The Geology of the Lower Shag Valley, N.E. Otago.

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Introduction.

The Lower Shag Valley comprises some fifty square miles of the Moeraki Survey District, North-east Otago (plate 7). The western portion consists of ancient metamorphic rocks (Maniototo Schists) overlain by residual patches of coal-measures which constitute the lowest unit of a series of Cretaceous to Miocene sediments covering the eastern portion of the area. In the north-east, however, in the Horse Range and near Shag Point, the basement-rock beneath the coal-measures is the only slightly-metamorphosed Kakanui Semi-schist.

Physiographically also, the area consists of three units, the western, central, and north-eastern portions respectively. The first exhibits the now largely stripped and partially dissected peneplain cut in the schist; the broad, flat-topped interfluves bearing patches of the coal-measures are separated by steep-sided valleys. The central portion is the most extensive, and is characterised by the more subdued topography developed in the softer sandstones and mudstones, from which rise the highest points—Janet's Peak (522 ft.), Smyler's Peak (675 ft.), and Puketapu (1092 ft.) capped by igneous rocks. The Shag River follows a south-easterly or easterly course through this portion of the area, and is flanked by widely extending gravel-terraces. North-east of this the Horse Range rises abruptly to a height of about 700 ft., though further east it presents a gentler seaward slope. The coast is mainly bounded by cliffs over 80 ft. high bordered by low-tide beaches.

The earliest geological work here was that of Mantell (1850), who distinguished between the concretions in the sediments at Katiki,† in the north-east of our area, and those at Moeraki, eight miles further north, and noted also the occurrence of coal at Shag Point. This coal was examined in more detail by Haast in 1871. Hutton (1875) assigned the Shag Point coal-measures to the Cretaceous, and the beds exposed around Palmerston to the Tertiary, believing that the two series were unconformable. Cox (1883) recognised the presence of a fault along the western margin of the Horse Range, and classified the unmetamorphosed sedimentary formations of the area into a single uninterrupted series of Cretaceo-Tertiary age. This view was supported by McKay (1884, 1887*a*), who included this area

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* On account of the author's departure from New Zealand, a condensation of his manuscript into publishable length has been made by Drs. W. N. Benson and F. J. Turner.

† The spelling herein adopted is that which has hitherto been used by the Geological Survey, and, the writer has been informed, will be used by that body in future. It has been approved by the official Geographic Board (1934) for future use in maps to be issued by the Department of Lands and Survey in preference to "Kartigi," which appears on most of the current maps issued by that Department and is used for the name of a railway station.—W. N. B.

within a large region mapped by him, and traced two fault-lines west of the Horse Range. Hector (1886) examined the coal-seams in Pleasant Valley, and (1892) discussed the greensands in this neighbourhood. McKay (1892) made similar examinations of the coal-measures near Shag Point. At various later dates Park (1903, 1910, 1911, 1912) discussed the relation of the coal-measures of the Shag Point and Pleasant Valley areas, concluding that the former constituted the basal member of a Cretaceous series unconformably overlain by a Tertiary series of which the Pleasant Valley coal-measures form the lowest member. This view was followed by Macdonald (1912), who described the occurrence of coal at Shag Point. Marshall (1912), however, held that the two sets of coal-measures belonged to the same Cretaceo-Tertiary series, and that their present position was the result of faulting, as McKay had indicated.

The writer's field-studies in this region were for the most part carried out early in 1938, in preparation for a thesis for the M.Sc. degree. He was helped therein by experience gained previously while assisting Mr. D. A. Brown in mapping, for the Geological Survey, the Hampden district immediately north of this area. After the commencement of the writer's independent work, Mr. Brown's studies for the Geological Survey were extended into this area, and a general summary thereof, including data from the Lower Shag Valley, has been published (Brown, 1938). The writer records his thanks for criticism and assistance to Professor Benson and Dr. F. J. Turner, under whom this work was carried out in the University of Otago, to Drs. Marwick and H. J. Finlay for palaeontological advice, and to the Director of the Geological Survey, Dr. J. Henderson, for permission to offer this work for publication and for helpful criticism.

SUMMARY OF GEOLOGICAL HISTORY.

The oldest rocks are the Maniototo Schists (? Upper Palaeozoic), and the less intensely metamorphosed Kakanui Semi-schist, phyllite and slate with the intercalated Blue Mountain Limestone (? Lower Mesozoic). As these two rock-groups comprise different metamorphic facies of sedimentary formations deposited possibly during several but as yet unknown ages, which may have been in part coeval (cf. Turner in Williamson, 1939, pp. 42–3), it is not strictly permissible to class them as products of distinct sedimentary series, as has commonly been done. It seems, however, very probable that there may be a difference in age between the most metamorphosed and the least altered of the rocks here considered. They were brought into apposition by down-faulting of the latter during the orogeny after the close of the Jurassic period. By the middle or later part of the Cretaceous period a peneplain had been cut in these two formations crossing the intervening fault-zone. Movements along the fault-zone have recurred on several occasions. The deposits laid down on this peneplain were as follows:—

(1) Coal-measures: of Senonian or rather greater age. Conglomerates, grits, sandstones, and shales with seams of coal. As a result of the renewed down-warping or down-faulting of the northern portion, the coal-measures here are about 1200 ft. thick as contrasted with 120 ft. in the southern portion.

(2) Abbotsford Beds: approximately Danian. Katiki Beach Sandstone; non-glauconitic, containing spherical and ellipsoidal concretions in the middle layers; about 600 ft. thick in the southern portion of the area and apparently only 250 ft. thick in the centre between the Horse Range faults.

(3) Green Island* Loose Sandstone: Eocene. A more or less incoherent micaceous sandstone, about 120 ft. thick.

(4) Burnside Mudstone; Upper Eocene. A fine-grained grey mudstone about 220 ft. thick.

(5) Upper Greensand (? Basal Miocene). A band of current-bedded glauconitic greensand about three feet thick, probably marking a disconformity at the top of the Burnside Mudstone.

(6) Caversham Sandstone; Lower Miocene. A yellowish, calcareous sandstone, at least 350 ft. and probably 900 ft. thick.

(7) Goodwood Limestone: Miocene. An arenaceous limestone in bands alternating with calcareous sandstone. About 300 ft. of this formation remains after erosion.

The sequence of marine sedimentation was brought to a close after the deposition of the Goodwood Limestone. The area was raised, folding and faulting took place accompanied by the intrusion of quartz porphyry into one of the fractures of the Horse Range fault-zone. The development of a second peneplain followed. The newly planed surface was then partly covered by tuffs and basalts. Faulting along the older north-west—south-east Horse Range fault-zone then recommenced causing a displacement of the younger peneplain by about 400 feet. On this differentially uplifted surface was initiated the erosion which is responsible for the present topography. The most recent movements affecting the area are indicated by three sets of terraces respectively 120–100, 60–40, and 30–20 ft. above the present river-level, and by raised wave-cut platforms 35–20 ft. above sea-level.

The Metamorphic and Semi-metamorphic Rocks.

Distribution.

The metamorphic and semi-metamorphic rocks include the Maniototo Schist (Wanaka or Otago "series") on the one hand and the Kakanui "Series" (Blue Mountain Limestone and Kakanui Semi-schist) on the other. The former lies to the south-west of the Shag Valley, while the latter, outcropping further to the north-east, is the basement on which the coal-measures of the Horse Range rest. There is thus an abrupt change in the facies of the metamorphic rocks occurring on opposite sides of the Shag Valley. The Blue Mountain Limestone is probably in the form of a lens in the Kakanui Semi-schist; but as it occupies only a small area near the northern boundary of our district, and is disturbed by the Horse Range faults, its exact form is not clearly shown.

* The name Green Island has been introduced and will in future be used to indicate the type locality for this formation between those of the Abbotsford and Burnside beds.—W. N. B.

Maniototo Schist.

The rocks of this facies are quartz-albite-chlorite-muscovite-schists having a schistose and foliated structure resulting from the alternation of layers of quartz and feldspar with foliae rich in chlorite and muscovite. These laminae may be either parallel to the schistosity planes or folded and inclined to them. In the former case the chlorite and muscovite give a lustrous appearance to the schistosity surfaces. The rocks have an average grain-size of 0·1 mm. to 0·3 mm., and contain quartz and albite in approximately equal amounts, together forming at least 75% of the total composition. The albite is in clear, usually untwinned irregular grains and has a composition of $Ab_{98}An_2$. The chlorite, which is a dark green or slightly yellowish-green type showing distinct pleochroism, has a small optic axial angle with negative sign, and is apparently identical with the type recently determined by Dr. C. O. Hutton (1940) as an aluminous pro-chlorite. It makes up between 10% and 15% of most sections. Muscovite is usually as abundant as chlorite, with which it is often interlaminated.

The accessory minerals include epidote, tourmaline, zircon, and magnetite, all of which were found in the concentrates obtained by separation with bromoform. The epidote is chiefly a colourless, poorly-birefringent clinozoisite in the form of subidioblastic crystals (0·1 mm.) elongated roughly parallel to the muscovite flakes. In some sections, there are also slender prisms of a ferriferous epidote having a yellowish-green colour and a higher birefringence. Tourmaline was not commonly observed in thin sections, although it was invariably present in abundance in the concentrations obtained from crushed specimens. It is typically in prisms ranging up to 0·75 mm. long, crowded with minute black inclusions and terminated at one end only, brown at the pyramidal end and blue at the other; secondary outgrowths are rarely developed from the former end in a direction parallel to the *c* axis. Clear dark blue, angular tourmaline was also recorded. Zircon was observed only in the concentrates, where it was always present as slightly corroded, clear, prismatic crystals and as rounded grains with dusty inclusions.

