The Basic Igneous Rocks of Eastern Otago and Their Tectonic Environment.

By W. N. Benson.

PART IV.—THE MID-TERTIARY BASALTS, THOLEIITES, AND DOLERITES OF NORTH-EASTERN OTAGO.

Section A: Distribution and Geological Occurrence.

(With Age-determinations by H. J. Finlay.)

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Introduction and Stratigraphy.

The rocks considered herein occur within a quadrant extending twenty-five miles south-west to north-west of Oamaru. So far as is at present known there are no massive Older or Middle Tertiary basic igneous rocks in Otago outside those limits. Their geological occurrence may be described briefly. With but few exceptions they are found less than a thousand feet above sea-level. The basement formations exposed in the high land west of this quadrant consist of semi-schistose Late Palaeozoic (?) to Early Mesozoic greywackes and argillites with a very small amount of unfossiliferous limestone, and make up the Kakanui Ranges. They are overlain by Upper Cretaceous conglomerate and sandstone followed by marine sediments, largely glauconitic sandstone, siltstone, and mudstone containing molluscan and foraminiferal faunas ranging from Late Cretaceous to Late Eocene, including the well-known Bortonian (Middle Eocene) and Tahuian (Upper Eocene) stages (Finlay and Marwick, 1940, pp. 106–110), and others the details of which will appear in the forthcoming Geological Survey Bulletin on the Moeraki subdivision. Above these are the submarine agglomerates and bedded tuffs of the Waiarekan series in the upper portion of which (Marwick, 1926, p. 308) is a fauna considered Lower Oligocene by Finlay and Marwick (1940, p. 110), though in the Moeraki region the lowest portion of this formation is interstratified with the highest part of the Tahuian beds. It remains to be demonstrated to what extent this formation wedges out or merges into coeval glauconitic sediments in the western portions of the Oamaru District (cf. Uttley, 1920, pp. 154-182). In the regions between the Waitaki and Kakanui valleys these tuffs are covered by the Late Lower and Middle Oligocene, Lower and Upper Ototaran limestones. In the regions adjacent to Oamaru there occurs between these two limestones a westward-thinning wedge of basic tuffs and breccias (Deborah tuff or Kakanui breccia), with which are interstratified the effusive masses of basalt, largely pillow-lava, the geological description of which forms the first part of this paper. Dykes, sills, plugs and dome-like—possibly laccolitic—masses of basaltic rocks invade all the formations below the Kakanui breccia. South of the Kakanui River dykes and intrusive sheets occur widely in the Waiarekan, earlier Tertiary, and Cretaceous formations; but in the writer's view, and contrary to previously expressed opinions, no surface-flows have been proved to exist here. In spite of Park's not very explicit remarks (Park, 1918, pp. 75-76), no igneous material has been proved to break through the Upper Ototaran limestone or to rest upon it save as detrital fragments. The limestone is followed by Late Oligocene greensands and varied early Miocene sediments, largely mudstones. This brief statement must be regarded as a simplification (sufficient for our present purpose) of some complex details of facies-change and disconformities in the stratigraphical succession in Upper Oligocene-Lower Miocene times. After folding in Middle-Upper Tertiary times extensive flood-plains were cut from the softer formations, which thus became partially covered with widespread sheets of alluvium partly shown in our map, and now standing at elevations of several hundred feet, above which remain as small monadnocks portions of the larger masses of basalt and dolerite. Renewed uplift permitted the dissection of these high-level alluvial plains and the formation of the present system of valleys with their low-level alluvial plains, the extent of which is shown on the map herewith. Other details of topographic evolution are here omitted.

The region is one of considerable stratigraphic interest and has attracted much attention beginning with the rapid but acute observations of Mantell (1850) during his first southward exploratory journey. Later observations concerning the igneous rocks were recorded by Hector (1864, 1864a, 1865), Haast (1872, 1877), Hutton (1875, 1887, 1889), McKay (1877, 1884, 1887), Park (1887, 1905), Thomson (1906), and Uttley (1916, 1918, 1920, 1920a). Park's (1918) very useful general account of the region between the Waitaki and Kakanui rivers was supplemented and modified in certain particulars by Uttley (1920b). Within recent years the region south of the Kakanui River has been carefully surveyed by Mr. D. A. Brown (1938), whose official bulletin thereon awaits publication. The petrographical study of the massive basic igneous rocks was commenced by Hutton (1887, 1889) and continued later by Uttley (1918) and Park (1918); that of the Kakanui tuffs was made by Thomson (1906, 1907). Brief mention of the petrography of the region has been made by Marshall (1907, 1925). The present paper is an expansion of a chapter prepared for the Geological Survey Bulletin on the Moeraki Subdivision, and is now published by courteous permission of the Director of the Geological Survey.

The map (Fig. 1) is compiled from Park's (1918) map of the Oamaru District and McKay's (1887) of the regions south of the Kakanui River, modified to include (by permission) some of the features noted by Mr. Brown, and others noted by the writer, more particularly in the Moeraki Peninsula. The estimates of the geological age of the sedimentary formations cited are in the main those of Finlay and Marwick (1940) or Brown's (1938) earlier note in which age determinations were based on Finlay's preliminary microfaunal studies, later extensions of which into the immediate vicinity of Moeraki have (by permission) been cited herein. The writer's cordial thanks are due to the Director of Geological Survey, Dr.

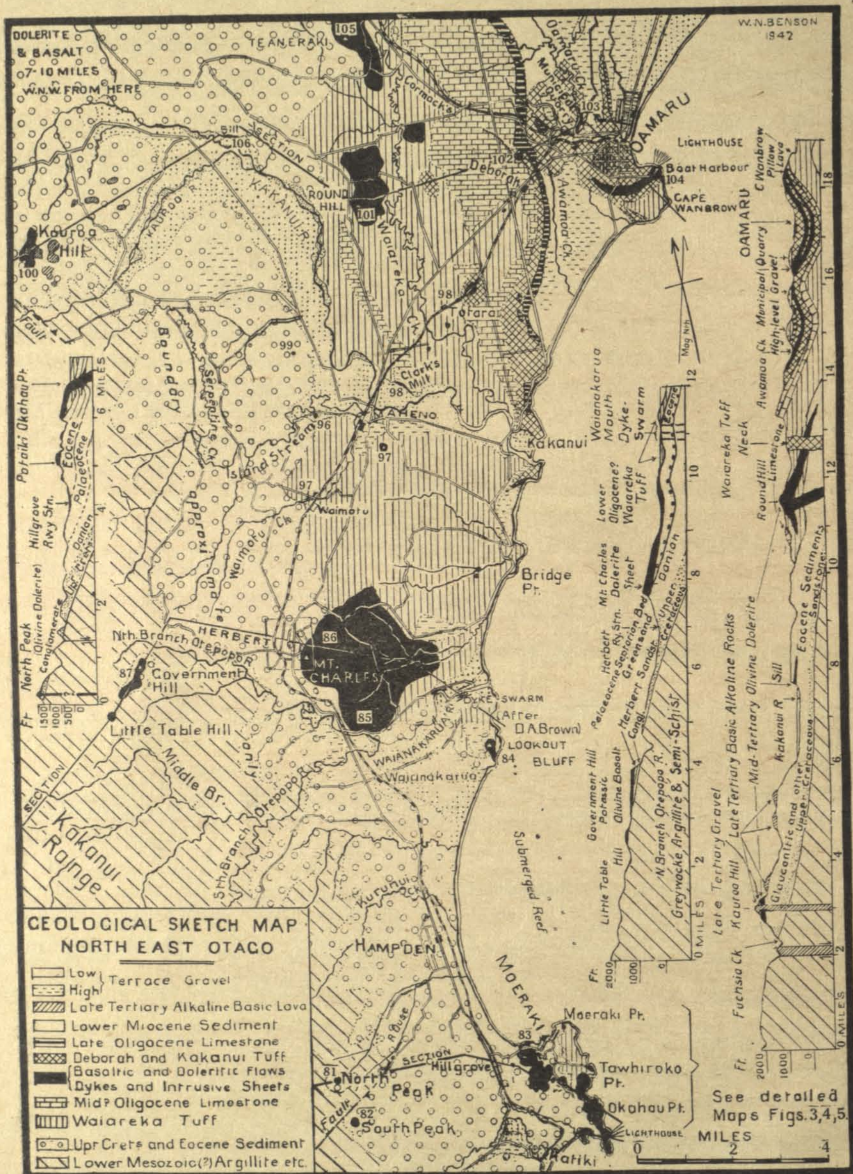

FIG. 1.

