3: Albite dolerite; 4: Quartz-albite dolerite; 5: Albite dolerite; 6: Red Hill teschenite.

TABLE V.—Chemical analyses of the Kaiwhata Sill rocks, the Red Hill teschenite, a variolitic basalt flow, an alkali olivine basalt, and average spilite. A. Red Hill teschenite—from Red Hill, head of Opokongoruru Stream, west side of Brocken Range. B. Olivine dolerite—from Kaiwhata Sill—40 chains upstream from bridge at Ngahape. C. Variolitic basalt, Ngahape "bluff" near bridge at Ngahape. D. Quartz-albite dolerite, same locality as for B. E. Albite dolerite, same locality as for B. F. Albite dolerite, same locality as for B. (Analyses A, B, C, D, E, and F taken from Hutton, 1943. Analyst: F. T. Seelye.) G. Average spilite (Sundius, 1930: 9). H. Alkali-olivine basalt. (Campbell, Day and Stenhouse, 1934. v. 13: 349.)

	A	B	C	D	E	F	G	H
SiO_2	41.06	44.79	44.45	47.20	49.18	53.37	51.22	45.33
Al_2O_3	12.75	11.45	12.78	12.24	14.46	15.22	13.66	14.99
Fe_2O_3	2.24	0.65	4.98	5.37	5.29	4.23	2.84	3.38
FeO	11.48	9.06	4.91	7.83	7.04	4.89	9.20	8.75
MgO	6.53	5.03	6.82	7.12	4.05	2.22	4.55	6.93
CaO	9.55	12.29	9.53	3.08	5.84	5.43	6.89	8.06
Na_2O	4.22	2.93	3.13	3.93	4.96	6.88	4.93	2.94
K_2O	0.80	0.75	0.44	0.78	1.29	0.91	0.75	1.00
H_2O^+	3.78	0.98	1.98	4.76	2.67	1.97	{ 1.88	5.66
H_2O^-	0.40	1.56	5.36	2.05	0.90	0.90		
CO_2	trace	6.61	1.40	0.34	nt. fd.	1.38	0.94	0.15
TiO_2	6.35	2.91	3.17	2.57	3.22	1.82	3.32	2.23
P_2O_5	0.39	0.73	0.72	1.49	0.88	0.70	0.29	0.28
MnO	0.12	0.14	0.13	0.14	0.19	0.10	0.25	0.20
Rest	0.32	0.365	0.334	0.23	0.273	0.155	-	0.18
Total	99.99	100.26	100.13	100.13	100.25	100.18	100.72	100.08

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R. GRAPES,
Geology Department,
Victoria University of Wellington,
New Zealand.