Schistosity is usually well-defined in these rocks, the planes dipping at low angles towards the east (Text-fig. 3). They are seen, in many cases, to cut across a complexly folded foliate structure, which has resulted from small-scale contortions of the quartz-albite and mica-chlorite laminae (see Plate 5, Figs. 1 to 5). The folds might have resulted from the distortion of initially horizontal foliae or they may represent a stage in the development of a horizontal from a vertical structure. In some specimens the schistosity-planes cut horizontally across the apices of the folds. However, whether the earlier structure was sub-horizontal or vertical, the ultimate result is in all cases a gently dipping main schistosity. The structures, though on a larger scale, are comparable with those further south described by Dr. F. J. Turner (1938b), who (1940, p. 169, figs. 55–66) has also given a complete petrographic analysis of a specimen supplied from this area illustrated by Plate 5, Fig. 5, herewith. A lineation resulting partly from elongation and parallel arrangement of mica and chlorite flakes, and partly from the above

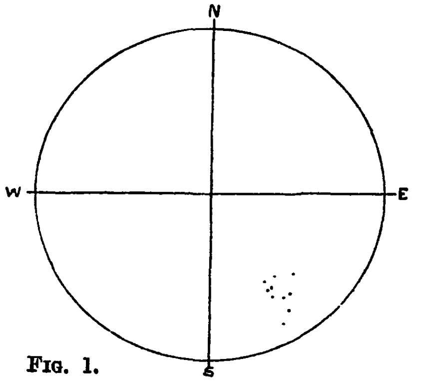

FIG. 1.

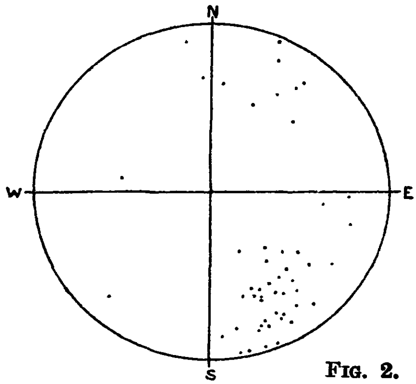

FIG. 2.

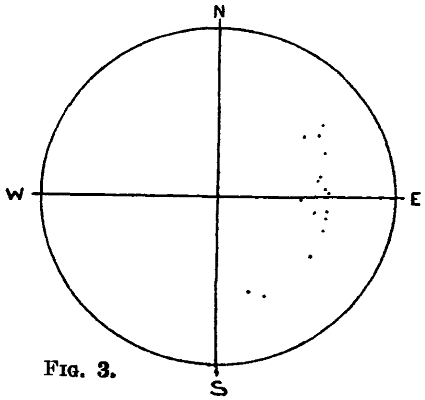

FIG. 3.

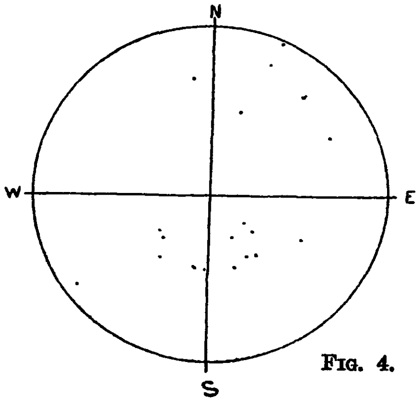

FIG. 4.

FIG. 1—Stereographic projection showing emergence (on the lower hemisphere) of the lineation of the Maniototo Schist.

FIG. 2—Stereographic projection showing the poles of the major-joint planes in the Maniototo Schists.

FIG. 3—Stereographic projections showing the poles of the schistosity-planes in the Maniototo Schists.

FIG. 4—Stereographic projection showing the poles of the major joint-planes of the Kakanui Semi-schist.

small-scale folding is a characteristic feature of rocks of the Maniototo Schists. This lineation is constant in direction (Text-fig. 1), with an average bearing of 144° and a dip of 21° E. In one specimen a second lineation bearing at 127° crossed the main lineation. These rocks are well jointed, and two joint-systems are present (Text-fig. 2). Subvertical joints of the better-marked system occur throughout the whole of the area occupied by the schist, and usually strike between 55° and 66°. It is noteworthy that as in many other regions of dynamically metamorphosed rocks (Fairbairn, 1935), these joints are approximately perpendicular to the lineation, but not exactly so. In this area, data collected in the field regarding the structure are summarised:—

(1) *Tectonic Axis* (lineation).

The tectonic axis is almost constant in direction with an average bearing of 144° and a dip of 21° E. (see Text-fig. 1), in which lineations are plotted on the lower hemisphere according to the usual convention (Knopf and Ingerson, 1938, p. 226).

(2) *Joints* (only major joints are plotted).

(a) A major system in which the individual joints are approximately at right angles to the lineation, the average bearing and dip of the poles of the joints being 148° and 15° E. respectively.

(b) An ill-defined system consisting of subvertical joints which are occasionally developed, and strike about N.W.–S.E. (see Text-fig. 2).

(3) *Schistosity.*

The schistosity-planes dip eastwards at an average angle of 26° (Text-fig. 3).

Kakanui Semi-schists, Phyllites, Slates, etc.

The rocks of the Kakanui facies consist of semi-schists and locally a micro-crystalline limestone (Blue Mountain Limestone). The semi-schists are fine-grained non-foliated rocks usually having a poorly-developed schistose structure. They consist principally of sub-angular clastic grains of quartz and feldspar set in a finely crystalline matrix of quartz, feldspar, sericite, and carbonaceous and chloritic material. The quartz-grains (0·2 mm.) are clear and always show undulose extinction; the feldspar is largely altered to sericite and kaolin. The percentage of relict grains is often between 10% and 15%, but in some cases they are entirely absent, with the result that the rock consists of minute reconstituted mineral grains. In this latter type the schistosity becomes more pronounced and the rock approaches a phyllite in macroscopic character. Of the heavy minerals separated by bromoform, pyrite was the most abundant and constant. Other minerals noted were detrital zircon, pink garnet, rare epidote, and rutile (probably authigenic). The rare tourmaline present is in the form of clastic fragments distinct from the abundant idioblastic types observed in concentrates from the rocks of the Maniototo Schist. In addition to the usual forms of zircon recorded from the Maniototo Schists, an unusual yellow-coloured grain was observed in one concentrate. Ferruginous epidote, in minute grains, is a minor constituent of the concentrates. The rare occurrence of tourmaline is noteworthy in contrast with its constant presence in the Maniototo Schists; in the Kakanui semi-schists only the clear dark blue angular variety was present (cf. Turner, 1939, p. 40).

The Blue Mountain Limestone is a white, crystalline limestone composed almost completely of micro-crystalline carbonate, which, from the negative result of staining with solutions of ferric chloride, and yellow ammonium sulphide, appears to be entirely calcite. It is brecciated along the line of the Horse Range fault No. 1 near the northern limits of the area.

Schistosity in the Kakanui rocks as opposed to that in the Otago Schist is apparently a simple structure. In the fine-grained rocks it is well-defined, which might possibly be a result of a mechanical breaking down of the larger clastic grains, but the absence of augen-structure representing an intermediate stage in phyllonitisation would suggest that these rocks were originally fine-grained types and therefore are phyllites rather than phyllonites. Faint traces of a lineation were observed in a few specimens. The rocks are well-jointed, but the joints are irregular and do not fall into any definite system (see Text-fig. 4).

The fine and coarse rock-types are comparable respectively, with the slates and greywacke-schists described by Mackie (1936) from the Mount St. Mary Range, which lies about fifty miles to the north-west. The Kakanui rocks belong chiefly to the Chl. 2 Sub-zone of Hutton and Turner (1936a).

Metamorphism and Age of the Maniototo Schist and Kakanui Semi-schist.

The structure here observed in the Maniototo Schists agrees with Dr. F. J. Turner's conception of an intense deformational metamorphism involving shearing movements on sub-horizontal planes. Further, the direction of the tectonic axis (parallel to the main lineation) in the present district accords with the general N.W. to N.N.W. trend recorded by Dr. Turner for Eastern Otago.

The widespread occurrence of tourmaline in the Maniototo Schists as previously recorded by Turner (1939) and Hutton (1939) in other parts of Otago holds good also for the present area. Both these writers believe that it owes its presence to boron-bearing emanations from a subjacent intrusion of granite synchronous with metamorphism. Lack of tourmaline in residues obtained by the writer from the Kakanui rocks in the Lower Shag Valley area confirms Dr. Turner's observations in the Naseby Subdivision, to the north-west. This latter writer has suggested that the distribution of tourmaline in the two series in question may afford a clue to whether or not they have undergone simultaneous metamorphism of different grades.

The observed structural differences between the two groups of rocks, the lack of petrographic or field transition between them, and finally the persistent presence of tourmaline in the one and almost complete absence in the other, seem almost sufficient grounds for treating the Maniototo Schists and the Kakanui rocks as two distinct geological units with different metamorphic histories. It should be noted that here, as in some other parts of Otago, the boundary between the two sets of rocks is a fault-zone (cf. Mackie, 1936).