Distribution of Mid-Tertiary Basic Igneous Rocks in North-East Otago, with generalised cross-sections and Locality-Numbers of occurrences of described rocks.

Henderson, for thus affording facilities for the early completion of this paper; to Drs Finlay, Marwick, and Hutton, Mr D. A. Brown, and Mr A. W. Hampton, of the Geological Survey, for help in various ways; to Mr J. D. Raeside, of the Soil Survey, for assistance in the Moeraki area, and to Mr Gourlay, head master of the Moeraki School, for ascertaining the Maori names of certain places.

THE PILLOW-LAVAS AND OTHER MASSIVE FLOWS NEAR OAMARU.

Hector (1865) first recognised the submarine origin of the flows and breccias beneath the Oamaru Lighthouse, and Hutton (1875) noted that they contained " fragments of altered limestone " and of tachylite. McKay (1877) termed them " tufas and volcanic rocks as large spheroidal masses with interspaces filled with altered limestone." Hutton (1887), reversing his former view, concluded that the ' limestone ' and the ' limestone dykes ' (see Park 1918, Plate 9) among the breccia were not altered but were merely segregation-veins though fossiliferous. It may be suggested that they were formed by the downward-filling of fissures resulting from earthquakes or volcanic explosions and extending to the sea-floor, which was littered with small loose remains of bryozoa, echinoderms, etc., subsequently compacted to form the Upper Ototaran limestone, and that the induration of these veins has resulted from recrystallisation. They cut through tachylite-breccia more or less changed to palagonite, and through masses of broken bombs of hypocrystalline basalt, or " magma-basalt " within a tachylite envelope, recalling the small basalt-lava masses " which occur sometimes in bombs and vesicular spheroidal masses which are in part embedded in tuff " (Rosenbusch, 1908, p. 1277). Hutton (1887, pp. 417-8, 1889, pp. 147, 150) gave brief petrographic descriptions of the partially crystalline dolerite within the bombs (sp. gr. 2·80), and of their tachylite or " magma-basalt " selvedges (sp. gr. 2·72).

Beneath this coarsely fragmental material is a layer of soft fossiliferous tuff, with a fauna similar to that in the Upper Ototaran limestone. This has been eroded into the little cove termed Boatman's Harbour (Locality 104). It lies on what Hutton (1887) described as " a remarkable agglomerate formed of large basalt-bombs up to six feet in diameter, each encased in a layer of tachylite about an inch thick, and having their lower surfaces curved around the underlying bomb." Park (1905, pp. 573–4) was the first to recognise this as pillow-lava, and both he (Park, 1918, Plate 4, pp. 38–39) and Uttley (1918, pp. 113-6) have described and illustrated its features in some detail. There was, however, some uncertainty as to its stratigraphic position. Park (1918) described it as occurring in the highest portion of the Waiarekan tuffs, and drew a carefully measured section (*op. cit.*, Plate 2B) in illustration thereof; but his accompanying map indicated that it occurred at a higher horizon, i.e., within the local equivalent of the Deborah tuffs, a view supported by Uttley (1920b, p. 180–1), which the writer deems the more probable. It may be added that it was poured out over unconsolidated tuffs in which, beneath the load of 80–90 feet thick of heavy forward-thrusting lava, slump-structures were developed. Below these tuffs are two thin bands of strongly calcified breccia, an " impure " or hard limestone 3-12 ins. thick, containing large, angular pieces of basalt (Park, 1905, p. 515. 1918, Plate 2b). The lower band rests with local unconformity on the Waiarekan tuffs and may represent the lower Ototaran limestone.

Park (1918, p. 41) and Uttley (1918, P. 113; 1920b, p. 181) called attention to the occurrence of coeval pillow-lava in Awamoa Creek (Locality 102) where the pillows are up to eighteen feet in diameter, and again above the massive dolerite flow in the Corporation Quarry in Oamaru Creek (Locality 103) (Uttley, 1918, p. 113). Uttley remarked that several authors have recognised that pillow-lava may form not only as subaqueous flows poured over the floors of lakes or of the sea, but also when the magma flows through the unconsolidated silts forming the sea floor into which it was thus intrusive, but he did not apply this explanation (as the writer would) to the peculiar relations of the pillow-lava to the fine-grained tuffs overlying it at Locality 103. Finally it may be noted that Park (1918, p. 43) recorded the presence of pillow-lava [possibly the lava noted by McKay (1877, p. 50, fig. 3) *above* the lower Ototaran limestone] in the railway-cutting a quarter of a mile north of the Totara Station, (Locality 98A). Park's map indicates that it occurs among the Waiarekan tuffs; but the writer concurs in McKay's view of its stratigraphic position. It lies among Deborah tuffs in a local depression or thinning of the lower Ototaran limestone which is visible at one point beneath the pillow-lava in the cutting but rises to higher levels on either side of the railway line. Tentatively it may be inferred that most if not all flows of basalt and dolerite in the Oamaru District and the dykes, etc., which fed them, were erupted in the interval between the periods of deposition of the Lower and Upper Ototaran limestones, i.e. in early Mid-Oligocene times.

The several stages in the process of crystallisation displayed in a series of sections taken at intervals from the glassy selvedge (sp. gr. 2.74) to the tholeiitie or hypocrystalline central portion (sp. gr. 2·830) of the large lava-pillow in Awamoa Creek were described by Uttley (1918).

Basalts, Tholeiites, and Dolerites North-West, West and South-West of Oamaru.

(Chiefly or Wholly Intrusive.)

1. *North of the Kakanui River.*

Though Hector's (1864) first manuscript geological map of Otago showed basic igneous rock south-west of the junction of the Kurow and Waitaki rivers 35 miles N.N.W. of Oamaru, this record was not confirmed by McKay (1877) nor by the more detailed studies of Uttley (1920b) and Marwick (1935). McKay (1877, p. 66), however, noted the dolerite beneath the limestone crossing the Maruwenua* River five miles south of its junction with the Waitaki. Uttley (1920b, p. 150) held that this comprised two sills invading greensand in the lower part of the Waiarekan formation, though later (1920a, p. 168) he remarked that the evidence for their intrusive character is inconclusive. These sheets extend two miles to the N.W., rising into Basalt Hill, 1210 feet high (Trig. T of Maruwenua Survey District,† 21 miles W.N.N. of Oamaru). What is probably the eastward extension of this sheet is the olivine tholeiite noted by Uttley (1920a) and the writer (Slide No. 5725)‡ three miles S.S.E. of Basalt Hill and

* Considerable variation exists in the spelling of this name in official Publications. The above is the form used by the Lands and Survey Department.

† Hereinafter abbreviated to S.D.

‡ Slide Nos. without the prefix P. are those in the catalogue of the Geological Department, University of Otago.

two miles N.W. of Tokarahi, where again nothing definite was determined concerning its intrusive or effusive character. Since then Uttley (pers. com.) has found pillow-lava on what appears to be approximately the same horizon two miles east of Tokarahi. The overlying limestone is not, however, of Upper Ototaran Mid-Oligocene age, but belongs to the younger Late Oligocene Waitakian Stage (Park, 1918. pp. 25, 83; Allan, 1933, p. 97; Finlay and Marwick, 1940, p. 115). It thus seems possible that the geensand enclosing the basalt is coeval with the Deborah rather than with the Waiarekan tuffs, but no palaeontological evidence has been adduced concerning this as yet. If the suggested comparisons be substantiated, the whole series of basic flows and sheets between Basalt Hill and Boatman's Harbour may be coeval with the Deborah tuffs. The microscopic features of the Tokarahi rock (5725), though differing in minor details from those of the pillow-lava (5753) in Awamoa Creek. are similar to it in all essentials.