The age of the Maniototo Schist is not known, but the date of metamorphism is believed by Turner (1938a) to be Late Palaeozoic or Early Triassic. The Kakanui rocks also are of unknown age. If, as it seems possible, they are in part coeval with the fossiliferous Mid-Triassic rocks of Mount St. Mary, their slightly metamorphosed condition must have been imprinted upon them at some later date, probably during the Late Jurassic folding.

The Younger Sedimentary Formations.

The Coal-measures.

North of the Shag Valley the semi-schists of the Horse Range are covered by conglomerate, sandstone, and shale, including the coal-seams of Shag Point, in all about 1200 ft. thick. Previous estimates of this thickness have varied between 6000–7000 ft. (Hutton, 1875) and 1250 ft. (Marshall, 1912). The lower portion is a strongly cemented conglomerate with lenses of sandstone, containing among the heavy minerals, tourmaline of the type occurring in the Otago Schists. The pebbles therein are subangular up to four inches in diameter and usually consist of semi-schists, though many pebbles are of schist or quartz, the last gradually becoming more abundant towards the upper part of the series which, apart from the coal-seams and associated shale, consists almost wholly of well-rounded quartz pebbles and sand. This seems to form into limonite-stained sandstone about 80 ft. thick containing rare marine mollusca, the Herbert series of Brown (1938), who notes the difficulty of mapping it as a unit separate from the coal-measures in which it is here included.

In the Pleasant Valley area south-west of Shag Valley, the coal-measures rest on Maniototo Schist and are, at most, 150 ft. thick. West of Smyler's Peak, the basal portion is a cemented quartz-conglomerate containing rarely fragments of schist. Elsewhere it is chiefly quartz-sandstone with pebbly bands identical in character with the higher beds at Shag Point. The highest portion is of finer grain-size and is possibly the equivalent of the molluscan beds, as Brown (1938) suggests, though no fossils have been seen in it.

Plant-impressions and impersistent layers of valueless coal occur in the shales in the basal beds of the Horse Range. The more persistent and valuable seams are near the top of the series in the quartz-conglomerate and sandstones beneath the limonitic sandstone. Haast (1877) noted 9 or 10 thin (3–12 ins.) seams in Terapupu Creek, two (one 3 ft. 9 in. thick) on the flanks of Pukeiwitai, and 8 (including one 6 ft. 6 in. thick) in Mount Vulcan, where Macdonald (1912) noted 11 seams more than a foot thick when the field was being actively exploited. At present two small mines near Shag Point are working seams respectively 6 ft. and 3 ft. 6 in. thick, the latter occurring in the sandstone immediately below the molluscan beds. No coal has been found in the Pleasant Valley area herein mapped, though it was noted in the adjacent portion of the Goodwood District (Haast, 1877; Hector, 1892; Service, 1934).

Opinions have varied as to the mutual relations of the formations here grouped together as the Coal-measures. Haast (1877) thought that two unconformable formations were present within the Horse Range series as here considered, and correlated the younger of these with the coal-measures in Pleasant Valley. Others have seen no unconformity within the Horse Range beds. Hutton (1875), Park (1903, 1910, 1911, 1912), and Macdonald (1912) thought a general unconformity occurred immediately above the Katiki Beach beds coeval with that below the Pleasant Valley coal-measures. Cox (1883), McKay (1887*a*), Hector (1886), and Marshall (1912) thought that the coal-measures on either side of the Shag Valley were members of a single sedimentary series. In the writer's view the lower portion of the Horse Range conglomerates were accumulated in a depression during or immediately after its formation by faulting and down-warping on the north-eastern side of the fault-zone, and therefore material derived from the weathering of the Maniototo Schist as well as larger fragmental blocks of semi-talus origin derived from the semi-schist, were incorporated in these conglomerates. When the depression was filled, these deposits were covered conformably by quartz-conglomerates and sandstones which overlapped beyond it to lie directly on the schist on the south side of the Shag Valley. From here similar siliceous beds lying on schist have been traced almost continuously southwards into the Dunedin district, where they are overlain by (?) Danian (Boulder Hill) or (?) Senonian (Brighton) fossiliferous beds and have been correlated with the Taratu coal-measures near Kaitangata, 80 miles south-west of Palmerston (Ongley, 1939).

Lithological continuity is not, however, proof of simultaneous deposition of these siliceous coal-measures throughout this distance. The estimate of the age of the Shag Point coal-measures as Eocene based on the 39 plant forms recognised by Ettingshausen (1891) has not been accepted by New Zealand geologists. The mollusca recorded from the Limonitic Sandstone are: *Lahillia* cf. *luisa* (Wilck.), *Arrhoges haastianus* Wilck., *Perissoptera waiparaensis* Wilck., *Neritopsis* sp., *Protodolium speighti* (Trech.), *Pleurotoma otagoensis* Wilck. and *Tubulostium* cf. *discoideum* Stol., to which may be added *Callistina* (*Tikia*) sp. noted by Dr. Marwick in the writer's collection from Little Pukeiwitai. This assemblage is probably of late Senonian age (Wilckens, 1924, p. 544). Unless the small local unconformity between the molluscan Limonitic Sandstone and the terrestrial sediments of the coal-measures noted by Brown (1938) and Haast (?) has a noteworthy time-significance, the age of the upper portion at least of the coal-measures correlated with the Taratu beds may be about Lower Senonian. If the crustal disturbance which caused the unconformity between the Taratu and the earlier Kaitangata (Mid-Cretaceous?) beds was coeval with that occurring in this area preceding the deposition of the Horse Range Conglomerates, the latter would be more nearly the age of the Taratu than of the Kaitangata coal-measures. It is, however, possible that they may be of Kaitangatan age as Dr. Henderson (1929, p. 891) has indicated.

Abbotsford Beds.

The Katiki Beach Sandstone.

The Katiki Beach Sandstone rests conformably on the Coal-measures along the coast to the north of Shag Point and also occurs in a small area between the Horse Range Faults No. 1 and 2. In the latter area the bed reaches a thickness of 350 ft.; in the former at least 300 ft. It could not be mapped south of the Shag Valley as a phase of sedimentation separable from the greensand (cf. McKay, 1884), but it is perhaps represented by the lower portion of these greensands there. Though linked by passage-beds with the coal-measure sandstone, it differs from the latter in being more argillaceous and in containing spherical and ellipsoidal concretions up to 12 ft. in diameter.

Greensand.

The Greensand is a rather varied formation which lies conformably on the Coal-measures in the western portion of the district, where it reaches 600 ft. in thickness, but decreases to 250 ft. between the Horse Range faults, where it overlies conformably the Katiki Beach Sandstone. The transition between these beds is clearly shown along the Katiki Beach, one and a half miles north of the present area. The lowest portion of the greensand contains but little glauconite, but typical richly glauconitic greensands occur towards the middle of the formation and contain numerous concretions. These, however, are hollow and differ in this respect from those of the Katiki Beach beds. The greensand is noticeably ferruginous, and in the Pleasant Valley area contains up to 38% iron (Hector, 1892). The writer could see no evidence comparable with that given by Galliher (1935) that the glauconite had been formed from biotite, although the rarity of detrital minerals in the heavy-mineral concentrate suggests that it is of chemical origin. Above the concretionary layers the proportion of glauconite decreases, and the sediments gradually become argillaceous: so that the uppermost 100 ft. of the formation consists of a fine-grained, slightly sandy mudstone with only occasional glauconitic bands up to 3 ft. thick. No fossils could be found in the Lower Shag Valley district, but the formation has been traced forty miles southwards to Abbotsford in the Dunedin district, where it contains foraminifera which have been assigned to the Danian by Dr. H. J. Finlay (private communication).

Green Island Loose Sandstone.

The Green Island Loose Sandstone, which contains abundant muscovite, rests with apparent conformity on the Greensand. It outcrops, in the present area, on the northern and western slopes of Puketapu and in four areas lying in the valley of the Shag River; but in the adjoining Goodwood district, Service (1934, p. 269) could find no sign of its presence. It appears again south of the Waikouaiti River, whence it has been traced into the Dunedin District (Dr. Benson, private communication). The thickness of the bed in the Lower Shag Valley district seems to be constant at about 120 ft., but its lithology is rather variable. On the slopes of Puketapu the bed tends to be more argillaceous than in the Shag Valley, and considerably more so than in the arenaceous phase of this formation as it is developed in the Dunedin district. The identity of the bed in the Shag Valley district, however, is shown by its characteristic heavy-mineral assemblage, by which a correlation with the Green Island Loose Sandstone of the Dunedin district was carried out. (See later section.) No fossils have been found in this formation in the Lower Shag Valley district, but because of its position between the Abbotsford bed and the Upper Eocene Burnside Mudstone it is considered to be of Eocene age.

Burnside Mudstone.

The Burnside Mudstone is fine-grained and about 220 ft. thick, lying conformably on the Loose Sandstone. The outcrop of the bed encircles Janet's Peak and partly surrounds Puketapu, while it appears again as a patch to the north-east of Bushey. According to the map prepared by McKay (1887a), this formation along with the beds now described as the Green Island Loose Sandstone and the uppermost portion of the Greensand, was placed in one series which he termed "Marly Clays."

Fossils definitely from this formation have been recorded only from the mudstone at Burnside in the Dunedin district, where foraminifera, bones and teeth of fishes including *Isurus retroflexus* Agassiz, *Notidanus marginalis* Davis, *Odontaspis elegans* Agassiz, and *O. attenuata* Davis, as well as bones of a seal have been obtained. McKay, however, states that in the "Marly Clays" of the Shag Valley "*Pecten zitteli* Hutton, *Leda* and foraminifera are not rare" (McKay, 1887b, p. 237). Chapman (1926), from the determination of foraminifera collected at Burnside, concluded that the mudstone was probably of Upper Eocene age, which is in accordance with the result of Dr. Finlay's later investigations (Finlay and Marwick, 1940).

The Upper Greensand.

In the Goodwood district the Upper Greensand shows current-bedding and rests on a well-defined uneven surface of Burnside Mudstone which contains no glauconite, marking a break in the sequence of sedimentation of considerable time-significance. Above this the greensand passes very irregularly up into the Caversham Sandstone, which contains some glauconite for several feet above its base (Service, 1934, p. 271). The greensand itself ranges up to 4 ft. in thickness. In the Lower Shag Valley district, however, only the glauconitic base of the Caversham Sandstone is exposed. This portion is exposed on the south-western and north-western slopes of Puketapu.

The Caversham Sandstone.

The Caversham Sandstone covers an area lying to the south of the Shag River in the eastern portion of the district, and also outcrops for a short distance on the north bank of the river to the east of Bushey. It is at least 350 ft. thick, but because of the Puketapu fault a precise determination of the total thickness could not be made. In the section (see map), therefore, the thickness was taken as about 900 ft., which it reaches in the Goodwood district (Service, 1934, p. 269). The bed is a yellow calcareous sandstone of constant character and contains scarce fossils (cf. McKay, 1887b, p. 236); but Service's mapping shows it to be continuous with the sandstone at Waikouaiti, about eight miles to the south. This latter formation was determined to be equivalent in age to the Upper Hutchinsonian (Thomson, 1918, p. 196) or Lower Miocene (Finlay and Marwick, 1940).

The Goodwood Limestone.

The Goodwood Limestone occupies a triangular area bordering the coastline between the lower reaches of the Shag River and Stony Creek. It consists of alternating bands of mudstone, calcareous sandstone, and impure limestone which thus distinguish it from the underlying Caversham Sandstone. The hard bands weather into conspicuous ledges in the cliff-faces, displaying honeycomb weathering. These bands range from nine inches to two feet in thickness, and although usually regularly developed, may show some degree of bending. In this case one band may be bent fairly sharply whilst the next overlying is only slightly distorted. This suggests that the structure was developed before the consolidation of the beds; in which case it may have been formed by the gliding or slumping of surface layers on an inclined sea-floor (cf. Grange, 1927, p. 28).

McKay (1887a, p. 8) suspected the existence of an unconformity between this formation and the underlying Caversham Sandstone; but no evidence in support of this view could be seen either by Service (1934, p. 270) or by the writer. Moreover, similar heavy minerals occur in the two formations (see later section). Fossils are present in the Goodwood formation in both hard and soft bands; McKay (1887b, p. 237) recorded about twenty forms. Additional fossils collected by the writer were determined by Dr. J. Marwick as follows: *Nucula* sp., *Neilo* cf. *sinangula* Finlay, *Mesopeplum costato-striatum* (Marshall), *Ostrea* cf. *wollastoni* Finlay, *Spissatella* aff. *trailli* (Hutton), *Neothyris novara* (Ihering) [large type].

These forms, together with those obtained in the Goodwood area (Service, 1934, p. 270), and in precisely comparable formations near Dunedin (Finlay and McDowell, 1923, p. 108), are sufficient to justify the correlation of the Goodwood Limestone with the Awamoan stage of Miocene age (Finlay and Marwick, 1940).

THE HEAVY MINERALS OF THE SEDIMENTARY FORMATIONS.

Petrography.

Some forty samples of rock representative of the sedimentary formations of Cretaceous and Tertiary age were treated for examination of their heavy mineral content. The sample in each case was crushed to pass a 50 mesh IMM sieve, panned with water, dried, and finally treated with bromoform. In this way a concentrate consisting of minerals with specific gravity greater than 2·9 was obtained, from which magnetite was remove with a hand-magnet.

The constituent minerals (see Plate 6) are much the same as those described from the Dunedin area by Hutton and Turner (1936*b*, pp. 266–269); the following notes merely supplement or indicate points of difference from the details given in that paper.

Andalusite. A single grain in one concentrate from the Green Island Loose Sandstone (the horizon to which this mineral is also restricted in the Dunedin district).

Apatite. Mainly in the Burnside Mudstone, Caversham Sandstone and Goodwood Limestone. Its frequent presence in the pure greensands of the Abbotsford beds is interesting.

Epidote, including both iron-rich and clinozoisitic types, is specially characteristic of the Caversham Sandstone and Goodwood Limestone.

Garnet is widely distributed, but never plentiful.

Hornblende. Two irregular grains occur in a concentrate from the Greensand of the Abbotsford beds.

Hypersthene. A single prism with schiller structure and marked pleochroism in a concentrate from near the top of the Goodwood Limestone.

Iron-ores, in part of an indeterminate character including *ilmenite* and *limonite* (some of which is derived from glauconite), are often plentiful, but are only in part detrital. *Magnetite* is the sole component of the magnetic fraction. *Pyrite* or *marcasite* occurs mainly as authigenic concretions of microscopic size in the Burnside Mudstone and to a less extent the Green Island Loose Sandstone and Abbotsford Beds. Sharply defined rhombs and micro-concretions of authigenic *siderite* are abundant in one concentrate from a pure greensand in the Abbotsford beds.

Kyanite is present in two concentrates from the Loose Sandstone. Though the grains are rare, their presence confirms the petrographic individuality of the Loose Sandstone established by Hutton and Turner, since this mineral is not known from any other rock in the Dunedin or Shag Valley districts.

Strati-graphic Unit.	Horizon.	Andalusite	Apatite	Epidote	Garnet	Hornblende	Hypersthene	Iron Ore (indet.)	Kyanite	Magnetite	Pyrite or Marcasite	Rutile	Siderite	Sphene	Tourmaline	Vesuvianite	Zircon	Zoisite
Goodwood Limestone	Upper		m	p	r		r										r	
	Upper		fa	a	r												m	
	Lower		m	m						fa		r		r	r		fa	
Caversham Sandstone	Upper		m	m	r			p				r			r		fa	
	Middle		m	a	r			a				r			r		m	
	Lower		m	a				r							fa		fa	
	Derived Material ..		r	p	r			a							r		m	
Burnside Mudstone			m					a			a				r		m	
			m							a	a				r		fa	
Green Island Loose Sandstone		r			r			p	r			m		r	fa		a	
				m				p		r		m			fa	r	a	r
				a				a				r			m		fa	
			r	r				m		r	r	r		r	fa		a	
				m				fa	r						fa		a	
			m	m	r			p		m		r			fə		a	
			r	r	r			p		m		r			fa		a	
Abbotsford Beds:— Greensand	*Uppermost		r	m		r		p		m		r			r		fa	
	Uppermost		r					p			r	r					fa	
	Upper Middle		m					p		r	r	r		r	fa		fa	
	Middle		r					m			r		p		r		m	
	Lower							a			r	r			m		a	
	Lower		r					p		m	r				m		fa	
	Lower					r		p							m		fa	
Abbotsford Beds:— Katiki Beach Sandstone	Upper (between H.R. Faults No. 1 and 2)							a			r	r			m		a	
	Upper (North-east of Fault No. 1)				r			p			r				m		a	
	Lower Middle (North-east of Fault No. 1)							a									a	
	Lower (North-east of Fault No. 1) ..							p			r				r		a	
Coal Measures	S.E. of H.R. Faults							p		m					fa		r	
	S.E. of H.R. Faults							p		m					fa		m	
	S.E. of H.R. Faults				m			p		r					r		r	
	N.E. Up. (Sandstone)							p									a	
	N.E. Upper (Qtz. grit)							a							p		a	
	N.E. Upper Middle ..							p							r		a	
	N.E. Lower							p		m		r			fa		fa	

* South-western portion of the area.

Distribution of Heavy Minerals in Cretaceous and Tertiary Sediments. p = predominant (60%); a = abundant (20–60%); fa = fairly abundant (5–20%); m = minor (0.1–5%); r = rare. (All estimates of abundance as per cent. of total concentrate were made by inspection.)

Rutile is widely distributed and includes deep red-brown and light yellow varieties. Slight rounding of the prismatic crystals indicates almost certain detrital origin.

Sphene. Nearly colourless grains from the Green Island Loose Sandstone and the Greensand of the Abbotsford beds.

Tourmaline is an almost constant, often plentiful and varied member of the heavy-mineral assemblages. The varieties noted are much the same as those described by Hutton and Turner (1936*b*, p. 268). The slender blue, brown-tipped prisms crowded with dark inclusions which are so typical of the Maniototo Schists also predominate in the rocks now under discussion. The prevalence of this type of tourmaline in the lowest beds of the Coal-measures is significant, since it shows that members of the Maniototo Schists furnished part of the material for even the earliest strata in this series. Clear brown tourmaline, often in doubly terminated crystals, is characteristic of, but not confined to, the Green Island Loose Sandstone.

Vesuvianite. A single grain in a concentrate from this Loose Sandstone.

Zircon is the most abundant and widely distributed of the heavy minerals, and includes all varieties distinguished by Hutton and Turner (1936*b*, p. 269).

Zoisite, one grain of pale yellow colour ($X > Y$), strong dispersion ($\rho < v$) and positive optical character, almost uniaxial for red light, was recorded from the Green Island Loose Sandstone.