Hutton (1887, p. 415, Plate 26, Section 3) noted at Enfield (= Teaneraki Locality 105), six miles W.N.W. of Oamaru, an extensive mass of basic rocks, which he considered finely crystalline lava-flows. These he considered to mark a volcano, and not finding any olivine therein he classed them as augite andesite *(loc. cit.)* or augite porphyrite (Hutton, 1889, p. 130). Park (1887, p. 139; 1918, p. 33) described these occurrences as " prominent outcrops of dyke-like masses or sills of dolerite that penetrate the Waiarekan sandstone," and described the rock as an ophitic dolerite with sp. gr. 2.94. Microscopically at least one rock from here (6785 = P5604 in the Geological Survey Collections) is indistinguishable from that (5753) in the centre of the large pillow on Awamoa Creek. Four miles W.S.W. of this, the lower Waiarekan sandstones are invaded by a sill of decomposed ophitic dolerite, which extends for 550 yards along the northern cliffs of the Kakanui Valley near Trig. S. Oamaru Survey District (Park, 1918, p. 33).

Round Hill (Locality 101), which McKay (1877) figured as the apex of an anticlinally folded basalt sheet, may perhaps be the upper surface of a thick sill. It is an olivine dolerite (5724). The mass of " basalt " mapped by Park (1918) as occurring a mile east of this proves, however, to consist of agglomerate containing large fragments of ultrabasic rock and coarsely granular dolerite, and is probably a vent through which was erupted some of the material in the Deborah-Kakanui breccias traversing and including portions of a dolerite-sheet. A mile north of this, and west of Cormack's Railway Station a sheet of columnar basalt among Waiarekan tuff was classed by Park (1918, p. 47) as a flow without citation of evidence distinguishing it from a sill.

Four miles south of Round Hill, and a mile east of Maheno, the lower Ototaran limestone forms the cliffs behind Clark's flour-mill (Locality 98). Here porphyritic augite olivine basalt (5721) forms an irregular sill invading the lower portion of the limestone, into which it sent ramifying veins, as was described and figured by Park (1905, pp. 508–9, 1918, p. 44, fig. 11) and is illustrated here (Fig. 2). Before the intrusive veinlets of basalts had been noted this section was cited (McKay, 1877, pp. 65–6) as evidence that the dolerites were older than the overlying limestone, and therefore older than the basaltic lavas at Oamaru.

Other minor intrusions of basic igneous rocks within two miles north and east of Clark's mill [including a plug of rather decomposed olivine basalt (5866) half a mile south of Totara railway station (Locality 98A) and several dykes not yet examined petrographically] have been noted by Park (1918).

2. South of the Kakanui River.

Near the Kakanui River at Locality 99 (Trig. O, Oamaru S. D.) a small plug of dolerite invading sandstone rises into a small craggy peak, "Old Man Hill." It is coarse and very decomposed.

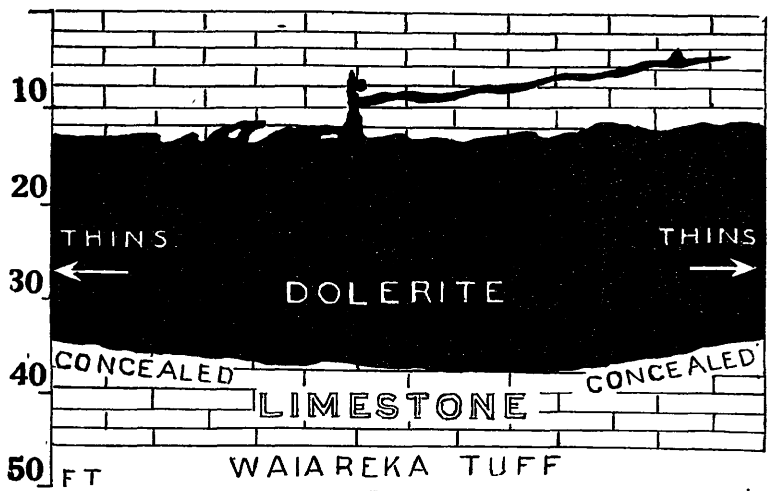

FIG. 2.

Dolerite sill in the Lower Ototaran Limestone by Clark's Mill, Maheno.

Description of the occurrences of basic igneous rocks further south of the Kakanui River may be prefaced by the comment that here the sequence of Upper Cretaceous and Lower Tertiary sediments is more varied and extensive than in the Oamaru District north of this river. The information summarised in Brown's (1938) preliminary account has since been extended and modified by field and micropalaeontological studies, resulting in more detailed subdivision of the sequence of beds developed, the statement of which will be given in the forthcoming official bulletin on the Moeraki district. Here advantage will be taken of the courtesy of the Geological Survey to mention only the minimum amount of the stratigraphical data required to throw light on the occurrence of the igneous rocks. The Cretaceous conglomerates and sandstones are followed by various sandy, silty, or muddy marine sediments, glauconitic or not, and greensands referable to very late Cretaceous or Lower Eocene rocks. The highest of the sediments recognised below the tuffs of the Moeraki Peninsula are grey mudstones, which have been provisionally determined to be of Tahuian (Upper Eocene) age. Tuffs here classed with the Waiarekan tuffs rest on the Tahuian mudstones immediately east of Moeraki Point, and near Tawhiroko

Point appear to be interstratified with their higher portions (See Fig. 4). It would seem, therefore, that the base of the Waiarekan tuff at Moeraki is older than that portion of this formation developed west of Oamaru to which Finlay and Marwick (1940) have assigned an early Kaiatan (Lower Oligocene) age.

The main mass of these tuffs forms the low undulating coastal strip between the Kakanui and Waianakarua rivers, and contains interstratified foraminiferal beds at Bridge Point (*fide* Dr. Finlay). It is represented also at Lookout Bluff (Location 84) which Hutton (1887, pp. 428–9) described (incorrectly?) as an old volcano, and forms much of the north-eastern part of Moeraki Peninsula. Brown (1938) at first followed the earlier workers in considering that the dolerites of Mount Charles (Locality 86), Lookout Bluff, Moeraki Peninsula (Locality 83), and also those of Trig. S. (Locality 97), Waimotu (Locality 96A), Government Hill, and Little Table Hill (Locality 87), and North and South Peaks (Localities 81 and 82), were portions of flows closely associated with the eruptions of the Waiarekan tuff; but he has since (pers. com.) and in the light of observations recorded below, accepted the writer's view that they are younger intrusive masses.

The higher sedimentary formations, the Ototaran limestone and associated and succeeding Middle Tertiary strata, which, south of the Kakanui River, occur only in the immediate vicinity of its mouth, have no bearing on our present topic.

The Maheno-Government Hill Sheet.

The basalt and dolerite sheets of the Maheno-Government Hill-Little Table Hill group, of Mount Charles, and of the Moeraki group dip eastward with a general inclination less than that of the Cretaceous and Lower Tertiary sediments with which they are associated, and are accordingly in contact with younger sediments as they extend eastwards. They do not, however, rest, like the Late Tertiary igneous rocks, on a plane of erosion obliquely truncating the plane of stratification of these sediments; but, wherever contacts are well exposed, they may be seen to invade these sediments. This is less obvious in the northern groups than in the Moeraki group. There is an obvious petrographic difference between the rocks of the first group, which form a unit, and the other basic igneous rocks south of the Kakanui River. Those of Mount Charles, the Moeraki group, and the residual masses on North and South Peak, south-west of Hampden, are similar to one another, but can hardly be considered to have been portions of one formerly very extensive sheet. The rocks at Lookout Bluff have been so far little studied. The single section examined (5752) differs from any rock found in Mount Charles or the Moeraki sheets, but not sufficiently to indicate it is unrelated thereto.