The accompanying table gives the total distribution of heavy minerals in the concentrates taken from several exposures of the formations and examined by the writer.

Provenance.

The main conclusions reached are as follows:—

(1) The predominant minerals, zircon and tourmaline, are identical with varieties of both minerals prevalent in concentrates obtained from Otago Schists, and are therefore thought to have been derived mainly from that source. Epidote, garnet, apatite, sphene, rutile, and magnetite probably have a like origin. The well-rounded "dusty" grains of zircon mentioned by Hutton and Turner, and also noted by the writer, are believed to have come from the Kakanui semi-schists, in which they have now been found. There is nothing to add to the conclusions of Hutton and Turner (1936*b*, p. 271) regarding the source of kyanite and andalusite.

(2) Relative abundance of zircon, tourmaline, and magnetite, and lack of other minerals characterises concentrates from all horizons within the Coal-measures. The constancy of this assemblage supports the writer's view that the members of the Coal-measures are mutually conformable, and the consistent presence of tourmaline like that of the Maniototo Schists shows that the latter furnished part of the detritus for the lower as well as for the upper Coal-measures.

(3) The assemblages obtained from the lower portion of the Abbotsford Beds are much the same as those obtained from the Coal-measures. There is more variety, however, in the heavy minerals of the Greensands: apatite is almost constantly present, tourmaline

of several types is common, and a few grains of rutile can be observed in most concentrates. Except that clear acicular zircons were not found in samples collected in the Shag Valley district, there is a close similarity between the assemblages of the Greensand and those of the stratigraphically equivalent Abbotsford Mudstone in the region around Dunedin (cf. Hutton and Turner, 1936*b*, pp. 270, 272).

(4) The heavy minerals of the Green Island Loose Sandstone make up an assemblage which, as in the Dunedin district, is characterised by the variety of habit displayed by both tourmaline and zircon, presence of rare grains of andalusite, kyanite or zoisite, and almost constant occurrence of epidote and rutile. Zircon of acicular habit was not observed in concentrates from any other horizon.

(5) As in the Dunedin district the assemblage of minerals in the Burnside Mudstone is much less varied than that of the underlying Loose Sandstone, and is dominated by concretionary pyrite; tourmaline and zircon are minor or rare constituents.

(6) Constant presence of apatite and epidote and comparative rarity of tourmaline are distinctive features of concentrates from both the Caversham Sandstone (cf. Hutton and Turner, 1936*b*, p. 271) and the Goodwood Limestone, and suggest a conformable relationship between the two formations.

(7) In most respects the assemblages of heavy minerals show close similarity with those recorded from corresponding horizons in the Dunedin district by Hutton and Turner. A striking and significant discrepancy is afforded by the prevalence of tourmaline of the type common in Maniototo Schist in concentrates from the Coal-measures of the present area, compared with its rarity in concentrates from the Kaitangata coal-measures of Dunedin and absence in assemblages from the Taratu coal-measures 40 miles south of Dunedin. [It is abundant, however, in samples from the Taratu Series within the Dunedin area itself (Hutton and Turner, 1936*b*, pp. 265, 266).]

It would appear then that in the Cretaceous land-surface from which the sediments of the East Coast coal-measures were derived there were exposed only greywackes and semi-schists during the early stages of their deposition in the Kaitangata district in the south, but both Maniototo Schists and less altered formations were exposed during all stages of Cretaceous and Lower Tertiary sedimentation in the north (Shag Valley).

The Igneous Rocks.

Quartz Porphyry.

A vertical dyke of quartz porphyry (the felsite of McKay) outcrops seven chains east of the Horse Range fault No. 2, to which it is approximately parallel. It probably represents the earliest phase of igneous activity in the Lower Shag Valley, but no direct evidence of its age is available other than that it was certainly post-Senonian. Probably, however, it was injected into one of the fissures of the Horse Range series of faults during crust-movements in post-Awamoan time prior to the development of the younger (Late Miocene?) peneplain. No other rock of this type is known in Eastern Otago. It is perhaps comparable with the post-Awamoan rhyolites, the eruption of which preceded the basalt-effusions of Banks Peninsula, 160 miles to the north-east (Speight, 1935, p. 316), but it is quite unlike any of the late Tertiary volcanic rocks known or likely to occur in genetic association with the basalt-trachybasalt-phonolite-trachyte assemblage of flows in the Dunedin district (cf. Kennedy, 1933).

Petrography.

It is a cream-coloured rock containing small phenocrysts of biotite, quartz, oligoclase and orthoclase visible in hand specimen, set in a groundmass, slightly devitrified, forming 75% of the rock. The quartz (12%) is present as corroded crystals ranging up to 2 mm. in length. The feldspar phenocrysts (averaging 0·8 mm. long) are mainly oligoclase with a composition of $Ab_{79}An_{21}$, with sometimes less sodic centre ($Ab_{71}An_{29}$); phenocrysts of sanidine are rare. The feldspar microlites of the groundmass are too small to be determined (0·06 mm. long). Partially chloritised biotite in crystals and ragged flakes from 0·07 mm. to 0·8 mm. in length makes up about 3% of the rock. Iron-ore now represented by haematite dust occurs as a result of exsolution from the material of the groundmass. Fairly numerous cavities averaging 0·05 mm. long have been completely filled in by zeolites. (5090, 5091, 5092.)*

Basalts and Associated Rocks.

The effusion of basalts, etc., over the Late Tertiary peneplain occurred probably during Pliocene times. The sequence of events in the Shag Valley area has been inferred in part by comparison of their products with material obtained by Service (1934) during his study of the more varied volcanic rocks in the adjacent Goodwood district. The opening phase of volcanic activity in this area is represented by (1) the basic tuffs at Little Mountain and a dyke cutting the Coal-measures north-east of Taieri Peak. Following this an explosion mainly centred at Little Mountain resulted in the deposition of (2) the feldspathic tuff now underlying the flows on Puketapu and Janet's Peak, as well as the uppermost flow on Mount Royal† and the flow at Bobby's Head. The tuff is about 280 ft. thick on Puketapu, but it thins out southwards to only a few feet at Mount Royal (Service, 1934, p. 272), and northwards to about 100 ft. at Janet's Peak. Other occurrences of feldspathic tuff are as a dyke on the northern slopes of Puketapu, and on the western side of Smyler's Peak.

Next come (3) the medium-grained basalts capping Puketapu and Janet's Peak, and also occurring as a dyke on Little Mountain, which on petrographic grounds is correlated with the rock described by Service (1934, p. 275) from Bobby's Head. A fine-grained basalt (4) capping Taieri Peak is regarded as approximately coeval with these, though not a portion of the same flow. It is analogous to the "trachytic basalt" forming the upper flow on Mount Royal in the Goodwood area (Service, 1934, p. 272).

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* The numbers in brackets refer to slides in the collection of the Department of Geology, University of Otago.

† Mount Royal and Bobby's Head are in the adjoining Goodwood district.

The latest phase of activity is represented by the intrusion of (5) analcite-dolerite on the western slope of Puketapu.

The olivine-dolerite of Smyler's Peak has not been mentioned in the above discussion, since it has no obvious affinity with other rocks from the Shag Valley district, nor yet with the rocks described by Service. It is either a plug or a remnant of a local flow possibly occupying a depression in the surface of the Mid-Tertiary peneplain. An intrusive mode of origin is suggested by the directions of the jointing developed in the rock-mass.

Petrography.

(1) *Vitric Basic Tuff.* The following description applies in general to rocks from Little Mountain, and in particular to that of the dyke near east of Taieri Peak (5681*). The tuff consists of fragments of light-brown and black-coloured glass and schist, and also grains of quartz, augite, and olivine, with earthy iron-ore. The fragments of glass (2 mm.) form about 50% of the rock and occasionally enclose grains of augite and olivine, while the dark glass often contains laths of plagioclase in a parallel arrangement. The augite is only slightly weathered, but most of the olivine grains show alteration to opal and carbonate, or in a few cases to a greenish serpentine with mesh-structure. Lithic fragments of quartz are numerous. Vesicles are often present in the glass, and are infilled with carbonate and a light-greenish coloured opal. This rock is classified as a vitric tuff following the classification of pyroclastic rocks put forward by Howell Williams (1926, p. 228), although it lacks the vitroclastic structure usually shown in his vitric tuffs. According to Pirsson (1915), however, it would be placed as a crystal vitric tuff, in which crystals of intratelluric origin make up between 10% and 15% of the total composition of the rock.

(2) *Medium-grained Basalt.* Rocks from the summit of Puketapu (5675), from Janet's Peak (5676), and from a dyke cutting Caversham Sandstone at the south-west base of Little Mountain possess a seriate porphyritic structure, and consist principally of basic labradorite ($Ab_{40}An_{60}$ to $Ab_{30}An_{70}$) 55%–60%, augite 25%–30%, olivine 10%–15%, and magnetite 5%–10%. The plagioclase, although usually restricted to the groundmass, in which it takes the form of laths showing some degree of fluxional orientation, may also be present as phenocrysts up to 1 mm. in length. The phenocrystic augite is pale purplish, while that of the groundmass in colourless. The slightly corroded subidiomorphic grains of olivine ranging up to 3 mm. in length are either fresh or show slight alteration to a greenish serpentine or to carbonate. Apatite is usually the only accessory mineral, though one grain of biotite occurred in a section of the dyke-rock from Little Mountain and one resorbed grain of hornblende was noted in the Janet's Peak rock.