The distinctive feature of the rocks of the first mentioned group is their slightly potassic character, expressed by the presence of a little anorthoclase and biotite in the olivine basalt of Maheno, and the olivine basalt of Goverment Hill, the occurrence also of analcite in the fine grained dolerite over a mile west of Maheno, and more especially by the coarsely granular basic syenite rich in anorthoclase, analcite and biotite at Waimotu (Locality 97A), a mile south of the last, which may be considered a " wet " or pegmatoid phase of this sheet. The southernmost portion of it is probably the basaltic rock capping Little Table Hill (1684 feet), and has not yet been examined microscopically. It rests directly on Palaeozoic (?) argillite (Brown, pers. com.), and is thought to have been injected between this and the Cretaceous sediments. In Government Hill (1493 feet) it is in contact with the Herbert (Upper Cretaceous, limonitic) sandstone of Brown, (1938). It makes a prominent mesa nearly a mile long, in which the basalt is separated by friable sediments from the more steeply sloping surface of the argillite below (the Cretaceous peneplain), as has been well illustrated by Cotton (1922, p. 147, fig. 152). At Waimotu (129 feet) it invades Waiarekan rocks, but probably invades Bortonian (*fide* Brown) where it appears beneath terrace-gravels a mile west of Maheno. At Trig. S. (250 feet), half a mile south of Maheno, it is among Waiarekan tuffs.

The Mount Charles Sheet and Smaller Isolated Masses.

The Mount Charles sheet is about 150 feet thick, at its highest point (744 feet) and covers a nearly circular area two miles across, dipping eastward at about 3°, and passing into or below Waiarekan tuff and high-terrace gravel (190 feet) near the coast. Its lower contact with the Danian (provisional determination by Finlay, pers. com.) glauconitic sediments exposed in the scarp near the Otepopo road and railway bridges shows little sign of alteration of the latter other than a slight induration and pyritisation extending for an inch below the dolerites, but all rocks here are very decomposed. On its upper surface near Trig. B, two miles S.E. of Mount Charles, there are isolated blocks of indurated mudstone (5089) like the porcellanite formed at the contact of the Moeraki sheets with the Mid- and Upper Eocene (Bortonian and Tahuian) sediments. Brown (pers. com.) has since found similar material near the summit of Mount Charles. McKay's (1877, p. 65) account of the south-eastern extension of this sheet as exposed in the " Otepopo "[1] or Waianakarua valley a mile and a-half from its mouth, indicates that it is there bent into an anticline and lies above greensand and below marl and tuff. This exposure has not been examined by the writer, and the eastern portion of the section on Fig. 1 must be regarded as merely suggestive.

The rock of this sheet is generally coarse, rich in deuteric carbonates, and commonly so decomposed as to be almost friable. It was described by Hutton (1887, p. 428; 1889, p. 130) first as dolerite, and later as augite diorite. Though no detailed examination of the sheet has yet been made, the range of characters in the available unlocalised specimens, viz., olivine dolerite to olivine-free quartz dolerite is so like that in the Moeraki sheets as to suggest that the Mount Charles sheet is also gravitationally differentiated.

The porphyritic stilbite (?) bearing olivine basalt (5752) capping Lookout Bluff is less coarse, and is probably a portion of a thinner and more quickly chilled sheet than that of Mount Charles. Its relation to the adjacent Waiarekan tuffs and associated Tahuian mudstones, which locally dip steeply eastward, has been rather obscured by slumping, and by the covering high-terrace gravels; but the suggestion may be made that it is portion of a relatively small sheet.

which was thrust obliquely into deformed semi-plastic sediments and tuffs, as will be shown to have been probably the case with the Moeraki dolerites. This locality has been mapped by Brown, and will be described in his forthcoming bulletin. Between it and the Mount Charles sheet Brown (pers. com.) has found by the Waianakarua estuary a swarm of basic dykes, with a general north-easterly trend. No specimens from these have been available for microscopic study, so that their possible rôle as feeders for the Mount Charles sheet or the Lookout Bluff rocks cannot yet be discussed.

The conical caps of dolerite on North (1475 feet) and South Peaks nearly four miles S. W. of Hampden rest on Upper Cretaceous conglomerate and sandstone; and their relation thereto, whether as residuals of an intrusive sheet or (less probably?) plugs, could not be ascertained. McKay (1887, p. 240)) thought that they were probably coeval with the Late Tertiary lavas capping the peaks south of the Shag River since described by Service (1934), Paterson (1941), and Benson (1942); but their petrographical nature is against this correlation. They are of the Mid-Tertiary type, and find analogues among the Moeraki rocks four miles to the east.

Evidence of the intrusive nature of the Moeraki rocks can be seen at several points along the coast, though inland it is obscured by soil-creep and alluvium. Nevertheless their effusive nature has hitherto been accepted on the authority of Haast (1877, p. 256) and Hutton (1887), p. 428), both of whom observed but misunderstood the significance of the critical evidence. Thus Haast comments: "Above the septarian beds follows a great thickness of more or less glauconitic deposits, during the formation of which eruptions of basaltic rocks took place repeatedly, which in the Moeraki Peninsula can well be studied, and where the volcanic streams have altered the sandy beds near them to porcelain jasper and rocks of similar character. Basalt tuffs are also associated with them ". Hutton noted that " the blue clay has been altered by contact of a lava flow and turned white for a distance of 2 feet to 4 feet." Haast's map and section showed the presence of five sheets of basalt interstratified with the Moeraki greensands. McKay (1887, p. 240) noted the greater complexity of the structure of the peninsula, recognising three sedimentary formations there. He distinguished three sheets of basic volcanic rocks, realised that his lower sheets were composed of the same grey dolerites as those on Mount Charles, thought they occupied the same or nearly the same horizon in the sedimentary sequence, and assigned them to the Cretaceo-Tertiary period. The supposed "youngest lava streams" in this peninsula, he grouped tentatively with the rocks of North Peak and considered them coeval with those capping the peaks in the lower part of Shag Valley, "which (at Bobby's Head) have broken through and disturbed the youngest of the Miocene rocks of the district, so that there can be no doubt that they belong to the Upper Miocene or to the Pliocene period ". As will appear below, the distinctions drawn by McKay are invalid. The Moeraki dolerite or basaltic rocks are not flows, but are all the product of Mid-Tertiary intrusions, *The Stratigraphy and Structure of Moeraki Peninsula.*

Though the Moeraki Peninsula was examined by Mr. D. A. Brown during his general survey of the large Moeraki subdivision, the interest of this small area is such that the Director of the Geological Survey has approved the writer's making a more detailed study of it prior to the publication of the official memoir. As the area appeared to be one in which the co-operation of a geologist and soil surveyor was likely to be mutually helpful, the writer, with the permission of Dr. L. I. Grange, the Director of the Soil Survey, was joined in this detailed mapping by Mr. J. D. Raeside, who was in charge of the Soil Survey's operations in Canterbury and North Otago. Age-determinations of the various sediments are necessary to make clear the structure of the Peninsula: and courteous permission has been given to the writer by those most concerned, the Director and the Micropalaeontologist, (Dr. H. J. Finlay) of the Geological Survey, to make brief use of the series-names and age-determinations which it is proposed to adopt in the official memior. Except for the minimum of stratigraphical and palaeontological data essential to our present purpose, all details concerning the sedimentary rocks and the fossils contained therein are reserved for discussion in that memoir.

The rocks exposed on the shore nearest Hillgrove Station are the glauconitic siltstone of the Moeraki series in which occur the well-known septarian concretions. It contains a good assemblage of arenaceous foraminifera indicative of a Wangaloan (Danian) age, (Finlay and Marwick, 1940, pp. 105–6), and extends throughout the western-most portion of the area here mapped in detail (Fig. 3).