(3) A variant, differing from the above (2) mainly in the increased percentage of augite (35%–40%) with corresponding relative decrease in plagioclase (40%), is represented by rocks collected from the base of the flow capping Puketapu (5677).

(4) *Fine-grained Basalt.* The rocks here included are represented by specimens obtained from Taieri Peak (5671, 5678). They present a rather distinctive microscopic appearance owing to the

presence of phenocrysts of titanaugite (1·5 mm.) and olivine (0·4 mm.) in a very fine-grained groundmass of plagioclase laths, augite prisms and granules, and magnetite grains. The phenocrysts in all form about 15% of the rock, titanaugite predominating slightly over the partly serpentinized olivine. Zoning in the augite with a purple outer, and a very pale green inner, zone, is not infrequent. The plagioclase laths (0·3 mm.) of composition ($Ab_{45}An_{55}$) form about 55% of the total composition of the rock and tend to develop flow orientation. Magnetite, as rare grains ($<0{\cdot}6$ mm.) and abundant minute granules, makes up about 10% of the rock. Apatite is present in very small amounts. An unusual feature of one section was the presence in it of a large clot of orthoclase crystals.

(5) *Analcite-bearing Dolerite.* A medium-grained analcite-bearing dolerite (5680) with phenocrysts of olivine and titaniferous augite, forms a dyke on the western slopes of Puketapu. The slightly serpentized olivine grains (0·2 mm. to 1 mm.) make up 10% of the rock. The augite (30%) is in unaltered subidiomorphic grains averaging 1 mm. in length and pale green and purplish minute prisms. The phenocrysts of augite are commonly zoned; the pale green inner zone contains magnetite inclusions, the outer is pale purplish and clear. About 45% of the rock consists of plagioclase laths (0·2 mm.), while 10% is made up of interstitial analcite. Fairly plentiful equant grains of magnetite, and rare slender prisms of apatite are the only other constituents.

(6) *Olivine-dolerite.* Specimens collected from Smyler's Peak (5672-3-4-9) are the sole representatives of this rock-type. The structure is seriate porphyritic (Iddings, 1906). About 65% of the rock consists of plagioclase having a composition in the phenocrysts of $Ab_{25}An_{75}$, contrasting with $Ab_{37}An_{63}$ in the laths of the groundmass. Olivine partly altered to bowlingite makes up between 5 and 10% of the total composition, and occurs as rounded grains with an average length of 0·4 mm. although rarely they reach 3 mm. Pale purple prisms (0·1 mm.) and occasional pale green granules of augite together make up 25% of the rock. Magnetite (5%) occurs in two generations, as equant grains and as dust forming dendritic aggregates. Apatite and biotite are constant accessories, and traces of interstitial orthoclase and deuteric carbonate were observed in one section. Sections from the summit of Smyler's Peak show a noteworthy development of chlorophaeite (Peacock, 1930), similar to bowlingite, but occurring in interstices between the different mineral grains, instead of as a product of direct replacement of olivine.

From the above it appears that the variety of basaltic rocks present in the southern part of Shag Valley are outlying members of the comparable series of basalts which, in the adjacent Dunedin district, are associated with trachybasalts, trachytes and phonolites (Marshall, 1906).

PYROXENES IN RELATION TO PETROGENESIS OF THE BASALTIC ROCKS.

Different opinions as to the course of crystallisation of pyroxenes in basaltic magmas have been expressed by Barth (1931, 1936), Kennedy (1933), Kuno (1936) and others, with particular reference to the basalts of the Pacific region, but as yet no single hypothesis has been generally accepted. Current views have recently been summarised by Benson and Turner (1940), and a more detailed statement has been given by Edwards (1935).

With the aim of testing the contrasted hypotheses, the writer has determined optic axial angles of typical pyroxenes of basalts from the Lower Shag Valley district, using the standard Universal Stage procedure described by Nikitin (1936).

The results are tabulated below:—

Rock Type.	Mineral.	Axial Angle.	Remarks.
Olivine-dolerite (Smyler's Peak)	Titanaugite	67°+	Groundmass
	,,	66°+	,,
	,,	70°+	,,
	,,	60°+	,,
	,,	50°+	,,
	Olivine	74°—	,,
	,,	84°—	,,
Medium-grained Basalt (Janet's Peak)	Titanaugite	53°+	Phenocryst inner zone
	,,	61°+	Phenocryst outer zone
	Olivine	86°—	Microphenocryst
	,,	74°—	Groundmass
	,,	73°—	,,
	,,	76°—	,,
(Little Mountain)	Titanaugite	60°+	Phenocryst
	Augite	64°+	Groundmass
	,,	56°+	,,
	Olivine	82°—	,,
(Puketapu. Base of flow)	Augite	60°+	Phenocryst
	,,	56°+	,,
	,,	56°+	,,
	,,	55°+	,,
	,,	60°+	Groundmass
	,,	54°+	,,
	,,	52°+	,,
	,,	53°+	,,
	Olivine	86°—	Microphenocryst
	,,	80°+	Groundmass
(Puketapu. Base of flow)	Augite	51°+	Phenocryst
	,,	58°+	,,
	,,	57°+	Phenocryst inner zone
	,,	50°+	Phenocryst outer zone
	,,	54°+	Phenocryst
	,,	56°+	Groundmass
	Olivine	88°—	,,
	,,	80°—	,,
	,,	90°—	,,
Fine-grained Basalt (Taieri Peak)	Titanaugite	60°+	Phenocryst
	,,	58°+	,,
	,,	52°+	,,
			(Groundmass too fine-grained for axial angle determination.)

These results are generally similar to those obtained by Benson and Turner (1940), who have found that typical pigeonite is never present in the rocks examined by them, but that olivine is commonly a constituent of the groundmass in Dunedin basalts. Evidence obtained by the writer as to the course of crystallisation of pyroxene in the basaltic magma of the Shag Valley may be summarised as follows:—

(1) Diopsidic augite (average 2V = 59·5°) is the single phase present as phenocrysts; the lowest recorded value of 2V is 50°.

(2) Diopsidic augite and olivine occur in groundmass.

(3) Zonary structure of the normal type (Barth, 1931) and of the reverse type (cf. Kuno, 1936) was recorded in rare crystals of augite.

STRUCTURAL GEOLOGY.

To illustrate the structure of the area under consideration a structure-contour map (Text-fig. 5) has been prepared, in which contours have been drawn on four horizons, viz., the Cretaceous surfaces of the Maniototo Schist and Kakanui Semi-schists, the upper surface of the Greensand of the Abbotsford beds, and the base of the Goodwood Limestone. This procedure was necessary, firstly, because any estimation of the variation in thickness of the Coal-measures occurring in the Shag Valley depression would be purely conjectural, while secondly there is no evidence as to the total displacement across the Puketapu fault.

The central structural feature is a shallow synclinal depression, which with its axis dipping gently towards the south-east, is bounded on the north-east by the Horse Range, and on the west by the down-warped Cretaceous surface of the Maniototo Schist. Towards the southern boundary of the area the ancient peneplain surface is more uniform and continues into the Goodwood district, in which it has previously been described (Service, 1934, p. 276) as dipping in a direction generally south of east. The faults in the Lower Shag Valley district follow either the older or younger dominant strike-directions, viz., north-west to south-east, and north-east to south-west, as exemplified by the Horse Range and Puketapu faults respectively.

Folds.

The Cretaceous and Tertiary beds in the Lower Shag Valley are characterised by the dip at low angles throughout, the average being about 5°, and towards the centre of the depression they are almost horizontal. They appear, however, to be slightly bent up along the Horse Range fault No. 2, and between faults Nos. 1 and 2 slight warping is again apparent; to the south-east, fault No. 2, itself, dies out into a warp. North-east of the fault No. 1 is the upfaulted block of the Horse Range and Shag Point areas, which include the Horse Range anticline pitching south-eastwards, Mount Vulcan dome and the intervening syncline. In this portion of the area the dips of the Cretaceous rocks are in general greater, reaching as much as 65°.

The inclination of the south-western flank of the Shag Valley syncline is shown by the surface of the Maniototo Schist, disturbed locally by small faults. To the west of one of these, viz., the Palmerston fault, a structural terrace is developed. Towards the south of the district the dip of the schist-surface increases towards the east. It is probably a warp representing the dying out of the principal fault in the Goodwood district.