On this rests the Kurinui series to which a Lower Eocene age has been assigned. It was at first " temporarily included with the Bortonian as Lower Bortonian " (Finlay and Marwick, 1940, p. 106), and comprises the lower portion of the Onekakara beds of McKay (1887, p. 6). As exposed on the beach 400–1000 yards east of Hill-grove Station the series consists of glauconitic mudstones and silt-stones containing one or more thin (1–2 feet) bands of greensand or glauconitic limestone, which stand in relief above the low-tide plat-form cut in the siltstone, and show a considerable variation in dip (usually southwards or eastwards) probably resulting from dislocation caused by the injection of the dolerite-magma and in part perhaps from the thrust of the large masses of dolerite slipping on to this semi-plastic formation. It is cut off to the east by a normal fault of small displacement. Traced southwards a weathered outcrop of the calcareous greensand is seen on a spur 300 yards S.S.E. of Hill-grove Station; and Kurinuian sediments were recognised by Brown (priv. com.) beside the railway a mile further in the same direction.

The Onekakara marly clays of the Moeraki Peninsula (McKay, 1887) are in the main of Bortonian (Middle Eocene) age. They are extremely prone to mass-movement and are the formations respon-sible for the numerous striking landslips around Onekakara Bay. They are very homogeneous, have almost the consistency of pipeclay, and fret on weathered surface just as does the Upper Eocene Tahuian Burnside mudstone of the Dunedin district.

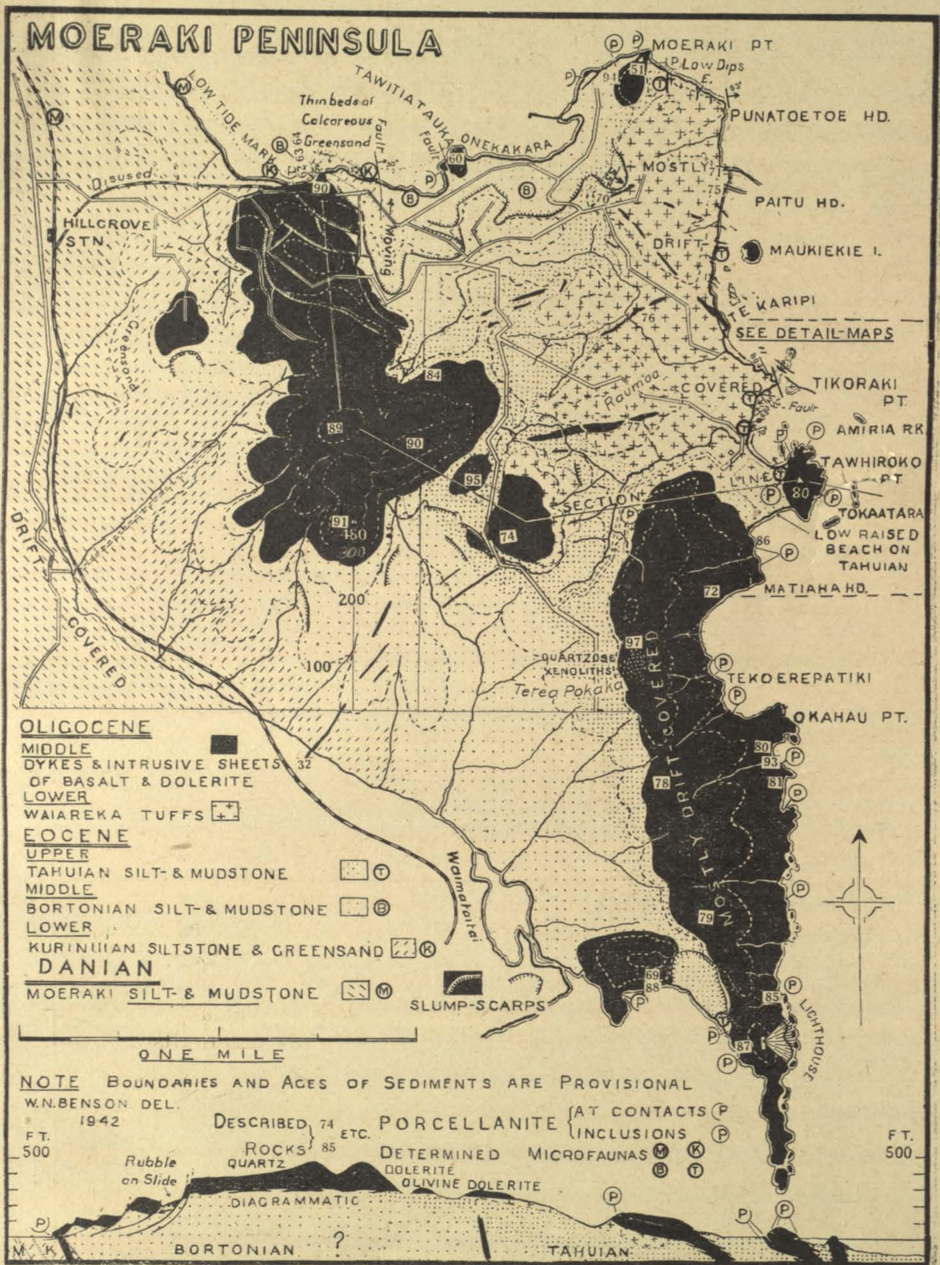

FIG. 3.

Geological Map of the Moeraki Peninsula.

NOTE.—The positions of the rocks described are indicated by the *last two digits* of their corresponding numbers in the Catalogue of Rock-slides in the Geological Department of Otago University; e.g., "51" and "60" for 5751 and 5860 respectively.

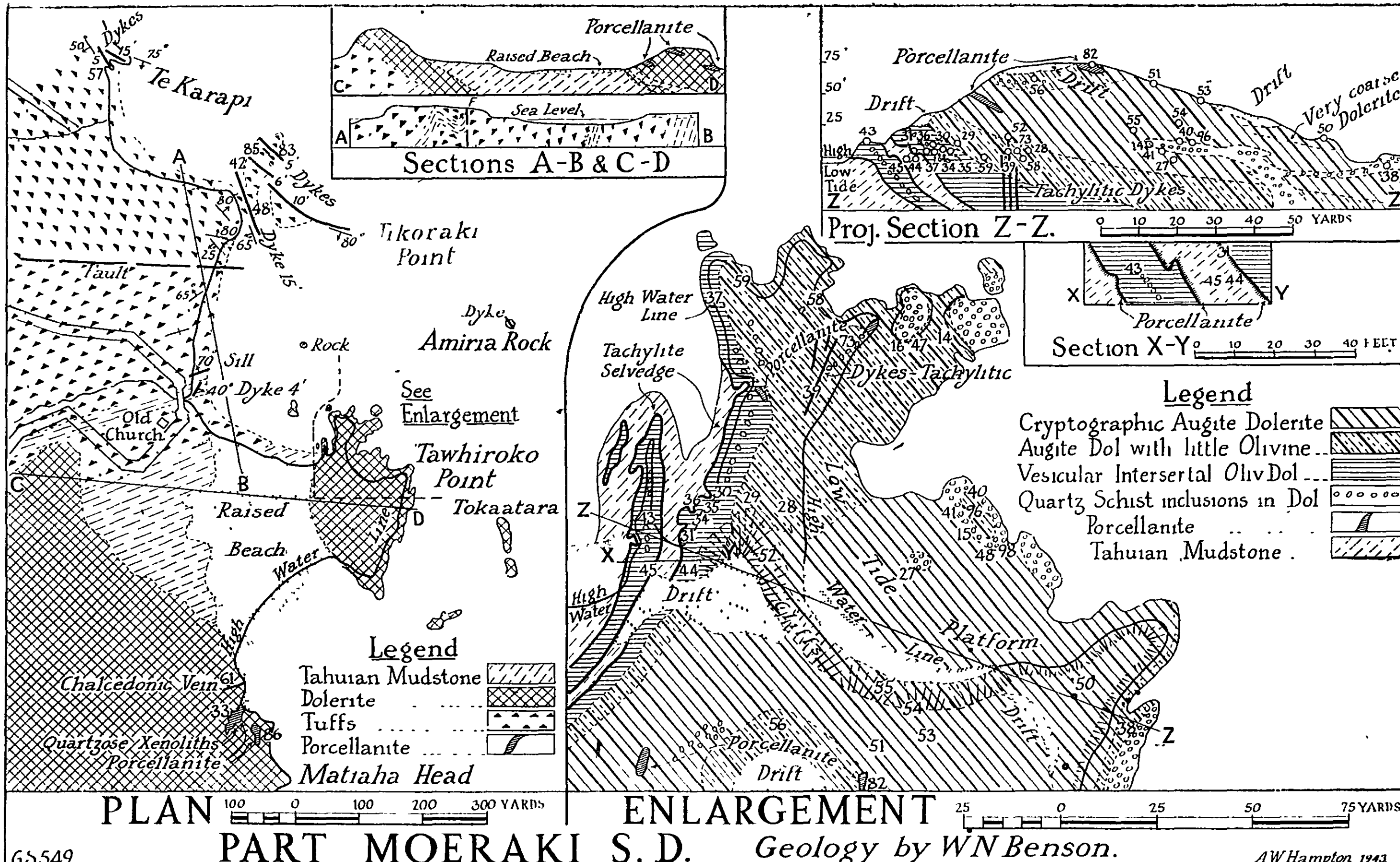

Fig 4.—Detailed Geology of the Coastline between Te Karipi Point and Matiaha Head.

Fig 5—Detailed Geological Map and Projected Section, Tawhiroko Point. Locality-Numbers of described rocks as for Fig. 3.

This last-named formation is, however, typically represented in the eastern portion of the Moeraki Peninsula, the faunal correlations being very definite (Finlay, priv. com.), the lithological resemblance being no less marked. Two facies can be distinguished. The lower resting on the Bortonian beds and lithologically indistinguishable therefrom, is that which most resembles the light grey or bluish grey Burnside mudstone. It is clearly invaded by dolerite west of the Lighthouse and of Tawhiroko Point, and again at Moeraki Point, and shows the porcellanized contact-facies at all these points: at the two last the metamorphic effect may be seen both above and below the injected material. Upon this grey mudstone rests the base of the Waiarekan tuff, the superposition being clearly visible west of Tawhiroko Point, less so east of Moeraki Point. The other facies is a mudstone with similar micro-fauna* and texture, but coloured pale greyish olivine-green. It makes a bed about 20 feet thick, interstratified with the lower portion of the Waiarekan tuff rather less than 300 feet above its base by the bridge west of Tawhiroko Point. It here dips steeply to the N.W. (see Fig. 4), but appears again in the crest of a faulted anticline 220 yards to the north, near Tikoraki Point, and at the base of the cliffs 150 yards north of Te Karipi.

The grey Tahuian mudstone adjacent to the Tawhiroko sheet contains, in addition to its distinctive foraminifera, a number of indeterminable diatoms and radiolaria, and various sponge spicules, some of which resemble forms occurring in Waiarekan beds near Oamaru (Hinde and Holmes, 1892). The bedded tuff, McKay's (1887, p. 6) correlation of which with the Waiarekan tuff is here accepted, extends along the coast from near Moeraki Point almost to Tawhiroko Point, continues inland for a short distance further south, and reaches a thickness probably in excess of 600 feet. Its macroscopic characters closely resemble those of the Waiarekan tuff of the type area and the tuffs developed at and near Cape Wanbrow. Its granular constituents and included fragments of tachylite and basalt are so decomposed that no attempt has been made at present to examine it microscopically, though such investigation and particularly the study of the heavy or weather-resistant minerals might well yield interesting results. Though the inclination of the bedding planes is well marked in some surfaces exposed to wave-action, the slumping of weathered detritus on other steep surfaces and the general covering of drift on the higher portions inland, obscure the general structure of the formation, which has, however, been so strongly dislocated that the beds stand at all angles up to the vertical. West of Tawhiroko Point the beds strike E.N.E. and dip steeply northwards, and are quite vertical midway between Tawhiroko and Tikoraki Points. Near the latter the series is broken by a fault with a southward downthrow, north of which greyish olive-green Tahuian mudstone apparently below but more probably within the lower part of the tuff is seen in the crest of a north-westerly pitching anticline, north of which the tuff strikes N.N.W. and dips steeply east (see Fig. 4). The next recorded dip, at Punatoetoe Head, is also eastward, as is that of the tuffs exposed in the high slump-scarp a quarter of a mile south of Moeraki Point. Between

* Determined by Dr. Finlay at all three occurrences noted.

this point and Punatoetoe Head the recorded eastward dips vary between 10° and 53°. In the middle of the Peninsula the dip cannot be estimated save by comparing the westward-rising elevations of the springs and indications of slumping on the mudstone beneath the tuff, which suggest a dip about 10° to the E.N.E. consonant with the general strike of the sediments forming the bulk of the Peninsula and of the basement rocks of the adjacent regions. The strongly dislocated area is thus near the north-eastern coast of the Peninsula just beyond the present limits of the massive dolerite-sheet, and is intersected by many minor intrusions striking in various directions, including the relatively large bulbous mass at Moeraki Point, apparently the southern member of a series of minor intrusions, the submarine outcrops of which make the reef extending intermittently from this point to Lookout Bluff (see Fig. 1). The relation between the strikes of the several groups of dykes in this area and the structure of the Pre-Cretaceous foundation of the region are noted below. It is here suggested that the strong local deformation of the Lower Tertiary sediments noted above is not due so much to regional tectonic forces, as to the injection of relatively large masses of basic magma into the weak Lower Tertiary sediments, the plasticity of which at the time of the intrusion is shown by the bulbous and indented forms of the margins of the intrusive sheets (cf. Figs. 5 and 8). The plasticity remains to-day as a feature expressed in major and minor slumping of these sediments. That these intrusions of magma producing localised plastic deformation in the invaded younger sediments may have been associated with localised fracturing at depth is suggested by the fact that it is only in the region of very deformed, younger formations—i.e., east of a line between Moeraki Point and the Lighthouse, that the dolerite dykes and sheets contain an abundance of fragments of quartzose schists.

The Dykes of Moeraki Peninsula.

The massive basic igneous rocks occur in dykes and sheets. The former are numerous and are generally less than 30 feet thick. They occur either singly, (e.g.) the largest dyke half a mile west of Tawhiroko Point, or in pairs, e.g., near Paitu Head, or in a long series of overlapping dykes arising possibly from a single fissure in the basement rocks, e.g., at Tikoraki Point and south of the Trig. Station E (480 feet). Some branch and many are nearly vertical, but some dip at lower angles down to 40°. They fall roughly into five groups. (a) Those that trend E.N.E. approximately perpendicular to the regional strike of the basement sediments. They include the largest dyke, perhaps a feeder of the main sheet and also the feeder at its north-western margin, the surface of which dipping S.S.E. at 30° is exposed on the beach half a mile east of Hillgrove Station. This is also the trend of most dykes in the swarm by the Waianakarua estuary. (b) The series of intrusions assumed to extend intermittently from Moeraki Point to Lookout Bluff, if correctly interpreted, extends N.N.W. parallel to the regional tectonic axis or strike of the basement formations. Two dykes crossing the Waianakarua River have this trend. (c) Dykes running W.N.W. to N.W. diagonally to these in northern half of the Peninsula, especially at and near Paitu Head, make bold outcrops (Fig. 6) and some occur in pairs. (d) Dykes following the other diagonal trending N.N.E. to N.E. are more common in the southern half of the Peninsula. (e) Small groups of dykes exposed between Paitu Head and Te Karipi radiate from Maukiekie Island, a volcanic plug, the seaward face (at least) of which is composed of horizontal columns perpendicular to its former vertical margin. Horizontal columnar structure is also displayed by some of the larger dykes.