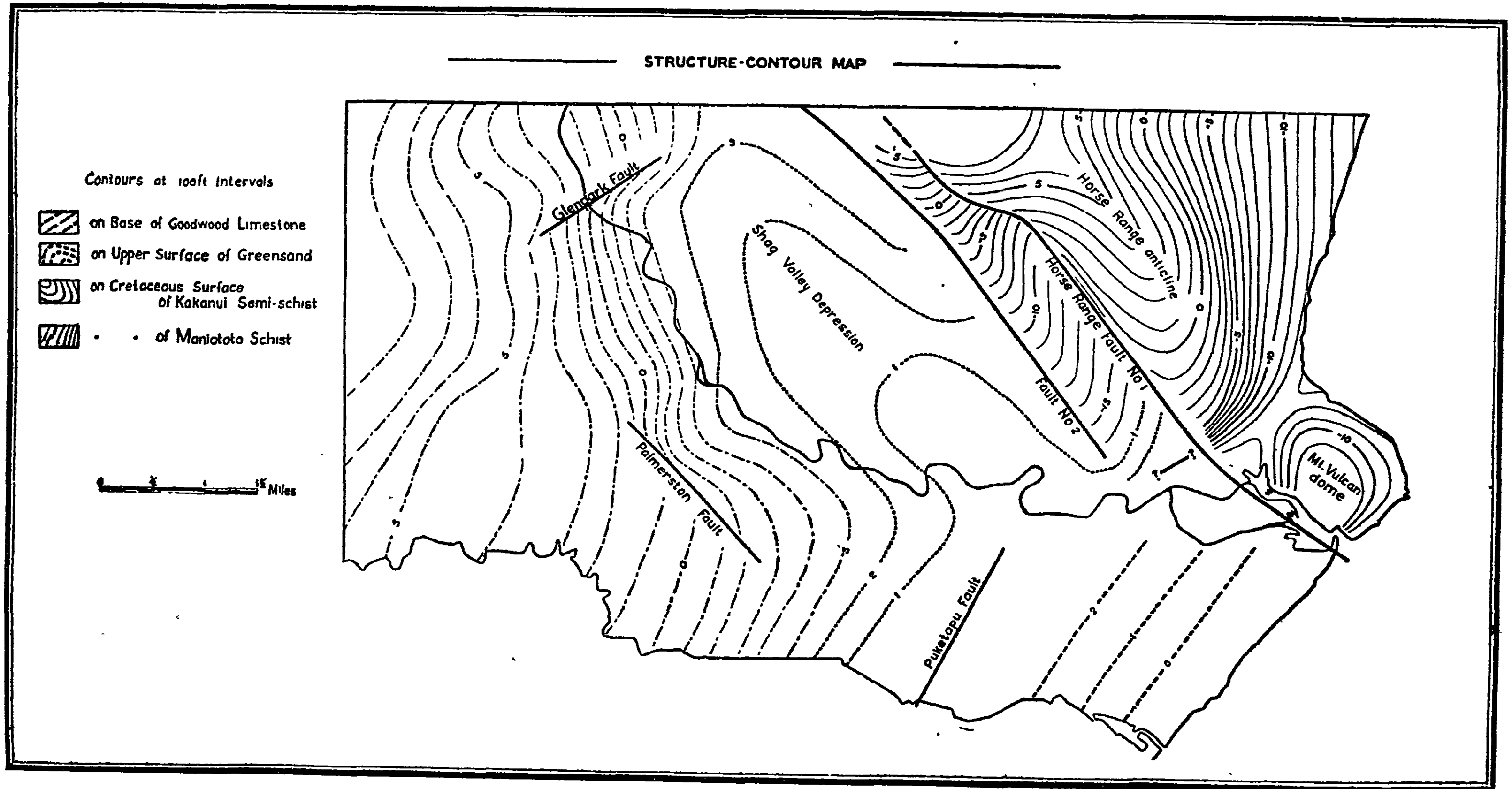

Fig. 5—Structure-contour map of the Lower Shag Valley.

Faults.

(1) Faults trending north-west.

This group includes the Horse Range faults Nos. 1 and 2 and the Palmerston fault. The first two may be considered members of a splintered fault-zone. Fault No. 1 continues from seawards of the Shag River mouth, where its throw is greatest (Hector, 1887), to beyond Pukeiwitai, where its throw is 1500 feet, the throw decreasing to less than 500 feet near the northern boundary of the area mapped. On the other hand, the throw of fault No. 2, which dies out near Bushey, increases as the fault is followed north-westwards. The maximum displacement of the Palmerston fault is only about 150 feet.

(2) Faults trending north-east.

This group includes the Glenpark and Puketapu faults and is parallel to the dominant direction of faulting traced southwards from here through the Dunedin and Kaitangata district by Professor Benson and Mr. Ongley. The Puketapu fault, in the writer's view, continues southwards into the Goodward district under the basalts of Mount Royal, though Service did not see it here. On the other hand, the principal fault traced by him in the Goodwood district does not extend into the Palmerston area. The same is true of the minor fault mapped by Service as crossing the head of Stony Creek. The position of the fault shown as occurring north-east of Bushey is hypothetical, but if the thickness of the Caversham Sandstone in this area is comparable with that in the Goodwood district, some such fault must occur near this position. It is possibly a continuation of the Puketapu fault.

The mapping shows that here, as in the Goodwood area, faulting along the north-east trend occurred before the late Tertiary peneplanation. The same is probably true of much of the faulting along the north-west trend, though as has been pointed out repeated movements have occurred along the Horse Range fault-zone, and the occurrence of some displacement here after the formation of this younger peneplain may be inferred from the modern topography. The scarp of the Glenpark fault, though it may be the result of such late movement, is more likely to result from differential erosion, i.e., it is a fault-line scarp.

PHYSIOGRAPHIC DEVELOPMENT.

The present topography has resulted from erosion initiated on an irregularly uplifted surface, and has therefore been determined partly by differential uplift and partly by differential erosion. Stages in the physiographic development can be recognised and connected with the main tectonic movements which affected the area at intervals, while the periods of erosion immediately subsequent to these movements can be distinguished by the physiographic-forms developed. These are (a) an older peneplain, (b) a younger peneplain, and (c) the modern topography resulting from dissection of these surfaces.

In Cretaceous times the mountains formed during the crust-foldings at the close of the Jurassic period were reduced to a peneplain, the stripped and dissected remnants of which still occupy considerable areas in Otago (Cotton, 1922), but are exposed only in the north-west portion of our area. This peneplain was submerged and the Cretaceous and Tertiary beds were deposited. Then

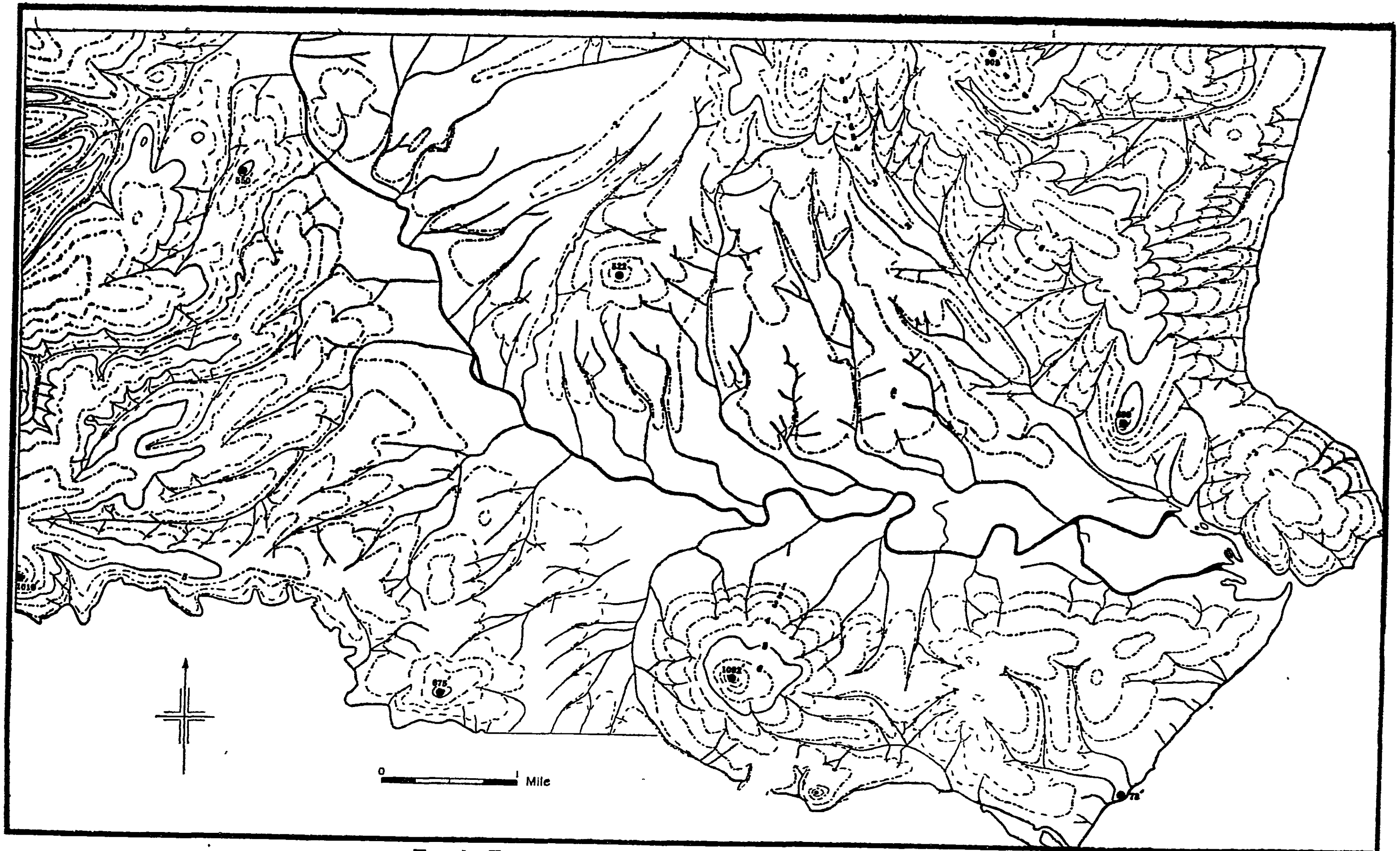

FIG. 6—Topographic contour map of the Lower Shag Valley.

uplift accompanied by folding and faulting as described in the previous section took place, after which a second period of erosion ensued with the cutting of a younger peneplain obliquely across the younger sedimentary beds (cf. Service, 1934), (Benson, 1935). On this peneplained surface, tuffs and lavas were poured out. Such deep erosion has since occurred that the existence of the younger peneplain in the area here discussed is not at first obvious, but may be inferred from the levels of the bases of masses of volcanic rocks which are residuals of a former cover resting on this peneplain. Some suggestion of its former presence is given also by the accordance of summit-levels along the Horse Range, and by the approximately even surface of the Goodwood Limestone east of Puketapu. After and possibly during the volcanic activity (cf. Benson, 1935) the district suffered regional uplift with slight warping, and renewed but reversed movement along the Horse Range faults, *i.e.,* with downthrow on the southern side. These movements revived the drainage on the now dislocated younger peneplain surface, and the present cycle of erosion was commenced by streams consequent thereon. The Shag Valley occupied a depression—part fault-angle, part syncline—much shallower than the present valley. Its western tributaries, which at first flowed over the younger sedimentary rocks, have since been superposed on the surface of the older Cretaceous peneplain cut in schist into which they have become entrenched in meandering valleys up to 500 feet deep. Locally, as in Gorge Creek, there is some indication of the influence of the joint-systems in the schist on the directions of these streams.