The following are notes on certain of these intrusions. The eastern dyke at Moeraki Point is olivine dolerite (5751), and is about 50 feet thick at the water's edge, extending inland as a prominent ridge and broadening out into a flask-shaped mass. It has been quarried near the sea, where its western margin dips eastward at 35°, and has changed the adjacent mudstone in a hard greyish-green porcellanite which breaks sub-conchoidally and merges through less indurated rock into normal mudstone two feet from the dolerite. This was used by the Maoris for making implements. These rocks recall the so-called " adinole " also used for implements and derived from Mesozoic mudstones in contact with the Cretaceous dolerites of Tasmania, with which the writer has been familiar from boyhood (cf. Twelvetrees, 1901, Edwards, 1942); though there has not been noted any evidence of albitisation either of the Moeraki dolerites or of the porcellanites, nor, indeed, of the comparable Tasmanian porcellanites, which form of additive metamorphism is the essential feature of true adinole. Irregularly torn sheets of porcellanite derived from Tahuian (and Bortonian?) rocks are included within the dolerite at various points above its base, and some alteration of the mudstone can also be observed on the eastern side of the intrusion. The dyke of hypocrystalline basalt at Paitu Head strikes N.W. and forms a strong outcrop both in the cliff face (Fig. 6) and on the shore, from which it extends seaward for 50 yards. It is but a few feet thick, and shows a vertical flow-structure marked by its many vesicles. The approximately parallel dyke at Te Karipi is the largest of the N.W. group running for nearly half a mile; and divides at the coast into two portions, respectively 25 feet and 6 feet thick. It is a hypocrystalline olivine basalt (5782), and contains many angular inclusions of quartz schist, and rare xenocrysts of andesine (5857). The same series of dykes occurs at Tikoraki Point, some of which extend out towards Amiria rock, while another with a more nearly meridional trend extends towards Tawhiroko Point. These dykes are about 5–10 feet thick, dip steeply south-westward, and consist (5742, 5748) of more or less tholeiitic vesicular olivine dolerite, and contain many quartzose inclusions. They form resistant groins about which an extensive low-tide platform has been carved out of the Waiarekan tuff.

Westward of Tikoraki Point, the most massive of the E.N.E. group of dykes extends towards Trig. E and has formed the " retaining wall " for the hill Raumoa.

The dyke which crosses the railway line a mile and a-half N.W. of the Lighthouse is about 12 feet thick, forms a low ridge extending to the N.N.E., and consists (5832) of rather coarsely granular augitic (olivine) dolerite.

The Tawhiroko Sheet.

The mode of occurrence and number of the major intrusive sheets are not so obvious. Tentatively two will be recognised. The smaller Tawhiroko Sheet is well exposed and has been studied in greater detail than the main sheet; hence its greater complexity is perhaps only apparent (See Fig. 5). It is noteworthy for the abund-

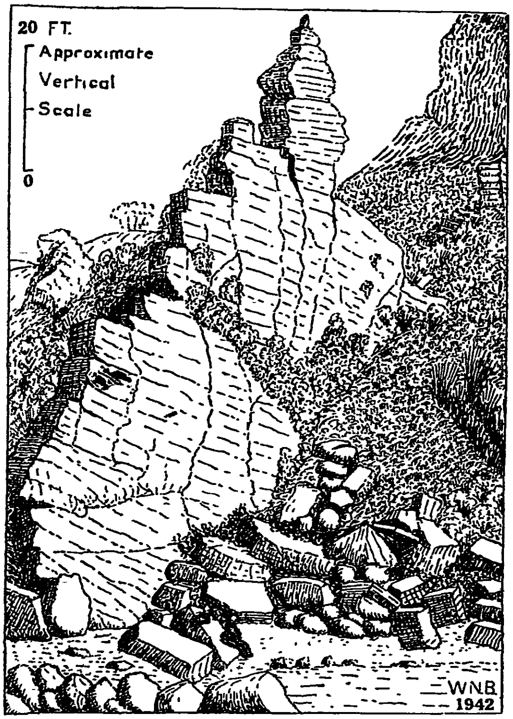

Fig. 6.

Paitu Head traced from a photograph.

ant evidence of gravitational differentiation which it affords. There is strong suggestion that it is connected genetically with the dyke striking S.S.E. through Tikoraki Point, which seems to continue through the rock in the centre of the bay into the small spur-sheet immediately west, and probably projecting from the base of the main Tawhiroko sheet. Both the Tikoraki dyke (5742) and this spur-sheet (5743) consist of similar olivine tholeiite or intersertal olivine dolerite, contain abundant inclusions of quartzose schist, and intersect obliquely the invaded formations, Waiarekan tuff and Tahuian siltstone respectively, and have each margins with such locally varying inclinations, that the different dips shown on the map do not invalidate the suggested correlation. The spur-sheet inclines southward towards the base of the main sheet and probably merges with it. Its outcrop terminates northward into a lobed hook just beneath the low-tide mark. Like it, the main sheet has a tachylite selvedge (5731) a fraction of an inch thick on its bulbous embayed lower margin. This dips locally westward but generally eastward at varying angles. Above this selvedge follows a vesicular olivine tholeiite (e.g. 5836 sp. gr. 2·84 which is lower than the normal figure because of vesicularity and the decomposition of the olivine). Its grainsize increases and content of glass decreases with increasing distance from the margin, and a holocrystalline porphyrite dolerite follows enriched in olivine by gravitative settling. Between this and the tholeiitic material is a narrow zone containing abundant xenoliths of vein-quartz and quartzose schist. Higher up is a transitional zone containing sporadic olivine, merging upwards into feldspathic augite dolerite with a noteworthy amount of platy ilmenite. The feldspars are here largely andesine in place of the labradorite present at lower levels and there is a varying amount of interstitial alkali-feldspar and crypto- or micrographic quartz-feldspar intergrowth. In or just above this transition a subsidiary sheet of a rather more basic dolerite was injected into the main sheet just after it had consolidated, but while it was still hot, and this instrusive material contains such an immense number of quartzose xenoliths that it resembles conglomerate (Cf. Harker, 1904, p. 351). The character of these inclusions and the effects resulting from their interaction with the enclosing magma will be the subject of Section C of this paper.

The central feldspathic phase of the intrusion reaches its coarsest grainsize in a pegmatoid rock (5750) derived from a "wet" differentiate of the magma. It has the minimum density (2·75) for a non-vesicular rock and occurs about 20 feet above the adjacent Tawhiroko Point. It has, however, been altered deuterically and also weathered, and the specimen analysed (No. 5 of table of analyses to be given in Part B) is less dense (2·66) and its iron more oxidized than in one found later, which however contains siderite. The vesicularity of portions of this sheet, the extensive deuteric oxidation, and subsequent weathering of most of the rocks therein prevent the use of specific gravity determinations in following the trend of differentiation.

Higher than the coarse rock last mentioned the olivine-free feldspathic and cryptographic dolerites continue for about twenty feet, and the interstitial quartz locally becomes recognisable apart from cryptographic intergrowths. Then as the upper margin is approached the feldspar decreases in alkalinity, relative abundance, and grainsize; pyroxene becomes more abundant, and small pseudomorphs after olivine and glass are present. The upper margin of the sheet has, however, been removed and a covering of silt rests on the eroded surface of the rock, which lay a few feet below that margin.

The slight inclination of the several zones of distinctive petrographic phases in the sheet suggest that it has as a whole a gentle eastward inclination and was fed from a fissure rising with indeterminable inclination somewhere near its present eastern limit.

In addition to the above-mentioned intrusion into the sheet while it was still hot, other small injections of basic magma penetrating it after it had become thoroughly chilled, have given rise to small tachylite dykes sharply transecting the dolerite. Thin finely granular veins of calcite and chalcedony also cut this sheet, and are perhaps the product of deuteric solutions. (But see Section B of this paper.)

Besides the abundance in this sheet of xenoliths of schistose rocks derived from great depths, there are irregular inclusions of porcellanite adjacent to its western margin clearly derived from the adjacent Tahuian rocks, and others near the northern and eastern margins of the sheet suggesting that its original limits at any given level were not far from those it now possesses.

Since the porcellanite inclusions in the dolerite along the seaward face of the Tawhiroko sheeet are held to indicate the proximity of the margin of that mass, the dolerite forming the outlying Tokaatara islets is thought to be either part of a satellite intrusive sheet with unknown inclination or an upfaulted portion of the Tawhiroko sheet.

The Main Moeraki Sheet.

The Main Sheet rises steeply through Tahuian mudstone, and converts it into porcellanite immediately west of the Lighthouse (Fig. 7), adjacent to which are large or small inclusions of porcellanite

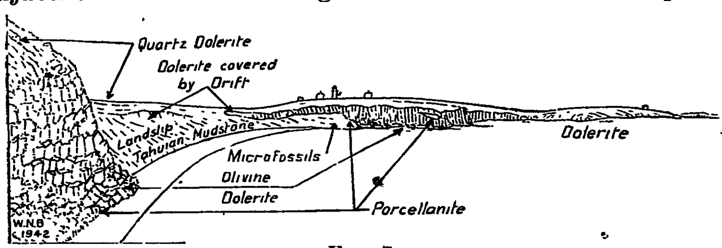

FIG. 7.

The Southern Point of Moeraki Peninsula. The dolerite sheet rising steeply through porcellanized mudstone with the dolerite laccolite (?) in the foreground.

within the dolerite both west of the Lighthouse and at various points along the eastern coast, and near the north-western extremity of this intrusion, here seeming to rise through Waiarekan tuff. The largest of these extends for about a hundred yards south of Okahau Point, a torn slab of radiolarian mudstone standing almost vertically and intimately interpenetrated by basic magma consolidated to form tachylite. The bulbous margin of the tachylite formed by injection into semi-plastic material, is particularly well seen in the small embayment north of Matiaha Head (see Fig. 8), where the invaded marly sediments have been changed to calc-silicate hornfels.

The structural relation of this sheet to the isolated mass forming the hill half a mile N.W. of the Lighthouse is not clear; and though their petrographic features are identical, there is not sufficient evidence to show whether the former is a faulted outlier or laccolitic satellite of the latter. The evidence of gravitational differentiation is strong. Olivine dolerite occurs at the lower contact with mudstone at sea-level west of the Lighthouse, and in the outlying mass, and again at sea-level near Matiaha Head. Micrographic dolerite and quartz dolerite occur in the higher portion of the outlying mass and along the ridge extending northward from the Lighthouse. An aggregate of quartose xenoliths occurs in the olivine dolerite near Matiaha Head,

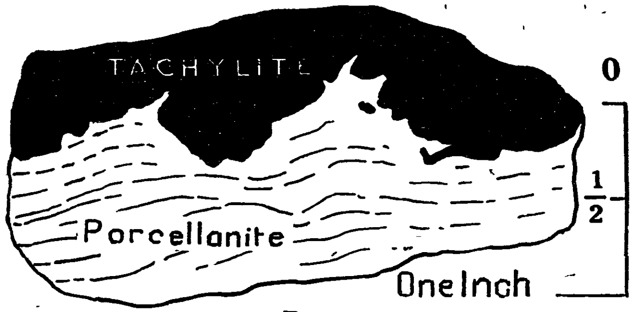

FIG. 8.

Detail showing form of tachylitic margin of dolerite against an inclusion of porcellanized marl, a very finely granular calc-silicate hornfels, from near Matiaha Head.

and in the micrographic dolerite in the highest point of the ridge known to the Maoris as Tetea Pokaka. About west and north-west of Matiaha Head the massive olivine dolerite forming the two patches half a mile east of Trig. E, the olivine dolerite half way down the slope half a mile N.N.E. of this point, also that on the shore three-quarters of a mile east of Hillgrove Station, and the small outlying patch on Tawitiatauka Point may all be considered basal portions of the same sheet. The tops of Trig. E* and of the two adjacent hills consist of micrographic quartz dolerite, the lighter differentiate from the intrusive sheet occurring about 200 feet above the olivine dolerite at the base. In view of the greater thickness involved, it is appropriate that differentiation and the concentration of silica, as well as deuteric alteration should be further advanced in these rocks than it is in the most sialic portion of the thinner Tawhiroko sheet. There are, however, certain other and minor differences notably the smaller content of apatite, which suggest, though inconclusively, that the Tawhiroko sheet was formed as an intrusion independent of the main Moeraki sheet.

The latter illustrates again the eastward-rising by transgression through the invaded sediments already noted in the petrographically unrelated Maheno-Government Hill sheet. It will be seen that half a mile east of Hillgrove the Moeraki sheet is either directly in contact with the Lower Eocene Kurinuian rocks or closely adjacent thereto (according to whether the dolerite rising through them is part of the sheet or only of a feeder thereof, the exact relation being obscured by slipped material). East of this, at Tawitiatauka, the sheet rests on and invades porcellanized Upper Bortonian siltstones. To the S.S.E. of this it transgresses into the Lower Tahuian sediments, its irregular porcellanized contact with which is seen adjacent to the Lighthouse, and finally it is in contact with the lower portion of the Waiarekan tuffs and the interstratified Upper Tahuian silts a quarter of a mile west of Tawhiroko Point.

Where were the feeding channels for this sheet is not clear. The dolerite rising through the Kurinuian sediments noted a few lines above, the dyke running N.E. from the railway line south of Trig. E, the large dyke running E.N.E. between Trig. E and Tikoraki all have the composition to be expected of dykes feeding this sheet. Along

* Trig. E is known to the local Maoris as Puketeraki, and the hill-top a quarter of a mile to the north thereof is called Potaiki.

the outer coast extending north from the Lighthouse there are the large and abundant inclusions of porcellanitized sediments which, in the case of the Tawhiroko sheet, were considered to mark the proximity of a major feeder, and it is only adjacent to this coast that abundant quartzose xenoliths have as yet been found in the main Moeraki sheet. Its anticlinal form, however, was probably not original but the result of the gentle folding prior to Late Tertiary planation which affected the adjacent Oamaru District (see Fig. 1 and Benson, 1942, p. 212, fig. 2, Section X). This new view as to the nature and posture of the Moeraki dolerites makes the correction of the earlier conception illustrated in Section A of the 1942 figure just cited foreshadowed in the legend thereto.

The Landslides of Moeraki Peninsula.

An interesting feature of the Moeraki sheet is the manner in which it has been fractured by the bulging of the downward creeping underlying mudstone and the seaward slumping of the broken strips. The road a quarter of a mile south of the northern shore of the peninsula passes between a slump-scarp rising nearly 150 feet above it, and the much lower but still steep face of the dolerite-block, which, displaced from the high scarp, has slipped northward, leaving a trough more than a hundred yards wide containing hillocks of dolerite-rubble fallen from the splintering face of the slump-scarp. Between this trough and the sea, the displaced portion of the dolerite sheet has broken into a complex of variously tilted masses of which only a simplified indication is given in the map. Its connection with the feeding dyke seems to have sheared across, and the dolerite-sheet has slipped forward to form the point 1100 yards east of Hillgrove Station. On the bush-clad surface of this very irregularly "jumbled" mass of sheet-fragments, a number of "summer cottages" are picturesquely situated.

Drifted Alluvium.

A feature of the Moeraki district worthy of note is the widespread covering of drift over nearly all the gently sloping surfaces less than 250 feet above sea level, apparently unrelated to any raised beaches or terrace-levels. This may be material that crept down the slopes formed during the dissection of a peneplain which in Late Tertiary times extended over this area. The cover is in places up to thirty feet or more thick, though generally less. It has a basal layer of small pebbles of greywacke and quartz, and grades upwards into a silty loam resembling loess save for the presence of occasional small rounded quartz pebbles. As a result the soils developed on gentle slopes at moderate elevations, notably those above the tuffs and dolerites at the northern and southern ends of the Moeraki Peninsula and on the mudstones elsewhere, are unrelated to the rocks lying unconformably beneath. Only on the higher masses of dolerite, which remained in relief during the production of a late mature topography after the first stage of the uplift of the Late Tertiary peneplain or on the steep sides of the valleys cut since the later stages of that uplift, are immature soils derived at least partly from the underlying formations. The further development of this topic is however beyond the scope of this series of papers.

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