Subsequent streams have been developed where the Burnside Mudstone, the Green Island Loose Sandstone, or the Abbotsford beds were exposed of the surface of the younger peneplain. Palmerston Creek, *e.g.,* takes a course mainly following the position once occupied by an outcrop of Burnside Mudstone, though it has now cut over 400 feet below the level of that older surface, the younger peneplain.

Further adjustment of streams to structure is shown by the fault-line streams of which Woolshed Creek is a good example, where it follows directly along the line of the Horse Range fault No. 1. The small creeks at the north and south ends of the Horse Range faults No. 1 and 2 respectively, and also that part of Gorge Creek which flows eastwards along the line of the Glenpark fault, are further examples.

Obsequent streams have partly dissected the scarp of the Horse Range, and in many cases are bounded by steep walls. The scarp of the Horse Range (plate 5, fig. 7) is of a composite naturė, being determined by both differential erosion and differential uplift. The last displacement across the Horse Range faults took place later than the extrusion of the volcanic rocks on the younger peneplain surface, and the erosion following during the present cycle has proceeded more rapidly on the softer sedimentary rocks occupying the Shag Valley depression than on those forming the uplifted Horse Range block.

Interruptions in the present cycle of erosion are shown by terraces above the present river level at heights of:—

(1) 120 feet to 100 feet.
(2) 60 feet to 40 feet.
(3) 30 feet to 20 feet.

The gravels consist of pebbles of quartz, schist, semi-schist and basaltic material.

(1) The highest gravels are the most widespread and are found mainly north of the Shag River. Their thickness ranges up to 60 feet. Related to this level are the erosion-level in the vicinity of Palmerston and also the gravels occurring at heights from 80 feet to 100 feet along the coast south of the Shag River estuary. The last resemble remnants of marine gravels, but because of the absence of marine shells are more probably river-deposits, formed when the coastline extended further eastwards. The remnant of the 120-foot wave-cut platform at Shag Point, however, is directly comparable with this terrace-level.

(2) The 40-foot to 60-foot gravels, with the exception of those bounding Muir's Creek on the south, are found only in small patches bordering the Shag River and along a few of its tributaries. This level was not recorded in the Goodwood area (Service, 1934), but was found by the writer to be developed in the area adjoining the Shag Valley district on the north. It may represent an intermediate period of still-stand in the uplift which produced the higher terraces.

(3) The lowest terrace-gravels stand out as perfect terraces, and are mainly found flanking the Shag River. Related to them is the wave-cut platform, 35 feet high, present at Shag Point (plate 5, fig. 6), and the 20-foot to 30-foot platform bordering Katiki Beach near the northern limits of the present area.

Since the final uplift, coastal erosion has proceeded rapidly with rapid cliff recession along that part of the coast formed in the fairly soft formations. At the mouth of the Shag River, which is somewhat protected by the nearby headland, a sandspit has been built out from the southern bank thus enclosing a tidal estuary. Numerous moa-bones and implements used by the Moa-hunters and the Maoris have been collected from the sands of the spit (Haast, 1874; Teviotdale, 1924).

The Shag River has now attained grade within the area here considered, and meanders across an alluvial belt, while its tributary creeks are graded to within short distances of their heads.

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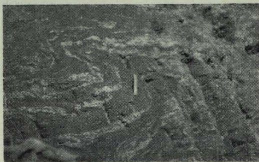


FIG. 1.

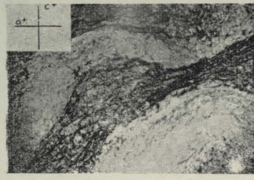


FIG. 2.

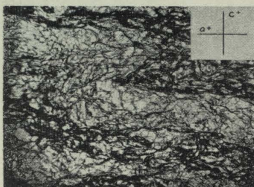


FIG. 3.

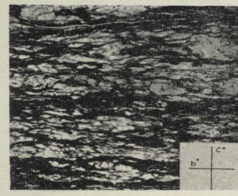


FIG. 4.

FIG. 5.

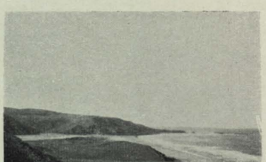


FIG. 6.

FIG. 7.

FIG. 1—Contorted quartz-albite and mica-chlorite foliae of the Maniototo Schist. Six-inch rule in the centre of view.

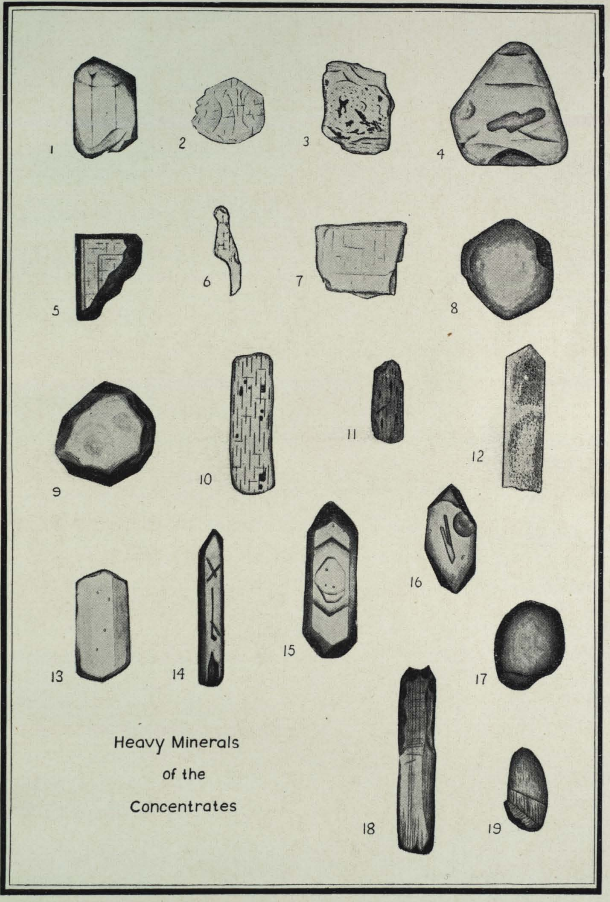
FIGS. 2, 3 and 5—Photomicrographs of Maniototo Schist cut perpendicular to band and showing contorted early *S* planes. × 8. 5 = slide 4715 in collection of Geological Department, University of Otago.

FIG. 4—Photomicrograph of Maniototo Schist cut perpendicular to *a*. × 8.

FIG. 6—Shag Point, showing the platform raised to an elevation of 35 feet above which is a remnant of the platform at an elevation of 120 feet. Mouth of the Shag River in the middle distance. Site of the Moa-hunters' encampment nearer the foreground.

FIG. 7—The composite scarp of the Horse Range, showing in the middle distance Little Pukeiwitai, the block dragged down along the line of the Horse Range fault No. 1, with Woolshed Creek at its foot. Pukeiwitai rises behind this.

To face page 56]



Heavy minerals separated from Cretaceous and Tertiary sediments of the Lower Shag Valley.

FIG. 1—Apatite. Greensand × 150. FIG. 2—Apatite. Greensand × 150. FIG. 3—Epidote. Caversham Sandstone × 125. FIG. 4—Epidote. Goodwood Limestone × 110. FIG. 5—Vesuvianite. Loose Sandstone × 150. FIG. 6—Kyanite. Loose Sandstone × 125. FIG. 7—Kyanite. Loose Sandstone × 110. FIG. 8—Garnet. Coal-measures × 150. FIG. 9—Garnet. Goodwood Limestone × 150. FIG. 10—Hypersthene. Goodwood Limestone × 150. FIG. 11—Hypersthene. Goodwood Limestone × 70. FIG. 12—Tourmaline. Coal-measures × 100. FIG. 13—Tourmaline. Loose Sandstone × 150. FIG. 14—Zircon. Loose Sandstone × 150. FIG. 15—Zircon. Coal-measures × 150. FIG. 16—Zircon. Greensand × 150. FIG. 17—Zircon. Coal-measures × 150. FIG. 18—Rutile. Loose Sandstone × 150. FIG. 19—Rutile Greensand × 150.

Geological Map and Section, Lower Shag Valley District.

To follow plate 6]

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